The Ocean in a High-CO_2 World

Ocean Acidification

Third Symposium • Monterey • California • 24-27 September • 2012

PROGRAM AND ABSTRACTS

Scientific sponsors

International Council for Science SCOR Scientific Committee on Oceanic Research

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THIRD INTERNATIONAL SYMPOSIUM ON THE OCEAN IN A HIGH CO_2 WORLD

PROGRAM AND ABSTRACTS

As part of the commitment of the International Organizing Committee to minimize the impact of the Symposium on the environment, this program book has been printed on partially recycled products.

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MONTEREY BAY AQUARIUM

Your conference badge is your ticket to the Monterey Bay Aquarium. The Aquarium will provide complimentary admission for meeting participants and their families from Monday, September 24 through Friday, September 28, 2012. The conference badge is required for admission.

The Aquarium is also offering behind-the-scenes tours on Friday, September 28 at the Aquarium Member rate to conference participants and their families, ages 6 and up. Tours are available, on a first-come, first-serve basis, at 10:30am and 12noon. Reservations must be made in advance, by phone at (831) 647-6886 or (866) 963-9645, or online at www.montereybayaquarium.org. Choose the Aquarium member price of $10 and be sure to show your conference badge during tour check-in.

ABOUT THIS BOOK

We hope that you will find this book a useful reference both during and after the Symposium. A few words of explanation may be helpful:

- The abstracts presented herein reflect the status of the detailed program as this book went to print on August 31st. Changes will be announced and posted at the Symposium and you are advised to look for these announcements on a notice board in the registration area.
- Similarly, the list of participants at the end of this book will not reflect cancelations or new registrations received after August 31st.
- The abstracts are arranged in three sections, and the pages of each section are numbered independently:
    - Plenary sessions
    - Parallel sessions
    - Poster sessions
- In each of these sections, the abstracts will be found in alphabetical order by the surname of the first author, regardless of whether that author is presenting the work at the Symposium or not. If there is more than one author, the presenting author's name is underlined.

Elizabeth Gross,
Symposium Manager

Third Symposium on the Ocean in a High-CO_2 World

INTRODUCTION

It was only eight years ago that scientists gathered at UNESCO headquarters in Paris for the *1st Symposium on the Ocean in a High-CO_2 World.* The term ocean acidification was hardly used at that time and few scientists had investigated its possible impacts on marine life. In fact, one of the main topics of the symposium was to evaluate potential strategies to artificially enhance ocean carbon uptake as a measure of mitigating atmospheric CO_2 increase and related climate change. By the end of this meeting it was clear that uptake of anthropogenic CO_2 by the ocean through natural processes and the associated changes in ocean chemistry have the potential to endanger marine organisms and ecosystems ocean-wide. As Jim Orr stated in his forward to the second symposium in this series in Monaco, "That 1st symposium marked a turning point for many of us".

A remarkable scientific endeavor has occurred since the Paris symposium in 2004. With barely 20 publications per year on possible impacts of CO_2-induced changes in ocean chemistry in 2004, this number has increased to 130 per year at the time of the 2nd *Symposium on the Ocean in a High-CO_2 World* in 2008 and is expected to pass 300 publications per year in 2012. Major national and international research projects on ocean acidification are active around the globe and numerous high-profile reports on the consequences of ocean acidification have been released over the past eight years. Ocean acidification and the associated threat for marine life are now widely recognized, not only in the scientific community, but increasingly in the general public and are starting to be acknowledged among policy makers. Whereas the 4th Assessment Report (2007) of the Intergovernmental Panel on Climate Change's (IPCC) briefly acknowledged ocean acidification as a wide-spread environmental problem, the 5th IPCC Assessment Report due in 2014 will include an in-depth assessment of both ocean climate change and acidification. There are few other examples in which an area of marine research has gained as much attention and visibility in as short a time as that on ocean acidification.

Notwithstanding the impressive progress made since the *1st Symposium on the Ocean in a High-CO_2 World,* major challenges still remain. Whereas much knowledge has been gained on the effects of ocean acidification on individual organisms, in particular calcifying taxa, we still know little about how organismal responses will play out at the community and ecosystem level. Moreover, ocean acidification doesn't happen in isolation, but co-occurs with other major changes in environmental conditions, including ocean warming and deoxygenation, and interacts with other human-induced stresses, such as over-fishing and eutrophication. Without proper knowledge of these interacting effects at the ecosystem level, it is difficult to project biogeochemical consequences and climate system feedbacks and to assess overall economic and social impacts. It is encouraging to see that many of these aspects are now being addressed by contributions to this symposium and it is inevitable that future research programs will continue to expand in this direction. Further progress is also needed in terms of international coordination of ocean acidification research, including observing networks, data management, capacity building, inter-comparison exercises, joint platforms and facilities. To that end, the launch of the Ocean Acidification International Coordination Centre (OA-ICC), hosted by the International Atomic Energy Agency (IAEA) in Monaco, marks an important step forward. Needless to say, *The Ocean in a High-CO_2 World* symposium series has played an important role in helping our community to summarize the state of knowledge, develop directions for future research and pave the path outlined above.

I would therefore like to grasp this opportunity to thank SCOR, IOC-UNESCO, and IGBP, for initiating and convening *The Ocean in a High-CO_2 World* symposium series, in particular Ed Urban and Liz Gross of SCOR and Wendy Broadgate of IGBP for their excellent work in organizing the symposia. I thank the international scientific planning committee for defining the symposium topics, reviewing the abstracts, and developing the program and the subcommittees on early-career development, chaired by Ken Denman, and on symposium press briefings, chaired by Joanie Kleypas for their dedicated work. I am truly grateful to the Monterey hosts Jim Barry, George Matsumoto, and their team for pulling the strings on all local matters with great efficiency and commitment. I am also indebted to Dan Laffoley of IUCN and Owen Gaffney of IGBP for organizing the Policy Day with admirable dedication, and to Liz Neeley of COMPASS and Jana Goldman of NOAA for coordinating the work with the media. Thanks to Adina Paytan, her students, and the many mentors who are working with early-career scientists to help them get the most out of this event. It has been a great experience for me to be part of this enthusiastic and dedicated team. Finally, I join the conveners in thanking the many financial sponsors of the symposium, listed elsewhere in this program, for making this event possible and for committing to helping support the participation of a large number of early career scientists.

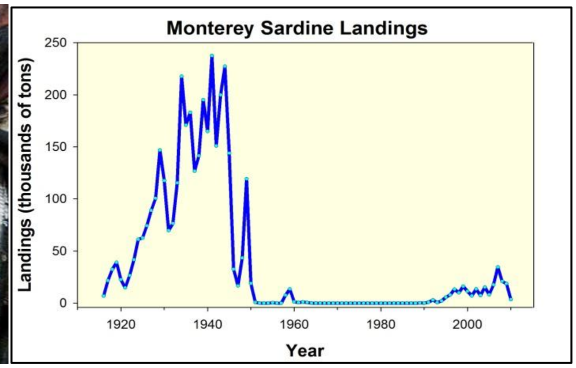
I wish all of us a scientifically stimulating and personally enlightening symposium with many exciting discussions, new perspectives and fond memories. Enjoy *The Ocean in a High-CO_2 World III* symposium in Monterey 2012.

Ulf Riebesell
Chair, International Scientific Planning Committee

WELCOME FROM THE LOCAL ORGANIZING COMMITTEE

We, the local organizing committee, are delighted to welcome visitors for the 3rd Symposium of *The Ocean in a High-CO_2 World* to the central coast of California.

Monterey has a rich history. Native Americans were the earliest known inhabitants of Monterey, including the Esalen and the Ohlone, whose descendants live here today. The Spanish explorer Viscaino arrived in 1602 and named Monterey, but Spanish colonization didn't blossom until ca. the 1770s. From 1777 to 1846, Monterey was the capital of Alta California and was the sole port of entry for international goods. Charles Dana's *Two Years Behind the Mast* is an excellent chronicle of these early days along the California coast. Monterey's stature in government and international trade diminished over time, but was replaced by bustling abalone, whaling and fisheries industries. Whaling ended by 1880, but Monterey was the *Sardine Capital of the World* from the 1920s to 1940s. The rollicking life around Cannery Row during this period is known widely through John Steinbeck's novels, such as *Cannery Row, Sweet Thursday,* and *Tortilla Flat.* Ed Ricketts, immortalized as "Doc" in Steinbeck's *Cannery Row*, was a pioneer of intertidal ecology, and authored *Between Pacific Tides* in 1939. The sardine catch declined precipitously in the 1940s and 1950s, leading to the creation (in 1949) of the California Cooperative Fisheries Investigations (CalCOFI) to conduct biological – oceanographic surveys to understand processes underlying the sardine collapse.



CalCOFI surveys continue today, representing one of the longest oceanographic / biological time-series data sets in existence, and now contribute to our understanding of ocean acidification in the N.E. Pacific. CalCOFI data and other studies suggest that natural, decadal-scale climate variation, rather than overfishing alone, is a driver of sardine population abundance. The sardine harvest returned to Monterey Bay in the 1990s, but the dilapidated processing plants along Cannery Row had since been transformed to encourage tourism, with the Monterey Bay Aquarium as its feature attraction. The Aquarium, built on the site of the Hovden Cannery, restored sections of the cannery and preserves it history.

We hope that visitors have some spare time to enjoy a few of the varied attractions of the region. The The Monterey Bay Aquarium (www.montereybayaquarium.org) is a premier attraction for the Monterey region, and will host a Wednesday evening event that shouldn't be missed by symposium participants. There should be something to please just about everyone, from enjoying the natural beauty of the coast. The shores of Monterey and Pacific Grove are wonderful - Pt. Lobos, just 15 minutes south is spectacular. Robert Louis Stevenson described Pt. Lobos as 'the most beautiful meeting of land and sea on Earth', and legend has it that it inspired his *Treasure Island* novel. Carmel is renowned for its artsy tourist shopping and famous golf (Pebble Beach). Wineries throughout the county can be tasted at various venues in the area. The Monterey County Convention and Visitors Bureau (http://www.seemonterey.com) has an excellent website with lists of many attractions, activities, and events in the area. With over 30 education and/or research organizations in the area, Monterey Peninsula is an ideal location for this Symposium and we are so pleased to welcome you to the Monterey Peninsula the 3rd Symposium on *The Ocean in a High CO_2 World*.

Third Symposium on the Ocean in a High-CO_2 World

ORGANIZING COMMITTEES

International Planning Committee:

Ulf Riebesell (Chair)	Leibniz Institute of Marine Sciences (IFM-GEOMAR), Germany
Claire Armstrong	University of Tromsø, Norway
Peter Brewer	Monterey Bay Aquarium Research Institute, USA
Ken Denman	University of Victoria, Canada
Richard Feely	National Oceanic and Atmospheric Administration, USA
Kunshan Gao	Xiamen University, China
Jean-Pierre Gattuso	Observatoire Océanologique, Laboratoire d'Océanographie, France
Dan Laffoley	Natural England & the International Union for the Conservation of Nature, UK
Yukihiro Nojiri	National Institute for Environmental Studies, Japan
James Orr	Laboratoire des Sciences du Climat et l'Environnement, France
Hans-Otto Poertner	Alfred Wegener Institute, Germany
Carlos Eduardo Rezende	Universidade Estadual do Norte Fluminense, Brazil
Daniela Schmidt	University of Bristol, UK
Anya Waite	University of Western Australia

Local Organizing Committee:

Adina Abeles, Center for Ocean Solutions
Jim Barry, Monterey Bay Aquarium Research Institute
Chris Harrold, Monterey Bay Aquarium
Ginger Hopkins, Monterey Bay Aquarium
George Matsumoto, Monterey Bay Aquarium Research Institute
With the assistance of:
- **Ruth Buell**, Monterey Bay Aquarium
- **Patricia Palacio**, Monterey Bay Aquarium
- **Judith Connor**, Monterey Bay Aquarium Research Institute
- **Jim Covel**, Monterey Bay Aquarium
- **Miki Elizondo**, Monterey Bay Aquarium
- **Adina Paytan**, University of California, Santa Cruz
- **Monterey County Convention and Visitors Bureau**

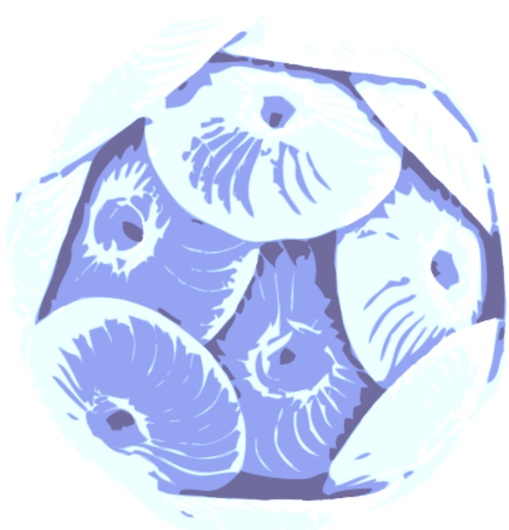
Sponsors' Representatives:

Edward R. Urban, Jr	SCOR
Wendy Broadgate	IGBP
Owen Gaffney	IGBP
J. Luis Valdes	IOC
Elizabeth Gross	Symposium Manager

CO-SPONSORS

The International and Local Organizing Committees are grateful to the following organizations and institutions for their financial support and assistance with logistics and local arrangements:

- Center for Ocean Solutions
- COMPASS
- Gordon and Betty Moore Foundation
- International Geosphere-Biosphere Programme
- International Union for the Conservation of Nature
- Intergovernmental Oceanographic Commission of UNESCO
- Monterey Bay Aquarium Research Institute
- Monterey Bay Aquarium
- Monterey Bay National Marine Sanctuary
- Monterey Bay Sanctuary Foundation
- National Marine Sanctuaries
- Naval Postgraduate School
- Scientific Committee on Oceanic Research
- U.K. Ocean Acidification Research Programme
- U.S. National Science Foundation
- World Commission on Protected Areas



COMPASS

SUNDAY

Opening Panel - Steinbeck Forum - 4:00pm

OCEAN TAPAS: SMALL BITES OF BIG OA ISSUES

The Third International Symposium on the Ocean in a High CO_2 World will kick off with a rapid-fire discussion pairing top environmental journalists and scientists to explore the latest findings, greatest challenges, and social context of ocean acidification research. Join us in this fast-paced debate moderated by Nancy Baron (COMPASS, author of Escape from the Ivory Tower) and lively conversation that will continue into the reception that follows.

MONDAY

Cocktail Reception - Serra Ballroom II - 6:30pm

COMPASS MARINE MIXER - MEET THE PRESS

Meet and mingle with journalists from a variety of outlets who have come to the meeting looking for good story ideas. COMPASS will introduce the OHCO2W Journalist Fellows and other media, and and help you make new connections. As the poster session winds down, join us for hors d'oeuvres, drinks, networking, and a fun icebreaker.

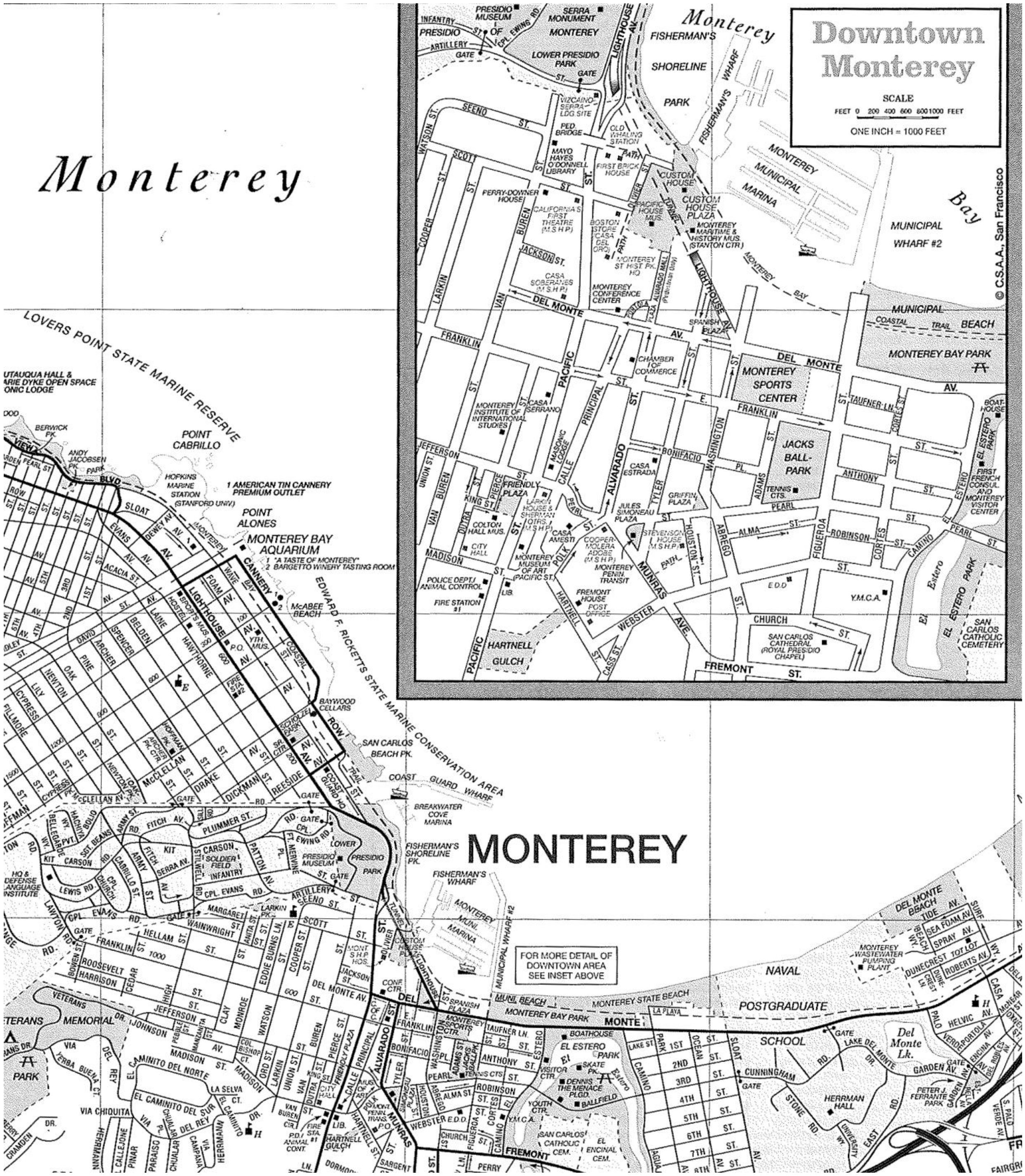
MEDIA FELLOWSHIP

COMPASS is dedicated to helping scientists find their voices and bringing science into the conversation. We are pleased to sponsor a travel fellowship to bring a multi-talented group of journalists to this conference. Keep an eye out for them and introduce yourself!

Alok Jha The Guardian	Eric Scigliano Freelance author	Lizzie Grossman Freelance author	Rose Eleveth Freelance
Chris Turner Freelance author	Erik Vance Freelance	Mark Fischetti Scientific American	Sally Ingleton Filmmaker
Christopher Joyce NPR	Juliet Eilperin Washington Post	Michael Todd Pacific Standard	Stephen Leahy Freelance
David Malakoff Science	Kate Gammon Freelance	Nancy Lord Author	Valerie Brown Freelance
Emily Gertz Freelance	Ken Weiss LA Times	Peter Frederici Freelance	Virginia Gewin Freelance

SCIENCE THAT RESONATES

www.COMPASSonline.org



The two stars in the inset map of the downtown area indicate the locations of the Monterey Conference Center and the Monterey Marriott Hotel.
The two stars on the main map indicate the locations of the Hopkins Marine Station and the Monterey Bay Aquarium.
Note the Monterey Bay Coastal Trail, a beautiful walking trail along the shoreline, and very easily reached from the Conference Center and Marriott Hotel.

RESTAURANTS IN MONTEREY

Thanks to the staff of the Monterey Bay Aquarium Research Institute for the following lists of restaurants near the Conference Center. For other ideas of things to do in Monterey, see their Web site at http://www.mbari.org/education/highco2/.

Coffee/breakfast and lunch nibbles

Starbucks - 316 Alvarado Street
Pinkberry - 316 Alvarado Street
Jamba Juice - 398 Alvarado Street
Cafe Trieste - 409 Alvarado Street
Reds Doughnuts - 433 Alvarado Street
Peets Coffee - 560 Munras Street
Trader Joes - 570 Munras Street
Wild Plum - 731 Munras Street
East Village - 498 Washington Street
Paris Bakery - 271 Bonifacio Place

Quick Lunch Locations

(These or some of the $$ restaurants below. There are also some fast food places like Taco Bell and Round Table Pizza).

Subway - 195 Franklin Street - chain offering inexpensive sandwiches
Turtle Bay - 431 Tyler Street - good inexpensive Mexican food, casual
Papa Chanos - 462 Alvarado Street - Mexican fast food; cash only, casual - reviews & menu
Denny's 398 Fremont Street

$$ Restaurants ($10-$20)

Cibo Ristorante Italiano - 301 Alvarado -
Rosines - 434 Alvarado - great family style restaurant, huge desserts
Kokos - 419 Alvarado - a little expensive for small portions
Ocean Sushi - 165 Webster- small, but excellent food
Crown and Anchor - 150 West Franklin - English pub food
London Bridge Pub - Wharf #2 - nice outdoor patio

$$$ Restaurants ($20-$30)

Benihana
Sapporo - review - nice dinner show
Esteban's - wonderful tapas. outdoor and indoor seating
Fisherman's Wharf restaurants
Cibo Restaurante Italiano

$$$$ Restaurants ($30-$50) - reservations recommended

Montrio Bistro – 414 Calle Principale
Restaurant 1833 – 500 Hartnell Street

Third International Symposium on the Ocean in a High-CO_2 World

PROGRAM AT A GLANCE

<table>
<tr><th></th><th>Sun., Sept 23</th><th>Mon., Sept 24</th><th>Tues., Sept 25</th><th>Wed., Sept 26</th><th>Thurs, Sept. 27</th></tr>
<tr><td>8:30-10:30</td><td rowspan="6"></td><td>Plenary Session[1]
Steinbeck Forum</td><td>Plenary Session[1]
Steinbeck Forum</td><td>Plenary Session[1]
Steinbeck Forum</td><td rowspan="10">All events are a partnership with the Blue Ocean Film Festival, and take place at the Golden State Theatre, 417 Alvarado Street. See page 28 for details</td></tr>
<tr><td>10:30-11:00</td><td>Break</td><td>Break</td><td>Break</td></tr>
<tr><td>11:00-12:30</td><td>3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td><td>3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td><td>3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td></tr>
<tr><td>12:30-14:00</td><td>Lunch</td><td>Lunch</td><td>Lunch</td></tr>
<tr><td>14:00-15:30</td><td>3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td><td>3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td><td>3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td></tr>
<tr><td>15:30-16:00</td><td>Break</td><td>Break</td><td>Break</td></tr>
<tr><td rowspan="2">16:00-17:30</td><td>Registration opens (16:00)
Steinbeck Lobby</td><td rowspan="2">3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td><td rowspan="2">3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td><td rowspan="2">3 Parallel Sessions[2]
Steinbeck Forum
San Carlos III & IV</td></tr>
<tr><td>Poster rooms open (16:00)
Ferrante & Serra I</td></tr>
<tr><td rowspan="2">17:30-19:30</td><td>COMPASS Ocean Acidification Panel (16:00-17:00)
Steinbeck Forum</td><td rowspan="2">Poster Session and COMPASS “Mixer” Reception
Ferrante, Serra I & II</td><td rowspan="2">Poster Session and Reception
Ferrante & Serra I</td><td>Closing session (17:30-18:00)
Steinbeck Forum</td></tr>
<tr><td>Symposium “Icebreaker” Reception (17:00-19:00)
Steinbeck Lobby</td><td>Aquarium Dinner[3]
Steinbeck Lobby</td></tr>
</table>

[1] Plenary sessions all take place in the Steinbeck Forum. There is overflow seating, with closed-circuit television, in the Colton Room.

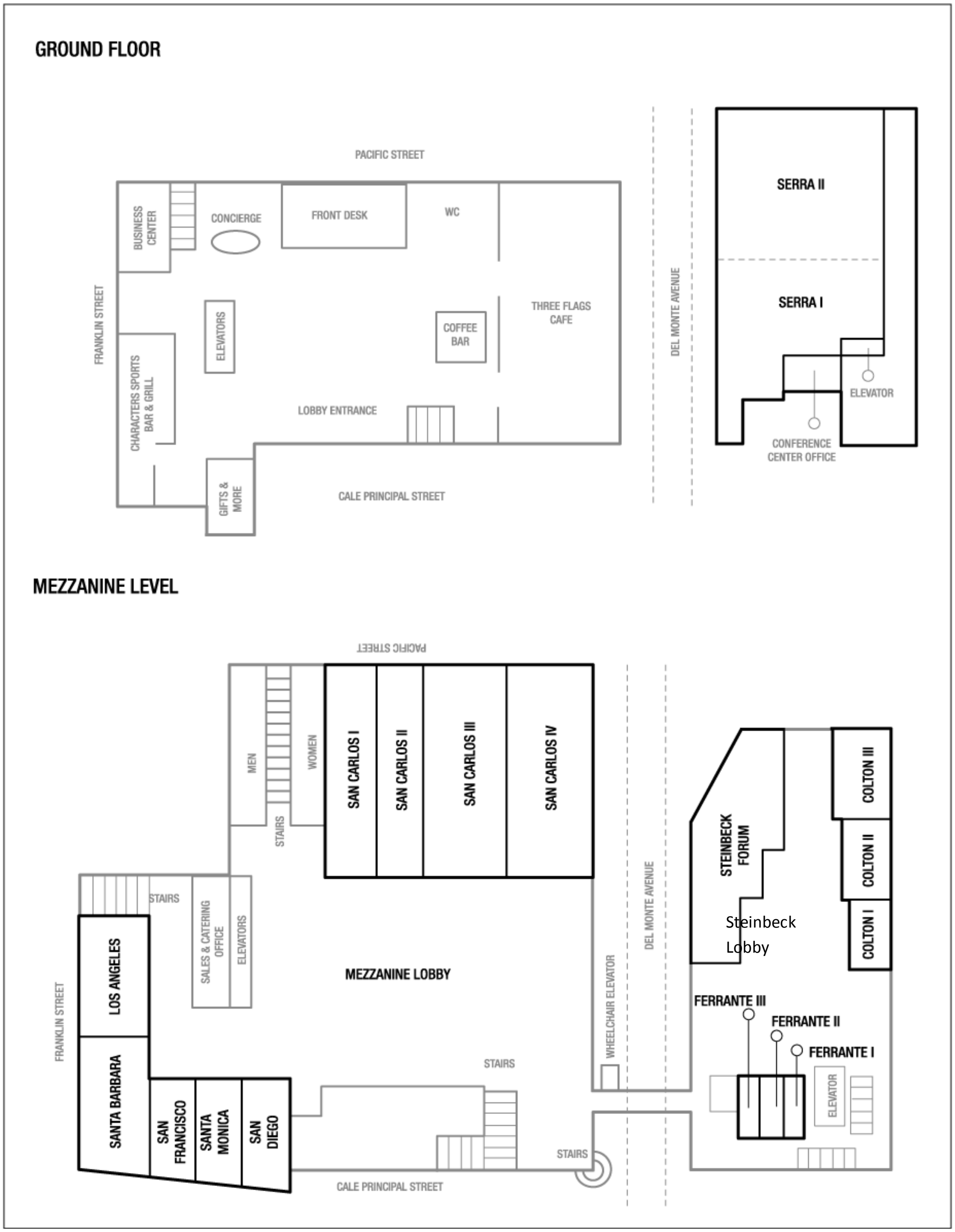
[2] Parallel sessions take place in the Steinbeck Forum in the Conference Center and in San Carlos Rooms III and IV in the Marriott Hotel, across the Sky Bridge from the Conference Center – consult the following detailed program for specific locations for each session.

[3] The Symposium dinner will be held at the Monterey Bay Aquarium. The entire Aquarium will be open for participants and registered guests from 19:30 to 23:00. Symposium badges must be worn to ensure admission to the Aquarium. The walk from the Conference Center to the Aquarium is about 1.1 miles (about 1.75 km), along the Monterey Bay Coastal Trail. A map and directions will be available at the hospitality desk in Steinbeck Lobby. Four trolleys will also be leaving from the Conference Center for the Aquarium every 10 minutes, beginning at 18:30, and will make the return trip later in the evening. The Aquarium will open its doors to us at 19:30 – please do not wait to take the last trolley, as each of them seats about 45 people. Volunteers will be available to assist you.

See the floor plan on the next page.

FLOOR PLAN

Monterey Conference Center and meeting rooms in the **Monterey Marriott Hotel**.
(Note the connection via the "Sky Bridge" over Del Monte Avenue.)



Third International Symposium on the Ocean in a High-CO_2 World

DETAILED PROGRAM

SUNDAY, 23 SEPTEMBER

16:00 Registration desk opens. Steinbeck Lobby
Poster rooms open. Authors are encouraged to bring their posters to be mounted at this time. Serra I and Ferrante Rooms
16:00-17:00 COMPASS Ocean Acidification Tapas Panel Discussion. Steinbeck Forum (see p 8)
17:00-19:00 Icebreaker Reception. Steinbeck Lobby.
19:30 Registration area and poster rooms close.

MONDAY, 24 SEPTEMBER

Steinbeck Forum - Moderator: Ulf Riebesell, Chair, Planning Committee, GEOMAR, Kiel, Germany

Opening & Welcome

8:30-8:45 Julie Packard, Monterey Bay Aquarium
8:45-9:00 Ulf Riebesell, GEOMAR, Kiel, Germany

History of Ocean Acidification Science

9:00-9:30 Peter Brewer, Monterey Bay Aquarium Research Institute

Plenary Session 1

9:30-10:00 Responses of marine organisms and ecosystems to multiple environmental stressors: Hans-Otto Pörtner, Alfred-Wegener-Institute, Germany
10:00-10:30 Acclimation and adaption to ocean acidification: Genomics, physiology, and behavior: Gretchen Hofmann, University of California, Santa Barbara

10:30 – 11:00 - ***Coffee Break***

Parallel Sessions

Responses of marine organisms and ecosystems to multiple environmental stressors

Steinbeck Forum – Session Chair: Hans-Otto Pörtner, Alfred Wegener Institute, Bremerhaven, Germany

11:00 Ocean acidification and changing structures of ocean ecosystems – Ken Denman
11:15 Multistressor controls on biodiversity: lessons from global oxygen-minimum, carbon-maximum zones – Lisa Levin and Christina A. Frieder

11:30 Deep-sea gas exchange rates in a high CO_2 world: Oxygen – Andreas Hofmann, Edward T. Peltzer, and Peter G. Brewer
11:45 Deep-sea gas exchange rates in a high CO_2 world: Carbon dioxide – Peter G. Brewer, Andreas F. Hofmann, and Edward T. Peltzer
12:00 Interactive effects of ocean acidification and temperature on benthic invertebrate behaviour affect nutrient cycling over longer timescales – Jasmin Godbold and Martin Solan
12:15 Summary/Discussion

Ecosystem change and resilience in response to ocean acidification

San Carlos III - Session Chair: Anya Waite, University of Western Australia, Crawley, Australia

11:00 Reef resilience and vulnerability consequences of ocean acidification – Kenneth R. Anthony
11:15 The Atlantic Ocean acidification test bed: measurements of net ecosystem calcification by five different methods in Puerto Rico and the Florida Keys – Chris Langdon, Dwight Gledhill, Wade McGillis, Brice Loose, Derek Manzello, and Ian Enochs
11:30 Ocean Acidification Refugia of the Florida Reef Tract – Derek P. Manzello, Ian C. Enochs, Nelson Melo, Dwight K. Gledhill and Libby Johns
11:45 Coral reefs and CO_2 seeps: Direct CO_2 effects, flow-on ecosystem changes and thresholds along CO_2 gradients – Katharina E. Fabricius
12:00 Ocean acidification affects recruitment and competition in benthic communities surrounding natural CO_2 vents – Kristy J. Kroeker, Fiorenza Micheli, and Maria C. Gambi
12:15 Summary/Discussion

Acclimation and adaptation to ocean acidification: Genomics, physiology, and behavior

San Carlos IV - Session Chair: Philip Munday: James Cook University, Townsville, Australia

11:00 A four year experimental evolution study of adaptation to increased CO_2 in the N_2-fixing cyanobacterium *Trichodesmium* – David A Hutchins, Nathan G. Walworth, Eric A. Webb, Nathan S. Garcia, Avery O. Tatters, Elizabeth K. Yu, Cynthia Breene, and Feixue Fu
11:15 Rapid evolution of a key phytoplankton species to ocean acidification – Kai T. Lohbeck, Ulf Riebesell, and Thorsten Reusch
11:30 Long-term effects of CO_2 and temperature on the pennate diatom *Cylindrotheca fusiformis* – Michael Y. Roleda, Yuanyuan Feng, Feixue Fu, Avery Tatters, Catriona L Hurd, Philip W. Boyd, and David A. Hutchins
11:45 Effects of ocean acidification on the eco-physiology of calcareous and toxic dinoflagellates – Tim Eberlein, Dedmer B. Van De Waal, Uwe John, and Björn Rost
12:00 Combined effects of different CO_2 levels and nitrogen sources on the N_2-fixing cyanobacterium *Trichodesmium* – Meri Eichner, Sven A. Kranz, and Björn Rost
12:15 Summary/Discussion

12:30-14:00 – ***Lunch***

Parallel Sessions (continued)

Responses of marine organisms and ecosystems to multiple environmental stressors

Steinbeck Forum – Session chair: Ken Denman, University of Victoria, British Columbia, Canada

14:00 Is ocean acidification a significant threat to tropical coral reefs? – Andy Ridgwell, Elena Couce, and Erica Hendy

14:15 Interactive effect of elevated pCO_2 and temperature on coral physiology and calcification: A glimmer of hope? – Andrea G. Grottoli, Verena Schoepf, Mark E. Warner, Wei-Jun Cai, Todd Melmann, Justin Baumann, Yohei Matsui, Daniel T. Pettay, Kenneth Hoadley, Hui Xu, Yongchen Wang, Quian Li, and Xinping Hu

14:30 Combined effects of ocean acidification and petroleum-related drilling mud: A study with the scleractinian coral *Lophelia pertusa* – Bechmann, Renée K., Stig Westerlund, Nadia Aarab, Arve Osland, Ingrid C. Taban, and Thierry Baussant

14:45 A fine-scale analysis of bioerosion rates in response to natural environmental variability – Nyssa Silbiger, Oscar Guadayol, Florence Thomas, and Megan Donahue

15:00 Effects of ocean acidification versus global warming on reef bioerosion - lessons from a clionaid sponge – Max Wisshak, Christine Schönberg, Armin Form, and André Freiwald

15:15 Summary/Discussion

Ecosystem change and resilience in response to ocean acidification

San Carlos III **-** Session Chair: Chris Langdon, University of Miami, Florida, USA

14:00 Physiological changes in crustose coralline algae scale up to alter competitive interactions in response to acidification – Sophie J. McCoy, Robert T. Paine, Catherine A. Pfister, and J. Timothy Wootton

14:15 Effects of ocean acidification on benthic biogeochemistry and primary production – Natalie R. Hicks, Ashleigh Currie, and Henrik Stahl

14:30 Changes to an Arctic sediment nitrogen cycling community in response to increased CO_2 – Karen Tait, Bonnie Laverock, and Stephen Widdicombe

14:45 Impact of ocean acidification on the sea urchin *Echinometra mathaei* and its roles as grazer and bioeroder in coral reefs – Laure Moulin, Julien Leblud, Antoine Batigny, Philippe Dubois, and Philippe Grosjean

15:00 Determining the resilience of ecologically-important intertidal invertebrates to elevated CO_2 and temperature: physiological responses and energetic trade-offs – Samuel P. Rastrick, Piero Calosi, Helen Findlay, Helen Graham, Jasmin Godbold, Chris Hauton, Ana Queiros, Martin Solan, John I. Spicer, Nia M. Whiteley, and Stephen Widdicombe

15:15 Summary/Discussion

Acclimation and adaptation to ocean acidification: Genomics, physiology, and behavior

San Carlos IV **-** Session Chair: David Hutchins, University of Southern California, Los Angeles, USA

14:00 Resistance to CO_2-driven seawater acidification in larval purple sea urchins – Tyler G. Evans and Gretchen E. Hofmann

14:15 Mechanism of compensation for CO_2 induced acid-base balance disturbance in marine fish – Martin Grosell, Rachael Heuer, and Andrew Esbaugh

14:30 Near-future ocean acidification really does influence fertilization success in marine invertebrates? A meta-analysis – Jon N. Havenhand, Mary Sewell, and Jane Williamson

14:45 High CO_2 rearing slows early development and alters metabolic status of larval kina, the sea urchin *Evechinus chloroticus* – Daniel W. Baker, Michael E. Hudson, Anthony Hickey, and Mary A. Sewell

15:00 Long term exposure to high-CO_2 compares paternal effect in the calcareous tube building polychaete *Hydroides elegans* – Ackley C. Lane and Vengatesen Thiyagarajan

15:15 Summary/Discussion

15:30 – 16:00 - ***Coffee Break***

Parallel Sessions (continued)

Responses of marine organisms and ecosystems to multiple environmental stressors

Steinbeck Forum – Session chair: Kai Schulz: GEOMAR, Kiel, Germany

16:00 Rising carbon dioxide and increasing light exposure act synergistically to reduce marine primary productivity – Kunshan Gao, Juntian Xu, Guang Gao, Yahe Li, David A. Hutchins, Bangqin Huang, Ying Zheng, Peng Jin, Xiaoni Cai, Donat-Peter Häder, Wei Li, Kai Xu, Nana Liu, and Ulf Riebesell

16:15 Climate change effects on summer and spring bloom phytoplankton communities? Two multifactorial studies on ocean acidification, temperature and salinity – Maria Karlberg, My Björk, Melissa Chierici, Julie Dinasquet, Malin Olofsson, Lasse Riemann, Franciska Steinhoff, Anders Torstensson, and Angela Wulff

16:30 Climate change effects on seagrasses, macroalgae and their ecosystems: Elevated DIC, temperature, OA and their interactions – Marguerite S. Koch, George E. Bowes, Cliff Ross, and Xing-Hai Zhang

16:45 Combined impacts of climate warming and ocean carbonation on eelgrass (*Zostera marina* L.) – Richard C. Zimmerman and Victoria J. Hill

17:00 Low level dissolved oxygen and ph effects on the early development of market squid, *Doryteuthis opalescens* – Michael O. Navarro, Christina A. Frieder, Jennifer Gonzalez, Emily Bockmon, and Lisa A. Levin

17:15 Summary/Discussion

Biogeochemical consequences of ocean acidification and feedbacks to the Earth system

San Carlos III – Session Chair: Scott Doney, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA

16:00 The effect of ocean acidification and temperature increase on benthic ecosystem functioning in contrasting sediment types – Jan Vanaverbeke, Ulrike Braeckman, Carl Van Colen, and Magda Vincx

16:15 Permeable carbonate sands modify the carbon chemistry of overlying waters – Bradley D. Eyre, Isaac Santos, and Tyler Cyronak

16:30 Drivers of seawater carbonate chemistry on shallow-water coral reef systems of the Great Barrier Reef – Rebecca Albright and Kenneth Anthony

16:45 The high variability CO_2 world of Hawaiian coral reefs – Patrick S. Drupp, Eric H. De Carlo, Robert Thompson, Fred T. Mackenzie, Frank Sansone, Andreas Andersson, Sylvia Musielewicz, Stacy Maenner-Jones, Christopher L. Sabine, and Richard A. Feely

17:00 Does ocean acidification amplify global warming by reducing marine biogenic sulfur production? – Katharina D. Six, Silvia Kloster, Tatiana Ilyina, Ernst Maier-Reimer, Kai Zhang, and Stephen D. Archer

17:15 Summary/Discussion

Acclimation and adaption to ocean acidification: Genomics, physiology, and behavior

San Carlos IV - Session Chair: Adina Paytan, University of California, Santa Cruz, USA

16:00 Transcriptome-wide scan reveals genes potentially affected by ocean acidification in red abalone (*Haliotis rufescens*) along the California coast – Pierre De Wit and Stephen R. Palumbi

16:15 Changes in prey-predator interaction and avoidance behavior may result from ocean acidification – Patricio H. Manriquez, Marco A. Lardies, Cristian A. Vargas, Rodrigo Torres, Loreto Mardones, Maria Elisa Jara, Cristian Duarte, Jorge M. Navarro, and Nelson A. Lagos

16:30 Transgenerational acclimation to ocean acidification in reef fish – Gabrielle M. Miller, Sue-Ann Watson, Jennifer M. Donelson, Mark I. McCormick, and Philip L. Munday

16:45 Ocean acidification alters behaviour and interferes with brain function in marine fish – Philip Munday

17:00 Adult exposure influences offspring response to ocean acidification in oysters – Laura M. Parker, Pauline M. Ross, Wayne A. O'Connor, Larissa Borysko, David A. Raftos, and Hans-Otto Pörtner

17:15 Summary/Discussion

17:30-19:30 – ***Poster Session – Serra I***

18:30 ***Reception (COMPASS Mixer) - Serra II*** *(adjoining the poster session,* *see p 8**)*

TUESDAY, 25 SEPTEMBER

Steinbeck Forum - Moderator: James P. Orr, Laboratoire des Sciences du Climat et l'Environnement, Saclay, France

Plenary Session 2

8:30-9:00 Biogeochemical consequences of ocean acidification and feedbacks to the Earth system: Richard Matear

9:00-9:30 Interactions of ocean acidification with physical climate change: Laurent Bopp

9:30-10:00 Rates of change of ocean acidification: Insights from the paleorecord: Daniela Schmidt

10:00-10:30 Changes in ocean carbonate chemistry since the Industrial Revolution: Richard Zeebe

10:30 – 11:00 - ***Coffee Break***

Parallel Sessions

Responses of marine organisms and ecosystems to multiple environmental stressors

Steinbeck Forum – Session chair: Jon Havenhand, University of Gothenburg, Tjärnö Marine Biological Laboratory, Strömstad, Sweden

11:00 Reproduction in a changing ocean: The effects of long term exposure to combined multiple stressors – Helen Graham, Samuel Rastrick, Gary S. Caldwell, Matthew G. Bentley, Stephen Widdicombe, and Anthony S. Clare

11:15 Persistent, multistressor effects across life stage transitions in Olympia oysters – Annaliese Hettinger, Brian Gaylord, Eric Sanford, Tessa M. Hill, and Ann D. Russell

11:30 Physiological responses of invertebrate sperm to a contaminated, high CO_2 ocean: Mechanisms and consequences? – Ceri Lewis, Karen Chan, and Sam Dupont

11:45 Physiological response of the stenothermal Antarctic fish *Notothenia rossii* to ocean warming and acidification – Felix C. Mark, Anneli Strobel, Elettra Leo, Swaantja Bennecke, Martin Graeve, and Hans-Otto Pörtner

12:00 Populations living along a thermo-latitudinal gradient vary in their response and vulnerability to ocean acidification and warming – Piero Calosi, Sedercor Melatunan, Jonathan J. Byrne, Robert L. Davidson, Mark Viant, Steve Widdicombe, and Simon Rundle

12:15 Summary/Discussion

Interactions of ocean acidification with physical climate change

San Carlos III - Session Chair: Rik Wanninkhof, National Oceanic and Atmospheric Institution, Miami, Florida, USA

11:00 Projected acidification in the IPCC AR5-era Earth System models – James C. Orr, Laurent Bopp, P. Cadule, V. Cocco, P. Halloran, C. Heinze, Fortunat Joos, Andreas Oschlies, J. Segschneider, J. Tjiptura, and Ian Totterdell

11:15 Ocean productivity and carbonate saturation state enhanced by the calving of the Mertz Glacier tongue – Elizabeth H. Shadwick, Bronte Tilbrook, and Steve Rintoul
11:30 Evaluating the controls on organic matter transport efficiency in an Earth System model: Implications for future warming and ocean acidification – Lauren J. Gregoire and Andy Ridgwell
11:45 The Southern Ocean in a high-CO_2 world: Changes in inorganic and organic carbon fluxes – Judith Hauck, Christoph Voelker, Tingting Wang, Mario Hoppema, Martin Losch, and Dieter A. Wolf-Gladrow
12:00 Impact of rapid sea-ice reduction in the Arctic Ocean on the rate of ocean acidification – Akitomo Yamamoto, Michio Kawamiya, Akio Ishida, Yasuhiro Yamanaka, and Shingo Watanabe
12:15 Summary/Discussion

Acclimation and adaption to ocean acidification: Genomics, physiology, and behavior
San Carlos IV - Session Chair: Laura Parker, University of Western Sydney, Australia

11:00 Acclimation and adaptation potential of corals to calcification at low saturation - Insights from field observations – Adina Paytan, Elizabeth D. Crook, Anne L. Cohen, Laura Hernandez-Terrones, and Mario Rebolledo-Vieyra
11:15 Assessing physiological tipping points in response to ocean acidification – Narimane Dorey, Pauline Lancon, Mike Thorndyke, and Sam Dupont
11:30 Austral vs. Antarctic notothenioids: Mitochondrial responses to ocean acidification – Anneli Strobel, Hans-Orro Pörtner, and Felix C. Mark
11:45 Proteomic responses of mollusks to elevated pCO_2: Signs of oxidative stress – Lars Tomanek, Marcus J. Zuzow, Anna V. Ivanina, Elia Beniash, AND Inna M. Sokolova
12:00 Physiological sensing of acid/base conditions via soluble adenylyl cyclase and cyclic AMP – Martin Tresguerres, Jinae N. Roa, and Megan E. Barron
12:15 Summary/Discussion

12:30-14:00 - ***Lunch***

Parallel Sessions (continued)

Responses of marine organisms and ecosystems to multiple environmental stressors
Steinbeck Forum – Haruko Kurihara, University of the Ryukyus, Okinawa, Japan

14:00 Long term, trans-generational impacts of temperature and ocean acidification in keystone intertidal species-– Nova Mieszkowska and Mike T. Burrows
14:15 Interactive effects of ocean acidification and warming on aspects of the developmental ecophysiology of the European lobster, *Homarus gammarus* – Daniel P. Small, Piero Calosi, John I. Spicer, Dominic Boothroyd, and Steve Widdicombe
14:30 Effects of ocean acidification and warming on cellular processes in gills of the great spider crab *Hyas araneus* – Lars Harms, Melanie Schiffer, Felix C. Mark, Daniela Storch,

Christoph Held, Hans-Otto Pörtner, Stephan Frickenhaus, Lars Tomanek, and Magnus Lucassen

14:45 Barnacles? Response to ocean acidification and other stressors – Christian Pansch, Iris Schaub, Ali Nasrolahi, Jonathan Havenhand, and Martin Wahl

15:00 Impact of elevated seawater pCO_2 on thermal tolerance and response to thermal stress in spider crab larvae – Melanie Schiffer, Lars Harms, Hans-Otto Pörtner, Felix C. Mark, Jonathon Stillman, and Daniela Storch

15:15 Summary/Discussion

Effects of ocean acidification on calcifying organisms

San Carlos III - Session Chair: Daniela Schmidt, University of Bristol, UK

14:00 Are oceanic scallop and abalone molluscs less resilient to ocean acidification? –Pauline M. Ross, Laura M. Parker, Elliot Scanes, and Wayne A. O'Connor

14:15 Consequences of ocean acidification for North Atlantic larval bivalves – Christopher J. Gobler and Stephanie C. Talmage

14:30 Impacts of ocean acidification on *Macoma balthica* larvae in the Baltic Sea – Anna E. Jansson, Joanna Norkko, and Alf Norkko

14:45 Clam early life history in a high CO_2 world: ocean acidification effects on fertilization, embryogenesis and larval development of *Macoma balthica* – Carl Van Colen, Elisabeth Debusschere, Ulrike Braeckman, Dirk Van Gansbeke, and Magda Vincx

15:00 The proteome response of larval stages of *Crassostrea hongkongensis* to long term exposure to high-CO_2 – Dineshram Ramadoss and Thiyagarajan Venkatesan

15:15 Summary/Discussion

Acclimation and adaption to ocean acidification: Genomics, physiology, and behavior and New concerns in ocean acidification research

San Carlos IV – Session Chair: Jean-Pierre Gattuso, Laboratoire d'Océanographie, Villefranche-sur-mer, France

14:00 A physiological trade-off in mussels exposed to ocean acidification-immune system plasticity ensures survival but at the cost of reproduction – Robert P. Ellis, Helen Parry, John I. Spicer, Thomas H. Hutchinson, and Steve Widdicombe

14:15 A mechanistic basis to the response of corals to ocean acidification: Seawater acidification reduces intracellular and extracellular pH at the tissue-skeleton interface – Alexander A.Venn, Eric Tambutté, Michael Holcomb, Julien Laurent, Denis Allemand, and Sylvie Tambutté

14:30 Ocean acidification impairs prey detection in deep sea hermit crabs but varies greatly among individuals – Taewon Kim, Josi Taylor, Chris Lovera, and Jim Barry

14:45 The need to manipulate natural variability in pH in ocean acidification experiments – Christopher E. Cornwall, Christopher D. Hepburn, Christina McGraw, Kim Currie, Conrad Pilditch, Keith A. Hunter, Phillip W. Boyd, and Catriona L. Hurd

15:00 Anthropogenic changes to seawater buffer capacity induce extreme future CO_2 conditions on a pristine coral reef – Emily Shaw, Ben McNeil, Bronte Tilbrook, and Richard Matear

15:15 Summary/Discussion

15:30 – 16:00 - ***Coffee Break***

Parallel Sessions (continued)

Responses of marine organisms and ecosystems to multiple environmental stressors

Steinbeck Forum – Session chair: Kunshan Gao, Xiamen University, China

16:00 Changes in Arctic phytoplankton community composition in response to increasing atmospheric carbon dioxide concentrations – Kai G Schulz, Richard G. Bellerby, Corina Brussaard, Sgine Koch-Klavsen, Michael Meyerhöfer, Gisle Nondal, Anna Silyakova, Annegret Stuhr, and Ulf Riebesell

16:15 Combined effects of ocean acidification and iron availability on Southern Ocean phytoplankton communities – Clara Jule Marie Hoppe, C. Hassler, C. D. Payne, P. D. Tortell, B. Rost, and S. Trimborn

16:30 Ocean acidification and growth limitation synergistically magnify cellular toxicity in multiple harmful algal bloom species – Avery O. Tatters, Feixue Fu, and David A. Hutchins

16:45 Polar diatoms in a changing climate – Anders Torstensson , Mikael Hedblom, and Angela Wulff

17:00 Short-term response of natural microbial community to ocean acidification on and around the northwest European continental shelf – Sophie Richier , Christopher M. Moore, David J. Suggett, Alex J. Poulton, Ross Holland, Mark Stinchcombe, Mike V. Zubkov, Eric P. Achterberg, and Toby Tyrrell

17:15 Summary/Discussion

Effects of ocean acidification on calcifying organisms

San Carlos III – Session Chair: Katarina Fabricius, Australian Institute of Marine Science, Townsville, Australia

16:00 Unraveling the effect of ocean acidification on coral reefs – Andreas J. Andersson, Nicholas Bates, Samantha de Putron, Andrew Collins, Dwight Gledhill, Christopher Sabine, Todd Martz, Patrick Drupp, Eric De Carlo, Fred Mackenzie, Coulson Lantz, Sam Kahng, and Chris Winn

16:15 The effects of ocean acidification on the precious Mediterranean red coral –Lorenzo Bramanti, Sergio Rossi, Maricel Gouron, Juancho Movilla, Andrea Gori, Ángela Martínez, Carlos Dominguez-Carriò, Jordi Grinyo, Angel Lopez, Carles Pelejero, Eva Calvo, and Patrizia Ziveri

16:30 Ecophysiological changes of hermatypic scleractinians in high pCO_2 chemostat – Julien Leblud, Antoine Batigny, Laure Moulin, and Philippe Grosjean

16:45 The biomineralization response of the cold-water coral *Lophelia pertusa* to ocean acidification – Laura C. Foster, Federica Ragazzola, Marlene Wall, Armin Form, and Daniela N. Schmidt

17:00 Mediterranean rocky shores under global change: response of macroalgae and sea urchins to ocean acidification – Valentina Asnaghi, Mariachiara Chiantore, Luisa Mangialajo, Frédéric Gazeau, Patrice Francour, Samir Alliouane, and Jean-Pierre Gattuso

17:15 Summary/Discussion

Changes in the oceanic carbonate system from the paleorecord to present

San Carlos IV – Session Chair: Richard Feely, National Oceanic and Atmospheric Administration, Seattle, Washington, USA

16:00 Acidification rates of Iceland seawater masses – Jon Olafsson, S.R. Olafsdottir, A. Benoit-Cattin and M. Danielsen

16:15 Observed changes in ocean acidification in the Southern Ocean over the last two decades – Andrew Lenton, B. Tilbrook and N. Metzl

16:30 Decadal change in the rate of ocean acidification in the western Pacific equatorial zone – Masao Ishii, N. Kosugi, D. Sasano, K. Enyo, S. Saito, T. Nakano, T. Midorikawa, and H.Y. Inoue

16:45 Coralline algae as pH recorders on seasonal to centennial time scales – Jan Fietzke, Federica Ragazzola , Jochen Halfar, Haine Dietze, Laura C. Foster, Thor T. Hansteen , and Anton Eisenhauer

17:00 Ocean Acidification insights from exceptional coccolithophore fossils –Paul Bown, Samantha Gibbs, and Jeremy Young

17:15 Summary/Discussion

17:30-19:30 - ***Posters and Reception (Serra I)***

WEDNESDAY, 26 SEPTEMBER

Steinbeck Forum - Moderator: James P. Barry, Monterey Bay Aquarium Research Institute, Moss Landing, California, USA

Plenary Session 3

8:30-9:00 Ecosystem change and resilience in response to ocean acidification: Steve Widdicombe

9:00-9:30 Impacts of ocean acidification on food webs and fisheries: Beth Fulton

9:30-10:00 Understanding the economics of ocean acidification: Luke Brander

10:00-10:30 Policy and governance in the context of ocean acidification: Implications, solutions, and barriers: Beatrice Crona

10:30 – 11:00 - ***Coffee Break***

Parallel Sessions

Responses of marine organisms and ecosystems to multiple environmental stressors

Steinbeck Forum – Session Chair: Felix Mark, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

11:00 Giant clams in a high-CO_2 world and interacting effects of temperature – Sue-Ann Watson, Paul C. Southgate, Jonathan A. Moorhead, Gabrielle M. Miller, and Philip L. Munday

11:15 Physiological effects of elevated temperature and ocean acidification in two commercially important shellfish species from the Irish Sea – Nia M. Whiteley, Clara L. Mackenzie, Ruth E. Nicholls, Richard L. Patton, Daniel Lee, Ian D. McCarthy, and Shelagh K. Malham

11:30 Impact of ocean acidification on thermal tolerance related to acid-base regulation capacity of *Mytilus edulis* from the White Sea – Zora Zittier, Christian Bock, and Hans-Otto Pörtner

11:45 Synergistic effects of ocean acidification and warming on shell dissolution and oxygen consumption of overwintering thecosmome pteropods in the Arctic (Spitsbergen) –Sile Lischka and Ulf Riebesell

12:00 Impact of ocean basin on pteropod exposure and response to high CO_2 and low O_2 – Amy E. Maas, Zhaohui 'Aleck' Wang, and Gareth Lawson

12:15 Summary/Discussion

Effects of ocean acidification on calcifying organisms

San Carlos III – Session Chair: Lisa Levin, Scripps Institution of Oceanography, La Jolla, California, USA

11:00 The role of ocean acidification on coccolithophore distributions in polar and temperate seas –Toby Tyrrell, Alex Poulton, Anastasia Charalampopoulou , Eithne Tynan, and Jeremy Young
11:15 Concept of carbonate chemistry dependent calcification rates in coccolithophores – Lennart T. Bach, Ulf Riebesell, and Kai G. Schulz
11:30 Disentangling the complexity behind the influence of OA on coccolithophore calcification: insights from differing cellular physiology in isochrysidale and coccolithale species – Magdalena A. Gutowska, Kerstin Suffrian, Nadja Fischer, Kai G. Schulz, Nina Himmerkus, Maria Mulisch, Martin Westermann, Ulf Riebesell, and Markus Bleich
11:45 Physiological performance and calcification of three coccolithophores under ocean acidification scenario – Slobodanka Stojkovic, Richard Matear, and John Beardall
12:00 The effects of ocean acidification on cellular physiology and release of DOM and TEP in multiple strains of *Emiliania huxleyi* – Kristine M. Okimura, I. Benner, S. Lefebvre, T. Komada[1], J.H. Stillman, and E.J. Carpenter
12:15 Summary/Discussion

The social science implications of ocean acidification

San Carlos IV - Session Chair: Claire Armstrong, University of Tromsø, Norway

11:00 Economic consequences of ocean acidification? Estimates for Norway – Isabel Seifert, Silje Holen, Claire Armstrong, and Ståle Navrud
11:15 The science into policy challenge of ocean acidification – Carol Turley
11:30 The need for new conservation strategies and policies in a high CO_2 world – Greg Rau, Elizabeth McLeod, and Ove Hough-Guldberg
11:45 Using existing laws to curb ocean acidification – Miyoko Sakashita
12:00 How to evaluate the socio-economic impacts of ocean acidification? – Nathalie Hilmi, Denis Allemand, Sam Dupont, Alain Safa, Gunnar Haraldsson, Paulo A.L.D. Nunes, Chris Moore, Caroline Hattam, Stéphanie Reynaud, Jason M. Hall-Spencer, Maoz Fine, Carol Turley, Ross Jeffree, James Orr, Philip L. Munday, and Sarah Cooley
12:15 Summary/Discussion

12:30-14:00 ***Lunch***

Parallel Sessions (continued)

Detection and attribution of ocean acidification changes and effects

Steinbeck Forum – Session Chair: Yukihiro Nojiri, National Institute for Environmental Studies, Tsukuba, Japan

14:00 Seasonal variability of the carbonate system along the Atlantic gateway to the Arctic Ocean – Eithne Tynan, Toby Tyrrell, and Eric Achterberg
14:15 The cost of (re-)calcification in a high CO_2 world – Sam Dupont, Kit Yu Karen Chan, Mike Thorndyke, and Paola Oliveri
14:30 Seawater carbonate chemistry of the Great Barrier Reef and Coral Sea – Bronte Tilbrook, Yukihiro Nojiri, Christopher Sabine, Andrew Lenton, Ken Anthony, Craig Neill, Erik van Ooijen, Richard Matear, and Craig Steinberg
14:45 An 8-month in situ ocean acidification experiment at Heron Island – David I. Kline, Lida Teneva, Kenneth Schneider, Thomas Miard, Aaron Chai, Malcolm Marker, Jack Silverman, Ken Caldeira, Brad Opdyke, Rob Dunbar, B. Gregory Mitchell, Sophie Dove, and Ove Hoegh-Guldberg
15:00 The impacts of ocean acidification, upwelling, and respiration processes on aragonite saturation and pH along the Washington-Oregon-California continental margin in late summer 2011 – Richard Feely, Simone R. Alin, Lauren Juranek, Burke Hales, Robert Byrne, and Mark Patsavas
15:15 Summary/Discussion

Effects of ocean acidification on calcifying organisms

San Carlos III – Session Chair: Frank Melzner – GEOMAR, Kiel, Germany

14:00 Changes in carbon production in the coccolithophore, *Emiliania huxleyi*, over 700 generations under elevated CO_2 and temperature condition – Ina Benner, Tomoko Komada, Jonathon H. Stillman, and Edward J. Carpenter
14:15 Influence of CO_2 and nitrogen limitation on the coccolith volume of *Emiliani huxleyi* (Haptophyta) – Marius N. Müller, Luc Beaufort, Olivier Bernard, Maria-Luiza Pedrotti, Amelié Talec, and Antoine Sciandra

14:30 Transcriptomic responses to ocean acidification and their modulation by light in the coccolithophore *Emiliania huxleyi* – Sebastian D. Rokitta, Uwe John, and Björn Rost
14:45 High CO_2 alters the calcification mechanism in marine *Synechococcus* – Nina Kamennaya, Elizabeth A. Holman, Marcin Zemla, Laura Mahoney, Jenny A. Cappuccio, Hoi-Ying N. Holman, Krystle L. Chavarria, Stephanie M. Swarbreck, Caroline Ajo-Franklin, Manfred Auer, Trent Northen, and Christer Jansson
15:00 Buffering of calcium carbonate polymorph change by coralline algae in response to pCO_2 enrichment – Nicholas A. Kamenos, Jonathan D. Dunn, Piero Calosi, Helen S. Findlay, Steve Widdicomble, Elena Aloisio, and Heidi L. Burdett
15:15 Summary/Discussion

Impacts of ocean acidification on foodwebs and fisheries

San Carlos IV - Session Chair: Ned Cyr, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA

14:00 Ocean acidification-induced food quality deterioration constrains trophic transfer – Dennis Rossoll, J. Rafael Bermúdez, Helena Hauss, Kai G. Schulz, Ulf Riebesell, Ulrich Sommer, and Monika Winder

14:15 CO_2 effects on nutritional quality of southern ocean phytoplankton as food for Antarctic krill larvae – Cathryn A Wynn-Edwards, Rob King, Andrew T Davidson, Simon W Wright, So Kawaguchi, Peter D Nichols, and Patti Virtue

14:30 Impacts of ocean acidification on early development of Antarctic krill –So Kawaguchi, Rob King, Natasha Waller, Zhongnan Jia, James P Robinson, Cathryn Wynn-Edwards, Bruce Deagle, Simon Jarman, Akio Ishida, Masahide Wakita, Stephen Nicol, Patti Virtue, Haruko Kurihara, Andrew Constable, Blair Smith, and Atsushi Ishimatsu

14:45 Consequences of ocean acidification for commercial species? Global case studies of the effects on fisheries and aquaculture – Christopher R. Bridges, Eva Kumpen, Claudia Tavares, Janina Kraft, Annika Ritter, Philipp Kinzler, Markus Schuett, Tanja Novak, Lutz Auerswald, Jarred Knapp, R.J .Atkinson, Philipp Smith, and Matt Naylor

15:00 Ocean acidification effects on the early life-stages of representative marine finfish of the Northeast USA – Christopher Chambers, E.A. Habeck, A.C. Candelmo, M.E. Poach, D. Wieczorek, B.A. Phelan, E.M. Caldarone, and K.R. Cooper

15:15 Summary/Discussion

15:30 – 16:00 - ***Coffee Break***

Regional impacts of ocean acidification

Steinbeck Forum –Session Chair: Toby Tyrell, National Oceanography Centre, Southampton, UK

16:00 Effects of elevated pCO_2 on calcifying invertebrates in a CO_2 enriched habitat: Laboratory and field studies – Frank Melzner, Jorn Thomsen, Isabel Casties, Christian Pansch, Magdalena A Gutowska, and Arne Körtzinger

16:15 The effects of benthic metabolism on coastal carbonate chemistry, seasonal reef dissolution and the subsequent consequences for predicting reef accretion and coral growth under ocean acidification – Nancy Muehllehner and Chris Langdon

16:30 Controls on carbonate mineral saturation states and ocean acidification on the southeastern Bering Sea shelf – Jessica Cross and Jeremy T. Mathis

16:45 Arctic ocean acidification: response to changes to the physical climate and biogeochemical cycling – Richard Bellerby

17:00 Transition decades for ocean acidification in the California Current System – Claudine Hauri, N. Gruber, M. Vogt, S.C. Doney, R.A. Feely, Z. Lachkar, A. Leinweber, A.M.P. McDonnell, M. Munnich, and G.K. Plattner

17:15 Summary/Discussion

Effects of ocean acidification on calcifying organisms

San Carlos III – Session Chair: Sam Dupont, The Sven Lovén Centre for Marine Sciences, Fiskebackskil, Sweden

16:00 Impacts of ocean warming and acidification on echinoderm life histories from the poles to the tropics: the developmental domino effect – Maria Byrne
16:15 Impact of ocean acidification and river discharges on the coastal domain: implications for the metabolism of larval invertebrates – Cristian Vargas, M. De la Hoz, V. San Martín, J.M. Navarro, N.A. Lagos, M. Lardies, P.H. Manríquez, and R. Torres
16:30 Physiological compensation for environmental acidification is limited in the deep-sea urchin *Strongylocentrotus fragilis* – Josi R. Taylor, Christopher Lovera, Patrick Whaling, Eric Pane, Kurt Buck, and James P. Barry
16:45 Properties of biological materials secreted by bivalves under a range of carbonate chemistries –Michael J O'Donnell, Matthew George, and Emily Carrington
17:00 Synergistic effects of temperature and pCO_2 on photosynthesis, respiration and calcification in the free-living coralline alga *Lithothamnion glaciale* –Penelope J. Donohue, Sebastian Hennige, Murray Roberts, Maggie Cusack, and Nicholas Kamenos
17:15 Summary/Discussion

Impacts of ocean acidification on foodwebs and fisheries

San Carlos IV - Session Chair: Edward Peltzer, Monterey Bay Aquarium Research Institute, Moss Landing, California, USA

16:00 Resiliency of walleye pollock across early life stages and seasons to projected levels of ocean acidification –Thomas P. Hurst, Elena Fernandez, Jeremy Mathis, and Charlotte Stinson
16:15 Effects of ocean acidification on the growth and organ health of Atlantic herring larvae – Andrea Y. Frommel, Rommel Maneja, David Lowe, Audrey J. Geffen, Arild Folkvord, Uwe Piatkowski, and Catriona Clemmesen
16:30 Using experiments and models to address the response of an estuarine food web to ocean acidification – Shallin Busch, Sarah Norberg, Michael Maher, Jason Miller, Jon Reum, and Paul McElhany
16:45 Are CO_2 emissions killing our sushi? Effects of ocean acidification on eggs and larvae of yellowfin tuna – Williamson, Jane, Jon Havenhand, Simon Nicol, Daniel Margulies, Don Bromhead, Vernon Scholey, Liette Vandine, Paul Duckett, Jeanne Wexler, Maria Santiago, Simon Hoyle, Peter Schlegel, and Michael Gillings
17:00 Growth and composition of phytoplankton cultivated at constant pH in present and future pCO_2 scenarios - Knut Yngve Børsheim

17:30-18:00 – ***Closing of the Symposium***
19:30 – 23:00 - ***Dinner at Monterey Bay Aquarium – it is about a 1.3 mile walk. Trolleys will be available outside the Conference Center and departing every 10 minutes, beginning at 18:30. The Aquarium will open at 19:30. Trolleys will also return from the Aquarium later in the evening.***

THURSDAY, SEPTEMBER 27, 2012-08-29

DAY 4 - Understanding the Ocean in a Changing World

A special event jointly organized by the Ocean in a High CO_2 World Symposium and the Blue Ocean Film Festival (BOFF) hosted by BOFF at the **Golden State Theatre, Monterey, 417 Alvarado Street.**

MORNING SESSION: The Third International Symposium on the Ocean in a High CO_2 World

0830 - 0840 **Introduction:** Dan Laffoley, Chair of Europe's Ocean Acidification Reference User Group

0840 - 0915 **Summary of the scientific results from the symposium**: Dr Joanie Kleypas, National Center for Atmospheric Research (Climate and Global Dynamics)

0915- 1145 **Keynote address: Understanding the Ocean in a Changing World**

His Serene Highness Prince Albert II of Monaco

Panel discussion: "Responding to ocean acidification"

- Dr. Jane Lubchenco (Chair) Administrator, National Oceanic and Atmospheric Administration
- HSH Prince Albert II of Monaco
- Dr. Jean-Pierre Gattuso, CNRS Senior Research Scientist, Laboratoire d'Océanographie, France
- Bill Dewey, Taylor Shellfish Farms, Washington
- Congressman Sam Farr (D-California)
- Media representative

With special guest interventions:

- The X-PRIZE* for ocean acidification sensor systems
- Google: the new ocean acidification tour in Google Earth

*The X PRIZE Foundation is a non-profit organization that designs and manages competitions to encourage technological development.

1145 – 1300 Lunch

AFTERNOON SESSION: Blue Ocean Film Festival

1300 – 1400 Igniting a movement: leveraging the power of celebrity – a panel discussion and insights on leveraging celebratory cachet for effective communications

1400 – 1545 DeepBLUE – Exploring our Deepest Oceans – a panel discussion moderated by Cpt. Don Walsh on the future of deep ocean exploration

1545 – 1650 DeepBLUE Micro talks – Life in the Abyss

2012 Blue Ocean Film Festival

Every two years ocean leaders, filmmakers, photographers, scientists, explorers, entertainment executives and the general public gather in Monterey at the Blue Ocean Film Festival to

celebrate the best in ocean filmmaking, to learn more about the issues facing our oceans, and to collaborate on improving the future of our oceans. The seven-day event is charged with energy as these diverse groups of people share knowledge and ideas with each other and with the general public.
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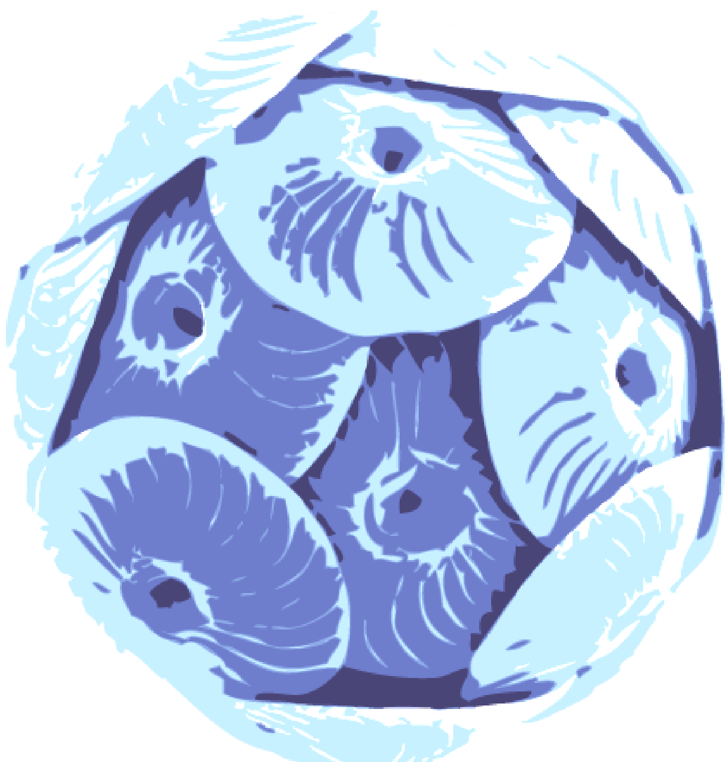


PLENARY SESSIONS: SPEAKERS' ABSTRACTS

INTERACTIONS OF OCEAN ACIDIFICATION WITH PHYSICAL CLIMATE CHANGE

Bopp, Laurent, Laure Resplandy, James C. Orr

In line with earlier results, the new multi-model projections performed for the recent Coupled Model Intercomparison Project 5 (CMIP5) show large decreases in pH and $[CO_3^{2-}]$ concentration during the 21st century for the surface waters of the world ocean. But how ocean acidification (OA) will propagate to the ocean interior and how OA will be combined with other human-induced modifications are still considered as largely open questions.

Here, using simulations conducted as part of CMIP5, we show how changes in carbonate chemistry differ between the different water masses of the major ocean basins in the 21st century. The role of climate change and of potential modifications of ocean ventilation and mixing in the propagation of the OA signal will also be addressed. Finally, we also show how these changes in carbonate chemistry will be combined with changes in oxygen and/or with heat storage in the ocean interior. Even if all simulations used here are global-scale simulations, we will focus on specific regions, i.e. the North Atlantic, the north Pacific, and the Southern Ocean.

We explore all the Representative Concentrations Pathways scenarios, proposed in the context of CMIP5, and we use the differences between the projections performed with different models to asses the uncertainties associated to these results

IPSL / LSCE, CNRS/CEA/UVSQ, Orme des Merisiers, CE Saclay, F-91191 Gif sur Yvette, France.

THE ECONOMIC IMPACTS OF OCEAN ACIDIFICATION

Brander, Luke

The consequences of ocean acidification for the provision of marine ecosystem services such as fisheries and the services generated by coral reefs are uncertain but potentially severe. In this paper we set out a framework for the economic assessment of impacts from ocean acidification. We review the existing economic literature on ocean acidification, which is nascent and sparse. To date only a partial set of the potentially impacted ecosystem services have been assessed, with a focus on the direct use values (e.g. fisheries) that can be more easily addressed. Gaps in the current knowledge are identified and avenues for future research are discussed. Comparing the existing economic impact estimates for ocean acidification with those for climate change show them to be an order of magnitude lower. Due to the relatively proximate impacts of ocean acidification, however, the implications for optimal mitigation of carbon dioxide emissions may be substantial.

Hong Kong University of Science and Technology, Flat 2408, Block F, 9-11 Hong Shing Street, Hong Kong, HONG KONG. lukebrander@gmail.com

THE HISTORY OF OCEAN ACIDIFICATION SCIENCE

Brewer, Peter G.

The history of ocean acidification science may be seen in three short eras. First the period from 1909 when the p[H] scale was first defined by Sorensen to the onset of the International Geophysical Year in 1957; during this time only crude data were available, and early scientists first explored the relationship between the natural p[H] field and marine biological and geochemical cycles. Second came the period from the IGY to about 1990 when the oceanic CO_2 field was mapped with accuracy and major breakthroughs in technique and fossil fuel CO_2 signal recognition occurred. Then the modern era as defined by the first IPCC scenarios of future levels at a rate for doubling atmospheric CO_2 more than a century earlier than anything envisaged at the start of the 20th century.

The scientific response has been swift. It was realized that declines in p[H] could affect coral reefs and early enclosed experiments showed this. And concerns over physical climate change lead to examination of ocean CO_2 disposal so as to by pass the atmospheric residence time step with its radiative consequences. Today ocean scientists must account for a triple or quadruple threat: ocean acidification and the recognition that for stabilization at 650 ppm some 7.5 Gt CO_2 will be transferred to the ocean, the near simultaneous rise in temperature, the associated decline in O_2, and the apparent decline in oceanic CO_2 uptake thereby accelerating the pace of climate change and vastly changing the ocean we knew just a few years ago.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039, USA (brpe@mbari.org)

POLICY AND GOVERNANCE IN THE CONTEXT OF OCEAN ACIDIFICATION: IMPLICATIONS, SOLUTIONS, AND BARRIERS

Crona, Beatrice

Ocean acidification is a serious threat to our oceans as we know them but it cannot be viewed in isolation. In fact, as a process it interacts with multiple other planetary processes and the outcomes associated with these interactions pose severe challenges for global environmental governance due to their inherent uncertainties and complex multi-scale dynamics. This keynote will examine some of the foreseen governance challenges resulting from these interactions, namely i) the interplay between Earth system science and global policies, and the implications of differences in risk perceptions in defining planetary scale boundaries, ii) the role and capacity of international institutions to deal with individual ‘planetary’ level processes, as well as interactions between them, and iii) the role of global governance in framing social–ecological innovations. However, global formal institutions are not the only way to address marine governance challenges, such as ocean acidification. Informal social networks are important conduits of information flow and mechanisms for building partnerships and cooperation. These informal arenas have been less examined but are likely to play a key role for global marine governance through their interaction with formal multilateral processes. The keynote will examine some ongoing initiatives to exemplify how such cross-sectoral, globally spanning networks play a role in marine governance transformation by providing structures that bridge poorly connected policy fields and arenas, and functioning as platforms for learning across regional initiatives, with potentially synergistic effects in terms of spread of new ideas, transfer of lessons learned etc.

Stockholm University, Stockholm,Sweden,10691. beatrice.crona@stockholmresilience.su.se

ARE WE LUCKY TO BE CONFRONTED WITH MULTIPLE STRESSORS OR IS IT TOO EARLY TO SAY?
Fulton, E.A.

Simple classifications of fauna based on existing experimental and observational data suggests less than 50% of the worlds catch by volume may be influenced directly by acidification; the exceptions to this pattern being in Australia and at the poles. Reclassification by value suggests that economically the exposure may be much larger (more than 95% exposure in Australia's case). Obviously exposure to the effects of ocean acidification, along with stressors such as other climate driven environmental changes or exploitation, will not be felt uniformly around the world or by all taxa or fisheries. Simulation models suggest that shifting interactions of environmentally driven change at different levels of fishing pressure may mean that adaptation is feasible in temperate systems. Although the picture may not be so nice for tropical systems. However, with new findings about non-lethal effects, acclimation, evolution and human adaptive capacity being released every day there is still a lot of uncertainty about what the future will really look like. Consequently, there is even more pressure to find cost effective means of supporting multi-scale adaptive management.

CSIRO, GPO Box 1538, Hobart, Tasmania 7001, Australia. beth.fulton@csiro.au

ACCLIMATION AND ADAPTION TO OCEAN ACIDIFICATION: GENOMICS, PHYSIOLOGY, AND BEHAVIOR
Hofmann, Gretchen E.

Ocean acidification (OA), the reduction of ocean pH via the absorption of anthropogenic atmospheric CO_2, is expected to impact marine ecosystems through its affects on marine calcifying organisms. These impacts are not well understood at the community and ecosystem level, although the consequences are likely to be substantial, involving range shifts and population declines. A current focus in OA research community is to understand the resilience that organisms possess to withstand such changes, and furthermore to extend these investigations beyond calcification, addressing impact on other vulnerable physiological processes. Using standard transcriptomic methods to profile gene expression, my lab group and I have investigated the impacts of high CO_2 conditions on the development of purple sea urchin larvae, a pelagic stage that forms a calcium carbonate endoskeleton during development. In our studies, the larvae were raised from fertilization to pluteus stage in seawater with elevated CO_2 concentrations. Our larger goals in these studies is to see if we can identify thresholds in the physiology of the larvae in response to high CO_2 conditions and to determine whether the transcriptional response might yield insight into genes and pathways that could underlie acclimatization and adaptation capacity to OA as an anthropogenic-change stressor. In this presentation, I will discuss data from experiments that include exposure to low pH (high CO_2, low carbonate conditions), a multistressor experiment where conditions reflected concomitant OA and ocean warming, and how the transcriptional response might vary among different populations of purple urchins across their biogeographic distribution.

Department of Ecology, Evolution and Marine Biology, UC Santa Barbara, Santa Barbara, CA 93106, USA. hofmann@lifesci.ucsb.edu

BIOGEOCHEMICAL CONSEQUENCES OF OCEAN ACIDIFICATION AND FEEDBACKS TO THE EARTH SYSTEM

Matear, Richard

The ongoing uptake of anthropogenic CO_2 by the ocean and the resulting ocean acidification has the potential to affect the major biogeochemical cycles in the ocean. This presentation will first review the potential for ocean acidification to alter major biogeochemical cycles and then assess the potential for such changes to feedback on climate change. The impact of ocean acidification does not occur in isolation, but in synergy with ocean warming and associated changes in the physical environment. A coupled carbon climate model that includes these potential interactive affects will be used to assess the biogeochemical feedbacks of ocean acidification on our future climate.

CSIRO Marine and Atmospheric Research, Hobart, Australia. Richard.Matear@csiro.au

INTEGRATING CLIMATE-RELATED STRESSOR EFFECTS ON MARINE ORGANISMS: UNIFYING PRINCIPLES LINKING MOLECULE TO ECOSYSTEM-LEVEL CHANGES?

Pörtner, Hans-O.

Climate change effects on marine ecosystems involve various drivers, predominantly temperature, hypoxia and CO_2, and possibly further anthropogenic stressors such as pollutants. All life forms respond to these drivers, following potentially common principles, which are, however, insufficiently understood. The specific understanding may be most advanced in animals where the concept of oxygen and capacity dependent thermal tolerance (OCLTT) appears as a suitable integrator of such effects, linking molecular to ecosystem levels of biological organisation. Recent studies confirm OCLTT involvement in the field, causing changes in species abundance, biogeographical ranges, phenology and species predominance. At whole animal level, performance capacity set by aerobic scope and energy budget, building on baseline energy turnover, link fitness (within thermal window) and functioning at ecosystem level. In the variable intertidal, animals also exploit their capacity for passive tolerance. While presently the temperature signal appears predominant in the field, effects may well begin to include other stressors, acting synergistically by modifying (narrowing) the aerobic OCLTT window. Recent findings support the OCLTT concept as a common physiological basis linking apparently disjunct effects of ocean warming, acidification and hypoxia. In brief, warming induced CO_2 accumulation in body fluids links to the effects of ocean acidification mediated by the weak acid distribution of CO_2. Temperature induced hypoxemia links to the hypoxia sensitivity of thermal tolerance. Future research needs to develop proxies for these effects and to also identify the principles operative in organisms other than animals and their underlying mechanisms. Mechanism-based modelling efforts are then needed to develop reliable, organism to ecosystem projections of future change.

Integrative Ecophysiology, Alfred-Wegener-Institute, Am Handelshafen 12, 27570 Bremerhaven, Germany. (Hans.Poertner@awi.de)

RATES OF CHANGE OF OCEAN ACIDIFICATION: INSIGHTS FROM THE PALEORECORD

Schmidt, Daniela N.[1] , Laura Foster[1], Suzy Jennions[1], Andy Ridgwell[2], Ellen Thomas[3]

An organism's or ecosystem's ability to adapt to environmental change depends on both the rate and magnitude of the change. Predictions on future ecosystem impacts are hard to make, as we have few long term experiments assessing the evolutionary and adaptive potential of most species. The geological record contains numerous examples of biotic responses to climate change including ocean acidification and therefore provides invaluable information about ecosystem response to warming, acidification and deoxygenation.

We will review a number of events in Earth history and the biotic response to the CO_2 perturbation: from time intervals with an atmospheric CO_2 similar to our current range to short term perturbations with significant ocean acidification. The Pliocene with CO_2 around 400ppm does not show any indicating of stress in any planktic calcifiers. In contrast, rapid warming and acidification associated with the Eocene hyperthermals led to reduction in benthic foraminiferal diversity and dwarfism for the smaller event and a calcification feedback and extinction for the larger one.

Importantly though, the geological record reveals that there was no event in the last 65 Ma which was as fast as current ocean acidification and that the current rate of pH change is unprecedented.

[1]School of Earth Science, University of Bristol, UK. d.schmidt@bristol.ac.uk
[2]School of Geographical Science, University of Bristol, UK
[3]Department of Geology and Geophysics, Yale, USA

ECOSYSTEM CHANGE, RESILIENCE AND RESISTANCE IN RESPONSE TO OCEAN ACIDIFICATION
Widdicombe, Steve

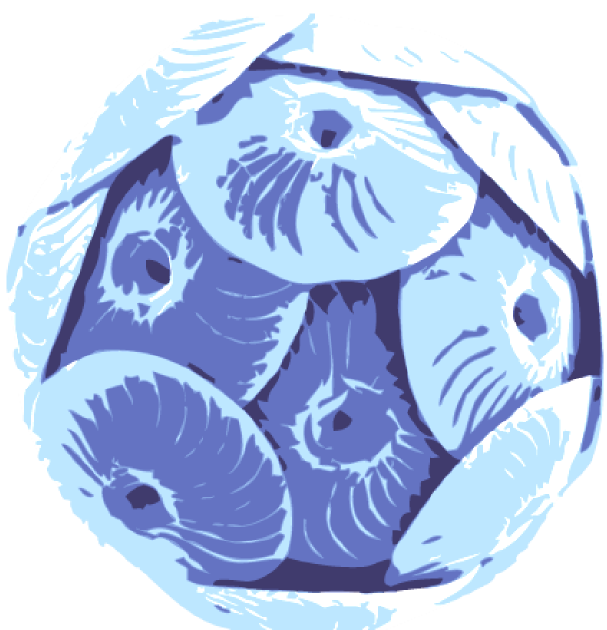
Whilst there is strong evidence that increasing levels of CO_2 (including the associated changes in pH and carbonate chemistry) within the marine environment will have significant effects on individual organisms and processes, the extent to which these effects will cause changes in ecosystem structure and function is still unclear. It is true that a few large mesocosm experiments and studies conducted within areas of naturally high levels of CO_2 have given us valuable insight into the potential changes we can expect at the community level. However, the extent to which these approaches can be considered as realistic representations of a future high CO_2 world may be limited by the timescales over which experiments can be performed, failure to capture key ecological processes (such as larval supply) or by an inability to control extreme, or erratic, environmental conditions. In light of this, researchers must continue to use experimental manipulation and observation to build up a conceptual understanding of how OA induced changes at the level of the individual will define population success, set community structure and thereby control the functioning of ecosystems. To do this particular consideration needs to be given to whether ecosystems possess the capacity to exhibit either resilience or resistance to the environmental stresses associated with ocean acidification. Again, in order to fully consider this idea there is a need to look at the physiological and ecological mechanisms which support resilience and resistance at multiple levels of biological organisation as the relative strength and effectiveness of these mechanisms will ultimate underpin any ecosystem level changes which occur.

Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, Devon PL1 3DH, United Kingdom.
swi@pml.ac.uk

CHANGES IN OCEAN CARBONATE CHEMISTRY BEFORE AND SINCE THE INDUSTRIAL REVOLUTION
Zeebe, Richard E.

Humans are continuing to add vast amounts of carbon dioxide (CO_2) to the atmosphere through fossil fuel burning and other activities. Anthropogenic carbon emissions reached a record high in 2010 of 37 billion metric tons of CO_2 per year - up by about 6% after a small drop in 2009 due to the global financial crisis. A large fraction of the CO_2 is taken up by the oceans, lowering ocean pH and carbonate mineral saturation
state. As a result, surface ocean pH has already dropped by 0.1 units relative to preindustrial levels and is expected to drop by 0.3 units until year 2100 under business as usual scenarios. In this presentation, I will discuss changes in ocean carbonate chemistry before and since the Industrial Revolution, including recent advances in observations and modeling efforts. While in specific regions changes in ocean chemistry due to acidification are amplified and effects on marine organisms may already be detectable, great care must
be taken to unambiguously attribute such effects to anthropogenic CO_2 invasion. Regarding changes in ocean chemistry in a historic/geologic context, I conclude that the ocean acidification event that humans are expected to cause is unprecedented in the geologic past, for which sufficiently well-preserved records are available.

School of Ocean and Earth Science and Technology, Department of Oceanography, University of Hawaii at Manoa, 1000 Pope Road, MSB 629, Honolulu, HI 96822, USA. zeebe@hawaii.edu



DRIVERS OF SEAWATER CARBONATE CHEMISTRY ON SHALLOW-WATER CORAL REEF SYSTEMS OF THE GREAT BARRIER REEF

Albright, Rebecca[1] and Kenneth R. N. Anthony[1]

Ocean acidification projections are mainly based on air-sea carbon exchange for open ocean environments, and implications for shallow or near-shore environments such as coral reefs are poorly understood. Coral reefs can naturally experience large fluctuations in seawater carbonate chemistry, driven primarily by benthic carbon flux processes: photosynthesis, respiration, calcification and calcium carbonate dissolution. Understanding how benthic processes interact with processes in the surrounding ocean is imperative to discerning the susceptibility of reef ecosystems to changing ocean chemistry. Here, we present a research initiative that formally analyses how physical, biological and biogeochemical processes interact in driving carbonate chemistry patterns on shallow-water coral reef systems, using Davies Reef (central Great Barrier Reef) and Heron Island (southern Great Barrier Reef) as case studies. Using a mixed Eulerian and Lagrangian approach, spatial patterns of changes in total alkalinity (A_T) and total dissolved inorganic carbon (C_T) are used to characterize benthic carbon fluxes (net photosynthesis and net calcification) and resulting changes in aragonite saturation state (Ω_a). Upstream and downstream autonomous water samplers are used to collect seawater samples every two hours, providing insight to the temporal and spatial variability in carbon chemistry across the reef flat. The data are used to calibrate and test models for how the oceanography, physical setting and biological reef composition determine carbonate chemistry feedbacks and the potential for 'biobuffering' or exacerbation of ocean acidification in reef habitats.

[1]Australian Institute of Marine Science, PMB 3 Townsville MC, Townsville, QLD 4810, Australia (r.albright@aims.gov.au)

UNRAVELING THE EFFECT OF OCEAN ACIDIFICATION ON CORAL REEFS

Andersson, Andreas[1], Nicholas Bates[2], Samantha de Putron[2], Andrew Collins[2], Dwight Gledhill[3], Christopher Sabine[4], Todd Martz[1], Patrick Drupp[5], Eric De Carlo[5], Fred Mackenzie[5], Coulson Lantz[6], Sam Kahng[6], and Chris Winn[6]

The success of coral reefs is dependent on the deposition and formation of $CaCO_3$ structures and complexity. Therefore coral reefs have been identified as one of the most vulnerable ecosystems to ocean acidification (OA). However, as opposed to the open-ocean environment where it is fairly straightforward to model future changes in seawater CO_2 chemistry, accurately predicting changes to coral reef seawater chemistry is challenging. Many coral reefs already experience seawater pCO_2 levels >500 µatm at certain times, the benthic community strongly influences the seawater chemistry, which varies depending on hydrographic regime, community composition and the relative contributions from net community production (NCP) and net ecosystem calcification (NEC). Thus, seawater CO_2 chemistry on coral reefs varies greatly across time and space. Identifying how coral reef seawater chemistry will change under OA, how this change will affect benthic communities and biogeochemical processes (e.g., primary production, respiration, calcification, bioerosion and $CaCO_3$ dissolution), and how these changes will feed back into the regulation of seawater chemistry, are key elements essential to understand before we can predict how this ecosystem will be affected by OA. Seawater CO_2 chemistry and biogeochemical data from coral reefs in Bermuda, Hawaii, and Puerto Rico provide new insights on the variability, complexity and nuances of coral reef biogeochemistry, but also reveal the common denominators across these locations that may provide important clues on the control and response of coral reefs to OA.

[1] Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0202, USA (aandersson@ucsd.edu)
[2] Bermuda Institute of Ocean Sciences, St. George's, Bermuda.
[3] NOAA Ocean Acidification Program, Silver Spring, MD, USA
[4] NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA
[5] Department of Oceanography, University of Hawaii, Honolulu, HI, USA
[6] Hawaii Pacific University, Waimanalo, HI, USA

REEF RESILIENCE AND VULNERABILITY CONSEQUENCES OF OCEAN ACIDIFICATION

Anthony, Kenneth R.N.

Ocean acidification represents a steady increase in pressure on physiological and biogeochemical processes in coral reef organisms. While the consequences for reef calcification and the biology of species groups is becoming clearer, we do not yet have a deep understanding of how acidification will affect ecosystem resilience and vulnerability. Here, I use a mechanistic ecosystem model to analyse how ocean acidification contributes to a lowering of reef ecosystem resilience under a number of environmental scenarios. Results show that acidification steadily erodes reef resilience via reduced coral growth and recruitment and by suppressing the coral equilibrium state though interaction with other stressors. Projections of coral abundance under scenarios that incorporate a trend of increasing frequency and severity of bleaching events and stronger storms demonstrate that ocean acidification will increasingly limit the scope for reef recovery during the century. Also, projections incorporating interactions between corals and weedy macroalgae, whose growth rates and competitive strength are often enhanced by high CO_2, indicate that acidification may act as a bottom-up driver of regime shifts on reefs in the future, especially in combination with nutrient enrichment. Lastly, I present results of sensitivity analyses enabling quantitative assessments of how acidification is likely to affect reef vulnerability, directly and indirectly via interactions with other stressors, across a set of environmental and human-use scenarios.

Australian Institute of Marine Science, Townsville Q 4810, Australia k.anthony@aims.gov.au

MEDITERRANEAN ROCKY SHORES UNDER GLOBAL CHANGE: RESPONSE OF MACROALGAE AND SEA URCHINS TO OCEAN ACIDIFICATION

Asnaghi, Valentina[1,2], Mariachiara Chiantore[1], Luisa Mangialajo[2], Frédéric Gazeau[3,4], Patrice Francour[2], Samir Alliouane[3,4], Jean-Pierre Gattuso[3,4]

Macroalgal communities dominate shallow Mediterranean rocky coasts and exhibit different sensitivities to ocean acidification, depending on their content of calcium carbonate and its deposition pathway. In future scenarios of increasing atmospheric CO_2 calcifying coralline algae would be less competitive, leading to dominance of fleshy species which are less or not affected by the decrease in pH. The higher production of fleshy macroalgae could potentially be offset by increased grazing. Yet, sea urchins, the most important herbivore species in littoral ecosystems, are also sensitive to pH decrease,

and may not be able to prevent the overgrowth of fleshy algae. To better quantify these relationships, a laboratory experiment was set up under different pH scenarios, corresponding to pCO_2 values of 390, 550, 700 and 1000µatm. Results mainly confirmed previous findings about the different sensitivity of non-calcifying and calcifying seaweeds, pointing out that coralline species are likely to face dissolution due to pH decrease in the next decades. Direct negative effects on urchins due to high pCO_2 conditions were also observed, as well as indirect effects: the carbonate content of calcifying macroalgae turned out to be important for strengthening the Aristotle's lantern and urchin test, amplifying the direct negative effects of pH decrease through indirect effects mediated by the diet. Aristotle's lantern size and test robustness are directly linked to the sea urchin ability to control fleshy algae overgrowth and anti-predator defenses respectively. A future increase of pCO_2 could dramatically impact this top-down control and then the ecosystem structure in rocky shallow areas.

[1]Department for the Study of the Territory and of its Resources (DipTeRis) - University of Genoa, Italy (valentina.asnaghi@unige.it)
[2] Université de Nice-Sophia Antipolis, Laboratoire ECOMERS, Avenue de Valrose, BP71, 06108 NICE cedex 2 France
[3] CNRS-INSU, Laboratoire d'Océanographie de Villefranche, BP 28, 06234 Villefranche-sur-Mer Cedex, France
[4] Université Pierre et Marie Curie-Paris 6, Observatoire Océanologique de Villefranche, 06230 Villefranche-sur-Mer Cedex, France

CONCEPT OF CARBONATE CHEMISTRY DEPENDENT CALCIFICATION RATES IN COCCOLITHOPHORES

Bach, Lennart T., Ulf Riebesell, and Kai G. Schulz

Ocean acidification (OA) has been identified as potential threat for coccolithophores. However, since the influence of OA on calcification rates differed between species and strains, it remains challenging to derive a general response pattern. Here, we present a conceptual framework that allows reconciling seemingly deviating responses of coccolithophorid calcification to OA. The concept is based on several recent experiments showing a consistent optimum-curve like response in coccolithophore calcification rates when cultured over a large pCO_2 range. As projected OA reflects a relatively small portion of the applied pCO_2 range, it is critical whether OA covers the increasing, the optimum, or the decreasing part of the optimum curve. On the left side of the optimum (low to intermediate pCO_2), calcification is limited by low substrate availability (presumably low bicarbonate). On the right side (high pCO_2, low pH), it is inhibited by high proton concentrations. The shape of the optimum curve depends on individual sensitivities to the concentrations of substrate and inhibitor. Sensitivities are species- and strain-specific, can change through evolutionary adaptation, and can be modified by environmental parameters such as light and temperature. Increasing temperature, for example, was found to shift the optimum for calcification rates towards higher pCO_2 levels. As a result, the response of calcification rates to OA can be positive or negative, depending on culture conditions. The concept presented above of carbonate chemistry dependent calcification rates could be part of a theoretical basis for assessing the success of coccolithophores in the future ocean.

[1] Helmholtz Centre for Ocean Research Kiel (GEOMAR), 24105, Kiel, Germany. lbach@geomar.de

HIGH CO_2 REARING SLOWS EARLY DEVELOPMENT AND ALTERS METABOLIC STATUS OF LARVAL KINA, THE SEA URCHIN *EVECHINUS CHLOROTICUS*.

Baker, Daniel W.[1], Michael E. Hudson[1], Anthony Hickey[2] and Mary A. Sewell[1]

Oceanic CO_2 concentrations and the resultant ocean acidification are predicted to reach levels capable of significantly altering marine ecosystems by the end of this century. As the biological mechanisms responsible for these changes remain poorly described, increased understanding of the physiological effects associated with elevated CO_2 will improve predictions of how and which species will be most greatly impacted. We used a well-described larval echinoderm model to examine the response of development, whole animal metabolism and mitochondrial function to exposure to elevated CO_2 during the early life stages between fertilization and onset of feeding (<72h post-fertilization). We tested metabolic function through analysis of larval oxygen consumption rates (MO_2) using purpose built flow-through micro-respiratory chambers, and investigated mitochondrial function *in situ* using novel protocols and cutting edge high resolution respirometry through the use of Oroboros™ oxygraphs. Larval sea urchins reared at IPCC predicted near future CO_2 levels exhibited developmental delay within 6 h and malformation by 48 h. MO_2 and mitochondrial function were both affected by high CO_2 rearing, but these effects differed between genetically dissimilar crosses, suggesting that the metabolic-CO_2 sensitivity of larvae may be related to genotype, or the environmental history of parents. These findings will be discussed with reference to the current body of transcriptomic and metabolic research, both within and outside of our research laboratory. This research aims to expand the toolbox (both methodical and experimental) available for eco-physiologists, in order to better elucidate the potential physiological challenges faced in future marine ecosystems.

[1.] Ecology, Evolution and Behaviour, School of Biological Sciences, University of Auckland, Auckland, NZ, presenter contact e-mail: dan.baker@auckland.ac.nz
[2.] Applied Surgery and Metabolism, School of Biological Sciences, University of Auckland, Auckland, NZ

COMBINED EFFECTS OF OCEAN ACIDIFICATION AND PETROLEUM-RELATED DRILLING MUD: A STUDY WITH THE SCLERACTINIAN CORAL *LOPHELIA PERTUSA*

Bechmann, Renée K., Stig Westerlund, Nadia Aarab, Arve Osland, Ingrid C. Taban, Thierry Baussant

Cold-water coral (CWC) ecosystems have been living undisturbed for thousands of years in the deep ocean. Nowadays, oil and gas (O&G) exploration and the rapid release of anthropogenic CO_2 from the burning of fossil fuels are posing a potential threat to these ecosystems. Will they be able to tackle these challenges?

We made laboratory tests with the scleractinian coral *Lophelia pertusa* using exposure scenarios with pH 7.6 (OA) and/or drilling mud (DM) conditions lasting for two months. Decreased skeleton weight was detected for corals exposed to OA and OA+DM, indicating that the skeleton of *Lophelia pertusa* slowly dissolves at pH 7.6. No significant difference in coral respiration rate was detected between treatments. Time-lapse video pictures revealed that polyps from OA and OA+DM were retracted for longer periods than the polyps in the control and the DM treatment. By measuring the total area of mucocytes in comparative polyp tissue sections, we showed that corals exposed to DM and to OA were stressed compared to control but that the OA+DM treatment enhanced significantly that response compared to DM and OA treatments alone. Additionally, we found that gene expression of catalase, HSP70 and HSP90 in some coral individuals was increased in OA and DM treatments and that the levels of transcripts for catalase and HSP 90 were even higher in response to the combined OA+DM exposure

than in the control. Overall, these results indicate that a combination of OA and DM enhanced the effect responses measured on *Lophelia pertusa* compared to single stressors.

IRIS - International Research Institute of Stavanger - Mekjarvik 12, N-4070 Randaberg, Norway.
rkb@iris.no

ARCTIC OCEAN ACIDIFICATION: RESPONSE TO CHANGES TO THE PHYSICAL CLIMATE AND BIOGEOCHEMICAL CYCLING

Bellerby, Richard[1,2,3]

Changes to Arctic Ocean biogeochemistry will result from a complex array of climate and chemical perturbations over the next decades. Changes to freshwater and nutrient supply through ice melt and continental runoff; warming of the ocean and an increasing ocean acidification through partial equilibrium with a rising anthropogenic CO_2 load will change the nature of Arctic Ocean ecological and biogeochemical coupling. This presentation will document our combined approach of studying Arctic biogeochemical change through coupled observational, experimental and modelling campaigns. We have identified large changes in recent anthropogenic carbon transport to the Arctic and have characterised the associated regional and water mass ocean acidification. We have determined, through targeted Arctic pelagic ecosystem perturbations experiments, changes to ecosystem structure, succession and biogeochemical cycling under high CO_2. Observations have been incorporated into regional, coupled physical-ecosystem-carbon biogeochemical models (informed at the boundaries by downscaled global earth system models) to develop scenarios of change in biogeochemical pathways. We have identified large regional variability in ocean acidification that is shown to impact on ocean biogeochemistry, ecosystems and climate feedbacks in the Arctic Ocean.

[1] Norwegian Institute for Water Research, Thormøhlensgate 53 D, N-5006 Bergen, Norway, (richard.bellerby@uni.no)
[2] Bjerknes Center for Climate Research, Allégaten 55, 5007 Bergen, Norway
[3] Geophysical Institute, University of Bergen, Allégaten 70, 5007 Bergen, Norway

CHANGES IN CARBON PRODUCTION IN THE COCCOLITHOPHORE EMILIANIA HUXLEYI OVER 700 GENERATIONS UNDER ELEVATED CO_2 AND TEMPERATURE CONDITION

Benner, Ina, Tomoko Komada, Jonathon Stillman, Edward Carpenter

The coccolithophore Emiliania huxleyi plays an important role in the marine carbon cycle through production of organic matter and calcium carbonate. Several studies have examined acclimation of *E. huxleyi* to high carbon dioxide (CO_2), but most studies to date have mostly been short-term. To investigate the long-term response of *E. huxleyi* to high CO_2 and elevated temperatures over 700 generations, we grew *E. huxleyi* (strain CCMP 371) in continuous cultures at 850 ppm and 24°C and at 400 ppm and 20°C as a control. Samples for particulate organic carbon (POC) and nitrogen (PON), particulate inorganic carbon (PIC), primary production, calcium carbonate production, and coccolith morphology were taken after 20, 200, 400, and 700 generations. Increases in calcium carbonate production and PIC per cell, but not primary production and POC per cell were observed after 200 generations in the high CO_2, high temperature treatment. This increase in calcium carbonate production and PIC per cell did not change after 200 generations. These results show a possible positive feedback of calcification on atmospheric CO_2 levels after only 200 generation grown under future ocean condition (high CO_2 and elevated temperature), but also a possible increase in ballast material for carbon export due to higher calcification in *E. huxleyi*. An increases carbon export in the future ocean would have a negative feedback on atmospheric CO_2 levels.

Romberg Tiburon Center for Environmental Studies (SFSU), 3152 Paradise Drive, Tiburon, CA 94920, USA (ibenner@sfsu.edu)

GROWTH AND COMPOSITION OF PHYTOPLANKTON CULTIVATED AT CONSTANT pH IN PRESENT AND FUTURE pCO_2 SCENARIOS

Børsheim, Knut Yngve

Biological experiments for the investigation of ocean acidification effects meet with the challenge of keeping carbonate chemistry in growth media under strict control. All living organisms are either net producers or consumers of CO_2, and media for microorganisms are usually heavily buffered to avoid major pH changes. This strategy is not recommended when the purpose of the experiment is to simulate natural carbonate chemistry in future scenarios with elevated pCO_2 levels. We have designed a facility where future pCO_2 scenarios are produced and controlled in large tanks that serve to feed experimental aquaria for various types of marine plankton organisms. The investigation presented here has incorporated phytoplankton cultures into this facility. The cultures are enclosed in dialysis tubes, which conveniently serve to keep the microalgae confined while also allows the carbonate chemistry to continually equilibrate with the large volume of strictly controlled seawater circulating in the system. The half life of the [H^+] in the dialyzed cultures were approximately 17 minutes, sufficient to keep the pH in the enclosure essentially constant. The effects of four regimes from of pCO_2 from 380 ppm to 1000 ppm on the chemical composition and growth of the cultures were investigated. A further refinement of the experimental set up will involve feeding of zooplankton with phytoplankton cultures reared at future pCO_2 scenarios.

Institute of Marine Research, Nordnesgaten 33, NO-5817 Bergen, Norway.

OCEAN ACIDIFICATION INSIGHTS FROM EXCEPTIONAL COCCOLITHOPHORE FOSSILS

Bown, Paul R.[1], Samantha J. Gibbs[2], and Jeremy R. Young[1]

Coccolithophores are phytoplanktonic marine calcifiers and an ‘at risk’ group from ocean acidification (OA). Culture and mesocosm experiments provide information on OA effects over short timescales for a small number of taxa. However, coccolithophores are also major components of marine sediments and provide an archive of abundance, diversity and calcification for the last 225 million years. Through study of past environmental change events that incorporate OA we can quantify response over timescales that include acclimatization and adaptation. Results from geological OA events have provided little support for significant extinction or disruption of large-scale calcification, although there are claims of malformation or minor biometric shifts in a handful of taxa. It is possible that OA was not significant at these events, or that coccolithophores were insensitive to the OA change, or that the metrics measured do not provide appropriate description of the response. To extract more information from the geological record we have sought out sediments that provide exceptional preservation of coccolithophores and minimize the biases inherent in fossil records. These sediments preserve intact coccospheres that facilitate direct comparison between modern and fossil cells. They reveal large disparity in cell size and a wide range in calcification types, and allow us to estimate cellular inorganic and organic carbon,

variations in cellular/skeletal biometry, and observe intracellular calcification. Preliminary results suggest that some measures of skeletal biometry are sensitive to surface water carbonate chemistry change but we see no unambiguous examples of malformed fossil coccospheres or disruption in growing coccoliths (protococcolith rings).

[1] Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK. (prb@ucl.ac.uk)
[2]Ocean and Earth Sciences, National Oceanography Centre, Southampton, University of Southampton, Southampton, SO14 3ZH, UK

THE EFFECTS OF OCEAN ACIDIFICATION ON THE PRECIOUS MEDITERRANEAN RED CORAL

Bramanti, Lorenzo[1], Sergio Rossi[3], Maricel Gouron[2], Juancho Movilla[2], Andrea Gori[3], Ángela Martínez[2], Carlos Dominguez-Carriò[2], Jordi Grinyo[2], Angel Lopez[2], Carles Pelejero[4], Eva Calvo[3], and Patrizia Ziveri[3]

Climate change may affect dynamics of marine populations. Mortality events, associated with temperature increase, recently affected several benthic suspension feeders in the Mediterranean Sea. Moreover predictions based on different scenarios indicate that ocean pH will decrease by 0.3 to 0.4 units by the end of the century.
Red coral (*Corallium rubrum*) is a modular anthozoan endemic to the Mediterranean Sea. This slow growing, long living species has been harvested since ancient times due to its high economic value linked to the use of the axial skeleton as raw material for jewellery leading to overexploitation. Moreover the Mg rich calcite skeleton make red coral more vulnerable to ocean acidification.
In order to understand the effects of elevated pCO_2 on this species, colonies of *Corallium rubrum* were maintained for one year in aquarium tanks at 2 pH levels (8,16 and 7,84) by bubbling seawater with pure CO_2 to decrease pH. Data on buoyant weight of the colonies, biochemical balance (protein, carbohydrates and lipids) and spicules geometry were taken periodically. Buoyant weight increment resulted significantly different between control and acidified treatment. Presence of aberrant spicule shapes was observed only in the acidified treatment. Total organic matter resulted significantly higher in acidified treatments while carbohydrates, lipids proteins and fatty acid composition did not resulted significantly different between the two treatments. The higher variability in non-acidified controls suggests an effect of elevated pH on the metabolism of colonies.

[1] California State University Northridge. 18111 Nordhoff st. 91330 Northridge, USA. (philebo@gmail.com).
[2] Institut de Ciències del Mar, CSIC, Passeig Marítim de la Barceloneta 37-49, 08003, Barcelona, Spain
[3] ICTA-UAB, UAB Campus Cn s/n Cerdanyola del Vallés 08193 Barcelona, Spain.
[4] Centre Scientifique de Monaco, Avenue Saint Martin 98000 Monaco, Principality of Monaco
[5] Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain

DEEP-SEA GAS EXCHANGE RATES IN A HIGH CO_2 WORLD: CARBON DIOXIDE

Brewer, Peter G., A.F. Hofmann, and Edward T. Peltzer

Discussion of the impacts of higher CO_2 levels has focused only on the oceanic bulk fluid properties (pH, pCO_2 etc). Here we describe the rate problem for animals who must export CO_2 through the diffusive boundary layer at about the same rate at which O_2 is consumed. The problem is more complex than that for a non-reactive gas since, as with gas exchange of CO_2 at the air-sea interface, the influence of the

ensemble of reactions within the CO_2 -bicarbonate - carbonate acid-base system must be considered. These appear as an enhancement factor which facilitates CO_2 efflux compared to O_2 intake at equal temperature, pressure and flow rate under typical oceanic concentrations.
By this chemical advantage marine animals can respond to external CO_2 stress by metabolic adjustment to elevate internal boundary p CO_2. This is energetically more favorable than mechanically increasing flow over their surface to thin the boundary layer as is required to alleviate O2 stress, although the elevated p CO_2 metabolic cost is non-zero and impacts must occur. Regionally as with O2 the combination of T, P, and pH/pCO_2 creates a zone of maximum CO_2 stress at around 1000 m depth. The net result is that the combination of an increase in T with declining O_2 poses a greater respiratory challenge to marine life than does increasing CO_2, but the effects are intertwined. The gas exchange rate relationships developed here provide improved prediction of the impacts on marine life from the combined effects of changing T, O_2, and CO_2.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039, USA (brpe@mbari.org)

CONSEQUENCES OF OCEAN ACIDIFICATION FOR COMMERICIAL SPECIES – GLOBAL CASE STUDIES OF THE EFFECTS ON FISHERIES AND AQUACULTURE

Bridges, Christopher R.[1], Eva Klumpen[1], Claudia Tavares[1], Janina Kraft[1], Annika Ritter[1], Philipp Kinzler[1], Markus Schütt[1], Tanja Novak[1], Lutz Auerswald[2], Jarrid Knapp[2,5], R.J.Atkinson[3], Philipp Smith[3], and Matt Naylor[4]

The effects of Ocean Acidification and Warming (OAW) have been studied in three crustacean species, *Cancer pagurus*, *Nephrops norvegicus* and *Jasus lalandii*, which are the subject of multi-million Euro commercial fisheries in Europe and South Africa. A fourth study on a further calcifying species the abalone, *Haliotis midae*, an important aquaculture species of the southern hemisphere completed the work. Organisms were treated to both short term acute expositions with high CO_2 levels above 1900µatm over 24hrs and also long-term experiments (60 days +) at differing levels ranging from control 390µtm to 3000µtm. Acid base balance was perturbed in all three crustacean species but with compensation within a few hours in the acute exposures. In long-term exposures compensation was achieved at 10° but not at high temperatures (18°C+). In all three crustacean species compensation was brought about by increasing haemolymph bicarbonate levels. Morphological investigations in *C. pagurus* and *N. norvegicus* revealed both ultra structure changes and loss of chelipeds in the latter species. In the abalone, serious shell thinning occurred even after a 60 day exposure together with a loss of growth rate. The implications of OAW and its synergistic effects for the "oceans of the future" will be discussed together with possible scenarios for fisheries and aquaculture dependent upon the levels of CO_2 predicted for the future. Some remediation strategies for aquaculture will be put forward.

[1]Heinrich-Heine University, Düsseldorf, Institute of Metabolic Physiology, Ecophysiology, Germany (bridges@uni-duesseldorf.de)
[2] Branch Fisheries, Dept. Of Agriculture and Food and Fisheries, Cape Town , South Africa
[3] Millport Marine Station, Isle of Cumbrae, Scotland
[4] Midae Marketing, Hermannus , South Africa
[5] Stellenbosch University, South Africa

USING EXPERIMENTS AND MODELS TO ADDRESS THE RESPONSE OF AN ESTUARINE FOOD WEB TO OCEAN ACIDIFICATION

Busch, Shallin, Sarah Norberg, Michael Maher, Jason Miller, Jon Reum, and Paul McElhany

Puget Sound is a fjordal estuary in Washington State where the changes in seawater pH due to ocean acidification are added on top of pH conditions that are already naturally low and highly dynamic. Natural variation in pH in this estuary is caused by factors such as upwelling and phytoplankton blooms. We study how Puget Sound species respond to ocean acidification, focusing on those that strongly influence the food web or are commercially important. We use locally collected ocean carbonate data, including some collected in the microhabitats in which our study organisms live, to create CO_2 conditions in laboratory experiments that are relevant to current and future environments. These conditions are rarely similar to atmospheric carbon dioxide conditions and incorporate variability in carbonate chemistry. We will present results on how forage fish, squid, geoduck and other species respond to high and variable CO_2 conditions. Our results emphasize that species besides calcifiers respond to changes in carbonate chemistry and that not all species respond to elevated CO_2 conditions in a negative manner. We use results from our laboratory studies and other published works to create ocean acidification scenarios in food web models. We will discuss the results of some of these scenarios, emphasizing changes in ecosystem services and indirect effects on species that do not respond directly to predicted changes pH.

NOAA Northwest Fisheries Science Center, 2725 Montlake Blvd., E., Seattle, WA 98112 (Shallin.Busch@noaa.gov)

IMPACTS OF OCEAN WARMING AND ACIDIFICATION ON ECHINODERM LIFE HISTORIES FROM THE POLES TO THE TROPICS – THE DEVELOPMENTAL DOMINO EFFECT

Byrne, Maria

Global warming and increased atmospheric CO_2 are causing the oceans to warm, decrease in pH and become hypercapnic, stressors that have deleterious impacts on marine invertebrate embryos and larvae. The response of echinoderm life histories from across world latitudes and for species with calcifying and non-calcifying larvae indicates overall trends in species responses despite disparate phylogeny, region and ecology. Increasing temperature has a pervasive stimulatory effect on metabolism until lethal levels are reached whereas hypercapnia has a narcotic effect. Exposure to stress early in development can have negative downstream effects because performance of later ontogeny depends on the success of early stages. This highlights the importance to consider the early embryonic stages seldom investigated in ocean change studies. Early embryos generated on ocean change conditions are very sensitive to warming and may not reach the calcifying stage in the absence of parental acclimation and adaptation to a warming ocean. Embryo mortality due to warming may the bottleneck for progression to the early larva with flow on effects for populations. Larvae are sensitive to warming and acidification. The effects of acidification in reducing growth in calcifying and non-calcifying feeding larvae and increased abnormality indicate that the stunting effect of pH/pCO_2 is strongly influenced by hypercapnic suppression and teratogenic effects. In cross-development rearing experiments early juveniles were vulnerable to reduced calcification although modest warming may diminish the negative impact of acidification on calcification. Comparative resilience of intertidal species and species with non-feeding larvae has implications for persistence, faunal shifts and community function in a changing ocean.

Schools of Biomedical and Biological Sciences, University of Sydney, Australia. (mbyrne@anatmoy.usyd.edu.au)

POPULATIONS LIVING ALONG A THERMO-LATITUDINAL GRADIENT VARY IN THEIR RESPONSE AND VULNERABILITY TO OCEAN ACIDIFICATION AND WARMING

Calosi, Piero[1], Sedercor Melatunan[1], Jonathan J. Byrne[2], Robert L. Davidson[2], Mark R. Viant[2], Steve Widdicombe[3], and Simon Rundle[1]

Species populations living along a thermo-latitudinal gradient have been shown to vary in their responses to temperature, with range-edge populations considered to be the most susceptible to climate change. However, limited information is available on populations' vulnerability to ocean acidification (OA) and even less on their combined effect. Using an integrative molecular-macrophysiological-ecological approach, we show that populations of the periwinkle *Littorina littorea* collected from across its geographical range of distribution in the NE-Atlantic showed different responses following exposure to OA conditions. Whilst all populations showed decreased growth when exposed to reduced pH, range-edge populations showed greater decrease and also appeared to differ in their physiological (i.e. metabolic rates) and metabolomics (i.e. metabolites concentrations) responses. Southern populations showed metabolic depression, whilst northern populations showed minimal shift in metabolic rates, and central range populations showed the ability to up-regulate their metabolic rates. Metabolomic responses followed a complex pattern along the gradient, helping explaining difference observed in growth vulnerability. Our results suggest that existing levels of thermal-adaptation of different populations living along environmental gradients will likely influence species populations responses to future OA and warming scenarios. In addition, although they appear to use different metabolic mechanisms, northern and southern range-edge populations are the most vulnerable to future predicted environmental challenges, particularly suggesting that OA may represent another way through which anthropogenically-driven environmental change will impact species' biogeography. Our investigation shows the value of utilizing an integrative approach in order to improve our ability to define future species responses to the global change.

[1]Marine Biology and Ecology Research Centre, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK. (piero.calosi@plymouth.ac.uk)
[2] NERC Biomolecular Analysis Facility – Metabolomics Node (NBAF-B), School of Biosciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK.
[3] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, PL1 3DH, UK.

OCEAN ACIDIFICATION EFFECTS ON THE EARLY LIFE-STAGES OF REPRESENTATIVE MARINE FINFISH OF THE NORTHEAST USA

Chambers, R.C.[1], E.A. Habeck[1], A.C. Candelmo[1], M.E. Poach[1], D. Wieczorek[1], B.A. Phelan[1], E.M. Caldarone[2], and K.R. Cooper[3]

The limited available evidence about effects of high CO_2 and acidification of our oceans on finfish suggests that effects will differ across fish species, be subtle, and interact with other stressors. A carefully planned, experimental framework was developed to cast an extensive yet strategic inferential net. Three key elements of our approach are the use of 1) multiple marine finfish species of relevance to the northeastern USA that differ in their ecologies including spawning season and habitat; 2) a wide yet realistic range of environmental conditions (i.e., concurrent manipulation of CO_2 levels and water

temperatures), and 3) a diverse set of response variables related to fish sensitivity to elevated CO_2 levels, water temperatures, and their interactions. The response variable set reflects fish condition, fitness, and likelihood of recruitment, and includes measures of viability, physiology, histopathology, growth, development, and behavior expressed during fish early life-stages (i.e., gametes, embryos, and larvae). To date, separate two-way factorial experiments have been implemented on summer flounder (*Paralichthys dentatus*) and winter flounder (*Pseudopleuronectes americanus*). Initial results reveal survival of summer flounder embryos is compromised by pH < 7.7 (CO_2 > 790 ppm). These results were similar across offspring groups (i.e., different source parents). Responses of larvae of both flounder species are currently being assessed. The broader study will aid researchers and resource managers in identifying species types, life stages, and biotic responses that are most vulnerable to the expected future levels of CO_2 and water temperature in our oceans.

[1] Northeast Fisheries Science Center, NOAA Fisheries Service, Highlands, NJ 07732 (chris.chambers@noaa.gov)
[2] Northeast Fisheries Science Center, NOAA Fisheries Service, Narragansett, RI 02882,
[3] Department of Biochemistry & Microbiology, Rutgers University, New Brunswick, New Jersey 08901

THE NEED TO MANIPULATE NATURAL VARIABILITY IN PH IN OCEAN ACIDIFICATION EXPERIMENTS

Cornwall, Christopher E.[1], Christopher D. Hepburn[2], Christina McGraw[3], Kim Currie[4], Conrad Pilditch[5], Keith, A. Hunter[6], Phillip W. Boyd[4], and Catriona Hurd[1]

The pH of the world's oceans is decreasing due to the increased absorption of anthropogenic CO_2 emissions, a process known as ocean acidification (OA). These changes in seawater chemistry are predicted to have adverse effects on populations of many marine organisms. Daily changes in pH in productive coastal seas may be of a larger magnitude than those predicted due to OA over the next 100 years yet it is unknown how these short-term changes in pH may influence the susceptibility of coastal species to OA. A laboratory experiment was used to expose an important coastal calcifying organism (coralline algae) to conditions simulating today's coastal seas and to a future OA scenario. For both treatments, algae were exposed to either static pH (mimicking more stable oceanic waters similar to most OA experiments), or daily-fluctuating pH (typical of near-shore seas). Coralline algal growth decreased with mean reductions in pH and when exposed to diel pH fluctuations, while the physiological health, and survival of coralline algae did not differ between treatments. The reproduction of adults and the survival of juvenile coralline algae was also unaffected by pH. Our results imply that diel fluctuations in pH may adversely influence growth rates of coastal species on a similar magnitude as the mean reduction expected due to OA, and that not all coralline algae will be as negatively influenced by OA as previous studies have reported.

[1]Department of Botany, University of Otago, PO Box 56, Dunedin 9054, New Zealand (chris.cornwall@botany.otago.ac.nz)
[2]Department of Marine Sciences, University of Otago, PO Box 56, Dunedin, New Zealand
[3]School of Chemistry and Biochemistry, University of Clark, 950 Main Street, Worchester, Massachusetts, USA
[4]Department of Chemistry, National Institute for Water and Atmospheric Research Ltd (NIWA), Centre of Physical and Chemical Oceanography, University of Otago, PO Box 56, Dunedin, New Zealand
[5]School of Biological Sciences, Waikato University, Private Bag 3105, Hamilton, New Zealand
[6]Department of Chemistry, University of Otago, PO Box 56, Dunedin, New Zealand

CONTROLS ON CARBONATE MINERAL SATURATION STATES AND OCEAN ACIDIFICATION ON THE SOUTHEASTERN BERING SEA SHELF

Cross, Jessica N., and Jeremy T. Mathis

While models have predicted consistent aragonite undersaturations in arctic and sub-arctic regions by mid-century, some seasonal undersaturations of aragonite have already been observed on the Alaskan continental shelf. In the eastern Bering Sea, high concentrations of DIC in river discharge coupled with remineralization processes in the near-shore environment precondition coastal waters to have low carbonate mineral saturation states. In contrast, high rates of primary production (~97 – 103 Tg-C yr^{-1}) in spring and summer along the shelf break increases carbonate mineral saturation states in surface waters by consuming DIC, creating a strong seasonal sink for atmospheric CO_2. Due to an uncoupling of primary production and grazing, the majority of the organic matter produced is remineralized in bottom waters, creating high concentrations of DIC and suppressing carbonate mineral saturation states. This process causes a biological amplification of ocean acidification in this region. Additionally, upwelling of basin waters onto the shelf, the seasonal melting of sea ice, and periodic coccolithophore blooms also naturally suppress carbonate mineral saturation states on seasonal timescales. However, despite the presence of these natural mechanisms for carbonate mineral suppression in the Bering Sea, we show that it is ultimately the addition of anthropogenic CO_2 that causes broad areas of aragonite undersaturations as well as calcite undersaturations in areas where export production is highest. Some keystone species in the Bering Sea could be susceptible to reduced calcification rates under increasing ocean acidity and this may have profound implications for benthic ecosystems, including the commercially valuable crab fishery.

University of Alaska Fairbanks, School of Fisheries and Ocean Sciences, 245 O'Neill BLDG, Fairbanks, AK, 99775 USA. (jncross@alaska.edu)

TRANSCRIPTOME-WIDE SCAN REVEALS GENES POTENTIALLY AFFECTED BY OCEAN ACIDIFICATION IN RED ABALONE (*HALIOTIS RUFESCENS*) ALONG THE CALIFORNIA COAST

De Wit, Pierre and Stephen R. Palumbi

The oceanic environment is currently changing rapidly with a projected pH drop of up to 0.5 units within the next hundred years. Understanding how marine organisms will respond is crucial to conservation efforts. The coast of Northern California already experiences low aragonite saturation states due to upwelling of deep water, so by contrasting this population to ones that experience normal conditions, we can learn what changes we can expect in the future. By using high-throughput sequencing techniques, we can scan the transcriptomes (all expressed genetic material in a tissue) of organisms for genes under differential selective pressures.

In this study, we sequence mantle transcriptomes of 39 Red Abalone individuals from three locations: Monterey, Sonoma and Northern California. We create and annotate a *de novo* assembly and use a SNP detection pipeline to find 1.2 million variant sites, for which genotypes can be assigned to all 39 individuals at 21,285 sites. No overall geographic pattern is seen, corroborating previous research. However, using an F_{ST} outlier approach, we identify 42 genes potentially under differential natural selection, of which many are implicated in shell-formation. A functional enrichment analysis corroborates this pattern by showing that functions related to ion transport and cellular homeostasis are significantly enriched for high F_{ST} SNPs. Most notably, Pif177, found to be critical for nacre formation in Pearl Oysters, is notably different in Northern California compared to the other two populations. By focusing future research on these genes, we will better understand the impact of ocean acidification on calcifying organisms.

Sven Lovén Center for Marine Sciences, University of Gothenburg, Kristineberg 566, 451 78 Fiskebäckskil, Sweden. (pierre.de_wit@hotmail.com)
Hopkins Marine Station of Stanford University, 120 Ocean view Blvd., Pacific Grove, CA 93950, USA.

OCEAN ACIDIFICATION AND CHANGING STRUCTURES OF OCEAN ECOSYSTEMS

Denman, Kenneth

We expect surface pH to continue to decrease over this century, in concert with changes in other ocean variables associated with a changing climate. However, we have limited capability to predict the response/adaptation of individual species to the expected long term trend in pH, much less to predict the response/adaptation of whole ecosystems to changes in multiple stressors, which is a key question to be addressed in the future. At present our coupled climate carbon cycle models rarely exhibit abrupt change or regime shifts (e.g. in the decreasing area of summer Arctic Sea ice, the Meridional Overturning Circulation, or food web structure and function). In planktonic food web models, does this 'gradual change only' behavior result from the 'fixed' compartmental structure of current models, where few if any parameter values vary over time in response to the changing environment? Could adaptive distributional models (a subset of Complex Adaptive System models) give a more realistic view of how future ocean ecosystems might evolve? I present simulations with a simple CAS model (with a frequency distribution of phenotype/species traits that vary in response to changes in environmental variables) as a possible approach to this problem.

School of Earth and Ocean Sciences and VENUS Coastal Network, University of Victoria,
PO Box 1700, STN CSC, Victoria, BC, Canada, V8L 5G2 (denmank@uvic.ca)

THE PROTEOME RESPONSE OF LARVAL STAGES OF *Crassostrea hongkongensis* TO LONG TERM EXPOSURE TO HIGH-CO_2

Dineshram, R. and V. Thiyagarajan

Oysters are one of the most important commercially exploited species cultured in the molluskan hatcheries around the world. Due to rising CO_2 and subsequent decrease in seawater pH, their survival and shell forming processes are threatened globally. Our large-scale CO_2 perturbation experiments at a commercial hatchery setting showed that larval shell growth rate is significantly reduced at projected OA scenarios for the year >2100 in the oyster species (*Crassostrea hongkongensis*) compared to that of ambient CO_2 levels. 2DE-MALDI TOF/TOF based proteomics approach was used to examine the global (total) and the post translational modified proteins of oyster larvae exposed to OA over 32 d. Proteomic analysis of the eye-spot larvae of statistically similar size at the time of settlement, displayed protein expression pattern and/or phosphorylation levels decreased with increasing OA stress. The differential expressed proteins that are identified in this study are related to energy metabolism, calcium binding and cytoskeletal proteins. Disruption of cytoskeletal and calcification responsible proteins observed due to OA in the early stages of the edible oyster can be estimated to have a significant implication with its population structure and in its commercial production in particular to aquaculture. This study on early larval stages coupled with proteome change in OA conditions is the first step towards the search for novel protein expression signatures that can provide new insights into their role in tolerance and/or as biomarker for OA.

The Swire Institute of Marine Science, The University of Hong Kong, Cape d'Aguilar, Shek O, Hong Kong, dinbiot@hku.hk

SYNERGISTIC EFFECTS OF TEMPERATURE AND *p*CO_2 ON PHOTOSYNTHESIS, RESPIRATION AND CALCIFICATION IN THE FREE-LIVING CORALLINE ALGA *LITHOTHAMNION GLACIALE*

Donohue, Penelope J C[1], Sebastian Hennige[2], Murray Roberts[2], Maggie Cusack[1], and Nicholas Kamenos[1,3]

Anthropogenically accelerated global climate change may represent a major threat to marine calcifying organisms. This phenomenon includes multiple simultaneously changing environmental factors, of which ocean acidification (OA, decreasing ocean pH as a result of increasing seawater *p*CO_2) and rising global sea surface temperatures are two of the most widespread concerns for coastal areas. Red coralline algae are ubiquitous in coastal systems throughout the world and often provide an integral contribution to the local biogenic habitat, maintaining biodiversity and ecosystem provision. These calcifying algal species are highly sensitive to variations in temperature, which induces physiological changes and directly impacts growth rate. In addition, coralline algae are composed of high-Mg biogenic calcite, which is likely to be structurally very sensitive to decreases in ocean pH. However, very little in known about how the synergistic effect of temperature and OA may impact key physiological processes within coralline species. This study examined the response of photosynthesis, respiration and calcification in *Lithothamnion glaciale* to elevated *p*CO_2 (1000 ppm, 7°C), elevated temperature (380 ppm, 9°C) and combined elevated *p*CO_2 and temperature (1000 ppm, 9°C) and compared results to algae maintained under control conditions (*p*CO_2 380 ppm, temperature 7°C). This study presents evidence of how OA and elevated temperature may have a synergistic effect on the key physiological processes in coralline algae and highlights the importance of using multi-factor experiments to investigate the effects of global climate change in marine organisms.

[1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ (p.donohue.1@research.gla.ac.uk)
[2]School of Life Sciences, Heriot-Watt University, Edinburgh, EH14 4AS
[3]School of Life Sciences, University of Glasgow, Glasgow, G12 8QQ

ASSESSING PHYSIOLOGICAL TIPPING POINTS IN RESPONSE TO OCEAN ACIDIFICATION

Dorey, Narimane[1], Pauline Lancon[1], Mike Thorndyke[2], and Sam Dupont[1]

After nearly 15 years of research in the ocean acidification (OA) field, it is still difficult to make any generalization on future marine ecosystem changes. OA is often experimentally approached as a comparison between current average global pH (8.0) and pH predicted for near-future (e.g. 7.7). However, pH displays high variability in coastal surface waters and the pH experienced by organisms can be broad due to seasonal, diurnal and tidal changes. Classic experimental design might therefore test conditions that organisms are already occasionally experiencing. It is then important to discriminate between temporary physiological adaptation within the organism tolerance range and teratology when the physiological tipping point is exceeded and no recovery is possible.
In this study, we provide insights on the tolerance range of a sea urchin larvae (*Strongylocentrotus droebachiensis*) to a *p*CO_2-driven seawater acidification gradient. Dividing embryos were able to survive

in pH as low as 6.5 (≈18000 µatm) although no larvae was qualified as normal. Development of swimming larvae was possible at pH ≥ 7.1. However, below 7.5 a third to half of the larvae were abnormal. Low pH induced developmental delay along with increased mortality. Respiration rates linearly increased when pH was lowered. Morphometric measurements (body width and arm growth, arm symmetry and stomach volume) suggest that developmental anomalies significantly increased with lower pH. In conclusion, a physiological tipping point was identified below pH 7.5, corresponding to the extreme limit of the natural environmental variability.

[1]Department of Biological and Environmental Sciences, University of Gothenburg – Kristineberg, 45178, Fiskebäckskil, Sweden (narimane.dorey@gu.se)
[2]The Royal Swedish Academy of Sciences, The Sven Lovén Centre for Marine Sciences – Kristineberg, 45178, Fiskebäckskil, Sweden

THE HIGH VARIABILITY CO_2 WORLD OF HAWAIIAN CORAL REEFS

Drupp, Patrick S.[1], Eric Heinen De Carlo[1], Robert Thompson[1], Fred T. Mackenzie[1], Frank Sansone[1], Andreas Andersson[2], Sylvia Musielewicz[3], Stacy Maenner-Jones[3], Christopher L. Sabine[3], and Richard A. Feely[3]

A network of PMEL-MAPCO_2 buoys deployed in coastal waters of Oahu begun in 2005 has produced multiyear high temporal resolution CO_2 records in Hawaiian coral reefs. The buoys, located in lagoonal, fringing and barrier reef settings of Oahu, reveal a wide variability of environmental conditions that leads to large swings in seawater pCO_2. The range of pCO_2 (~200 to 1000 µatm) observed shows that coral reefs already experience, at times, conditions that might be expected in the future oceans under continued increases in atmospheric CO_2. Factors that control the high variability in seawater pCO_2 include both physical forcing as well as biological processes which, when acting in concert, can lead to undersaturation with respect to biogenic carbonate minerals, especially high magnesian calcite but also aragonite.
To date much of the research on the future impact of ocean acidification (OA) has focused on changes in the ability of organisms to calcify under increasing OA but very little attention has been paid to the reverse process, that of carbonate mineral dissolution. In order to address this topic, our group recently began to examine conditions extant in porewaters of coral reef sediments so as to examine the potential for carbonate mineral dissolution.
Our presentation will highlight how the biological cycles of productivity/respiration and calcification/carbonate dissolution are influenced by changing water column properties, physical processes (e.g. residence time) and atmospheric conditions, and how these processes ultimately lead to conditions in the water column and in porewater under which biogenic carbonate minerals may dissolve.

[1] Department of Oceanography, University of Hawaii at Manoa, Honolulu, HI 96822 (drupp@hawaii.edu)
[2] Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093
[3] NOAA/PMEL, 7600 Sand Point Way, Seattle, WA 98115

THE COST OF (RE-)CALCIFICATION IN A HIGH CO_2 WORLD

Dupont, Sam[1], Kit Yu Karen Chan [2], Mike Thorndyke [3], and Paola Oliveri [4]

To understand the present distribution and potential resilience of a given species in response to today's and to future environmental variability, it is crucial to understand its physiological ability to buffer and/or regulate when exposed to these changes. For example, it is believed that shells of marine calcifiers will be more exposed to dissolution under elevated *p*CO2 environment but very little information is available on mechanisms, energy costs and fitness consequences of perturbation in the balance between calcification/dissolution. Combining internal pH mapping techniques and a newly developed physiological assay to manipulate calcification/dissolution/re-calcification, we will show that sea urchin larvae possess an unexpectedly high resilience to low pH conditions. Under moderate ocean acidification conditions (e.g. ΔpH=0.4), sea urchin larvae are able to quickly compensate for environmental pH changes by using ion channels (e.g. H+/K+-ATP) and keep their cellular pHi constant (e.g. PMCs involved in calcification). Following the re-calcification process after a major dissolution, we were able to estimate the cost of calcification as less than 10% of the larval energy budget in control conditions. Under high pCO_2, an additional 10% energy cost is needed to regulate pHi. Impact of calcification/dissolution on sea urchin fitness was measured through larval performance (growth, calcification, settlement success, gene expression, swimming) and energy budget (respiration, feeding). We demonstrated that sea urchin larvae appeared to be much more resistant to elevated pCO_2 (e.g. normal development till pH>7.3) than previously expected and are able to quickly recover from major episodes of decalcification (e.g. 24h exposure to pH 5.3).

[1] Department of Biological and Environmental Sciences, The Sven Lovén Centre for Marine Sciences - Kristineberg, University of Gothenburg, Fiskebäckskil, 45178, Sweden (sam.dupont@bioenv.gu.se)
[2] School of Oceanography, University of Washington, Seattle, USA
[3] Royal Swedish Academy of Sciences, The Sven Lovén Centre for Marine Sciences - Kristineberg, University of Gothenburg, Fiskebäckskil, 45178, Sweden
[4] GEE & CDB Departments, University College London, Gower Street, London, WC1E 6BT, UK

EFFECTS OF OCEAN ACIDIFICATION ON THE ECO-PHYSIOLOGY OF CALCAREOUS AND TOXIC DINOFLAGELLATES

Eberlein, Tim[1], Dedmer B. Van de Waal[1], Uwe John[2], and Björn Rost[1]

The consequences of ocean acidification (OA) on marine phytoplankton have been intensively studied ranging from cellular to ecosystem level. These investigations, however, almost exclusively focused on coccolithophores and diatoms. Dinoflagellates also represent an important group of phytoplankton, featuring the photosynthetic key enzyme type II RubisCO, with very low affinities for its substrate CO_2. Hence, we expect this group to be particularly sensitive to changes in CO_2 concentrations. In this study, we therefore investigated the impact of OA on the eco-physiology of two dinoflagellate species, the calcareous *Scrippsiella trochoidea* and the toxic *Alexandrium tamarense*, by using dilute batch incubations over a range of CO_2 levels. Our results show that with rising pCO_2, growth rates and chlorophyll *a* contents remained relatively unaltered, but also species-specific differences were observed. For instance, *Scrippsiella* displayed a strong decrease in organic carbon production, and *Alexandrium* showed a shift in its toxin profile towards less toxic variants under elevated CO_2. To understand these eco-physiological responses, several aspects of inorganic carbon (Ci) acquisition were investigated by means of membrane-inlet mass spectrometry. Both species featured efficient carbon concentrating mechanisms (CCMs), which in *Scrippsiella* was further facilitated by a high carbonic anhydrase activity. In *Scrippsiella,* maximum photosynthetic rates increased while Ci affinities decreased. Interestingly, in *Alexandrium* the opposite response pattern was observed. Our results show that dinoflagellate species have different strategies to adjust their Ci acquisition, which may enable them to keep their growth rates unaffected over a range of CO_2 levels.

[1]Marine Biogeosciences, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany (Tim.Eberlein@awi.de)
[2]Chemical Ecology, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

COMBINED EFFECTS OF DIFFERENT CO_2 LEVELS AND NITROGEN SOURCES ON THE N_2-FIXING CYANOBACTERIUM *TRICHODESMIUM*

Eichner, Meri [1], Sven A. Kranz[2], and Björn Rost[1]

In view of the current increase in atmospheric pCO_2 and its feedbacks to the marine environment, it is crucial to assess and understand responses of ecologically relevant phytoplankton species. The cyanobacterium *Trichodesmium* spp. contributes about half of marine N_2 fixation and thus plays an important role in the biogeochemical cycling of carbon and nitrogen. Previous studies showed an exceptionally strong CO_2 sensitivity in this species and further suggested these effects to be caused by reallocation of energy between metabolic key processes. This study focused on combined effects of different pCO_2 levels (180, 380, 950 and 1400 µatm pCO_2) and nitrogen sources (N_2 vs. NO_3^-) on *Trichodesmium*, aiming to allow an insight into the plasticity of energy allocation under different energetic requirements imposed by the varying nitrogen sources. While no significant effect on growth rates by either pCO_2 or nitrogen source was shown, production of POC and PON proved sensitive to both parameters. Cell quotas of POC as well as PON were elevated and POC:PON ratios decreased in response to the switch from N_2 fixation to NO_3^- consumption. Measurements of the underlying processes revealed, for instance, high rates of NADPH-dependent internal carbon cycling in NO_3^--grown cells, which reduced CO_2 leakage and improved the efficiency of carbon acquisition. Overall, our findings highlight the pivotal role of energy allocation in explaining the effects of different nitrogen sources and CO_2 levels.

[1] Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, D-27568 Bremerhaven, Germany (meri.eichner@awi.de)
[2] Princeton University, 153 Guyot Hall, 08540 Princeton, NJ, USA.

A PHYSIOLOGICAL TRADE-OFF IN MUSSELS EXPOSED TO OCEAN ACIDIFICATION – IMMUNE SYSTEM PLASTICITY ENSURES SURVIVAL BUT AT THE COST OF REPRODUCTION

Ellis, Robert P.[1,2*], Helen Parry[1], John I. Spicer[2], Thomas H. Hutchinson[3], and Steve Widdicombe[1]

The immune response is an organism's principle defence against any pathogenic insult. Yet, despite its importance little is known of how this response trades off against other life-history traits under stressful environmental conditions. By exposing the blue mussel (*Mytilus edulis*) to ocean acidification and increasing temperature, we show that reducing seawater pH is accompanied by a reduction in the mussel immune response. However, with the immune system protecting an organism from infectious disease, this physiological process should be measured functionally rather than immunologically. Therefore, in subsequently exposing mussels to a bacterial challenge, we were able to demonstrate that the initial reduction in host defence was in fact a trade-off of immune system maintenance costs, with mussels maintaining the capacity to up-regulate their immune response when required. However, whilst maintaining this immune system plasticity ensures mussels are able to survive a pathogen exposure; such a strategy comes at a cost, measured in this study as a reduction in the allocation of resources to reproduction. This study therefore demonstrates that to fully understand the impact of anthropogenic climate change, it is vital to measure physiological processes functionally, accounting for any physiological trade-offs.

[1.] Plymouth Marine Laboratory, Prospect Place, Plymouth, Devon, PL1 3DH, UK
[2.] School of Marine Science and Engineering, University of Plymouth, Drakes Circus, Plymouth, Devon, PL4 8AA, UK
[3.] Centre for Environment, Fisheries & Aquaculture Science, Barrack Road, The Nothe, Weymouth, Dorset DT4 8UB, UK
*Present address: College of Life and Environmental Sciences, University of Exeter, Exeter, Devon, EX4 4QD, UK (R.P.Ellis@exeter.ac.uk)

RESISTANCE TO CO_2-DRIVEN SEAWATER ACDIFICATION IN LARVAL PURPLE SEA URCHINS

Evans, Tyler G and Gretchen E Hofmann

Coastal zones of the Northeast Pacific Ocean are highly dynamic environments that experience natural fluctuations in pCO_2 and pH as a result of oceanic up-welling. We hypothesized that exposure to up-welling during evolutionary history may have directed the evolution of adaptations that enhance tolerance toward pCO_2/pH stress in marine species inhabiting these areas. To address this hypothesis, we cultured larval purple sea urchins (*Strongylocentrotus purpuratus*), which encounter up-welling events during their extensive time in the plankton, in CO_2-acidified seawater representative of present day (400 μatm) and future ocean conditions (800 and 1200 μatm). Physiological performance was then assessed at gastrula and pluteus stages using a genome-wide microarray. Resulting gene expression patterns reveal two important trends. Firstly, larval urchins quickly acclimatize (within approximately two days) to a high CO_2 environment. Differential gene expression suggests that buffering intra- or extracellular pH through free phosphate and ion transport as well as altering the bioavailability of calcium, represent potential mechanistic bases for acclimatization. Secondly, larval urchins use divergent physiological strategies for dealing with different magnitudes of pCO_2/pH stress: actively modifying physiology through changes in gene expression under moderate pCO_2 conditions (i.e. 800 μatm), but employing a quiescent-like strategy for severe elevations in pCO_2 (i.e. 1200 μatm). Collectively, these data support the hypothesis that marine organisms inhabiting up-welling zones have evolved enhanced capabilities to cope with increases in pCO_2. That there exist species potentially more resistant to ocean acidification is important information when attempting to forecast the impact of climate change in future oceans.

Ecology, Evolution and Marine Biology, University of California Santa Barbara, Santa Barbara, CA 93106-9620, USA (tyler.evans@lifesci.ucsb.edu)

PERMEABLE CARBONATE SANDS MODIFY THE CARBON CHEMISTRY OF OVERLYING WATERS

Eyre, Bradley D., Isaac Santos, and Tyler Cyronak

Permeable $CaCO_3$ sediments cover the floor of most coral reefs and support both heterotrophic and autotrophic communities. Generally these sediment are considered fairly biogeochemically inert due to

their low carbon content. However, porewater advection in permeable sands efficiently transports reactants deep into the sediment, enhancing the effective area where exchange takes place and magnifying benthic biogeochemical processes. This presentation will briefly review the drivers of porewater advection in permeable sediments and present a case study from Heron Island that demonstrates the role of permeable sands in proton (H^+), O_2 and CO_2 cycling in a coral reef lagoon water column. The diel ranges in the reef lagoon water chemistry (dissolved oxygen: 28-463 µM; pH: 7.69-8.44; aragonite saturation state: 1.7-6.8) appear to be the broadest, and the night-time values are among the lowest ever reported for healthy coral reefs. Night-time pH (7.69) was comparable to worst-case scenario predictions for seawater pH in 2100. The net contribution of coarse carbonate sands to the whole system H^+ fluxes was only 9% during the day, but approached 100% at night when small scale (i.e., flow and topography-induced pressure gradients) and large scale (i.e., tidal pumping as traced by radon) seawater recirculation processes were synergistic. Reef lagoon sands were a net sink for H^+ and CO_2 and the sink strength was a function of porewater flushing rate. Our observations suggest that the metabolism of advection-dominated carbonate sands may provide a currently unknown feedback to ocean acidification.

Centre for Coastal Biogeochemistry, Southern Cross University. bradley.eyre@scu.edu.au

CORAL REEFS AND CO_2 SEEPS: DIRECT CO_2 EFFECTS, FLOW-ON ECOSYSTEM CHANGES AND THRESHOLDS ALONG CO_2 GRADIENTS

Fabricius, Katharina

Volcanic seeps of pure CO_2 in eastern Papua New Guinea were used to assess the effects of long-term exposure to elevated CO_2 on coral reef communities. CO_2 was elevated for > 70 years, i.e., for a time span that is relevant for long-lived corals. Reefs persist around the seeps in areas down to pH values of 7.8 units, however exposed reefs have substantially reduced diversity, structural complexity and coral juvenile densities. We highlight some of the latest ecological results from work at these sites, quantify changes along the three gradients in seawater carbonate chemistry, and contrast ecological functions of coral reefs exposed to high CO_2 with those of control sites. We also contrast direct effects of elevated CO_2 on biota with indirect effects, derived from loss in structural complexity. Finally, we present some data on the combined effects of high CO_2 and heat stress on corals. This study suggests that ocean acidification alone will lead to profound changes in the ecology of coral reefs throughout this century, and that the effects of ocean acidification on coral reefs will be exacerbated by increasing seawater temperatures.

Australian Institute of Marine Science, PMB 3, Townsville, Queensland 4810, Australia (k.fabricius@aims.gov.au)

THE IMPACTS OF OCEAN ACIDIFICATION, UPWELLING, AND RESPIRATION PROCESSES ON ARAGONITE SATURATION AND pH ALONG THE WASHINGTON-OREGON-CALIFORNIA CONTINENTAL MARGIN IN LATE SUMMER 2011

Feely, Richard A.[1], Simone R. Alin[1], Lauren W. Juranek[2], Burke Hales[2], Robert H. Byrne[3], and Mark Patsavas[3]

The continental shelf region off the Washington-Oregon-California coast is seasonally exposed to conditions of low aragonite saturation state by coastal upwelling of deep waters. However, the extent of its evolution in late summer has been largely unknown. Along this continental margin, ocean acidification, upwelling, biological productivity, and respiration processes in subsurface waters are major contributors to the variability in dissolved inorganic carbon (DIC), pH and aragonite saturation state. In the late summer of 2011, we conducted a large-scale chemical, biological, and hydrographic survey of the region in order to better understand the interrelationships between these natural and human-induced processes and their effects on calcium carbonate saturation. The uptake of anthropogenic CO_2 has caused the aragonite saturation horizon to shoal by approximately 50 m since preindustrial times so that it is well within the density layers that are currently being upwelled along the west coast of North America to depths between 10 and 80 m. Although the majority of the corrosive character of these waters is the result of respiration processes (59 to 74% of the total change in DIC) at intermediate depths in off-shore waters, ocean acidification and respiration processes locally at shallower depths on the continental shelf contribute from 26 to 41% of the increase in DIC (and decrease pH and aragonite saturation). These local processes expose coastal organisms living in the water column or at the sea floor to less saturated waters, further exacerbating the biological impacts.

[1] NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA
[2]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA
[3]College of Marine Science, University of South Florida, St. Petersburg, FL, USA

CORALLINE ALGAE AS PH-RECORDERS ON SEASONAL TO CENTENNIAL TIMESCALES

Fietzke Jan[1], Federica Ragazzola[1,2], Jochen Halfar[3], Heiner Dietze[1], Laura C Foster[2], Thor T Hansteen[1], and Anton Eisenhauer[1]

Increasing CO_2 in the atmosphere over the last century has driven a reduction of the average global surface ocean by 0.1 pH unit and a lowering of the carbonate saturation state.
Very little is known about the regional variability of ocean acidification on decadal to centennial time-scales and thus reconstruction of ambient seawater pH is essential in order to evaluate possible strategies of acclimatisation/adaptation of marine calcifying organisms. We analysed the spatial distribution of boron isotopes in a cold water specimen of *Clathomorphum nereostratum,* a long-lived crustose coralline alga that exhibits annual growth increments.
Our boron isotope data show a long-term pH-decrease with a drop of ~0.08(2) pH units from 1900-1990 which is in agreement with the value expected from atmospheric CO_2 time-series data. A seasonal cycle of pH-variability (up to 0.1 pH units) is recorded too with highest pH values during late spring/early summer. Nearby instrumental CO_2 measurements show a rapid pH increase of up to 0.15 units during the spring bloom .This is most likely a result of the CO_2 consumption during the spring microalgal bloom.

[1] GEOMAR, Helmholtz Centre for Ocean Research, Wischhofstraße 1-3 , 24148 Kiel, Germany.
f.ragazzola@bristol.ac.uk
[2] Dept. of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, BS8 1RJ, UK.
[3] University of Toronto, 22 Russell Str., Toronto Canada

THE BIOMINERALIZATION RESPONSE OF THE COLD-WATER CORAL *LOPHELIA PERTUSA* TO OCEAN ACIDIFICATION

Foster, Laura C. [1] Federica Ragazzola[1,2], Marlene Wall[3], Armin Form[2], and Daniela N. Schmidt[1]

Cold-water corals provide an important function in the formation of deep-water ecosystems and at high latitudes. It is estimated that by end of the century 70% of the currently known *Lophelia pertusa* bioherms will be exposed to waters under-saturated with regards to aragonite [Guinotte et al., 2006]. To assess *L. pertusa's* response to ocean acidification it was cultured at pCO_2 levels of 604, 778, 982 µatm. The long term incubation experiments show acclimatization in growth rates [Form and Riebesell, 2012]. To further investigate how this acclimatization occurs, we analyzed the geochemistry, morphology and skeletal structure of *L. pertusa*. The results were combined with Synchrotron X-ray Tomography (SXRTM) to reconstruct growth changes in 3D and Raman spectroscopy to examine for changes in the biomineralisation. In-situ Secondary Ionization Mass Spectrometry (SIMS) was used to quantify trace element (Mg, Sr) and $\delta^{11}B$ composition (a proxy for pH). Results from $\delta^{11}B$ shows that *L. pertusa* elevates the pH compared to that of the ambient seawater and exhibits similar systematic variation as seen in a previous study [Blamart et al., 2007]. Our data also shows lower values under high pCO_2 than that of the control for the calyx wall. This gives new insight in the calcification process and a first indication for palaeo-pH reconstruction in *L. pertusa*.

[1]Department of Earth Sciences, University of Bristol, UK (l.c.foster@bristol.ac.uk)
[2]GEOMAR, Helmholtz Centre for Ocean Research, Kiel, Germany
[3] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

EFFECTS OF OCEAN ACIDIFICATION ON THE GROWTH AND ORGAN HEALTH OF ATLANTIC HERRING LARVAE

Frommel, Andrea Y.[1], Rommel Maneja[1,2], David Lowe[3], Audrey J. Geffen[2], Arild Folkvord[2], Uwe Piatkowski[1], and Catriona Clemmesen[1]

Herring (*Clupea harengus*) is one of the most important commercial fish species in the North Atlantic. Fluctuations in recruitment are mainly caused by high mortality during the early life stages, which are most vulnerable to sub-optimal conditions. Within the framework of EPOCA and BIOACID, we tested the effects of three levels of OA (control: pH = 8.08, 380 ppm CO_2, medium: pH = 7.45, 1800 ppm CO_2 and high: pH = 7.08, 4200 ppm CO_2) on larval herring that were reared from eggs to seven weeks post hatching in large outdoor mesocosms. Under increased CO_2 larvae showed decreased growth rates compared to the control group. Furthermore, histological analyses revealed severe tissue damage in many internal organs as a result of CO_2, with the severity increasing with CO_2 concentration. Results on herring will be compared to previous studies on Atlantic cod larvae.

[1] GEOMAR | Helmholtz Centre for Ocean Research, Duesternbrooker Weg 20, 24105 Kiel, Germany
afrommel@ifm-geomar.de
[2] Department of Biology, University of Bergen, PO Box 7803, N-5020, Bergen, Norway
[3] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, UK

RISING CARBON DIOXIDE AND INCREASING LIGHT EXPOSURE ACT SYNERGISTICALLY TO REDUCE MARINE PRIMARY PRODUCTIVITY

Gao, K[1].; J. Xu[1], G. Gao[1], Y. Li[1], D.A. Hutchins[2], B. Huang[1], Y. Zheng[1], P. Jin[1], X. Cai[1], D.P. Häder[3], W. Li[1], K. Xu[1], N. Liu[1], and Riebesell, U.[4]

Carbon dioxide (CO_2) and light are the two main ingredients of photosynthesis. Rising CO_2 levels in oceanic surface waters in combination with ample light supply are therefore usually considered stimulatory to marine primary production (PP). Here we show that the combination of elevated CO_2 and increased light exposure negatively impacts photosynthesis and growth of marine primary producers. When exposed to CO_2 concentrations projected for the end of this century, natural phytoplankton assemblages of the South China Sea (SCS) responded with decreased photosynthetic carbon fixation and increased non-photochemical quenching (NPQ, an indicator of light stress) at light intensities representative of the upper surface layer. The community composition of these experimental phytoplankton assemblages shifted away from diatoms, the dominant phytoplankton group encountered during our field campaigns. To examine the underlying mechanisms of the observed responses, we grew three species of diatoms at different CO_2 concentrations and under varying levels (5-100%) of solar radiation to mimic the range of photosynthetically active radiation (PAR) experienced by the phytoplankton at different depths of the euphotic zone. Above 22-36% of incident surface solar radiation, corresponding to 26-39 m depths in the SCS, growth rates in the high CO_2-grown cells were inversely related to light levels, and exhibited reduced thresholds at which PAR becomes excessive, leading to higher NPQ. Future ocean warming will cause a shoaling of upper mixed layer depths, exposing phytoplankton to increased mean light intensities. This, in combination with rising CO_2 levels, may cause a widespread decline in marine primary production.

[1]State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, 361005, China.(ksgao@xmu.edu.cn)
[2]Marine Environmental Biology, Department of Biological Sciences, University of Southern California, 3616 Trousdale Parkway, Los Angeles, CA 90089 USA.
[3]Neue Str. 9, 91096 Möhrendorf, Germany.
[4]Leibniz Institute of Marine Sciences (IFM-GEOMAR)Marine Biogeochemistry- Biological Oceanography - Düsternbrooker Weg 2024105 Kiel, Germany

CONSEQUENCES OF OCEAN ACIDIFICATION FOR NORTH ATLANTIC LARVAL BIVALVES

Gobler, Christopher J. and Stephanie C. Talmage

We have investigated the effects of elevated levels of CO_2 on larvae and early stage juveniles of three species of commercially and ecologically valuable bivalve shellfish native to the North Atlantic. *Mercenaria mercenaria* and *Argopecten irradians* larvae grown under low CO_2 concentrations (250ppm) displayed significantly higher survival as well as faster growth and metamorphosis compared to individuals grown under higher CO_2 levels ($\geq$400ppm). Longer term experiments demonstrated that *A. irradians* reared under low CO_2 (250ppm) as larvae were still significantly larger than those reared under higher levels ($\geq$400ppm) after ten months of growth under ambient CO_2 levels. Exposure of bivalve larvae to high CO_2 (750ppm) for only four days was enough to significantly decrease survival compared to normal levels (400ppm). These findings suggest ocean acidification during the past two centuries may be inhibiting the survival of larvae from these bivalves. In contrast, *Crassostrea virginica* suffered reduced survival only under higher CO_2 levels ($\geq$700ppm). Physiological impairment of larvae due to elevated CO_2 included significantly decreased size, shell thickness, RNA:DNA ratios, calcification rates,

and lipid content, all physiologically changes that could promote enhanced mortality in an ecosystem setting. Additional stressors common to coastal environments such as high temperatures or harmful algal blooms combined with acidification depressed survival further than acidification alone. Larval stages of bivalves were found to be significantly more vulnerable to high CO_2 levels than juveniles. Collectively, these findings demonstrate that larval stage exposure to high CO_2 concentrations has profound implications for bivalve populations.

Stony Brook University, School of Marine and Atmospheric Sciences, Southampton, NY 11968 USA

INTERACTIVE EFFECTS OF OCEAN ACIDIFICATION AND TEMPERATURE ON BENTHIC INVERTEBRATE BEHAVIOUR AFFECT NUTRIENT CYCLING OVER LONGER TIMESCALES

Godbold, Jasmin A. and Martin Solan

The interactive effects of enhanced sea surface temperature and atmospheric CO_2 concentrations on ocean chemistry and, in turn species distributions and physiological processes are well known across a range of marine phyla. Conclusions on the biological and ecological response of communities are, however, largely based on short-term (days – weeks) exposure experiments and uncertainty remains over whether marine organisms are able to maintain biological processes and ecosystem functioning over longer time scales. Here we will present data from an 18-month exposure, in which two functionally important infaunal invertebrates (brittlestar *Amphiura filiformis*; nereid polychaete *Alitta* (*Nereis*) *virens*) were exposed to three levels of atmospheric CO_2 concentration (380, 750, 1000 ppm) crossed with two temperature regimes (ambient and ambient + 4°C). We will show how the higher maintenance costs associated with surviving in an acidified ocean impacts species behaviour (sediment reworking and burrow irrigation), thereby altering the functional role of individual species and fundamentally changing the balance of the major pathways of macronutrient cycling that underpin the food web and, ultimately, the delivery of goods and services necessary for human well-being.

Ocean and Earth Science, National Oceanography Centre, Southampton, University of Southampton, Waterfront Campus, European Way, Southampton, SO14 3ZH, UK (j.a.godbold@soton.ac.uk)

REPRODUCTION IN A CHANGING OCEAN: THE EFFECTS OF LONG TERM EXPOSURE TO COMBINED MULTIPLE STRESSORS

Graham, Helen E. [1], Samuel P. S Rastrick[2], Gary S. Caldwell [1], Matthew G. Bentley[1], Stephen Widdicombe[3], and Anthony S. Clare[1],

Atmospheric CO_2 enrichment is a key factor contributing to global climate change. Major consequences of climate change include increasing sea surface temperature and decreasing seawater pH– both of which are predicted to lead to an increase in ocean hypoxic events. Early ontogenetic stages of invertebrates have shown sensitivity to these environmental changes, but little is known regarding long term effects on reproduction. We address this short coming for reproduction and early embryonic development of the economically and ecologically important sea urchin *Paracentrous lividus*. The extent of successful fertilisation and early embryogenesis were significantly reduced under conditions of increased pCO_2, at 9 and 13°C after 12 months exposure. Sperm motility – determined by computer assisted sperm analysis (CASA) - showed a significant increase in average swimming speed measured as curvilinear velocity (VCL) at increased CO_2 levels at 6 months but by 12 months VCL levels had decreased, and there was no significant effect of pCO_2 on VCL. There was a significant reduction in

fertilisation success under hypoxic conditions, however increasing pCO_2 levels appeared to buffer the effects of hypoxia, with significantly lower success observed only under hypoxic conditions at ambient pCO_2, suggesting that the optimal activation pH for sperm is less than that of today's oceans. This project highlights the need for further long term investigation to multiple potential stressors, to understand more fully the long term effects arising from changing oceanic chemistry.

[1]School of Marine Science and Technology, Newcastle University, Ridley Building, Claremont Road, Newcastle upon Tyne, NE1 7RU, England, UK (helen.graham@ncl.ac.uk)
[2]Plymouth University, Davy Building, Drake Circus, Plymouth, Devon, PL4 8AA
[3]Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, PL1 3DH.

EVALUATING THE CONTROLS ON ORGANIC MATTER TRANSPORT EFFICIENCY IN AN EARTH SYSTEM MODEL: IMPLICATIONS FOR FUTURE WARMING AND OCEAN ACIDIFICATION

Gregoire, Lauren and Andy Ridgwell

Mineral particles, in particular CaCO3, are thought to act as ballast for the sinking of organic matter to the deep ocean. If this is the case, then ocean acidification could impact the flux of organic matter to the deep ocean through a reduction in pelagic calcification. More recent studies have favoured an alternative theory that rather than being controlled by ballast minerals, the efficiency of organic matter export to the deep ocean is determined by the composition of the ecosystem at the surface. In that case, future changes in the flux of organic matter to the deep ocean may be more affected by temperature driven changes in ecosystem distributions.
In an earth system model of intermediate complexity, we tested different representations of the ballasting and ecosystem dependency of deep organic matter export. With a Latin Hypercube Sampling method, we calibrated ballast parameters and adjusted other biogeochemical parameters in the model. This produced a small ensemble of models that simulate the present day ocean biogeochemical cycles well. We then used that ensemble of models to simulate future changes in the ocean carbon cycle to compare the effect of different parameterisations of deep organic matter export.

University of Bristol, School of Geographical Sciences, University Road, Bristol BS8 2YF, UK (lauren.gregoire@bristol.ac.uk)

MECHANISM OF COMPENSATION FOR CO_2 INDUCED ACID-BASE BALANCE DISTURBANCE IN MARINE FISH

Grosell, M., R. Heuer, and Andrew Esbaugh

The effects of elevated CO_2 on marine calcifying organisms have been studied extensively; however, effects of current and imminent CO_2 levels on teleost acid-base and respiratory physiology have yet to be examined. Exposure for 24 hours to 1000 and 1900 µatm CO_2, but not lower levels, resulted in a characteristic compensated respiratory acidosis response in the gulf toadfish (*Opsanus beta)*. Time course experiments showed the onset of acidosis occurred after 15 min of exposure to 1000 and 1900 µatm CO_2, with full compensation, by elevated plasma HCO_3^-, by 4 and 2 h, respectively. Exposure to 1900 µatm also resulted in significantly increased intracellular white muscle pH after 24 h. No effect of 1900 µatm was observed on branchial acid flux; however, exposure to hypercapnia and HCO_3^- free seawater compromised compensation, suggesting branchial HCO_3^- uptake rather than acid extrusion as part of the compensatory response. Exposure to 1900 µatm resulted in down-regulation in branchial carbonic anhydrase (CA) and slc4a2 expression. In addition, Na^+/K^+ ATPase enzyme activity also decreased after 24 h of exposure. While the full physiological impacts of increased blood HCO_3^- are not known, it seems likely that chronically elevated blood HCO_3^- levels could compromise several physiological systems, including intestinal osmoregulatory processes, and furthermore may explain recent reports of increased otolith growth during exposure to elevated CO_2.

RSMAS, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida, 33149. Corresponding author: mgrosell@rsmas.miami.edu

INTERACTIVE EFFECT OF ELEVATED pCO_2 AND TEMPERATURE ON CORAL PHYSIOLOGY AND CALCIFICATION: A GLIMMER OF HOPE?

Grottoli, Andrea G.[1], Verena Schoepf [1], Mark E. Warner [2], Wei-Jun Cai[3], Todd Melmann[4], Justin Baumann[1], Yohei Matsui[1], D. Tye Pettay[2], Kenneth Hoadley[2], Hui Xu[3], Yongchen Wang[3], Quian Li[3], and Xinping Hu[3]

Increases in ocean acidification and temperature threaten coral reefs globally. However, the interactive effect of both lower pH and higher temperature on coral physiology and growth are poorly understood. Here, we present findings from a replicated controlled experiment where four species of corals (*Acropora millepora, Pocillopora damicornis, Montipora monasteriata, Turbinaria reniformis*) were reared under three pCO_2 levels (400ppm, 620ppm, 775ppm) at two temperatures (26.5°C, 29.0°C) with a twice weekly feeding regimen of 2-day old brine shrimp nauplii for three weeks. Overall, there were no significant decreases in calcification, efficiency of photosystem II photochemistry (F_v/F_m), biomass, or energy reserve concentrations (lipid, protein, carbohydrate) with increases in pCO_2 or temperature for both plating coral species (*M. monasteriata* and *T. reniformis*) though carbohydrate or protein concentrations did increase in *M. monasteriata* with temperature at all pCO_2 levels. At the same time, calcification increased in *P. damicornis* despite decreases in F_v/F_m and no changes in energy reserves when reared at 775ppm pCO_2 and 29.0°C. However in *A. millepora*, calcification and F_v/F_m declined while lipid and protein concentrations rose at the highest pCO_2 level and skeletal dissolution was observed when pCO_2 and temperature were both maximally elevated. Thus, the interactive effects of both ocean acidification and elevated temperature are negligible and/or beneficial for three of the four species examined here suggesting that in the absence of bleaching-inducing temperatures, some coral species might be able to cope with reef conditions predicted for the end of this century.

[1] School of Earth Sciences, The Ohio State University, 125 South Oval Mall, Columbus, OH 43210, USA (grottoli.1@osu.edu)
[2] School of Marine Science and Policy, University of Delaware, 700 Pilottown Rd., Lewes, DE 19958, USA
[3] Department of Marine Sciences, The University of Georgia, Athens, GA 30602, USA
[4] Reef Systems Coral Farm, 8459 Peter Hoover Rd., New Albany, OH 43054, USA

DISENTANGLING THE COMPLEXITY BEHIND THE INFLUENCE OF OA ON COCCOLITHOPHORE CALCIFICATION: INSIGHTS FROM DIFFERING CELLULAR PHYSIOLOGY IN ISOCHRYSIDALE AND COCCOLITHALE SPECIES

Gutowska, Magdalena A.[1], Kerstin Suffrian[2], Nadja Fischer[2], Kai G. Schulz[1], Nina Himmerkus[2], Maria Mulisch[2], Martin Westermann[3], Ulf Riebesell[1], and Markus Bleich[2]

Predicting the influence of OA on coccolithophore calcification has been complicated by reports of variable sensitivities in monoclonal laboratory experiments. A mechanistic understanding of the cellular processes affected by OA would make it possible to identify the functional root underlying complex response patterns. However, our knowledge of the cellular physiology supporting lith morphogenesis is limited.

We present new findings on differences in cell morphology and calcification relevant substrate transport between coccolithophore species representing the two primary groups of extant calcifying haptophytes, the Isochrysidale *Emiliania huxleyi* and Coccolithale *Calcidiscus leptoporus*. Using HPF/FS and freeze fracture transmission electron microscopy approaches we show that the cortical membranes previously interpreted to be peripheral endoplasmic reticulum constitute a unique cell cover in *E. huxleyi*. The alternate morphology we propose requires a revision of the currently accepted transport pathway of Ca^{2+} into the cell. In-vivo microfluorimetry results corroborate our conclusion that calcification relevant substrate transport differs between Isochrysidales and Coccolithales. Experimental work with out-of-equilibrium seawater solutions indicates that the two examined species use different cellular pathways to transport C_i and H^+.

We hypothesize that the evident heterogeneity in cortical cell ultrastructure and ion transport pathways influence species specific responses of calcification processes to changes in seawater carbonate chemistry. Our results underline the nascent state of coccolithophore cell physiology and the importance of a mechanistic understanding of the cellular pathways underlying calcification to better understand variable responses to OA.

[1] GEOMAR Helmholtz Centre for Ocean Research Kiel, Dusternbrooker Weg 20, Kiel 24105, Germany (mgutowska@geomar.de)
[2] Christian Albrechts University, Hermann-Rodewald Str. 5, Kiel 24118, Germany
[3] Friedrich Schiller University, Ziegelmuhlenweg 1, Jena 07743, Germany

EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON CELLULAR PROCESSES IN GILLS OF THE GREAT SPIDER CRAB *HYAS ARANEUS*

Harms, Lars, Melanie Schiffer, Felix Christopher Mark, Daniela Storch, Christoph Held, Hans-Otto Pörtner, Stephan Frickenhaus, Lars Tomanek, and Magnus Lucassen

Due to advances in DNA-sequencing technologies over the last years, analyses of the whole transcriptome have become more and more attractive to study how environmental changes impact the biology of marine organisms. Transcriptomic approaches now provide us with the possibility to investigate the entire active genomic response to environmental changes. As the ability to adjust to changing conditions depends on complex changes in gene regulatory networks and cellular pathways, the use of gene expression studies is an excellent opportunity to identify the early responses to Ocean Acidification and Global Warming.

We carried out an Illumina high-throughput based transcriptomic analysis to investigate the regulatory response to Ocean Acidification and Warming in a potentially sensitive species, the osmoconforming spider crab *Hyas araneus* from Arctic waters. To this end, adult males were acclimated to four different

PCO_2 concentrations and two different temperatures (390, 1000, 1960 and 2500 ppm; 5 °C and 10 °C) over a period of ten weeks. Sequences obtained from Illumina high-throughput sequencing of each treatment were mapped on the transcriptome generated by 454 pyrosequencing. Over 400 significantly influenced annotated transcripts could be identified in the gills of *Hyas araneus*, indicating great influences in immune response and cell structure organization. However, only moderate response in major cellular processes, e.g. acid-base regulation and metabolism could be found.
As gene expression does not necessarily reflect changes in protein expression, further proteomic studies are a useful tool to understand how transcriptomic responses are transferred into physiological functions. A comparative proteomic approach is therefore in progress and first results will be presented.

Alfred Wegener Institute for Polar and Marine Research, P.O. Box 12 01 61, 27570 Bremerhaven, Germany (Lars.Harms@awi.de)

THE SOUTHERN OCEAN IN A HIGH-CO_2 WORLD: CHANGES IN INORGANIC AND ORGANIC CARBON FLUXES

Hauck, Judith, Christoph Völker, Tingting Wang, Mario Hoppema, Martin Losch, and Dieter A. Wolf-Gladrow

Two different processes control changes in the current and future Southern Ocean carbon uptake. First, the increase of atmospheric CO2 leads to more uptake of anthropogenic carbon. However, also the "natural" carbon budget is modified due to anthropogenic changes of the atmospheric circulation. The predominant climate mode in the southern hemisphere is the Southern Annular Mode (SAM). In recent decades, the SAM showed a trend toward its positive phase, characterized by stronger westerlies. This trend is related to a warming atmosphere and is predicted to continue in the future.
We analyze the response of the Southern Ocean carbon fluxes to the SAM trend in a hindcast simulation of a general circulation model (MITgcm) coupled to an ecosystem model with two phytoplankton classes (REcoM-2).
During a positive SAM event, stronger westerlies lead to more Ekman pumping. More carbon- and nutrient-rich deep water is brought into the mixed layer. On the one hand, this leads to more outgassing of natural carbon, in line with previous model studies. On the other hand, the anomalous silicate and iron input favors primary production by diatoms and causes an overall increase of net primary production in our model. Accordingly, the export of organic carbon via the soft-tissue pump is increased. Primary production is responsible for a significant drawdown of the entrained carbon and its immediate return to the subsurface ocean, thereby reducing the amount of carbon available for sea-air gas-exchange. Latitudinal gradients in the different carbon fluxes will be discussed.

Alfred Wegener Institute for Polar and Marine Research, Postfach 12 01 61, 27570 Bremerhaven (judith.hauck@awi.de)

TRANSITION DECADES FOR OCEAN ACIDIFICATION IN THE CALIFORNIA CURRENT SYSTEM

Hauri, Claudine[1], N. Gruber[1], M. Vogt[1], S.C. Doney[2], R.A. Feely[3], Z. Lachkar[1], A. Leinweber[4], A.M.P. McDonnell[1], M. Munnich[1], and G.K. Plattner[5]

Due to seasonal upwelling the California Current System (CCS) has a naturally low pH and aragonite saturation state (Ωarag), making it particularly prone to ocean acidification. We define transition decades as the time period when chemical changes induced by the long-term trends exceed those experienced over the annual cycle. To do so we use a CCS set up of the Regional Ocean Modeling System (ROMS). Despite the large variability of pH and Ωarag, the present day levels are already distinctly different from those during the preindustrial era. By 2040 pH and Ωarag of the nearshore 50 km are expected to be distinctly different than today. The aragonite saturation horizon is projected to permanently shoal into the upper 75 m in approximately 2030. The model tends to underestimate the annual variability of the system and overestimate pH and Ωarag, which implies that transition decades are expected later, while permanent undersaturation is expected earlier. We show that organisms of the CCS will be forced to rapidly adjust to conditions that are inherently chemically challenging and also distinctly different from the present day.

[1] ETH Zurich, Zurich, Switzerland, claudine.hauri@env.ethz.ch,
[2]Woods Hole Oceanographic Institution, Woods Hole, USA,
[3]Pacific Marine Environmental Laboratory / NOAA, Seattle, USA,
[4]University of California, Los Angeles, Los Angeles, USA
[5]University of Bern, Bern, Switzerland

NEAR-FUTURE OCEAN ACIDIFICATION REALLY DOES INFLUENCE FERTILIZATION SUCCESS IN MARINE INVERTEBRATES – A META-ANALYSIS

Havenhand, Jon[1], Mary Sewell[2], and Jane Williamson[3]

Fertilization is the key process that begins each life cycle, which for the majority of marine animals involves the release of sperm and eggs freely to the water column. Several reviews of the effects of ocean acidification on fertilization success in these animals have concluded that fertilization is “robust” to ocean acidification by 0.3 - 0.4 pH units. While this conclusion accurately reflects much (though not all) of the available literature, many published studies were designed in such a way that negative effects may not have been detectable, and any positive effects of acidification on fertilization success could not have been detected. Our re-analysis of published data reveals that effects of ocean acidification on fertilization are: i) highly variable, both inter- and intra-specifically; ii) generally negative; and that iii) a neutral (“robust”) response is rare. This pattern reflects that from reviews of the effects of OA on other life-stages. Carry-over effects on fertilization success can be complex and pervasive, causing reduced recruitment and changed population dynamics and genetics. These results indicate the need for more detailed analyses of fertilization success.

[1] Department of Biological & Environmental Sciences, Tjärnö Marine Biological Laboratory, Gothenburg University, S-45296 Strömstad, Sweden (jon.havenhand@gu.se)
[2] School of Biological Sciences, University of Auckland, Private Bag 92019, Auckland, New Zealand.
[3] Department of Biological Sciences, Macquarie University, NSW, 2109, Australia

PERSISTENT, MULTISTRESSOR EFFECTS ACROSS LIFE STAGE TRANSITIONS IN OLYMPIA OYSTERS

Hettinger, Annaliese[1], Brian Gaylord[1], Eric Sanford[1], Tessa M. Hill[1,2], and Ann D. Russell[2]

Different life stages interact with the environment in distinct ways, and stresses experienced during one life stage can “carry over” to influence subsequent stages. Assessments of population responses to global change must consider how effects propagate across life-history transitions. We investigated consequences of multiple stressors (e.g., ocean acidification, desiccation, temperature, nutrition) for early life stages of the Olympia oyster, a native and imperiled foundation species in many Pacific-coast

estuaries. Our laboratory experiments demonstrated that exposure of larval oysters to high pCO_2 decreased growth. Impacts were more pronounced in juveniles, but the impacts originated largely from exposure during the larval phase, indicating a strong carry-over effect. Adverse impacts of early exposure to high pCO_2 persisted at least 4 months into juvenile life, and were modified by stress in the juvenile habitat. For example, oysters reared as larvae under high pCO_2 that were outplanted to field sites exhibited lower juvenile growth at higher shore elevations where emersion stress was greater compared to juveniles reared as larvae under control pCO_2. Impacts of elevated pCO_2 were also influenced by larval nutritional state and seawater temperature. Together these findings emphasize that a stringent focus on a single phase of the life cycle may neglect critical impacts that can be transferred across life stages. Moreover, the strength of carry-over effects due to ocean acidification can be heavily modulated by interactions with other environmental stressors and the availability of food. Although the full scope of potential demographic consequences of these interactions remains yet unexplored, they appear considerable.

[1]Bodega Marine Laboratory, University of California Davis, Bodega Bay, CA 94923, USA.
ahettinger@ucdavis.edu
[2]Department of Geology, University of California Davis, Davis, CA 95616, USA.

EFFECTS OF OCEAN ACIDIFICATION ON BENTHIC BIOGEOCHEMISTRY AND PRIMARY PRODUCTION

Hicks, Natalie, Ashleigh Currie, and Henrik Stahl

Little is known about the effects of ocean acidification, and rising temperature, on marine coastal sediments, where a significant proportion of primary production and global nutrient cycling occurs. Changes to the biogeochemical cycles that occur on and within the sediments under future environmental scenarios are likely to have reverberating effects throughout marine benthic ecosystems. Here we use custom-built flume tanks to expose cohesive and permeable sediments to projected CO_2 levels and elevated temperature treatments under natural flow and light conditions. The sediments were collected from a site with high biomass of microphytobenthos, and were run under manipulated environmental conditions (CO_2, temperature, and light) for four weeks. Weekly water column measurements of pH, DIC, nutrients and alkalinity were taken in both light and dark regimes to identify effects of photosynthesis by microalgae, and the effects of elevated CO_2 and temperature, on nutrient fluxes. Statistical modeling of results show a strong interaction of environmental variables (temperature, CO_2) and light influences nutrient concentration, although this varies with sediment type and nutrients measured (ammonia, nitrate). This manipulative medium-term study contributes to understanding how ocean acidification is likely to affect global nutrient cycles under future environmental scenarios.

Scottish Association for Marine Science, Oban, Scotland, PA37 1QA, United Kingdom
natalie.hicks@sams.ac.uk

HOW TO EVALUATE THE SOCIO-ECONOMIC IMPACTS OF OCEAN ACIDIFICATION?

Hilmi, Nathalie[1,2], Denis Allemand[1], Sam Dupont[3], Alain Safa[4], Gunnar Haraldsson[5], Paulo A.L.D. Nunes[6], Chris Moore[7], Caroline Hattam[8], Stéphanie Reynaud[1], Jason M. Hall-Spencer[9], Maoz Fine[10], Carol Turley[8], Ross Jeffree[11], James Orr[12], Philip L. Munday[13], and Sarah Cooley[14]

Ocean acidification is increasingly recognized as a critical component of global change that, in the future, could be responsible for a wide range of impacts on marine organisms, the ecosystems they live in, and the goods and services they provide humankind. To determine these potential socio-economic impacts, it is necessary to cross disciplines and involve biologists, chemists, oceanographers, economists and social scientists in a joint effort. Significant knowledge gaps are preventing economists from estimating the welfare impacts of ocean acidification. For instance, economic data on the impact of ocean acidification on significant markets such as fisheries, aquaculture and tourism are very limited (if not non-existent) and non-market valuation studies on this topic are not yet available. Ocean acidification is a relatively new area of research and our paper aims to highlight both the current scientific understanding of future impacts and to characterize the information needed by economists to shed light on the socioeconomic dimensions of the potential impacts. We anticipate that this will result in new multidisciplinary collaborative research.

1. Centre Scientifique de Monaco, Avenue Saint-Martin, MC-98000 Monaco, Principality of Monaco
2. IAEA, 4, Quai Antoine 1er, MC-98000 Monaco, principality of Monaco
3. Department of Marine Ecology, University of Gothenburg, The Sven Lovén Centre for Marine Sciences – Kristineberg, 45178 Fiskebäckskil, Sweden
4. IPAG Nice, France
5. OECD Fisheries, France
6. The Mediterranean Science Commission – CIESM, Monaco pnunes@ciesm.org
7. National Center for Environmental Economics, Environmental Protection Agency, Washington, DC, USA
8. Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, PL1 3DH
9. University of Plymouth, UK
10. Bar Ilan University, Israel
11. School of the Environment, C3, Faculty of Science, University of Technology, Sydney, Australia
12. Laboratoire des Sciences du Climat et de l'Environnement CEA-CNRS-UVSQ, France
13. ARC Centre of Excellence for Coral Reef Studies, and School of Marine and Tropical Biology, James Cook University, Townsville, QLD 4811, Australia
14. Woods Hole Oceanographic Institution, USA

DEEP-SEA GAS EXCHANGE RATES IN A HIGH CO_2 WORLD: OXYGEN

Hofmann, Andreas, Edward T. Peltzer, and Peter G. Brewer

A high CO_2 ocean is also a warmer and more oxygen deficient ocean and this combination can pose challenges for marine life. The limit is traditionally reported as a mass concentration property without temperature, pressure or flow rate dependency. We treat it as a dynamic gas exchange problem for the animal analogous to gas exchange processes at the sea surface. A combination of temperature, salinity, hydrostatic pressure, flow rate over the respiratory surface, and oxygen concentration defines diffusive boundary layer transport at animal gas exchange surfaces and thus defines the supply side ability of the ocean to match the demand side of an animal.
We define three quantities: 1) the minimal oxygen concentration Cf to support a given oxygen demand rate 2) the maximal oxygen uptake rate Emax associated with a particular oceanic environment, and 3) the flow velocity offset Δu100 needed to physically compensate for given ocean warming and deoxygenation scenarios.
We find that temperature and pressure dependencies of diffusion and partial pressure create zones of greatest physical constriction on the diffusive transport in the boundary layer typically at around 1000 m depth, coinciding with oxygen minimum zones. In some shallow and warm waters the enhanced diffusion and higher partial pressure from higher temperatures can slightly overcompensate

for oxygen concentration decreases. However, since cold deep water regions comprise the vastly greater part of the ocean volume, the net effect of ocean warming and lower oxygen is expected to be negative for marine life.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing CA 95039, USA (brpe@mbari.org)

COMBINED EFFECTS OF OCEAN ACIDIFICATION AD IRON AVAILABILITY ON SOUTHERN OCEAN PHYTOPLANKTON COMMUNITIES

Hoppe, Clara J. M.[1], C. Hassler[2], C. D. Payne[3], P. D. Tortell[3], B. Rost[1], and S. Trimborn[1]

Accounting for about 20% of the global annual phytoplankton production, the Southern Ocean (SO) exerts a disproportional control on the global carbon cycle and contributes to a large proportion to the oceanic sequestration of anthropogenic CO_2. Primary production in that area is mainly controlled by iron and light availability as well as by grazing, but also carbonate chemistry was shown to have significant effects. While combined effects of iron and light have received a lot attention, knowledge on combined effects with ocean acidification is sparse. We present results of shipboard incubation experiments conducted with a phytoplankton community from the Weddell Sea testing the combined effects of p CO_2 and iron availability. Phytoplankton communities were exposed to three different p CO_2 levels (180, 380 and 800 µatm) under iron-deplete and -replete conditions. Species composition, primary production and photophysiology were found to strongly differ in response to ocean acidification. Responses were further modulated by iron availability. Our study confirms that primary production and species composition of SO phytoplankton communities are sensitive to increased p CO_2. Under iron-limitation, however, the CO_2-sensitivity of primary production is strongly reduced. With respect to species composition, pronounced shifts in species composition at intermediate and high p CO_2 levels were observed, resulting in either *Pseudo-nitzschia*- or *Chaetoceros*-dominated communities. Effects of iron availability were also modulated by p CO_2, as stimulating effects by iron only occurred under elevated p CO_2 levels. These interactive responses have the potential to influence the biological carbon pump and thus the predictions for the CO_2 drawdown in the SO.

[1]Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, Bremerhaven, Germany. Clara.Hoppe@awi.de
[2] University of Technology Sydney, PO Box 123, Broadway NSW 2007, Australia
[3] University of British Columbia, 6339 Stores Road, Vancouver, BC Canada

RESILIENCY OF WALLEYE POLLOCK ACROSS EARLY LIFE STAGES AND SEASONS TO PROJECTED LEVELS OF OCEAN ACIDIFICATION

Hurst[1], Thomas P., Elena Fernandez[2], Jeremy Mathis[2], and Charlotte Stinson[3]

Several consequences of ocean acidification have been documented in invertebrates and tropical marine fishes. Less work has been done examining potential responses of the temperate and boreal marine fish species that support major capture fisheries. We examined the growth responses of walleye pollock to environmental pH at four early life history stages: eggs, larvae, juveniles, and yearlings. At each stage, groups of fish were reared in the laboratory at ambient (~8.05) and 3 reduced pH treatment levels (7.9, 7.6, and 7.2). The juvenile experiment included both a warm (8°C) and cold (2.5°C) phases to evaluate seasonal variation in sensitivity. At pH 7.2, there was slight delay in the time to hatch of

walleye pollock eggs, but there was no consistent effect of pH on size at hatch or yolk volume at hatch. During 12 weeks of rearing at summer temperatures, length growth in juvenile walleye pollock was 7.2% faster in the two lower pH treatments than in the higher pH treatments. Consumption rates were correlated with tank mean growth rates, but were not directly affected by pH treatment. During the low temperature phase, there was no significant effect of pH on growth rate. Among yearlings, there was no effect of pH on growth or condition. While not exhaustive of potential interactive environmental factors, these experiments demonstrate a general resiliency of growth potential among early life stages of walleye pollock to the direct effects of pH changes predicted for the Gulf of Alaska and Bering Sea in the next century.

[1] Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Hatfield Marine Science Center, Newport, OR 97365 USA (thomas.hurst@noaa.gov)
[2] School of Fisheries and Oceanography, University of Alaska Fairbanks, PO Box 757220
Fairbanks, AK 99775, USA
[3] Hatfield Marine Science Center, Oregon State University, Newport, OR 97365 USA.

A FOUR YEAR EXPERIMENTAL EVOLUTION STUDY OF ADAPTATION TO INCREASED CO_2 IN THE N_2-FIXING CYANOBACTERIUM *TRICHODESMIUM*

Hutchins, David A., Nathan G. Walworth, Eric A.Webb, Nathan S. Garcia, Avery O. Tatters, Elizabeth K.Yu, Cynthia Breene, and Feixue Fu

The biogeochemically-critical N_2-fixing cyanobacterium *Trichodesmium* supplies new nitrogen to oligotrophic regimes worldwide. Short-term culture studies show that its physiological responses to projected future pCO_2 increases are among the largest yet reported for any marine microbe, but its capacity to adapt under persistent selection by elevated pCO_2 is unknown. We report results of an experimental evolution study in which *Trichodesmium* IMS101 was maintained for ~four years (450-600 generations) at either elevated pCO_2 (~750 ppm) or ambient pCO_2 (~380 ppm) in order to explore its long-term physiological, biogeochemical, and transcriptomic (Illumina RNA-seq) responses.
After four years, N_2 fixation rates were still nearly twice as high in the 750 ppm-adapted versus 380 ppm-adapted cultures. 380 ppm-adapted cultures switched to 750 ppm for one week also showed increased N_2 fixation rates, consistent with previous short-term studies. Surprisingly, 750 ppm-adapted cultures maintained their elevated N_2 fixation rates even after being switched back to 380 ppm, suggesting true adaptive changes. Increased nitrogenase enzyme complex expression and decreased carbon concentrating mechanism expression levels were observed in both the 750 ppm-adapted cultures, and in the 750 ppm-adapted lines switched back to 380 ppm. Intriguingly, transcriptomic results show very high levels of intergenic DNA expression, particularly in the 750 ppm-adapted cell lines, suggesting the potential importance of non-coding regions in regulatory responses to high pCO_2. Both our physiological and transcriptomics data indicate that increased N_2 fixation is a long-term and potentially adaptive response to elevated pCO_2 in *Trichodesmium*, with major implications for the future of the marine nitrogen cycle.

Marine Environmental Biology, University of Southern California, Los Angeles, CA 90089, USA
dahutch@usc.edu

DECADAL CHANGE IN THE RATE OF OCEAN ACIDIFICATION IN THE WESTERN PACIFIC EQUATRIAL ZONE

Ishii, Masao[1,2], Naohiro Kosugi,[1] Daisuke Sasano[1,2], Kazutaka Enyo[1,2], Shu Saito[2], Toshiya Nakano[1,2], Takashi Midorikawa[3], and Hisayuki Y. Inoue[4]

Ocean acidification is threatening many habitats of coral reef that are distributed in the tropical and subtropical regions of the western North Pacific. In this study, we analyzed the changes in the ocean carbonate chemistry including pH and aragonite saturation level (Ω_{arag}) in the open equatorial zone of the western Pacific (2ºS – 2ºN, 145ºE – 160ºW) for the past two decades. For this analysis, we used SOCAT database v.1.5 for fCO$_2$, data of underway pCO$_2$ measurements recently acquired by Japan Meteorological Agency (JMA), data of underway measurements of DIC, pH and pCO$_2$ we made for 1994 – 2003, and PACIFICA database for ocean interior CO_2.
In the warm water pool (t > 28ºC, S <34.8) that usually prevails in this zone, the mean rates of changes in pH and Ω_{arag} were -0.018±0.001 decade^{-1} and -0.136±0.010 decade^{-1} for 1986 – 1998. They were faster than the rates that are expected from the buffer capacity of seawater and the rate of atmospheric CO_2 increase for the same period (-0.014 decade^{-1} for pH and -0.096 decade^{-1} for Ω_{arag}). However, they slowed down to -0.001±0.001 decade^{-1} for pH and -0.019±0.003 decade^{-1} for Ω_{arag} for 1999 – 2011. Together with the results from JMA's time-series measurements of carbonate chemistry at 3ºN – 34ºN of 137ºE meridian, it is clear that the ocean acidification is being in progress in these tropical and subtropical regions. However, it is likely that the other processes, possibly changes in the ocean circulation around the equatorial zone, are also significantly affecting the trend of acidification.

[1] Meteorological Research Institute, JMA, Tsukuaba, 305-0052 Japan (mishii@mri-jma.go.jp)
[2] Climate and Marine Department, JMA, Tokyo, 100-0081 Japan
[3] Nagasaki Marine Observatory, JMA, Nagasaki, 850-0931 Japan
[4] School of Environmental Earth Science, Hokkaido University, Sapporo, 060-0810 Japan

IMPACTS OF OCEAN ACIDIFICATION ON *MACOMA BALTHICA* LARVAE IN THE BALTIC SEA

Jansson, Anna[1], Joanna Norkko[2], and Alf Norkko[2]

CO_2-related changes in pH are predicted to be 2-5 times faster in the Baltic Sea than in oceanic waters and ecosystem-wide effects of this change are predicted to be far-reaching, but are currently poorly understood. In order to develop an understanding of the effects of ocean acidification on the health and function of benthic communities in the Baltic Sea, we concentrate on soft-bottom communities, and specifically on the bivalve *Macoma balthica* - a key component of the community. The impact of predicted near-future ocean acidification on the larval stage of *M. balthica* was investigated in a 4-week exposure experiment. pH manipulation was acquired through controlled CO_2-addition, and the experiment was conducted with 4 environmentally relevant pH-levels (control, 7.7, 7.4 and 7.1). Survival and growth parameters of the bivalves were studied by measuring growth (shell length) and by studying changes in the larval structure. Our results show that decreasing pH negatively affects survival and development during the larval stage. This implies that ocean acidification will impact the system that is already affected by multiple stressors, such as eutrophication, overfishing and pollution. Given the importance of *M. balthica* in the Baltic Sea ecosystem through its effects on sediment biogeochemistry and nutrient dynamics, and as food for higher trophic levels, it is likely that the negative effects of ocean acidification on *M. balthica* will have cascading effects on the whole ecosystem.

[1]Åbo Akademi University, Turku, Finland (anna.jansson@abo.fi)
[2]Tvärminne Zoological Station, University of Helsinki, Hanko, Finland

HIGH CO_2 ALTERS THE CALCIFICATION MECHANISM IN MARINE *SYNECHOCOCCUS*.

Kamennaya, Nina[1], Laura Mahoney[1], Elizabeth Holman[2], Marcin Zemla[1], Jenny Cappuccio[1], Hoi-Ying Holman[1], Krystle Chavarria[6], Stephanie Swarbreck[7], Caroline Ajo-Franklin[1], Manfred Auer[1], Trent Northen[1], and Christer Jansson[1]

Oceanic "whiting" events, *i.e.* massive formation and precipitation of fine $CaCO_3$ particles, are part of the carbonate pump and subsequently of a global biological pump and therefore are of an ecological and geological importance. Several studies determined whitings to be associated with growth of cyanobacterial populations. Marine cyanobacterium *Synechococcus* 8806 (*S.* 8806) is particularly known to induce calcium carbonate mineralization under ambient conditions. We use the strain as a model system to assess a change in its mineralization potential under high (5 and 15%) CO_2. Specifically, we address the influence of a high CO_2 levels on the cell surface properties of *S. 8806* and the ability of *S. 8806* to form carbonate minerals in a high-CO_2 and low-pH environment. We apply a multi-pronged approach involving cell surface assays with time-of-flight secondary ion mass spectrometry (ToF-SIMS), synchrotron radiation Fourier transform infrared (SR-FTIR) spectromicroscopy, Zeta Potential measurements, and electron and fluorescence microscopy, to monitor cell surface properties and biomineralization capacity in cells grown under different CO_2 concentrations. We show that, counter intuitively, *S. 8806* is highly efficient in forming carbonate minerals under high CO_2 levels. However, we ascribe this ability to a change in the mechanism of mineralization and not to direct intensification of the mineralization process.

[1] Lawrence Berkeley National Laboratory, 1 Cyclotron rd., Berkeley, CA 94720, USA (nkamennaya@lbl.gov)
[2] University of California Berkeley, CA 94720, USA
[3]SCRIPPS institute of Oceanography, University of California San Diego, CA 92121, USA
[4]University of East Anglia, Norwich, NR4 7TJ, UK

BUFFERING OF CALCIUM CARBONATE POLYMORPH CHANGE BY CORALLINE ALGAE IN RESPONSE TO *p*CO_2 ENRICHMENT

Kamenos, Nicholas A.[1], Jonathan D. Dunn[1], Piero Calosi[2], Helen S. Findlay[3], Steve Widdicombe[3], Elena Aloisio [3], and Heidi L. Burdett[1]

Recently, attention has focused on the potential for marine *p*CO_2 enrichment as a consequence of increasing atmospheric *p*CO_2 and CO_2 releases from carbon capture and storage (CCS) facilities. Red coralline algae are found in temperate, tropical and polar waters with evidence suggesting mixed responses to *p*CO_2 enrichment. It is critical we understand how red coralline algae will respond to projected *p*CO_2 enrichment as they are important ecosystem service providers and are starting to play a key role as palaeoclimatic proxies. Using raman spectroscopy we investigated if *p*CO_2 enrichment under ocean acidification (OA) and CCS release scenarios changed the polymorph of skeletal calcium carbonate present in the temperate red coralline algae *Lithothamnion glaciale.* We show that while alive, *L. glaciale* had the capacity to buffer environmental *p*CO_2 enrichment in both OA and CCS scenarios allowing them to maintain their high-Mg calcite skeletal structure. Once dead, *L. glaciale* skeletons lost substantial Mg from their skeletal material under of both OA and CCS *p*CO_2 enrichment. The buffering capacity while alive may be due to photosynthetic CO_2 assimilation. This led to a change in skeletal calcium carbonate polymorph from the least stable high Mg calcite to a more stable polymorph. Our results thus suggest that when alive, red coralline algae may be able to buffer against future *p*CO_2 enrichment.

[1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, United Kingdom (nick.kamenos@glasgow.ac.uk)
[2]Marine Biology and Ecology Research Centre, University of Plymouth, Plymouth, UK, PL4 8AA
[3]Plymouth Marine Laboratory, Prospect Place, Plymouth, UK, PL1 3DH

CLIMATE CHANGE EFFECTS ON SUMMER AND SPRING BLOOM PHYTOPLANKTON COMMUNITIES – TWO MULTIFACTORIAL STUDIES ON OCEAN ACIDIFICATION, TEMPERATURE AND SALINITY

Karlberg M.[1], M. Björk[2], M. Chierici[2], J. Dinasquet[3,4], M. Olofsson[1], L. Riemann[4], F. Steinhoff [1], A. Torstensson[1], and A. Wulff[1]

Global climate change is a potential threat to all ecosystems. For the Baltic Proper, the second largest brackish water body in the world, a future business as usual (A1FI) scenario has been projected: by 2100 temperature may rise 3-5°C, atmospheric CO_2 levels may rise up to 960 ppm, while precipitation may increase, resulting in a salinity decrease from 7 to 4. The projected scenario was tested in two outdoor experiments where, A) interactive effects of decreased salinity and elevated levels of pCO_2 on the microbial phytoplankton community during summer and, B) interactive effects of increased temperature and elevated levels of pCO_2 on the microbial community with inoculated cyanobacteria during spring. In Expt A, *Aphanizomenon* sp. initially dominated (87% of the cyanobacterial biovolume) but by the end of the experimental period, >80% of the biovolume belonged to *Dolichospermum* sp. with highest biovolume in the A1FI treatment. Diatoms and the cyanobacterium *N. spumigena* had higher biovolume in the present day salinity treatment. In Expt B, the cyanobacteria could not outcompete the spring bloom species and only *N. spumigena* tolerated the abiotic factors in the experimental treatments. Among the spring bloom species there was a trend for increased biovolume of diatoms with present day levels of temperature and pCO_2. In both experiments, the pH increased due to primary production, but decreased in control treatments without phytoplankton. In conclusion, our results stress the importance of studying interactions between species in experiments aiming at answering questions about how climate change will affect pelagic primary producers.

[1] Dept. of Biological and Environmental Sciences, University of Gothenburg, Box 461, SE 405 30 Göteborg, Sweden (maria.karlberg@bioenv.gu.se)
[2] Dept. of Chemistry, University of Gothenburg, SE-412 96 Göteborg, Sweden
[3] Dept. of Natural Sciences, Linnaeus University, SE-39182 Kalmar, Sweden
[4] Marine Biological Section, University of Copenhagen, Strandpromenaden 5, DK-3000 Helsingør, Denmark

IMPACTS OF OCEAN ACIDIFICATION ON EARLY DEVELOPMENT OF ANTARCTIC KRILL

Kawaguchi, So[1,2], Rob King[1], Natasha Waller[1], Zhongnan Jia[3], James P. Robinson[3], Cathryn Wynn-Edwards[3], Bruce Deagle[1], Simon Jarman[1], Akio Ishida[4,5], Masahide Wakita[4,6], Stephen Nicol[3], Patti Virtue[3], Haruko Kurihara[7], Andrew Constable[1,2], Blair Smith[1], and Atsushi Ishimatsu[8]

Antarctic krill (hereafter krill) is the key species of the Antarctic marine ecosystem as well as a target of commercial fishery in the Southern Ocean, which compels careful predictions about potential impacts of Ocean Acidification (OA) and warming on this species and the associated ecosystem ramifications. Krill lay eggs at the surface that sink 1000 m before hatching; their larvae then actively swim to the surface to feed on phytoplankton thus exposing them to varying levels of CO_2. We have modelled future CO_2

concentrations in the Southern ocean and have experimentally examined the effects of the predicted CO_2 levels on krill early development. Our model projections demonstrate some parts of Southern Ocean pCO_2 could rise up to 1400 µatm within krill's depth range under the IPCC IS92a scenario by the year 2100 (atmospheric pCO_2 788 µatm). Our laboratory study reveals krill embryonic development is negatively affected, with its hatch rate rapidly decreasing beyond 1000 µatm and total inhibition at 2000 µatm pCO_2. This effect was milder at a higher temperature (at $3.0^{O}C$ vs $0.5^{O}C$). The first 3 days of embryonic development) were more susceptible compared to later embryonic stages. These results indicate a high susceptibility of krill embryos to OA compared to other pelagic crustaceans such as copepods. We are also currently analysing these effects at molecular levels through investigating CO_2-related changes in gene expression. We will present a circumpolar potential risk map for krill early development to further understand how the OA might impact future distribution of krill.

[1] Australian Antarctic Division, Kingston Tasmania, 7050, Australia (So.Kawaguchi@aad.gov.au)
[2] Antarctic Climate and Ecosystems Cooperative Research Centre, Sandy Bay, Hobart, Tasmania, 7001, Australia
[3] Institute for Antarctic and Marine Studies, University of Tasmania, Sandy Bay, Tasmania, 7005, Australia
[4] Research Institute for Global Change, JAMSTEC, Yokosuka, 237-0061, Japan
[5] Fuji Tokoha University, Fuji, Shizuoka, 417-0801, Japan
[6] Mutsu Institute for Oceanography, JAMSTEC, Mutsu, 035-0022, Japan
[7] University of the Ryukyus, Okinawa, 903-0213, Japan
[8] Nagasaki University, Nagasaki, 851-2213, Japan

OCEAN ACIDIFICATION IMPAIRS PREY DETECTION IN DEEP SEA HERMIT CRABS BUT VARIES GREATLY AMONG INDIVIDUALS

Kim, Taewon, Josi Taylor, Chris Lovera, and Jim Barry

Deep-sea animals are generally expected to be less tolerant of ocean acidification than shallow water taxa. Future ocean pH is projected to drop considerably at all depths as surface water continues to absorb rising levels of atmospheric CO_2 . To better understand the effect of ocean acidification on the survival of deep sea animals, we compared behavioral and physiological features of deep-sea (~900m) hermit crabs (*Pagurus tanneri*) between pH 7.6 (ambient control) and pH 7.1 (experimental) lab conditions. No significant difference was detected between treatments for some parameters, such as oxygen consumption or the "boldness" of the crabs, measured as time withdrawn into shell after attack by a potential predator (octopus). At lower pH treatment (pH 7.1), however, hermit crabs decreased their rates of antennular flicking ("sniffing") and also tended to have a slower speed for prey detection, indicating that lower pH can impair prey detection ability. Interestingly, hermit crabs at lower pH showed higher individual variation in antennular flicking rates, prey detection speeds, and respiration rates. This pattern suggests that although ocean acidification influences some abilities linked to survival in the deep sea environment, the ability to cope with lower pH appears to vary considerably among individuals, which should promote population survival.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA95309, USA.
ktwon@mbari.org

AN 8-MONTH *IN* SITU OCEAN ACIDIFICATION EXPERIMENT AT HERON ISLAND

Kline, David I.[1,2], Lida Teneva[3], Kenneth Schneider[4], Thomas Miard[2], Aaron Chai[2], Malcolm Marker[5], Jack Silverman[6], Ken Caldeira[4], Brad Opdyke[7], Rob Dunbar[3], B. Greg Mitchell[1], Sophie Dove[2,8], and Ove Hoegh-Guldberg[2,8]

Anthropogenic CO_2 is increasing rapidly in the atmosphere; driving major changes to the CO_2 concentration, carbonate chemistry and pH of ocean waters, posing significant challenges for calcifying marine organisms. These challenges are particularly serious for carbonate coral reef systems where reduced calcification rates may decrease calcification rates relative to physical and biological erosion. Previous experimental studies on the impact of future predicted pH levels on coral reefs, however, have mostly used highly artificial enclosed aquarium systems where coral fragments have been removed from nature and placed under artificial light, flow, temperature, microbial and other conditions. To avoid these potential experimental artifacts, we developed and deployed the Coral–Proto Free Ocean Carbon Enrichment System (CP-FOCE), the first *in situ* CO_2 enrichment system for coral reefs, and present results from a 8-month deployment on the Heron Island reef flat. Four replicate experimental chambers were used, two that were maintained as controls (ambient seawater) and two chambers in which CO_2 was added, gradually reducing pH by 0.2 units below controls. Five replicate living and 5 recently dead *Porites cylindrical* colonies were placed in each chamber and the calcification rates (inside and outside the changes) monitored daily along with diurnally varying carbonate chemistry and other environmental problems. Our results confirm that ocean acidification drives reduced growth rates in living colonies and promotes greater dissolution of the recently dead colonies. This study represents an important step in understanding and verifying the impacts of ocean acidification on a range of critical coral reef processes.

[1] Scripps Institution of Oceanography, University of California San Diego, Integrative Oceanography Division, Sverdrup Hall Rm 2241, 9500 Gilman Drive, MC 0218, La Jolla, CA 92093-0218, USA. dkline@ucsd.edu
[2] Global Change Institute and The School of Biological Sciences, Coral Reef Ecosystems Laboratory, The University of Queensland, Level 7, Gerhmann Building (#60), St Lucia, QLD 4072, Australia.
[3] Stanford University, Environmental Earth System Science, Braun Hall (Bldg 320), Stanford, CA 94305, USA.
[4] Carnegie Institution, Department of Global Ecology, Carnegie Institution of Washington, 260 Panama St., Stanford, CA 94305, USA.
[5] Faculty of Engineering, Architecture and Information Technology, The University of Queensland, Hawken Engineering Building (#50), St Lucia, QLD 4072, Australia.
[6] Israel Oceanographic & Limnological Research Ltd., Kinneret Limnological Laboratory P.O.B. 447, Migdal, 14950, Haifa, Israel.
[7] Australian National University, Earth Environment Research School of Earth Sciences Canberra, 0200, Australia.
[8] ARC Centre of Excellence for Coral Reef Studies, University of Queensland, St Lucia 4072 QLD, Australia.

CLIMATE CHANGE EFFECTS ON SEAGRASSES, MACROALGAE AND THEIR ECOSYSTEMS: ELEVATED DIC, TEMPERATURE, OA AND THEIR INTERACTIONS

Koch, Marguerite S.[1], George E. Bowes[2], Cliff Ross[3], and Xing-Hai Zhang[4]

Marine autotrophs will respond to elevated CO_2, [DIC], temperature as well as acidification. Rising ocean CO_2 may discriminate between autotrophic species that are CO_2-only-users and those that also use

HCO_3^- for photosynthesis, as well as those with and without carbon concentrating mechanisms (CCMs) that concentrate inorganic C (Ci) for photosynthesis and calcification. A recent synthesis of data by the authors show that the majority of marine macro-autotrophs are C_3 species, possess the capacity to utilize HCO_3^-, however are mostly not saturated at current seawater [DIC]. Thus, they will likely respond positively to elevated CO_2. Further, CO_2 is predicted to significantly elevate photosynthesis in C_3 species at high temperatures because of a reduction in photorespiration and ability to raise thermal limits. Higher temperatures can also elevate electron transport capacity, sucrose synthesis, and promote photosynthetic reactions under enzymatic control. However, stimulation of photosynthesis in response to temperature can be dependent on light saturation. While it is hypothesized that species relying on CCMs for Ci will be unresponsive to elevated CO_2, elevated temperature effects on Ci sequestration and CCMs, as well as downregulation processes are unknown. Although, HCO_3^- and CO_2 use can be facultative. Calcifying species will be challenged to respond to CO_2 because of lower [CO_3^{2-}] and their presumed reliance on HCO_3^- and recycled CO_2. Thus, calcifiers will have a dual challenge to compete against non-calcifying C_3 species and expend more energy to calcify. Field studies to date support this supposition; however more mechanistic research and long-term field studies are warranted.

[1]Aquatic Plant Ecology Laboratory, [1,4]Biological Sciences Department, Florida Atlantic University, 777 Glades Road, Boca Raton, FL 33431, USA. (mkoch@fau.edu)
[2]Department of Biology, University of Florida, 220 Bartram Hall, Gainesville, FL 32611, USA
[3]Department of Biology, University of North Florida, 1 UNF Drive, Jacksonville, FL 32224, USA

OCEAN ACIDIFICATION AFFECTS RECRUITMENT AND COMPETITION IN BENTHIC COMMUNITIES SURROUNDING NATURAL CO_2 VENTS

Kroeker, Kristy J.[1], M. Cristina Gambi[2], and Fiorenza Micheli[1]

Our understanding of the ecosystem impacts of ocean acidification is still very limited. The few model systems available demonstrate whole ecosystem shifts in acidified environments towards communities with fewer calcareous species and less diversity, but the processes underlying these changes are unknown. In order to expand our forecasts beyond model systems, an understanding of the processes underlying community reorganization is necessary. Here, we monitored the development of benthic communities on recruitment tiles for the period of one year in three pH zones caused by natural CO_2 vents in the Mediterranean Sea: extreme low pH (pH<7.2), low pH (pH=7.5-7.8), and ambient pH. At the end of one year, the assemblages were significantly different among pH zones. The successional trajectories reveal that calcified taxa never recruited to the tiles in the extreme low pH zones, where filamentous algae quickly colonized and persisted for a year. In contrast, the assemblages in ambient and low pH zones continued to become more diverse through time, until fleshy algae overgrew and outcompeted calcified species in the low pH zone. While our results suggest recruitment may limit the abundance of calcified species in extremely acidified environments, calcified species recruited and grew at similar rates in ambient and near-future acidification conditions. Instead, the decreased abundance of calcified species corresponded with an increase in fleshy algae. Thus, we reveal a novel mechanism – an altered competitive balance between calcified species and fleshy algae – that may represent a key leverage for community reorganization in an acidified ocean.

[1] Stanford University, Hopkins Marine Station, 100 Oceanview Blvd., Pacific Grove, CA 93950, USA (kkroeker@stanford.edu)
[2] Laboratory of Functional and Evolutionary Ecology, Stazione Zoologica "Anton Dohrn," Punta San Pietro, Ischia, Naples, Italy 80077

LONG TERM EXPOSURE TO HIGH-CO_2 COMPARES PATERNAL EFFECT IN THE CALCAREOUS TUBE BUILDING POLYCHAETE *HYDROIDES ELEGANS*

Lane, Ackley C. and Vengatesen Thiyagarajan

The long term and gradual changes associated with anthropogenic CO_2 emissions will greatly influence the ecosystems of future oceans. Experiments commonly find that marine organisms suffer negative effects when exposed to high-pCO_2 seawater. However, experiments rarely address the potential of marine organisms to adapt to this stressor over time. As pCO_2 concentrations increase, more tolerant marine organisms will be eventually selected for. Observations to date commonly state that tolerance to high-pCO_2 varies between individuals of a singles species, but rarely has the within species variation been quantified and linked to hereditary sources.
Adaptations can occur within tens of generations, and experiments to date have already observed variation in tolerance between clonal animals, and higher tolerances in organisms previously selected for disease resistance. It is therefore reasonable to expect that variation in tolerance exists in many species worldwide, and that that variation may be selected for, potentially resulting in more tolerant future populations. By examining variation between and within groups of highly related individuals, adaptation potential can be estimated.
In this study the tube worm *Hydroides elegans* is examined for variation in tolerance to high-pCO_2 resulting from male genetic input. Eggs from one female source (to eliminate variation due to maternal experience) are divided equally and fertilized by multiple males. Offspring of each cross were divided into 16 replicates, 8 of which were exposed to control, and 8 to high-pCO_2 (~1000ppm). High pCO_2 clearly reduces tube length, while variation in tolerance, based solely on male input (only genetic) is less obvious.

Swire Institute of Marine Science, Cape d' Aguilar Rd, Shek O, Hong Kong, China (alane@hku.hk)

THE ATLANTIC OCEAN ACIDIFICATION TEST BED: MEASUREMENTS OF NET ECOSYSTEM CALCIFICATION BY FIVE DIFFERENT METHODS IN PUERTO RICO AND THE FLORIDA KEYS

Langdon, Chris[1], Dwight Gledhill[2], Wade McGillis[3], Brice Loose[4], Derek Manzello[5], and Ian Enochs[5]

Reduced coral calcification is one of the best-established consequences of ocean acidification. However, most of this evidence comes from laboratory experiments with the exception of a few coral core and CO_2 vent studies. If ocean acidification presents a real threat to the continued existence of coral reefs it should be possible to document a long-term decline in the aragonite saturation state of reef waters and a parallel decline in net ecosystem calcification (NEC). The Atlantic Ocean Acidification Test-bed (AOAT) is a collaborative effort taking place in the Caribbean to first develop and then systematically employ the methods needed to quantify the changes in reef water carbonate chemistry and the rates of reef-wide annual NEC. A number of different methodologies are being investigated as we search for a method is that is accurate, can be automated and can be successfully employed at remote locations. To date we have tried Eulerian, Lagrangian, enclosure, Be-7 residence time/alkalinity anomaly and gradient flux-boundary layer methods. Preliminary analysis of data we have collected at La Parguera, Puerto Rico and at several reefs in the Florida Keys will be presented. Reassuringly, the different methods agree fairly well. The reefs in La Parguera exhibited little seasonality and an annual average of 24 ± 22 mmol m^{-2} d^{-1}. The reefs in the Florida Keys exhibited stronger seasonality (summer 18-24 and winter -13 to -18 mmol

m^{-2} d^{-1}) and a much lower average annual rate of 5 ± 53 mmol m^{-2} d^{-1}. The implications of these very low rates will be discussed.

[1]RSMAS, Uni of Miami, 4600 Rickenbacker Cswy, Miami, FL 33149, USA (clangdon@rsmas.miami.edu)
[2]NOAA, Silver Springs, MD, USA
[3]LDEO, Columbia Uni, Rt 9W, Palisades, NY 10964, USA
[4]GSO, Uni of Rhode Island, Narragansett, RI 02883, USA
[5]AOML, NOAA, 4300 Rickenbacker Cswy, Miami, FL, USA

ECOPHYSIOLOGICAL CHANGES OF HERMATYPIC SCLERACTINIANS IN HIGH pCO_2 CHEMOSTAT

Leblud, Julien[1], Antoine Batigny[1] Laure Moulin[2,1], and Philippe Grosjean[1]

Understanding the physiological response of hermatypic scleractinians to higher pCO_2 is critical to predict the future of coral reefs. Our aim is to investigate key aspects of the coral holobiont physiology: calcification, photosynthesis efficiency and nutrients assimilation. Two *Acroporidae* (*Acropora digitifera* and *Acropora muricata*) and two *Pocilloporidae* (*Pocillopora damicornis* and *Seriatopora hystrix*) are studied in original, patented chemostats (total volume: 1.25L). They allow to maintain scleractinians in controlled and monitored environment (temperature 26±0.1 °C, salinity 34±0.1, total alkalinity 2.40±0.02 meq.kg-1,[N] 1±0.5 µmol.L-1,[P] 0.4±0.2 µmol.L^{-1},12h/12h light/dark phases, 250 µE.m^{-1}.s^{-2}). Four replicates for each species are placed in two contrasted pH (8.05+-0.02 & 7.80+-0.02) during a 24h period. Complete balance of photosynthesis, respiration, calcification, CO_2 fluxes and nutrients assimilation is calculated every four hours. PSII complex efficiency is also estimated by pulse amplitude modulation (PAM) fluorometry.
Under current pCO_2, we observe equilibrium between net photosynthesis and dark respiration for each species: primary production by zooxanthellae is high enough to sustain the metabolism of the holobiont, including its high calcification rate. At short term and under higher pCO_2, calcification rate is not affected, but we observe a clear change of carbon fluxes, that is, a decrease in net photosynthesis, and higher dark-phase respiration rate. Nutrients assimilation, which occurs primarily during the light-phase, is also affected: a decrease is observed both for N and P. Experiments after a longer acclimation phase are planned to assess if there is any recovery of the equilibrium after adjustment of symbioses to the lower pH conditions.

[1]Laboratory of Numerical Ecology of Aquatic Systems, Mons University, 20 place du Parc, B7000, Mons, Belgium. Julien.Leblud@umons.ac.be
[2] Laboratoire de Biologie Marine, Université Libre de Bruxelles, CP 160/15 avenue F.D. Roosevelt, B1050, Brussels, Belgium

OBSERVED CHANGES IN OCEAN ACIDIFICATION IN THE SOUTHERN OCEAN OVER THE LAST TWO DECADES.

Lenton, Andrew[1,2], Bronte Tilbrook[2,3], and Nicolas Metzl[4]

As the oceans take up anthropogenic CO_2, slowing the rate of global warming, carbonate ion concentrations are simultaneously being reduced, leading to ocean acidification. While decreases in pH have been measured in the Subtropical Gyres e.g. ESTOC, BATS, HOT, the Southern Ocean changes in pH are yet to be well quantified. The Southern Ocean plays a key role in the global carbon cycle, and is projected in coming decades to become under-saturated with respect to aragonite at high latitudes.

Clearly understanding where and how fast the Southern Ocean is acidifying is critical for: detecting and monitoring biological impacts; understanding the impact of variability on rates of ocean acidification; and validating coupled and ocean model used to make projections and understand processes.
To quantify the ocean acidification changes in the Southern Ocean we use the recently released Surface Ocean Carbon ATlas (SOCAT). This dataset, comprising more than 7.5 million oceanic pCO_2 measurements collected globally since 1968, offers unprecedented Southern Ocean coverage in summer and winter. We use these Southern Ocean measurements of pCO_2 and published relationships of Alkalinity with Salinity and Sea Surface Temperature to calculate pH and the saturation states of aragonite and calcite. From these values we calculate trends over the last decades. To understand the integrated response of the Southern Ocean we calculate trends in each of the major zones between the fronts, as derived from satellite altimetry. Finally we contrast the response in each of these zones between the three major ocean basins of the Southern Ocean.

[1] CSIRO, 1 Castray Esplanade, Battery Point,Tasmania, Australia,7004. andrew.lenton@csiro.au
[2] CSIRO Wealth from Oceans National Research Flagship, PO Box 1538, Hobart, TAS 7001, Australia
[3]Antarctic Climate and Ecosystems CRC, Hobart, TAS 7001, Australia
[4]LOCEAN-IPSL, CNRS, Université P. et M. Curie - Case 100, 4, place Jussieu - 75252 Paris Cedex 5, France

MULTISTRESSOR CONTROLS ON BIODIVERSITY: LESSONS FROM GLOBAL OXYGEN- MINIMUM, CARBON-MAXIMUM ZONES

Levin, Lisa A.[1,2] and Christina A. Frieder[2]

Intense respiration and absence of ventilation can generate high pCO_2, low O_2 conditions in varied environments including rocky tide pools, estuaries, coastal dead zones and open ocean oxygen minimum zones (OMZs). As persistent features that exhibit sharp O_2, pCO_2 and temperature gradients on upwelling margins, OMZs provide an outstanding natural laboratory to examine biological effects of multiple stressors. We have compiled continental slope macrofaunal community data and hydrographic data from the Arabian Sea, Bay of Bengal, Oregon, California, Costa Rica, Peru, and Chile margins to examine the interactive effects of pCO_2, Ω, O_2, and temperature. OMZ benthic communities represent ecosystems that have adapted to extreme conditions (low oxygen, high pCO_2, low $\Omega_{aragonite}$) over geological timescales. We sought community-level insight about stressor effects from patterns of taxon composition, abundance, species richness and evenness. Analyses suggest that pCO_2 does not greatly affect taxon composition or density. Oxygen drives diversity patterns at low oxygen levels, with higher-temperature regions being most sensitive. Carbonate chemistry exhibits a greater influence on species richness and evenness at higher oxygen and lower temperature levels. Some calcified mollusks and echinoderms can survive at $\Omega_{aragonite} < 0.5$ in these evolutionarily stable systems. Faunal patterns across naturally occurring carbon-maximum, oxygen-minimum zones suggest that temperature modulates biotic responses to hypercapnia and hypoxia. Such patterns could provide insight into how present-day margin ecosystems may change in response to 'hypHOxic' (low pH, low O_2) conditions associated with expanding OMZs and intensified upwelling.

[1] Center for Marine Biodiversity and Conservation, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0218
[2] Integrative Oceanography Division, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0218 (llevin@ucsd.edu)

PHYSIOLOGICAL RESPONSES OF INVERTEBRATE SPERM TO A CONTAMINATED, HIGH CO_2 OCEAN: MECHANISMS AND CONSEQUENCES?

Lewis, Ceri[1], Karen Chan[2], and Sam Dupont[3]

Marine invertebrates adopt a vast array of reproductive strategies and demonstrate considerable variation in sperm morphology and physiology according to phylogeny, spawning habitat and fertilisation strategy, yet the free swimming sperm remains a component of most marine species life histories. The combined influences of rising atmospheric CO_2 and environmental pollution are now fundamentally altering the physicochemistry of the seawater into which these animals spawn at a rate exceeding anything in the historical and recent geological record. Here we report on recent research aimed at understanding the mechanisms by which exposure to predicted future pCO_2 conditions and environmental contaminants, such as heavy metals can act to disrupt sperm functioning in a number of broadcast spawning marine invertebrate species. Our results have clearly demonstrated that both sperm motility and metabolic rate are affected by a CO_2 induced pH reduction, with reduced motility and respiration at near future pH (7.9-7.5) but then 'hyper-activation' at lower pH (7.3-6.5). We've shown environmental contaminants can be spermiotoxic via two distinct mechanisms; reduced sperm swimming speeds which lead to a reduction in fertilization success, and/or DNA damage in the sperm which causes developmental abnormalities and reduced fitness in subsequent offspring. Interactions between OA and the contaminant copper on sperm physiology were observed for a number of species but not all species investigated. Strong species-specific differences in the level of response to these stressors, as single stressors and in combination, have been observed, suggesting reproductive processes in some species will be more susceptible to environmental change than others.

[1]Biosciences, College of Life and Environmental Sciences, Hatherly Laboratories, University of Exeter, Prince of Wales Road, Exeter, UK, EX4 4PS. (c.n.lewis@exeter.ac.uk)
[2]School of Oceanography, University of Washington, Seattle, 98195-7940. USA.
[3]Kristineberg Marine Station, Sweden.

SYNERGISTIC EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON SHELL DISSOLUTION AND OXYGEN CONSUMPTION OF OVERWINTERING THECOSMOME PTEROPODS IN THE ARCTIC (SPITSBERGEN)

Lischka, Silke and Ulf Riebesell

Polar seas are particularly vulnerable to ocean acidification because the high solubility of CO_2 in cold waters results in naturally low carbonate saturation specifically during winter. Moreover, the Arctic is responding more rapidly to global warming. Due to their aragonitic shell, thecosome pteropods – having a key role in the Arctic food web – are expected to be among the first group of calcifying organisms to be adversely affected by $CaCO_3$ undersaturation.

Ocean acidification and warming effects on dissolution and oxygen consumption of overwintering juveniles of the polar *Limacina helicina* and the Atlantic *L. retroversa* were investigated in winter 2010 on Spitsbergen. Experiments were carried out at three temperatures (2, 5, 7°C) and pCO_2 concentrations (380, 650, 1100 µatm).

Dissolution of both species rose significantly with pCO_2. For *L. helicina*, temperature synergistically amplified the pCO_2 effect at 1100 µatm. Dissolution was significantly higher for *L. retroversa* (38%) than for *L. helicina* (22%) at 1100 µatm. Winter growth cessation (i.e. calcification) found for both species makes net dissolution at aragonite undersaturation likely. Active counteraction against dissolution was suggested for both species.

Isolated and synergistic effects of CO_2 and temperature on oxygen consumption were determined only for *L. helicina* with metabolic up-regulation at 650 µatm and 7°C.
In a high CO_2 ocean, thecosome pteropods in the Arctic are likely to be constrained to raise their maintenance costs, thereby decreasing their chance to survive wintertime. When compared with a similar study in fall 2009, a higher vulnerability to ocean change in winter is suggested.

Helmholtz Centre for Ocean Research Kiel (GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany (slischka@geomar.de)

RAPID EVOLUTION OF A KEY PHYTOPLANKTON SPECIES TO OCEAN ACIDIFICATION

Lohbeck, Kai T.[1,2], Ulf Riebesell[2], and Thorsten B. H. Reusch[1]

The biological effects of ocean acidification are currently intensely studied, with likely consequences for biodiversity and ecosystem functioning emerging as a consensus. Most experiments have focused on short-term effects of elevated CO_2 in marine organisms, while the potential for rapid evolutionary changes has been widely neglected. Considering the short generation time and large population size of unicellular algae, this group lends itself for testing the evolutionary potential to respond to projected future ocean changes.
To investigate the evolutionary potential of a key phytoplankton species to ocean acidification and more specifically to study the role of novel mutations and genotype selection, we designed two 500-generation selection experiments using the prominent coccolithophore *Emiliania huxleyi*. Both experiments were run in parallel as semi-continuous batch cultures, starting from either a single clone or an equal contribution of six different clones. We tested for adaptation by measuring growth rates as fitness proxy and calcification rates as biogeochemically relevant phenotypic trait in reciprocal experiments.
Populations adapted to elevated CO_2 revealed higher growth rates compared to control populations kept at ambient CO_2 when tested under ocean acidification conditions. Calcification rates were partly restored in adapted compared to non-adapted populations, tested under elevated CO_2 conditions. To keep track of further adaptive changes the experiments are currently extended to 1000 generations. Our results suggest that adaptive evolution may help to maintain the functionality of microbial processes at the base of marine food webs and as driver of biogeochemical cycles on climate change relevant time scales.

[1]Evolutionary Ecology, Helmholtz-Centre for Ocean Research Kiel (GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany (klohbeck@geomar.de)
[2]Biological Oceanography, Helmholtz-Centre for Ocean Research Kiel (GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany

IMPACT OF OCEAN BASIN ON PTEROPOD EXPOSURE AND RESPONSE TO HIGH CO_2 AND LOW O_2

Maas, Amy E., Zhaohui 'Aleck' Wang[2], and Gareth L. Lawson[1]

Pteropods are a group of pelagic gastropods found throughout the world's oceans that are thought to be sensitive to acidification. The "Ocean Acidification Pteropod Study" (OAPS) project takes advantage of present-day differences in the aragonite compensation depth of the NE Atlantic and NW Pacific Oceans between 35°N and 50°N as a natural experiment to determine how CO_2 impacts the distribution and abundance of pteropods. Animal distribution was sampled via a combination of devices including nets, optics, and acoustics, concurrent to carbonate chemistry measurements, taken along the CLIVAR lines A20 (Atlantic) and P17N (Pacific). Along A20 the compensation depth is ~2000m throughout the latitudinal range whereas it decreases from 600m to 50m with increasing latitude along P17N. This difference in CO_2 is directly tied to decreases in O_2 concentration, making it important to disentangle the impact of low O_2 as an environmental stressor. Here we report on shipboard experiments conducted during the OAPS cruises that compared the physiological sensitivity of closely related species of pteropod from the two ocean basins to present day CO_2 concentrations and the level of CO_2 expected by the end of the century (390 vs. 800 ppm) in a factorial design with O_2 stress (10% vs. 21% O_2). Our results indicate that there are species specific sensitivities to hypercapnia, hypoxia, and an often significant synergistic impact of these two environmental variables.

[1] Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543
amaas@whoi.edu
[2] Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543

CHANGES IN PREY-PREDATOR INTERACTION AND AVOIDANCE BEHAVIOR MAY RESULT FROM OCEAN ACIDIFICATION

Manríquez Patricio H.[1,2], Marco A. Lardies[3], Cristian A. Vargas[4], Rodrigo Torres[5], Loreto Mardones[2], María Elisa Jara[2], Cristian Duarte[1] Jorge M. Navarro[1], and Nelson A. Lagos[6]

Ocean acidification, a consequence of rising global carbon dioxide levels, is expected to have negative impacts on marine shell-forming organisms. While, most studies have concentrated on aspects related to shell formation, few studies have concentrated on behavioral traits. On wave-swept rocky shores the capacity for self-righting and predator avoidance behavior in gastropods reduces the probability of predation. The consequences of ocean acidification on the self-righting behavior of *Concholepas concholepas* reared under differing conditions of seawater acidification were investigated. We report that in the absence of the predatory crab *Acanthocyclus hassleri* significantly shorter righting times were recorded in specimens reared in experimental mesocosms with increased nominal CO_2 levels (750 and 1200 ppm CO_2) compared to current levels of seawater acidification (380 ppm CO_2). Similar results were found in the presence of predatory crabs, though self-righting times were twice as fast. Successful and speedy righting ensures protection against predators or recovery after dislodgement on wave-swept rocky shores. Juveniles reared from competent larvae and early settlers at current-day and 750 ppm CO_2 significantly avoided predatory crab effluents in y-maze experiments. Similar results were found for juveniles specimens of similar sizes collected from the field. However, the predator avoidance behavior was disrupted or not recorded in experimental juveniles reared under the most CO_2-enriched conditions (1200 ppm). Our results suggest some behavioral aspects related to prey-predation interactions on wave-swept shores may be sufficiently affected by ocean acidification as to alter the functioning of marine ecosystems.

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[1]Instituto de Ciencias Marinas y Limnológicas, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile (pmanriquez@uach.cl)
[2]Laboratorio Costero de Recursos Acuáticos de Calfuco, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile.
[3]Facultad de Artes Liberales, Universidad Adolfo Ibáñez, Santiago, Chile.

[4]Laboratorio de Funcionamiento de Ecosistemas Acuáticos, Centro de Ciencias Ambientales, Universidad de Concepción, Universidad de Concepción, Concepción, Chile.
[5]Centro de Investigación en Ecosistemas de la Patagonia (CIEP), Coyhaique, Chile.
[6]Facultad de Ciencias Básicas, Universidad Santo Tomás, Ejercito 146, Santiago, Chile.

OCEAN ACIDIFICATION REFUGIA OF THE FLORIDA REEF TRACT

Manzello, Derek P.[1,2], Ian C. Enochs[1,2], Nelson Melo[1,2], Dwight K. Gledhill[3], and Libby Johns[2]

Ocean acidification (OA) is expected to reduce the calcification rates of marine organisms, yet we have little understanding of how OA will manifest within dynamic, real-world systems. Natural CO_2, alkalinity, and salinity gradients can significantly alter local carbonate chemistry, and thereby create a range of susceptibility for different ecosystems to OA. As such, there is a need to characterize this natural variability of seawater carbonate chemistry, especially within coastal ecosystems. Since 2009, carbonate chemistry data have been collected on the Florida Reef Tract (FRT). During periods of heightened productivity, there is a net uptake of total CO_2 (TCO_2) which increases aragonite saturation state (Ω_{arag}) values on inshore patch reefs of the upper FRT. These waters can exhibit greater Ω_{arag} than what has been modeled for the tropical surface ocean during preindustrial times, with mean (± std. error) Ω_{arag}-values in spring = 4.69 (± 0.101). Conversely, Ω_{arag}-values on offshore reefs generally represent oceanic carbonate chemistries consistent with present day tropical surface ocean conditions. This gradient is opposite from what has been reported for other reef environments. We hypothesize this pattern is caused by the photosynthetic uptake of TCO_2 mainly by seagrasses and, to a lesser extent, macroalgae in the inshore waters of the FRT. These inshore reef habitats are therefore potential acidification refugia that are defined not only in a spatial sense, but also in time; coinciding with seasonal productivity dynamics. Coral reefs located within or immediately downstream of seagrass beds may find refuge from OA.

[1]CIMAS, RSMAS, University of Miami, 4600 Rickenbacker Cswy., Miami, FL 33149, USA
[2]NOAA/AOML, 4301 Rickenbacker Cswy., Miami, FL 33149, USA (Derek.Manzello@noaa.gov)
[3]Ocean Acidification Program, NOAA, 1315 East West Hwy., Silver Spring, MD 20910, USA

PHYSIOLOGICAL RESPONSE OF THE STENOTHERMAL ANTARCTIC FISH *NOTOTHENIA ROSSII* TO OCEAN WARMING AND ACIDIFICATION

Mark, Felix C., Anneli Strobel, Elettra Leo, Swaantja Bennecke, Martin Graeve, and Hans O. Pörtner

Ongoing ocean warming and acidification have been found to particularly affect polar marine ecosystems. However, few data exist about the ability of Antarctic fish to respond to environmental change. We therefore studied the acclimatory capacities of the Antarctic fish *Notothenia rossii* after 4-6 weeks of acclimation to 7°C, hypercapnia (0.2 kPa CO_2) and the combination of both. We analysed routine metabolic rate (RMR) during acute thermal challenge and after acclimation, extra- and intracellular acid-base status, mitochondrial as well as enzymatic capacities and lipid composition.
Our results showed partially compensated RMR after warm acclimation and no effect of increased PCO_2 on the RMR. Hypercapnic acclimation led to a general overcompensation of extracellular pH. Intracellular pH displayed a slight acidosis in liver after warm normocapnic/hypercapnic acclimation, whereas white muscle remained well buffered under hypercapnia. Mitochondrial state III respiration in liver was unaffected by temperature acclimation, but depressed in the hypercapnia acclimated animals, which went along with reduced rates of proton leak. The activities of the mitochondrial enzymes citrate

synthase and cytochrome c oxidase increased during hypercapnia acclimation in red and white muscle, but not in liver and heart. Furthermore, there was a trend towards an enrichment of poly-unsaturated fatty acids in liver mitochondria towards the warm hypercapnic conditions.
We conclude that *N. rossii* possesses basic acclimatory capacities towards ocean warming and acidification. However, these capacities are confined within strict limits, becoming obvious in metabolically more active organs like heart and liver that show less plasticity than muscle and ultimately define animal survival.

Alfred Wegener Institute for Polar and Marine Research, 27570 Bremerhaven, Germany (fmark@awi.de)

PHYSIOLOGICAL CHANGES IN CRUSTOSE CORALLINE ALGAE SCALE UP TO ALTER COMPETITIVE INTERACTIONS IN RESPONSE TO ACIDIFICATION

McCoy, Sophie J.[1], Robert T. Paine[2], Catherine A. Pfister[1], and J. Timothy Wootton[1]

The effects of environmental changes in natural ocean ecosystems can best be detected at locales where species dynamics and interactions have been studied concomitant with physical and chemical features of coastal seawater. A wealth of ecological studies provides a baseline for community function and species interactions along the Northeast Pacific coast over the past several decades. Furthermore, our coastal dataset records an unexpectedly rapid decline of seawater pH, ten-fold faster than predicted over the last 13 years, while other measured parameters including temperature, salinity, and nitrate remain relatively constant over this interval.
To identify ecological changes in response to this temporal gradient in acidity, we repeated competition experiments identical to those performed 1981-1999 among crustose coralline red algae. These experiments quantify overgrowth competition hierarchies between coralline algal crusts and determine the strength of competitive interactions as a function of herbivory pressure. We find large changes in competitive interactions of all species over time when we compare between 2010-2012 and 1981-1999. The historical competitive dominant, *Pseudolithophyllum muricatum*, has experienced both a reduction in its local abundance and its competitive abilities, now winning only 35% of competitive bouts in the natural presence of grazers, compared to 99% previously. We document changes in species-specific traits such as maximum growth rates, tissue thickness, and density of calcified tissue, that correspond both to our observed changes in species interaction strengths in the field and expected physiological responses of coralline algae to acidification. This work demonstrates community-level responses to acidification in a natural system.

[1] Department of Ecology and Evolution, The University of Chicago, Chicago, IL 60637, USA (mccoy@uchicago.edu)
[2] Department of Biology, University of Washington, Seattle, WA 98195, USA

EFFECTS OF ELEVATED pCO_2 ON CALCIFYING INVERTEBRATES IN A CO_2 ENRICHED HABITAT: LABORATORY AND FIELD STUDIES

Melzner, Frank, Jörn Thomsen, Isabel Casties, Christian Pansch, Magdalena A. Gutowska, and Arne Körtzinger

High seawater pCO_2 is encountered in the Baltic Sea during summer and autumn; average summer pCO_2 values of ca. 1,000 µatm have been recorded during the reproductive season and peak pCO_2 reaches values of >2,500 µatm during upwelling events. Owing to a low alkalinity, this brackish habitat is almost permanently under saturated with respect to aragonite. Despite adverse carbonate system conditions, benthic communities are dominated by calcifying invertebrates. We present data from laboratory experiments that demonstrate that dominating bivalves (*Mytilus edulis*) (i) can calcify at very high rates under high pCO_2 (ii) that calcification and maintenance of shell integrity are functions of the energy budget and (iii) that calcification and somatic growth are more strongly influenced by habitat energy density than by pCO_2. Additionally, field experiments indicate that mussel growth and calcification is increased at high pCO_2 sites in comparison to low pCO_2 sites. These effects are primarily due to high particulate organic carbon (POC) at high pCO_2 sites, indicating that in eutrophic, hypercapnic habitats, increased food supply can outweigh negative effects of elevated seawater pCO_2. However, model calculations indicate that future changes in atmospheric CO_2 concentrations will lead to very high CO_2 partial pressures in such CO_2 enriched coastal habitats, with peak values exceeding 4,000 µatm by the year 2100.

Helmholtz Centre for Ocean Research Kiel (GEOMAR), fmelzner@geomar.de

LONG TERM, TRANS-GENERATIONAL IMPACTS OF TEMPERATURE AND OCEAN ACIFIDICATION IN KEYSTONE INTERTIDAL SPECIES

Mieszkowska, Nova [1] and Mike T. Burrows[2]

Long-term mesocosm experiments coupled with monthly field studies spanning a decade and annual biogeographic surveys dating back to the 1950s demonstrate the differential impacts of temperature and ocean acidification on geographic distribution, abundance, morphometrics, timing and extent of reproduction and the resultant survival of F1 recruits from the mesocosm and a field population. Two species of gastropod, the lusitanian grazing trochid *Osilinus lineatus* and the boreal predatory whelk *Nucella lapillus* show different responses to climate change within field populations around the UK and thermally manipulated conditions, but similar responses to simulated ocean acidification treatments within the mesocosm.

O. lineatus has shown one of the fastest range extensions recorded globally in response to climate warming, due to increased recruitment success close to the northern range edge and greater propagule dispersal beyond distributional limits. *N. lapillus* has not shown significant changes in abundance in the UK over the past decade. Within long-term mesocosm experiments the greatest impacts were observed in organisms exposed to a combination of elevated temperature and pCO_2, greater than for individuals exposed to even higher pCO_2 at ambient seawater temperatures. Female *N. lapillus* became reproductively active, laying egg capsules with a time delay across the 380ppm, 380ppm +4°C and 750ppm with no females reproducing in 750ppm+4°C or 1000ppm conditions during springtime. The F1 mesocosm juveniles and juveniles sampled from the field population are being monitored to detect differences in survival, shell size, shell calcification and soft tissue weight, with the results up to 6 months of age being presented.

[1]Marine Biological Association of the UK, Citadel Hill, Plymouth, PL1 2PB, UK (nova@mba.ac.uk)
[2]Scottish Association for Marine Science, Dunstaffnage, Oban, PA37 1QA, UK

TRANGENERATIONAL ACCLIMATION TO OCEAN ACIDIFICATION IN REEF FISH

Miller, Gabrielle M., Sue-Ann Watson, Jennifer M. Donelson, Mark I. McCormick, and Philip L. Munday

Many studies have demonstrated that elevated CO_2 and ocean acidification can affect the metabolism, growth and survival of marine organism, yet very little is known about the potential for parental effects to alter the response to high CO_2 (transgenerational acclimation). We investigated the effects of ocean acidification on juvenile Cinnamon Clownfish, *Amphiprion melanopus*. The potential for transgenerational acclimation to mediate these effects was tested by comparing the performance of juveniles from parents held under control and elevated CO_2 treatments. Wild caught breeding pairs were held for a 9 month period, inclusive of the austral summer breeding season, under control (430µatm), moderate (~600µatm) and high (~1000µatm) CO_2 and allowed to spawn naturally under these conditions. Egg clutches were then either hatched into their parental CO_2 conditions, or for some clutches from control parents, switched up to and hatched under high CO_2 treatment. Juveniles were reared in their respective CO_2 treatments for 32 days. Juveniles from control parents raised at high CO_2 were significantly smaller, had lower survivorship, and higher resting metabolic rates compared to control juveniles. In contrast, juveniles from high CO_2 parents that were reared under high CO_2 treatments were of a comparable size and had similar survivorship and metabolic rates to the control juveniles suggesting transgenerational acclimation has occurred. This study is the first to demonstrate transgenerational acclimation to rising CO_2 levels in reef fishes.

School of Marine and Tropical Biology and ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD, 4810, Australia (gabrielle.miller1@my.jcu.edu.au)

IMPACT OF OCEAN ACIDIFICATION ON THE SEA URCHIN *ECHINOMETRA MATHAEI* AND ITS ROLES AS GRAZER AND BIOERODER IN CORAL REEFS

Moulin, Laure[1,2], Leblud Julien[2], Batigny Antoine[2], Dubois Philippe[1], and Grosjean Philippe[2]

Coral reefs are particularly vulnerable to ocean acidification resulting from the increase of anthropogenic carbon dioxide in the atmosphere and its dissolution in seawater. Their existence depends on the calcification rate of hermatypic corals that must remain higher than erosion. Sea urchins are, on the one hand, key species for the resilience of coral reefs through their grazing activities of invading macroalgae. On the other hand, they are also major bioeroders of reef substrate.

One objective of this study was to evaluate the effect of ocean acidification on the growth and the physiology of sea urchins. The impact of acidification on the balance between coral accretion and bioerosion by sea urchins has also been investigated.

The study was conducted in two identical artificial reef mesocosms. Experimental tanks were maintained respectively at mean pH_{total} 7.7 and 8.05 (with field-like night and day variations). The major physico-chemical parameters were identical, only *p*CO2 and pH differed. The growth, the carbonate chemistry of the coelomic fluid and the respiration rate of sea urchins were monitored throughout the experiment, as well as the growth of corals. Biomechanical analyses were performed on sea urchins and coral skeletons. Bioerosion by sea urchins was estimated. Preliminary results indicate that *Echinometra mathaei* can maintain growth and metabolism, at least at short term and under this moderate acidosis. On the other hand, coral growth was negatively affected. These opposite effects could have an impact on the subtle and dynamic balance between bioerosion by sea urchins and bioaccretion of corals and on the long term survival of coral reefs.

[1] Laboratoire de Biologie Marine, Université Libre de Bruxelles, CP 160/15 avenue F.D. Roosevelt, B1050, Brussels, Belgium. Email: lmoulin@ulb.ac.be
[2] Laboratoire d'Ecologie Numérique des Milieux Aquatiques, Université de Mons, 20 place du Parc, B7000, Mons, Belgium

THE EFFECTS OF BENTHIC METABOLISM ON COASTAL CARBONATE CHEMISTRY AND SEASONAL REEF DISSOLUTION AND THE SUBSEQUENT CONSEQUENCES FOR PREDICTING REEF ACCRETION AND CORAL GROWTH UNDER OCEAN ACIDIFICATION

Muehllehner, Nancy and Chris Langdon

Benthic metabolism, particularly from large photosynthesizing and calcifying communities can exert a strong control on coastal water chemistry. During summer in the Florida Keys, benthic metabolism results in a strong drawdown of pCO_2, subsequently elevating aragonite saturation state (Ω_a) inshore by as much as 0.73 relative to oceanic waters due to benthic photosynthesis on the reef. In this study, 2 years of seasonal fluctuations in CO_2 were assessed through repeat cruises transecting over 7 reef flat areas in 160km of the Florida Reef Tract and showed the same trend with drawdown's exceeding 165 $\mu mol\ kg^{-1}$ of total dissolved inorganic carbon over the 4.4 km from outer to inner reefs. In turn, wintertime respiration rates led to greatly increased pCO_2, depressed Ω and strong seasonal dissolution ranging from -9.8 to -16.8 mmol $CaCO_3\ m^{-2}d^{-1}$ in 2009 and 2010 respectively. While saturation states of >3.2 in the field were associated with reef structure dissolution, net calcification of the fast growing *Acropora cervicornis* in the lab was observed even after long exposures (2 months) to under-saturation (Ω_a 0.89 and 0.52). Thus, the field study of seasonal trends of dissolution transitioning to net calcification at relatively high Ω_a sharply contrasts the lab studies of coral calcification demonstrating some corals can maintain calcification despite exposure to highly under-saturated water. This indicates that predictions of reef accretion are much more likely to be specific to location and the surrounding coastal community metabolism versus being directly scalable from basic lab experiments of the Ω-calcification relationship.

Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Cswy, Miami, Fl, 33149, USA. nmuehllehner@rsmas.miami.edu

INFLUENCE OF CO_2 AND NITROGEN LIMITATION ON THE COCCOLITH VOLUME OF *EMILIANIA HUXLEYI* (HAPTOPHYTA)

Müller, Marius N.[1], Luc Beaufort[2], Olivier Bernard[3], Maria-Luiza Pedrotti[4,5], Amelié Talec[4,5], and Antoine Sciandra[4,5]

Coccolithophores, a key phytoplankton group, are one of the best studied organisms with regard to the response to ocean acidification/carbonation. The biogenic production of calcareous coccoliths has made coccolithophores a promising group for paleoceanographic research aiming to reconstruct past environmental conditions. Recently, geochemical and morphological analyses of fossil coccoliths have gained increased interest in regard to changes in seawater carbonate chemistry. The cosmopolitan coccolithophore *Emiliania huxleyi* was cultured over a range of CO_2 levels in controlled laboratory experiments under nutrient replete and nitrogen limited conditions. Measurements of photosynthetic activity and calcification revealed, as previously published, an increase in organic carbon production and a moderate decrease in calcification from ambient to elevated CO_2. The enhancement in particulate organic carbon production was accompanied by an increase in cell diameter. Coccolith volume was best

correlated with the coccosphere/cell diameter and no significant correlation was found between coccolith volume and particulate inorganic carbon production rate. The conducted experiments revealed that the coccolith volume of *E. huxleyi* is variable with aquatic CO_2 concentration within the tested range but appears to be a primary function of the coccosphere/cell diameter both under nitrogen limited and nutrient replete conditions. Comparing coccolith parameters like volume, mass and size to physiological parameters under controlled laboratory conditions is an important step to understand variations in fossil coccolith morphology and geometry.

[1]Institute for Marine and Antarctic Studies (IMAS), Private Bag 129, Hobart, TAS 7001, Australia (Marius.Muller@utas.edu.au)
[2]CNRS/Université Aix-Marseille, CEREGE, F-13545 Aix-en-Provence, Cedex 4, France
[3]INRIA (French National Institute for Research in Computer Science and Control), COMORE Research Team, 2004 Route des Lucioles, 06902 Sophia-Antipolis, France
[4]UPMC Univ Paris 06, UMR 7093, LOV, Observatoire océanologique, F-06234 Villefranche/mer, France
[5]CNRS, UMR 7093, LOV, Observatoire océanologique, F-06234 Villefranche/mer, France

OCEAN ACIDIFICATION ALTERS BEHAVIOUR AND INTERFERES WITH BRAIN FUNCTION IN MARINE FISH

Munday, Philip L.

One of the most unexpected advancements in ocean acidification research has been the discovery that predicted future CO_2 levels interfere with a range of behaviours and sensory activities of marine fishes. Behavioural changes include increased activity and boldness, loss of lateralization in movement, altered auditory preferences, and impaired olfactory function. Here, I describe the ecological consequences of these sensory and behavioural changes to population sustainability, predator-prey interactions, homing ability and habitat selection in reef fishes. I then describe the underlying mechanism responsible for these diverse impacts. New experiments show that exposure to elevated CO_2 has a systemic effect on behaviour and sensory performance of marine fish by interfering with brain GABA-A receptor function. Larval reef fish exhibit impaired behaviour and olfactory preferences when exposed to high CO_2, but these abnormality are rapidly reversed by treatment with a GABA-A receptor antagonist. These results indicate that elevated CO_2 can directly interfere with neurotransmitter function, a previously unrecognized threat to marine species. Given the ubiquity and conserved function of GABA-A receptors we predict that rising CO_2 levels could cause sensory and behavioural impairment in other marine species, especially those that tightly control their acid-base balance through ion regulation.

ARC Centre of Excellence for Coral Reef Studies, and School of Marine and Tropical Biology, James Cook University, Townsville, QLD 4811, Australia (Philip.Munday@jcu.edu.au)

LOW LEVEL DISSOLVED OXYGEN AND PH EFFECTS ON THE EARLY DEVELOPMENT OF MARKET SQUID, *DORYTEUTHIS OPALESCENS*

Navarro, Michael O.[1,3], Christina A. Frieder [1], Jennifer Gonzalez[1], Emily Bockmon[1], and Lisa A. Levin[1, 3]

Spawning aggregations of market squid can cover the benthos with “beds” of capsules. Increased upwelling, ENSO frequency, and other environmental conditions associated with climate change sometimes work together to shoal oxygen minimum zone waters to depths < 90 m, exposing embryos to low levels of dissolved oxygen (DO) and pH. We hypothesized that low DO (90 µmol/kg) and pH (7.5) levels affect squid embryonic development. In the laboratory, squid embryos were initially exposed to

two treatments at a constant temperature (11 °C): one with low levels of DO and pH (90 µmol/kg, pH=7.5) and the other with "normal" levels (i.e. DO=240 µmol/kg, pH=7.9). At the end of the experiment, squid were photographed, morphometric data were collected using imagej™ software, and JMP ™ software was used for statistical analysis. Low DO and pH caused significant slowing of embryogenesis, delaying development by approximately 5-7 days. A second experiment, imposing low DO and pH separately, suggests that DO is responsible for most of the observed developmental delays. These delays may exert carry-over effects into the paralarval stage such as match-mismatch in timing of their hatching with availability of their prey, zooplankton, during their critical period of first feeding. If so, suitable habitat for market squid embryogenesis may be significantly compressed with only the most shallow areas (<20 m depth) producing paralarvae able to find adequate food for survival. Ongoing studies are using samples from these studies to investigate physiological effects on embryos and geochemical changes in statolith elemental composition during embryogenesis.

[1] Integrative Oceanography Division, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0208 (monavarr@ucsd.edu)
[2] Geosciences Research Division, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0244
[3] Center for Marine Biodiversity and Conservation, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0218

PROPERTIES OF BIOLOGICAL MATERIALS SECRETED BY BIVALVES UNDER A RANGE OF CARBONATE CHEMISTRIES

O'Donnell, Michael J., Matthew George, and Emily Carrington

Organism interactions with the physical environment are mediated by biological structures such as shells, which isolate organisms from the external environment, and adhesives, which keep organisms located in suitable habitat. Like many chemical processes, creating these structures takes place in the context of the local seawater chemistry. Many investigations have explored the effects of altered carbonate chemistry on the rate at which structures are produced, but little is known about the relative quality of these materials for performing their assigned tasks. Here we report on the properties of biological materials created by *Mytilus trossulus* exposed to a range of pCO_2 conditions (from ~400 to 1600 µatm) to elucidate the shape of the response curve. Byssal threads attach *Mytilid* mussels to the shore. Most regions of these threads showed no variability in response to altered pH with the exception of the adhesive that secures the thread to the substratum. Across a similarly broad range of carbonate chemistries, we also looked at shell repair in response to simulated drilling predation. Organisms inhabiting high intertidal areas experience highly variable environmental conditions and are likely adapted to a much broader, and more variable, range of seawater chemistries than those experienced in the open-ocean.

University of Washington, Friday Harbor Laboratories, 620 University Rd., Friday Harbor, WA 98250, USA. mooseo@uw.edu

THE EFFECTS OF OCEAN ACIDIFICATION ON CELLULAR PHYSIOLOGY AND RELEASE OF DOM AND TEP IN MULTIPLE STRAINS OF *EMILIANIA HUXLEYI*

Okimura, K.M.[1], I. Benner[1], S. Lefebvre[2], T. Komada[1], J.H. Stillman[1], and E.J. Carpenter[1]

Ocean acidification (OA) is a pervasive environmental stressor caused by anthropogenic emissions of CO_2. Changes in extracellular release of dissolved organic matter (DOM) and transparent exopolymer particles (TEP) by phytoplankton in response to OA has the potential to alter oceanic carbon sequestration rates. In order to determine the direction and magnitude of carbon cycle response, we investigated the effects of OA on physiology and extracellular release of two *E. huxleyi* strains (RCC 1251 & RCC 1258) cultured at three pCO_2 levels (380 ppmv, 600 ppmv, and 900 ppmv). Changes in the particulate inorganic carbon to particulate organic carbon ratio (PIC:POC), DOM, and TEP production were measured. While pCO_2 did not have an effect on growth pattern or primary productivity in RCC 1251, cell concentration and productivity were significantly reduced under 900 ppmv compared to other pCO_2 treatments in RCC 1258 during exponential growth. Growth and productivity were also different between strains. These data suggest that future TEP production in response to OA varied between *E. huxleyi* strains.

[1] Romberg Tiburon Center for Environmental Research SFSU, 3152 Paradise Dr. Tiburon, CA 94920 (kokimura@sfsu.edu)
[2] J. Craig Venter Institute 10355 Science Center Dr. San Diego, CA 92121

ACIDIFICATION RATES OF ICELAND SEA WATER MASSES

Olafsson, Jon[1,2], Solveig R. Olafsdottir[2], Alice-Benoit Cattin[2], and Magnus Danielsen[2]

Iceland is in the North Atlantic Ocean in the vicinity of fronts between Arctic and temperate influences. Relatively warm and saline Atlantic Water (S>35) flows west of the island from the south into the Iceland Sea. Cold and dense Arctic Water flows from the Iceland Sea across the Greenland-Iceland-Faroes-Ridge. This is a source region for the Global Thermohaline Circulation. We examine time series observations, some extending back to 1983, for carbonate chemistry variations in these waters. They exhibit distinct differences reflecting physical processes, freshwater influence and air-sea exchanges in the high latitudes. The mean partial carbon dioxide pressure, pCO_2, of the Iceland Sea waters shows significant CO_2 undersaturation throughout the year such that the region is a sink for carbon dioxide. However, the sea water carbon dioxide partial pressure is increasing at a rate of 2.1µatm/yr, faster than in the atmosphere. This shows a weakening of the sink for atmospheric CO_2. Comparing the subsurface overflow source waters with time series results for the surface water, reveals that the rate of change in pH and the saturation states of both aragonite and calcite are faster for the deep overflow source waters.

Faculty of Earth Sciences, Askja, Sturlugata 7, IS 107, Reykjavik, Iceland (jon@hafro.is)
Marine Research Institute, Skulagata 4, IS 121, Reykjavik, Iceland

PROJECTED ACIDIFICATION IN THE IPCC AR5-ERA EARTH SYSTEM MODELS

Orr, J. C.[1], L. Bopp[1], P. Cadule[1], V. Cocco[2], P. Halloran[3], C. Heinze[4], F. Joos[2], A. Oschlies[5], J. Segschneider[6], J. Tjiptura[4], and I. Totterdell[3]

Model projections discussed in IPCC AR4 reveal large future decreases in pH and carbonate ion concentrations during the 21st century across the surface ocean, but most did not include effects from climate change. Since then, we have combined results from seven AR4-era Earth System Models (ESMs) in a publicly available archive (ocmip5.ipsl.fr), computed relevant acidification variables, and compared projected changes in surface pH and carbonate ion concentrations. By definition, ESMs account for climate change as well as increasing atmospheric CO_2. For AR5, projections have been updated by exploiting the large archive of results from the new generation of ESMs that are participating in the Coupled Model Intercomparison Project (CMIP5). We have analyzed 8 new ESMs run under the CMIP5 historical and RCP scenarios. The AR4 simulations under the A2 scenario ended in 2100; the new simulations under the RCP scenarios end 200 years later. Projected acidification in 2300 under the RCP85 scenario is more severe than considered previously, e.g., surface pH declines by nearly 1 pH unit in the Arctic Ocean as atmospheric CO_2 climbs to 1900 ppm. By 2100, both the surface Arctic and Southern Ocean become undersaturated with respect to all forms of $CaCO_3$. The AR5-era model projections differ less because for a given scenario, the atmospheric CO_2 trajectory is identical in all models. But they still disagree substantially, especially in the deep ocean. We quantify how agreement improves dramatically after removing each model's modern bias, i.e., adding its perturbation to the modern observed state of the ocean.

[1]LSCE/IPSL, CEA-CNRS-UVSQ, CEA Saclay, F-91191 Gif-sur-Yvette, France (orr@cea.fr)
[2]Climate and Environmental Physics, Physics Institute, University of Bern, Switzerland
[3]Met Office, Hadley Centre for Climate Prediction and Research, Exeter, UK
[4]Berknes Centre for Climate Research, Bergen, Norway
[5]GEOMAR, Düsternbrooker Weg 20, Kiel, Germany
[6]Max Planck Institut für Meteorologie, Hamburg, Germany

BARNACLES' RESPONSE TO OCEAN ACIDIFICATION AND OTHER STRESSORS

Pansch, Christian[1], Iris Schaub[1], Ali Nasrolahi[1], Jonathan Havenhand[2], and Martin Wahl[1]

Organisms from habitats with naturally high fluctuations in pCO_2 might have evolved a better tolerance to future ocean acidification (OA) than organisms from more stable environments. An additional threat for marine organisms will, however, be the simultaneous occurrence of further stressors possibly acting in synergy with OA in the future. We investigated the effect of pCO_2 (combined with temperature stress or food limitation) on various life stages of the barnacle *Amphibalanus improvisus* in populations from Kiel, Germany and Tjärnö, Sweden. The Kiel Fjord is characterized by strong seasonal fluctuations in pCO_2 whereas Tjärnö waters display a more stable pCO_2 environment. Nauplius and cypris larvae as well as juveniles were reared at different pCO_2, temperature and food treatment combinations in several experiments over a three-year period. Kiel barnacles showed a pronounced tolerance to all applied pCO_2 levels, irrespective of the life stage. Nauplii were, however, impacted when pCO_2 stress was combined with temperature stress. While Tjärnö nauplii were tolerant of OA, juveniles compensated for 1000µatm pCO_2 when food conditions were ample but were impacted under food limitation. A pCO_2 of 3000µatm negatively impacted growth of Tjärnö barnacles in both feeding treatments. These results demonstrate the importance of considering multiple stressor interactions when assessing climate change impacts. They also support the hypothesis that barnacle populations from fluctuating pCO_2 environments are

more tolerant of OA than barnacles from more stable pCO_2 habitats. This highlights a need for further comprehensive ecological studies investigating the effects of environmental background on possible adaptation to future OA.

[1]GEOMAR | Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany. cpansch@geomar.de
[2]University of Gothenburg, Dept. of Marine Ecology, Tjärnö, 452 96 Strömstad, Sweden

ADULT EXPOSURE INFLUENCES OFFSPRING RESPONSE TO OCEAN ACIDIFCATION IN OYSTERS

Parker, Laura M.[1], Pauline M. Ross[1], Wayne A. O'Connor[2], Larissa Borysko[1], David A. Raftos[3], and Hans-Otto Pörtner[4]

It is essential to predict the impact of elevated pCO_2 on marine organisms and habitats in order to anticipate the severity and consequences of future ocean chemistry change. Despite the importance of carry-over effects in the evolutionary history of marine organisms, few studies have considered links between life-history stages when determining how marine organisms will respond to elevated pCO_2, and none have considered the link between adults and their offspring. We exposed adults of wild and selectively bred Sydney rock oysters, *Saccostrea glomerata* to elevated pCO_2 during reproductive conditioning and measured the development, growth and survival response of their larvae. We found that elevated pCO_2 had negative impacts on larvae of *S. glomerata* causing a reduction in growth, rate of development and survival. Exposing adults to elevated pCO_2 during reproductive conditioning, however, had positive carry-over effects on larvae. Larvae spawned from adults exposed to elevated pCO_2 were larger, developed faster but displayed similar survival compared to larvae spawned from adults exposed to ambient pCO_2. Further, selectively bred larvae of *S. glomerata* were more resilient to elevated pCO_2 than wild larvae. Measurement of the standard metabolic rate (SMR) of adults showed that at ambient pCO_2, SMR is increased in selectively bred compared to wild oysters and is further increased during exposure to elevated pCO_2. This study suggests that sensitive marine organisms may have the capacity to acclimate or adapt to elevated pCO_2 over the next century and a change in energy turnover indicated by SMR may be a key process involved.

[1]School of Science and Health, University of Western Sydney, Hawkesbury H4, Locked Bag 1797, Penrith South DC 2751, Sydney, New South Wales, Australia (l.parker@uws.edu.au)
[2]Industry and Investment NSW, Port Stephens Fisheries Centre, Taylors Beach, New South Wales 2316, Australia
[3]Department of Biological Sciences, Macquarie University, North Ryde, NSW, 2109, Australia
[4]Alfred Wegener Institute for Polar and Marine Research in the Hermann von Helmholtz Association of National Research Centres e. V. (HGF), Am Handelshafen 12, 27570, Bremerhaven, Germany

ACLIMATION AND ADAPTATION POTENTIAL OF CORALS TO CALCIFICATION AT LOW SATURATION - INSIGHT FROM FIELD OBSERVATIONS

Paytan, Adina[1] Elizabeth, D. Crook[1], Anne, L. Cohen[2], Laura, Hernandez-Terrones[3], and Mario, Rebolledo-Vieyra[3]

Decline in coral calcification in response to decreasing aragonite saturation state is predicted. The predictions are based on model calculations of future saturation and the observed response of select coral species in short-term laboratory-based or mesocosm carbonate chemistry manipulation

experiments. Observations of net coral reef ecosystem calcification responses to changes in aragonite saturation state *in-situ*, also provide valuable information but are harder to interpret. Key questions, however remain, regarding the acclimation and adaptation potential of coral-calcification to ocean acidification. Specifically, if coral reefs are maintained in healthy condition and are given sufficient time will they adapt to ocean acidification and maintain high calcification rates.

To address this question field-based observations, at sites where corals have been naturally exposed to chronic low pH conditions for centuries to millennia, were conducted. Calcification rates in colonies of a common Atlantic coral, *Porites astreoides*, which have been growing in an environment of low pH and low aragonite saturation for time scales potentially sufficient for acclimation and adaptation were quantified and compared to calcification rates of neighboring populations of the same species living under ambient conditions and to results from short term manipulation experiments.

While calcification rates declined considerably at the low saturation sites the observed reduction in calcification was similar to that observed in short term laboratory exposure experiments. Thus indicating that the sensitivity to ocean acidification after 2 weeks in a tank, and after 10,000 years in the natural environment appear to be the same possibly indicating lack of adaptation.

[1] UCSC, 1156 High Street, Santa Cruz, CA 95064, USA (apaytan@ucsc.edu)
[2] WHOI, 266 Woods Hole Rd., Woods Hole, MA 02543-1050, USA.
[3] CICY, Ciencias del Agua, Calle 8, No 39, Cancun, QR, 77500, Mexico.

DETERMINING THE RESILIENCE OF ECOLOGICALLY-IMPORTANT INTERTIDAL INVERTEBRATES TO ELEVATED CO_2 AND TEMPERATURE: PHYSIOLOGICAL RESPONSES AND ENERGETIC TRADE-OFFS.

S.P.S. Rastrick[1], P. Calosi[1], H. Findlay[2], H. Graham[3], J. Godbold[4], C. Hauton[4], A. Queiros[2], M. Solan[4], J. Spicer[1], N.M.Whiteley[5], and S. Widdicombe[2].

To assess the effect of future temperature increase and ocean acidification on intertidal benthic ecosystems, key physiological responses (oxygen uptake, acid-base status and ion-regulation) and energy demanding processes (immune-function, behavior, growth, and reproduction) were measured over 12 month exposures to present and future CO_2 and temperature conditions (380ppm, 750ppm, 1000ppm CO_2 at seasonal ambient temperatures, and 380ppm, 750ppm CO_2 at +4˚C ambient temperatures) in three soft sediment and four hard substrate invertebrate species. These were selected due to their importance for the composition and functioning of coastal benthic ecosystems.

As the ability of these organisms to cope and survive ocean changes is to some extent determined by their capacity for physiological acclimatization, it is vital to understand the mechanisms underlying their physiological plasticity in the face of environmental change and their metabolic limitations. The underlying physiological responses will be discussed in terms of their effect on energy consumption and trade-offs between immune function, behavior, growth, and reproduction. As such trade-offs can determine a species life-history strategy and ecological distribution this provides a way to link physiological and ecological responses to climate change. Previous studies describing the impacts of global change drivers on organismal functions have focused on relatively few physiological processes, investigated over relatively short-term exposures. However, we show that such studies risk missing long-term shifts in physiological responses that may underlie trade-offs between energy demanding processes and have an impact on performance and fitness determining the resilience of ecologically important species in response to ocean acidification and global warming.

[1] Marine Biology & Ecology Research Centre, Plymouth University, Drake Circus, Plymouth, Devon, PL4 8AA, UK (Samuel.Rastrick@plymouth.ac.uk)

[2] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH, UK.
[3] Newcastle University, Newcastle upon Tyne, Tyne and Wear, NE1 7RU, UK.
[4] University of Southampton, University Road, Southampton SO17 1BJ, UK.
[5] Bangor University, Deiniol Road, Bangor, Gwynedd, LL57 2UW, UK.

THE NEED FOR NEW CONSERVATION STRATEGIES AND POLICIES IN A HIGH CO_2 WORLD

Rau, Greg H.[1], Elizabeth McLeod[2], and Ove Hough-Guldberg[3]

Increasing atmospheric CO_2 is thermally and chemically impacting the ocean and its ecosystems. Both the magnitude and rapidity of these changes will likely surpass the ability of numerous marine species to adapt and survive. Regional and ecosystem differences in forcings and biological responses are anticipated, but with impacts felt from tropical to polar oceans. Trillions of dollars in economic benefit are at risk, not to mention priceless environmental services provided by the ocean. Our concern is that the specific actions identified in current policy statements to counter such impacts will prove inadequate or ineffective.

In particular stabilization of atmospheric and hence ocean CO_2 and pH appears unlikely to be achieved in the foreseeable future. While use of conventional management methods (e.g., marine protected areas, and integrated coastal management that includes pollution reduction strategies and watershed management) are essential in promoting biotic resilience and adaptation to global pH depression, these methods may ultimately prove ineffective against this unconventional stressor. Therefore, a much broader range of marine management and mitigation options needs to be considered.

Some physical, chemical, and biological methods of mitigating or offsetting the effects of ocean acidification have been proposed, additional ideas need to be solicited, and all options should be evaluated for their efficacy. Such a policy would provide a more robust and potentially successful conservation action plan that would complement efforts to rapidly stabilize or decrease CO_2 and ocean acidity, and efforts to promote marine ecosystem resilience and adaptability using conventional methods.

[1]Institute of Marine Sciences, University of California, 1156 High St., Santa Cruz, CA 95064, USA.
ghrau@sbcglobal.net
[2]The Nature Conservancy, Hawaii Field Office, Honolulu, HI 96817, USA
[3]Global Change Institute, University of Queensland Brisbane QLD 4072, Australia

SHORT-TERM RESPONSE OF NATURAL MICROBIAL COMMUNITY TO OCEAN ACIDIFICATION ON AND AROUND THE NORTH WEST EUROPEAN CONTINENTAL SHELF

Richier, S.[1,2], C.M. Moore[1], D.J. Suggett[3], A.J. Poulton[4], R. Holland[4], M. Stinchcombe[4], M. Zubkov[4], E.P. Achterberg[1], and T. Tyrrell[1]

All areas of the ocean will experience elevated pCO_2, and in turn ‘ocean acidification’ (OA) this century. However, our understanding of the potential ecosystem-scale impacts of OA are still confounded by the diversity of responses observed at the species-scale. Here, we report results of the first campaign of ship-board bioassay experiments specifically directed at studying OA. These experiments, in which we follow the emergent microbial community level response, constitute one of the few studies that have examined the response of natural communities. Experiments were initiated on and around the North West European Continental Shelf following the spring bloom period in a range of settings characterized by differing plankton communities and environmental conditions (*e.g.* nutrients, initial pCO_2). We assessed short-term (48-96h) physiological and community structure responses of microbes to four pCO_2 levels (ambient, 550 µatm, 750 µatm and 1000 µatm). A strong group-specific response to lowered pH/enhanced pCO_2 was repeatedly observed across the majority of bioassay experiments. Such responses have important implications for trophic dynamics and biogeochemical cycling in both present day and future oceanic ecosystems.

[1]National Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, UK (s.richier@noc.soton.ac.uk)
[2]INSU CNRS, Lab. Oceanog. Villefranche, UPMC Univ. Paris 06, Observ. Oceanol. Villefranche F-06234 Villefranche Sur Mer, France
[3]Department of Biological Sciences, University of Essex, Colchester CO4 3SQ, UK
[4]National Oceanography Centre, Waterfront Campus, Southampton, SO14 3ZH, UK.

IS OCEAN ACIDIFICATION A SIGNIFICANT THREAT TO TROPICAL CORAL REEFS?

Ridgwell, Andy[1], Elena Couce[1,2], and Erica Hendy[2,3]

Ocean acidification is widely considered a serious concern for tropical coral reefs. Although experimental manipulations show calcification rates in coral generally decline at lower saturation, many physical and biological factors are involved in driving rates of both carbonate accretion and erosion of reefs. With so many unknowns in ecosystem response, identifying the current geographical limits of coral reefs simply in terms of saturation (and hence implicitly, coral calcification rate) has been highly influential. From this, a rapidly shrinking zone of future suitable habitat has been projected. However, while surface saturation contracts equatorwards, future warming will tend to drive the zone of suitable coral reef habitat polewards. What will be the net outcome of these spatially divergent stresses on the World's tropical coral reef ecosystems?
We map the synergistic tension between these two 'high CO_2 world' stressors using statistical modeling experiments. We project a marked temperature-driven decline in the future for many of the most significant and bio-diverse coral regions, particularly the central Indo-Pacific. However, we also project a temperature-driven poleward range expansion through to 2070 despite on-going ocean acidification. Furthermore, the combined impact of warming and acidification leads to little, if any, degradation in future habitat suitability across much of the Atlantic and areas currently considered 'marginal' for tropical corals, such as the Eastern Equatorial Pacific. While ocean acidification does influence future habitat suitability, it is rather less influential than warming and has its deleterious effects centered at latitudes between 5-20°.

[1] School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, UK (andy@seao2.org)
[2] School of Earth Sciences, Queens Road, University of Bristol, Bristol BS8 1RJ, UK
[3] School of Biological Sciences, Woodland Road, University of Bristol, Bristol BS8 1UG, UK.

TRANSCRIPTOMIC RESPONSES TO OCEAN ACIDIFICATION AND THEIR MODULATION BY LIGHT IN THE COCCOLITHOPHORE EMILIANIA HUXLEYI

Rokitta, Sebastian[1], Uwe John[2], and Björn Rost[1]

To investigate effects of ocean acidification (OA) and their energy-dependent modulation in *Emiliania huxleyi*, diploid cells (RCC 1216) were acclimated to present and future CO_2 partial pressures (pCO_2; 380 vs. 1000 µatm) under low and high light (50 vs. 300 µmol photons m^{-2} s^{-1}). Microarray-based transcriptome profiling was used to screen for cellular processes that underlie the physiological responses observed earlier (Rokitta & Rost 2012). OA was shown to influence fluxes of organic metabolites within and across compartments, and their partitioning between oxidative (e.g. glycolysis) and reductive pathways (e.g. pentose phosphate pathway), which is the likely cause for increased POC production. Furthermore, altered signal-transduction (e.g. phosphatidylinositolphosphate- and sphingosine-based signals) and membrane-potentials (e.g. by altered active ion transport) seem to be a major cause of impaired calcification under OA. While OA influenced signal-transduction and ion homeostasis independent of the light level, the effects of OA on the carbon metabolism were prominently modulated by energy availability. This interdependence of carbon metabolism and light physiology likely derives from their reliance on the redox equilibria of NAD^+ and $NADP^+$, which are cellular sensors for energy state and stress level. Due to the fundamental role of the affected processes, responses to OA are likely to occur similarly in other marine protists.

[1]Marine Biogeosciences, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany (Sebastian.Rokitta@awi.de)
[2]Chemical Ecology, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

LONG-TERM EFFECTS OF CO_2 AND TEMPERATURE ON THE PENNATE DIATOM *CYLINDROTHECA FUSIFORMIS*

Roleda, Michael Y.[1], Yuanyuan Feng[1], Feixue Fu[2], Avery Tatters[2], Catriona L. Hurd[1], Philip W. Boyd[3], and David A. Hutchins[2]

Marine diatoms play major roles in the marine carbon cycle, contributing ~40% of the marine and ~20% of the total global primary production. Moreover, precipitation of their siliceous frustules dominates the reverse weathering of silica into the deep ocean. Diatoms in general possess efficient carbon concentrating mechanisms (CCMs) to compensate for the low CO_2 concentration in the aquatic environment. For this reason, it is of interest to study whether the increase in dissolve inorganic carbon associated with ocean acidification (OA) will have a positive effect or the consequent decrease in pH and increase in H^+ ions have negative effects on their physiology. Parallel cultures of the same *Cylindrotheca fusiformis* isolates from New Zealand coastal waters were grown semi-continuously in laboratories in New Zealand and the USA for >150 generations under a matrix of three pCO_2 levels (180ppm, 400ppm, and 700ppm), and two temperature conditions (14°C and 19°C). After 12 months, both sets of cultures were analyzed for growth rates, elemental composition [particulate organic carbon (POC), particulate organic nitrogen (PON), and biogenic silica (BSi)], dissolved organic carbon (DOC) content, cell size, sinking rate, primary productivity and gene expression under the different pCO_2 and temperature conditions. Our results suggest that both temperature and CO_2 had significant effects on growth, photosynthesis and DOC production of *C. fusiformis*. Our results provide vital information in understanding the adaptive capacity of *C. fusiformis* under changing marine environment under ocean acidification and rising sea surface temperature.

[1] Department of Botany, University of Otago, 464 Great King Street, Dunedin, 9016 New Zealand (michael.roleda@otago.ac.nz)
[2] Department of Biological Sciences, University of Southern California, Los Angeles, California 90089, USA
[3] National Institute of Water and Atmosphere, Centre of Chemical and Physical Oceanography, Department of Chemistry, University of Otago, Dunedin, 9016 New Zealand

ARE OCEANIC SCALLOP AND ABALONE MOLLUSCS LESS RESILIENT TO OCEAN ACIDIFICATION?

Ross, Pauline[1], Laura Parker[1], Elliot Scanes[1], and Wayne O'Connor[2]

It is expected that the anthropogenic increase of CO_2 and the subsequent ocean acidification will greatly affect most marine organisms, but those most vulnerable will be calcifying organisms, such as molluscs, which secrete calcium carbonate shells. In one of the only studies worldwide to investigate resilience and acclimatisation through chronic transgenerational experiments, Parker et al. (2012) found that exposure of adults of the Sydney Rock oysters, *Saccostrea glomerata*, to elevated CO_2 influenced positively the resilience of the larvae, facilitating acclamatory processes. This may be anticipated for Sydney rock oysters and other estuarine species of molluscs which live in intertidal habitats characterised by natural fluctuations in environmental parameters such as pH and salinity. It is less likely that oceanic subtidal molluscs, which live in environments where pH and salinity are stable, will share the same resilience and capacity for acclimation to ocean acidification. The aim of this study was to determine using transgenerational experiments whether adult commercial species of oceanic molluscs namely the Doughboy scallop (*Chlamys asperrima)* and the abalone (*Haliotis rubra)* and their larvae were able to acclimatise and adapt to chronic exposure of CO_2 acidified water during reproductive conditioning. We report here on the adult physiology and mortality, growth, settlement, and the nutritional condition of late stage larvae including the rate of protein synthesis using DNA: RNA ratio and analysis of lipid content used to measure energetic reserves. Disturbance to metamorphosis and settlement of larvae from ocean acidification has flow-on effects to commercial and recreationally fished stocks of scallops.

[1]School of Science and Health, University of Western Sydney, Hawkesbury K12 New South Wales, Locked Bag 1797, Penrith South DC, 2753, Australia. pm.ross@uws.edu.au
[2]Industry and Investment New South Wales, Port Stephens Fisheries Centre, Taylors Beach, New South Wales 2316, Australia.

OCEAN ACIDIFICATION-INDUCED FOOD QUALITY DETERIORATION CONSTRAINS TROPHIC TRANSFER

Rossoll, Dennis[1], J. Rafael Bermúdez[1], Helena Hauss[1], Kai G. Schulz[1], Ulf Riebesell[1], Ulrich Sommer[1], and Monika Winder[2]

Increasing CO_2 emissions alter the ocean's carbonate chemistry and pH. While this alteration has been shown to affect the performance of marine phytoplankton, its effects on phytoplankton macromolecular composition and related impacts on trophic webs are largely unknown. Fatty Acids (FA), and polyunsaturated fatty acids (PUFAs) in particular, are a critical factor that regulates energy transfer efficiency between trophic levels.

The copepod *Acartia tonsa* was grown at ambient (380 ppm) and elevated (740 ppm) CO_2 and fed with the diatom *Thalassiosira pseudonana* cultured under the same conditions in four laboratory treatment combinations. FA content, development and egg production rate per female were measured.

The PUFAs in *T. pseudonana* were significantly reduced when cultured at high CO_2 (4,3±1,1 fg-cell^{-1}) relative to those at low CO_2 (13,0±3,0 fg-cell^{-1}). The PUFA composition of *A. tonsa* mirrored that of the diatom, displaying significantly lower amounts in the cultures with high CO_2 (0,8±0,2 ng-ind.$^{-1}$) when compared with the low CO_2 (8,9±5,6 ng-ind.$^{-1}$).

Copepods raised at high CO_2 showed a delay in stage development of 1 to 2 days. Egg production decreased from 34 eggs female^{-1} day^{-1} at low CO_2 to 5 eggs female^{-1} day^{-1} at high CO_2. As adult *A. tonsa* females invest the majority of their energy and lipids into reproduction, the decrease of PUFAs due to nutrient-poor food is most likely the reason for the decline in egg production.

The possible effect of CO_2 in the diatom-copepod relationship observed in our study, if representative for natural conditions, may have far-reaching consequences in food webs since FAs originating in phytoplankton are sequentially incorporated into zooplankton and fish larvae.

[1] Helmholtz Centre for Ocean Research Kiel (GEOMAR), Kiel, Germany. (jrbermudez@geomar.de)
[2] Department of Systems Ecology, Stockholm University, Stockholm, Sweden.

USING EXISTING LAWS TO CURB OCEAN ACIDIFICATION
Sakashita, Miyoko

Ocean acidification is one of the greatest overarching concerns in the marine environment and it threatens to alter nearly every marine ecosystem. The emerging science on ocean acidification should inform management decisions and policy considerations when it comes to ocean health and resources. We will discuss how scientific understanding about ocean acidification can bring it forefront into environmental policymaking and ecosystem management. Ocean acidification must become an important policy consideration driving local, national and international efforts to reduce carbon dioxide emissions.
We highlight that the U.S. has the ability and the duty to regulate carbon dioxide pollution that is causing ocean acidification under existing U.S. law. Specifically, we will explain how the Clean Water Act and other environmental laws may be brought to bear to force such reductions. The Clean Water Act is the nation's strongest law protecting water quality, and it specifically regulates changes in acidity. We discuss new developments under the Clean Water Act concerning waters impaired by acidification, and how the pollution controls under the law may apply to regulation of carbon dioxide. We also discuss how other environmental laws, including the Endangered Species Act-- which already protects vulnerable calcifying species such as corals--can be employed to protect marine species against ocean acidification.

Center for Biological Diversity, 351 California St. #600, San Francisco, CA, USA (miyoko@biologicaldiversity.org)

IMPACT OF ELEVATED SEAWATER PCO_2 ON THERMAL TOLERANCE AND RESPONSE TO THERMAL STRESS IN SPIDER CRAB LARVAE
Schiffer, Melanie[1], Lars Harms[1], Hans-Otto Pörtner[1], Felix Christopher Mark[1], Jonathon Stillman[2], and Daniela Storch[1]

CO_2-induced acidification of the world's oceans alone has the potential to threaten species survival, but it is also accompanied by global ocean warming. Thus, it is crucial to study the synergistic impacts of both factors to assess species vulnerability to climate change. Evidence is growing that elevated seawater PCO_2 narrows thermal windows of marine ectotherms, especially in larvae. Therefore, we investigated the effects of high seawater PCO_2 (3000µatm) on the thermal tolerance of different larval stages of the spider crab *Hyas araneus*. Larvae were reared at two different CO_2 concentrations (390µatm and 3000µatm). Larval thermal windows were determined by measuring heart rate and oxygen consumption during continuous warming in all larval stages (zoea I, zoea II and megalopa). Furthermore, gene expression of heat shock proteins as part of the general stress response was determined to investigate the physiological response to acute temperature stress under elevated seawater PCO_2.

We found a stage-dependent shift in the larval temperature tolerance window at both PCO_2 levels indicated by a decrease in heart rate and oxygen consumption. Under control conditions, larval upper critical temperature (Tc) limit decreased from 25°C in zoea I and zoea II larvae to 22°C in megalopa larvae. In larvae reared at elevated seawater PCO_2, a shift of the upper Tc from 25°C to 22°C could be detected in the zoea II stage. While zoea I larvae reached the upper Tc at 25°C, the zoeaII and megalopa larvae experienced their critical temperature at 22°C.
In line with earlier studies, our data reveal the impact of elevated seawater PCO_2 on larval thermal tolerance and highlight the need to consider the impact of ocean acidification and warming on different life stages separately.

[1] Department of Integrative Ecophysiology, Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany (melanie.schiffer@awi.de)
[2] Stillman Laboratory, Romberg Tiburon Center 3150 Paradise Drive, B36, Room 104 Tiburon, CA 94920.

CHANGES IN ARCTIC PHYTOPLANKTON COMMUNITY COMPOSITION IN RESPONSE TO INCREASING ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS

Schulz, Kai G.[1], Richard G. J. Bellerby[2,3,4], Corina Brussaard[5], Signe Koch-Klavsen[1], Michael Meyerhöfer[1], Gisle Nondal[2,3], Anna Silyakova[2,3], Anngret Stuhr[1], and Ulf Riebesell[1]

Increasing levels of atmospheric carbon dioxide (CO_2) acidify the ocean, with potential impacts on marine organisms and ecosystems. A natural plankton community was subjected to increasing seawater CO_2 levels during the EPOCA Arctic campaign in 2010 at Svalbard, Norway. In seven out of nine mesocosms, containing about $50 m^3$ of seawater each, the seawater carbonate system was manipulated by additions of CO_2, resulting in an overall gradient of CO_2 partial pressures from ~180 up to ~1420 µatm. A phytoplankton bloom developed in all mesocosms, mainly fueled by initially available ammonium and phosphate. While phytoplankton community composition during this first phase of the experiment was very similar in all mesocosms, it started to diverge when inorganic nutrients were added after the collapse of the first bloom. Then picophytoplankton was growing to higher abundances and drawing down inorganic nutrients faster at higher CO_2, seemingly profiting from increased levels. After the collapse of this second bloom, probably by viral infection, nanophytoplankton was increasing in numbers with higher abundances at lower CO_2 as concentrations of remaining inorganic nutrients were still higher at those levels. Here we describe this community shift by chlorophyll *a*, HPLC and flow-cytometry data, as well as microscopic counts. The statistically significant changes in abundance of several phytoplankton groups such as prasinophytes, haptophytes, diatoms and autotrophic dinoflagellates in response to increasing seawater CO_2 concentrations, namely the shift from nano- to picophytoplankton may impact the transfer of organic matter to higher trophic levels, potentially changing future productivity of this marine ecosystem.

[1] Helmholtz-Centre for Ocean Research (GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany (kschulz@geomar.de)
[2] Bjerknes Center for Climate Research, Allégaten 55, 5007 Bergen, Norway
[3] Uni Bjerknes Centre, Allégaten 55, N-5007 Bergen, Norway
[4] Norwegian Institute for Water Research,Thormøhlensgate 53D, N-5006 Bergen
[5] Royal Netherlands Institute for Sea Research (NIOZ), 1797 SZ 't Horntje (Texel), The Netherlands

ECONOMIC CONSEQUENCES OF OCEAN ACIDIFICATION – ESTIMATES FOR NORWAY

Seifert, Isabel[1], Silje Holen[1], Claire Armstrong[2], and Ståle Navrud[3]

Ocean acidification is expected to change the chemical and biological conditions in the oceans. This will also have an impact on ecosystem goods and services, provided by the oceans and exploited by humans. The aim of this paper is to assess and quantify the economic impacts of ocean acidification in Norway on a time scale of 100 years. An assemblage of data on biological and chemical effects is used to design impact scenarios, but points also out the current knowledge gaps. For the provisioning service of “fisheries and aquaculture” a market-based approach and for the regulating service of “carbon storage” a damage-cost approach are used to estimate the economic consequences. Depending on the used data and the economic settings as e.g. discount rate we estimated for fisheries and aquaculture negative as well as positive effects in the range of several Million NOK (2010). For carbon storage by the Norwegian sea the estimated negative impacts are one order of magnitude higher than for fisheries and aquaculture. Beside these results, the study highlights again the urgent need for further interdisciplinary research in the field of ocean acidification.

[1] Norwegian Institute for Water Research, 0489 Oslo, Norway (isabel.seifert@niva.no)
[2] University of Tromsø, Tromsø, Norway
[3] Agricultural University of Norway, Ås, Norway.

OCEAN PRODUCTIVITY AND CARBONATE SATURATION STATE ENHANCED BY THE CALVING OF THE MERTZ GLACIER TONGUE

Shadwick, Elizabeth[1], Bronte Tilbrook[1,2], and Steve Rintoul[1,2]

Coastal polynyas are areas of diminished sea-ice cover in the midst of heavy pack ice, hosting high rates of dense water formation and biological production. The Mertz polynya is formed in the Adélie and George V Land region by persistent katabatic winds and the ice barrier created by the northward extension of the Mertz Glacier Tongue (MGT). The resulting exposure of the surface waters to sunlight promotes primary production, a fraction of which is exported by the sinking of dense water, supporting a thriving deep-sea coral and sponge community. In early 2010 the repositioning of a large iceberg caused the calving of the MGT and the release of multi-year pack ice into the region. Here we show that this calving event caused significant freshening of the surface waters, a more than twofold enhancement of biological production, and corresponding increase in the calcium carbonate saturation state. This is in contrast to recent observations of decreased saturation state associated with sea-ice melt in the Arctic Ocean. The large inorganic carbon drawdown was sufficient to increase the aragonite saturation state by ten times the expected decrease due to dilution. Polar ice shelves are responding to elevated temperatures with increased ice melt, motion and calving. Our results indicate that the physical and biogeochemical impacts of these calving events may be substantial.

[1]Antarctic Climate & Ecosystems CRC, Hobart, Tasmania, Australia (Elizabeth.shadwick@utas.edu.au)
[2] CSIRO Marine and Atmospheric Research, Hobart, Tasmania, Australia

ANTHROPOGENIC CHANGES TO SEAWATER BUFFER CAPACITY INDUCE EXTREME FUTURE CO_2 CONDITIONS ON A PRISTINE CORAL REEF

Shaw, Emily[1], Ben McNeil[1], Bronte Tilbrook[2], and Richard Matear[2]

Measurements from coral reefs show that these environments are exposed to large natural variability in the partial pressure of CO_2 (pCO_2). This natural variability will likely influence the resilience of species and ecosystems to future ocean acidification. However natural variability is presently not included in future carbonate chemistry projections for coral reefs. Here we measured the natural carbonate chemistry variability of a coral reef in the Great Barrier Reef and incorporated this variability into future projections to the end of the century under business as usual CO_2 emissions. We show that higher future Revelle factors, from an increase in anthropogenic CO_2, lead to a strong non-linear amplification of future CO_2 conditions on the reef. Presently, daily natural respiration of organic material was found to increase reef seawater pCO_2 levels by up to 1000 μatm on diurnal timescales, however by 2100 the same biological process will lead to a two-fold amplification of daily pCO_2, with levels reaching up to 3200uatm as a result of the increasing Revelle factor. These extreme future ocean acidification conditions estimated here are likely to lead to physiological effects in fish and other marine species, where the response of these organisms will depend on both the magnitude of the pCO_2 and the exposure time.

[1] Climate Change Research Centre, The University of New South Wales, Sydney NSW 2052, Australia (e.shaw@student.unsw.edu.au)
[2] CSIRO Wealth from Oceans National Research Flagship, PO Box 1538, Hobart, Tas 7001, Australia

A FINE-SCALE ANALYSIS OF BIOEROSION RATES IN RESPONSE TO NATURAL ENVIRONMENTAL VARIABILITY

Silbiger, Nyssa, Oscar Guadayol, Florence Thomas, and Megan Donahue

Management efforts to sustain coral reef ecosystems often focus on coral health and coral growth rate, but reef resilience also depends on bioerosion rates and their response to local and global human impacts. Corals and other calcifying organisms build reefs through the accretion of calcium carbonate ($CaCO_3$) skeletons and bioeroders break them down by grazing on or boring into the reef structure. A persistent challenge for coral reef scientists is to distinguish the effects of climate change from other forms of environmental variation. In this context, we tested how bioerosion rates respond to natural environmental variability within a lagoon reef in Kāne`ohe Bay, Hawai`i. Using micro computer-aided tomography, we calculate highly accurate bioerosion rates from micrometer-scale 3-dimensional images of $CaCO_3$ blocks deployed on the reef. We then correlated these bioerosion rates with a suite of high resolution environmental sensors that measure microhabitat variation in pH, salinity, temperature, oxygen, water flow, and other parameters at the small scale experienced by bioeroder communities. We specifically focus on the relationship between small-scale variation in pH and bioerosion rates, which may be an important indicator of reef response to ocean acidification and thus the ability of coral reef ecosystems to maintain their delicate accretion-erosion balance.

Hawaii Institute of Marine Biology, PO Box 1346, Kaneohe, HI 96744 (Silbiger@hawaii.edu)

DOES OCEAN ACIDIFICATION AMPLIFY GLOBAL WARMING BY REDUCING MARINE BIOGENIC SULFUR PRODUCTION?

Six, Katharina D.[1], Silvia Kloster[1], Tatiana Ilyina[1], Ernst Maier-Reimer[1], Kai Zhang[2], and Stephen D. Archer[3]

The continuous oceanic uptake of anthropogenic CO_2 changes the chemical composition of the marine realm resulting in a lowering of pH (ocean acidification). Recent mesocosm studies indicate that the concentration of dimethylsulfide (DMS), a biogenic sulfur compound, might be sensitive to changes in seawater pH: The DMS concentration was significantly reduced in a high CO_2 and low pH ocean. As marine DMS emissions are the largest natural source for atmospheric sulfur, changes in the source strength could alter the Earth's radiation budget. For this study we determine a relationship between DMS and pH using data from mesocosm studies and investigate the impact of ocean acidification on production and emission of marine DMS with the Earth System Model of the Max Planck Institute for Meteorology. At the end of the 21th century we find a decrease of global oceanic DMS emission by 17 \% compared to preindustrial time due to the combined effects of ocean acidification and CO_2 induced climate warming. Climate warming alone reduces the global oceanic DMS emission only by 7 %. We calculate a warming potential of +0.38 W/m^2 at the end of year 2100 due to the impact of ocean acidification on the DMS emission. This can be transferred to an equilibrium temperature response of 0.21 to 0.45 °C which adds up to the climate warming by greenhouse gases.

[1] Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany (katharina.six@zmaw.de)
[2] Pacific Northwest National Laboratory, PO Box 999, MSIN K9-24, Richland, WA 99352, USA
[3] now: Bigelow Laboratory for Ocean Sciences, 180 McKown Point Rd.,West Boothbay Harbor, ME, 045750475, USA

INTERACTIVE EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON ASPECTS OF THE DEVELOPMENTAL ECOPHYSIOLOGY OF THE EUROPEAN LOBSTER, *HOMARUS GAMMARUS*

Small, Daniel[1, 2, 3], Piero Calosi[1], John I. Spicer[1], Dominic Boothroyd[2], and Steve Widdicombe[3]

While much is known of the effect of individual environmental factors on animal function, little is known of how such factors interact. Consequently we investigated the effects of ocean acidification (OA, pH8.1, pH7.7) and ocean warming (17°C, 21°C) on aspects of the developmental ecophysiology (oxygen consumption, growth, and survival) of larval stages 1 to 4 (S1-S4) and juveniles (7 months post larvae) of the European lobster, *Homarus gammarus*.
OA negatively affected larval survival to S2 at low temperature, while we have some evidence that in juvenile *H. gammarus*, OA causes a decrease in survival due to failed moult attempts compared with control pH regardless of temperature. Elevated temperature caused an increase in juvenile growth compared to control temperature.
The response of larval oxygen consumption was complicated. Oxygen consumption of S1 larvae decreased at high temperature, with a decreased survival to S2. A further decrease in oxygen consumption occurred at high temperature at S4, with a decrease in size and body mass. Conversely, oxygen consumption increased in S2 and S3 at high temperature, with greater survival to S3 and S4. S2 and S3 were more tolerant to elevated temperature than S1 and S4.
In conclusion while temperature was the major driver of lobster larval and juvenile ecophysiology, OA impacted larval survival/juvenile moulting, and no significant interaction between temperature and OA was detected. Thus we predict that future warming could have a greater impact on the larval biomass

and recruitment of this economically important species, whilst OA may have important, marginal consequences.

[1] Marine Biology and Ecology Research Centre, Plymouth University, Drakes Circus, Plymouth, PL4 8AA, UK (daniel.small@plymouth.ac.uk)
[2] National Lobster Hatchery, South Quay, Padstow, PL28 8BL, UK
[3] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, PL1 3DH, UK

PHYSIOLOGICAL PERFORMANCE AND CALCIFICATION OF THREE COCCOLITHOPHORES UNDER OCEAN ACIDIFICATION SCENARIO

Stojkovic, Slobodanka[1,2], Richard Matear[1], and John Beardall[2]

Increased CO_2 levels in the atmosphere are having an impact on carbonate chemistry of the ocean, changing its speciation and reducing pH, with expected values to drop to 7.7 by 2100. This will impact various marine organisms, but in particular ones that use carbonate ions for calcification (i.e. corals and calcifying phytoplankton, such as Coccolithophores). Coccolithophores are bloom forming phytoplankton, important for carbon pump, due to their ability to fix carbon through both photosynthesis and calcification. Their performance under ocean acidification scenarios is still under debate. We focused our efforts on three Coccolithophores isolated from Australian waters – two strains of *Emiliania huxleyi* and *Gephyrocapsa oceanica*. Cells were grown as batch cultures, under various CO_2 levels (280ppm, 380 ppm, 750ppm and 1000ppm), whereby media was bubbled with particular CO_2 level prior to cells inoculation. Cells were kept at low number to avoid changes in carbonate chemistry for at least 10 generations at each CO_2 levels, and subsequently transferred to a higher CO_2 level. We measured calcification and photosynthetic rates with ^{14}C microdiffusion technique, as well as cell size, pigment and protein concentrations and photosynthetic performance using PAM fluorometry. Additional information on calcite and macromolecular composition was obtained using FTIR microscopy. Photosynthetic performance showed that efficiency of photosynthesis declines with increased CO_2 levels. Response of macromolecular composition as well as calcite was depended on the strain investigated, but changed under various CO_2 levels. Data indicate there is no uniform response of Coccolithophores to ocean acidification but strong species-specific response.

[1]CSIRO, CMAR, Hobart, Tas., Australia
[2]Monash University, School of Biological Sciences, Vic 3800, Australia
(slobodanka.stojkovic@monash.edu)

AUSTRAL VS. ANTARCTIC NOTOTHENIOIDS: MITOCHONDRIAL RESPONSES TO OCEAN ACIDIFICATION

Strobel, Anneli, Hans-Otto Pörtner, and Felix Mark

Antarctic fish species possess very low metabolic rates and poor metabolic plasticity, thus making them extremely vulnerable to changing environmental conditions. Mitochondria are a key element in shaping whole organism energy turnover and functional capacities. In our study, we compared two nototheniid fish, the Austral black cod (*Notothenia angustata*, New Zealand) and the Antarctic marbled rockcod (*Notothenia rossii*, Antarctic Peninsula) for their abilities of metabolic compensation for rising temperature and PCO_2 at the intracellular level. We acclimated *N. angustata* to control conditions (PCO_2 of 0.04 kPa) and to an ambient PCO_2 of 0.2 kPa for 11 days, and kept *N. rossii* at a PCO_2 of 0.04 kPa. We assessed permeabilized heart fibre oxygen consumption at various respiratory states (e.g. state III complex I/ II, state IV (leak), uncoupled/ ETS capacity, complex IV) in acutely hypercapnic (PCO_2 of 2 kPa, corresponds to intracellular PCO_2 under 0.2 kPa ambient hypercapnia) *vs.* normocapnic (PCO_2 of 0.04 kPa) respiration media. In all respiratory states, acute exposure to the hypercapnic respiration medium resulted in reduced mitochondrial capacities, in the Austral and the Antarctic notothenioids Yet, overall heart fibre respiration was higher in the hypercapnia acclimated *N. angustata* than in their control group. This suggests that chronic acclimation of the fish to moderately elevated PCO_2 levels might enhance mitochondrial aerobic capacities, involving e.g. changes in enzyme capacities or mitochondrial proliferation. Our data indicate that while acute high PCO_2 levels of 2 kPa reduce mitochondrial oxidative capacities in Austral and Antarctic notothenioids, at least the Austral fish seem to be able to compensate for these acutely reduced metabolic capacities by hypercapnia acclimation.

Alfred Wegener Institute for Polar and Marine Research, Integrative Ecophysiology, Am Handelshafen 12, D-27570 Bremerhaven, Germany (anneli.strobel@awi.de)

CHANGES TO AN ARCTIC SEDIMENT NITROGEN CYCLING COMMUNITY IN RESPONSE TO INCREASED CO_2

Tait, Karen, Bonnie Laverock, and Steve Widdicombe

To investigate the impact of ocean acidification on sediment microbial communities, intact sediment cores collected from the harbour of Ny Alesund, Svalbard were exposed to a range of CO_2 concentrations (ambient, 540, 750, 1120 and 3000 ppm) for 14 days. Nucleic acid was extracted from surface sediments, and community composition within each sediment core analysed in detail using 16S rRNA V6 454-GSflx pyrosequencing. The only changes evident were an increase in the numbers of sequences most closely related to the Classes *Nitrospira*, known nitrite oxidising bacteria, and Planctomycetacia, which contain anammox bacteria, within the higher CO_2 treatments. To investigate the impact of increased CO_2 on microbes involved in nitrogen cycling (N) in more detail, RT-qPCR was used to measure the number of mRNA transcripts g^{-1} sediment of key genes involved in N cycling: bacterial and archaeal ammonia oxidation (*amoA*), *nirS* denitrification and anammox specific 16S rRNA. Analysis of *amoA* revealed a linear relationship between the ratio of archaeal and bacterial *amoA* mRNA transcripts and pH, favouring archaeal *amoA* at lower pH. Also evident were strong correlations between numbers of bacterial *amoA* and *nirS*, and archaeal *amoA* and anammox mRNA transcript copies g^{-1} sediment, indicating a possible shift from *nirS* denitrification to anammox activity at elevated CO_2. In conclusion, although the 454 sequence data indicated very little changes to the microbial communities, more detailed analysis of the abundance of N cycling gene transcripts revealed significant changes to the balance of N cycling microbes within the sediment cores in response to elevated CO_2 levels.

Plymouth Marine Laboratory, Prospect Place, Plymouth, PL1 3DH (ktait@pml.ac.uk)

OCEAN ACIDIFICATION AND GROWTH LIMITATION SYNERGISTICALLY MAGNIFY CELLULAR TOXICITY IN MULTIPLE HARMFUL ALGAL BLOOM SPECIES

Tatters, Avery O., Feixue Fu, and David A. Hutchins

Ongoing alterations of seawater carbonate chemistry are influencing the physiology and biochemistry of marine phytoplankton, including toxic algal groups that form ecologically and economically damaging blooms. The frequency and intensity of these harmful blooms is thought to be increasing worldwide. Along with other human influences such as warming, eutrophication, and ballast water transport, it is possible that progressive anthropogenic CO_2 'fertilization' and accompanying ocean acidification may play a significant role in this global proliferation of increasingly virulent blooms. Rising CO_2 will affect harmful algal growth, competition, and underlying cellular processes in combination with other changing environmental variables, yet the potential for interactive effects between them remains largely unexplored.

We describe a series of CO_2 enrichment experiments with the notoriously harmful dinoflagellates *Alexandrium catenella* and *Karlodinium veneficum*, and two species of the globally-distributed toxic diatom genus *Pseudo-nitzschia.* Our results demonstrate that ocean acidification conditions (pCO_2 ~750 ppm) dramatically enhance cellular toxin quotas and production in all of these species, especially when their growth rates are simultaneously limited by nutrient availability (P or Si) or temperature. Overall, our strikingly parallel results with each of these taxonomically distant toxic bloom species point to a general physiological principle by which high CO_2 and environmentally relevant growth-limiting conditions can interact to strongly stimulate the synthesis of phycotoxins such as domoic acid, saxitoxins, and karlotoxins. These findings serve as a warning that the future ecosystem and human health impacts of toxic harmful algal blooms in general could be greatly exacerbated by ocean acidification.

Marine Environmental Biology, University of Southern California, 3616 Trousdale Parkway, Los Angeles, CA 90089 USA, tatters@usc.edu

PHYSIOLOGICAL COMPENSATION FOR ENVIRONMENTAL ACIDIFICATION IS LIMITED IN THE DEEP-SEA URCHIN *STRONGYLOCENTROTUS FRAGILIS*

Taylor, Josi R., Chris Lovera, Patrick Whaling, Eric Pane, Kurt Buck, and James P. Barry

Anthropogenic CO_2 is now reaching depths over 1000m in the Eastern Pacific, overlapping with the Oxygen Minimum Zone (OMZ). Deep-sea animals living in this energy-limited environment have evolved in relatively stable biochemical conditions and are subject to minimal variation in water chemistry compared to shallow marine ecosystems. The deep sea urchin *Strongylocentrotus fragilis* lives at depths of approximately 200-1200m, at the brink of the saturation horizon for aragonite and calcite in Monterey Bay, CA, USA. We have investigated the physiology (acid-base balance, metabolism, growth, and reproductive indices) and behavior (feeding and locomotion) of *S. fragilis* on exposure to four levels of pH (7.9, 7.6, 7.2, and 6.6) and two levels of O_2 (surface O_2 of 220±10uM and ambient OMZ ~20±5uM O_2) at 5°C, using a gas-controlled aquarium system, over a period up to four months. Results show *S. fragilis* has no significant acid-base compensatory mechanism in place at the levels of acidification tested. Feeding frequency and quantity were significantly reduced within three days of exposure to pH 6.6, for the duration of the experiment; feeding quantity was significantly reduced after two weeks' exposure to pH 7.2, but recovered after three months' exposure. Expectedly, high O_2 levels led to elevated feeding frequency and quantity. Feeding, high pH and high O_2 were all significantly correlated with high reproductive indices. Our data indicate that *S. fragilis* is highly vulnerable to adverse effects of ocean acidification; work is in progress to gauge the ecological consequences of these findings.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039, USA. josi@mbari.org

SEAWATER CARBONATE CHEMISTRY OF THE GREAT BARRIER REEF AND CORAL SEA

Tilbrook, Bronte[1,2], Yukihiro Nojiri[3], Chris Sabine[4], Andrew Lenton[1], Ken Anthony[5], Craig Neill[1], Erik van Ooijen[1], Richard Matear[1], and Craig Steinberg[5]

Changes in seawater carbonate chemistry due to the uptake of increasing levels of atmospheric CO_2 are considered a major threat to the health and sustainability of coral reef ecosystems. We report on the first large-scale observations from ships and moorings of the seawater carbonate chemistry along the length of the Great Barrier Reef (GBR) and in the GBR source waters of the Coral Sea.

As waters from the Coral Sea flow onto the GBR shelf, calcification/dissolution and production/respiration in the many reefs and coastal regions of the GBR decrease the carbonate ion concentration and the aragonite saturation state of the waters. The lowest values are observed inshore and to the south, partly due to the flushing of the shelf waters and riverine inputs or remineralisation of organic matter close to shore. The observations are consistent with net calcification/production through the GBR shelf region and currently show no evidence of large-scale net dissolution of carbonates in sediments or reefs of the GBR.

The aragonite saturation state of the surface waters of the Coral Sea is estimated to have been about 0.7 to 0.8 units greater in preindustrial times than today's value of about 3.6. The changes have resulted in the waters of the GBR and Coral Sea shifting to conditions considered less favourable for supporting calcification in reef ecosystems. Ocean models indicate the offshore values will be less than about 3.0 when atmospheric CO_2 levels rise to 450ppm.

[1] CSIRO Wealth from Oceans National Research Flagship, Hobart, Australia 7001 (bronte.tilbrook@csiro.au)

[2] Antarctic Climate and Ecosystems CRC, Hobart, Australia 7001

[3] Center for Global Environmental Research, National Institute for Environmental Studies, CGER-NIES, Tsukuba, Ibaraki 305-8506, Japan

[4] NOAA Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE Seattle, WA 98115

[5] Australian Institute of Marine Science, Townsville, Australia 4810

PROTEOMIC RESPONSES OF MOLLUSKS TO ELEVATED P_{CO2}: SIGNS OF OXIDATIVE STRESS

Tomanek, Lars[1], Marcus Zuzow[1], Anna V. Ivanina[2], Elia Beniash[3], and Inna M. Sokolova[2]

Little is known about the cellular level effects on mantle tissues of mollusks exposed to ocean acidification. We exposed eastern oysters, *Crassostrea virginica*, to elevated P_{CO2} (357Pa P_{CO2} or pH 7.5) or control conditions (39 Pa P_{CO2} or pH 8.3) for two weeks and characterized proteomic changes in mantle tissue using two-dimensional gel electrophoresis and tandem mass spectrometry.

Exposure to high P_{CO2} resulted in a significant shift in the proteome of mantle tissue, with 12% of protein isoforms (54 out of 456) showing different abundances under high P_{CO2} compared with control conditions. Among the proteins identified, two main functional categories were upregulated in response to hypercapnia: proteins associated with the cytoskeleton (e.g. several actin isoforms) and several proteins involved in responding to oxidative stress (e.g., superoxide dismutase, several peroxiredoxins and a thioredoxin-related nucleoredoxin). These results indicate that hypercapnia induces oxidative stress in oyster mantle tissue and suggests that the cytoskeleton is a major target of oxidative stress. Oxidative stress may be caused by higher P_{CO2} levels either indirectly through lower pH levels activating the Fenton reaction or through the reaction of CO_2 with other reactive oxygen species to form more free radicals. We are currently expanding our studies to *Mytilus* congeners that differ in tolerance towards temperature and osmotic stress, two stressors that also cause oxidative stress at the

cellular level. Integrating these diverse stressors and their cellular effects into a common framework will help us improve our predictions of how ocean acidification will affect the physiologies of marine organisms.

[1] Environmental Proteomics Laboratory, California Polytechnic State University, San Luis Obispo, CA 93407, USA (ltomanek@calpoly.edu)
[2] Department of Biology, University of North Carolina at Charlotte, Charlotte, NC 28223, USA.
[3] Department of Oral Biology, University of Pittsburgh, Pittsburgh, PA 15261, USA.

POLAR DIATOMS IN A CHANGING CLIMATE

Torstensson, Anders, Mikael Hedblom, and Angela Wulff

Cold-water oceans have a high capacity of absorbing atmospheric CO_2 and slow metabolic processes of polar organisms may restrict their ability to compensate for increased CO_2 levels. Consequently, high-latitude oceans are susceptible to changes in atmospheric pCO_2, and are projected to be the first oceans to be impacted by ocean acidification. Marine diatoms play an important role in carbon biogeochemistry and in polar food webs. The responses of diatoms to elevated pCO_2 indicate many taxa-specific differences. These differences are probably linked to variations in their ability to regulate CO_2 levels at the site of carbon fixation, processes mainly controlled by carbon concentrating mechanisms (CCMs). We have performed ecophysiological experiments on Arctic and Antarctic pennate diatoms to investigate how growth rate and carbon fixation may be regulated during a scenario of increased temperature and elevated pCO_2. The efficiency of external carbonic anhydrase activity was measured, an important component of the CCMs, along with photophysiological parameters. Results are currently being analyzed and preliminary data from the experiments will be presented at the symposium. A temperature increase of 4°C elevated growth rates up to 43%, and both negative and no effects of CO_2-enrichment on growth rates were observed. Many research gaps still exist on CCMs and diatom carbon sequestration – two key points in understanding how diatom populations and carbon biogeochemistry will change in a high CO_2 world.

Department of Biological and Environmental Sciences, University of Gothenburg, P.O. Box 461, Gothenburg SE40530, Sweden (anders.torstensson@bioenv.gu.se)

PHYSIOLOGICAL SENSING OF ACID/BASE CONDITIONS VIA SOLUBLE ADENYLYL CYCLASE AND CYCLIC AMP

Tresguerres, Martin, Jinae N. Roa, and Megan E. Barron

Physiological responses to ocean acidification (OA) are highly variable and species-specific. For example, OA has been reported to induce negative, neutral, or even positive effects on biological calcification, as well as on metabolism, reproduction and behavior in diverse organisms. Additionally, other studies have found significant interactions between OA, temperature, and feeding. These observations suggest that some physiological responses to OA are largely determined by acid/base and metabolic statuses, and that at least some organisms have the capacity to sense OA and regulate their physiology accordingly. The enzyme soluble adenylyl cyclase (sAC) has been implicated in sensing metabolic and environmental CO_2, pH and HCO_3^- in diverse species ranging from cyanobacteria to mammals. sAC produces the messenger molecule cAMP, which can modulate multiple aspects of biology via post-translational modifications on target proteins. Using genomic, transcriptomic, proteomic and/or enzymatic methods, we have detected sAC in four species of corals, in oyster mantle, gill and hemocytes, and in multiple fish species and tissues. We are currently investigating the roles of sAC and the cAMP signal transduction pathway in regulating physiological responses to OA, including pH regulation, calcification, and gene expression.

Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92037, USA (mtresguerres@ucsd.edu)

THE SCIENCE INTO POLICY CHALLENGE OF OCEAN ACIDIFICATION

Turley, Carol

Ocean acidification is a recently recognised phenomenon and its study is still in its infancy, but the phenomenon is real and has the potential for widespread and significant effects that will impact humans and society. It requires scientists, policy makers and stakeholders to work together to understand the broad implications of ocean acidification in order to take up the challenges of mitigating ocean acidification and adapting to possible future scenarios. Ocean acidification poses threats to both the marine ecosystem and the human population therefore the communication of possible impacts and timescales requires careful management. It is paramount that responses to policy makers are open and well-informed and based on sound evidence. In the last five years, the outreach to policy makers and other stakeholders, including the public, has been extraordinary. Here I trace the journey of ocean acidification and its arrival as a mainstream climate change, biodiversity and sustainability issue. I will highlight some of the dangers encountered on the journey and describe some of the challenges. There are future challenges both for researchers, policy makers and society which I would like to explore with the audience.

\Plymouth Marine Laboratory, prospect Place, The Hoe, PLYMOUTH, PL1 3DH, UK (ct@pml.ac.uk) , the UK Ocean Acidification Research Programme (UKOARP) and the Mediterranean Sea Acidification under Changing Climate project (MedSeA).

SEASONAL VARIABILITY OF THE CARBONATE SYSTEM ALONG THE ATLANTIC GATEWAY TO THE ARCTIC OCEAN

Tynan, Eithne, Toby Tyrrell, and Eric P. Achterberg

Strong seasonal changes in the carbonate system occur in the Arctic as a result of temperature variation, ice-melt and formation, and biological productivity. However, very little is known about the exact dynamics of these changes, partly due to the lack of winter data for the Arctic. In this study we present a unique carbonate chemistry dataset of year-round observations along an Arctic Ocean transect between mainland Norway and Svalbard. Biological activity was found to dominate the seasonal variation of the carbonate system with DIC drawdown associated to blooms in spring and summer, resulting in an average increase of 0.5 in Ω_{Ar}. In winter, when biological activity was at a minimum, saturation states followed a latitudinal trend, with values further north decreasing with temperature (Ω_{Ar} (south) = 2.0 to Ω_{Ar} (north) = 1.7). With the onset of primary production this trend disappeared (Ω_{Ar} (south) = 2.4 to Ω_{Ar} (north) = 2.5) due to carbon overconsumption at higher latitudes. Seasonal sea-ice covered the northernmost region and sea-ice melt during spring and summer had a small impact on saturation states decreasing Ω_{Ar} by less than 0.1.

Ocean and Earth Sciences, National Oceanography Centre Southampton, University of Southampton, Southampton SO14 3ZH, United Kingdom (e.tynan@soton.ac.uk)

THE ROLE OF OCEAN ACIDIFICATION ON COCCOLITHOPHORE DISTRIBUTIONS IN POLAR AND TEMPERATE SEAS.

Tyrrell, Toby[1], Alex Poulton[2], Anastasia Charalampopoulou[1], Eithne Tynan[1,] and Jeremy Young[3]

While anthropogenic CO_2 is accumulating in all surface waters, it has a more pronounced impact on the carbonate chemistry of high latitude oceans which have naturally high CO_2 concentrations due to temperature effects on CO_2 solubility. Therefore, in polar oceans, the influx of anthropogenic CO_2 adds to an already very high baseline level of CO_2. This in turn depresses Ω, the saturation state with respect to $CaCO_3$, which is lowest in high latitude oceans. There is therefore much concern as to the fate of calcifying organisms in future polar oceans where the onset of $CaCO_3$ undersaturation occurs earliest. This presentation reviews evidence from many recent observational studies of coccolithophores in polar and temperate seas: the Arctic Ocean between Tromsø and Svalbard, northwest European shelf seas, the Baltic Sea, the Barents Sea, the Patagonian Shelf, the Bay of Biscay, and Drake Passage in the Southern Ocean. They are seen to be completely absent from some of the high latitude seas (further south in the Southern Ocean, during winter in the Arctic near to Svalbard, in the Baltic Sea) but conversely to bloom elsewhere (for instance the Barents Sea and the Patagonian Shelf).
A number of different suggestions have been made as to how ocean acidification might impact on coccolithophores. We evaluate these hypotheses by comparing to the observational evidence from the studies listed. In particular we consider whether it is the wintertime conditions that are critical in determining the viability of a location for coccolithophores.

[1] Ocean and Earth Science, National Oceanography Centre Southampton, European Way, Southampton SO14 3ZH, UK (tt@noc.soton.ac.uk)
[2] National Oceanography Centre, Waterfront Campus, Southampton, SO14 3ZH, UK
[3] Earth Sciences, University College London, Gower Street, WC1E 6BT, UK

CLAM EARLY LIFE HISTORY IN A HIGH CO_2 WORLD: OCEAN ACIDIFICATION EFFECTS ON FERTILIZATION, EMBRYOGENESIS AND LARVAL DEVELOPMENT OF *MACOMA BALTHICA*

Van Colen, Carl, Elisabeth Debusschere, Ulrike Braeckman, Dirk Van Gansbeke, and Magda Vincx

We investigated the effects of experimentally manipulated seawater carbonate chemistry on several early life history processes of the Baltic tellin (*Macoma balthica*), a widely distributed bivalve and key species to the functioning of many coastal habitats.
Fertilization and formation of a D-shaped shell during embryogenesis were severely diminished: fertilization was reduced by 11 % at a 0.6 pH unit decrease from present conditions, while hatching success was depressed by 34 and 87 %, respectively at a 0.3 and 0.6 pH unit decrease. Under reduced pH conditions, larvae are still able to precipitate a shell during the post-embryonal phase, though higher larval mortality rates with decreasing pH indicate that fewer larvae that are competent to settle will develop in an acidified ocean. The cumulative impact of acidification on early life history processes is an estimated 38 % and 89 % reduction in the number of competent settlers, respectively at a 0.3 and 0.6 pH unit decrease. Additionally, slower growth rates and a delayed metamorphosis at a smaller size may further diminish the recruit population size due to enhanced predation and longer subjection to stressors during larval development.

In general, effects are most pronounced at low pH conditions which are characterized by an undersaturated state with respect to aragonite. Since recent models predict a comparable decrease in pH in coastal waters already in the near future, the present study indicates that future populations of *Macoma balthica* are likely to shrink down, if these organisms are unable to adapt to ongoing ocean acidification.

Ghent University, Department of Biology, Marine Biology Section, Krijgslaan 281/S8, B-9000 Ghent, Belgium. carl.vancolen@ugent.be

THE EFFECT OF OCEAN ACIDIFICATION AND TEMPERATURE INCREASE ON BENTHIC ECOSYSTEM FUNCTIONING IN CONTRASTING SEDIMENT TYPES

Vanaverbeke, Jan, Ulrike Braeckman, Carl Van Colen, and Magda Vincx

Research so far provided little evidence that benthic ecosystem functioning is affected by ocean acidification. However, most of these investigations did not take into account seasonality, and sediment type. While coarse, permeable sediments make up the bulk of coastal sediments, they are largely neglected in acidification research as most of the research was targeted towards relatively fine sediments. We investigated whether a pH decrease of 0.3, in combination with a temperature increase of 4°C affects sediment community oxygen consumption (SCOC), nutrient exchange, denitrification and nitrification processes and alkalinity generation in coastal permeable and non-permeable sediments. The effect of advective currents through permeable sediments was taken into account by using benthic stirring chambers for our incubations. As benthic ecosystem functioning is largely affected by the seasonality of phytoplankton bloom deposition, we repeated our incubations in February, April and September 2012. In February, vertical oxygen profiles confirm the well-known deeper oxygenation of permeable sediments compared to non-permeable sediments, while a temperature rise decreased oxygen penetration depth. Our most striking result however, was a lower SCOC in all treatments with a decreased pH compared to ambient pH. This suggests that benthic oxygen consuming processes (i.e. nitrification) are hampered at lower pH. Data on nutrient fluxes across the sediment-water interface, from our February and April incubations will be used to further explore the hypothesis that ocean acidification indeed affects benthic ecosystem functioning.

Ghent University, Biology Department, Marine Biology Research Group, Krijgslaan 281/S8, B-9000 Gent, Belgium. jan.vanaverbeke@ugent.be

IMPACT OF OCEAN ACIDIFICATION AND RIVER DISCHARGES ON THE COASTAL DOMAIN: IMPLICATIONS FOR THE METABOLISM OF LARVAL INVERTEBRATES

Vargas C.A.[1], M. De la Hoz[1], V. San Martín[1], J.M. Navarro[2], N.A. Lagos[3], M. Lardies[4], P.H. Manríquez[2], and R. Torres[5]

Coastal ecosystems receive persistent acid inputs as a result of freshwater discharges from river basins into the coast. Since shellfishes and aquaculture activities predominantly occur in nearshore areas, it is expected that species inhabiting river-influenced benthic ecosystems will be exposed persistently to acidic conditions that are suboptimal for shellfish development. In a wider ecological context, little is also known about the potential impacts of OA on the performance of larvae and juveniles of almost all the marine species inhabiting these benthic ecosystems. Within the main objective, the RIVOM Project, we evaluate the main role of river discharges in the export of dissolved inorganic carbon (DIC) from

different sources (δ^{13}C-DIC) on local OA processes off Central Chile. In addition, as part of another project (ANILLOS ACT132) a mesocosm system has been designed and implemented in a coastal research laboratory in southern Chile to evaluate under controlled conditions the effect of such increasing pCO_2 and low-pH on the larval feeding of the economically valuable gastropod *Concholepas concholepas.* Experiments evidenced that pCO_2-driven OA may radically impact which kind of food particle was ingested by *C. concholepas* larvae. Larvae switched diet from diatoms to tiny and highly abundant nanoflagellates and cyanobacteria as pCO_2 increased. Due the critical relationship between this life history trait with metamorphosis success, larval development, performance of post-settlers, and finally recruitment, current findings support to notion that feeding should be a key physiological processes that might be influenced by acidification driven by both atmospheric pCO_2 increase and/or persistent effects of acid freshwater discharges.

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[1] Aquatic Ecosystem Functioning Lab (LAFE), Environmental Sciences Center EULA Chile, Universidad de Concepción, Concepción, Chile
[2] Institute of Marine and Limnological Sciences, Coastal Marine Research Laboratory of Calfuco, Universidad Austral de Chile, Valdivia, Chile
[3] Faculty of Sciences, Universidad Santo Tomás, Santiago, Chile
[4] Facultad de Artes Liberales, Universidad Adolfo Ibáñez, Santiago, Chile
[5] Patagonian Ecosystem Research Center (CIEP), Coyhaique, Chile

A MECHANISTIC BASIS TO THE RESPONSE OF CORALS TO OCEAN ACIDIFICATION: SEAWATER ACIDIFICATION REDUCES INTRACELLULAR AND EXTRACELLULAR PH AT THE TISSUE-SKELETON INTERFACE

Venn, Alexander[1,2], Eric Tambutté[1,2], Michael Holcomb[1,*], Julien Laurent[1], Denis Allemand[1,2], and Sylvie Tambutté[1,2]

The physiological basis behind why reef coral calcification can be impaired by ocean acidification is not known, limiting insight into how corals may or may not physiologically acclimate to increasing pCO_2. Several authors have hypothesized that seawater acidification drives down pH and aragonite saturation state in the fluid medium at the coral tissue-skeleton interface (subcalicoblastic medium). In previous research we mapped pH under the calcifying tissue of corals and showed how corals elevate extracellular pH (pHe) in the subcalicoblastic medium and tightly regulate intracellular pH (pHi) in calcifying cells. In the current study we analysed pHe and pHi in the calcifying tissue of *Stylophora pistillata* exposed to acidified seawater (by bubbling with CO_2) for more than one year. Live tissue imaging of pHi and pHe at the tissue-skeleton interface was performed by confocal microscopy of corals mounted in a seawater perfusion system of known carbonate chemistry. Our results show the relationship of declines of pH in the surrounding seawater with declines in pHe in the subcalicobalstic medium and the calcifying cells. We investigate the impact of these declines in pH on calcification by measuring the growth of newly formed skeletal crystals and the lateral extension of whole coral colonies grown on glass slides. Our findings contribute towards a physiological mechanistic understanding of why coral calcification may be susceptible to ocean acidification.

[1] Centre Scientifique de Monaco, Avenue Saint Martin, Monaco
[2] LEA CNRS-CSM « BIOSENSIB », Centre Scientifique de Monaco, Avenue Saint Martin, Monaco
* Present address: University of Western Australia, Crawley, WA 6009, Australia

GIANT CLAMS IN A HIGH-CO_2 WORLD AND INTERACTING EFFECTS OF TEMPERATURE

Watson, Sue-Ann[1], Paul C. Southgate[2], Jonathan A. Moorhead[2], Gabrielle M. Miller[1], and Philip L. Munday[1]

Giant clams form the largest bivalve shells in the world. Protected species and icons of the coral reef, giant clams promote tourism, provide a protein source for Pacific Island and SE Asian communities and are important to the ornamental aquarium industry. The effects of global warming and ocean acidification on giant clams are completely unknown and this knowledge gap limits the capacity to mitigate the effects of climate change on these iconic species. Already subject to anthropogenic pressures, four tridacnids are listed as vulnerable on the IUCN Red List of Threatened Species. To determine the effects of ocean acidification on giant clams, juvenile fluted clams *Tridacna squamosa* were exposed to seawater treated with CO_2 to simulate ocean conditions relevant to IPCC climate predictions including: A) present-day (control pCO_2), B) year 2050 (moderate pCO_2) and C) year 2100 (high pCO_2). CO_2 treatments were cross-factored with seawater temperature. Juvenile giant clam survival decreased with increasing pCO_2 and decreased slightly with increasing seawater temperature, but the combination of increasing pCO_2 and increasing seawater temperature resulted in particularly low survival. Acidification and temperature also affected giant clam growth, shell morphology, activity and respiration. These measures have important ecological relevance and will determine the success of juvenile clams in avoiding predation, selecting a suitable habitat to settle and scope for growth. These results will inform the management of wild populations and hatchery rearing to help enhance the survival of giant clams in a changing climate.

[1] ARC Centre of Excellence for Coral Reef Studies & School of Marine and Tropical Biology, James Cook University, Townsville, QLD, 4811, Australia (sueann.watson@jcu.edu.au)
[2] Centre for Sustainable Tropical Fisheries and Aquaculture, School of Marine & Tropical Biology, James Cook University, Townsville, QLD, 4811, Australia

PHYSIOLOGICAL EFFECTS OF ELEVATED TEMPERATURE AND OCEAN ACIDIFICATION IN TWO COMMERCIALLY IMPORTANT SHELLFISH SPECIES FROM THE IRISH SEA

Whiteley, Nia M.[1], Clara L. Mackenzie[2], Ruth E. Nicholls[2], Richard L. Patton[1], Daniel Lee[2], Ian D. McCarthy[3], and Shelagh K. Malham[2]

As part of a European-funded project investigating the sustainability of shellfish stocks in the Irish Sea (SUSFISH INTERREG 4A Ireland – Wales programme), we are examining the combined effects of elevated temperature and CO_2 on the physiological responses of the blue mussel, *Mytilus edulis*, and the edible crab, *Cancer pagurus*. Both species are being exposed to present and future CO_2 conditions for 6 months at two temperatures (ambient 12°C and an increase of 4°C) and two CO_2 levels (ambient 50 and 110 Pa) as predicted under the IPCC IS92a CO_2 emission scenario. The ability of each species to compensate for the effects of ocean acidification and temperature change are being assessed via the determination of haemolymph acid-base status. Whole-animal changes in rates of oxygen uptake and protein synthesis are also being examined to investigate whether the various treatments will influence two important indicators of animal performance, metabolism and growth. To date, it has been shown in *M. edulis* that haemolymph pH levels are more affected by temperature than by elevated CO_2. Haemolymph bicarbonate buffering capacities vary in all treatments, and are slightly elevated after 3 months but return to control levels after 6 months. Comparisons will be made between the abilities of the two species to cope with ocean acidification and warming. The subsequent effects on metabolism and

protein synthesis will be discussed with a view to predicting the future vulnerabilities of the stocks of both species in the Irish Sea.

[1]School of Biological Sciences and [3]School of Ocean Sciences, College of Natural Sciences, Bangor University, Bangor, Gwynedd, LL57 2UW, UK (n.m.whiteley@bangor.ac.uk)
[2]Centre for Applied Marine Sciences, Bangor University, Bangor, Gwynedd, LL57 2UW, UK

ARE CO_2 EMISSIONS KILLING OUR SUSHI? EFFECTS OF OCEAN ACIDIFICATION ON EGGS AND LARVAE OF YELLOWFIN TUNA

Williamson, Jane[1], Jon Havenhand[2], Simon Nicol[3], Daniel Margulies[4], Don Bromhead[3], Vernon Scholey[5], Liette Vandine[1], Paul Duckett[1], Jeanne Wexler[4], Maria Santiago[4], Simon Hoyle[3], Peter Schlegel[1], and Michael Gillings[1]

Evidence is mounting that non-calcifying organisms can be highly vulnerable to ocean acidification (OA), especially during their early life history stages. If tolerance to OA is variable on an individual level, and if this variation is heritable, ocean acidification may lead to rapid selection for resistant genotypes.
The Pacific tuna fisheries are among the largest, most complex and valuable fisheries resources in the world. In 2010, the total tuna catch in the Pacific was approximately 2.9 million tonnes and comprised 60% of the world's tuna catch, making this a globally significant renewable resource. It is already established that ocean acidification has negative impacts on growth, survival and/or behaviour of many fish species and thus may influence population dynamics and abundance. For tuna, early life history stages are sensitive to environmental change but potential impacts of OA on tuna populations are unknown.
Using yellowfin tuna (*Thunnus albacares*) as a model species, this study assesses whether offspring survival when exposed to different CO_2 levels is associated with their genetic composition or level of genetic variation. Tissue collections of eggs and larvae were taken at set time intervals from fertilisation to 6 days post feeding in 15 tanks comprising 5 (pH) treatments. This research will anticipate which genetic variants are best suited to extreme OA scenarios, along with genetic modifications that may arise in response to OA.

[1]Department of Biological Sciences, Macquarie University, NSW, 2109, Australia (jane.williamson@mq.edu.au)
[2]Department of Biological & Environmental Sciences, Tjärnö Marine Biological Laboratory, Gothenburg University, S-45296 Strömstad, Sweden
[3]Secretariat of the Pacific Community (SPC)
[4]Inter-American Tropical Tuna Commission (IATTC), La Jolla, California, USA
[5]IATTC, Achotines Laboratory, Las Tablas, Republic of Panama

EFFECTS OF OCEAN ACIDIFICATION VERSUS GLOBAL WARMING ON REEF BIOEROSION – LESSONS FROM A CLIONAID SPONGE

Wisshak, Max[1], Christine Schönberg[2], Armin Form[3], and André Freiwald[1]

In the recent discussion how biotic systems may react to raised carbon dioxide partial pressure (pCO_2) and temperatures in the marine realm, substantial research is devoted to calcifying organisms such as stony corals, whereas the antagonistic process – biologically induced dissolution via bioerosion – is largely being neglected. As opposed to skeletal growth, bioerosion by chemical means can be expected to be facilitated under the more acidic environment in a high-CO_2 world. In order to elucidate the combined effects of ocean acidification and global warming on bioerosion, the zooxanthellate sponge *Cliona orientalis*, one of the most abundant and detrimental bioeroders at Australia's Great Barrier Reef, was exposed to lowered as well as elevated levels of both pCO_2 and temperature. Our results show a significant enforcement of the sponges' bioerosion capacity with increasing pCO_2 (decreasing pH), whereas temperature had comparatively little effect. This finding implies that tropical reef ecosystems are facing the combined effect of weakened coral calcification and accelerated bioerosion, resulting in critical pressure on the fragile balance between biogenic carbonate build-up and degradation.

[1] Senckenberg am Meer, Abteilung für Meeresforschung, 26382 Wilhelmshaven, Germany (max.wisshak@senckenberg.de)
[2] Australian Institute of Marine Science, Crawley, WA 6009, Australia
[3] GEOMAR - Helmholtz Centre for Ocean Research, Marine Biogeochemistry, 24105 Kiel, Germany

CO_2 EFFECTS ON NUTRITIONAL QUALITY OF SOUTHERN OCEAN PHYTOPLANKTON AS FOOD FOR ANTARCTIC KRILL LARVAE

Wynn-Edwards Cathryn[1,2,3,4], Rob King[3], Andrew T. Davidson[3,4], Simon W. Wright[3,4], So Kawaguchi[3,4], Peter D. Nichols[1,2,4], and Patti Virtue[1]

Ocean acidification decreases seawater pH but increases the availability of carbon in the form of CO_2 and HCO_3^-. Experiments with ocean mesocosms and lake ecosystems suggest that increased carbon availability changes the species composition and also biochemistry and thus nutritional quality of individual phytoplankton as food for grazers. Deterioration in food quality and / or quantity could prove detrimental to larvae of Antarctic krill, *Euphausia superba*, which is a key species in the Antarctic food web and dependent on both sufficient and adequate food. Here we present the results of high-CO_2 exposure experiments with the diatoms *Pseudonitzschia subcurvata* and *Synedropsis hyperborea* and the effect on Antarctic krill larvae when feeding on these phytoplankton. In addition chemostat experiments examined the nutritional content of four ecologically important Southern Ocean species in response to CO_2: *Phaeocystis antarctica*, *Fragilariopsis cylindrus*, *Pyramimonas gelidicola* and *Gymnodinium sp*. While elevated CO_2 reduced the nutritional quality of *P. subcurvata* and increased larval krill mortality when feeding on it, all other phytoplankton species tested showed no clear trends with increasing pCO_2. Given the large differences in nutritional value of phytoplankton species, we propose that changes in species composition due to increased CO_2 concentration will have more impact on nutritional quality than biochemical changes occurring in individual phytoplankton species. Further research, including species competition experiments under various CO_2 concentrations, will be necessary to answer the question whether ocean acidification will adversely impact nutritional quality of phytoplankton communities as food source for grazers.

[1]Institute of Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart Tas 7001, Australia
[2] CSIRO Wealth from Oceans Flagship, Division of Marine and Atmospheric Research, GPO Box 1538, Hobart Tas 7000, Australia
[3]Australian Antarctic Division, 203 Channel Hwy, Kingston Tas 7050, Australia (cathryn.wynn-edwards@aad.gov.au)
[4] Antarctic Climate and Ecosystems Cooperative Research Centre, Private Bag 80, Hobart Tas 700, Australia

IMPACT OF RAPID SEA-ICE REDUCTION IN THE ARCTIC OCEAN ON THE RATE OF OCEAN ACIDIFICATION

Yamamoto, Akitomo[1], Michio Kawamiya[2], Akio Ishida[3], Yasuhiro Yamanaka[1], and Shingo Watanabe[2]

The reductions in pH and aragonite saturation state in the Arctic Ocean have been caused by the melting of sea ice as well as by increase in the concentration of atmospheric carbon dioxide. Therefore, future projections of pH and aragonite saturation in the Arctic Ocean will be affected by how rapidly the reduction in sea ice occurs. The observed recent Arctic sea-ice loss has been more rapid than projected by many of the climate models that contributed to IPCC AR4. In this study, the impact of sea-ice reduction rate on projected pH and aragonite saturation state in the Arctic surface waters was investigated, using two versions of earth system model which projects summer ice-free condition by 2040 and 2090. The Arctic surface water was projected to be undersaturated with respect to aragonite in the annual mean when atmospheric CO_2 concentration reached 513 (606) ppm in year 2046 (2056) in new (old) version. At an atmospheric CO_2 concentration of 520 ppm, the maximum differences in pH and aragonite saturation state between the two versions were 0.1 and 0.21 respectively. Our results suggest that the future reductions in pH and aragonite saturation state could be significantly faster than previously projected if the sea-ice reduction in the Arctic Ocean keeps its present pace. We will discuss the mechanisms promoting ocean acidification due to rapid sea-ice reduction in the presentation.

[1]Graduate school of Environmental Science, Hokkaido University, Sapporo, Japan (akitomo@ees.hokudai.ac.jp)
[2] Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan
[3] Department of Social Environment, Fuji Tokoha University, Fuji, Japan

COMBINED IMPACTS OF CLIMATE WARMING AND OCEAN CARBONATION ON EELGRASS (*ZOSTERA MARINA* L.)

Zimmerman, Richard C. and Victoria J. Hill

Anthropogenic effects are transforming biogeochemical processes across the planet, especially in coastal environments that support highly productive seagrass ecosystems. As with other impacts of climate change, ocean acidification will elicit both negative and positive responses, ultimately potentiating ecological losers and winners. Despite numerous adaptations to a submerged existence, seagrasses have high light requirements that results from high reliance on dissolved aqueous CO_2 [$CO_{2(aq)}$]for photosynthesis, making them vulnerable to rising temperatures and declining water quality. This work explored the response of eelgrass to rising [$CO_{2(aq)}$] in a warming coastal ocean using a combination of manipulative experiments, physiological/biochemical investigations and mathematical modeling. Rising $CO_{2(aq)}$ increases temperature tolerance of eelgrass by increasing ratios of photosynthesis to respiration, leading to higher growth rates, improved survival of vegetative shoots at high temperature, and even flowering output and seed production. By focusing on key relationships between environmental parameters that have both negative (ocean warming) and positive (ocean carbonation) impacts on the light requirements and dynamics of carbon balance, we gain predictive insight into how climate change may alter the geographic distribution of this critically important species in a variety of coastal environments that may be subjected to different levels temperature stress combined with ocean acidification.

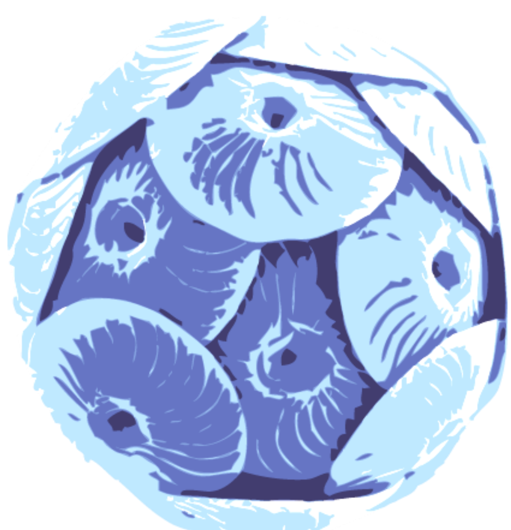
Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, VA 23029, USA.

IMPACT OF OCEAN ACIDIFICATION ON THERMAL TOLERANCE RELATED TO ACID-BASE REGULATION CAPACITY OF *MYTILUS EDULIS* FROM THE WHITE SEA

Zittier, Zora M.C., Christian Bock, and Hans-O. Pörtner

With global climate change ocean warming and acidification occur concomitantly. The survival and distribution of species will depend on their existing ability to exploit their physiological plasticity. pH regulation and the energetically costly processes involved appear crucial to sustain the performance of marine organisms and shaping their sensitivity to ocean acidification. Especially under rising temperatures, small pH disturbances in body fluids might already exert critical impact on physiological processes. We therefore studied the effects of ocean acidification on thermal tolerance and acid-base regulation capacity of a sub-Arctic population of *Mytilus edulis*. Mussels were acclimated for 4 weeks at 10°C and incubated under normocapnia (390µatm) and hypercapnia (1120µatm) for further 2 weeks, before being subjected to an acute warming protocol (10-28°C; 3°C/night). The temperature induced increase in oxygen consumption led to Q_{10}-values of 2.4 (normocapnia) and 2.2 (hypercapnia) indicating a mild limitation of aerobic metabolism in hypercapnic animals. Anaerobic metabolites accumulated above 25°C indicating an upper critical temperature independent of CO_2 albeit anaerobic metabolism was lower under hypercapnia. The decrease in haemolymph pH during warming followed the alphastat pattern, with animals under hypercapnia consistently displaying an acidosis when compared to controls. Mantle intracellular pH was initially maintained during warming before a sudden acidification set in. The intracellular acidosis occurred earlier under hypercapnia indicating reduced energy allocation to intracellular pH regulation. The earlier reduction of energy-dependent processes under combined hypercapnia and warming may enhance passive tolerance to temperature extremes in this intertidal specie. However, permanent hypercapnia may only be sustained at the expense of organismic performance, especially at the limits of the thermal performance window.

[1]Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany (Zora.Zittier@awi.de)



OCEAN ACIDIFICATION IMPACT ON LARVAE STAGES OF EUROPEAN LOBSTER (*HOMARUS GAMMARUS*), UNDER TWO TEMPERATURE REGIMES

Agnalt, Ann-Lisbeth, Eva Farestveit, Felicia Keulder, Ellen Sofie Grefsrud, Tom Hansen and Are Olsen

Trends of increasing temperatures and ocean acidification are expected to influence benthic marine resources of Arctic waters, primarily calcifying organisms. The European lobster (*Homarus gammarus*) is among those species at risk. This lobster species is found along the continental shelf in the northeast Atlantic, from warm waters off Morocco to colder waters above the Arctic Circle in northern Norway. A project was initiated in 2011 aiming to investigate effects of projected increases in ocean acidification on the life cycle of lobster.

Ovigerous females were bought from commercial fishermen in October 2010 and kept in holding tanks until hatching late fall 2011. Hatching larvae were reared in semi-flow rearing tanks (40l Hughes Kreisel), and fed daily with frozen *Artemia* sp. The larvae were exposed to pCO_2 levels of 380, 750 and 1200 ppm, at two temperature regimes; 10 and 18°C. Newly hatched larvae are pelagic and undergo three moultings before settling. At each moulting stage larvae from each treatment were sampled. Individually carapace length and dry weight was recorded and some larvae were stored for further analysis of calcium content. At 18°C the development from stage I to IV lasted from 14 to 16 days. Growth was very slow at 10°C and resulted in very few larvae reaching stage IV, independently of pCO_2 levels, thus indicating the lower threshold temperature of *H. gammarus* larvae. Results on development, moulting, growth, survival, calcification and deformities during the pelagic phase will be presented.

Institute of Marine Research, P.O. Box 1870 Nordnes, N-5817 Bergen, Norway (ann-lisbeth.agnalt@imr.no)

IMPACTS OF GLOBAL CLIMATE CHANGE ON THE COASTAL RESOURCES OF BANGLADESH

Ahmed, Md. Kawser[1] and Shamima Sultana[2]

Increased SST may alter coastal ocean currents that have influence on the residence time of water in near shore environments which may have negative consequences on the growth and survival of many aquatic animals. Carrying capacity of the Bay of Bengal (BOB) is likely to be changed due to increase in total chlorophyll leading considerable change in the distribution of the various pelagic fishes and consequent change in the location of the fishing grounds. Contribution of estuarine zone is likely to increase due to expansion of area. Migratory routes of different species may change e.g. Tuna fishery areas may enlarge in the Bangladesh waters of the BOB. Hilsha migration route may extend southwards and anadromy in the Ganges-Meghna-Brahmaputra rivers diverted to the Myanmar rivers. Catadromy of larvae of tiger shrimp may follow changed routes. Offshore fisheries may be the least affected. However, there will be a profound change in the near shore marine fisheries. The greatest impact may be on fish species, which are dependent on the estuaries and creeks of the coastal zone for breeding or spawning.

Climate-related episodes, particularly those associated with increased sea-surface temperatures have significant impacts on coral reef ecosystems. Bangladesh will be the worst victim of global temperature and sea level rise. St. Martin's Island, only coral island in Bangladesh, supports a total of 66 sceleratianian coral, 86 fish, 4 Zooanthids, 4 Echinoids, 1 Asteroids, 1 Holothuroid, 4 Crinoids and 61 species of Molluscs are in great threats of high water temperature during summer season.

[1] Ecology, Environment and Climate Change Lab., Department of Fisheries
University of Dhaka, Bangladesh. kawser@univdhaka.edu
[2] Ecological and Environmental Economics Group, Department of Economics Bangladesh University of Business and Technology, Bangladesh. Shamima_quniv@yahoo.com

EMPIRICAL RELATIONSHIPS FOR ESTIMATING CARBONATE SYSTEM PARAMETERS IN THE NORTHERN CALIFORNIA CURRENT SYSTEM

Alin, Simone R.[1], Richard A. Feely[1], Lauren W. Juranek[2], Burke Hales[2], William Peterson[3], Jay Peterson[4], Jan Newton[5], Christopher Krembs[6], Ed Bowlby[7], Patrick A'Hearn[7], Liam Antrim[7], George Galasso[7], Rick Fletcher[7], and Debby Ianson[8].

The northern California Current System (CCS) is a region of strong, seasonal upwelling of old, nutrient- and CO_2-rich, and O_2-poor waters. It is a site of intense biogeochemical cycling, with high rates of primary production, air-sea CO_2 exchange, and carbon export to the open-ocean and sediments. Both the retention and recycling of material on the continental shelf in this region are higher than in the southern CCS. These features predispose northern CCS ecosystems to being susceptible to the combined stressors of hypoxia and biomineral corrosivity (i.e. lowered calcium carbonate saturation states from the combination of ocean acidification and natural processes such as upwelling and respiration). We have extended and refined previously developed relationships for characterizing the carbonate system (i.e., pH, calcium carbonate saturation states, carbonate ion concentration, dissolved inorganic carbon concentration, and alkalinity) based on proxy variables such as oxygen, temperature, and salinity. We now have two calibration data sets from coast-wide cruises in 2007 and 2011, along with several new verification data sets. We have successfully extended the relationships to the ocean surface and are subjecting the new relationships to rigorous verification testing to determine under what conditions the relationships can and cannot be applied robustly. We will also test the relationship in Puget Sound, Washington, to determine whether this approach can be used continuously along an estuarine salinity gradient. The relationships provide an important tool for reconstructing carbonate system parameters relevant to ocean acidification at times when and places where such measurements were not directly made.

[1]NOAA Pacific Marine Environmental Laboratory, Seattle, Washington, USA (simone.r.alin@noaa.gov)
[2]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.
[3]NOAA Northwest Fisheries Science Center, Newport, Oregon, USA.
[4]Hatfield Marine Science Center, Oregon State University, Newport, Oregon, USA.
[5]Applied Physics Laboratory, University of Washington, Seattle, Washington, USA.
[6]Washington State Department of Ecology, Olympia, Washington, USA.
[7]NOAA Olympic Coast National Marine Sanctuary, Port Angeles, Washington, USA.
[8]Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, British Columbia, Canada.

LOOKING AT SHELL DEVELOPMENT OF SCALLOP LARVAE IN OCEAN ACIDIFICATION SCENARIOS.

Andersen, Sissel[1], Ellen Sofie Grefsrud[2], Torstein Harboe[1], and Anders Mangor-Jensen[1]

An ongoing research project at the Institute of Marine Research in Norway is looking at possible effects of ocean acidification on shell and veliger development of the scallop *Pecten maximus* L.

Ocean acidification scenarios are produced by adding CO_2 gas to seawater. An acid stock solution of pH 5.8 is diluted to give four different pH levels in 16 flow-through 40 liters exposure tanks.
Local scallop broodstock was conditioned at in a hatchery for 8 weeks (Jan-Mar) and spawning induced by an increase in temperature. Eggs were cross fertilized with sperm from 2-3 individuals and when cell division was observed embryos were incubated in the exposure tanks at a stocking density of 13 ml^{-1}. The tanks were stagnant over night then flow adjusted to 10L h^{-1} d. Embryos and larvae were exposed to the different pH levels for seven days. Temperature was recorded using a logger set to read hourly values. pH was measured daily and flow adjusted twice a day. Alkalinity was analyzed twice during the experiment.
Larvae were sampled after 1, 2, 3, and 6 days to observe any shell deformities and to observe calcification of the shell. After seven days all larvae were collected, preserved in formalin and stored in ethanol. Survival was calculated from these samples.
Both photo documentation and quantitative results will be given on shell and veliger development.

[1] Institute of Marine Research, Austevoll Research Station, 5392 Storebø, Norway (sissel.andersen@imr.no)
[2] Institute of Marine Research, P.O. Box 1870 Nordnes, 5817 Bergen, Norway

SIBERIAN SHELF SEAS - AN AREA OF NATURAL(?) OCEAN ACIDIFICATION

Anderson, Leif G.[1], Irene Wåhlström[1], Göran Björk[2], and Anders Omstedt[2]

In the summer 2008 the waters of the eastern Laptev Sea, the East Siberian Sea and the western Chukchi Sea were investigated with respect to its hydrography including the inorganic carbon system. The findings reveal substantial biochemical transformation of carbon. In the Laptev Sea and the south western East Siberian Sea decay of organic matter cause high pCO_2 and low pH all from the surface to the bottom. In the central and eastern East Siberian and Laptev Seas decay of organic matter results in a nutrient rich bottom water, which is high in p CO_2 and has a low pH, often well below 7.5, leading to a low degree of calcium carbonate saturation. However, the surface layer shows "normal" ocean summer conditions. The difference is mainly due to terrestrial organic matter being the main source of OM to the west and marine OM being the source in the east. The high nutrient and p CO_2 bottom waters flow off the shelf into the central deep Arctic Ocean from the East Siberian Sea as well as along the Herald canyon in the western Chukchi Sea. Data will be shown and compared to the output from a 1-D model under different forcing conditions.

[1]Department of Chemistry and Molecular Biology, University of Gothenburg, Gothenburg, Sweden
[2]Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden
Email: leifand@chem.gu.se

COMBINED EFFECTS OF OCEAN ACIDIFICATION AND OIL SPILL ON THE DEVELOPMENT OF THE GREEN SEA URCHIN (*STRONGYLOCENTROTUS DROEBACHIENSIS*)

Arnberg, Maj[1,2], Sam Dupont[3], Sjur Vingen[1], Stig Westerlund[1], Thierry Baussant[1], and Renée K. Bechmann[1]

The future ocean will suffer from an increasing environmental pressure from several anthropogenic activities like offshore oil and gas industry, increasing ship transport and global climate change. These combined stressors will pose an increasing threat for the marine ecosystems. Currently, the effects of

stressors like ocean acidification (OA), resulting from the increasing CO_2 level in the atmosphere, are mainly studied independently from other stressors and scarce information about the potential combined effects exist. To improve our capability to predict the consequences for the marine ecosystems in a future high CO_2 world, more knowledge about the sensitivity of different species to these intricate environmental challenges is needed. The aim of this work was to address the impact of a combined exposure to OA and an oil spill scenario on the embryo-larval development and settlement of the green sea urchin (*Strongylocentrotus droebachiensis*).
Four different scenarios were simulated in a laboratory experiment: 1) Control (pH 8.1), 2) OA (pH 7.6), 3) Control (pH 8.1) + 4 days oil spill (0.5 mg/L) and 4) OA (pH 7.6) + 4 days oil spill (0.5 mg/L). Hatching success, survival, feeding, respiration and growth were studied. The larvae showed reduced feeding, increased mortality and decreased settlement success when exposed to oil treatments with or without the OA scenario. OA alone did not affect these parameters but preliminary results from larval growth measurements show reduced growth for larvae exposed to OA compared to control larvae. From this study, the general conclusion is that the effects of a short oil exposure on embryo/larval stages of the green sea urchin are expected to be similar in the current or the future ocean.

[1]IRIS-International Research Institute of Stavanger, Randaberg, Norway (maj.arnberg@iris.no)
[2]Marine Biology and Ecology Research Centre School of Marine science and Engineering, University of Plymouth, Plymouth, UK
[3]Department of Biological and Environmental Sciences, University of Gothenburg, Fiskebäckskil, Sweden

MULTI-STRESSOR RESPONSE OF THE PLANKTONIC ECOSYSTEM IN THE NORTH-WESTERN EUROPEAN SHELF

Artioli, Yuri[1], Jerry C. Blackford[1], Gisle Nondal[2], and Richard G.J. Bellerby[2,3,4]

Shelf seas are experiencing significant changes due to the action of multiple drivers, including climate change, Ocean Acidification (OA), changes in circulation, riverine loads and atmospheric deposition. Assessing the combined impact of all these drivers is a challenging task, as the response of organisms is highly variable and still uncertain, as evidenced by OA research over the last several years.. Furthermore, these interaction are potentially complex with both masking or exacerbating effects, yet to be fully understood. Ecosystem models are perhaps the only tool available to investigate how all of these drivers interact and contribute in shaping the global response of the ecosystem. In this work we use the coupled oceanographic-ecosystem model POLCOMS-ERSEM driven by climate forcing to give a first estimate of the interaction between climate change, OA and eutrophication in the planktonic ecosystem of the North-Western European Shelf. We focus in particular on primary production and nitrogen speciation, two processes for which initial parameterisation of the effect of the drivers are available. We run the model in different configurations to analyse the effect of the single drivers first, and then to assess the combined impacts. The model shows significant interaction among the drivers, with positive and negative feedbacks, and high variability in the spatial response of the ecosystem. Results indicate that changes in production driven by OA compare in magnitude with those predicted as a consequence of climate change. Although computationally expensive, models such as presented here can provide some insight for future management of change, based on a range of carefully chosen scenarios. Predictions will improve as impacts of individual drivers emerge with more precision in parallel with the development and evaluation of modelling tools.

[1] Plymouth Marine Laboratory, Prospect Place, Plymouth, PL1 3DH (UK)
[2] Uni Research, Bjerknes Centre for Climate Research, Bergen, Allégaten 55 N-5007 (Norway)

[3] Norwegian Institute for Water Research,Thormøhlensgate 53 D, N-5006 Bergen
[4] Geophysical Institute, University of Bergen, Allégaten 70, N-5007 Bergen

TOWARDS AN OCEAN ACIDIFICATION DATA STEWARDSHIP SYSTEM

Arzayus, Krisa and Hernan Garcia

To support NOAA's Ocean Acidification Program and the scientific community, the National Oceanographic Data Center (NODC) will serve as the NOAA Ocean Acidification (OA) data management focal point by providing dedicated online data discovery, access, and long-term archival for a diverse range of OA data.
This effort seeks to build a collaborative relationship with shared responsibilities among scientists, data managers, and NODC staff towards the implementation of an OA data stewardship system (OADSS).
OADSS is comprised of robust data documentation (metadata), dynamic data discovery and web services, and coordinated data flow among data providers, assembly centers, and NODC.
OADSS will leverage NODC's standard web services, including a new Geoportal discovery tool, OPeNDAP, THREDDS, and Live Access Server (LAS) to provide OA data in a variety of data formats that can be utilized by different audiences and machine-to-machine interfaces.
OADSS will include robust metadata building upon community best practices that span the diverse range of data types that fall within the scope of OA data: biological, chemical, and physical.
Coordinated data flow both to and from OADSS will ensure that audiences will always have access to authoritative versions of the data, regardless of where they are accessing the data.
Finally, NODC will preserve OA data following the Open Archival Information System Reference Model, ensuring access to original datasets as well as subsequent versions, for this and future generations of data users.

NOAA National Oceanographic Data Center, 1315 East-West Hwy, Silver Spring, MD 20910
(Krisa.arzayus@noaa.gov)

RECOVERY DYNAMICS OF MEDITERRANEAN SHALLOW ROCKY SHORE COMMUNITIES UNDER SCENARIOS OF MULTIPLE STRESSORS AND OCEAN ACIDIFICATION

Asnaghi, Valentina[1,2], Simon Thrush[3], Jean-Pierre Gattuso[4,5], Judi Hewitt[3], Luisa Mangialajo[2], Carlo Nike Bianchi[1], Patrice Francour[2], and Mariachiara Chiantore[1]

In the next decades multifaceted impacts of human-induced global change are expected to act on marine coastal ecosystems. In this changing scenario, a considerable challenge is to study how coastal benthic communities will recover from perturbations under acidified conditions. A first effort to make general predictions about recovery dynamics of Mediterranean rocky shore communities under ocean acidification could be made integrating information from *in situ* observations, manipulative experiments in the field and laboratory experiments on different key species. Along Mediterranean coasts, shallow rocky shore communities are dominated by macroalgae that exhibit different sensitivities to direct human impacts, such as coastal exploitation, urbanization and pollution, with a consequent loss of structuring canopy forming species in favour of coralline turf. Through a manipulative experiment we provide evidences of the role of coralline algae, as key elements in the recovery from disturbance, both as pioneer species and playing as a substrate for later colonists. Yet, these algal species are those more threatened by ocean acidification, as assessed through laboratory experiments. The dynamics described suggest a gradual shift toward communities where the loss of structuring macroalgae, due to direct human impacts, cumulates with a loss of coralline turf, suffering from the pH decrease, leading to a dominance of less complex fleshy algae. The lower fitness of coralline algae at lower future pH would lead to altered recovery dynamics, accelerating the process of simplification of the ecosystem.

[1]Department for the Study of the Territory and of its Resources (DipTeRis) - University of Genoa, Italy (valentina.asnaghi@unige.it)
[2] Université de Nice-Sophia Antipolis, Laboratoire ECOMERS, Avenue de Valrose, BP71, 06108 NICE cedex 2 France
[3] NIWA, Hamilton (New Zealand)
[4] CNRS-INSU, Laboratoire d'Océanographie de Villefranche, BP 28, 06234 Villefranche-sur-Mer Cedex, France
[5] Université Pierre et Marie Curie-Paris 6, Observatoire Océanologique de Villefranche, 06230 Villefranche-sur-Mer Cedex, France

TEMPORAL VARIABILITY OF CARBONATE SATURATION STATES IN DAVIS STRAIT AND INFLUENCE OF DIFFERENT FRESHWATER SOURCES

Azetsu-Scott, Kumiko[1], Brian Petrie [1], and Craig Lee [2]

Davis Strait connects the Labrador Sea with the Arctic Ocean through the Canadian Arctic Archipelago (CAA) and Baffin Bay. It is an ideal gateway to observe the propagation of changes from the Arctic into the Labrador Sea, the intrusion of the warm and saline Atlantic water into Baffin Bay and the freshwater contribution of the Greenland Ice Sheet to the northern North Atlantic.
$CaCO_3$ saturation states (Ω) and pH were studied along Davis Strait from 2004. The distribution of dissolved inorganic carbon (DIC) and total alkalinity (TA) are strongly influenced by water mass structure. Low Ω was associated with the Arctic outflow in the upper 300 m on the western side, extending to >50 km offshore. The highest Ω and pH_{total} were observed over the wide West Greenland Shelf. However, the decreasing rate of Ω and pH_{total} during the study period from 2004 to 2010 was also highest in this water mass. TA and salinity decreased with no significant increase in DIC concentrations in West Greenland Shelf Water. The dominant freshwater source on West Greenland Shelf is glacial meltwater. The influence of glacial meltwater on Ω and pH was studied in Disko Bay, a deep ocean fjord with a large outlet glacier. At the glacial front, Ω and pH_{total} were low (1.08 and 8.06, respectively) and increased as the salinity increased away from the glacial front. This implies observed changes in West Greenland Shelf Water are due to the increased glacial meltwater input on the shelf.

[1] Department of Fisheries and Oceans, Bedford Institute of Oceanography, 1 Challenger Dr. Dartmouth, Nova Scotia, B2Y 4A2, Canada (Kumiko.Azetsu-Scott@dfo-mpo.gc.ca)
[2] Applied Physics Laboratory, University of Washington, Seattle, Washington, 98105-6698 USA

EFFECTS OF OCEAN ACIDIFICATION ON *MYTILUS GALLOPROVINCIALIS* AND *PATELLA CAERULEA* AT NATURAL CO_2 VENTS

Baggini, Cecilia, Riccardo Rodolfo-Metalpa, and Jason M. Hall-Spencer

Increasing anthropogenic atmospheric CO_2 is altering the chemistry of surface seawater worldwide, resulting in ocean acidification. Current research into ocean acidification is mainly based in aquaria or mesocosms and whilst this has been invaluable in determining effects on a range of biological and

physical processes it is nevertheless difficult to extrapolate the findings to predict effects on whole marine ecosystems.
Here we show the effect of CO_2 on shell thickness, strength and mineralogy of two widespread Mediterranean molluscs, *Mytilus galloprovincialis* and *Patella caerulea*, were investigated using CO_2 vents (Ischia, Italy) as a natural laboratory. Mussels were transplanted and maintained up to 7 months along a gradient of pH_T (7.2-8.1) whereas *P. caerulea* already lived intertidally near the vents, where CO_2 levels were higher than those expected for the next 300 years. Their shells were analysed using SEM; shell strength and periostracum integrity were also measured for *M. galloprovincialis*.
Mussels transplanted to mean pH_T 7.2 had larger areas of damaged periostracum (due to adjacent mussels rubbing together) than those transplanted to mean pH_T 8.1 (6.4 ± 3.1% and 0.4 ± 0.9%, respectively), suggesting a decreased ability to repair periostracum at low pH. There was significant thinning of the aragonitic layer and reduced shell strength near the umbo. *P. caerulea* living at mean pH_T 6.5 had significantly thinner shells than those at pH_T 8.04, but only in the old part of the shell, likely due to higher dissolution rates.
Our results show that these common rocky shore molluscs can calcify at pH levels lower than those predicted for 2100 but that their shell dissolve and the mineralogy is altered as CO_2 levels increase.

Marine Institute, Marine Biology and Ecology Research Centre, Plymouth University, Plymouth PL4 8AA, UK. Email: cecilia.baggini@plymouth.ac.uk

GENETIC AND PHYSIOLOGICAL PLASTICITY IN EXTANT PHYTOPLANKTON ASSEMBLAGES

Balestreri, Cecilia[1,2], Andrea Highfield[1], Matt Keys[1], Jack Allum[1], Ros Rickaby[2], Jeremy Young[3], Colin Brownlee[1], and Declan Schroeder[1]

A species response to rapid environmental change can result in either extinction or migration to a new habitat or acclimation; the latter being more likely in species with large population sizes and large inherent genetic variability. The response of natural *Emiliania huxleyi* populations to ocean acidification has yet to be fully determined. Contradictory reports on *E. huxleyi* response to future carbonate chemistries were based largely on *in vitro* studies carried out on different strains. Moreover, many of these strains were maintained for many years and thus multiple generations in artificially controlled laboratory conditions. Our hypothesis is that an inherent genetically based phenotypic plasticity within *E. huxleyi* populations already exist. The strains best suited to the particular projected climatic scenarios will be selected for. The exploration of naturally occurring extant *E. huxleyi* populations will provide a unique window into the true response of this globally important species to a rapidly changing environment. Here we report on the first of a five part scientific cruise based programme (NERC funded UK Ocean Acidification and NSF funded southern ocean Coccolithophore Belt research programmes) were unique *E. huxleyi* strains are being investigated for their adaptive features.

[1] Marine Biological Association of the United Kingdom, Citadel Hill, Plymouth, PL1 2PB, UK (cecbal@mba.ac.uk)
[2] University of Oxford, Department of Earth Sciences, South Parks Road, Oxford, OX1 3AN, UK
[3] University College London, O110, 3 Charlton Terrace, Tonbridge, Kent, TN9 1PG, UK

EFFECTS OF INCREASING SEAWATER CARBON DIOXIDE CONCENTRATIONS ON CHAIN FORMATION OF THE DIATOM *ASTERIONELLOPSIS GLACILIS*

Barcelos e Ramos, Joana[1], Kai G.Schulz[2], and Eduardo B. Azevedo[1]

Some marine diatom species form chains, thereby potentially influencing buoyancy, predator evasion, light absorption and nutrient uptake. Chain length has been observed to vary with temperature and nutrient availability as well as being positively correlated with growth rate. However, the potential effect of enhanced carbon dioxide concentrations and consequent changes in seawater carbonate chemistry are still unknown. Adjacent cells in chains establish connections through different processes. In the case of *Asterionellopsis glacilis* cells attach at the valve apices by exuded mucilage pads. Here we report on laboratory experiments with semi-continuous cultures of the freshly isolated diatom *Asterionellopsis glacilis* grown under increasing CO_2 levels, ranging from 330 to 4100 µatm. Our results show that the number of cells comprising a chain increases with increasing CO_2 concentrations. Moreover, while cell division might slightly increase between 330 and 750 µatm, it decreases again towards higher levels. Further analysis of production of particulate organic carbon, nitrogen and phosphorus, chlorophyll *a* and nutrient uptake rates are being conducted to understand the mechanisms behind the observed trends and infer implications for nutrient uptake of the species and potential effects on their sinking rates in the future ocean.

[1] Centre of Climate, Meteorology and Global Change of the University of the Azores, Rua Capitão d'Ávila, São Pedro, PT - 9700-042 Angra do Heroísmo, Açores - Portugal, joanabr@uac.pt
[2] GEOMAR | Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg, D-24105 Kiel, Germany

HYPOXIA, RATHER THAN OCEAN ACIDIFICATION IS THE DOMINANT CONSTRAINT ON METABOLIC RATES OF BATFISH (*DIBRANCHUS SPONGIOSA*) IN THE OXYGEN MINIMUM ZONE OF THE GULF OF CALIFORNIA

Barry, James P., Kurt R. Buck, Josi R. Taylor, Robert Herlien, Chris Lovera, Patrick J. Whaling, and Linda Kuhnz

Environmental hypercapnia is expected to be more stressful for marine animals when combined with other simultaneous environmental stresses. Oxygen minimum zones (OMZs) in productive coastal regions typically have extremely low oxygen tensions (<25 µmoles $O_2 \cdot kg^{-1}$) that are known to be stressful for many organisms. Although OMZs typically have low pH levels due to the accumulation of respiratory CO_2, further pH reduction caused by increased anthropogenic CO_2 may be particularly stressful when combined with extremely low ambient oxygen levels.

The batfish, *Dibranchus spongiosa*, inhabits the extreme OMZ in the Guaymas Basin of the Gulf of California where ambient oxygen and pH levels (<5 µmoles $O_2 \cdot kg^{-1}$, pH 7.6) are extremely low. We measured the metabolic rates of batfish using an *in situ* respiration system designed to allow repeated measurements of oxygen consumption for each of 8 metabolic chambers holding experimental animals. Chamber water was flushed automatically between incubation periods, with the option of injecting either CO_2- or O_2-saturated seawater at the beginning of an incubation period to experimentally manipulate chamber conditions.

Batfish responded strongly to changes in oxygen tensions, with significant increases in metabolic rates with increasing oxygen levels over the small range of oxygen observed (0.5-3 µmoles $O_2 \cdot kg^{-1}$). Response to elevated pCO_2 (pH 6.6–7.6) varied among individuals, but was not statistically significant for any individual or for all batfish combined (n=7). These results indicate that small variation in oxygen levels is a more important constraint on batfish metabolism than pH, over the range of values expected under most climate scenarios.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039.
barry@mbari.org

OXYGEN STRESS IS MORE IMPORTANT THAN OCEAN ACIDIFICATION FOR DEEP-SEA URCHINS (*STRONGYLOCENTROTUS FRAGILIS*) INHABITING THE OXYGEN MINIMUM ZONE OFF CALIFORNIA

Barry, James P., Kurt R. Buck, Eric F. Pane, Josi R. Taylor, Michael Risi, Craig Okuda, and Patrick J. Whaling

The oxygen minimum zone (OMZ) off central California from ~300 to 1800 m depth is naturally low in oxygen and pH (<30 µmoles $O_2 \cdot kg^{-1}$, pH_{min} = 7.6). It is well known that hypoxia is stressful for marine animals, but less known if low ambient pH levels impair animal function in the OMZ. As anthropogenic carbon dioxide increases, the pH of the OMZ is expected to decrease, along with additional deoxygenation. Will these changes increase stress for OMZ megafauna?
We examined the effects of reduced oxygen and pH levels on the metabolic rates of the deep-sea fragile urchin (*Strongylocentrotus fragilis*), whose bathymetric range (~200-1200 m) straddles the OMZ. An automated *in situ* respiration system was used to measure rates of oxygen consumption for individuals in the core of the OMZ under ambient conditions (pH_{tot}=7.6, ~10 µmoles $O_2 \cdot kg^{-1}$ SW), and under experimentally manipulated levels of pH (6.7 to 7.6) and oxygen (5-300 µmoles $O_2 \cdot kg^{-1}$ SW). Oxygen consumption was lowest at ambient (OMZ) oxygen tensions and low pH, and rose rapidly with increasing oxygen levels; consumption tripled with levels of 30 µmoles $O_2 \cdot kg^{-1}$ SW or higher. Reduced pH levels caused modest, significant reductions in oxygen consumption, but were less important than oxygen in the OMZ. The combined stress of both low pH and hypoxia do not appear to be synergistic for *S. fragilis*, which is adapted to the low pH levels typical of the OMZ. Related laboratory studies indicate that pH levels expected with future climate change impair physiological function in *S. fragilis*.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039.
barry@mbari.org

EFFECT OF HIGH CO_2 ON COMPETITION AND COMMUNITY COMPOSITION OF A NATURAL PHYTOPLANKTON ASSEMBLAGE

Bermúdez, J. Rafael[1], Aud Larsen[2], Ulf Riebesell[1], Kai G. Schulz[1], and Monika Winder[3]

Rising atmospheric CO_2 alters the seawater carbonate chemistry and lowers its pH, with potential consequences for marine phytoplankton community composition.
Phytoplankton species show different optima for pH, CO_2 saturation and CO_2 uptake capacity. An increased CO_2 level may change their competition capacity by altering those parameters, favoring some species and triggering a shift in the community composition.
In nine off-shore mesocosms moored off Bergen (Norway) a pCO_2 gradient was established ranging from ~280 up to ~3000 µatm, with five mesocosm covering the range projected for the course of this century. After a first phytoplankton bloom phase, nutrients were added (N:P ~30) to stimulate coccolithophorid growth.
Maxima in phytoplankton biomass occurred before and after nutrient addition, with higher values at high CO_2 during the first bloom and vice versa during the second bloom. The total cumulative sum of biomass was negatively correlated with CO_2 concentration.

The phytoplankton community composition differed significantly between CO_2 treatments. Small cells (cyanobacteria, picoeukaryotes and small flagellates) were abundant at high CO_2 and dominant at the end of the experiment. The abundance of the coccolithophore *Emiliania huxleyi* was negatively correlated with CO_2, being almost absent at high and dominant at low levels. Diatoms prevailed at high CO_2 before nutrient addition, with a reduction after this point, particularly at high CO_2.
This study showed that some phytoplankton species are highly sensitive to elevated CO_2 (coccolithophores), while others are more resilient and apparently perform better (picophytoplankton). CO_2-induced shifts in phytoplankton species composition will alter prey availability and will have significant effects on trophic transfer, particle sedimentation and nutrient cycling.

[1] Helmholtz Centre for Ocean Research Kiel (GEOMAR), Kiel, Germany. (jrbermudez@geomar.de)
[2] Uni Environment, Uni Research, Bergen, Norway.
[3] Department of Systems Ecology, Stockholm University, Stockholm, Sweden.

EVIDENCE OF DECLINE IN NET COMMUNITY CALCIFICATION AT A FLORIDA KEYS PATCH REEF AND A PUERTO RICAN FRINGING REEF

Bernstein, Whitney [1,2], Chris Langdon[3], and Konrad Hughen[1]

The successful persistence of coral reefs largely depends on the continued ability of reef communities to accumulate a robust carbonate framework. Massive corals build the foundation of the reef, enabling it to keep pace with changes in sea level. Coralline algae, foraminifera, and sand serve as the infill and cement, and coral colonies of diverse morphologies create the complex habitat that supports the diverse reef ecosystem. Controlled laboratory studies demonstrate that calcification is sensitive to changes in temperature, light, aragonite saturation state (Ω_{Ar}), and nutrient concentrations. Coral reef communities show similar sensitivities, and may be particularly susceptible to the compounded effects of ocean acidification and warming, in addition to the local stresses imposed by coastal development, harmful fishing practices, invasive species, and disease. In this study, we have quantified the net community calcification rate at two Caribbean sites using the Lagrangian flow respirometry method. The net calcification rates were quite low: 2±6 (1σ) $mmol/m^2/h$ for Puerto Rico, August 2011; 1±5 (1σ) $mmol/m^2/h$ for Puerto Rico, December 2011; 4±12 $mmol/m^2/h$ in the Florida Keys in February 2012. In contrast, similar surveys conducted on a Jamaican reef in June 1980 yielded net calcification rates of roughly 9 $mmol/m^2/hr$ (Kinsey 1982, 1985). Rates measured in Puerto Rico (August and December 2011) and in the Florida Keys (February 2012) are 11%, 22%, and 44% of the Jamaican estimate, respectively. This is in agreement with the observation that coral cover in the Caribbean reefs has declined by as much as 80% since the 1970's.

[1]Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, 360 Woods Hole Rd. Woods Hole, MA 02543 (wbernstein@whoi.edu)
[2]Earth, Atmospheres and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
[3]Marine Biology and Fisheries, University of Miami, RSMAS, 4600 Rickenbacker Cswy Miami, FL 33149

INCREASED OTOLITH SIZE AND DENSITY IN THE LARVAE OF A SUBTROPICAL MARINE FISH: NEW INSIGHTS INTO THE EFFECTS OF OCEAN ACIDIFICATION USING MICRO-COMPUTED TOMOGRAPHY

Bignami, Sean[1], Ian C. Enochs[2], Derek P. Manzello[2], Su Sponaugle[1], and Robert K. Cowen[1]

Micro-computed tomography (micro-CT) is one of the newest techniques to be utilized in the rapidly evolving field of ocean acidification research. Similar to medical CT-scans, micro-CT facilitates the visualization and quantitative analysis (e.g., density, surface area, volume) of complex structures in three dimensions at resolution as fine as 6.6 µm. We present the first application of this technology to the study of acidification impacts on the larvae of marine fish, using larval cobia (*Rachycentron canadum*) raised for three weeks under predicted future ocean acidification conditions (800 and 2100 µatm pCO_2). Initial otolith analysis was performed on 8 and 22 days post hatch (dph) larvae using established dissection and digital image analysis techniques, revealing a 2-D surface area increase from 10 to 33% at 800 and 2100 µatm, respectively. To date, this is the lowest pCO_2 to enhance otolith growth. Analysis of 22 dph larvae using micro-CT (13 μm^3 voxels) confirmed an increase in otolith volume and surface area under 2100 µatm pCO_2. Furthermore, micro-CT densitometry revealed, for the first time, an increase in otolith density due to acidification, with a ~ 6 % increase for fish raised at 2100 µatm pCO_2. Although the biological impacts of increased otolith size and density are currently unknown, density is inherent to the functioning of otoliths as auditory and mechno-sensory organs. Further analysis of bone density, skeletal volume, and structural ontogeny, as well as inclusion of larval mahi mahi (*Coryphaena hippurus*), will provide additional insight into the effect of ocean acidification on marine fishes.

[1]RSMAS, University of Miami, 4600 Rickenbacker Cswy, Miami, FL 33149 USA (sbignami@rsmas.miami.edu)
[2]AOML, NOAA, 4301 Rickenbacker Cswy, Miami, FL 33149 USA

THE RESPONSES OF A MICROZOOPLANKTON COMMUNITY FROM THE COASTAL ARABIAN SEA (OFF KOCHI, SOUTH WEST COAST OF INDIA) TO INCREASING CO_2 CONCENTRATION DURING A SHORT TERM INCUBATION EXPERIMENT.

Biswas, Haimanti[1], S. D. Gadi[2], C.K Haridevi.[3], A. Parvathi[3], J. Vijayan[3], J. Sebastian[3], and D. Bandyopadhyay[1]

Marine ciliates often contribute a major percentage of coastal microzooplankton communities and play many crucial roles in marine trophodynamics. Virtually, our knowledge about the responses of microzooplankton community to future increasing CO_2 concentration is occasional, hence worthy to study. A short term incubation experiment was conducted to investigate the responses of natural microzooplankton community from the coastal Arabian Sea (Off Kochi, South west coast of India) to increasing CO_2 concentration.

Our results revealed that the initial relative abundance of tintinnids was almost doubled in the untreated control, whereas, threefold increase was noticed in the high CO_2 treatments. This might be attributed to the dominance of small and fast growing diatoms which can be utilized as food by tintinnids. The relative abundance of *Thalassionema frauenfeldii* was found to be 34 percent decreased under elevated CO_2 level than observed in the control and could be largely because of grazing by tintinnids. The simple and quick way of reproduction like binary fission might have enabled the ciliates to show a rapid enhancement in number during our short term incubation experiment. The abundance of the large diatom *Chaetoceros lorenzianus* was quite high in the untreated control and was found to be drastically minimized in the high CO_2 treatments.

These results are in well agreement with our earlier observations from the coastal Bay of Bengal. It is likely that, in the future ocean scenarios, under less nutrients and high CO_2 concentrations, smaller diatom might outperform the larger species by the virtue of their higher cell surface area to volume ratio which could potentially influence microzooplankton mediated energy transfer in the marine environment.

[1]National Institute of Oceanography, Regional Center, 176 Lawson's Bay Colony, Visakhapatnam-530017, A.P, India (haimanti.biswas@nio.org)
[2] Carmel College of Arts, Science and Commerce for Women, Department of Zoology, Nuvem, Goa – 403 601.
[3]National Institute of Oceanography, Regional Center, Kochi, Dr. Salim Ali Road, Postbox number 1913, Kochi -682018, India

MULTI-SCALE VARIABILITY OF OCEAN ACIDIFICATION IN THE NORTH-WESTERN EUROPEAN SHELF

Blackford, Jerry C., Yuri Artioli, and Momme Butenschön

Shelf seas are complex environments that respond to a variety of drivers operating over a range of scales: the long term climatic signal is often masked by the resulting high variability or by opposing processes. We describe spatial and temporal variability in the carbonate system in the NW European Shelf Sea using a hydrodynamic-ecosystem model (POLCOMS-ERSEM). Trends in the carbonate system drawn from a 40 year hindcast illustrate how distinct areas responded to the recent increase of atmospheric CO2 and other driving factors, which include biological production, nutrient and alkalinity discharge from rivers and physical processes.
The model has been run under the climate scenario SRES A1B using the IPSL climate model for forcing and boundary conditions. Simulations of the end of the century indicate an average state significantly different from the present one in the majority of the domain. High variability persists in the future scenario simulation, potentially opening 'windows of opportunity' where the future state of the carbonate system would overlap or be close to the present one, particularly where the variability is maximum, as in the coastal areas and the most productive regions. It is possible to hypothesise that these windows could be exploited by organisms, thus increasing the global resilience of the ecosystem to Ocean Acidification. Alternately, it can be hypothesised that high variability might increase the opportunity for deleterious thresholds to be breached. In either case we suggest that an appreciation of variability is essential to understanding how organisms and processes interact with ocean acidification.

Plymouth Marine Laboratory, Prospect Place, Plymouth, PL1 3DH (UK), jcb@pml.ac.uk

ECOPHYSIOLOGIAL RESPONSES OF A PHYTOPLANKTON COMMUNITY TO INCREASING CO_2 CONCENTRATION UNDER CONSTANT AND VARIABLE PH

Blanco-Ameijeiras, Sonia[1], Kai Georg Schulz[2], Mário Cachão[3], Eduardo Brito Azevedo[1], and Joana Barcelos e Ramos[1]

Ocean acidification refers to the decrease of seawater pH caused by increasing atmospheric CO_2, and hence seawater concentrations. This study aims to determine whether the pH decrease or the concomitant increase in seawater CO_2 concentration ($[CO_2]$) is the factor responsible for community changes observed in previous ocean acidification experiments. A phytoplankton community from the central North Atlantic (Azores, Portugal) was grown in closed microcosms under increasing partial pressures of CO_2 (pCO_2) (~230, ~520 and ~960 µatm), corresponding to pH_{total} levels of ~8.3, ~8 and ~7.7, and under constant pH_{total} (~7.93 using the buffer HEPES). This approach allows to independently investigate their ecophysiological response in terms of community structure, growth, primary production and calcification, and separate between pH and CO_2 effects. The community was dominated by *Chaetoceros* sp. (~90%) in all treatments independent of pCO_2 and pH. Other diatom species represented ~9.5% of the community, dinoflagellates ~0.5 % and coccolithophores ~0.0001%. Preliminary results show that the increase in [CO_2], at constant and variable pH, only changed the occurrence of the less abundant species, but not the major structure of the community. Shannon's diversity index slightly decreased under constant pH conditions with increasing [CO_2], while with decreasing pH conditions diversity had a potentially optimum at ~500 µatm. The global response of the community growth rate was dominated by diatom growth, masking small responses observed in dinoflagellates and coccolithophores. Ongoing analyses of particulate organic carbon, nitrogen and phosphorus, chlorophyll *a* and nutrients will provide further information on the overall community response.

[1] Center of Climate, Meteorology and Global Change (CMMG); University of Azores, Rua do Capitão d'Ávila, PT 9700-042 Angra do Heroísmo, Açores, Portugal (sbameijeiras@uac.pt)
[2] GEOMAR. Helmholtz Centre for Ocean Research Kiel. Düsternbrooker Weg 20, 24105, Kiel, Germany.
[3] Department of geology, Faculty of Sciences, University of Lisbon, Campo Grande, PT 1749-016 Lisbon, Portugal.

CARDIOVASCULAR PERFORMANCE OF THE EDIBLE CRAB *CANCER PAGURUS* UNDER THE EFFECTS OF OCEAN ACIDIFICATION

Bock, Christian, Faruk Dogan, and Hans-O. Pörtner

Recent investigations on the effects of ocean warming and acidification have shown that marine crustaceans respond to increased CO_2 concentration with an elevation of heart rate, limiting their residual scope for performance and thus shifting their heat tolerance limits to cooler temperatures (Walther et al. 2009). Aim of this study was to develop a better understanding of the mechanisms behind. Therefore, real-time cardiac and blood flow MR imaging techniques were developed for observations of heart functioning in a marine crustacean, the edible crab *Cancer pagurus*. Velocity mapping and real-time cardiac MRI were used to investigate the effect of elevated CO_2 partial pressures according to predicted future ocean acidification scenarios (PCO_2 levels of 0.12 kPa, hypercapnia) at 10°C acclimation temperature. Interestingly, heart performance and associated haemolymph output increased under acute hypercapnia, represented in brightened images from inside the heart. Unexpectedly, blood flow in the *Aorta sternalis* from velocity maps remained more or less unchanged under these elevated CO_2 concentrations. These contrasting findings may indicate shifts in blood flow distribution associated with the rise in heart performance. Further studies of the systemic blood circulation are needed to investigate the respective options. Overall, high-resolution MRI recordings can monitor cardiovascular performance as an indicator of heat tolerance, and its responses to ocean acidification.

Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany (Christian.Bock@awi.de)

AN EXPERIMENTAL AQUARIUM SYSTEM WITH CAREFULLY CONTROLLED CARBONATE CHEMISTRY, OXYGEN LEVELS, AND TEMPERATURE, FOR MULTI-STRESSOR INVESTIGATION OF THE IMPACTS OF OCEANIC CLIMATE CHANGE

Bockmon, Emily, Jeremy Lord, and Andrew G. Dickson

The effects of ocean acidification are an ongoing field of interest. Although some natural environments mimic the expected changes, the opportunities for studying ocean acidification *in situ* are limited. Instead, we turn to laboratory experiments to understand the impacts of ocean acidification on biological organisms. Unfortunately, correctly modifying and controlling the carbonate chemistry of seawater in an experimental laboratory setting is not a trivial task.
In this experimental aquarium system, the desired gas composition (N_2, O_2, CO_2) is carefully mixed using mass flow controllers. Equilibration between seawater and the gas mixture is achieved by recirculation of temperature-controlled seawater through a Liqui-Cel® membrane contactor. This constant equilibration enables precise and continuous control over the CO_2 and O_2 levels. Each aquarium can be set up as a closed seawater system, or as a flow-through setup with raw seawater input. The independent control of CO_2, O_2 and temperature allows for investigation into multi-stressor interactions of many kinds. Autonomous monitoring using a Honeywell Durafet® and Aanderaa Optode®, in combination with discrete measurements, ensures that the tanks are maintained at the desired treatment levels. The pH and oxygen saturation are maintained using feedback loops in LabVIEW®. This allows for particularly consistent and careful control over the target parameters.

Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0244 (ebockmon@ucsd.edu)

EFFECT OF OCEAN ACIDIFICATION ON FERTILIZATION SUCCESS OF AN ARCTIC SEA URCHIN SPECIES, *STRONGYLOCENTROTUS DROEBACHIENSIS* (O. F. MÜLLER, 1776)

Bögner, Desislava, Ulf Bickmeyer, and Angela Köhler

Sea urchins as broadcasting spawning invertebrates are particularly vulnerable to ocean acidification. In this study, we assessed the effects of ocean acidification on fertilization success of *Strongylocentrotus droebachiensis*, collected at Spitzbergen/ Arctic. We achieved acidification by bubbling CO_2 into filtered seawater. The seawater pCO_2 used were 180, 380, 980, 1400 and 3000 µatm and not-treated filtered seawater as control. We diagnosed aberrations under different acidic exposure scenarios after post-fertilization periods of 1h and 3h. We recorded fertilization rate and morphological alterations in experiments with and without pre-incubation of the eggs. We observed an increasing polyspermy rate in relation to high seawater pCO_2. This is indicative for a failure on the formation of the fertilization membrane. Our experiments showed anomalies such as fertilized eggs displaying incomplete fertilization membrane lifting-off with partial or total attachment to the egg surface, hyaline membrane blebs, complete loss of fertilization membrane, as well as drastic malformations with or without fertilization membrane formation, consisted of cytoplasm constriction, extrusion or vacuolization and irregular cell division until 2- to 4-cell stages. In addition, we conducted measurements of intracellular pH using BCECF/AM in unfertilized eggs exposed to acidified seawater for 1h. In fact, intracellular pH decreased significantly from 1400 µatm on. All results indicate a decreasing fertilization success at CO_2 concentrations equal and higher than 1400 µatm, accompanied by the cellular pathologies described before. Exposure time to low pH seems also to be a threatening factor for the cellular buffer capacity, viability, and development after fertilization.

Alfred Wegener Institute for Polar and Marine Research. Am Handelshafen 12, 27570 Bremerhaven, Germany (dboegner@awi.de)

ESTIMATING CARBONATE SATURATION AND pH IN THE SOUTHERN OCEAN FROM HYDROGRAPHIC DATA

Bostock, Helen[1], Sara Mikaloff-Fletcher[1], Mike Williams[1] Kim Currie[2], and Scott Nodder[1]

Our understanding of the carbonate concentrations and saturation in the oceans has been considerably advanced by the collection of large global datasets over the last 50 years (GEOSECS 1960-1970s, GLODAP 1990s, CARINA and PACIFICA 2000s). However, there are still many areas of the globe that have had little sampling for carbonate parameters.

We have used the global datasets from the Southern Ocean (south of 25°S), with measured dissolved inorganic carbon (DIC) and alkalinity to develop multiple linear regressions (MLR) to estimate alkalinity and DIC from the common hydrographic parameters; temperature, salinity, depth/pressure and oxygen. We find 3 distinct regimes based on water masses, where the alkalinity and DIC have different relationships with the hydrographic parameters. In order to objectively determine the best dividing points for these three regimes, we undertook a Monte Carlo simulation in which 5,000 different pairs of dividing points were used in the MLR.

The aim of this work is to use all the hydrographic data for the region to produce detailed maps of the carbonate parameters: pCO_2, pH, $[CO_3^{2-}]$, aragonite saturation, calcite saturation, that take into account local currents, especially around complex topography e.g. around New Zealand. These maps will be ground-truthed with opportunistic sampling for alkalinity and DIC on future voyages, especially in coastal regions where the relationship between the hydrographic and the carbonate parameters may not hold. It will also be important to continue to measure DIC and alkalinity as their relationship with hydrographic parameters will change over time due to increasing uptake of anthropogenic CO_2, therefore the MLR algorithms will vary in the future.

[1] National Institute of Water and Atmospheric Research (NIWA), Kilbirnie, Wellington, New Zealand, (helen.bostock@niwa.co.nz)
[2] NIWA, Dunedin, New Zealand

OCEAN ACIDIFICATION EFFECTS ON PTEROPOD LARVAL AND ADULT STAGES AT “IN-SITU” CONDITIONS DURING A MESOCOSM EXPERIMENT.

Büdenbender, Jan[1], Nicole Hildebrand[2], Niehoff, Barbar [2], and Ulf Riebesell[1]

Present anthropogenic CO_2 emissions are causing acidification of the world’s surface oceans. There is increasing experimental evidence that CO_2 induced changes in seawater carbonate chemistry negatively affects the development of calcifying planktonic metazoa. Pteropods, shelled euthecosomate mollusks, are key species in epipelagic food webs as consumers and prey for various marine organisms. Contributing significantly to organic matter and biogenic calcium carbonate export, pteropods are relevant for global biogeochemical cycles. The Bergen 2011 KOSMOS study was investigating ocean acidification effects on a North Atlantic plankton community from physiology to food chain ecology. 9 mesocosms with a volume of each 80 m^3 enclosed the natural plankton community including the boreal-temperate pteropod species *Limacina retroversa* for a period of 40 days. Mortality of pteropod larval and adult stages was significantly correlated to increased CO_2 levels. Shell corrosion was observed at increased CO_2 levels, but not in the control mesocosms. With prospect on the high sensitivity already to

moderate CO_2 concentrations as expected within this century, pteropods are highly endangered if CO_2 emissions are not mitigated. The disappearance of pteropods from the marine ecosystem could have considerable consequences for commercially important fisheries as well as biologically mediated ocean carbon sequestration. This is the first time that CO_2 effects could be investigated at "in-situ" conditions and for an extended time period on these fragile organisms.

[1] Helmholtz Centre for Ocean Research Kiel (GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany, (jbuedenbender@geomar.de)
[2]Alfred Wegener Institute for Polar and Marine Research (AWI), Am Handelshafen 12, 27570 Bremerhaven, Germany.

THE ACTIVITY OF CARBONIC ANHYDRASE (CA) ENZYME IN MARINE DIATOMS.

Bulbul, Afroza, Russell Frew, Robert Strzepek, and Keith Hunter

Carbonic anhydrase is zinc-containing enzyme that catalyzes the reversible reaction between carbon dioxide hydration and bicarbonate dehydration and is used for inorganic carbon acquisition by some phytoplankton. In some regions of the oceans where zinc (Zn) is nearly depleted, diatoms can use cadmium (Cd) as a catalytic metal atom in cadmium carbonic anhydrase (CdCA).
Measurements from a transect across the Otago Shelf, New Zealand, have shown that during summer Cd is depleted in Sub-Antarctic water because of enhanced biological uptake. Zn concentrations in these waters are also extremely low. Cd levels decline significantly during summer probably as a result of iron-induced biological growth. We suggest that the most likely mechanism for uptake of Cd under Zn-limiting conditions is the formation of cadmium containing carbonic anhydrase (CdCA) enzyme.
We collected water samples along the Otago transect bimonthly over one year. Carbonic anhydrase enzymes in the samples were assayed using a Spectrophotometric method and the total CA (µg/L) of all samples was calculated. The measured enzyme content ranged from (1 – 6 µg/L). Laboratory experiments with manipulated concentrations of Zn and Cd were undertaken to understand the factors influencing the production of the enzyme. Results from Zn depleted cultured samples showed a positive correlation between CA enzyme production and Cd repletion.

Department of Chemistry, The University of Otago, PO Box 56, Dunedin. NZ. (bafroza@chemistry.otago.ac.nz)

THE EFFECT OF LOW AND LOW-SPIKED pH ON THE INTRACELLULAR DMSP PRODUCTION AND EPITHELIAL CELL MORPHOLOGY OF RED CORALLINE ALGAE

Burdett, Heidi L.[1], Elena Aloisio[2], Piero Calosi[2], Helen S. Findlay[3], Steve Widdicombe[3], Angela D. Hatton[4], and Nicholas A. Kamenos[1]

The release of dimethylsulphoniopropionate (DMSP) by marine algae has major impacts on the global sulphur cycle and may influence local climate through the formation of dimethylsulphide (DMS). However, the effect of global change on DMSP/DMS (DMS(P)) production by algae is not well understood. This study examined the effect of low pH on DMS(P) production and epithelial cell morphology of the free-living red coralline alga *Lithothamnion glaciale*. Three pH treatments were used in the 80 day experiment: (1) current pH level (8.18, control), (2) low, stable pH representing a 2100 ocean acidification scenario (7.70) and (3) low, spiked pH (7.75, with a 3-day spike to 6.47), representing acute variable conditions that might be associated with leaks from carbon capture and storage infrastructure, at CO_2 vent sites or in areas of upwelling. DMS(P) production was not significantly enhanced under low but stable pH conditions, indicating that red coralline algae may have some resilience to OA. However, intracellular and water column DMS(P) concentrations were significantly higher than the control when pH was low and spiked. Cracks were observed between the cell walls of the algal skeleton in both low pH treatments. It is proposed that this structural change could cause membrane damage that allows DMS(P) to leak from the cells into the water column, with subsequent implications for the cycling of DMS(P) in coralline algae habitats.

[1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, G12 8QQ, United Kingdom (nick.kamenos@glasgow.ac.uk)
[2]Marine Biology and Ecology Research Centre, University of Plymouth, Plymouth, UK, PL4 8AA
[3]Plymouth Marine Laboratory, Prospect Place, Plymouth, UK, PL1 3DH
[4]Scottish Association for Marine Science, Oban, Argyll, UK, PA37 1QA

METABOLIC PLASTICITY AND ADAPTATION IN POLYCHAETE SPECIES INHABITING A CO_2 VENT COASTAL SYSTEM

Calosi, Piero[1], Sam Rastrick[1], Chiara Lombardi[2], Jörg D. Hardege[3], Adriana Giangrande[4], Anja Shulze[5], and Maria-Cristina Gambi[6]

Most marine invertebrates respond to high CO_2 conditions *via* drastically decreasing their metabolic rates, so called *metabolic depression*. However, with the increased focus on the investigation of the effect of exposure to elevated CO_2 on marine invertebrates' metabolic rates, a range of responses to the exposure to elevated pCO_2/low pH conditions have been reported: including increased rates, non-monotonic changes, or no change. Nevertheless, the level and significance of metabolic plasticity and the scope for further metabolic adaptation, in light of future CO_2 scenarios are largely unknown. In addition, most studies have to date focused on calcifying organisms. We carried out a series of transplantation experiments on polychaete species living in and around a shallow-water CO_2 vent system off Ischia (Naples, Italy), and characterized the metabolic responses and possible metabolic adaptation in four 'vulnerable' (found exclusively outside the vent area) and three 'tolerant' (present both within and outside the vents areas) species. Our results show that specimens of both vulnerable and tolerant taxa collected in the control areas, under normal pH values show metabolic depression when exposed to elevated pCO_2/low pH conditions, whilst specimens of tolerant species exposed to control condition do not show a reciprocal response to that shown by their conspecific from the control areas transferred into the acidified conditions. This indicates the potential of the existence of physiological adaptations in the vent worms. This evidence is partly supported by preliminary phylogenetic and phylogeographic information on some of the tolerant species.

[1]Marine Biology and Ecology Research Centre, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK. (piero.calosi@plymouth.ac.uk)
[2] Marine Ecology Laboratory, Marine Environment and Sustainable Development Unit ENEA, Via Forte Santa Teresa Pozzuolo di Lerici 19100, La Spezia, Italy
[3] Department of Biological Sciences, University of Hull, HU6 7RX, UK.
[4] DiSTEBA, University of Salento, Lecce, Italy.
[5] Department of Marine Biology, Texas A&M University at Galveston, 5007 Avenue U, Galveston, TX 77551, USA)
[6] Stazione Zoologica Anton Dohrn, Laboratory of Functional and Evolutionary Ecology, Villa Comunale 80121, Napoli (Italy).

AN INITIAL USE OF MICROFLUIDICS FOR INVESTIGATING THE EFFECTS OF CHANGES IN CARBONATE SYSTEM ON PHYTOPLANKTON

Carbonnel, Vincent [1,2], Liping Zhou [1,2], Chunxiong Luo [3,4], and Qi Ouyang [3,4]

Most of laboratory-based experimental investigations on the effects of changes in seawater carbonate system on phytoplankton have been conducted in volumes ranging from a few hundreds of milliliters to tens of liters, thus with a large number of cells. Such approaches allow observations of specific effects at population levels, which provided valuable insights to forecast the future responses of the phytoplankton community, as well as the consequences in the ocean carbon cycle. However, our ability to perform such predictions is still limited by the lack of understanding of the effects of these environmental changes on response mechanisms at the cellular level. In addition, little is known about the effects on phytoplankton elemental ratios and nutrient consumption despite the importance of this issue in the future ocean, where competition between phytoplankton species for limiting nutrients will increase due to enhanced stratification. Here we report preliminary results of our use of microfluidics for investigating the effects of changes in the carbonate system on phytoplankton. This technique offers a unique opportunity to perform experiments on a single or limited number of phytoplankton cells, and to easily, quickly and precisely control the medium composition at the vicinity of the cell. Experiments with phytoplankton grown in microfluidic environments are designed to investigate how certain phytoplankton species would respond to different CO_2 concentrations and nutrient regimes, and in particular how the perturbations affect the way they consume nutrients and respond to nutrient shortage. These results will be discussed in comparison with data obtained in conventional cultures.

[1] Department of Geography, Peking University, 100871 Beijing, China (carbonnel.vincent@gmail.com)
[2] Center for Ocean Research, Peking University, 100871 Beijing, China
[3] Center for Microfluidic and Nanotechnology, The State Key Laboratory for Artificial Microstructures and Mesoscopic Physics, School of Physics, Peking University, 100871 Beijing, China
[4] Center for Theoretical Biology, Academy for Advanced Interdisciplinary Studies, Peking University, 100871Beijing, China

RESPONSE OF MUSSELS TO MULTIPLE ENVIRONMENTAL STRESSORS: AN ECOMATERIALS PERSPECTIVE

Carrington, Emily, Michael O'Donnell, Laura Newcomb, and Matthew George

The performance of any organism in its natural environment is often constrained by its structural integrity. This physical constraint is clearly evident in coastal marine ecosystems, where shells and spines deter predators, body size, shape and flexibility influence hydrodynamic stress, and the strength of tethers and adhesives secure attachment to benthic substrates. It has been shown that ocean acidification can alter calcification rates as well as resource allocation to non-calcified tissues. How do these structural modifications at the organismal level affect ecological performance? This study builds on our previous work with mussel byssus, the collagenous fibers that tether these bivalve mollusks to hard substrates. Natural and farmed populations are prone to "fall-off" events in late summer, when increased storms coincide with weak attachment. To isolate which environmental conditions contribute to byssus weakening, we exposed the mussel *Mytilus trossulus* to a broad suite of environmental conditions ($p\mathrm{CO_2}$, temperature, food supply) for several weeks in laboratory mesocosms and then quantified the material properties of the byssal threads produced. Threads were weaker in mussels held in elevated $p\mathrm{CO_2}$ conditions, as well as in elevated water temperature or reduced food supply. These results suggest multiple environmental stressors, including ocean acidification, can combine to critically compromise the structural integrity of mussels. In extending these findings to real world conditions, it will be important to consider the timing and magnitude of environmental fluctuations encountered by mussels in nature.

Friday Harbor Laboratories, University of Washington, 620 University Road, Friday Harbor WA 98250, USA. (ecarring@uw.edu)

IMPACT OF OCEAN ACIDIFICATION ON THE METABOLISM AND ENERGETICS OF INTERTIDAL PORCELAIN CRAB EARLY LIFE HISTORY STAGES

Carter, Hayley, Lina Ceballos, Nathan Miller, and Jonathon Stillman

It is probable responses to ocean acidification (OA) relate to an organisms' habitat and their capacity to buffer environmental change. Few studies assess physiological impacts on coastal intertidal organisms living in environments with CO_2-induced pH decline greater than IPCC OA projections. We use intertidal crab *Petrolisthes cinctipes* to explore how energetic processes are altered at different stages during exposure to low pH. Physiological mechanisms allowing larvae to transition from stable pH environments (pelagic) to habitats with pH fluctuations (intertidal) are poorly understood. Do metabolic responses to OA vary among early developmental stages? Metabolic rates, total protein, dry weights, total lipids and C/N were determined in late embryos, zoea I larvae and juvenile crabs reared in ambient pH (7.96±0.04) or low pH (7.60±0.06). Embryos exposed to pH 7.60 (7 to 10 d) displayed 11% and 6% mean reduction in metabolism and dry weight, respectively, however responses varied by clutch indicating significant maternal effects among six females. Larval and juvenile metabolism was not affected by CO_2. Larvae contained 7% less nitrogen and C/N was 6% higher in individuals reared at pH 7.60, representing a switch from lipid to protein metabolism. Dry weight was 19% reduced in juveniles after 8 d in pH 7.60, however differences disappeared at 33 d suggesting compensation after long-term exposure. Differences in energy partitioning likely underlie varying sensitivities to OA among stages and clutches. Understanding organism responses to high CO_2 in variable pH environments is vital in predicting future influences of OA on near shore ecosystems.

San Francisco State University, Romberg Tiburon Center for Environmental Studies
3152 Paradise Drive, Tiburon CA 94920 (hacarter@sfsu.edu)

EFFECTS OF OCEAN ACIDIFICATION ON EARLY LIFE-HISTORY STAGES OF THE PORCELAIN CRAB PETROLISTHES CINCTIPES (DECAPODA; ANOMURA)

Ceballos, Lina, Hayley Carter, Nathan Miller, and Jonathon Stillman

Intertidal zone organisms naturally experience daily pH fluctuations reaching values at or below predicted ocean acidification (OA) levels. The intertidal zone porcelain crab, *Petrolisthes cinctipes*, was used to study responses to OA across early life history stages that occur in habitats with different pH characteristics. In these crabs, embryonic development occurs in the intertidal zone, larvae mature in the more stable planktonic pH environment, and at settlement juvenile crabs return to benthic intertidal zone. The aim of this study was to assess the sublethal consequences of sustained OA during the potentially vulnerable embryonic, larval and juvenile stages. Hatching success did not differ between pH conditions after short-term exposure, but ranged from 30-95% among broods. Larval survival was not affected by 9d of acidification. Juvenile survival was lower during 40d exposure to low pH. Embryo and larval heart rates were 37% and 20% lower at low pH, and there was a brood-specific response to low pH in embryos. Embryonic and larval cardiac output were reduced by 52% and 21% respectively under

low pH with little or no modification of stroke volume. Egg size did not change after 4 days under low pH compared to a 15% increase in ambient conditions. Embryos and larvae of *P. cinctipes* showed a sublethal response to short-term acidification that involves a reduction in cardiac performance with no subsequent effect on hatching success or survival. We conclude that long-term sustained acidification could be detrimental to some organisms despite historical exposure to naturally fluctuating hypercapnic environments.

San Francisco State University/ Romberg Tiburon Center. 3150 Paradise Dr Tiburon, CA 94920 (linaco@sfsu.edu)

REAL TIME MONITORING OF SEA WATER ACIDIFICATION, EUTROPHICATION AND HYPOXIA OFF THE CHANGJIANG ESTUARY

Chen, Jianfang[1, 2], Xiaobo Ni [2], Daji Huang[2], Kui Wang[1], Haiyan Jin[1], and Hongliang Li[1]

Inputs of anthropogenic nutrients and carbon dioxide-rich fresh waters to the coastal waters can not only lead to eutrophication in the surface water and hypoxia in the bottom water, but also will enhance acidification of coastal water. Ten cruises of comprehensive survey of water quality monitoring (DO, pH, Alk, DIC, nutrients and *Chl a* etc.) in the Changjiang estuary and adjacent area were carried out since 2006. Our results and other previously studies suggested that the Taiwan warm current intrusion, the Changjiang diluted water plume and summer water column stratification were the main factors determining the spatial and temporal variation of eutrophication and hypoxia water distributions, among which nutrients-rich Changjiang diluted water variation is the dominated one. In order to understand the details mechanism of concurrence of eutrophication, acidification and hypoxia in the Changjiang Estuary, a real time monitoring system has been established since 2010 under the support of Chinese National Key Technologies R&D Program and Chinese Marine Research Special Funds for Public Welfare Projects. The platforms of the monitoring system includes a 3-meter buoy with water column chain unit and a seabed mounted unit, the sensors includes those can detect wind speed and direction, air and water temperature, salinity, currents, PAR, DO, pH(Sami), nutrients, *Chl a*, turbidity and pCO_2 etc..

[1]Laboratory of Marine Ecosystem and Biogeochemistry, Second Institute of Oceanography, SOA, Hangzhou 310012, P R China (jfchen@sio.org.cn)
[2]State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, SOA, Hangzhou 310012, P R China

BIOGEOCHEMICAL CONTROLS ON THE CALCIUM CARBONATE SATURATION STATE IN THE WESTERN ARCTIC

Chierici, M.[1,2], A. Fransson[3], L.A. Miller[4], E. Shadwick[5], and H. Thomas[6]

We investigated the annual cycle of carbonate system in the polar mixed layer (PML) of the circumpolar flaw lead in the Amundsen Gulf, Arctic Ocean. During 11-months we sampled and measured total alkalinity, and total inorganic carbon, and calculated the carbonate ion concentration ($[CO_3^{2-}]$), and the aragonite saturation state (ΩAr). Based on the empirical relationships between ($[CO_3^{2-}]$ and ΩAr, with nitrate, salinity and temperature, we found that biological processes (photosynthesis and respiration) accounted for about 50% of the monthly variations in both $[CO_3^{2-}]$ and ΩAr. Vertical mixing and salinity changes had equal impacts over the annual cycle. The impact of sea-ice melt water resulted in

decreasing Ω values in summer, but most of this change was offset by the Ω increase as a result of CO_2 drawdown during biological photosynthesis. The seasonal variability of ΩAr is discussed in a context of the life cycle of aragonite-forming organisms, such as *Limacina helicina*. Our observation that the annual biological cycle has a strong influence on $CaCO_3$ saturation states emphasizes the importance of full annual data coverage of the oceanic carbonate system if we are to ultimately understand the impact of ocean acidification in the Polar Ocean.

[1]Institute of Marine Research, Tromsø, Norway
[2]University of Gothenburg, Göteborg, Sweden (melissa@imr.no, melissa@chem.gu.se)
[3]University of Gothenburg, Göteborg, Sweden, now at Norwegian Polar Institute, Tromsø, Norway
[4] Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC, Canada
[5] CSIRO and Antarctic Climate and Ecosystems Cooperative Research Center, Hobart, TAS, Australia;
[6]Department of Oceanography, Dalhousie University, Halifax Nova Scotia, Canada

DISSOLUTION OF BIOGENIC CALCIUM CARBONATES IN RESPONSE TO OCEAN ACIDIFICATION

Chou, Lei[1], Marion Gehlen[2], and Daniela Schmidt[3]

Present-day's surface ocean is oversaturated with respect to calcium carbonate polymorphs calcite and aragonite, and is at saturation with respect to Mg-calcite containing 15 mole % Mg. Anthropogenic emission of CO_2 since the beginning of the industrial era has resulted in acidification of surface seawater, leading to a decrease in the saturation state of various biogenic calcium carbonates. Future projections show that high latitude and cold water marine calcifiers are at imminent risk to ocean acidification and that shallow marine carbonate sediments containing high Mg-calcites could dissolve. The dissolution of shallow carbonate sediments will alter the habitat for benthic biota and, being a source of alkalinity to the ocean, interact with the global C cycle.
Dissolution kinetics of calcium carbonates of mineral and biogenic origin in synthetic seawater was investigated using pH free-drift method at 25°C and at pCO_2 close to 3000 ppmV (1 atm total pressure). Biogenic carbonates studied include coccoliths, foraminifera and Mg-calcites such as sea urchin tests and spines. Samples are in addition examined for surface dissolution features using Scanning Electron Microscopy after dissolution experiments. In order to interpret the results in terms of reaction orders with respect to the saturation state, solubilities of the corresponding pure phases were also re-evaluated under the same experimental conditions. Rate constants and reaction orders obtained in this study are compared to those reported in the literature. Impact of ocean acidification on carbonate dissolution is also discussed. Ultimately, this study will derive improved parameterization of $CaCO_3$ dissolution kinetics for implementation in numerical models.

[1]Service de Biogéochimie et Modélisation du Système Terre – Océanographie Chimique et Géochimie des Eaux, Département des Sciences de la Terre et de l'Environnement, Université Libre de Bruxelles, Campus de la Plaine – CP 208, Boulevard du Triomphe, B-1050 Brussels, Belgium (Lei.Chou@ulb.ac.be)
[2]Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS-UVSQ, CEN de Saclay / L'Orme des Merisiers, Bât.712, F-91191 Gif-sur-Yvette Cedex, France
[3]Department of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, United Kingdom

STRUCTURAL AND FUNCTIONAL VULNERABILITY TO ELEVATED *p*CO_2 IN MARINE BENTHIC COMMUNITIES

Christen, Nadja[1,2,3], Piero Calosi[1], Caroline L. McNeill[2], and Steve Widdicombe[2]

The effect of low pH/elevated *p*CO_2 on marine invertebrate benthic biodiversity, community structure and the functional responses which underpin ecosystem services (e.g. productivity and calcification) was tested in a medium-term (30 d) mesocosm experiment. Standardised macrobenthic communities, collected using artificial substrate units (ASUs), were exposed to one of seven pH treatments (8.05, 7.8. 7.6, 7.4, 7.2, 6.8 and 6.0). Community respiration, net calcification/dissolution rates, changes in biomass, and community structure and diversity were measured at the end of the experimental period. Communities showed significant changes in structure and reduced diversity in response to reduced pH: shifting from a community dominated by calcareous organisms to one dominated by non-calcareous organisms around either pH 7.2 (number of individuals and species) or pH 7.8 (biomass). These results were supported by a reduced total weight of $CaCO_3$ structures in all major taxa at lowered pH and a switch from net calcification to net dissolution of the entire community around pH 7.4 (Ω_{calc} = 0.78, Ω_{ara} = 0.5). Overall community soft tissue biomass did not change with pH and high mortality was observed only at pH 6, although molluscs and arthropods showed significant decreases in soft tissue. Finally, community respiration did not differ between pH treatments at 30 d exposure. This study supports and refines previous findings on how ocean acidification can induce changes in marine biodiversity, underlined by differential vulnerability of different phyla. In addition, it shows for the first time significant changes in fundamental community functional responses underpinning changes in ecosystem services.

[1]Marine Biology and Ecology Research Centre, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK.(piero.calosi@plymouth.ac.uk)
[2]Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, PL1 3DH, UK.
[3]Current address: Centre for Ecology & Conservation, University of Exeter Cornwall Campus, Penryn, Cornwall, TR10 9EZ.

SIZE SELECTIVE MORTALITY IN LARVAL ATLANTIC COD, *GADUS MORHUA* L. IN RELATION TO OCEAN ACIDIFICATION REVEALED BY OTOLITH ANALYSIS

Clemmesen, Catriona[1], Maneja, Rommel H.[1], Frommel, Andrea Y.[1], Geffen, Audrey J.[2], Folkvord, Arild[2], and Uwe Piatkowski[1]

The effect of ocean acidification on size selective mortality of larval Atlantic cod (*Gadus morhua* L.) was investigated by rearing cod at three *p*CO_2 concentrations, control-370, medium-1800, and high-4200 ppm from March to May 2010 in Espegrend, Norway in land-based outdoor mesocosms at ambient temperature and light conditions as well as natural food. Direct mortality could not be estimated due to the large size of the tanks (2300 l) and the large number of fish larvae (10.000 per tank) introduced to these systems. Therefore an indirect estimate of mortality using otolith microstructure analysis had to be applied. Otolith microstructure analysis can be used to determine ages, growth rates and selective mortality. Under mesocosm settings repeated samplings within the same population allow for an accurate determination of size-selective mortality by comparison of otolith size-at-age based on samples from different dates and back calculations. Here we provide an example using otolith microstructure analysis to evaluate mortality patterns during the transition from cutaneous respiration to gill respiration in cod larvae being treated with different levels of CO_2 during their larval development. This will allow determining whether survival in response to CO_2 treatment is random or whether a selection

for a certain size group exists. The hypothesis to be tested is that "the survivors from the high CO_2 treatment are the slower growing fish, which are still capable of managing their osmoregulatory capacities via the skin". The analysis will give new insights into the "characteristics of the survivors" after CO_2 treatment.

[1] Helmholtz Centre for Ocean Research Kiel (GEOMAR), Düsternbrooker Weg 20, 24105 Kiel, Germany
[2] Department of Biology, University of Bergen, PO Box 7803, N-5020 Bergen, Norway
Email: (cclemmesen@geomar.de)

ACID-BASE BALANCE IN THE CIDAROID SEA URCHIN EUCIDARIS TRIBULOIDES

Collard, Marie[1,2], Dery Aurélie[1], and Dubois Philippe[1]

The increase in atmospheric CO_2 due to anthropogenic activity results in an acidification of the surface waters of the oceans. The impact of these chemical changes depends on the considered organisms, in particular on their ability to regulate the pH of their extracellular fluids. Some organisms present a higher buffer capacity in their inner fluids than that of seawater. Such capacity was recorded in the sea urchin *Paracentrotus lividus*. It is due both to the presence of coelomocytes in the coelomic fluid and to a compound of an apparent size larger than 3 kD. Decreased seawater pH induces a gradual increase of this capacity. Interestingly, only Euechinoidea (most sea urchins, heart urchins and sand dollars) present this high buffer capacity while cidaroids (the other sub-class of sea urchins), starfish and holothurians have a lower one. This is quite surprising as cidaroids are important components of the deep-sea benthos, which often lies below the saturation horizon for calcium carbonate. In the present study, we investigated the effects of decreased pH on the acid-base balance and buffer capacity in the cidaroid *Eucidaris tribuloides* in order to determine the resilience of this taxon in front of future ocean acidification.

[1] Laboratoire de Biologie Marine, Université Libre de Bruxelles, 50 avenue F.D. Roosevelt, B-1050 Brussels, Belgium (marie.collard9@gmail.com)
[2] Laboratorium voor Analytische Chemie, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

THE IMPACT OF OCEAN ACIDIFICATION AND NUTRITION ON *B. ELEGANS* LARVAL RECRUITMENT AND EARLY CALCIFICATION

Crook, Elizabeth D., Helen O'Brien, Rachel Fabian, Niko Pogorevcnik, Donald Potts, and Adina Paytan.

In light of future ocean acidification events, it is understood that tropical, hermatypic corals may respond negatively to decreasing surface ocean pH. While it is clear that calcification is energetically costly, the response of cold-water corals to ocean acidification in nutrient-rich upwelling regimes, where the pH of the water often drops below future projections, is less well documented. *Balanophyllia elegans* (the "orange cup" coral) is an inter/subtidal solitary coral that lacks symbionts, is endemic to the California coastal area, and thus thrives in high nutrient, low pH waters. We assess the impact of ocean acidification on *B. elegans* larval recruitment and juvenile and adult growth over a 6 month study period. Calcification rates under three CO_2 treatment groups (380, 750, and 1200ppmV) and two feeding regimes (nutrient replete and nutrient deplete conditions) are quantified. We address the impact of nutrition (i.e. energy consumption) on the calcification process and how cold water corals may respond to ocean acidification in a high CO_2 world.

University of California, Santa Cruz, Department of Earth and Planetary Sciences, 1156 High Street, Santa Cruz, CA 95064 (ederse@ucsc.edu)

EFFECTS OF OCEAN ACIDIFICATION ON BENTHIC OXYGEN DYNAMICS IN MUDDY AND SANDY SEDIMENTS

Currie, Ashleigh, Natalie Hicks, and Henrik Stahl

Coastal and estuarine areas are of global importance due to their capacity for primary production and cycling of elements. Shallow water sediments play a major role in fundamental processes, such as, mineralisation and resupply of nutrients from early diagenesis of organic matter into the water column where it can fuel further primary production. Benthic primary producers, micro- and macroalgae and seagrasses, are imperative to maintain healthy and viable local food webs. With increased global and regional anthropogenic impacts, it is essential to further our understanding how elemental processes may shift or become altered. To date, the effects of ocean acidification on major biogeochemical processes is limited and as levels of atmospheric CO_2 continue to rise, research efforts are needed to provide a clearer understanding of how benthic primary production will be impacted in a high-CO_2 world. In the present study, cohesive and permeable sediments are subjected to ambient and projected CO_2 levels in combination with elevated temperature treatments under natural flow and light conditions. The sediments are exposed to the manipulated environmental conditions (CO_2, temperature, light) for four weeks and contained within custom-built flume tanks. Weekly oxygen (O_2) profiles, from oxygen microelectrodes, were collected under both light and dark conditions in the flumes to determine the O_2 penetration depth as well as the benthic O_2 flux as a proxy for net primary production/mineralization under the different treatments. This approach is used to aid our understanding of how OA impacts benthic oxygen dynamics and the availability of oxygen in coastal sandy and muddy sediments, a key parameter for regulating benthic biogeochemical cycling of important elements like carbon and nutrients.

Scottish Association for Marine Science, Oban, Scotland, PA37 1QA, United Kingdom (Ashleigh.Currie@sams.ac.uk)

TRENDS AND SEASONAL VARIABILITY OF THE CARBON CYCLE IN SUBANTARCTIC SURFACE WATER IN THE SOUTH WEST PACIFIC OCEAN

Currie, Kim[1], Holger Brix[2], and Sara E. Mikaloff Fletcher[3]

Few southern hemisphere time-series measurements of biogeochemical tracers are available, and this scarcity is a major impediment in understanding the processes underlying the oceanic carbon and nutrient cycles in vast parts of the global oceans. We make use of bi-monthly measurements of carbonate parameters from 1998 through 2010 in upper subantarctic surface water east of New Zealand to investigate seasonal and long term variability. We observe positive trends in DIC and pCO_2 that are smaller than would be expected from the anthropogenic increase in atmospheric pCO_2, possibly due to a decrease of the average temperature over the observational period. The seasonal cycle of pCO_2 is dominated by that of DIC, but is substantially modified by the influence of the annual cycle of sea surface temperature. For an investigation of the mechanisms controlling the seasonal cycle of DIC we used a modified version of a diagnostic box model that has been used previously for similar investigations of carbon budget at Stations ALOHA and BATS. Preliminary results point to a dominance of biological processes for the observed seasonal variations.

[1] National Institute of Water and Atmospheric Research (NIWA), Dunedin, New Zealand, (kim.currie@niwa.co.nz)
[2] Department of Atmospheric and Oceanic Science, University of California, Los Angeles, U.S.A
[3]NIWA, Wellington, New Zealand

DIRECT EVIDENCE FOR DECREASING pH IN SUB-ANTARCTIC SURFACE WATERS DURING THE LAST DECADE

Currie, Kim[1], Malcolm Reid[2], and Keith Hunter[3]

Detection of changing seawater pH and attribution of any observed changes to natural and anthropogenic perturbations requires long-term high quality measurements at representative sites throughout the marine environment. Currently there are few such time series, and the majority of these are in the northern hemisphere. Surface pH has been directly measured on the Munida time series transect in the South West Pacific Ocean near New Zealand since December 2000. In sub-antarctic surface water annual variability is primarily due to biological effects dominating over thermodynamic and mixing effects. The 11 year time series indicates that CO_2 is in equilibrium with the atmosphere in the (austral) winter, and is a sink for atmospheric CO_2 in spring and summer. A long term decrease in pH(25^oC) of 0.0021 +/- 0.0007 pH units per year is observed, in agreement with the theoretical annual decrease of 0.0017 expected for equilibration of constant alkalinity seawater with atmospheric CO_2, as measured at Baring Head, New Zealand.

[1] National Institute of Water and Atmospheric Research (NIWA), Dunedin, New Zealand. kim.currie@niwa.co.nz
[2] Department of Chemistry, University of Otago, Dunedin, New Zealand

ELEMENT BUDGETS IN AN ARCTIC MESOCOSM CO_2 PERTURBATION STUDY

Czerny, Jan[1], R. G. J. Bellerby[2], T. Boxhammer[1], A. Engel[1], S. Krug[1], A. Ludwig[1], K. Nachtigall[1], B. Niehoff[3], K.G. Schulz[1], and Ulf Riebesell[1]

Recent studies on the impacts of ocean acidification on pelagic communities have identified changes in carbon to nutrient dynamics with related shifts in elemental stoichiometry. In principle, mesocosm experiments provide the opportunity of determining the temporal dynamics of all relevant carbon and nutrient pools. In practice, attempts to budget mesocosm enclosures are often hampered by uncertainties in some measured pools and fluxes, in particular due to uncertainties in constraining air/sea gas exchange, particle sinking, and wall growth. In an Arctic mesocosm study on ocean acidification using the “KOSMOS” system, all significant element pools and fluxes of carbon, nitrogen and phosphorus were measured. Water column concentrations of particulate and dissolved organic and inorganic constituents were determined daily. New approaches for quantitative estimates of material sinking to the bottom of the mesocosms and gas exchange with 48 h temporal resolution, as well as estimates of wall growth were developed to close the gaps in element budgets. Future elevated pCO_2 was found to enhance net autotrophic community carbon uptake but did not significantly affect particle elemental composition. Enhanced carbon consumption appears to result in the accumulation of dissolved organic compounds under nutrient recycling summer conditions. During a phase of nutrient replete conditions picoeukaryotic phytoplankton profited from high pCO_2. The out-competition of large-sized diatoms by these comparatively small algae caused reduced export of carbon, nitrogen and

phosphorus under future ocean CO_2 conditions. In contrast to findings for mesocosms in boreal Norwegian waters, this study suggests a future weakening of the biological carbon pump in the Arctic.

[1]Helmholtz Centre for Ocean Research (GEOMAR), 24105 Kiel, Germany (jczerny@geomar.de)
[2]Bjerknes Centre for Climate Research, 5007 Bergen, Norway
[3]Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

INVESTIGATING ADVANCED UNDERGRADUATE SCIENCE STUDENTS' CONCEPTIONS & MISCONCEPTIONS OF OCEAN ACIDIFICATION

Danielson, Kathryn I. and Kimberly D. Tanner

There is a tacit assumption that advanced undergraduate science students – of junior/senior class standing – in the disciplines of Biology, Chemistry, and Environmental Studies understand ocean acidification. However, there is little science education research that supports this assumption. A study published in February 2011 entitled "Students' Conceptions about the Greenhouse Effect, Global Warming, and Climate Change" contained no assessment of ocean acidification, and few surveys have examined public awareness of ocean acidification (Logan 2010; Shepardson 2011). Considering the multi-disciplinary science curriculum of an undergraduate science major, one would predict an advanced undergraduate science student would be able to understand the biological, chemical, and environmental implications of ocean acidification. To what extent are these advanced undergraduate science students 'emerging experts' with regards to ocean acidification? How do advanced undergraduate science students' conceptions of ocean acidification compare to one another? Employing a mixed-methods research design, data was collected through written assessments about students' conceptions of ocean acidification (Biology, n=133), Chemistry, n=60), Environmental Studies, n=52) and follow-up interviews with smaller subpopulations. Results indicate: 1) ocean acidification literacy is low among all three populations of advanced undergraduate science students, 2) Environmental Studies majors are more likely to have heard of ocean acidification, as well as provide scientifically accurate conceptions of the causes and effects of ocean acidification, and 3) newly documented student misconceptions about ocean acidification are present among all three populations of advanced undergraduate science students. To our knowledge, this is the first investigation of ocean acidification literacy among undergraduate science students.

EPAL : The Science Education Partnership & Assessment Laboratory, Department of Biology, San Francisco State University, 1600 Holloway Ave., San Francisco, CA 94132-1722 (kdaniels@mail.sfsu.edu)

APPROACHES TO STUDY THE EFFECT OF CLIMATE CHANGE ON MARINE ORGANISMS: A MICROBIAL PERSPECTIVE

Das, Surajit

Climate change has significant impact on marine microbes, potentially altering their diversity, function and community dynamics. There is no robust prediction of how marine microbes will be affected by increased CO_2 and pH changes. Among the marine organisms, bacteria are generally the first organisms respond by any changes in the environmental parameters. In response to UV damage, bacteria show different repair pathways, including photoenzymatic repair (PER), nucleotide excision repair (NER) (also called dark repair), and recombinational repair (postreplication repair). If there is a heavy damage due to climate change factors in marine environment (UVR, high CO_2 and low pH) SOS response (ultimate

repair mechanism) will fail to repair the damage. Since marine bacteria are under threat of climate change, at certain point of damage bacterial repair mechanisms will fail to repair DNA damage. Therefore, studies on the consequence of climate change on marine bacteria will be helpful in predicting the vulnerability of marine organisms. Climate change induced changes in the composition of bacterial communities can be determined using DGGE. Survival percentage and growth curve of selected bacterial isolates in response to stress viz. temperature, pH and UVR can be estimated to identify the winner species under conditions of high temperature, pH and UVR. Construction of mutants and studies on DNA damage and repair pathway (photoreactivation, NER pathway and RecA expression) in a model bacterium (showing higher survival to stress) can be studied to see the role of these genes in repair.

Laboratory of Environmental Microbiology and Ecology (LENME), Department of Life Science, National Institute of Technology, Rourkela- 769 008, Orissa, India (surajit@nitrkl.ac.in)

FORAMINIFERAL WEIGHT AND COCCOLITH DIAMETER RESPONSE TO PLIOCENE CLIMATE VARIABILITY

Davis, Catherine[1], Marcus Badger[2], Marilyn Potts, Paul Bown[3], and Daniela Schmidt[4]

With ocean acidification a serious concern for the future of the oceans and calcifying plankton as fundamental contributors to the ocean ecosystem, carbon cycle and sensitive to the ocean-atmosphere-climate dynamic, understanding the biotic response of calcifying plankton during periods of heightened acidity is crucial. Between 3.3-2.6Ma, the Pliocene saw a significant shift in global climate and from levels similar to modern to near pre-industrial levels. As a measure of biotic response of calcifying organisms to changes in CO_2, cocolithophorid lith diameter and foraminiferal weights were measured at two sites in the Atlantic, ODP 999 on the Sierra Rise (*Reticulofenestra*, *Globigerinoides ruber)* and DSDP 607 in the North Mid-Atlantic (*Reticulofenestra, Globigerinida bulloides*, *Globorotalia punticulata*). Size-normalized weight in *G. ruber, G. bulloides* and *G. punticulata* are highly variable and do not appear to follow long-term trends in CO_2 although they may correlate with local temperature fluctuations. Between 3.1-2.8Ma, potentially orbitally-driven variability in coccolithophore size trends become distorted with an abrupt drop in the number of large sized lith from the North Atlantic and a mirrored increase at the Sierra Rise, coinciding with some a significant decline in pCO_2.

[1]Department of Geology, University of California, Davis, CA 95616, USA; cvdavis@ucdavis.edu
[2]School of Chemistry, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, UK
[3]Paul Bown, Department of Earth Sciences, University College, London, Gower St, London WC1E 6BT
[4]School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, UK

EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON THE CALCIFICATION AND RESPIRATION OF THE COLD-WATER CORAL *LOPHELIA PERTUSA*

de Francisco-Mora, Beatriz [1] Kim Last[1] Henrik Stahl[1], and Murray Roberts[1,2]

It is well known that ocean acidification and warming will have important impacts on marine biota particularly on calcifying organisms, due to shoaling saturation horizons of calcite and aragonite and an increased in metabolic pressures. However, to date there is limited information about the coupled effects of acidification and warming on physiology. To address this, the physiological response of *Lophelia pertusa* to acidification and warming was determined. *L. pertusa* nubbins were exposed to four experimental treatments (ambient = 8°C – 380pCO_2; elevated pCO_2 = 8°C – 750pCO_2; elevated

temperature = 12°C – 380 pCO_2 and elevated temperature and pCO_2 = 12°C – 750 pCO_2) for a six week period. Results show a differential effect of temperature and pCO_2 on respiration and calcification, where temperature is the main driver for changes in respiration and pCO_2 is mainly responsible for changes in calcification. The interaction between the stressors resulted in an additive effect for respiration and a synergistic effect for calcification. Only elevated pCO_2 treatments resulted in dissolution at both temperatures. A strong negative relationship between the amount of coral polyp tissue and respiration was determined and to a lesser extent with calcification. This would suggest that the faster growing sections of the reef i.e. with more coral polyp tissue will be more severely impacted by ocean warming and acidification.

[1] Scottish Association for Marine Science, Scottish Marine Institute, Oban, Argyll, PA37 1QA, UK (beatriz.defrancisco@sams.ac.uk)
[2] Centre for Marine Biodiversity and Biotechnology, Heriot-Watt University, Edinburgh, EH14 4AS, UK

CRUMBLING CORALS? MICROSTRUCTURAL CHANGES IN *LOPHELIA PERTUSA* SKELETON IN RESPONSE TO OCEAN ACIDIFICATION AND WARMING

de Francisco-Mora, Beatriz [1] Fifion Lowe[1,2] Ruth Paterson[1], Henrik Stahl[1] and Kim S. Last[1]

The cold-water coral *Lophelia pertusa* is a widespread reef building coral that plays a key biodiversity role in the North Atlantic, providing habitat for more than 1000 species. Reef development for this species results from live sections growing on top of older, dead coral skeleton sections, generating massive three-dimensional structures. Recent studies suggest that *L pertusa* is able to calcify under future predicted elevated temperature and pCO_2, though at lower rates than currently observed. However results also show that elevated pCO_2 causes important changes to the microstructure of the skeletons implying that *Lophelia* reefs may actually become highly susceptible to mechanical erosion even though there may still be calcification at the living coral sections. This response may threaten the integrity of the physical reef structure and therefore the ecological role of the species as a habitat provider.

[1] Scottish Association for Marine Science, Scottish Marine Institute, Oban, Argyll, PA37 1QA, UK (beatriz.defrancisco@sams.ac.uk)
[2] University of St. Andrews, College Gate, St Andrews, Fife, KY16 9AJ, UK.

ARE CIDAROID PRIMARY SPINES ADAPTED TO OCEAN ACIDIFICATION ?

Dery Aurélie[1], Ana I. Catarino[1], Virginie Guibourt[1], Chantal De Ridder[1], Philippe Compère[2], and Philippe Dubois[1]

Cidaroids are a sister group to all other extant echinoids, that shows particular features among which unusual primary spines. The latter lack an epidermis when mature, exposing their high-magnesium skeleton to sea water and allowing the settlement of numerous epibionts. Also, their spines are made of an inner core of classical monocristalline skeleton while the outer layer is made of polycristalline magnesium-calcite. Interestingly cidaroids survive the Permien-Trias crisis characterized by a severe acidification of the ocean. Currently, members of this group inhabit the deep ocean below the saturation horizon for their magnesium calcite skeleton. This suggests that members of this taxon may have characteristics allowing them to resist the ongoing ocean acidification linked to global change. Therefore, the goal of the present work was to determine the impact of acidified seawater on structure and morphology of cidaroid spines. In a first step, we compare the effect of acidified sea-water (pH 7.2, 7.6, 8.2) on mature spines with a fully developed cortex vs young spines in which only the stereom core was developed. This showed that mature spines where much more resistant to etching. In a second step, we investigated the properties of the cortex that could be responsible for his resistance, namely morphology, organic matrix, magnesium concentration and the intrinsic concentration of the material. Results showed that the lower solubility of the cortex is probably due to its lower porosity, allowing a lower contact surface with etching solution.

[1] Laboratoire de Biologie Marine, Université Libre de Bruxelles, 50 avenue F.D. Roosevelt, B-1050 Brussels, Belgium (auredery@gmail.com)
[2] Département des sciences et gestion de l'environnement, Université de Liège, Bât. B6c, allée du 6 Août 10; 4000 Liège, Belgium.

C-CAN: WORKING TOGETHER TO CHARACTERIZE OCEAN ACIDIFICATION

Dickson, Andrew G.

The West Coast shellfish industry has been observing shellfish recruitment failures and larval mortalities both in hatcheries and the wild for the past few years. One hypothesis is that these dramatic declines in productivity are related to increasing ocean levels of carbon dioxide found along the West Coast, and the corresponding decrease in the saturation state of the carbonate minerals that shellfish use to create their shells.
The California Current Acidification Network (C-CAN) was formed as a collaborative effort between members of the West Coast shellfish industry and scientists to explore what is causing shellfish losses on the Pacific coast, what role ocean acidification and other factors might be playing in this problem, and how to adapt to these changes in order to sustain West coast shellfish resources.
Our first goal (supported by the Gordon & Betty Moore Foundation) has been to develop a roadmap for integrating ocean acidification observing activities on the US West Coast that ensures balanced participation of academic, governmental, and commercial stakeholders. The collaborative approach we are recommending is based on presentations and discussions that took place at two workshops (in July 2011 and in December 2011) that discussed the physical, chemical, and biological measurements that were felt essential, the uncertainty required, as well as plans for data distribution. We are proposing to finalize the plan and to discuss implementation at a third workshop (scheduled for the end of July 2012) and will be able to present it in its final form at this meeting.

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, USA (adickson@ucsd.edu)

TRANSCRIPTOME RESPONSE OF *EMILIANIA HUXLEYI* TO HIGH TEMPERATURE AND CO_2

Dorfman, Rachel E.[1], Ina Benner[1], Stephane Lefebvre[2], Jonathon Stillman[1], Tomoko Komada[1], and Edward J. Carpenter[1].

Calcifying marine phytoplankton (i.e. coccolithophores) play a major role in the global carbon cycle *via* photosynthesis and calcification. Field and laboratory studies indicate that future oceanic conditions will affect the molecular and physiological responses of coccolithophores. However, the world's most abundant coccolithophore, *Emiliania huxleyi,* exhibits contrasting physiological responses to increased CO_2 and/or temperature. Although *E. huxleyi*'s physiological response to elevated CO_2 has been extensively studied, very little is known about the molecular mechanisms involved in the response to increasing CO_2 and/or temperature. *E.huxleyi* (Strain CCMP371) was grown in continuous chemostat cultures for over 200 generations at "present" (380 ppm, 20°C) and "future" (800 ppm, 24°C) ocean conditions. Samples were taken at 200 generations from each treatment, and RNA-seq libraries were constructed for next generation sequencing using the Illumina platform in order to gain insight into the transcriptome response. Here, we present preliminary data of the response of *E.huxleyi* to elevated CO_2 and temperature, focusing on genes that are expressed differentially between treatments. Transcriptomic information paired with physiological data provide a powerful and comprehensive system, revealing the molecular processes underlying physiological responses of *E.huxleyi* to changing environmental conditions.

[1] San Francisco State University, Romberg Tiburon Center for Environmental Studies, Tiburon, CA 94920, USA. (Racheld@mail.sfsu.edu)
[2] J. Craig Venter Institute, San Diego, California 92121, USA

INTRAESPECIFIC VARIABILITY IN THE RESPONSES OF THE MUSSEL *Mytilus chilensis* EXPOSED TO INCREASED CO_2 LEVELS.

Duarte, Cristian [1], Jorge M Navarro [1], Karin Acuña [1], Rodrigo Torres [2], Patricio H Manríquez [1,3], Marcos A Lardies [4], Cristian A Vargas [5], Nelson A Lagos[6], and Victor Aguilera[5]

Ocean acidification (OA) has shown to affect significantly the net calcification process and growth rate of many marine organisms. Recent studies have showed that the responses of these organisms to OA can vary significantly between species. Much less, however, is known about the intraspecific variability in response to the OA. In this study we compared the responses of two populations of the mussel *Mytilus chilensis* exposed to OA. One of the populations is located in a bay that receives a permanent input of freshwater, whereas the other one is located in a bay without freshwater inputs. Since freshwater discharges have shown to act as a "local acidification process", we hypothesized that the population constantly exposed to these discharges will be more adapted, and therefore, less affected by the increase in the CO_2 levels in the seawater. When reared in increased CO_2 levels, we registered that net calcification process and growth rate were not affected in the population associated to freshwater discharges, a contrary situation to that recorded in the other population, where both the calcification rate and growth rate were negatively affected by the CO_2 increase. These results highlight that the responses to OA can be very variably even within of a same species. Therefore more studies across the distribution of the species and covering different environments are necessary to better understand the consequences of OA.
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[1]Instituto de Ciencias Marinas y Limnológicas, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile (cduarte@uach.cl)
[2]Centro de Investigación en Ecosistemas de la Patagonia (CIEP), Coyhaique, Chile.
[3]Laboratorio Costero de Recursos Acuáticos de Calfuco, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile.
[4]Facultad de Artes Liberales, Universidad Adolfo Ibáñez, Santiago, Chile.
[5]Laboratorio de Funcionamiento de Ecosistemas Acuáticos, Centro de Ciencias Ambientales, Universidad de Concepción, Concepción, Chile.
[6]Facultad de Ciencias, Universidad Santo Tomas, Ejercito 146, Santiago, Chile.

ADULT ECHINODERMS FROM FLUCTUATING ENVIRONMENTS: SCOPE FOR ADAPTATION OR ACCLIMATIZATION TO OCEAN ACIDIFICATION?

Dubois, Philippe[1], Ana Catarino[1], Marie Collard[3], Aurélie Dery[1], Kim Laitat[1], Laure Moulin[1,2], and Philippe Grosjean[2]

Numerous echinoderm species structure the community in which they live, principally through trophic interactions. Therefore, any impact on these species could affect the whole community. Due to their low metabolism and ion regulation ability, adult echinoderms have been suggested to be particularly sensitive to ocean acidification. However, numerous echinoderms live in habitats characterized by low or fluctuating pH such as upwelling zones, intertidal pools or the deep-sea. This suggests that members of this phylum have adaptation or acclimatization abilities. Therefore, we investigated the response to acidification of different echinoderm species living in such fluctuating environments. The results indicate that different strategies are used in front of acidification. Sea urchins (except cidaroids) have a higher buffer capacity in their extracellular fluids than that of seawater and this capacity is increased when exposed to lower pH. Their respiratory metabolism is either increased or unaffected. On the contrary, starfish have a buffer capacity in their inner fluids similar to that of seawater and decrease their metabolism at lower pH. In both taxa, this results in reduced differences between the pH of seawater and that of the inner extracellular fluids with decreasing pH. At short term (2 to 4 weeks), neither growth nor protein levels (expressed as RNA/DNA ratios) were affected by reduced pH. These results suggest that adult echinoderms from habitats with fluctuating conditions do have the ability to acclimatize to low pH, at least at short term.

[1] Laboratoire de Biologie Marine, Université Libre de Bruxelles, CP 160/15 avenue F.D. Roosevelt, B1050, Brussels, Belgium. (phdubois@ulb.ac.be)
[2] Laboratoire d'Ecologie Numérique des Milieux Aquatiques, Université de Mons, 20 place du Parc, B7000, Mons, Belgium
[3] Laboratorium voor Analytische Chemie, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium

EARTH SYSTEM MODEL HISTORICAL AND FUTURE OCEAN ACIDIFICATION, $CaCO_3$ CYCLING, AND BIOGEOCHEMICAL FEEDBACKS

Dunne, John P. and Jasmin G. John

We assess the ocean's present and future ability to take up anthropogenic carbon and the impact of this ocean acidification in the fully coupled biogeochemical context using NOAA/GFDL's earth system models (ESM2M and ESM2G) with alternative representation of ocean physics, but the same ocean biogeochemical component. The models were forced with historical and future projections of Representative Concentration Pathways (RCPs) of radiatively active gases as part of the fifth Coupled Model Intercomparison Project. We describe the geographical and vertical extent of ocean acidification in these models, finding approximately 10% more rapid CO_2 uptake in the z-coordinate ESM2M than isopycnal ESM2G but otherwise very similar responses. Modeled calcite and aragonite production is depressed by 16-17% at the end of the 20th century and 67-72% at the end of the 21st Century. These responses provide additional acid neutralizing capacity in the surface ocean of 0.23 PgC a^{-1} at the end of the 20th century and 0.98 PgC a^{-1} at the end of the 21st Century. However, associated changes in the mineral ballasting of sinking organic material combine with enhanced physical stratification to reduce ballasting and shoal the remineralization of organic material with acidification feedbacks. With respect to sediment feedbacks, we find that acidification supplies additional acid neutralizing capacity of 0.11

PgC a^{-1} at the end of the 20th century, and 0.76 PgC a^{-1} at the end of the 21st Century, 0.14 PgC a^{-1} due to direct reduction in calcite supply to the sea floor and the rest due to enhanced dissolution.

NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA (john.dunne@noaa.gov)

DISTRIBUTION OF GASTROPODA AND BIVALVIA IN ICELANDIC WATERS IN RELATION TO ARAGONITE SATURATION AND OTHER ENVIRONMENTAL PARAMETERS

Egilsdottir, Hronn[1,2], Jonas Pall Jonasson[1], and Jon Olafsson[1,2]

Continuing increase in atmospheric CO_2 consequent ocean acidification is resulting in globally decreasing carbonate saturation states. At high latitudes, aragonite is already nearing undersaturation in surface waters and becomes undersaturated at relatively shallow depths (due to the negative effect of pressure and low temperatures). Carbonate chemistry time series have revealed alarmingly rapid shoaling rates of the aragonite saturation horizon (ASH) in the Iceland Sea. Olafsson et al. 2009 reported a shoaling rate of 4 meters per year, with ASH presently at 1700 m depth. Thus, based on the Iceland Sea topography, 800 km^2 of benthic habitat is added to undersaturated areas every year.
Gastropoda and Bivalvia are highly diversified classes from the phylum Mollusca that commonly inhabit benthic substrates. Majority of species within both classes produce aragonite shells, either partly (in addition to calcite) or purely. Along with various other invertebrate fauna, molluscs were sampled and identified in relation to a benthic sampling program (BIOICE), conducted around Iceland over the years 1994 to 2004 with ~1200 samples collected from a depth range of 20-3000 meters.
In this study of data from the BIOICE program we relate the distribution of Gastropoda and Bivalvia around Iceland to observed aragonite saturation levels and other environmental variables.

[1] Marine Research Institute, Skulagata 4, 121 Reykjavik, Iceland
[2] University of Iceland, Faculty of Earth Science, Askja, Sturlugata 7, 101 Reykjavik, Iceland

SLOWDOWN OF OCEAN ACIDIFICATION IN THE SUBTROPICAL WESTERN NORTH PACIFIC DUE TO OCEAN CIRCULATION CHANGE

Enyo, Kazutaka[1,2], T. Nakano[1,3], Y. Takatani[1,2], Y. Iida[1], A. Kojima[1,2], N. Kosugi[2], D. Sasano[2,1], M. Ishii[2,1], and T. Midorikawa[4]

The tropical and subtropical western North Pacific are the regions where there are many islands with coral reefs. The Japan Meteorological Agency has been measuring the partial pressure of CO_2 in surface seawater (pCO_2) since early 1980s and total dissolved inorganic carbon (DIC) since 1994 by R/Vs Ryofu Maru and Keifu Maru. For a decade until late 1990s, the mean rates of increase in pCO_2 in winter (Jan. – Feb.) were consistent with the rate of the atmospheric CO_2 increase over the zones between 3ºN and 30ºN at 137ºE meridian. However, the increase of pCO_2 has been slow on the average since late 1990s, in particular, in the southern subtropics (5ºN – 20ºN). By contrast, no significant change has been determined in the salinity-normalized total alkalinity as calculated from pCO_2 and DIC over these regions. Consequently, the rates of decreases in aragonite and calcite saturation levels as well as pH have also been slow since late 1990s. The similar trends of the seawater CO_2 parameters have also been observed along 165ºE meridian since 1996. These trends in the southern subtropics are likely to have been caused by the effect of the ocean circulation change, i.e., the multi-decadal oscillation of the subtropical cell, that is superposed on the trend of ocean acidification due to the atmospheric CO_2 rise.

[1] Global Environment and Marine Department, Japan Meteorological Agency, 1-3-4 Otemachi, Chiyoda-ku, Tokyo 100-8122, Japan (kenyo@met.kishou.go.jp).
[2] Geochemical Research Department, Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan.
[3] Oceanographic Research Department, Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan.
[4] Nagasaki Marine Observatory, 11-51 Minamiyamatemachi, Nagasaki, Nagasaki 850-0931, Japan.

COLD-WATER REEF SYSTEMS: TIDAL DOWN-WELLING AND IMPLICATIONS FOR FUTURE OCEAN ACIDIFICATION AND WARMING

Findlay, Helen S[1], Malcolm Woodward[1], Juan Moreno Navas[2], Sebastian Hennige[2], Laura Wicks[2], Veerle Huvenne[3], and Murray Roberts[2]

Several studies have investigated relationships between hydrodynamics impinging on topography and the abundance of suspension- and filter- feeders at depth. The Mingulay reef complex is one such cold-water coral system that is associated with surface water down-welling resulting from a tidal pulse. The Mingulay reef also experiences deep-water advection during peak tides. These physical drivers not only bring particles to the reef, and thereby enhance food supply, but they also create a variable environment with respect to temperature. These cold-water reef systems are believed to be at risk from ocean acidification because future uptake of high CO_2 will cause a shoaling of the lysocline; hence we investigated the carbonate chemistry over the Mingulay reef complex. We discuss the variability in pH, calcium carbonate mineral saturation states and temperature across the tidal cycle and the relative importance of the down-welling under present conditions, but also the implications for future acidification and warming. Understanding the natural dynamics experienced on these reef systems will provide better interpretation of experimental findings of the response of reef organisms to future scenarios of high CO_2.

[1] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, England, PL1 3DH (hefi@pml.ac.uk)
[2] Centre for Marine Biodiversity & Biotechnology, School of Life Sciences, Heriot-Watt University, Edinburgh, Scotland, EH14 4AS
[3] National Oceanography Centre Southampton, European Way, Southampton, England, SO14 3ZH

VERMETID REEFS IN THE WARM TEMPERATE MEDITERRANEAN SEA ARE FACING LOCAL EXTINCTION.

Fine, Maoz[1,2] and Marco Milazzo[3]

Vermetid reefs, constructed by the gregarious gastropod *Dendroma petraeum* and the coralline alga *Neogoniolithon brassica-florida* are commonl~~y~~ growing around mean sea level in southern coasts of the Mediterranean Sea. The framework builders of the reefs are the tubular shells of the gastropod, cemented by the calcareous red algae, forming a continuous marginal rim. Vermetid reefs are of great ecological and economical importance to southern sectors of the Mediterranean, being a hot spot of biodiversity, preventing shores erosion and sheltering some world heritage sites. In recent years, a decrease in *D. petraeum* live cover was recorded in many sites, with some documented local extinctions within just a few years. Yet the sensitivity of vermetid reefs to elevated temperature, sea level rise and ocean acidification is hitherto unknown. Here we report results from field surveys, transplanting and laboratory experiments demonstrating high sensitivities of each of the two partners to ocean acidification and elevated seawater temperature. While these sensitivities can only partially explain local

extinction of these reef-building organisms, recovery from this state under an increasingly warming sea is unlikely.

1 The Mina and Everard Goodman Faculty of Life Sciences, Bar-Ilan University,
2 The Interuniversity Institute for Marine Science in Eilat, P.O.B 469 Eilat 88103, Israel
maoz.fine@biu.ac.il
3 Dipartimento di Scienze della Terra e del Mare – ULR CoNISMa, University of Palermo via Archirafi 28 90123 Palermo, Italy

BIOMINERALISATION: PROTEIN AND MINERAL RESPONSE OF *MYTILIS EDULIS* TO OCEAN ACIDIFICATION

Fitzer, Susan, Vernon Pheonix, Maggie Cusack, and Nick Kamenos

Ocean acidification poses a problem for those calcareous organisms which utilise carbonate to produce their exoskeletons. Biomineralisation is the process through which organisms produce minerals to harden their exoskeletons. Biogenic calcium carbonate forms two major polymorph, calcite and aragonite, which are utilised in the marine environment by organisms such as coccoliths, corals and molluscs. The common blue mussel *Mytilus edulis* in particular combines the use of both of these polymorphs of carbonate into their shells. A pH reduction associated with ocean acidification will bring about the dissolution of calcium carbonate minerals, with aragonite being more susceptible than calcite. However, while declining carbonate concentrations at the sea surface threatens marine biogenic growth, living organisms can control the production of biominerals through proteins expressed for growth. It is therefore vital to examine combined impact of ocean acidification on biomineralisation, geochemical and biological controls. This project examines long-term ocean acidification impact on the protein and mineral components of *M. edulis*. In particular protein expression has been monitored by the activity of carbonic anhydrase in extrapallial fluids, and mineral components have been monitored by the physical and material properties of biogenic calcite and aragonite in the shell of *M. edulis*.

School of Geographical and Earth Sciences, Gregory Building, University of Glasgow, Glasgow, G12 8QQ, Scotland, UK (susan.fitzer@glasgow.ac.uk).

EFFECT OF SEA ICE AND BRINE REJECTION ON THE CALCIUM-CARBONATE SATURATION STATE IN THE AMUNDSEN GULF, ARCTIC OCEAN

Fransson, Agneta[1,2], Melissa Chierici[2,3], Lisa A. Miller[4], Gauthier Carnat[5], Elizabeth Shadwick[6], Helmut Thomas[7], and Tim N. Papakyriakou[5]

During the Circumpolar Flaw Lead System study, in the southern Beaufort Sea and Amundsen Gulf from November 2007 to May 2008, we sampled sea ice of various thicknesses, brine and under-ice water (UIW) to follow the seasonal evolution and rejection of total inorganic carbon (C_T), total alkalinity (A_T) and salinity with brines. Most of the changes in sea ice C_T concentration were explained by brine rejection. This resulted in increased C_T, salinity, and density in the under-lying water. The difference between measured C_T increase in UIW and than what was lost from the ice due to brine rejection was attributed to $CaCO_3$ particles trapped in the ice and/or CO_2 outgassing from the ice, or primary production. The A_T:C_T ratio and carbonate ion concentrations were at a minima in the ice-water interface during March, which is consistent with $CaCO_3$ precipitation in the ice. It is evident from our study that the sea-ice dynamics influence the variability of calcium-carbonate saturation.

[1] Norwegian Polar Institute, Fram Centre, N-9216 Tromsø, NorwayAgneta.Fransson@npolar.no
[2] University of Gothenburg, Göteborg, Sweden,
[3] Institute of Marine Research, Tromsø, Norway.
[4] Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC, Canada
[5] University of Manitoba, Winnipeg, Canada,
[6] University of Tasmania, Hobart, Australia,
[7] Dalhousie University, Halifax, Canada

VARIABILITY IN THE CARBONATE SYSTEM IN THE BALTIC SEA AREA

Fransson, Agneta[1,2], Leif Anderson[2], Aron Hakonen[2], Stefan Hulth[2], Sara Johansson[3], Bengt Karlson[3], Elisabeth Sahlsten[3], and Anna Willstrand Wranne[3]

The Baltic Sea and the Kattegat-Skagerrak is a large estuary and has a salinity range of 3 to 35. In a project aiming to describe the carbonate system in the area, high precision measurements of pH, partial pressure of carbon dioxide (pCO_2) and total alkalinity (AT) have been carried out using water sampling from research vessels and automated measurements using a FerryBox-system on a cargo vessel. The ship passes through a large part of the Baltic Sea and the Kattegat twice a week enabling high frequency sampling of near surface water and the research vessel cruises cover most seasons. Results from 2011 and 2012 will be presented. Preliminary data show large variability in pCO_2 in the surface water. This is likely to be related to primary production by phytoplankton and to short-term upwelling of deep water during storm events. Deeper in the water column, pH is relatively low compared to in the surface water due to elevated pCO_2 values, mainly as an effect of mineralization of organic matter. In the deepest parts in the Baltic, there is oxygen depletion, affecting both pH and AT. The spatial variability shows that total alkalinity and pH varies from the northern Baltic Sea area to the southern parts, with relatively low pH and AT in the low-salinity water.

[1] Norwegian Polar Institute, Fram Centre, N-9216 Tromsø, Norway Agneta.Fransson@npolar.no
[2] University of Gothenburg, Göteborg, Sweden
[3] Swedish Meterological and Hydrological Institute (SMHI), Göteborg, Sweden

THE DYNAMIC VULNERABILITY OF *MYTILUS CALIFORNIANUS* LARVAE TO LOW OXYGEN AND HIGH PCO_2

Frieder, Christina A.[1], Michael O. Navarro[1], Jennifer Gonzalez[1], Emily Bockmon[2], and Lisa A. Levin[1,3]

Oxygen and pCO_2 are tightly linked in marine ecosystems, particularly along eastern boundary upwelling systems. With concerns of shoaling oxygen minimum zones and intensified upwelling, ocean acidification and deoxygenation could act as a multistressor on coastal communities in upwelling regions. Under controlled-laboratory settings we investigated the effects of decreased oxygen and increased pCO_2 on the developmental rates, growth rates, and survivorship of early life stages of *Mytilus californianus*. Results thus far reveal that larvae of *M. californianus* develop and grow slower, but there is no effect on survivorship during the first seven days of development post-fertilization when exposed to low oxygen (28% saturation) and high pCO_2 (1440 µatm) characteristic of southern California upwelling events versus non-upwelling conditions (90% saturation and 536 µatm, respectively) at 11 °C. Ongoing studies investigate the independent versus interactive effects of oxygen and pCO_2 and the physiological response of larvae with emphasis on the sodium-potassium pump as well as how trace

metal incorporation (Mg, Mn, Pb, Cu, U, Ba, Sr, B) into larval shells varies under differing oxygen, pCO_2 and temperature treatments. These experimental studies, by incorporating oxygen, pCO_2, and temperature variation, provide insight into the dynamic vulnerability of early life stages to a changing marine oxygen and carbon climate in the Southern California Bight.

[1] Integrative Oceanography Division, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0218 (ctanner@ucsd.edu)
[2] Marine Physical Laboratory, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0244
[3] Center for Marine Biodiversity and Conservation, Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0218

LATITUDINAL VARIATIONS IN NEARSHORE pH ALONG THE WEST COAST OF NORTH AMERICA

Friederich, G.[1], A. Russell[2], F. Chan[3], C. Blanchette[4], B. Gaylord[2], E. Sanford[2], T. Hill[2], L. Washburn[4], M. McManus[5], and F.P. Chavez[1]

Latitudinal variations in nearshore pH along the west coast of North America were investigated during 2011 as part of a program to understand the response of intertidal mussels and urchins to varying levels of ocean acidity. Eight sites from Oregon to Santa Barbara, California with varying exposures to coastally upwelled corrosive water were instrumented with intertidal pH sensors. A number of these sites had nearby shallow moorings measuring carbon and oxygen parameters. The data set was analyzed in terms of tidal, diurnal, intraseasonal and seasonal variations of pH and in relation to local environmental parameters (winds, temperature, salinity). The results show surprisingly large small-scale tidal and diurnal variations as well as predictable latitudinal variations driven by upwelling intensity and source water characteristics.

[1]Monterey Bay Aquarium Research Institute, Moss Landing, CA (frge@mbari.org), [2]University of California, Davis, [3]Oregon State University, [4]University of California, Santa Barbara, [5]University of Hawaii, Manoa

PROTEOMIC RESPONSE OF PORCELAIN CRABS (*PETROLISTHES CINCTIPES*) TO THE SYNERGISTIC EFFECTS OF THERMAL AND ACIDIFICATION STRESS.

Garland, Michael A.[1], Adam Paganini[2], Jonathon H. Stillman[2], and Lars Tomanek[1]

Climate change is projected to affect marine species' physiology and ecology by changing several environmental factors simultaneously: temperature, salinity, hypoxia and pH. To predict the effects of multiple stressors on cellular processes we characterized the proteomic responses of gill and claw tissues to the synergistic effects of thermal and acidification stress in the intertidal porcelain crab, *Petrolisthes cinctipes*.
We exposed crabs to nightly acidic (pH 7.50) or ambient (pH 8.15) conditions accompanied by non-lethal elevated temperatures (up to 28°C, or steady 11°C for controls) during daily, simulated 4-hour low tide events for a two week time period. We then characterized the proteomes of gill and claw tissue by two-dimensional gel electrophoresis followed by tandem mass spectrometry to identify proteins. A preliminary study for this project entailed chronic thermal acclimations (10°C, 10-20°C, and 10-30°C) and accompanying acute heat shocks (30°C) of porcelain crabs. These results showed that the proteomic response of claw tissue to thermal stress (both acute and chronic) lacked any detectable molecular

chaperone response, but entailed a massive shift in cytoskeletal and arginine kinase protein isoforms accompanied by isoform shifts in metabolic (TCA cycle) and respiratory (hemocyanin) proteins. Developmental homeostasis (e.g. molting) was found to be influenced by chronic variations in temperature and acute heat stress. We are currently identifying the effects of acidification in our analysis in order to understand the combined effects of these two stressors, which will improve our comprehension of how various physical dynamics of climate change will affect marine crustaceans in the future.

[1] Environmental Proteomics Laboratory, California Polytechnic State University, San Luis Obispo, CA 93407, USA (mgarland@calpoly.edu)
[2] Romberg Tiburon Center for Environmental Studies, San Francisco State University, Tiburon, CA 94920, USA

INTERNATIONAL COORDINATION OFFICE ON OCEAN ACIDIFICATION

Gattuso, Jean-Pierre[1,2] and SOLAS-IMBER Working Group on Ocean Acidifcation

IMBER (1) and SOLAS (2) coordinate research aimed at understanding and predicting changes in oceanic food webs and biogeochemical cycles arising from global change. An integral part of this goal is to understand the changes in the marine carbon cycle that may occur as a result of a changing climate, increased atmospheric CO_2 levels and/or reduced oceanic pH. To address these key ocean carbon issues the two projects formed the joint SOLAS-IMBER Carbon, or SIC working group.
Sub-group 3 of the SIC working group (SOLAS-IMBER Ocean Acidification or SIOA) has the mandate to undertake synthesis activities and coordinate international research in the field of ocean acidification. Members of the working group contribute to several on-going synthesis activities, such as books and the 5th assessment report of the Intergovernmental Panel on Climate Change. The SIOA working group has worked extensively during the past three years to develop a package of activities critical to assess the effects of ocean acidification that must be carried out at the international level but are, for the most part, not funded by existing projects. Among these overarching activities are the promotion of joint experiments and exchange of young scientists, sharing of experimental platforms, data management, inter-comparison exercises, and communication and outreach activities. The SIOA, together with the iOA-RUG (3), initiated the launch of the Ocean Acidification International Coordination Office (OA-ICO) in summer 2012. This poster presents the activities of this Office.
(1) Integrated Marine Biogeochemistry and Ecosystem Research; (2) Surface Ocean Lower Atmosphere Study; (3) International Ocean Acidification Reference User Group.

[1] CNRS-INSU, Laboratoire d’Océanographie de Villefranche, BP 28, 06234 Villefranche sur Mer cedex, France (gattuso@obs-vlfr.fr)
[2] Université Pierre et Marie Curie-Paris 6, Observatoire Océanologie de Villefranche, 06230 Villefranche sur Mer cedex, France

EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON THE GROWTH AND METABOLISM OF THE MEDITERRANEAN MUSSEL, AN ANNUAL STUDY

Gazeau, F.[1,2], S. Alliouane[1,2], L. Bramanti[3], and M. Gentile[3]

An experiment focusing on the effects of ocean warming and acidification on the growth and physiology of a key Mediterranean species: the Mediterranean mussel *Mytilus galloprovincialis* is currently underway. This experiment that started in November 2011 is a contribution to the European project "Mediterranean Sea Acidification in a Changing Climate" (MedSeA). During one year, several hundreds of adult mussels (3-4 cm) will be exposed to warmer and acidified conditions such as the ones projected for the end of the present century (i.e. pH - 0.3/0.4 unit, temperature +2-3 °C). On a regular basis (every 2 months), various parameters and physiological processes will be measured in order to test the response of this very economically important species to these modified environmental conditions. Besides growth (both tissue and shell), physiological processes such as respiration, excretion and calcification will be measured. This poster will present an overview of this experiment as well as preliminary data based on 4 sampling periods covering winter, spring and summer conditions. Preliminary data from January 2012 suggest that mussels are not sensitive to warming and acidification in winter with no significant modifications of their growth and basic physiological processes.

[1] Université Pierre et Marie Curie-Paris 6, Observatoire Océanologique de Villefranche-sur-Mer, France (f.gazeau@obs-vlfr.fr)
[2] CNRS-INSU, Laboratoire d'Océanographie Villefranche-sur-Mer, France
[3] ICM-CSIC, Institut de Ciències del Mar, Spain

SEASONAL VARIABILITY OF PH AND CARBONATE SYSTEM IN A COASTAL MEDITERRANEAN AREA

Giani, Michele, Gianmarco Ingrosso, Cinzia Comici, Cinzia De Vittor, Claus Falconi, and Marina Lipizer

In the coastal areas, land, rivers, open sea, atmosphere, sediment and biota interact, leading to spatial and temporal variation in seawater pH, thus the trends of the ocean acidification are difficult to assess. The investigated coastal area (Gulf of Trieste) lies in the northernmost part of the Mediterranean Sea. Monthly sampling on a LTER site were carried out from March 2011 to March 2012, in the framework of MEDSEA FP7 project, in order to assess the seasonal variability of the carbonate system under marked influence of physical and biological processes.
Total alkalinity (A_T) and dissolved oxygen were measured by potentiometric titrations, pH by spectrophotometric m-cresol purple method, nutrients by a Bran Luebbe III autonalyzer. CTD profiles were acquired by a Idronaut 316 probe.
The seasonal variation of temperature ranged from 4.79 to 26.16 °C whereas the salinity fell in the 34.83-38.43 range. The A_T varied from 2663 to 2743 µmol kg^{-1} and was inversely correlated with salinity ($p<0.0001$) due to the inputs of local rivers with a karstic drainage basin.
The annual pH_T variations ranged from 7.878 to 8.259. Strong seasonal variations of pCO_2 occurred in the water column due to the thermal effect, to primary productivity and to the degradative processes. The thermal effect was predominant, the biological drawdown of CO_2 occurred mainly from March to July and was more relevant in the waters above the pycnocline. From August to September in the oxygen depleted bottom waters, the remineralization processes prevailed increasing the pCO_2 and nutrients.

OGS - Istituto Nazionale di Oceanografia e Geofisica Sperimentale, via A. Piccard 54 34151Trieste, Italy (gingrosso@inogs.it)

AN UNPRECEDENTED GLIMPSE INTO PLANKTON SENSITIVITY TO GLOBAL WARMING AND OCEAN ACIDIFICATION: MODERN PLUS FOSSIL COCCOLITHOPHORES FROM THE 'LAGERSTATTEN' OF TANZANIA AND THE US

Gibbs, Samantha J.[1], Chris Daniels[1], Paul R. Bown[2], Sarah O'Dea[1], Alex Poulton[3], and Jeremy R. Young[2]

The Paleocene Eocene Thermal Maximum (PETM) was a geologically abrupt global warming event approximately 56 million years ago that was triggered by the release or redistribution of massive amounts of organic carbon in less than 10 kiloyears. As such, it is a potential analogue for modern fossil fuel burning, but with the caveat that rates of carbon injection today are significantly higher than estimated for the PETM. As part of the UK Ocean Acidification programme, we present an unprecedented glimpse into the cellular-level behaviour of coccolithophores across the PETM, uniquely combining biometric information from modern culturing experiments with pristinely preserved whole coccolithophore cell coverings ('coccospheres') from shelf areas of the US and Tanzania. With equivalent data from modern and fossil coccolithophores, we have a new framework for understanding the relationships between growth rate, cell size and skeletal morphology across the PETM. Cell size data highlights species specific changes across the event with varying sensitivity to the combined effects of warming and seasonal growth rate cycles. While temperature and nutrient availability are often seen as clear controllers of fossil populations the role of ocean chemistry has proven more elusive. The additional information we have gained from the fossil cell data provide a more complete description of cellular calcification and we have looked for support for a significant ocean acidification control on these calcifiers in their cellular morphology.

[1] Ocean and Earth Sciences, National Oceanography Centre, Southampton, University of Southampton, Southampton, SO14 3ZH, UK (s.gibbs@noc.soton.ac.uk)
[2] Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK.
[3] Ocean Biogeochemistry and Ecosystems group, National Oceanography Centre, Southampton, SO14 3ZH, UK.

THE ATLANTIC OCEAN ACIDIFICATION TEST BED: EXTENDED TIME-SERIES ESTIMATE OF NET CORAL REEF COMMUNITY METABOLOSIM

Gledhill, Dwight[1], Langdon, Chris[2], Wade McGillis[3], Brice Loose[4], Derek Manzello[5], and Ian Enochs[5]

A key requirement towards detecting ocean acidification (OA) as part of a sustained monitoring effort within coral reef ecosystems is parsing out the effect of coral reef community metabolism on associated water column biogeochemistry. A three-year time-series of autonomous observations of air-sea pCO_2, temperature, salinity and oxygen have been acquired within the La Parguera Marine Reserve, Puerto Rico at the Atlantic Ocean Acidification Test-bed. These observations, obtained using a MAPCO2 system, are coupled with autonomous meteorological (wind, rain), and light (e.g. PAR) measurements acquired at the near-by ICON/CREWS station. Using a Revelle Factor-based approach, we've related short term (3hrly) changes in $pCO_{2,sw}$ to changes in total dissolved inorganic carbon (DIC) to derive estimates of total community net carbon productivity (NCP_{Total}) representing the sum effect of organic productivity and calcium carbonate production on DIC. The organic carbon net productivity (NCP_{org}) is derived from oxygen dynamics measured from the on-board Aanderaa optode. We use this time-series to explore the diel dynamics and primary controls on aragonite mineral saturation state (Ω_{arg}) within a shallow water Atlantic tropical reef environment. The Cayo Enrique reef appears to be net heterotrophic, exhibiting a median daily NCP_{org} of -5.6 ± 0.7 mmol C m^{-2} day^{-1} with maximum hourly rates observed in October (13.2 ± 1.2 mmol C m^{-2} hr^{-1}, daylight) and minimum in April (-8.15 ± 0.8 mmol C m^{-2} hr^{-1}). We find that NCP at the Cayo Enrique forereef can drive changes in Ω_{arg} by as much as 4% (0.15 Ω units) throughout a diurnal period.

[1]NOAA, Ocean Acidification Program, Silver Springs, MD, USA (dwight.gledhill@noaa.gov)
[2]RSMAS, Uni of Miami, 4600 Rickenbacker Cswy, Miami, FL 33149, USA
[3]LDEO, Columbia Uni, Rt 9W, Palisades, NY 10983, USA
[4]GSO, Uni of Rhode Island, Narragansett, RI 02883, USA
[5]AOML, NOAA, 4300 Rickenbacker Cswy, Miami, FL, USA

EFFECTS OF NEAR-FUTURE OCEAN ACIDIFICATION SCENARIOS ON GENE EXPRESSION PATTERNS AND DEVELOPMENT IN THE COPEPOD *CALANUS FINMARCHICUS*

Gustavson, Liv Marie[1], Iurgi Salaberria[1], Dag Altin[2], Anders J. Olsen[1], Ole Jacob Håkedal[1], Alice Tagliati[1], and Sindre A.Pedersen[1]

This research project investigates the impacts of near-future ocean acidification scenarios on the calanoid copepod *Calanus finmarchicus*. As *C. finmarchicus* is a keystone species in the North Sea and North Atlantic food webs, knowledge of its responses to long-term hypercapnia will aid in predicting the possible indirect impacts on other trophic levels. Previous research has tended to focus on acute short-term exposure of adult individuals only, and thus little is known about the effects of hypercapnia on the full life cycle and on subsequent generations. In this study, two consecutive generations of *C. finmarchicus* were reared under different CO_2 conditions. The levels of CO_2 exposure were chosen on the basis of published studies predicting near-future ocean acidification scenarios. The selected values for the elevated CO_2 treatments were 1080 ppm (predicted value for the year 2100), 2080 ppm (worst-case scenario for the year 2300), and 3080 ppm (a positive control treatment). The control groups, representing the present-day scenario, received 380 ppm. Representative samples were taken regularly in order to monitor the stage distribution, density and overall development in the different exposure groups. Preliminary results support the expectation of a delay in development in the high-exposure groups. Biometry and RNA-sampling was carried out on the C5 copepodite stage of both generations, and a microarray and quantitative real-time PCR will be used in order to reveal possible changes in gene expression patterns in response to long-term hypercapnia.

[1] Department of Biology, NTNU, Høgskoleringen 5, N-7491 Trondheim, Norway. (gustavso@stud.ntnu.no)
[2] BioTrix, N-7022 Trondheim, Norway.

EFFECTS ON ENERGY BALANCE OF THE COPEPOD *CALANUS FINMARCHICUS* DUE TO LONG TERM CARBON DIOXIDE EXPOSURE.

Haakedal, Ole Jacob, Sindre Andre Pedersen, Iurgi Imanol Salaverria-Zabalegui, Dag Altin, Anders J. Olsen, Liv Marie Gustavson, Alice Tagliati, and Lars Kristian Schjonhaug

As a part in the investigations of how marine organisms will be affected by the ongoing acidification of the oceans, an experimental setup has been developed for exposure of the copepod *Calanus finmarcichus* to carbon dioxide at concentrations close to predicted values for the future (1080, 2080,and 3080 ppm CO_2). *C. finmarchicus* is a widely distributed species and an important component in the ecosystem in North Arctic oceans. Little is known about how elevated CO_2 will affect this species. So far, no study has focused on the long-term effects of such exposure in this species. The exposure period spanned over two consecutive generations which enables studies of long term effects and possible adaptation to elevated CO_2. Among several endpoints studied, main focus has been on reproduction, growth and development during the full life cycle. Previous studies suggest that adult copepods are relative tolerant to elevated CO_2 concentrations, but eggs and earlier developmental stages may be more susceptible. Individual measurements of respiration, feeding, and excretion was performed on subadult animals (copepodite V) from each exposure regime. The results from the measurements will be used in calculations of energy balance (scope for growth) of the animals, to see if the CO_2 treatments reduce the energy available for growth and development.

Norwegian University of Science and Technology (NTNU), Department of Biology, Høgskoleringen 5, 7491 Trondheim (postmottak@bio.ntnu.no, olejah@stud.ntnu.no)

MODELING PH CHANGES IN COASTAL SEAS: WHY ARE THERE REGIONAL DIFFERENCES?

Hagens, Mathilde, Caroline P. Slomp, and Jack J. Middelburg

Ocean acidification, the lowering in pH driven by the absorption of increased atmospheric CO_2, is a major problem for present-day oceans. Projections for the open ocean reveal a decrease in pH of 0.0013-0.0020 unit/yr, a range confirmed by measurements. The few available long-term data sets of coastal regions, however, show variable trends, exceeding in some cases the open ocean decrease in pH by one order of magnitude. The differences with the open ocean rate and among data sets suggest that processes other than enhanced CO_2 uptake alone may be responsible for coastal acidification.
In this study, we investigate the relative importance of physical and biogeochemical processes responsible for acidification in coastal regions. To account for regional variability, four different coastal seas are examined: North Sea, Baltic Sea, Mediterranean Sea and South China Sea. We developed a box model including exchange of CO_2 with the atmosphere, primary production, respiration, nitrification and atmospheric deposition of sulfur (SO_x) and nitrogen (NO_x and NH_3).
In contrast to earlier work, the model shows that atmospheric deposition enhances acidification of coastal seas compared to CO_2-induced acidification alone. The relative contribution of atmospheric deposition to total acidification shows regional variability, depends on the rate of nitrification and increases with time, mainly because the buffering capacity of coastal seas will decrease by more than 50% during the 21st century. The model further reveals that changes in the production-respiration balance are the main drivers for changes in pH in coastal seas.

Department of Earth Sciences – Geochemistry, Faculty of Geosciences, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, The Netherlands (m.hagens@uu.nl)

PREDICTED LEVELS OF FUTURE OCEAN ACIDIFICATION AND TEMPERATURE RISE COULD ALTER COMMUNITY STRUCTURE AND BIODIVERSITY IN MARINE BENTHIC COMMUNITIES

Hale, Rachel[123], Piero Calosi[2], Louise McNeill[3], Nova Mieszkowska[4], and Steve Widdicombe[3]

The effects of pH and temperature on an intact marine invertebrate community were investigated in a mesocosm experiment. Standardised communities from a rocky low intertidal zone were exposed to one of eight nominal treatments (four pH levels crossed with two temperature levels). After 60 days exposure, communities showed significant changes in structure and diversity. At higher pH levels, elevated temperature treatments contained higher species abundances and diversity than the lower temperature treatments. At lower pH levels, elevated temperature treatments had lower species abundances and diversity than lower temperature treatments. These species losses were not randomly distributed through phyla examined. Molluscs showed the greatest reduction in abundance and diversity in response to low pH and elevated temperature, whilst annelid abundance and diversity was mostly unaffected by low pH and higher at the elevated temperature. Arthropods showed moderately reduced abundance and diversity at low pH and elevated temperature. Nematode abundance increased in response to low pH and elevated temperature, probably due to the reduction of ecological constraints. This mesocosm study supports suggestions that ocean acidification induced changes in marine biodiversity will be driven by differential vulnerability within and between different taxonomic groups and illustrates the importance of considering indirect effects occurring within multispecies assemblages. Further experiments will consider the effects of decreased ocean pH and increased temperature on intertidal sediment communities.

[1] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK (r.hale1@uea.ac.uk)
[2] Marine Biology and Ecology Research Centre, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK
[3] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, PL1 3DH, UK
[4] Marine Biological Association of the UK, The Laboratory, Citadel Hill, Plymouth, PL1 2PB, UK

SIMULATING THE EFFECTS OF LEAKAGE FROM SUB-SEABED STORAGE OF ANTHROPOGENIC CO_2 USING A HIGH PRESSURE TITANK

Hammer, Karen M., Sindre A. Pedersen, Murat Van Ardelan, Trond Nordtug, and Anders J. Olsen

Carbon capture and storage (CCS) of anthropogenic CO_2 in sub-seabed storage sites is one of the most promising alternatives for CO_2 emissions mitigation. However, leakage from such CO_2 reservoirs would create detrimental conditions for the ecosystems close to the storage site. The Utsira formation in the North Sea has been used for CO_2 storage for over 10 years, and is found deep below the seafloor at ocean depths of approximately 300 meters. Conducting field experiments in deep water is both challenging and difficult control. To simulate effects of potential CO_2 leakage scenarios on seawater chemistry and micro- and meiofauna under controlled seawater conditions, a high pressure titanium tank which can attain a pressure of up to 30 bar, equivalent to the pressure found at 300 meters depth, has been built. This high pressure tank will also be used to simulate future ocean acidification scenarios in deep water. The large volume of this vessel (1 m^3) makes it suitable to perform both short-and long-term mesocosm experiments. It is equipped with a robotic arm and a decompression chamber which allows for the collection of samples when the vessel is under pressure. A micro blood sampling system makes it possible to collect blood from cannulated animals, or pore water samples from sediments i*n situ.* Data on seawater carbonate chemistry obtained from test runs of the tank, as well as a description of the tank, its accessories and planned experiments will be presented.

[1] Department of Biology, Norwegian University of Science and Technology. karen.hammer@bio.ntnu.no
[2] Department of Chemistry, Norwegian University of Science and Technology
[3]SINTEF Materials and Chemistry, Marine Environmental Technology, N-7465 Trondheim, Norway

JAPANESE PROJECT ON SOUTHERN OCEAN ACIDIFICATION 2. -PRELIMINARY ACIDIFICATION EXPERIMENTS USING CARBONATE PLANKTERS (COCCOLITHOPHOLIDS)

Hattori, H.[1], H. Sasaki[2], H. Kurihara[3], H. Endo[4], S. Motokawa[5], T. Iida[6], K. Suzuki[4], S. Taguchi[5], G. Hashida[6], and T. Odate[6]

Southern Ocean is one of high biological productive areas in the whole ocean because large amount of primary production is occurred in the seasonal sea-ice zone. Predicted acidification in the sea water would affect the marine food web particularly the calcium carbonate phytoplankton such as coccolithophorids. Biological samplings were carried out along 110°E and 140°E in the Indian Sector of the Southern Ocean to represent the coccolithopholid biomass and to estimate the acidification effects on the phytoplankton communities during the T/V Umitaka-maru cruise in Austral summer of 2011/2012. This study is made as ~~a~~ part of the 53th Japanese Antarctic Research Expedition (JARE-53). In 2010/2011 (JARE-52), coccolithopholids mainly *Emiliania huxleyi* Type B/C were abundant in the area north of 50°S reaching around 800 $\times 10^3$ cells L^{-1}. Phytoplankton collected by a clean pump at 45°S and 60°S of 110°E and 50°S and 64°S of 140°E in the present study were replaced in around 750 µatm of pCO_2 water to compare the non-acidified natural condition. This experiment was done for three days. Changes in cell density of phytoplankton particularly coccolithopholids and phytoplankton pigment composition in the acidified and natural conditions were counted by using SEM and HPLC, respectively. We will show the outline of this study and the preliminary results on the present state on variations of CO_2 in sea water.

[1] Tokai Univ., Sapporo, Japan (mail address: hattori@tspirit.tokai-u.jp)
[2] Senshu Univ. Ishinomaki, Ishinomaki, Japan
[3] Univ. Ryukyu, Nishihara, Japan
[4] Hokkaido Univ., Sapporo, Japan
[5] Soka Univ., Hachiouji, Japan
[6] NIPR, Tachikawa, Japan

XFOCE: TECHNOLOGY FOR STUDYING OCEAN ACIDIFICATION

Headley, K., B. Kirkwood, P. Brewer, J.P. Barry, E. Peltzer, P. Walz, B. Herlien, C. Kecy, T. Maughan, K. Salamy, F. Shane, T. O'Reilly, and K. Gomes

Laboratory and mesocosm studies are only part of the tool set for ocean acidification (OA) studies. In situ experiments allowing studies of the response of natural marine communities to ocean acidification over periods of months or longer can lead to inference concerning the sensitivities of marine organisms that is not possible with laboratory studies.
Drawing on the long experience of terrestrial Free Air CO_2 Enrichment (FACE) experiments, MBARI has developed experimental methods and technologies for conducting in situ ocean acidification studies, culminating in the development of the Free Ocean CO_2 Enrichment experiments, or FOCE.
At its core, the goal of FOCE is to precisely control in situ pH chemistry within an ecosystem while introducing minimal disturbances to the natural environment compared with laboratory studies. The chemical and physical parameters of this are nuanced, and the marine environments of interest are varied and harsh. The technologies and techniques needed to execute FOCE required considerable time and expertise to develop.
In this presentation, we describe xFOCE, an open source package created to transfer FOCE technology to interested researchers. The xFOCE specification is intended to support a wide variety of OA researchers with multidisciplinary science interests, and to be extensible and adaptable to new ideas for OA research

topics. The ocean science community can use xFOCE to develop cost effective FOCE experiments in diverse marine environments over timescales of months.
We also review some of the past and present FOCE experiments featuring our collaborators worldwide and mention potential future directions for this technology.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 93950, USA (headley@mbari.org)

MODELING THE OCEAN CARBON CYCLE IN THE PALEOCENE-EOCENE THERMAL MAXIMUM WITH AN EARTH SYSTEM MODEL

Heinze, Mathias[1,2] and Tatiana Ilyina[1]

During the Paleocene-Eocene Thermal Maximum (PETM; ~55 million years ago) the climate underwent significant changes which affected the atmosphere, ocean and land system. A massive carbon release caused an intense heating of ocean and atmosphere, proven by a negative δ^{13}C-carbon isotope excursion and carbonate dissolution in the ocean. In terms of released carbon and concomitant changes in ocean carbon cycle, the PETM serves as the most adequate analogue for ongoing ocean acidification in Earth's history. However the dimension of the acidification during the PETM is still uncertain based on the ambiguous amount and time scale of the carbon release. We use the fully coupled Earth System Model of the Max Planck Institute for Meteorology (MPI-ESM) which includes ocean and atmospheric general circulation models (MPI-OM & ECHAM respectively) and models of ocean biogeochemistry (HAMOCC) and land vegetation (JSBACH). Such modeling system enables us to simulate the closed carbon cycle in the oceanic, land and atmospheric compartments. Moreover, by using a three-dimensional ESM we get a more detailed representation of the ocean biogeochemistry and the underlying physical processes. The model integrations display the onset of the PETM over several thousand years under different background climates. Within these experiments we focus on the horizontal and vertical distributions and regional gradients of ocean carbon variables. As this study is still in its initial stage, first model results and modifications implemented in HAMOCC for application to the PETM will be presented.

[1] Max Planck Institute for Meteorology, 20146 Hamburg (mathias.heinze@zmaw.de)
[2] International Max Planck Research School on Earth System Modeling, Hamburg

OCEAN ACIDIFICATION LEADS TO COUNTERPRODUCTIVE INTESTINAL BASE LOSS IN THE GULF TOADFISH (*Opsanus beta*)

Heuer, Rachael, Andrew Esbaugh, and Martin Grosell

Ocean acidification research on marine teleosts has revealed effects on behavior, anatomy, and sensory systems, especially in younger animals. Although teleosts are known to be strong acid-base regulators, recent work has demonstrated that CO_2 exposure as low as 1000 µatm induces an acidosis in adult toadfish (*Opansus beta*), leading to metabolic compensation by retention of blood HCO_3^- to defend blood pH. In the first portion of the present study, blood elevation of HCO_3^- and PCO_2 during acute 1900 µatm CO_2 exposure was predicted to increase intestinal base secretion rates and increase intestinal $CaCO_3$ precipitation. Rectal excretions collected from toadfish exposed to 1900 µatm CO_2 over 72 hours revealed higher rectal base excretion rates and higher rectal fluid HCO_3^- (mM) compared to 380 (control) exposures. These observations confirm that increased base loss occurs in the intestine during exposure to elevated CO_2 which seems counterproductive to whole-body compensation for acidosis. Contrary to expectations, isolated intestinal tissue from toadfish exposed to 1900 μatm CO_2 for two weeks exhibited significantly higher base secretion rates than control toadfish, suggesting that these fish do not have the capacity to reduce base loss during prolonged CO_2 exposure. Furthermore, the elevation of base secretion rates above control values suggests that chronic hypercapnia exposure likely incurs an increased intestinal tissue metabolic cost that could reallocate energy from other vital life processes.

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA. (rheuer@rsmas.miami.edu)

THE IMPACTS OF OCEAN ACIDIFICATION ON OXYGEN AND CARBON ISOTOPES OF LARGE BENTHIC FORAMINIFERS

Hikami, Mana[1], Toyoho Ishimura[2], Kazuhiko Fujita[3], Atsushi Suzuki[4], Yukihiro Nojiri[5], and Hodaka Kawahata[1]

Ocean acidification in response to rising atmospheric pCO_2 is generally expected to reduce rates of calcification by reef calcifying organisms, with potentially severe implications for coral reef ecosystems. Various studies have revealed potentially dramatic responses in a variety of calcareous organisms to the range of pCO_2 values projected to occur over this century. In this study, to shed light on the factors leading to different calcification response to ocean acidification between perforate and imperforate, we analyzed the stable isotope composition of reef-dwelling foraminifers: *Amphosorus hemprichii,* belong to imperforate species, *Baculogypsina sphaerulata,* and *Calcarina gaudichaudii* belong to perforate species, subjected to five varied acid seawater for twelve weeks. $\delta^{18}O$ value of cultured foraminiferal tests under five varied pCO_2 seawater indicated no significant correlation to pCO_2. Therefore $\delta^{18}O$ stay constant within narrower range from CO_3^{2-} concentration (111 to 264 μmol/ kg). On the other hand, $\delta^{13}C$ of foraminirferal tests indicated heavy trend with increasing pCO_2. Alteration of carbonate chemistry result from ocean acidification may be effect strongly on carbon isotope composition relate to metabolic system (i.e. photosynthesis and respiration). In perforate species, both of $\delta^{18}O$ and $\delta^{13}C$ was lighter than that in imperforate. For $\delta^{18}O$ variation possibility among species would be caused by their Mg-content concentration in calcite shells. The distinct difference in the level of $\delta^{13}C$ values between imperforate and perforate foraminifera indicates different amounts of metabolic CO_2 used for shell construction. Therefore, $\delta^{18}O$ and $\delta^{13}C$ of foraminiferal test have the potential to reveal calcification mechanism of two species.

[1]Atmosphere and Ocean Research Institute, University of Tokyo, Kashiwa, Chiba, Japan. hikami@aori.u-tokyo.ac.jp
[2] Hokkaido University, Sapporo, Hokkaido, Japan.
[3] Department of Physics and Earth Sciences, University of the Ryukyus, Okinawa, Japan.
[4] Geological Survey of Japan, AIST, Tsukuba, Japan.
[5] Center for Global Environmental Research, NIST, Tsukuba, Japan.

ZOOPLANKTON COMMUNITY DEVELOPMENT UNDER ELEVATED CO_2 – RESULTS FROM A MESOCOSM STUDY

Hildebrandt, Nicole[1], Niehoff, Barbara[1], and Schulz, Kai[2]

Zooplankton species are key players in pelagic marine ecosystems and link primary production to higher trophic levels. During a six-week mesocosm study conducted in the Raunefjord (Bergen, Norway) in

May/June 2011 we investigated how the zooplankton community responds to ocean acidification. Nine mesocosms of 25 m length enclosing approx. 80 m^3 of fjord water were enriched with eight different CO_2 concentrations (ca 280 (x2), 390, 560, 840, 1120, 1400, 2000, 3000 atm). Temperature and chlorophyll *a* content in the mesocosms were measured daily. On day 14 nutrients were added to induce a phytoplankton bloom. Once a week zooplankton samples from each mesocosm were taken with an Apstein net (mesh size: 55 µm) and fixed in buffered formalin for abundance analyses. The zooplankton community was dominated by copepods (*Calanus finmarchicus*, *Temora longicornis*, *Pseudocalanus elongatus*, *Oithona similis*), followed by meroplanktonic larvae. Over the course of the experiment, the total zooplankton abundance in the water column decreased in all nine mesocosms, mainly due to decreasing copepod abundances. Only *Pseudocalanus elongatus*, appendicularians and medusea increased in abundance. Species composition did not change with CO_2 concentration; however, some taxa (e.g. bivalves and gastropods) were less abundant in mesocosms with high CO_2 levels.

[1] Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany. Nicole.Hildebrandt@awi.de
[2] GEOMAR | Helmholtz-Zentrum für Ozeanforschung, Düsternbrooker Weg 20, 24105 Kiel, Germany

THE COASTAL MOSAIC OF OCEAN ACIDIFICATION: UPWELLING, RIVERINE INPUT AND GEOGRAPHIC INFLUENCE WITHIN THE CALIFORNIA CURRENT

Hill, T.M.[12], B. Gaylord[13], S.H. Miller[1], J. Hosfelt[1], A.D. Russell[2], E. Sanford[13]

Many questions remain about the natural temporal and spatial variability of the carbonate system, particularly in coastal systems, with clear relevance for interpreting the future impacts of ocean acidification. To understand the natural variability of the carbonate system in the California Current, we have developed a broad scale coastal transect (47 sites) from the US-Canada border to San Diego. These sites are sampled from the shore, where waters are interacting with rocky intertidal and sandy beach ecosystems. The sites have been sampled twice per year (2010-2012) for a suite of water chemistry parameters (T, S, O_2, pH, DIC, TA, isotopes). We observe seasonal differences in water chemistry, for example an overall decrease in pH during upwelling (May) vs. non-upwelling conditions (September). Additionally, the influence of riverine input is clear for portions of the US West Coast. Riverine water is associated with low alkalinity, high pH waters, likely due to algal blooms. We observe a wide range of pH (7.6-8.6), with the most acidic waters found in the Northern California-Southern Oregon upwelling region (38°N-45°N). We also interpret the presence of regions protected from upwelled waters (upwelling "shadows") with more buffered water chemistry. These results provide insight into the high spatial scale of variability encountered by organisms along the coast, and can be compared directly to high resolution time-series records of carbonate parameters from individual locations to understand the spatial and temporal variability of pH in the coastal zone.

[1]Bodega Marine Laboratory, UC Davis, 2099 Westside Road, Bodega Bay CA 94923 USA
tmhill@ucdavis.edu
[2]Department of Geology, UC Davis, One Shields Ave, Davis CA 95616 USA
[3]Department of Evolution & Ecology, UC Davis, One Shields Ave, Davis CA 95616 USA

MODELLING THE EFFECTS OF OCEAN ACIDIFICATION ON THE CALCIFYING FLUID OF SCLERACTINIAN CORALS

Hohn, Sönke and Agostino Merico

Rising atmospheric CO_2 concentrations due to anthropogenic emissions induce a reduction in ocean pH and several other changes in the carbonate chemistry of the oceans. This acidification process is expected to harm calcifying organisms such as corals. A severe decline in coral reef is, for example, expected by the end of this century with associated disastrous effects on reef ecosystems. Despite the growing importance of the topic, little progress has been made with respect to modelling the impact of acidification on coral calcification. Here we will present a model for a coral polyp that simulates the carbonate system in four different compartments: the seawater, the polyp tissue, the coelenteron, and the calicoblastic layer. Precipitation of calcium carbonate takes place in the metabolically controlled calicoblastic layer beneath the polyp tissue. The model is adjusted to a state of activity as observed by direct microsensor measurements. With CO_2 perturbation experiments we quantify the impact of changing seawater carbonate chemistry to the site of calcification.

Leibniz Center for Tropical Marine Ecology, Systems Ecology Group, Fahrenheitstraße 6, 28359 Bremen, Germany (soenke.hohn@zmt-bremen.de)

EFFECTS OF OCEAN ACIDIFICATION (OA) ON THE CYCLING OF DIMETHYL SULFIDE (DMS) AND ITS ALGAL PRECURSOR DIMETHYL SULFONIOPROPIONATE (DMSP) IN NW EUROPEAN SHELF WATERS.

Hopkins, Frances E.[1], Philip D. Nightingale[1], and Stephen D. Archer[2]

The effects of OA on the cycling of DMS and DMSP were investigated through joint experimental and observational work during the first UKOA research cruise covering natural carbonate chemistry gradients on the NW European shelf in June 2011. The results of five 96h on-deck CO_2 perturbation experiments (4 CO_2 levels: ambient, 550µatm, 750µatm, 100 µatm) showed strong and significant responses in the standing stocks of both DMS and DMSP. Each experiment saw an increase in DMS with increasing pCO_2 at 48h, whilst DMSP consistently showed the opposite trend, with the greatest number of significant differences seen at 750µatm and 1000µatm. By 96h, the results became less significant although the major trends remained the same. Rates of *de novo* DMSP synthesis (µDMSP) were determined for each CO_2 level at 0h, 48h and 96h by incorporation of $^{13}CO_2$ into particulate DMSP, and these samples will be analysed by proton transfer reaction-mass spectrometry. A novel stable isotope technique using tracer-level additions of ^{13}C-DMS and gas chromatography-mass spectrometry was employed to determine biological loss rates of DMS at ambient CO_2 and 750 µatm, and preliminary rate data will be presented. Observational work revealed highly spatially diverse surface concentrations and depth characteristics around the NW European shelf, with concentrations ranging from <0.1nM to 21.6nM for DMS, and < 1nM to 167.2nM for total DMSP. Our experimental results suggest that DMS and DMSP in NW European waters may be sensitive to OA, particularly at pCO_2 levels from 750µatm upwards, with implications for the marine atmospheric chemistry of this region.

[1] Plymouth Marine Laboratory, West Hoe, Plymouth, PL1 3DH U.K. (fhop@pml.ac.uk)
[2] Bigelow Laboratory for Ocean Sciences, East Boothbay, Maine, 04544, U.S.A.

ESTUARINE ACIDIFICATION: CAUSES, MECHANISMS AND LESSONS FOR OCEANIC ACIDIFICATION

Hossain, M. Belal[1,2] and David J Marshall[1]

Oceanic acidification due to anthropogenic CO_2 affects marine ecosystems significantly. But few studies focused on the effects of acidification on estuarine ecosystem. Estuaries are acidified in the all continents mainly by biogenic production of CO_2 and acid sulfate runoff whereas, surface ocean by anthropogenic atmospheric CO_2 and acid deposition. Data are lacking on estuarine acidification caused by increasing atmospheric CO_2. The pH of estuarine ecosystem was found to be as low as 1.5 and the pCO_2 being as high as 30000 µatm. Impacts of estuarine acidification are severe than surface ocean due to its shallowness, low buffering capacity, low salinity and high organic matter from land drainage. The most conspicuous biological impact of estuarine and oceanic acidification was evidenced in calcifying organisms for their shell dissolution and impaired growth. Some organisms may adapt with increasing acidity by increasing calcification rate but at a significant cost. There is a paucity of data on community level effects of acidification. A preliminary survey in a naturally acidified estuary shows that both species richness and diversity were low at low pH (5.73 to 7.2) upstream stations and comparatively rich at high pH (7.2 to 8.1) downstream stations. Some opportunistic polychaete was abundant at low pH area but diversity was low. Shell forming macroinfauna were absent or less abundant and less diverse in the low pH zone. The results inform us about the predicted negative impact of oceanic acidification in the future, and acidified estuary can be used as natural laboratory for understanding oceanic acidification phenomenon.

[1]Department of Biology, FOS, Universiti Brunei Darussalm, Brunei, BE1410
[2] Department of Fisheries and Marine Science, Noakhali Science and Technology University, Bangladesh- 3802. Email: mbhnstu@gmail.com

ECOPHYSIOLOGICAL AND MOLECULAR RESPONSES OF THECOSOME PTEROPODS TO SHORT-TERM OCEAN ACIDIFICATION

Howes, Ella[1,2], Aurélie Moya[1,3], Thomas Lacoue-Labarthe[4], Jean-Louis Teyssié[4], Sylvain Forêt[5], Jelle Bijma[2,6], and Jean-Pierre Gattuso[1,3]

Thecosome pteropods are a group of planktonic molluscs widely distributed in pelagic ecosystems of the world's oceans. They play a critical role as a food resource for higher trophic levels, including commercial fishes. Their aragonitic external shell is highly soluble under acidified conditions, potentially making them highly sensitive to projected changes in carbonate chemistry driven by anthropogenic CO_2 emissions. Despite this concern very little is known about the response of these animals to conditions of elevated pCO_2.

We subjected specimens of the Mediterranean thecosome pteropod *Limacina inflata* to acute exposure to elevated CO_2 projected by the IPCC CO_2 emission scenario A1B. Calcification rates, measured by ^{45}Ca incorporation into the shell, were significantly decreased under elevated pCO_2 conditions. Respiration rates were also measured using fibre optic microsensors. In order to obtain a mechanistic understanding of those ecophysiological observations, we measured gene expression by a large-scale RNA sequencing approach. Using the Illumina technology (100bp paired-end sequencing, 5Gb per sample), we (1) are constructing a sequences database that was not available for *Limacina inflata*, and (2) try to identify the molecular pathways involved in the response of this species to rising pCO_2, giving insights into how pteropods will cope with ocean acidification. This study provides a comprehensive and timely approach to evaluate the short-term response of the metabolic properties of pteropods to ocean acidification.

[1] Université Pierre et Marie Curie-Paris 6, Observatoire Océanologique de Villefranche, 06230 Villefranche-sur-Mer, France ella.howes@obs-vlfr.fr
[2] Marine Biogeosciences, Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, D-27570 Bremerhaven, Germany
[3] CNRS-INSU, Laboratoire d'Océanographie de Villefranche, BP 28, 06234 Villefranche-sur-Mer Cedex, France
[4] Marine Environmental Laboratories, International Atomic Energy Agency, 4 quai Antoine 1er 98000 Monaco, Principality of Monaco
[5] Research School of Biology, Australian National University, Canberra, Australian Capital Territory 0200, Australia
[6] Earth and Space Sciences, Jacobs University Bremen, Campus Ring 1, 28759 Bremen, Germany

ELEVATED *P*CO_2 AFFECTS ENERGY METABOLISM AND REGENERATION IN THE INFAUNAL BRITTLESTAR, *AMPHIURA FILIFORMIS*

Hu, Marian Y.[1], Isabel Casties[1], Meike Stumpp[1], Olga Ortega-Martinez[1], Michael Thorndyke[2], and Sam Dupont[1]

This work investigated the impact of elevated pCO_2, relevant for ocean acidification scenarios as well as potential leakages from sub-seabed CO_2 storage (CCS) sites on physiological parameters of the infaunal brittlestar *Amphiura filiformis*. In response to 4 weeks exposure to moderate (0.3 kPa) and high (0.6 kPa) hypercapnic conditions, metabolic rates were significantly reduced in the high pCO_2 treatment whereas ammonium excretion increased leading to decreased O:N ratios. These findings suggest enhanced utilization of proteins under elevated pCO_2 and increasing net extrusion of proton equivalents. We also determined significant expression changes in arm tissues for acid-base (*NHE6, NBCe and AQP9*) and metabolic (*G6PDH, LDH*) genes supporting the concept of metabolic depression in the high pCO_2 treatment. pO_2 and pCO_2 profiles were measured within burrows indicating that besides strong hypoxic conditions increases of environmental pCO_2 are additive to the naturally high pCO_2 within burrows. Finally, under hypercapnic conditions (0.6 KPa) the metabolic scope of regeneration is strongly depressed as indicated by unchanged metabolic rates accompanied by 80% reductions in arm length regeneration. The present work demonstrates that elevated seawater pCO_2 significantly affect the physiology of infaunal organisms. Depressed metabolic rates and reduced regenerative capacities may have negative repercussions on the ecological fitness and thus determine the long term-fate of ecologically important species.

[1] Department of Biological and Environmental Sciences, The Sven Lovén Centre for Marine Sciences - Kristineberg, University of Gothenburg, Fiskebäckskil, 45178, Sweden (sam.dupont@bioenv.gu.se)
[2] Royal Swedish Academy of Sciences, The Sven Lovén Centre for Marine Sciences - Kristineberg, University of Gothenburg, Fiskebäckskil, 45178, Sweden

MITIGATION POTENTIAL OF ARTIFICIAL OCEAN ALKALINIZATION FOR OCEAN ACIDIFICATION AND ATMOSPHERIC CO_2

Ilyina, Tatiana[1], Dieter Wolf-Gladrow[2], Guy Munhoven[3], and Christoph Heinze[4]

Fossil fuel CO_2 emissions result in climate change and ocean acidification. Enhanced weathering or artificial ocean alkalinization (AOA) has been proposed as a geoengineering method to mitigate further increase of atmospheric CO_2 and decrease of ocean pH. A variant of AOA involves reacting carbonates

and adding the dissolved materials into the upper ocean. The net effect of this approach is to increase ocean alkalinity, thereby increasing the oceanic capacity to store fossil fuel CO_2. Another effect of adding alkalinity would be to drive seawater to higher pH values and thus counteract the ongoing ocean acidification. We test implications of AOA for marine carbon cycle using the global ocean biogeochemical model HAMOCC. In our model scenarios we add alkalinity in the amounts proportional to fossil fuel emissions. We show that large-scale AOA scenarios in which large amounts of alkalinity are added would be necessary to avoid a significant increase in atmospheric CO_2 and to hold the global seawater pH close to today's value. Even a short-term AOA would have long-lasting effects on seawater chemistry. When AOA stops, atmospheric CO_2 (and pH) reverts back to rising (decreasing) at the rate determined by the fossil fuel CO_2 emissions growth, but the effect of AOA is permanent. Hence, in contrast to SRM, effects of AOA on seawater chemistry and atmospheric CO_2 retain after stopping alkalinity addition; AOA would not involve a long-term commitment.

[1]Max Planck Institute for Meteorology, Hamburg, Germany.
[2]Alfred Wegener Institute, Bremerhaven, Germany.
[3]Université de Liège, Liège, Belgium.
[4]University of Bergen, Geophysical Institute, Bjerknes Centre for Climate Research, Bergen, Norway.

EFFECT OF OCEAN ACIDIFICATION ON OXIDATIVE STRESS BIOMARKERS OF THE JUVENILE TIGER SHRIMP, PENAEUS MONODON

Inbakandan, D.[1,3], A. Ravikumar Reddy[1], C. Kumar[1], D. Magesh Peter[2], R. Kirubagaran[2], R. Venkatesan[2], and S. Ajmal Khan[3]

Changes in environmental climate conditions are presently occurring at an extraordinary rate due to large-scale perturbations induced by human activities. Biological activity has in turn directly affected climate by driving many of the global elemental cycles. Ocean acidification is the progressive increase in hydrogen ions (H+) in the world's oceans as a result of rising partial pressure of atmospheric carbon dioxide (CO_2), i.e. a decrease in seawater pH. Most marine invertebrates respond negatively to elevated CO_2 concentrations. The use of biomarkers to investigate the effects of environmental stress factors has increased and most studies have been conducted under laboratory conditions in which the factors that influence biomarkers responses are strict controlled providing an exposure–response relationship. On this back drop this research work focused on the exposure of the juvenile tiger shrimp (*Penaeus monodon)*, which is an economically important aquaculture species to seawater, induced with CO_2 to get acidified. The tissue damage and oxidative stress biomarker enzymes response were studied by the estimating the level of glutathione, lipid peroxide and catalase. Histological sections were done to observe the local tissue damage. The present results provide experimental evidence that ocean acidification induces alteration in the oxidative stress biomarker responses. The various parameters studied in this investigation can also be used as biomarkers for ocean acidification. It is suggested that appropriate ecotoxicological risk assessment should be made in the coastal areas to protect the aquatic animal's health from such global environment changing issues.

[1]Centre for Ocean Research, Sathyabama University, Chennai 600 119, India inbakandan@gmail.com
[2]National Institute of Ocean Technology, Pallikaranai, Chennai-600036, India
[3]Centre of Advanced Study in Marine Biology, Annamalai University, Parangipettai 608 502, India

SPECIES SPECIFIC STABLE ISOTOPE FRACTIONATION OF COCCOLITHOPHORIDS, WITH RESPECT TO CHANGING $CO_{2(AQ)}$ CONCENTRATIONS AND THE PH DEPENDENT C_I POOL

Isensee, Kirsten[1], Clara Bolton[2], Ana Mendez-Vicente[2], and Heather Stoll[2]

In response to changes in seawater pH and CO_2, coccolithophorids have shown species and strain-specific responses in calcification, growth, and morphology, complicating efforts to predict the reactions of this group to future ocean changes. In addition to the photosynthetic isotopic fractioning in the particulate organic matter, previous studies showed strong biological effects on the carbon and oxygen isotopic composition of coccoliths. The large (up to 5 permil) range of vital effects recorded in carbonate liths is hypothesized to be due to the variability of carbon concentrating mechanisms (CCMs). We conduct new culture experiments to assess if these relationships could be exploited to elucidate coccolithophorid response to past changes in seawater carbon chemistry. Our studies reveal strong plasticity in the magnitude of stable carbon and oxygen isotope vital effects in coccoliths of *Calcidiscus leptoporus* and *Emiliania huxleyi* with variable CO_2. At high CO_2 coccoliths of both species are isotopically enriched, but the magnitude is greater in *C. leptoporus,* leading to reduced interspecific offsets at high CO_2. Predicted offsets during photosynthetic isotopic fractionation, due to cell size are not observed, but within each species significant correlations exist between carbon isotope fractionation in POC and $CaCO_3$. A significant reduction in the magnitude of DIC accumulation in the C_i pool at high CO_2, referring to lower CCM activity, was not directly reflected in the stable isotopic fractionation of *E. huxleyi*. We interpret processes responsible for these patterns using a model of isotopic fractionation including cellular compartmentation and species specific carbon uptake mechanism/utilization.

[1]Biology Dept., Univeristy of Oviedo, Oviedo, Spain isenseekirsten@uniovi.es
[2]Geology Dept., Univeristy of Oviedo, Oviedo, Spain

EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON GROWTH AND PHYSIOLGICAL STATE OF ANTARCTIC KRILL

Ishimatsu, Atsushi[1], Awantha Dissanayake[1], So Kawaguchi[2,3], Robert King[2], and James Robinson[4]

Increasing atmospheric CO_2 concentration is acidifying and warming the earth's oceans, most rapidly in the Southern Ocean. In this study, we demonstrate the effects of ocean acidification and warming on growth and physiological state of adult Antarctic krill (*Euphausia superba*) during their main growth period. Krill well fed under summer light regime (summer group) or starved under winter light regime (winter group) were exposed for 21 days to hypercapnic (1900 µatm pCO_2) and warmer (4.5ºC) oceanic conditions as forecasted by the A1FI scenario (experimental) relative to present day controls (380 µatm pCO_2, 0.5ºC). The effects of the future oceanic conditions on krill varied between groups: instantaneous growth rate (IGR), routine oxygen uptake rate (ROU) and ammonia excretion rate (AER) all doubled under the future oceanic conditions in the summer group (IGR, 11.13 ± 0.30 vs. 6.09 ± 0.16%; ROU, 6.5 ± 0.1 vs. 3.7 ± 0.1 mmol O_2 mg dry mass^{-1} h^{-1}; AER, 2.2 ± 0.3 vs. 1.1 ± 0.2 mmol NH_4 mg dry mass^{-1} h^{-1}, mean ± SEM, n = 10). In contrast, IGR became negative (- 1.79 ± 0.09 vs. 0.85 ± 0.03%), ROU did not change (2.3 ± 0.1 vs. 2.1 ± 0.1) and AER slightly increased (0.24 ± 0.03 vs. 0.17 ± 0.02) in the winter group. Haemolymph pH in the experimental krill became slightly but significantly higher than in the control krill in both summer and winter (ΔpH ≈ 0.15). Life-history consequences of the present findings need to be investigated by longer-term exposure experiments.

[1]Institute for East China Sea Research, Nagasaki University, Taira-machi 1551-7, Nagasaki, 851-2213, Japan (a-ishima@nagasaki-u.ac.jp)

[2]Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050, Australia
[3]Antarctic Climate and Ecosystems Cooperative Research Centre, Sandy Bay, Hobart, Tasmania 7001, Australia
[4]Institute for Marine and Antarctic Studies, Sandy Bay, Hobart, Tasmania 7001, Australia

INTERACTIVE EFFECTS OF ELEVATED CO_2 AND TEMPERATURE ON PHYSIOLOGY OF TWO BIVALVE SPECIES

Ivanina, Anna[1], Omera B. Matoo[1], Rita Bagwe[1], Elia Beniash[2], and Inna M. Sokolova[1]

Estuarine bivalves are susceptible to environmental stressors such as ocean acidification and elevated temperature which can interactively affect their performance and survival. We tested the interactive effects of elevated CO_2 and temperature on energy metabolism, oxidative stress and activity of carbonic anhydrase in two common bivalves - *Crassostrea virginica* (Eastern oyster) and *Mercenaria mercenaria* (hard shell clam). Organisms were exposed for 2 and 15 weeks to a combination of two temperatures (22˚C and 27˚C) and two P_{CO2} levels – 380 and 800 ppm representative of the present-day conditions and a moderate IPCC scenario for the year 2100, respectively. Mortality during exposures to elevated temperature and P_{CO2} was significantly higher in oysters than in clams. In contrast, standard metabolic rates were significantly elevated in clams but not oysters exposed to high P_{CO2} and elevated temperature. In clams, long-term exposure to elevated temperature but not P_{CO2} led to a decline in the total antioxidant capacity (TAOC) and increased levels of oxidative stress biomarkers. In oysters, higher levels of oxidative damage and increased TAOC were detected after 15 weeks at elevated P_{CO2}. Carbonic anhydrase activity was significantly increased in clams and oysters exposed to combined stressors. Our results indicate that elevated temperature and P_{CO2} induce stress in these bivalves and may compromise their survival under future ocean conditions, and that sensitivity to elevated P_{CO2} such as expected in the case of ocean acidification is more pronounced in oysters than in clams. Supported by NSF award IOS-0951079 to E.B. & I.M.S.

[1]Department of Biology, University of North Carolina at Charlotte, 9201 University City Blvd. Charlotte, NC 28223, USA aivanina@uncc.edu
[2]Department of Oral Biology, University of Pittsburgh, 589 Salk Hall, 3501 Terrace Street, Pittsburgh, PA 15261, USA

DOES THE CARBON DIOXIDE-INDUCED WATER ACIDIFICATION AFFECT THE BALTIC ISOPOD *SADURIA ENTOMON*?

Jakubowska, Magdalena, Monika Normant, and Mateusz Jerzak

Baltic is a semi-enclosed, brackish sea in which the effect of ocean acidification is reinforced by high biological production and decomposition of organic matter. It causes large seasonal variations in CO_2 concentrations, especially near the bottom layers affecting organisms living there. One of the species temporary exposed to higher pCO_2 seems to be the isopod *Saduria entomon*, considered as glacial relict. Thus, we conducted a study of the effect of CO_2-induced water acidification on the behavior and physiology of this species.
Isopods were kept in containers with constant flow of water with different pH values (8.2 - control, 7.5 and 7.0) for 14 days. During the experimental period, the survival rate was measured and behavior observed. After two weeks of exposition the total metabolic rate was determined based on heat dissipation measurements carried out in an isothermal calorimeter of the Calvet type. Next the

hemolymph samples were collected from the heart of each animal to measure the osmolality, chloride concentration and extracellular pH. Carbon dioxide-induced water acidification did not significantly affect ($p>0.05$) the mortality, behavior and hemolymph chloride concentration in *S. entomon*. Significant changes ($p<0.05$) were observed in hemolymph pH and osmolality. The previous data suggest that lowering of water pH does not significantly affect the metabolic rate of *S. entomon*, however more measurements are still necessary to draw final conclusions.

Institute of Oceanography, The University of Gdansk, Al. Pilsudskiego 46, 81-376 Gdynia, Poland (ocemja@ug.edu.pl)

ANTARCTIC BIVALVE RESPONSE TO OCEAN ACIDIFICATION; A MODELLING AND HISTORIC PERSPECTIVE.

Jennions, Suzanne[1], Lauren J Gregoire[2], Andy Ridgwell[2],Daniela N. Schmidt[1], Katrin Linse[3], and Tom Scott[4]

High latitude marine environments are amongst regions most at risk from ocean acidification, as colder waters are naturally less saturated with respect to carbonate ions. Globally, surface ocean pH has decreased by 0.1 unit since pre-industrialisation[1] and global ocean models predict a further decrease of 0.3-0.5 pH units by 2100[1]. Predicted pH reduction caused by continued absorption of CO_2 from the atmosphere may lead to undersaturation of aragonite and calcite, both polymorphs of calcium carbonate used by marine calcifying organisms to precipitate shells and skeletons. Aragonite undersaturation is predicted to occur in Antarctic wintertime as soon as 2030 and may have a detrimental effect of the survival of calcifying organisms in the region[2].

We use the UVic model, an intermediate complexity model, to investigate seasonal temperature, dissolved inorganic carbon, alkalinity and pH stability around the Antarctic Peninsula over the past 100 years. To assess the impact of ocean acidification on bivalves in the Antarctic, UVic data is combined with bivalve shell life history reconstructions, analysing annual accretions of calcium carbonate via (i) growth increment analysis; (ii) geochemical proxies such as strontium/calcium for growth rate, magnesium/calcium for temperature, barium/calcium for primary productivity; and (iii) features of the microcrystalline structure such as the proportion of the more soluble aragonite vs. less soluble calcite polymorphs of calcium carbonate. Ultimately, life history reconstructions of historic (collected pre-1960s) and modern specimens of the epifaunal *Limatula hodgsoni* (Smith, 1907), *Limatula pygmaea* (Philippi, 1845), and *Limopsis marionensis,* Smith 1885 will be compared to assess the in situ effect of ocean acidification since pre-industrialisation, on these key habitat forming organisms.

[1] School of Earth Sciences, University of Bristol, UK (sj9731@bristol.ac.uk)
[2] School of Geographical Sciences, University of Bristol, UK
[3] British Antarctic Survey, Cambridge, UK
[4] Interface Analysis Centre, Department of Physics, University of Bristol, UK

MEETING THE PUBLIC NEED FOR OCEAN ACIDIFICATION INFORMATION IN THE US

Jewett, Libby

In 2009, the US Congress passed the Federal Ocean Acidification Research and Monitoring Act. The passage of this law ensures a long term commitment to ocean acidification monitoring and research which is primarily subject to change only by Congressional action. As a result, it is imperative that the US agencies involved be attentive to the information needs of the country and Congress, information which can be used to inform both mitigation and adaptation policies. The existence of a US OA law contrasts with the cohesive European efforts which were funded at ample levels years earlier than in the US but now are subjected to re-commitment of resources through a fully competitive process out of EU or individual country research general research funds. In the US, FOARAM requires that NOAA, NASA and NSF all make resource commitments to OA work for the foreseeable future. This enables the US to make broad scale commitments to long term OA observing and research capabilities and infrastructure. Delegates from each agency meet on a regular basis to coordinate activities across the federal government. At the state level, NOAA also works closely with state governmental agencies to study and address OA-related local impacts where possible, sharing both expertise and resources. The US is a strong supporter of the International Coordination Office for Ocean Acidification. Strong international collaboration will enable the most efficient use of resources, a more integrated data management framework and better flow of information and synthesis products.

National Oceanic and Atmospheric Administration, 1315 East West Highway, Silver Spring, MD 20910
Libby.Jewett@NOAA.gov

KEY CONTROLS ON THE SEASONAL AND INTERANNULA VARIAITONS OF THE CARBORNATE SYSTEM IN THE NORTHEAST ATLANTIC

Jiang, Zong-Pei, David J. Hydes, Toby Tyrrell, Susan E. Hartman, Mark C. Hartman, and Cynthia Dumousseaud

The seasonal-to-interannual biogeochemical variations in the Northeast Atlantic were examined by the high-frequency underway measurements combined with monthly sampling of carbon-related biogeochemical variables in the Bay of Biscay. The controlling mechanisms were investigated by distinguishing the contributions of various bio-physical processes to the monthly changes in dissolved inorganic carbon (DIC) and pCO_2. Winter mixing is identified to play a significant role in modulating the carbon variability both on seasonal and interannual timescales. The winter maxima and summer minima of DIC and nutrients were primarily driven by convective deep winter mixing followed by spring biological removal fuelled by the wintertime increase in nutrient. The annual cycle of pCO_2 (61-75 atm) showed two peaks associated with winter maximum DIC and summer maximum sea surface temperature, respectively. The interannual variability in DIC results mainly from the changes in the strength of winter mixing which can be linked to climate indexes. Cold years with deep MLD in the Bay of Biscay seem to be associated with negative indexes of the wintertime North Atlantic Oscillation (NAO) and the Eastern Atlantic pattern (EA). Although deep winter mixing tends to increase the seasonal amplitudes of DIC (47-81 µmol kg^{-1}) as well as the rates of biological production in the mixed layer, there is no clear link to consequent enhanced oceanic CO_2 uptake. Overall in 2009 and 2010 the Bay of Biscay was a CO_2 sink (-1.2 mol m^{-2} yr^{-1}) with stronger uptake in spring and early winter.

National Oceanography Centre Southampton, University of Southampton Waterfront Campus, European Way, Southampton, United Kingdom, SO14 3ZH (zongpei.jiang@noc.soton.ac.uk)

COMBATTING HEAT IN A CHANGING OCEAN: SEA URCHIN LARVAE ARE PREPARED FOR BATTLE

Kapsenberg, Lydia and Gretchen E. Hofmann

Ocean acidification and ocean warming present a significant threat to the Southern Ocean marine ecosystem, yet little is known regarding the biological consequences of these simultaneous and potentially interacting stressors. In this study, we assessed the thermal tolerance of sea urchin larvae of the Antarctic sea urchin, *Sterechinus neumayeri,* that were raised in seawater with variable pCO_2 conditions. At McMurdo Station Antarctica, larvae were reared in culture vessels under a flow-through regime in -0.7°C filtered seawater with pCO_2 levels of 424, 658, and 1074 µatm, to represent near present day and future levels of ocean acidification. Sea urchins at four different developmental stages (blastula, gastrula, prism, and 4-arm pluteus) were exposed to a range of temperatures (-1.7 to +25°C) for 1 hour, allowed a recovery period of ~20h, and scored for survival. Larvae of *S. neumayeri* exhibited unexpectedly high thermal tolerance, surviving temperatures up to 20°C. Survival was stage dependent, with blastula larvae being 5 °C less thermotolerant than gastrula, prism and pluteus larvae. For all stages, survivorship was largely unchanged across the three pCO_2 treatment groups, with the exception of a pCO_2 effect on thermotolerance of blastula larvae. We discuss a gene expression-based mechanism that might explain the pCO_2 effect observed at the blastula stage and the change in thermal tolerance through development. Our data highlight the importance of testing multiple stressors in order to understand sublethal and physiological effects of ocean change that single stressor studies might mask.

Dept. Ecology, Evolution and Marine Biology, University of California Santa Barbara, Santa Barbara, CA 93106 (lydia.kapsenberg@lifesci.ucsb.edu)

HIGH PRECISION MEASUREMENTS OF PH IN LARGE SALINITY RANGE WATERS USING A NOVEL FLUORESCENCE BASED METHOD IN A FERRYBOX-SYSTEM IN THE BALTIC SEA AREA

Karlson, Bengt[1], Leif G. Anderson[2], Agneta Fransson[3], Aron Hakonen[2], Stefan Hulth[2], Sara Johansson[1], Elisabeth Sahlsten[1], and Anna Willstrand-Wranne[1]

To observe changes in the marine carbonate system due to increased carbon dioxide (CO_2) input from the atmosphere, high precision and accuracy methods of pH measurements are important. A fluorophore indicator based pH determination method has been developed into an operational system installed as part of a FerryBox-system on a cargo vessel. The ship passes through the Baltic Sea area twice a week enabling frequent sampling in several sub basins. pH-data is collected every few minutes together with several other parameters, e.g. pCO_2, salinity, temperature and chlorophyll fluorescence, and is transmitted using satellite connection every hour. The salinity range is approximately 3-30. Results from measurements in 2011 And 2012 are presented. In addition results from a comparison of the novel method, the absorbance method based on the m-cresol purple indicator (Clayton and Byrne, 1993) and the classical electrode based method is presented.

[1]Swedish Meteorological and Hydrological Institute, Oceanographic Laboratory, Sven Källfelts gata 15, SE 426 71 Västra Frölunda, Sweden (bengt.karlson@smhi.se).
[2]University of Gothenburg, Department of Chemistry and Molecular Biology, Box 462, SE 405 30 Gothenburg, Sweden
[3]University of Gothenburg, Department of Earth Sciences, Box 460, SE 405 30 Gothenburg, Sweden

SIMULATED DIURNAL PH FLUCTUATIONS CAUSE UNANTICIPATED EFFECTS ON GROWTH OF BARNACLES

Karlsson, Louise [1], Anna-Lisa Wrange [2], and Jon Havenhand [2]

Several studies have shown substantial diurnal fluctuations in pH in coastal waters, especially in near-shore environments. The biological effects of ocean acidification in combination with these natural fluctuations have received little attention to date. We exposed multiple batches (different genotypes) of newly settled barnacles, *Balanus improvisus*, to constant pH under "control" (pH = 8.1) or "acidified" (pH = 7.7) conditions, as well as a treatment that simulated the maximum diurnal pH fluctuations seen in the near-shore habitats where this barnacle lives (7.5 ≤ pH ≤ 7.9). After 3 months (≈ sexual maturity) growth and survival of barnacles under fluctuating pH was different to that under either of the constant pH treatments. Notably, fluctuating pH caused barnacles to grow the most, although the magnitude of this result varied significantly with batch. Similarly, survival in the different treatments also varied significantly with batch, but was always lowest in pH 8.1. Shell plates from the "control" pH treatments were considerably stronger (penetrometry) than those from the other two treatments, yet Ca content, and the Ca:Mg ratio of the shell plates, did not vary between treatments or batches. These results show that barnacles living in fluctuating pH conditions respond differently to those exposed to constant pH. This highlights the need to include natural fluctuations in environmental variables when designing experiments to assess the likely future effects of ocean acidification on near-shore organisms.

[1] Department of Biological & Envrionmental Sciences, Gothenburg University, S-40530 Gothenburg, Sweden
[2] Department of Biological & Envrionmental Sciences, Tjärnö Marine Biological Laboratory, Gothenburg University, S-45296 Strömstad, Sweden (jon.havenhand@gu.se)

OCEAN ACIDIFICATION MODIFIES THE COMMUNITY STRUCTURE OF BENTHIC FORAMINIFERA

Khanna, Nikki[1], Jasmin Godbold[2], Martin Solan[2], William E. N. Austin[3], and David M. Paterson[1]

Elevated atmospheric concentrations of carbon dioxide, partly driven by anthropogenic activity, are changing the seawater carbonate chemistry and driving down the pH of the oceans. The implications on the marine environment include a reduction in the calcifying capacity of organisms, such as benthic foraminifera, that produce carbonate structures. Foraminifera are a dominant component of many marine communities and constitute one the most diverse groups of shelled microorganisms in both modern and ancient oceans. Our current knowledge of acidification is largely based on short-term (days-weeks) experiments and as a result the ability of these organisms to acclimate or adapt to the predicted changes is yet to be determined.

Here we will present results from 18 months of continuous mesocosm incubations (UK Ocean Acidification Benthic Research Programme). Sediment communities were exposed to three levels of atmospheric CO_2 (380, 750 and 1000 ppm) and two temperature regimes (seasonally varying ambient and 10°C constant). Replicated monthly surface sediment samples were taken from each mesocosm and processed using standard micropalaeontological techniques. The natural foraminiferal assemblages were extremely diverse (+40 species). Our results show a change in community structure at higher CO_2 levels, with a decrease in total diversity but a proportional increase in agglutinated (lacking calcium tests) individuals. Overall, foraminiferal growth and survival was greatly reduced, and deformation and dissolution features were consistently observed in the calcifying foraminifera with increasing CO_2 levels. Crucially, our work documents species-specific and community level impacts in addition to determining important physiological consequences (growth and survival) of long-term ocean acidification.

[1] Sediment Ecology Research Group, Scottish Oceans Institute, University of St Andrews, Scotland, KY16 9LB (nk274@st-andrews.ac.uk)
[2] Ocean and Earth Science, National Oceanography Centre, University of Southampton, SO14 3ZH
[3] School of Geography & Geosciences, University of St Andrews, Scotland, KY16 9AL

TEMPORAL VARIABILITY OF pCO_2 IN THE CALIFORNIA CURRENT DRIVEN BY COASTAL UPWELLING AND EL NIÑO/LA NIÑA SOUTHERN OSCILLATION

Kim, Hey Jin[1], SungHyun Nam[1], Uwe Send[1], Mark Ohman[1], Christopher Sabine[2], and Richard Feely[2]

The California Current Ecosystem (CCE) interdisciplinary biogeochemical moorings (CCE1 and CCE2) measure high resolution physical and biochemical variables including partial pressure of carbon dioxide (pCO_2) in the atmospheric marine boundary and the surface ocean. Time series of pCO_2 at the open ocean site (CCE1, 220km southwest from Point Conception) shows much smaller variability than pCO_2 at the upwelling ecosystem site (CCE2, approximately 35 km offshore from Point Conception). CCE2 is directly influenced by coastal upwelling processes. When wind stress is upwelling favorable, the CCE2 mooring time series show that the upper ocean is occupied by high pCO_2 nutrient-rich cold water. The upwelled high pCO_2 can be outgassed to the atmosphere, consumed by phytoplankton photosynthesis, or transported by horizontal advection. When upwelling favorable winds weaken, pCO_2 starts to decrease, and nitrate reduction and increase of oxygen and chlorophyll occur simultaneously, which is the signature of primary production contributing partly to the pCO_2 decrease. Interannual variability of pCO_2 shows influences of El Niño and La Niña. The connection between physical forcing, primary production, represented by fluorescence time series, and predation effect, represented by 75 kHz acoustic backscattering strength time series, will be examined.

[1] Scripps Institution of Oceanography, UCSD, La Jolla, CA, USA (hjkim@ucsd.edu)
[2] NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA

EFFECTS OF ELEVATED CARBON DIOXIDE IN SEAWATER ON THE EARLY LIFE HISTORY OF OLIVE FLOUNDER, *Paralichthys olivaceus*

Kim, Kyung-Su[1] JeongHee Shim[2], and Suam Kim[1]

Due to the increasing concentration of CO_2 in the atmosphere, the ocean is becoming acidified. However, little is known about how fishes respond to the reduced pH condition. We reared newly hatched larvae of the olive flounder, *Paralichthys olivaceus*, in three different concentrations of CO_2 (570, 980 and 1300 ppm atmospheric CO_2) for up to 28-days to examine the acidification impacts on early life stages of fish. After 4 weeks, all fish larvae were sampled and body lengths were measured for growth comparison. The whole bodies of fish larvae were vacuum freeze dried, and the concentration of calcium and some trace elements were measured using ICP-AES. Results indicated that body length of flounder larvae were significantly increased with increasing carbon dioxide concentration ($P<0.05$). Calcium and trace elements also showed increasing tendencies with increasing CO_2 in seawater, although there were no statistically significant differences.

[1] Department of Marine Biology, Pukyong National University, Busan, 608-737, R Korea. (ks-kim@pknu.ac.kr)

[2] National Fisheries Research and Development Institute, 152-1 Haeanro, Gijang-eup, Gijang-gun, Busan, 619-705, R Korea

LOW OXYGEN AND PH LEVELS DURING COASTAL UPWELLING AFFECT SURVIVORSHIP AND GROWTH OF THE RED ABALONE *HALIOTIS RUFESCENS*

Kim, Taewon[1,2], Jim Barry[1], and Fiorenza Micheli[2]

Exposure of nearshore animals to hypoxic, low pH waters upwelled from below the continental shelf and advected near the coast may be stressful to marine organisms and lead to impaired physiological performance. Along the west coast of California, episodes of upwelled, low O_2, low pH waters are observed frequently in nearshore areas. We mimicked these conditions in the laboratory and tested the effect of short-term exposure to water with low oxygen (40% saturation, 5mg/L) and/or low pH (pH 7.5) on the mortality and growth of juvenile red abalone (*Haliotis rufescens*, shell length 5-10mm). When exposed for 3 to 6 hours, at intervals of 3-5 days, the mortality rates of juvenile abalones did not differ between low O_2, low pH treatments and control conditions (O_2: 100% saturation, 12 mg/L; pH 8.0). However, when exposed for 24 hrs, twice over a 15 day period, juveniles experienced higher mortality in the low oxygen treatments compared to control conditions, regardless of pH levels (pH 7.5 vs. 8.0). In contrast, growth was significantly reduced when juveniles were exposed to low pH water. These results indicate that prolonged exposure to low oxygen concentration is detrimental for survival of red abalones, whereas pH (or related factors) is a crucial factor for their growth. Furthermore, our results imply that prolonged exposure (>24 hrs) to upwelled waters can significantly influence the mortality and growth rates of abalones.

[1]Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95305
[2]Hopkins Marine Station, Stanford University, 120 Oceanview Blvd., Pacific Grove, CA 93950
ktwon@mbari.org

TIME-SERIES BIOGENIC CARBONATE FLUXES IN THE ARCTIC SEA: PRODUCTION AND DESTRUCTION CHANGES FROM 2010 TO 2011.

Kimoto, K., O. Sasaki, J. Onodera, N. Harada, Y. Tanaka, and M.C.Honda

The Arctic Ocean is sensitive to global climate changes. It is believed that the increasing anthropogenic carbon dioxide emission will increase oceanic acidification and lead to the ecological reconstruction. We carried out time-series observations of sinking particles in the Arctic Sea to investigate the biogeochemical and ecological changes by using sediment traps. The time-series samples of sinking particles were obtained at Stn. NAP10t (75°N, 162°W, water depth 1,975 m) in the Northwind Abyssal Plain, the Chukchi Sea. Observation periods were from Oct. 2010 to Sep. 2011. The sediment trap cups were deployed at 180 m (shallow) and 1,300 m (deep) water depths and 26 samples were recovered from each water depths. Sampling interval for each bottle was 13-15 days.
Total mass flux (TMF, mg/cm2/day) at 200 m water depths showed clear relationship with the seasonal changes. Phyto- and zooplankton (diatoms, copepods, foraminifers, Shrimps, and other gelatinous plankton) were main contributors to TMF. As the biogenic carbonate producers, planktic foraminifers, pteropods, ostracods and planktic bivalves were observed in recovered samples, but the periods of occurrence were clearly different: planktic bivalves and pteropods mainly occurred in late autumn (November - December), 2010 and they were the primary producer of biogenic carbonate in this season (ca. 20-25 indiv./m2/day). On the other hand, planktic foraminifers appeared in the summer (August-

September) of 2011 (ca. 22 indiv./m2/day). Only pteropods occurred continuously through the year. These fluxes were basically consistent with the deep trap deployed at 1,300m water depth. It suggests that alternation of producer of biogenic carbonates occurred in the Arctic Ocean through a year.
We also performed morphological and density analysis of pteropods and foraminiferal shells by micro-focus X-ray CT. Shell density of pteropods greatly changed in each periods. It indicates that saturation states of aragonite shells frequently changed in the water column in the Arctic Ocean.

Japan Agency for Marine-Earth Science and Technology, 2-15, Natsushima-cho, Yokosuka, Kanagawa Pref., Japan,237-0061 kimopy@jamstec.go.jp

POTENTIAL EFFECTS OF OCEAN ACIDIFICATION ON THE NUTRITONAL COMPOSITION OF PHYTOPLANKTON FOR FISHERY-BASED FOODWEBS

King, Andrew L., Gary H. Wikfors, Lisa M. Milke, and Shannon, L. Meseck

The predicted future acidification of the ocean, expected to result from rising carbon dioxide (CO_2), could have positive and/or negative consequences for phytoplankton and the organisms that depend on their primary productivity. Modern lineages of phytoplankton, single-celled photosynthetic organisms that are at the base of aquatic food webs, are believed to have evolved some 150-400 million years ago concurrently with marine metazoans that are presently dominant in the world's oceans. Through unialgal culture experiments with representatives from several major phytoplankton classes, we have begun work to document the effects of CO_2 and pH on phytoplankton growth and relevant nutrition parameters including lipid, fatty acid, and elemental compositions that could affect grazers in marine ecosystems.

NOAA/NMFS, Northeast Fisheries Science Center, Milford Laboratory, 212 Rogers Ave., Milford, CT 06460, USA (andrew.king@noaa.gov)

DATA-BASED EVALUATION OF GLOBAL CARBON CYCLE MODELS USED FOR OCEAN ACIDIFICATION RESEARCH

Koeve, Wolfgang, Wolfgang Barkmann, Olaf Duteil, and Andreas Oschlies

Ocean biogeochemical models are routinely applied to assess the net global impact of ocean acidification and warming on pelagic $CaCO_3$ cycling. As with respect to the net change of global air-sea carbon fluxes affected by the reduced calcification under future CO_2 conditions, these models diverge by a factor of four. The standard method to evaluate modeled $CaCO_3$ cycles is to compare alkalinity and $CaCO_3$ saturation states with observations. In general, state-of-the-art models do feature strong deviations and it is unclear if, or to what extent, these are driven by a deficient representation of physics (ocean circulation) or a deficient representation of biogeochemistry. This points to a strong need for improvement of the data-based evaluation of the base state of global biogeochemical models used for ocean acidification research.
Here we apply the TA* method to output from a variety of model experiments and observations (GLODAP). This method was originally developed to separate the signals of $CaCO_3$ production and dissolution from the large, conservative alkalinity background in observations and is also a critical part of approaches used to quantify the inventory of anthropogenic CO_2 in the ocean.
The aim is our study is twofold. First, to assess the TA* method using additional explicit representations of preformed alkalinity, accumulated $CaCO_3$ dissolution, and organic matter remineralisation in our

models. And second, we aim to disentangle deficiencies in the physical and biogeochemical $CaCO_3$-cyle module in a series of ocean biogeochemical models of increasing complexity. Finally, our modeling study provides a critical assessment of the 'mystery of shallow $CaCO_3$ dissolution', i.e. apparent dissolution of major $CaCO_3$ minerals well above their saturation horizon.

GEOMAR, Biogeochemical Modelling, Düsternbrooker Weg 20, 24105 Kiel, Germany (wkoeve@geomar.de)

RECENT INTERANNUAL AND SEASONAL VARIABILITY OF pH IN THE NORTH-EASTERN BLACK SEA

Kostyleva, Anna V.[1] and Oleg I. Podymov[2]

Using data from more than 600 stations gathered by the P.P. Shirshov Institute of Oceanology in 1984-2011 we estimated average seasonal and annual variability of pH and dissolved oxygen in the north-eastern Black Sea along with calculated carbonate system elements. Analyzed water included coastal area and the open sea: surface layer, cold intermediate layer (CIL) and redox-layer. While no clear trend of pH decrease in the Black Sea that might testify progressive acidification was revealed, some correlations with climatic changes, particularly the North-Atlantic oscillations (NAO), were found.
Our studies showed that pH fluctuations in the Black Sea significantly correlated with the CIL oxygen changes, which in turn are consistent with the interannual variability of the winter vertical mixing intensity, regulated by large-scale climate formations like the NAO.

[1]Laboratory of Marine Chemistry, Southern Branch of P.P. Shirshov Institute of Oceanology, RAS, Prostornaya 1g, Gelendzhik, 353467, Russia. ventis-ire@yandex.ru
[2]Laboratory of Informatics and Applied Hydrophysics, Southern Branch of P.P.Shirshov Institute of Oceanology, RAS, Prostornaya 1g, Gelendzhik, 353467, Russia (huravela@yahoo.com).

DECADAL TREND OF ACIDIFICATION IN THE NORTH PACIFIC SUBTROPICAL MODE WATER AND ITS CONNECTION WITH CLIMATE VARIABILITY

Kosugi, Naohiro[1], Daisuke Sasano[1, 2], Masao Ishii[1, 2], Kazutaka Enyo[1, 2], Toshiya Nakano[1, 2], and Takashi Midorikawa[3]

Japan Meteorological Agency has a long-term time-series dataset of hydrography/hydrochemistry in surface and interior of the ocean in the western North Pacific. In the interior of its principal repeat line along 137ºE, spectrophotometric measurements of pH (pH_T) were started in 2003. Measurements of total dissolved inorganic carbon (DIC) started in 1994 also made it possible to calculate pH since 1994. In order to identify the trend of ocean acidification in the ocean interior along 137ºE, we interpolated the data on to isopycnal surfaces. It was clearly found that pH was steadily decreasing in the upper layers for the last decade. The decrease of pH was particularly prominent on $\delta_\theta = 25.2$ kg/m^3 in the North Pacific Subtropical Mode Water (NPSTMW) where pH decreased by -0.06 for the last 16 years. Nearly half of this pH decrease was explained by the DIC increase associated with biological activity as shown by the apparent oxygen utilization (AOU) increase.
There is a significant correlation between AOU and potential temperature in NPSTMW at 137ºE. The increase in AOU has been observed when the formation region of NPSTMW just south of Kuroshio Extension moved far to the east, i.e., NPSTMW took longer time from its formation region to reach to 137ºE while consuming more oxygen and producing more CO_2. These observations indicated that, in addition to the anthropogenic CO_2 increase in the atmosphere, changes in climate such as wind-forcing

on the ocean circulation and air-sea heat flux affect significantly on the trend of acidification in the ocean interior.

[1]Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki, 305-0052 Japan (nkosugi@mri-jma.go.jp)
[2]Japan Meteorological Agency, 1-3-4 Otemachi, Chiyoda-ku, Tokyo 100-8122 Japan
[3]Nagasaki Marine Observatory, 11-51 Minamiyamatemachi, Nagasaki, 850-0931 Japan

MECHANISMS OF ACID-BASE REGULATION AND CO_2 TOLERANCE IN MARINE FISH: CHARACTERISATION OF THE ENERGY BUDGET IN ISOLATED GILLS

Kreiss, Cornelia, Katharina Michael, Christian Bock, Magnus Lucassen, and Hans-O. Pörtner

Fish generally seem to be less sensitive to elevated CO_2 concentrations due to their efficient ion regulatory capacities. However, due to general constraints on functional capacity at the edges of a species' thermal window, sensitivity to elevated P CO_2 levels may be highest at extreme temperatures. Analyses of respiration rates in isolated gills arches are suitable to determine the fractional costs of various regulation processes in gill tissue. These analyses may help to identify thermal constraints on tissue functions, which exert their effects on the whole animal. In this study we used the isolated gill model for Atlantic cod acclimated long-term to various levels of CO_2 and temperature to determine the fractional costs of ion regulation and of protein and RNA synthesis in relation to the global energy budget by applying specific inhibitors. Furthermore we used temperature ramps to define the thermal window of isolated gill arches. First results showed a significantly reduced Na+K+-ATPase activity in gills of CO_2 exposed fish (2400 µatm) compared to the control group. No significant differences in respiration rates between control and CO_2 exposed specimens were observed with respect to the different temperatures applied and the inhibition of protein and RNA synthesis. These findings suggest that readjustment in the density of functional protein change capacity but do not lead to changes in their responsiveness to CO_2 or temperature. The now established method has been expanded to characterize the cost of bicarbonate exchangers, Na+-H+-Antiporters and the H+-ATPase in Atlantic cod at various CO_2 and temperature levels.

Alfred Wegener Institute for Marine and Polar Research, Am Handelshafen 12, D-27570 Bremerhaven, Germany (Cornelia.Kreiss@awi.de)

VARIABILITY OF ARAGONITE SATURATION STATE OF SURFACE SEAWATER IN THE WESTERN PACIFIC AT SEASONAL AND LONGER TIMESCALES

Kuchinke, Mareva [1] , Andrew Lenton[1], and Bronte Tilbrook[1,2]

Values of aragonite saturation state (Ω_{ar}) are often used as a proxy for estimating net calcification rates in corals. As CO_2 levels continue to rise in the atmosphere, ocean acidification and changes in seawater carbonate chemistry are likely to affect Ω_{ar} and the ability of reef ecosystems of Pacific island nations to show net growth. The goal of this study is to characterise and quantify seasonal and inter-annual variability in Ω_{ar} for surface waters of the Western Pacific island region (120°E:220°E, 35°S:30°N). As this region remains poorly sampled with respect to carbon, we first determined a new relationship between salinity and total alkalinity (TA) using historical data. To calculate the total inorganic carbon (TCO_2) and Ω_{ar} of the seawater, the calculated TA was used with surface partial pressure of CO_2 (pCO_2)

data from the Takahashi 2009 climatology for monthly rates and with pCO_2 data from the SOCAT database for inter-annual rates.
The variability of TCO_2 in surface waters was found to be the main driver of seasonal change in Ω_{ar}. In some regions of the study area, TA compensates the TCO_2 response (*e.g.* in the West Pacific Warm Pool and the South Equatorial Current). In these places, change in evaporation and precipitation is the main process responsible for the seasonality of TCO_2 and TA. The SST variability is also generally small except in the subtropical water on the northern and southern boundaries of our study region where SST variability is large. However, even in these regions, TCO_2 is still more important.
The inter-annual variability in Ω_{ar} was small and a general decrease in the saturation state became apparent on decadal time scales. The magnitude and trend of the decadal change in Ω_{ar} is similar across the entire region, indicating increased atmospheric CO_2 concentrations is driving most of the long term decrease in Ω_{ar}. The influence of regional changes in salinity and SST due to changes in the hydrological cycle were found to have only a minor role in influencing the variability rate of Ω_{ar} in the Western Pacific.

[1] CSIRO Wealth from Oceans National Research Flagship, PO Box 1538, Hobart, TAS 7001, Australia. mareva.kuchinke@csiro.au
[2] Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, Hobart, TAS 7001, Australia

IMPACTS OF OCEAN ACIDIFICATION ON THE CORAL-REEF ORGANISMS AND ECOSYSTEM
Kurihara, Haruko[1], Asami Takahashi[2], Tomoki Watanabe[2], Shihori Inoue[3], and Hajime Kayanne[3]

A number of studies have demonstrated that ocean acidification reduces the calcification rate of corals, and impact of acidification on the coral-reef ecosystem is on highly concern. However, most ocean acidification works have been focused on certain species of corals, and little is known about the impact on the other coral reef organisms. Because recent works suggest that ocean acidification intricately impact marine organisms at different levels, comprehensive works evaluating the impact of ocean acidification on the diverse coral-reef organisms, on the interaction between organisms and on community level is imperative.
In this presentation, we present laboratory and field works evaluating the effects of ocean acidification on different ecological functioning species including corals, soft-coral, sea grass, sea urchins and sea star. Results suggest that the response of corals to ocean acidification can differ between species and even within species. Studies also suggest the difference tolerance capacity of the organisms and life stages, and possible change on the interaction between organisms. Additionally, field studies at high CO_2 vent site studies suggested possible phase-shift from hard coral to soft coral dominant ecosystem. Based on the available studies we will discuss the potential impact of ocean acidification on the coral reef at ecosystem level and possible community shifts will be suggested.

[1] Transdisciplinary Research Organization for Subtropical and Island Studie*s*, University of the Ryukyus, Nishihara, Okinawa 903-0213, JAPAN (harukoku@e-mail.jp)
[2] Graduate school of engineering and science, University of the Ryukyus, Nishihara, Okinawa 903-0213, JAPAN
[3] Department of Earth and Planetary Science, Tokyo University, Bunkyo, Tokyo, 113-0033, JAPAN

TEMPERATURE AND OCEAN ACIDIFICATION EFFECTS ON BENTHIC INVERTEBRATES OF THE SOUTHERN PACIFIC COASTAL ECOSYSTEM (TOA SPACE PROJECT)

Lagos N.A.[1]; Lardies M.[2] , Ramajo L.[1]; Prado L.[1]; Labra F.[1]; Arias M.B.,[2] Vargas C.A.[3]; Navarro J.M. [4]; Manríquez P.H. [4], and R. Torres R.[5]

We study the geographic variability of several pCO_2-sensitive traits in benthic invertebrates (i.e., metabolism, shell morphology, heat-shock proteins expression, scaling relationships in calcium carbonate content and biomineralization in shells of gastropods and mussels) and assess how these responses can be ascribed to changes in pCO_2 levels and pH in seawater using experimental mesocosms. In general, our results indicate strong variation among individuals and populations in the evaluated biological response. In experimental conditions, we found an increased metabolism in juvenile gastropods and mussels as increased the pCO_2 level. However, an inverse pattern was found in the case of larval stages of gastropods. Geographic changes in shell morphology of gastropods and mussels suggest a role for the gradient in pCO_2 and temperature along the Chilean coast. However, we do not found differences in the proportion of calcite and aragonite among populations; instead we found differences in mineralization along the ontogeny of the individuals, being at larval stages more sensitive to corrosive waters. Population from northern Chile showed a significant increase in the level of HsP expression, suggesting the role of persistent high temperature in intertidal habitats. Field experiments, using river mouth as scenarios of reduced pH, suggest the role of changes in salinity and carbonate system parameters on reduced growth rates, calcification and metabolism of intertidal mussels. Our results highlight the complexities in the assessment of biological responses of marine organisms to stressor such as temperature, pCO_2, pH and salinity; and the importance of characterize variations in the studied biological responses among-individual, among-populations and across ontogenic stages.

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[1] Facultad de Ciencias, Universidad Santo Tomás, Santiago, Chile. nlagoss@ust.cl
[2] Facultad de Artes Liberales, Universidad Adolfo Ibáñez, Santiago, Chile
[3]Environmental Sciences Center EULA Chile, Universidad de Concepción, Concepción, Chile
[4] Institute of Marine and Limnological Sciences, Coastal Marine Research Laboratory of Calfuco, Universidad Austral de Chile, Valdivia, Chile
[5] Patagonian Ecosystem Research Center (CIEP), Coyhaique, Chile

SYNERGISTIC IMPACT OF OCEAN WARMING AND ACIDIFICATION ON PERFORMANCE OF SCALLOPS – A LATITUDINAL COMPARISON

Lannig-Bock, Gisela, Burgel Schalkhausser, and Christian Bock

Climate change with ocean warming and acidification (OWA) will have a significant impact on marine ecosystems in the near future especially at high latitudes. One of the largest uncertainties in predicting specific impacts of climate change on marine ecosystems is to understand cause-and-effect relationships. To test the hypothesis of restricted performance capacity under expected OWA conditions, we investigated the synergistic impact of OWA on an active calcifier, the commercially important scallop *Pecten maximus*.
Scallops from different populations (boreal, Norway and temperate, France) were long-term exposed to elevated temperature (ambient + 6°C and +10°C, respectively) and CO_2 level (115 Pa, hypercapnia). We investigated swimming performance as an indicator for survival success (escape response) and respiration rates under resting metabolism and after exercise as an indicator for energy metabolism and

aerobic scope. Determination of hemolymph parameters indicated only minimal regulation of extracellular acid-base status resulting in lower pH_e in hypercapnia-exposed than in control animals. Exposure to elevated temperature alone resulted in increased swimming force and number of claps during escape response of *P. maximus*. Following exposure to OWA conditions, preliminary results suggest impaired swimming performance in boreal but not in temperate scallops when compared to control animals investigated at elevated temperature but ambient pCO_2. Furthermore, aerobic scope from boreal scallops was significantly reduced compared to their control counterparts, indicating reduced aerobic capacity for organismic performance.
In conclusion, our study confirms the hypothesis that the synergistic effect of OWA narrows the performance window of marine ectotherms with putative population dependent differences in sensitivity.

Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany (Gisela.Lannig@awi.de)

GEOGRAPHIC VARIATION IN REACTION NORMS TO ACUTE RESPONSE OF OCEAN ACIDIFICATION IN PHYSIOLOGICAL TRAITS ON *CONCHOLEPAS CONCHOLEPAS*

Lardies, Marco A.[1]; Nelson A. Lagos[2]; María B. Arias[1]; M. Josefina Poupin[1]; Cristian A.Vargas[3]; Jorge M. Navarro[4]; Patricio H. Manríquez[4], and Rodrigo Torres[5].

The potential social, economic and ecological implications of ocean acidification highlight the need for research addressing the species-specific physiological and morphological responses and potential adaptation strategies of organisms. Geographically widespread species, as the gastropod *Concholepas concholepas*, must cope with environmental differences between habitats. This ability can, in principle, be achieved by genetic differentiation and/or phenotypic flexibility. The environmental effects on the phenotype of different genotypes may result in variation in reaction norms, and a significant genotype-by-environment (GxE) interaction. Unfortunately, few studies have considered the change in phenotypic plasticity among populations along an environmental gradient. We estimate the metabolic rate of post-metamorphic stage of *C. concholepas* from different populations along Chilean coast. Juveniles were exposed to short incubation in experimental conditions of pCO_2 equilibrated seawater which lead to different pH conditions. Further information about the underlying mechanism of high-pCO_2 / low-pH responses was attained measuring the expression of Heat–Shock–Protein (HsP), the 70-kDa. We found that metabolic rate increased significantly in both populations with as increased acidification but with differences in magnitude, showing that low latitude population has less plasticity to acidification levels as compared with high latitude population. Furthermore, the individual reaction norms show GxE interaction in both populations. In the same sense the levels of HsP70 increase in acidification conditions, but with differences in magnitude between populations. We demonstrated that populations of *C. concholepas* have geographic variation in response to ocean acidification scenarios highlighting that potential adaptation may vary between populations.

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[1]Facultad de Artes Liberales & Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Santiago, Chile. marco.lardies@uai.cl
[2]Faculty of Sciences, Universidad Santo Tomás, Santiago, Chile
[3]Environmental Sciences Center EULA Chile, Universidad de Concepción, Concepción, Chile
[4]Institute of Marine and Limnological Sciences, Universidad Austral de Chile, Valdivia, Chile
[5]Patagonian Ecosystem Research Center (CIEP), Coyhaique, Chile

NO RESPONSE OF NITROGEN FIXATION TO ELEVATED CO_2 IN MANIPULATION EXPERIMENTS IN THE SOUTH PACIFIC

Law, C.S[1], E. Breitbarth[2,4], L. Hoffmann[2,4], C. McGraw[2,3], R. Langlois[4], J. LaRoche[4], A. Safi K. Marriner[5], and K.I. Currie[6]

Preliminary studies indicate that nitrogen fixers in oligotrophic waters may benefit from increasing CO_2. Recent CO_2 manipulation experiments in the South Pacific, during the PINTS voyage in the Tasman Sea in 2010 and the NZ Geotraces voyage in 2011, were carried out using surface layer mixed plankton populations under trace metal clean conditions with continuous monitoring of pH. The results from four experiments show no significant difference between the Control and High CO_2, in contrast to the published responses of *Trichodesmium* in laboratory manipulation experiments. The lack of response to elevated CO_2 is discussed in terms of factors such as diazotroph community composition, iron availability and experimental conditions.

[1] National Institute of Water and Atmospheric Research (NIWA), Kilbirnie, Wellington, New Zealand, (cliff.law@niwa.co.nz)
[2] Department of Chemistry, University of Otago, Dunedin, New Zealand
[3] Clark University, School of Chemistry and Biochemistry, Worchester, Massachusetts, USA
[4] Helmholtz Centre for Ocean Research Kiel (GEOMAR), Kiel 24105, Germany
[5] NIWA, Silverdale Road, Hamilton, New Zealand
[6] NIWA, Dunedin, New Zealand

BIOMINERALIZING EPIPHYTES OF THE SEAGRASS *POSIDONIA OCEANICA* MEADOWS FROM A CO_2 VENTS COASTAL SYSTEM

Lombardi, Chiara[1], Maria-Cristina Gambi[2], Silvia Cocito[1], Anton Kearsley[3], Piero Calosi[4], and Paul D. Taylor[5]

Organisms secreting calcareous skeletons are particularly vulnerable to OA since calcium carbonate skeletons are potentially susceptible to dissolution in acidic waters. The degree of susceptibility is dependent not only on pH and carbonate saturation, but especially on the complex biomineralization processes leading to the formation of the skeleton. Deposition of biominerals, i.e. inorganic minerals and organic macromolecules, can be affected by environmental factors (i.e. seawater temperature, chemistry) but is also biologically controlled by the organisms themselves. Naturally adapted calcifying organisms inhabiting CO_2 vents represent good models for studying the responses of biomineralizing species to OA.

Naturally adapted biomineralizing epiphytes of the seagrass *Posidonia oceanica* leaves from a volcanic vent area were studied. Leaves were collected along a pH gradient at two sites on the north and south sides of Castello Aragonese (Ischia Island, Naples, Italy), and bryozoan and spirorbid species were investigated. Our results showed two bryozoan (*Patinella radiate* and *Collarina balzaci*) and two species of spirorbids (*Spirorbis* cf. *marioni* and *Neodexiospira* cf. *pseudocorrugata*) to be naturally adapted to live along the pH gradient. Scanning electron microscopy and stereo imaging, used to reconstruct and visualize bryozoan colonies and tube worms. Contrasting responses for the two bryozoans grown along pH gradient results by analyzing colony size and abundance, colony, zooid and skeletal wall developments. The two spirorbids decreased individual abundances with pH reduction, and skeletal alterations of the outer part of the tube were present when living at very low pH.

[1] Marine Ecology Laboratory, Marine Environment and Sustainable Development Unit ENEA, P.O. Box 224, 19100 La Spezia (Italy)
[2] Stazione Zoologica Anton Dohrn, Laboratory of Functional and Evolutionary Ecology, Villa Comunale 80121, Napoli (Italy)
[3] Imaging and Analysis Centre, Natural History Museum, Cromwell Road London SW7 5BD (UK)
[4] Marine Biology and Ecology Research Centre, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, UK.(piero.calosi@plymouth.ac.uk)
[5] Department of Palaeontology, Natural History Museum, Cromwell Road London SW7 5BD (UK)

TESTING THE EFFECTS OF HIGH CO_2 ON THE FEEDING BEHAVIOR OF DEEP-SEA URCHINS (*STRONGYLOCENTROTUS FRAGILIS*) USING A DEEP-WATER FOCE SYSTEM

Lovera, C.F., P.M. Walz, E.T. Peltzer, P.G. Brewer, and J.P. Barry

Echinoids in shallow environments, in general, show sensitivity to ocean acidification from increased atmospheric CO_2. Effects of high environmental CO_2 levels on deep-sea urchins have not been evaluated but may differ owing to the steep gradients of low pH and O_2 waters in well-developed oxygen minimum zones. We evaluated the effects of high CO_2 (low pH) levels on feeding behavior of the deep-sea urchin *Strongylocentrotus fragilis*, using a deep-sea FOCE (Free Ocean CO_2 Enrichment) system.
Batches of *S. fragilis* were exposed to elevated CO_2 (treatment; TCO_2: 2500 µmol/kg, pCO_2: 3064 µatm, pH: 7.17) or background levels (control; TCO_2: 2345 µmol/kg, pCO_2: 1050 µatm, pH: 7.62) in FOCE chambers sited 890 m deep off Monterey, CA from Sept 19 to Oct 22, 2011. Feeding trials (days 5, 26, 30, 35) were performed over a ~month. For each trial, 5 urchins were transferred from holding cages to the end of a 'raceway'; a mesh bag of giant kelp was placed opposite. Image recordings of urchin movements were used to compare potential differences in behavior between animal groups.
Feeding was highly variable within and between CO_2 treatments. Control chamber *S. fragilis* required 0.3 to 27 hrs to travel 0.75 m to food while the high CO_2 group ranged from 0.9 to >180 h. Total distance and speed traveled will also be compared. Initial results from this month-long experiment suggest that high CO_2 levels expected under future climate scenarios will have mild or no effects on feeding behavior by the deep-sea fragile urchin. Longer exposure may or may not result in cumulative impacts that impair feeding.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 93950, USA (lovera@mbari.org)

INCONSISTENCIES IN OCEAN ACIDIFICATION RATES MEASURED AT *IN SITU* TEMPERATURE OR AT 25°C

Lui, Hon-Kit and Chen-Tung Arthur Chen

Ocean acidification is an unavoidable consequence of increased anthropogenic CO_2, and even a small change in seawater pH may cause large impacts on aquatic ecosystems. In this study, acidification rates from two open access time-series studies are shown to compare with that of seven published time series studies. Conventionally, surface ocean is considered under or close to air-sea CO_2 equilibrium. As a result, pH was expected to have an average decreasing rate of $-0.0017 yr^{-1}$ within the past 2-3 decades. The results show that, although atmospheric CO_2 rises at similar rates globally, reported rates of change in pH either measured at *in situ* temperature (pH_{insitu}) or at 25°C (pH_{25}) vary from $+0.00018$~$-0.0024 yr^{-1}$ to -0.00071~$-0.0032 yr^{-1}$, respectively. Instead of acidifying, in the South East Asia Time-Series (SEATS) study of the world's largest marginal sea—the South China Sea—the pH_{insitu} changing rate is actually

slightly increasing. Conversely, pH_{25} decreases at a rate 75 % faster than expected under observed global atmospheric CO_2 increment. Although the CARIACO study has the second highest pH_{insitu} decreasing rate of $-0.0021 yr^{-1}$, it has the lowest pH_{25} decreasing rate of $-0.00071 yr^{-1}$. Such inconsistencies indicate that pH_{insitu} and pH_{25} changing rates may be incomparable.

Institute of Marine Geology and Chemistry, College of Marine Sciences, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan (m955030005@student.nsysu.edu.tw)

EFFECTS OF FUTURE OCEAN ACIDIFICATION AND WARMING ON BIOMINERALIZATION IN A COMMERCIAL SHELLFISH SPECIES, THE BLUE MUSSEL *MYTILUS EDULIS* L.

Mackenzie, Clara L. [1], Graham A. Ormondroyd[2], Nia M. Whiteley[3], Richard L. Patton[3], and Shelagh K. Malham[1]

Ocean acidification is accompanied by decreases in calcium carbonate saturation and is consequently a potential threat to calcareous marine species that depend on biomineralization for survival and thereby those fisheries that subsist on the production and export of such species. We suggest that any impacts to shell quality could have impacts at an ecological level, with respect to predator-prey interactions and at an industrial level, where shells must endure the rigors of harvesting processes. As part of a European-funded project investigating the sustainability of shellfish stocks in the Irish Sea (SUSFISH INTERREG 4A Ireland – Wales programme), this study examined the combined effects of future increases in temperature and ocean acidification to biomineralization in the blue mussel, *Mytilus edulis*. Adult *M. edulis* were exposed to present and future CO_2 conditions (380 and 750 ppm CO_2) for 6 months in an aquarium-based CO_2 system comprised of two temperatures (ambient 12°C and an increase of 4°C) and two pHs (ambient 8.08 and a decrease of 0.4 pH units) as predicted under the IPCC IS92a CO_2 emission scenario. Following exposure, impacts to shell strength were established as a measure of maximum load and extension. Results to date confirm that high temperature and low pH negatively impact shell strength. Additionally, changes in calcite-aragonite ratios and shell surface porosity will be presented to indicate potential effects to shell composition and structure. Finally, changes in enzyme activities of the mantle tissue will be discussed as further evidence of impacts to the biomineralization process.

[1]Centre for Applied Marine Sciences, Environment Centre Wales, Bangor University, Bangor, Gwynedd, LL57 2UW, UK (Telephone: +44 01248 3252, Email: osse01@bangor.ac.uk)
[2]BioComposites Centre and [3]School of Biological Sciences, Bangor University, Bangor, Gwynedd, LL57 2UW, UK

EUROPEAN FREE OCEAN CARBON-DIOXIDE ENRCHMENT (eFOCE) EXPERIMENT

Mahacek, Paul[1], Frédéric Gazeau[1], William Kirkwood[2], and Jean-Pierre Gattuso[1]

The objective of the eFOCE project is to develop, validate and implement an experimental system that enables scientists to investigate the long-term effects of acidification in situ on benthic marine communities. We have developed a system which can be used in relatively long term experiments (6 months and greater) in shallow waters (up to 30m). With the ultimate goal being to increase the number of these systems and make them available to the international scientific community via a science research network.
This poster focuses on the design process of the initial test system. This system is broken into three segments including a surface expression for material resupply, energy generation and storage, and data

handling; a wireless shore station for user interface and monitoring; and the science platform, which is primarily composed of a pair of 2m long by 1m wide by 1m tall chambers. One chamber will serve as a control, and the other one will be manipulated by injecting CO_2-enriched seawater. The science platform is equipped with a host of science instruments including pH, CTDO, ADCP, and PAR sensors, as well as an automated water sampler, and several other sensors.
This poster includes details of the mechanical, electrical, and software engineering design choices for this system, as well as highlighting options for future systems. It includes the results and lessons learned from the engineering field testing carried out in the bay of Villefranche during the summer of 2012, and discusses future work and planned science objectives for the following two years of the project.

[1] Laboratoire d'Océanographie, Université Pierre et Marie Curie and CNRS, 181 Chemin du Lazaret, Villefranche-sur-mer, 06230,France (mahacek@obs-vlfr.fr)
[2] Monterey Bay Aquarium Research Institute, Moss Landing, CA 95039, USA.

COMPARATIVE STUDY OF OCEAN ACIDIFICATION EFFECTS ON OTOLITH GROWTH OF LARVAL ATLANTIC COD (*GADUS MORHUA* L.) AND ATLANTIC HERRING (*CLUPEA HARENGUS* L.)

Maneja, Rommel H.[1], Andrea Y. Frommel[1], Audrey J. Geffen[2], Arild Folkvord[2], Uwe Piatkowski[1], and Catriona Clemmesen[1]

The aragonitic calcium carbonate composition of their otoliths can bring marine fishes in direct risk to ocean acidification. The potential effects of increase in atmospheric CO_2 on the growth of the otoliths were investigated by rearing Atlantic cod (*Gadus morhua* L.) and Atlantic herring (*Clupea harengu*s L.) in three pCO_2 concentrations, control-370, medium-1800, and high-4200 ppm in outdoor mesocosms at Espegrend Station, Norway from March to May 2010. Hypercalcification of otoliths was observed from 7 to 46-dph cod larvae cultured at elevated pCO_2 concentrations. The sagittae and lapilli were usually largest at the high pCO_2 treatment followed by medium and control treatments. The biggest difference in mean otolith surface area (normalized with fish length) was with sagittae at 11-dph with medium and high treatments being 46% and 43%, respectively, larger than the control group. Atlantic cod larvae did not show trends in fluctuating asymmetry of the otoliths *vis-a-vis* the increase in otolith growth from elevated pCO_2. In contrast, elevated pCO_2 concentrations exposed to herring larvae produced significantly smaller otoliths (both sagittae and lapillae) relative to the control group at 32 and 39-dph. The largest difference (33%) in otolith area was between the sagittae of control and high treatments at 32-dph. The possible mechanisms of the differences in the responses of net otolith growth between cod and herring larvae will be discussed.

[1]GEOMAR, Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany (rmaneja@geomar.de)
[2]Department of Biology, University of Bergen, PO Box 7803, N-5020 Bergen, Norway

EXPERIMENTAL STUDIES ON THE IMPACT OF ELEVATED SEAWATER pCO_2 CONCENTRATION ON STATOLITH MORPHOLOGY AND PREY CAPTURE ABILITY IN EARLY LIFE CUTTLEFISH, *SEPIA OFFICINALIS*

Maneja, Rommel H.[1], Marian Y.A. Hu[1], Audrey J. Geffen[2], Uwe Piatkowski[1], Catriona Clemmesen[1], Magdalena A.Gutowska[3], and Frank Melzner[1]

We investigated the influence of elevated seawater pCO_2 on statolith morphology and microstructure and on the prey capture ability in early life stages of the cuttlefish, *Sepia officinalis*. Cuttlefish were

reared at 15°C and 35 psu in a flow-through artificial seawater system under three pCO_2 conditions, 700 µatm (control), 1400 µatm, and 4000 µatm during 63 days in summer 2009. Statoliths of both, embryonic and hatchling cuttlefish raised under 4000 µatm showed a modified morphology and deformed microstructural characteristics leading to reduced statolith calcification, whereas those grown under control and 1400 µatm did not. The statolith morphometrics that showed the most remarkable changes were total statolith length, rostrum transects, wing area and statolith weight. Statolith microstructure was significantly affected by irregularly arranged statoconia, which were typical in the statolith wing area, replacing the highly compact and well arranged crystals of rostrum and spur in normal growing statoliths (control). This abnormal crystal structure can have profound effects on statolith density and consequently on its normal functioning as a tool for detecting acceleration and movement. At 4000 µatm cuttlefish showed a reduced ability to capture prey and were not able to successfully launch attacks against prey organisms. In order to certify these observations, a second experiment was conducted over 85 days in summer 2010 under natural seawater conditions. Statolith morphology and microstructure differed again in the 4000 µatm group. On the other hand, prey capture ability of the hatchlings showed recovery in the course of the experiment, indicating a possible acclimation.

[1]GEOMAR, Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany (rmaneja@geomar.de)
[2]Department of Biology, University of Bergen, PO Box 7803, N-5020 Bergen, Norway
[3]Institute of Physiology, Christian Albrecht University, Hermann-Rodewald-Straße 5, 24118 Kiel, Germany

A BIOTEST FACILITY FOR OCEAN ACIDIFICATION STUDIES ON SMALL ANIMALS

Mangor-Jensen[1], Anders, Torstein Harboe[1], Ragnfrid Mangor-Jensen[1], Sissel Andersen[1], and Ellen Grefsrud[2]

A facility for small scale ocean acidification effect studies has been constructed. It is based on water acidification by dissolving CO_2 in seawater to create an acidic stock solution of pH 5.8. Addition of the stock solution to four mixing tanks is controlled by feedback from pH electrodes to dosage pumps. The pH levels in the mixing tanks are set individually between 7.00 and ambient (8.05). The four water qualities are distributed by circulation pumps to a total of 36 exposure tanks of 40 L via four high mounted header tanks. Water levels in the header tanks and the mixing tanks are kept constant by flotation valves. The temperature in the seawater is controlled and adjusted to a preset value by a water to water heat pump. The flow to each exposure tank is controlled by flow meters between stagnant and 100 Lh^{-1}. Water is drained from the tanks to waste through a perforated standpipe covered with plankton mesh.

Temperature and pH in the exposure tanks are measured daily using a pH meter, and total alkalinity is measured twice a week. In addition, accurate pH measurements are performed using a spectrophotometer. The different pH values vary over time within 0.02 units from preset values, and have proven to be stable without adjustments for more than three months. The facility is currently applied for studies on egg- and larval stages of cod and great scallop.

[1] Institute of Marine Research, Austevoll Research Station, 5392 Storebø, Norway (amj@imr.no)
[2] Institute of Marine Research, P.O. Box 1870 Nordnes, 5817 Bergen, Norway

EFFECTS OF OCEAN ACIDIFICATION IN A WARMING CLIMATE ON SPECIES INTERACTIONS AT DISTRIBUTION BOUNDARIES: MECHANISMS AND CONSEQUENCES AT ECOSYSTEM LEVEL

Mark, Felix C.[1], C.H. Bock[1], C.R. Bridges[2], G. Claireaux[3], C. Clemmesen[4], S. Frickenhaus[1], C. Held[1], R. Knust[1], G. Lannig[1], S. Lischka[4], M. Lucassen[1], B. Niehoff[1], D. Storch, U. Piatkowski[4], H. O. Pörtner, and F.J. Sartoris[1]

Previous research on the effects of hypercapnia on marine fishes led to the general notion that due to their powerful mechanisms of ion regulation they are not particularly vulnerable to ocean acidification. However, several studies demonstrated chronic effects of environmental hypercapnia on juveniles, and a sensitivity of eggs and early life stages higher than in adults. For an integrative analysis of ocean acidification and warming (OAW), it is therefore important to consider the different sensitivities of the various life stages, as well as their interaction with their prey organisms and thus, their dependence on the foodweb.
We describe here our approaches within the second phase of the German programme BIOACID (2012-2015) to investigate how the combined effects of OAW will affect different life stages and interactions between Atlantic and Polar cod and their prey.
Objectives include addressing the question whether OAW affects interacting species differently due to divergent physiological optima and ranges, expressed in thermal tolerance windows and associated performance capacities and phenologies of specific life stages. We aim to identify fundamental mechanisms by unravelling the connections between levels of biological organisation, from genomic, molecular to cellular, individual and population level. Scopes for acclimation (physiology and behaviour) and adaptation (evolution) that together define species resilience will be studied in various life stages (eggs, larvae, juveniles, adults) and the most sensitive one(s) identified. Functional determinants of individual fitness such as ion and acid-base regulation, mitochondrial energy metabolism and immune response will also be examined. Furthermore, we aim to address how all these determinants may be influenced by food quality and availability.

[1] Alfred Wegener Institute for Polar and Marine Research, 27570 Bremerhaven, Germany (fmark@awi.de)
[2] Heinrich Heine Universität, 40225 Düsseldorf, Germany
[3] LEMAR (UMR-6539), Institut Universitaire Européen de la Mer, Plouzané, 29280 France
[4] Helmholtz Centre for Ocean Research Kiel (GEOMAR), 24105 Kiel, Germany

PLANKTONIC FORAMINIFERAL SHELL WEIGHT AS A PROXY FOR CHANGING CARBONATE ION CONCENTRATION IN THE CARIACO BASIN, VENEZUELA

Marshall, Brittney J.[1], Robert C. Thunell[1] Martha McConnell[2], and Yrene Astor[3]

Ocean acidification (OA), driven largely by anthropogenic inputs of CO_2 into the world's ocean during the last century, is lowering the pH and carbonate ion concentrations ($[CO_3^{2-}]$) of the surface waters. It has been proposed (Barker and Elderfield, 2002) that there exists a positive linear relationship between foraminiferal shell weight and the carbonate ion concentration $[CO_3^{2-}]$ of the waters in which they calcify. Such a relationship would provide a useful proxy for determining past changes in ocean carbonate chemistry. The Cariaco Basin, Venezuela (10°30' N, 65°31 W) is an ideal study area to determine the relationship between seawater $[CO_3^{2-}]$ and planktonic foraminiferal size-normalized shell weight as the region is characterized by the seasonal upwelling of low $[CO_3^{2-}]$ waters. In this study, biweekly sediment trap samples and concurrent hydrographic measurements collected between January 2005 and September 2008 in the Cariaco Basin are used to assess the relationship between

[CO_3^{-2}] and area-normalized shell weights (ANSW) for three planktonic foraminiferal species: *Globigerinoides ruber*, *Orbulina universa* and *Globigerinoides sacculifer*. Individuals of each species were picked, weighed and photographed for size analysis using the microscopic imaging program Macnification 2.0. It was found that *G. ruber, O. universa* and *G. sacculifer* ANSW increase as a function of increasing seawater [CO_3^{2-}] based on linear regression analyses (r2 = 0.86, 0.84 and 0.41 respectively). The results of this study suggest that the relationship between foraminiferal shell weight and [CO_3^{2-}] is species-specific and that the ANSW of certain species would provide a better proxy for past [CO_3^{2-}] than others.

[1] Department of Earth and Ocean Sciences, University of South Carolina, Columbia, SC 29208, USA (BrittneyJ.Marshall@gmail.com)
[2] National Research Council, The National Academies of Sciences, 500 Fifth Street, NW, Washington, DC 20001,USA
[3] Estacion de Investigaciones Marinas de Margarita, Venezuela

DISTRIBUTION AND ABUNDANCE OF BENTHIC FORAMINIFERA ALONG A pH GRADIENT

Martínez Fernández, Ana and Adina Paytan

In order to predict potential impacts and possible adaptations of benthic foraminifera to future ocean acidification we determined the abundance and distribution of benthic foraminifera along a saturation gradient in the vicinity of low pH springs. Most studies of impacts of ocean acidification on calcifying organisms and specifically on foraminifera have been performed in controlled laboratory experiments; however, these experiments do not capture the response of organisms that have been exposed to low pH water and low saturation conditions for millennia. Sediment and water samples were collected from the center of low pH submarine springs in the Yucatan Peninsula, Mexico and at 25 cm intervals along transects away from the discharge point. Water chemistry (total inorganic carbon, total alkalinity, temperature, pH, salinity, aragonite and calcite saturation state) changes along the transects were determined. Species assemblage species richness, size, weight and corrosion factors of the foraminifera and how they vary along the transects in relation to water chemistry will be presented.

Earth and Planetary Sciences Department. University of California Santa Cruz. California. 95060, USA. (amarti43@ucsc.edu)

INTERACTIVE EFFECTS OF SALINITY AND ELEVATED P_{CO2} ON METABOLISM AND BIOMINERALIZATION IN HARD SHELL CLAMS MERCENARIA MERCENARIA

Matoo, OmeraB.[1], Gary H. Dickinson[2], Elia Beniash[2], and Inna M. Sokolova[1]

Ocean acidification has been shown to increase mortality, alter energy metabolism and reduce biomineralization in marine calcifiers. In estuaries, fluctuations in salinity co-occur with elevated P_{CO2}, which can modify the effects of ocean acidification. We studied the interactive effects of elevated P_{CO2} and reduced salinity on standard metabolic rate (SMR) and biomineralization in hard shell clams *Mercenaria mercenaria*. Clams were exposed for 2 - 21 weeks to each possible combination of two salinities -30 and 15 PSU and three P_{CO2} levels – 380,800 and 2000 ppm representative of present-day levels, a moderate IPCC scenario for the year 2100 and its projection for the year 2250, respectively. At 15 PSU, all P_{CO2} groups had higher mortality compared to the respective groups at 30 PSU. Elevated P_{CO2} (800 & 2000 ppm) at 15 PSU lead to chalky shells with marked pitting after 8 weeks, while after 16 weeks, the hinge region had partially degraded resulting in easy separation of shell valves. Carbonic

anhydrase activity was lower in 2000ppm/15PSU compared to 2000 ppm /30ppt.At 30 PSU, elevated P_{CO2} led to a moderate increase in SMR after 8 weeks which returned to control levels at 800 ppm group but not at 2000 ppm. 15 PSU resulted in a marked increase in SMR which was especially pronounced when combined with elevated P_{CO2}. The data suggests that elevated P_{CO2} with fluctuating salinities in estuaries will have negative consequences for survival and performance of hard shell clams due to weakening of shells and increased metabolic costs of basal maintenance.

[1.] Department of Biology, University of North Carolina at Charlotte, Charlotte, NC, 28262, USA (obashir@uncc.edu)
[2.]Department of Oral Biology, University of Pittsburgh, Pittsburgh, PA,15261, USA

OCEAN ACIDIFICATION STATE IN SOUTHERN POLAR OCEAN SURFACE WATERS

Mattsdotter-Björk, My[1], Agneta Fransson[2], and Melissa Chierici[1,3]

Polar Regions are particularly vulnerable to ocean acidification due to relatively cold waters, and the ability to absorb atmospheric CO_2. Southern Polar Ocean is predicted to become undersaturated with regard to aragonite within the next five decades. During four cruises aboard the Swedish ice breaker Oden (Oden Southern Ocean expeditions, OSO2006, OSO2007/08, OSO2008/09 and OSO2010/11) we investigated the aragonite saturation in the surface waters of South Pacific Ocean, Amundsen Sea and Ross Sea in the austral summer. We embarked Oden in Punta Arenas in Chile and sailed south west, passing through different regimes, the permanent open ocean, the marginal ice zone and Amundsen and Ross Sea Polynya on the way to Ross Island. Discrete surface water were sampled for analysis of CO_2-system parameters, total alkalinity (A_T), total dissolved inorganic carbon (C_T) and/or pH to calculate the saturation state of aragonite and calcite. We investigated the natural variability in the carbonate system along the cruise track. We discuss the variability in context with physical (sea-ice cover, mixing, fronts) and biological processes.

[1.]Department of Chemistry and Molecular Biology, University of Gothenburg, Göteborg, Sweden. melissa@chem.gu.se
[2.] Department of Earth Sciences, University of Gothenburg, Göteborg, Sweden. Now at Norwegian Polar Institute, Tromsø, Norway
[3.] Institute of Marine Research, Tromsø, Norway

EFFECTS OF OCEAN ACIDIFICATION AND WARMING ON A NATURAL PLANKTON COMMUNITY OF THE MEDITERRANEAN SEA

Maugendre, L., F. Gazeau, and J.-P. Gattuso

An experiment focusing on the effects of ocean warming and ocean acidification on the functioning of a natural plankton community was performed in March 2012 as a contribution to the European project “Mediterranean Sea Acidification in a Changing Climate” (MedSeA). The experimental setup consisted in four different treatments: “control” (*in situ* temperature and pCO_2), “ocean warming” (*in situ* temperature +3°C and *in situ* pCO_2), “ocean acidification” (*in situ* temperature and pCO_2 of 750 µatm) and “greenhouse” (*in situ* temperature +3°C and pCO_2 of 750 µatm). Natural seawater from the bay of Villefranche, sieved onto 200 µm was incubated in sixty four 4 L bottles that were sampled after 2, 4, 8 and 12 days.

At each sampling time, various parameters and processes were measured. Besides basic environmental parameters (temperature, irradiance, carbonate chemistry, dissolved organic carbon, nutrients, particulate organic carbon and nitrogen, community composition, pigments…), net community production and community respiration were estimated based on changes in dissolved oxygen concentrations over 24 h incubations in, respectively, transparent and dark bottles. Gross primary production rates were measured using the $H_2^{18}O$ labelling technique over 12 h incubations in the light. The carbon transfer efficiency through the various compartments of the community (both particulate and dissolved) was followed using the ^{13}C tracing technique.
Net community production rates analysed from a subset of samples suggest that the community evolved from an autotrophic to a heterotrophic state during the experiment. Most of the analyses are underway and results will be presented at the meeting.

Université Pierre et Marie Curie-Paris 6, Observatoire Océanologique de Villefranche-sur-Mer, France
CNRS-INSU, Laboratoire d'Océanographie Villefranche-sur-Mer, France (maugendre@obs-vlfr.fr)

TRANSCRIPTOMIC RESPONSE OF LARVAL SCALLOPS TO INCREASES IN DISSOLVED CO_2 IN AN AQUACULTURE SETTING

McClelland, Erin[1], Manon Picard[2], Kristi Miller[1], Rob Saunders[3], and Ruth Withler[1]

As atmospheric concentrations of carbon dioxide have increased, partial pressure of dissolved carbon dioxide (pCO_2) in marine waters has risen leading to a decrease in ocean pH. These changes in ocean carbonate chemistry are anticipated to affect calcification rates and acid-base metabolism of many organisms. Consequences to shellfish may include shell malformation, reduced larval growth, decreased hatching success, and decreased survival. Small changes in the pH of surface waters can have a profound effect on the success of the shellfish aquaculture industry. Recently, mass mortality events and abnormal larval development have been reported from shellfish hatcheries and grow-out sites throughout the Strait of Georgia, British Columbia and Puget Sound, Washington. In order to predict the impact of environmental stress, like increased pCO_2, on marine organisms it is important identify affected physiological processes in these organisms. Functional genomic technology allows us to monitor expression of thousands of genes at once and assess environmentally-induced changes. A genomics approach illuminates the variation in physiological response present in populations and indicates the full range of physiological processes reacting to changes in pCO_2. We challenged larvae and spat of Japanese Scallops (*Patinopecten yessoensis*), to different levels of pCO_2 and assessed survival, growth, development, and feeding in response to these effects. We developed a microarray for scallops which was subsequently used to identify genes associated with impacts of increased pCO_2. These results will be used to inform the aquaculture industry on best hatchery practices and also indicate the potential impacts of increased pCO_2 on natural populations.

[1] Molecular Genetics Lab, Pacific Biological Station, Fisheries and Oceans Canada, 3190 Hammond Bay Rd, Nanaimo BC, V9T 6N7, Canada (Erin.McClelland@dfo-mpo.gc.ca)
[2] Department of Zoology, University of British Columbia #4200-6270 University Blvd, Vancouver BC, V6T 1Z4, Canada
[3] Island Scallops, Ltd., 5552 Island Hwy W, Qualicum Beach BC, V9K 2C8, Canada

COCCOLITHOPHORE CALCIFICATION RESPONSE TO CHANGING SATURATION STATE ON A GLACIAL / INTERGLACIAL TIMESCALE

McClelland, Harry-L.O.[1], Rosalind E.M. Rickaby[1], Michaël Hermoso[1], Ian R. Hall[2], and Luc Beaufort[3]

Calcification and photosynthesis respectively produce and consume carbon dioxide. The differential rate of carbon utilization via these two processes dictates whether primary productivity is an instantaneous net source or sink of carbon dioxide, and subsequently affects the composition of export and burial. These fluxes significantly influence the distribution of dissolved inorganic carbon and alkalinity throughout the ocean column, and hence the degree of carbon exchange between the atmosphere, ocean and seafloor sediments over a range of timescales.

Coccolithophores, the dominant calcifying marine primary producers, constitute a major component of the open ocean inorganic carbon pump, but their likely response to changes in ocean chemistry remains elusive. In coccolithophores, calcite is produced intracellularly in an environment highly buffered from the ambient waters, enabling a uniquely high degree of biological control over calcification. In general, marine calcifiers decrease calcification with increasing carbon dioxide concentration, but the coccolithophore calcification response is more complicated, and may be strongly species or even strain specific.

This study employs the geological record as a laboratory to investigate the long-term coccolithophore response to known variation in carbon dioxide concentration over two glacial terminations of contrasting magnitude, using sediments from the north Atlantic and the south Pacific. Computational techniques measure coccolith thickness and area, and determine species composition of the assemblages, whilst Coulter technology estimates carbonate particle volume frequency spectra. Preliminary results are discussed in the context of coccolithophore species specific and assemblage level calcification response to changing ocean saturation state on a timescale of many thousands of years.

[1]Department of Earth Sciences, Oxford University, South Parks Road, Oxford OX1 3AN, UK. (harrym@earth.ox.ac.uk)
[2]School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff CF10 3AT, UK
[3]CEREGE, CNRS-Aix-Marseille Universités, BP 80, F13545 Aix en Provence Cedex 04, France

IMPACTS OF OCEAN ACIDIFICATION IN COASTAL WASHINGTON AND OREGON: RESEARCH AT THE NOAA NORTHWEST FISHERIES SCIENCE CENTER

McElhany, Paul, D. Shallin Busch, Michael Maher, Jason Miller, Sarah Norberg, and Jonathon Reum

The Oregon and Washington coasts and estuaries have naturally high and highly variable pCO_2 concentrations. This produces a particular vulnerability to ocean acidification (OA). The NOAA Northwest Fisheries Science Center applies a multi-faceted approach to predicting impacts of OA in this region that encompasses field monitoring, species-response experiments and ecosystem modeling. Field monitoring uses coupled biological and chemical sampling to determine the carbon environment experienced by focal species in zooplankton and benthic communities. The species-response experimental system can dynamically control pCO_2, oxygen, temperature, light, and feeding in patterns that mimic diurnal cycles or complex events. Species used in experiments are selected based on vulnerability to acidification and their economic value, ecological importance or conservation concern. Response metrics include growth, survival, gene expression and behavior. Species evaluated included Pacific oyster, geoduck, bay mussel, Mediterranean mussel, Dungeness crab, market squid, Pacific krill, copepod (*C. pacificus*), Pacific herring, China rockfish, surf smelt, ling cod, and a hard-surface benthic assemblage. These data were used to modify food web ecosystem models to predict potential effects of OA on ecosystem services (e.g. harvest and conservation). The monitoring, experiments and modeling

paint a complex picture of the potential regional response to OA. The carbon chemistry environment is dynamic; species response's to increased pCO_2 range from decreases in function, to increases, to no effect; the modeling shows non-intuitive changes in species abundance from indirect interactions. Despite this complexity, some patterns are emerging on how OA will alter these communities.

NOAA Northwest Fisheries Science Center, 2725 Montlake Blvd. E., Seattle, WA 98112
paul.mcelhany@noaa.gov

INORGANIC CARBON AND PH LEVELS IN THE ROCKALL TROUGH 1991-2010

McGrath, Triona[1,2], Caroline Kivimae[1], Toste Tanhua[3], Rachel Cave[1], and Evin McGovern[2]

Monitoring carbonate parameters is necessary to understand potential impacts of ocean acidification on marine ecosystems. Total alkalinity and dissolved inorganic carbon were sampled across the Rockall Trough in Feb 2009 and Feb 2010, and results were compared with data from WOCE surveys completed in the Trough in 1991, 1994, 1996, and 1997. The temporal evolution of anthropogenic carbon (ΔC_{ant}) between the 1990s and 2010 was evaluated by (i) comparison of $\Delta C_{T\text{-}abio}$ (C_T corrected for biological activity) between surveys and (ii) an extended Multiple Linear Regression to calculate the ΔC_{ant} between 1991 and 2010 (ΔC_{ant}^{eMLR}). There was an increase in both $\Delta C_{T\text{-}abio}$ and ΔC_{ant}^{eMLR} of 18 – 19 ±4µmol kg^{-1} in subsurface waters between 1991 and 2010, equivalent to a decrease of 0.040±0.003 pH units over the 19 years. This is in line with a number of time series (e.g. BATS, HOT and ESTOC) who also measured a decrease in pH of 0.02 units per decade over the last 20 years. Data from the Mace Head Atmospheric Research Station measured an increase in pCO_2 of 38.1ppm between 1991 and 2010, equivalent to an increase in C_T of 18µmol kg^{-1} and decrease in pH of 0.038. There was an increase in both $\Delta C_{T\text{-}abio}$ and ΔC_{ant}^{eMLR} of 8±4µmol kg^{-1} in Labrador Sea Water (LSW) in the Trough and LSW has acidified by 0.029±0.002 pH units over the 19 years. A gradual decrease in aragonite and calcite saturation states was measured in the Trough, which may implications for the cold water corals in the region.

[1] Earth and Ocean Sciences, School of Natural Sciences, National University of Ireland, Galway, University Road, Galway, Ireland (triona_mcgrath@hotmail.com)
[2] Marine Institute, Rinville, Oranmore, Galway
[3] Helmholtz-Zentrum für Ozeanforschung Kiel (GEOMAR), Marine Biogeochemistry, Duesternbrooker Weg 20, D-24105 Kiel, Germany

CO_2 ENRICHMENT AND REDUCED SEAWATER pH HAD NO EFFECT ON THE EMBRYONIC DEVELOPMENT OF *ACROPORA PALMATA* (ANTHOZOA, SCLERACTINIA).

Medina-Rosas, Pedro, Alina M. Szmant, and Robert F. Whitehead.

The effects of decreased pH, caused by carbon dioxide (CO_2) dissolution in seawater (known as ocean acidification), on the development of newly fertilized eggs of the Caribbean reef-building coral, *Acropora palmata* was tested in three experiments conducted during the summers of 2008 and 2009 (two seasons). Three levels of CO_2 enrichment were used: present day conditions (400 µatm, pH 8.1) and two CO_2 enriched conditions (700 µatm, pH 7.9, and 1000 µatm, pH 7.7). No effects on the progression or timing of development, or embryo and larval size, were detected in any of the three experiments. The results show that the embryos and larvae of *A. palmata* are able to development normally under seawater pH of at least 0.4 pH units lower than present levels. This study only examined the non-calcifying part of the life cycle of this species, because *A. palmata* larvae do not usually begin to calcify

until after settlement. Most of the concern about the effects of ocean acidification on marine organisms centers on its effect on calcification. Negative effects of ocean acidification on the embryonic development of this species were not found and they may not manifest until the newly settled polyps begin to calcify.

University of North Carolina Wilmington. Center for Marine Science. 5600 Marvin K Moss Lane. Wilmington, NC. 28409. USA.
Universidad de Guadalajara. Centro Universitario de la Costa. Av U de G 203. Puerto Vallarta, Jalisco. 48280. Mexico. pedromedinarosas@gmail.com

MECHANISMS OF ACID BASE REGULATION AND CO_2 TOLERANCE IN MARINE FISH: CHARACTERISATION OF THE ION-REGULATORY TRANSCRIPTOME

Michael, Katharina, Cornelia Kreiß, Nils Koschnick, Andrea Frommel, Catriona Clemmesen, Hans-Otto Pörtner, and Magnus Lucassen

Anthropogenic CO_2 emissions and global warming threaten marine ecosystems by increasing water temperature and acidification. Fish seem to be less sensitive to ocean acidification as disturbances in acid-base status are compensated for by an efficient ion regulatory system.
However, due to general constraints on functional capacity at the edges of a species' thermal window, sensitivity to elevated PCO_2 levels may be highest at extreme temperatures. For a mechanistic understanding of the ion and pH regulatory system, we characterized transepithelial ion transporters and ATPases in marine fish in response to temperature and CO_2, respectively. Clear cold compensation occurred in the expression of essential transporters including the capacity of Na+/K+ -ATPase in gills of seasonally acclimatised adult Atlantic cod. In CO_2-exposed early larval stages of this species, suppression of ATP-dependent transporter expression indicates a delayed ontogeny of ion regulation, which however, was compensated for toward the end of the trials. Results in eelpout from different climate zones show a significant upregulation of gill bicarbonate transporter mRNA expression under combined CO_2 and temperature exposure, opposing the downregulation in the expression of these transporters upon temperature alone. This suggests differential effects of ocean acidification and warming on ion regulation capacity and efficiency in marine fish, in line with the hypothesis that CO_2 contributes to an earlier onset of thermal stress. Overall, our data indicate significant effects of ocean acidification on these highly evolved marine animals. Future work aims to characterize the entire ion regulatory transcriptome and to balance and localize the transepithelial ion transport of Atlantic cod in response to CO_2 and temperature.

Alfred-Wegener-Institute for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany, Katharina.Michael@awi.de
[1]IFM Geomar, Düsternbrooker Weg 20, 24105 Kiel, Germany

VARIATION IN RESPONSE TO OCEAN ACIDIFICATION ACROSS A LATITUDINAL GRADIENT

Miller, Seth H.[1], Eric Sanford[1,3], Brian Gaylord[1,3], Michèle LaVigne[1], Tessa M. Hill[1,2], Jessica Hosfelt[1], Ann D. Russell[2], Elizabeth Lenz[4], Megan K. Young[1], and Kelly Laughlin[1]

Many species worldwide have evolved across large geographic areas, thus exposing distant populations of the same species to a range of diverse environments. In the northeast Pacific, the mussel *Mytilus californianus* and the urchin *Strongylocentrotus purpuratus* occur along the entire U.S. coast, where they experience a latitudinal gradient in oceanographic conditions, including coastal upwelling. Populations in northern California have evolved with more persistent seasonal upwelling events that bring low pH waters to the surface, while populations in southern California have evolved under less corrosive conditions. On the other hand, northern and southern populations are not fully isolated but are connected to some degree through dispersal, leaving open the question of whether local adaptation to acidification stress could have arisen. To test whether populations across this latitudinal gradient might respond differently as the ocean becomes more acidic, we spawned adults from four regions (eight total sites) along the west coast of the U.S. and raised their larvae in common garden experiments under treatments representing current (385ppm) and projected future (1000ppm) pCO_2 levels. Measurements of larval surface area, mass, and trace element composition (Mg, Ca, Sr) revealed that larvae and metamorphosed juveniles from different locations along a species' range responded differently to decreases in ocean pH. These differences, while potentially originating from a number of sources, are consistent with local adaptation to regional differences in upwelling frequency, and may suggest that populations that have evolved in regions with periodic corrosive events will be more resilient to ocean acidification than naïve populations.

[1] Bodega Marine Laboratory, UC Davis, 2099 Westside Rd. Bodega Bay, CA 94923 USA.
shmiller@ucdavis.edu
[2] Department of Geology, UC Davis, One Shields Ave, Davis, CA 95616 USA
[3] Department of Evolution & Ecology, UC Davis, One Shields Ave, Davis, CA 95616 USA
[4] Department of Biology, CSU Northridge, 18111 Nordhoff St, Northridge, CA 91330 USA

A DETAILED MODELING INSIGHT OF THE CARBON CHEMISTRY VARIABILITY AROUND HERON ISLAND IN THE GREAT BARRIER REEF.

Mongin Mathieu[1], Bronte Tilbrook[1,2], Chris Roelfsema[3], Kenneth Anthony[4] and Craig Steinberg[4], and Scott Bainbridge[4]

The observed diurnal variability of pH over coral reefs is in some cases larger than values predicted under IPCC CO_2 emission scenarios. While this signal is potentially devastating for corals, its impact on coral physiology remains unknown. Understanding the drivers of this variability is key to understanding the impact of ocean acidification on coral reef ecosystems. We combined a high-resolution hydrodynamic model of the reef at Heron Island, Australia, with detailed maps of benthic communities and a biogeochemical model in order to model whole-of-reef ecosystem production and calcification . We use this model to explore the drivers of the observed pH and carbonate chemistry variability . Sensitivity analysis shows that the key parameters driving the pH variability is the flushing rate of the water out of the reef as well as the location of the most productive habitat on the reef. We also show that the current system is in a stable state balance between biological, chemical and hydrodynamic processes. Ocean acidification and climate change impacts such as sea level rise and bleaching can act to disrupt the balance with potentially devastating effect for the reef.

[1] CSIRO Wealth From Ocean National Research Flagship, Hobart, Australia 7001.
Mathieu.Mongin@csiro.au
[2] Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania Australia
[3] Biophysical Remote Sensing Group School of Geography, The University of Queensland, Brisbane, Australia
[4] Australian Institute of Marine Science, Townsville, Australia 4810

INVESTIGATING THE EFFECTS OF OCEAN ACIDIFICATION ON COCCOLITHOPHORES IN A SELF-ASSEMBLING ECOSYSTEM MODEL

Monteiro, Fanny[1], Andy Ridgwell[1], Mick Follows[2], and Stephanie Dutkiewicz[2]

We explore the sensitivity of ocean acidification on coccolithophores in a novel global ecological model. This model combines a global ocean model (MITgcm) with a self-assembling ecosystem model ('Darwin' model), accounting for a diverse and adapted population of marine phytoplankton. The structure of the virtual phytoplankton community is determined by the outcome of competition among the seeded organisms, randomly chosen from a broad range of morphological and physiological traits. We will present preliminary results on using this approach to test some of the hypotheses for the "reason" for calcification in coccolithophores (grazing protection, light collection, CO_2 enhancement for photosynthesis), and assess the implications of this for the sensitivity of coccolithophores and their calcification to ocean acidification.

[1] School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK (f.monteiro@bristol.ac.uk)
[2] Department of Earth, Atmosphere and Planetary Sciences, MIT, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

ACIDIFICATION RESPONSE OF MEDITERRANEAN SEA TEMPERATE AND COLD-WATER CORALS FROM MID- TO LONG-TERM EXPERIMENTS

Movilla, Juancho[1], Carles Pelejero[2], Rafel Coma[3], Andrea Gori[1,4], Eva Calvo[1], Covadonga Orejas[5], Àngel López-Sanz[1], Eduard Serrano[3], Elisa Fernández-Guallart[1], Jordi Grinyó[1], Carlos Domínguez[1], and Marta Ribes[1]

The Mediterranean Sea has certain characteristics that make it especially sensitive and vulnerable to changes in atmospheric CO_2. Recent studies are starting to confirm that the associated acidification, particularly in the Western Mediterranean, is taking place more rapidly than in the global oceans. Owing to these characteristics, we have run three mid- to long-term manipulative experiments to evaluate potential effects of acidification on corals from this basin. A first experiment (six months long) was run on the temperate corals *Cladocora caespitosa* and *Oculina patagonica*, and confirmed the *a priori* expected decrease in skeletal growth with decreasing pH for both species. Interestingly, a trend in calcification decrease was observed in colonies from the same species. Faster growing colonies were more affected by acidification that those that grew slower, which could be related to the energy requirements associated to the growing process. In a second experiment (ten months long), we tested the possible effects of acidification in the cold-water coral species *Lophelia pertusa*, *Dendrophyllia cornigera*, *Desmophyllum dianthus* and *Madrepora oculata*. Subtle differences in calcification were observed between the treatments, with the first three of these species growing slightly slower at low pH, although these changes were not statistically significant. In a third, still ongoing, experiment (expected to be ~twelve months long), we are combining pH and temperature manipulations in the temperate corals *Astroides calycularis* and *Leptopsammia pruvoti*. In this experiment, we are observing a synergistic decrease in coral calcification when pH is lowered and temperature is increased at the same time.

[1] Institut de Ciències del Mar, CSIC, Pg. Marítim de la Barceloneta 37-49, 08003 Barcelona, Catalonia, Spain.

[2] ICREA and Institut de Ciències del Mar, CSIC, Pg. Marítim de la Barceloneta 37-49, 08003 Barcelona, Catalonia, Spain (carles.pelejero@icrea.cat)
[3] Centre d'Estudis Avançats de Blanes, Accés Cala Sant Francesc 14, 17300 Blanes, Girona, Catalonia, Spain
[4] Centre Scientifique de Monaco, Avenue Saint Martin, 98000 Monaco, Principality of Monaco
[5] Instituto Español de Oceanografía (IEO), Centro Oceanográfico de Santander, Promontorio de San Martin s/n, 39004 Santander, Spain

DECADAL-SCALE CHANGES OF OCEAN ACIDIFICATION IN THE SUBTROPICAL REGION OF SOUTH PACIFIC

Murata, Akihiko, Kazuhiko Hayashi, Shinya Kouketsu, and Yuichiro Kumamoto

To assess degrees of ocean acidification, we investigated changes in pH (total scale), which was calculated form observed dissolved inorganic carbon and total alkalinity, and the saturation states of seawater with respect to calcite and aragonite along the 17°S parallel (WOCE P21 line) in the South Pacific by using high-quality data for the CO_2 system and related water properties obtained during two surveys separated 15 years (1994 and 2009). In 2009, surface seawater pH at in situ temperature along the P21 line was between 8.04 and 8.11. Changes of the pH between the two time periods showed a general decreasing trend ranging from -0.06 to 0.02. The increases were locally found around 70°W. pH at 25°C revealed a decreasing trend of a similar magnitude to pH at in situ temperature, although distributions of temporal changes were different between two types of pH; decreases of pH at in situ temperature (-0.03) observed west of 160°W were reduced for pH at 25°C (-0.01). In associated with the decreases of pH, saturation states of surface seawater with respect to calcite and aragonite also indicated decreases of about 0.18 and 0.12 on average, respectively.
Decreases of pH at 25°C and those of saturation states of calcite and aragonite in response to increases of atmospheric CO_2 (2.0 ppmv a^{-1}) were theoretically estimated to be 0.027, 0.26 and 0.17, respectively. The observed values were slightly smaller than these theoretical values, meaning that changes of oceanic conditions operated to weaken progression of ocean acidification.

[1]RIGC, JAMSTEC, 2-15 Natsuhima-cho, Yokosuka, Kanagawa, 237-0061, Japan murataa@jamstec.go.jp

SHELL WEIGHTS OF PLANKTONIC FORAMINIFERA *Globigerinoides ruber* IN HIGH CO_2 UPWELLING REGION OF THE ARABIAN SEA

Naik, Sushant S. and P. Divakar Naidu

The western Arabian Sea is a region of intense upwelling during the South-West monsoon unlike eastern Arabian Sea. The upwelling process brings cold, nutrient-rich and high CO_2 waters from a few hundred meters depth to the surface and increases the biological productivity in the euphotic zone.
Shell weights of planktonic foraminifera species *Globigerinoides ruber* in the narrow size range of 300-355μm were measured from sediment traps in the western and eastern Arabian Sea. In the Western Arabian Sea Trap (WAST) flux ranged from 33 to 437 #/m^2/day and shell weights ranged from 6.7 to 14. 2μg. Whereas, in the Eastern Arabian Sea Trap (EAST), flux ranged from 0.7 to 164 #/m^2/day and shell weights ranged from 10.8 to 14.3 μg. Shell weights of *G. ruber* versus flux showed significant correlation at both the sites which suggest that optimum growth conditions control shell calcification.
The pCO_2 and SST were calculated for the months wherein the flux and shell weight data are available and the values are averages for the years 1970-2000, obtained from the database of Takahashi et al.

(2009). Surface water pCO_2 and sea surface temperature (SST) do not show any influence on shell calcification in these regions.
Further, the similarity in shell weights between upwelling and non-upwelling regions suggests that upwelled high pCO_2, does not exert any discernible influence on shell weights of G. ruber in the Arabian Sea.

National Institute of Oceanography, Dona Paula, Goa 403004 India (sushant@nio.org)

SIGNIFICANCE OF CIRCULATION CHANGE AND HORIZONTAL ADVECTION ON TEMPORAL CHANGES IN DISSOLVED INORGANIC CARBON AND RELEVANT BIOCHEMICAL PARAMETERS IN CALIFORNIA CURRENT LTER REGION

Nam, SungHyun[1], Uwe Send[1], Hey Jin Kim[1], Todd Martz[1], David A. Demer[2], Andrew Dickson[1], Mark Ohman[1], Christopher L. Sabine[3], and Richard A. Feely[3]

Organisms along the US west coast may be significantly impacted by the combined effects of coastal upwelling, increased CO_2 concentration, and decreased pH in seawater (ocean acidification). Therefore, it is increasingly important to continuously monitoring carbonate chemistry and other relevant biochemical parameters, with high temporal sampling. Using surface moorings at two locations in the California Current LTER region (CCE1; offshore in the core of the California Current; and CCE2, inshore in 800 m depth), quasi-continuous measurements are made of pO_2, pCO_2, dissolved oxygen, pH, chlorophyll fluorescence, temperature, and salinity at several depths. Also measured are profiles of currents and acoustic backscattering strength (S_v) over the upper 500 m. Analyses of these data reveal that horizontal advection significantly influences the temporal dynamics of dissolved inorganic carbon, seawater density, chlorophyll a index, and S_v at 75 kHz (putatively from nektonic fishes). Changes in the upwelling intensity associated with local alongshore wind during the spring transition, sensed at CCE2, and mesoscale circulation in the meandering California Current, sensed at CCE1, are responsible for the horizontal advection. These observations underscore the importance of physical processes underlying the intensity, duration, and character of acidic incursion events along the west coast.

[1] Scripps Institution of Oceanography, UCSD, La Jolla, CA, USA (sunam@ucsd.edu)
[2] NOAA/NMFS/Southwest Fisheries Science Center, San Diego, CA, USA
[3] NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA

DEVELOPING POLICY RESPONSES TO OCEAN ACIDIFICATION IMPACTS ON AUSTRALIA AND NEW ZEALAND MARINE ENVIRONMENTS

Nash, Merinda C.[1], Ken Anthony[2], Will Howard[3], and Katherine Schmutter[4]

Recently the Australian and New Zealand OA research community recognised the need to upscale research from the organism to ecosystem scale to fully understand the complicated interactions of carbonate chemistry and biological responses so that appropriate and well informed policy can be developed. The community has written a position paper on OA and undertaken a consultation process with government policy makers and industry to identify relevant potential implications of OA. The aim of this work has been twofold, firstly to support development of a coordinated approach to OA research in Australia and New Zealand so that knowledge gaps are identified and addressed and that research replication is avoided, secondly to develop the policy questions that science needs to answer. This direct consultation process with Government has been successful at teasing out the implications however

identifying policy solutions is more difficult due to the complexity of the issues and lack of long term monitoring of key baseline marine chemistry and biology.
OA presents different policy challenges than climate change as tipping point thresholds may be triggered by different CO_2 levels than estimated for dangerous climate change. Thresholds will be species and region specific. Unlike terrestrial environmental policy that can address rehabilitation, policy options are generally limited to mitigation. OA adds vulnerability not accounted for, to sea level rise impacts on low lying coral based islands by limiting biogenic sediment production.
The very long term nature of the impacts won't easily be reversed and this puts a premium on early action.

[1]Research School of Physics, Australian National University, Canberra, ACT, Australia, merinda.nash@anu.edu.au
[2]Australian Institute of Marine Science, Townsville, QLD, Australia
[3]Office of the Chief Scientist, Canberra, ACT, Australia
[4]Dept. of Agriculture, Forestry and Fisheries, Canberra, ACT, Australia

LONG-TERM EXPOSURE TO HIGH PCO_2 LEVELS. ITS EFFECTS ON THE PHYSIOLOGICAL ENERGETICS AND AQUACULTURE OF THE JUVENILE MUSSELS *MYTILUS CHILENSIS*

Navarro, J.M[1]. R Torres[2], K. Acuña[1], C. Duarte[1] P. Manriquez[1] , M. Lardies[3], N. Lagos[4], C. Vargas[5], and V. Aguilera[5]

This study evaluated the impact of long-term exposure to elevated pCO_2 levels (750-1200 ppm) on the physiological processes and aquaculture (meat production) of juvenile mussels *Mytilus chilensis* over a period of 70 days in a mesocosm system. Three equilibration tanks filled with filtered seawater were adjusted to three pCO_2 levels: ~380 (control), ~750 and ~1200 ppm by bubbling air or an air - CO_2 mixture through the water. For the control, atmospheric air (with approx. 380 ppm CO_2) was bubbled into the tank; for the 750 and 1200 ppm treatments, dry air and pure CO_2 were blended to each target concentration using mass flow controllers for air and CO_2. No impact on feeding activity was observed at the beginning of the experiment, but a significant reduction in clearance rate was observed after 35 days of exposure to highly acidified seawater. Absorption rate and absorption efficiency were reduced at high pCO_2 levels. In addition, oxygen uptake fell significantly under these conditions, indicating a metabolic depression. These physiological responses of the mussels resulted in a significant reduction of energy available for growth (scope for growth) with important consequences for the aquaculture of this species during long-term exposure to acid conditions. This study clearly indicates that high pCO_2 levels in the seawater have a negative effect on the health of *M. chilensis*. Therefore, the predicted acidification of seawater associated with global climate change could be harmful to this ecologically and commercially important mussel.
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[1]Instituto de Ciencias Marinas y Limnológicas, Laboratorio Costero de Calfuco, Universidad Austral de Chile, Valdivia, Chile. jorgenavarroa@gmail.com
[2]Centro de Investigación en Ecosistemas de la Patagonia (CIEP), Coyhaique, Chile
[3]Facultad de Artes Liberales, Universidad Adolfo Ibáñez, Santiago, Chile
[4]Facultad de Ciencias, Universidad Santo Tomás, Santiago, Chile
[5]Unidad de Sistemas Acuáticos, Centro de Ciencias Ambientales, EULA, Universidad de Concepción, Concepción, Chile.

INTRODUCTION TO OCEAN ACIDIFICATION (OA) MONITORING IN THE CHUUK LAGOON, FEDERATED STATES OF MICRONESIA

Noh, Jae Hoon[1], Adrienne Sutton[2], Charity Lee[1], Chris Sabine[2], Dongseon Kim[1], Kitack Lee[3], and Dick Feely[2]

Chuuk Lagoon (Chuuk State, Federated States of Micronesia, Latitude 7.68°N - 7.38°N, Longitude 151.76°E -151.8°E), located in tropical western Pacific Ocean, is one of the largest semi-enclosed semi-triangular oceanic atoll lagoons in the world. It has a circumference of about 225 km-long protective barrier reef with about 61 km east-west and about 53 km north-south between the longest points. The Pacific Marine Environmental Laboratory (PMEL)/NOAA and the Korea-South Pacific Ocean Research Center (KSORC)/Korea Ocean Research and Development Institute (KORDI) established a long-term coral reef OA monitoring buoy (Chuuk K1) in Chuuk Lagoon in November 2011 as a collaborative project to monitor OA of this coral reef system. Currently, the parameters being transmitted eight times per day by the buoy are pCO_2 in atmosphere and seawater, pH, seawater temperature, salinity and chlorophyll concentrations. These data are expected to contribute in the global effort to monitor and understand the current trend in OA along with other PMEL collaborating buoys in Australia, Hawaii and Caribbean waters as shown in PMEL homepage. We are also hoping to contribute in the regional effort to understand the effect of current high CO_2 world on Chuuk and Pacific coral reef ecosystem. We are planning for the second buoy deployment in the future and continuing long-term ecosystem process study of the lagoon. The presentation will show the progress and status of current collaborative coral reef OA project in Chuuk Lagoon, and also introduce some of coral eco-environmental studies being conducted and future plans for the lagoon.

[1] KORDI, 787 Sadong Haeanro Ansan kyunggido 426-744 Korea (jhnoh@kordi.re.kr)
[2] PMEL/NOAA, 7600 Sand Point Way NE, Seattle, WA 98115 USA
[3] POSTECH, 31 Hyojadong Namju Phohang, Kyungbuk 790-784 Korea

PHOTOSYNTHETIC AND CALCIFICATION RESPONSES OF THREE SPECIES OF TEMPERATE CORALLINE ALGAE TO NEAR FUTURE OCEAN ACIDIFICATION

Noisette, Fanny [1,2], Hrönn Egilsdottir[3,4], Dominique Davoult[1,2], and Sophie Martin[1,2]

Coralline algae are major calcifying components of marine habitats from intertidal to deep subtidal zones. They are of significant ecological importance and play a major role in the carbon and carbonate cycles. However, they appear to be among the most sensitive calcifying organisms to ocean acidification. The effects of elevated pCO_2 were examined in three species of coralline algae from the Brittany coast: (i) *Corallina elongata*, a branched articulated coralline alga found in intertidal rocky pools, (ii) *Lithophyllum incrustans*, a crustose coralline alga covering small pebbles and rocks in the low intertidal zone, and (iii) *Lithothamnion corallioides* (maerl), a free living coralline alga from the subtidal zone. Specimens were grown for two months at pCO_2 of 380 (ambient pCO_2), 550, 750 and 1000 µatm (elevated pCO_2). Metabolic rates were assessed through measurements of oxygen and total alkalinity fluxes in the light and dark using incubation chambers. Calcite Mg/Ca ratios were analyzed using ICP-AES. No significant pCO_2 effect was found on gross production and respiration rates in the three species. Diel calcification rates significantly decreased at pCO_2 of 750 and 1000 µatm in *L. incrustans* and *L. corallioides* while no pCO_2 effect was detected in *C. elongata*. This was consistent with the higher skeletal Mg/Ca ratios (higher solubility) found in *L. incrustans* (0.20) and *L. corallioides* (0.20) relative to *C. elongata* (0.17). These results show that *C. elongata*, which experienced strong physico chemical variations in rocky pools is more resistant to high pCO_2 than *L. incrustans* and *L. corallioides* living in more stable environments.

[1] CNRS, UMR 7144, Laboratoire Adaptation et Diversité en Milieu Marin, Station Biologique de Roscoff, Place Georges Teissier, 29682 Roscoff Cedex, France. fanny.noisette@sb-roscoff.fr
[2] UPMC Univ Paris 6, UMR 7144, Laboratoire Adaptation et Diversité en Milieu Marin, Station Biologique de Roscoff, Place Georges Teissier, 29682 Roscoff Cedex, France
[3] Marine Research Institute, Skulagata 4, 121 Reykjavik, Iceland
[4] University of Iceland, Faculty of Earth Science, Askja, Sturlugata 7, 101 Reykjavik, Iceland

LARVAL ROCKFISH SURVIVAL DECREASES IN ELEVEATED CO_2 ENVIRONMENT

Norberg, Sarah E., D. Shallin Busch,and Paul McElhany

Information regarding the effects of high-CO_2 environments on fish is limited. In vertebrates, high levels of environmental pCO_2 can lead to lethal hypercapnia-induced acidification of intracellular body fluids. Fish can tolerate brief exposures to high pCO_2 because of their ability to accumulate buffering ions from the water through transport across cell membranes. Larval fish, which must meet the large daily energy requirements for growth and development, may not be able to contend with the extra energetic expense of increased ion transport. We explored the impacts of CO_2 on growth, development, and survival of China rockfish (*Sebastes nebulosa*) larvae. We reared larvae in 3 different pH treatments: 7.70, 8.05, and 8.10. These conditions approximate past (280 ppm), present (400 ppm), and future (1000 ppm) global average atmospheric pCO_2 levels. Larvae exposed to high pCO_2 had significantly lower survival over a 20 day period (21 %) than larvae exposed to moderate pCO_2 (70%). After two weeks of exposure to treatment conditions, larvae that survived in high pCO_2 were shorter than larvae in moderate and low pCO_2, though they had greater body depth than larvae in moderate pCO_2. At the end of the experiment, larval size and shape was similar in all treatments. However, otolith diameter relative to body size in larvae reared in moderate pCO_2 treatments was significantly larger than those reared in high and low pCO_2. From these results, we conclude that high pCO_2 conditions negatively impacted the growth, development and survival of larval China rockfish.

NOAA-NWFSC, 2725 Montlake Blvd. E., Seattle, WA, USA, (sarah.norberg@noaa.gov)

TWIN HEAT CONDUCTION CALORIMETER FOR METABOLIC INVESTIGATIONS OF MARINE ORGANISMS UNDER CO_2-INDUCED WATER ACIDIFICATION

Normant, Monika[1], Magdalena Jakubowska[1], Jerzy Drzazgowski[1], and Ingolf Lamprecht[2]

Escape reactions and shifts in type or rate of the standard metabolism are the first responses of an animal to a stress caused by different factors (changes in temperature (T), salinity (S), oxygen tension (pO_2) or pH). They can be determined in different ways, but the most accurate method seems to be direct calorimetry, which measures heat dissipation by an organism in both, aerobic and anaerobic processes. Unfortunately, inadequate technical parameters of commercially available calorimeters (e.g. sensitivity, vessel size and form) and high heat capacity of water cause that this tool is not very popular in studies of aquatic organisms. Against this background, we constructed a customer friendly, simple twin calorimeter of the Calvet type. It is of smaller total size and lower weight than most instruments on the market so that it can be easily transported to the field station or used onboard of research boats. This calorimeter has flatter and broader 24-ml vessels (measuring and reference) than usual instruments

permitting experiments of benthic organisms. Application of the flow-through system allows for control and change of water parameters (e.g. pH, T, S, pO_2) inside the vessels without interrupting the monitoring. Two bullet cameras positioned on top of the lids outside the vessels enable the observation of animal activity during the measurement. We will present construction details of this instrument as well as some first results concerning effects of carbon dioxide-induced water acidification on behavior and metabolic rates of the isopod *Saduria entomon* and the bivalve *Macoma balthica*.

[1]Institute of Oceanography, The University of Gdansk, Al. M. Pilsudskiego 46, 81-376 Gdynia, Poland (ocemn@univ.gda.pl).
[2]Institute for Zoology, Free University of Berlin, Koenigin-Luise-Straße 1-3, D 1495 Germany.

EFFECTS OF OCEAN ACIDIFICATION ON NORTH PACIFIC KRILL, *EUPHAUSIA PACIFICA*

O'Brien, Helen[1], Donald C. Potts [1], and Adina Paytan [2]

While many studies have demonstrated negative impacts of ocean acidification on a multitude of calcifying organisms, much less is known about its potential impacts on lightly-calcifying and non-calcifying organisms. Because krill form an important trophic link near the base of many marine food chains, their responses to changing ocean chemistry could have cascading impacts at higher trophic levels (including large fishes, marine mammals and sea birds) and on community and ecosystem dynamics. Laboratory experiments are comparing survival, growth, and molting frequency of a common Monterey Bay krill species (*Euphausia pacifica*) at three carbon dioxide levels (380, 740 and 1200 ppm) within the range predicted as possible within a 100 years by the IPCC. The experiments include two temperatures (10^{o}C and 16 ^{o}C) to isolate and quantify both individual and synergistic effects of decreasing pH and increasing temperature on *E. pacifica*. Understanding the effects of future ocean chemistry and temperature changes on such keystone species as *E. pacifica* is essential for predicting possible ecological consequences and protecting future ecosystems. Implications for food chains based on euphausiids will be discussed.

[1] Department of Ecology and Evolutionary Biology, University of California, Santa Cruz CA 95064 (hobrien@ucsc.edu)
[2] Institute of Marine Sciences, University of California, Santa Cruz CA 95064

COCCOLITHOPHORE CALCIFICATION ACROSS THE PALEOCENE EOCENE THERMAL MAXIMUM: EVIDENCE OF SENSITIVITY TO SURFACE WATER ACIDIFICATION?

O'Dea, Sarah[1], Samantha J Gibbs[1], Paul Bown[2], Cherry Newsam[1,2], Paul A. Wilson[1], Jeremy Young[2], Andy Purvis[3], and Luc Beaufort[4]

As abundant, globally cosmopolitan phytoplankton, coccolithophores are the dominant pelagic calcium carbonate producers in the modern ocean. To understand the potential impact of the current atmospheric CO_2 rise on marine ecosystems, it is important to assess the sensitivity of these organisms to CO_2-induced changes in surface water chemistry. The Paleocene Eocene Thermal Maximum (PETM; ~56 million years ago) provides a geological analogue for modern climate change, with global warming and ocean acidification associated with carbon cycle perturbation. Using birefringence techniques to estimate skeletal thickness of Paleogene nannofossils for the first time, we test for changes in coccolithophore calcification in the two dominant taxa across the PETM (*Coccolithus* and *Toweius*). Here we present a high resolution record of size-normalised thickness of pristine coccoliths at Bass River (New

Jersey) and consider these data within a global context, with additional new data from California and Tanzania. Our records reveal species-specific variations in coccolith thickness at Bass River that are independent of ecological patterns in cell size, with a common minimum thickness immediately prior to the carbon isotope excursion. We explore the implications of coccolithophore skeletal thickness for biogenic carbonate production and for estimating species-specific sensitivities to changes in surface water chemistry in a paleo context, and under future climate change scenarios.

[1]School of Ocean and Earth Science, National Oceanography Centre, Southampton, European Way, Southampton, SO14 3ZH, UK (sarah.odea@noc.soton.ac.uk)
[2]Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK
[3]Department of Life Sciences, Imperial College London, Silwood Park, Ascot SL5 7PY, UK
[4]CEREGE, CNRS/Université Aix-Marseille, Avenue L. Philibert BP80, 13545 Aix-en-Provence, Cedex 4, France

SIMULATED OCEAN ACIDIFICATION AND DEOXYGENATION FROM AN ARCTIC METHANE HYDRATE MELTDOWN

Orr, J. C.[1], L. Bopp[1], and C. Ethé[2]

Thousands of Pg of C is trapped as frozen methane hydrates in marine sediments. Much of that is stored in the Arctic between 300 and 600 m where colder waters allow methane hydrates to be stable at shallower depths. But this stability is threatened by bottom water warming from climate change. Methane released to the atmosphere would affect climate; conversely, if trapped by the ocean, its eventual oxidation would reduce oxygen and increase acidification. We developed a perturbation approach for CH_4 and applied it in a global-scale ocean biogeochemical model to assess two questions: (1) What is the efficiency of the ocean in retaining CH_4 injected from a meltdown of sedimentary CH_4 hydrates, and (2) What is the extent of associated oxygen depletion and ocean acidification (reduction in pH and saturation states).We made six 500-year sensitivity tests (offline forced by output from coupled climate simulations) with different oxidation rates and injection rates to study century-scale effects of a marine CH_4 hydrate meltdown. At the high release rate of 0.6 Pg CH_4 yr^{-1} from Arctic sediments at depths between 300-600 m, most of the CH_4 is oxidized in the ocean. The little that escapes is lost to the atmosphere but outside the Arctic. Under the same high release rate, the oceanic oxidation of CH_4 results in major changes to mid-depth waters of the Arctic, including widespread anoxia and reductions in pH and saturation states that are more severe than those projected for Arctic surface-waters from invasion of anthropogenic CO_2.

[1]LSCE/IPSL, Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ, Gif-sur-Yvette, France (james.orr@lsce.ipsl.fr)
[2]Institut Pierre Simon Laplace, Paris

EFFECTS OF PHOSPHORUS LIMITATION AND OCEAN ACIDIFICATION ON COCCOLITHOPHORES: A CASE STUDY IN THE MEDITERRANEAN SEA

Oviedo, Angela M.[1], Gerald Langer[1,2], and Patrizia Ziveri[1]

The Mediterranean Sea is characterized by very high water column anthropogenic CO_2 inventories and eastern Mediterranean surface water unequivocally *phosphorus limited*. Coccolithophores are dominant phytoplankton calcifiers in the Mediterranean Sea and we examine here the potential effects

of low phosphorous concentrations and ocean acidification that may alter the outcomes of acidification in this region. Controlled laboratory experiments, in dilute batch culture mode, using Mediterranean clones were conducted. Until today, it remains unclear how the combined effect of ocean acidification and phosphorus limitation could affect the cellular content of particulate inorganic and organic carbon (PIC and POC), its production and ratio. In the only two studies that have considered the question, a decrease in POC quotas with increased pCO_2 was observed; while in one of these studies, PIC quotas decreased only in the more limited treatments. Here we provide a wider data set, testing the combined effects of ocean acidification and phosphorus limitation on PIC and POC quotas, calcification and POC production, PIC:POC and coccolith morphology in two Mediterranean strains of *Emiliania huxleyi*. Results are compared with observations from field water samples collected along the Mediterranean Sea analyzing coccolithophores assemblages and morphology of *Emiliania huxleyi* coccoliths in relation to the sea water carbonate chemistry and nutrient concentration of the different water masses.

[1] ICTA, Autonomous University of Barcelona (UAB), 08193 Bellaterra, Spain (AngelaMaria.Oviedo@uab.cat)
[2] Alfred Wegener Institute for Polar and Marine Research (AWI), Am Handelshafen 12, 27570 Bremerhaven, Germany. Now at Department of Earth Sciences, Cambridge University, Downing St., Cambridge. CB2 3EQ. UK.

PHYSIOLOGICAL RESPONSES OF THE PORCELAIN CRAB *PETROLISTHES CINCTIPES* TO INCREASED CO_2, TEMPERATURE AND EMERSION

Paganini, Adam and Jonathon Stillman

Organisms that inhabit the intertidal zone experience large daily fluctuations in temperature, humidity and pH. Intertidal invertebrates may respond to these abiotic factors in ways that could alter their molecular, organismal, and, eventually, their community performance. Due to their large abundance and diverse habitat distributions in the intertidal zone, Porcelain crabs play an important role in intertidal ecosystems. We investigated the Porcelain crab *Petrolisthes cinctipes*' performance under future ocean conditions that included the synergistic effects of temperature, increased CO_2, and emersion. Adult *P. cinctipes* collected from Fort Ross, California, were exposed to three levels of emersion during the day; cold, warm, or none. At night the crabs in each treatment were exposed to either low or ambient pH. Metabolic rate and CT_{max} were measured, and samples were taken for proteomics and transcriptome analysis using RNA-seq. When constantly immersed, crabs showed increased metabolic rate under low pH while crabs that experienced cold emersion exhibited decreased metabolic rates under low pH stress. When crabs had a daily emersed heat spike pH did not alter metabolic rates. This study will help predict the response of *P cinctipes* to several environmental factors that are expected to change in future oceans.

San Francisco State University, Romberg Tiburon Center for Environmental Studies, Tiburon, CA 94920, USA. paganini@mail.sfsu.edu

PILOT STUDY ON THE DIRECT EFFECT OF INCREASING CO_2 ON COASTAL MACROALGAE SPECIES IN THE CONDITIONS OF NE BALTIC SEA

Pajusalu, Liina, Georg Martin, Arno Põllumäe, and Tiina Paalme

Studies on the effects of increasing acidification on marine communities have been in most cases carried out in the open sea conditions and outside of the Baltic Sea. Therefore studies on possible effects of

acidification on coastal macrophyte species in the Baltic are totally missing. The aim of current study was to address the question: How acidification induced by elevated atmospheric carbon dioxide is affecting macroalgae in conditions of NE Baltic Sea? Research methods included set of laboratory and *in situ* mesocosm experiments. Laboratory experiments were carried out using specimens of red algae *Furcellaria lumbricalis*. Set of mesocosm experiments was carried out during field season of 2011 in Kõiguste Bay, northern part of Gulf of Riga. Separate mesocosms were operated in each set with different treatment of CO_2 levels with control treatment in natural conditions. *In situ* incubations were carried out with three species – representing three different morphologic and ecological groups: *Enteromorpha intestinalis* – fastgrowing green algae, *Fucus vesiculosus* – perennial brown alagae, *Furcellaria lumbricalis* – perennial red alagae. As response variable photosynthetic activity was used measured as net oxygen production. In the laboratory experiments the macroalgae *Furcellaria lumbricalis* showed the highest primary production at lowest pH values (pH 6.5) while the natural level of pH showed the lowest primary production. *In situ* mesocosm results indicated that increased CO_2 levels in seawater may have positive effect on the photosynthetic activity of macroalgae *Ulva intestinalis* and *Furcellaria lumbricalis* but *Fucus vesiculosus* showed no response to elevated CO_2 during short term incubation.

Estonian Marine Institute, University of Tartu, Mäealuse 14, 12618 Tallinn, Estonia
(liina.pajusalu@ut.ee).

EXPLORING OPTIMAL FOSSIL FUEL EMISSION PATHWAYS FOR CALCIFYING BIOMES IN A HIGH-CO_2 WORLD

Pasquer, Benedicte[1,2], Richard Matear[2], and Ben McNeil[1]

As a consequence of the release of CO_2 to the atmosphere ocean acidification is expected to produce detrimental effect to the marine ecosystems, while climate change itself will alter the dynamics of ocean ecosystems. Using a coupled climate-carbon cycle model we explore and compare impacts for three calcifying biomes under alternative pathways of the carbon release. Business-as-usual, cumulative and 550ppm stabilization pathways are investigated to determine the magnitude of changes within the calcifying biomes over 100 and 500 year time-frames under climate change. The calcifying biomes are defined based on key marine calcifying organisms, namely Coccolithophorids, Pteropods and reef building corals, using environmental parameters constraining their distribution. Preliminary results show distinct variations in ocean acidification impact between biomes, coupled to varying responses under climate change. Key questions that we seek to explore are: Can we reduce the onset of unfavourable conditions in these calcifying biome through how we release fossil fuel? Does climate change accelerate or retard the onset of unfavourable conditions? Do calcifying biomes expand or contract with climate change?

Climate Change Research Center, University of New South Wales, Sydney, NSW 2052, Australia.
benedicte.pasquer@csiro.au
CSIRO Marine and Atmospheric Research, Hobart, TAS 7001, Australia

AGGREGATION AND OCEAN ACIDIFICATION

Passow, Uta

Ocean acidification research has focused largely on issues relating to calcification, whereas the potential impacts on the soft tissue pump have received less attention. The formation of large, rapidly sinking aggregates due to coagulation, e.g. collision and attachment of component particles, is a central factor determining the strength of the soft tissue pump and carbon sequestration by the ocean. The presence of sticky transparent exopolymer particles (TEP), which form abiotically from exudates released by microbes are a prerequisite for such aggregate formation.
Ocean acidification may potentially impact aggregation at all levels: (i) The formation of TEP-precursors by phytoplankton is sometimes, but not always enhanced under high pCO_2 conditions. (ii) The abiotic formation of TEP from their precursors is not directly impacted by high pCO_2 conditions, although changes in alkalinity impact the abiotic formation of TEP. (iii) The consequences of ocean acidification on the aggregation potential of particles, e.g on the fraction of material aggregated and on aggregate size distributions are ambiguous and dependent on environmental conditions.
Whereas it is clear that the carbonate system is an important parameter, structuring the environment and influencing environmental processes, synergistic interactions between different environmental triggers and the complexity of these effects make predictions on the changes expected in the future ocean currently impossible.

Marine Science Institute, University of California Santa Barbara, CA 93106, USA,
passow@lifesci.ucsb.edu

EFFECTS OF ELEVATED PCO_2 ON GROWTH AND DEVELOPMENT IN THE COPEPOD CALANUS FINMARCHICUS

Pedersen, Sindre Andre[1], Bjørn Henrik Hansen[2], Anders J. Olsen[1], and Dag Altin[3]

The high latitude crustacean copepod *Calanus finmarchicus* at times dominates the standing stock of zooplankton in the northern North Sea and North Atlantic. Given the key status of this species any negative effects of elevated CO_2-levels could influence the whole ecosystem. *C. finmarchicus* could potentially face exposure to elevated levels of CO_2 both from general absorption by the sea (ocean acidification) and potential leakage of CO_2 from sub seabed stories. Using a custom developed microcosms system the development from eggs to late copepodite stage was followed while exposing the animals to different CO_2-levels (390, 3300, 7300, 9700ppm CO_2). The one month long experiment revealed a significant reduction in the ontogenetic development speed in all exposed groups. A reduction in survival among the animals exposed to 7300 and 9700ppm CO_2 was also found. Morphometric analysis revealed significant effect on the size and fat accumulation in copepodite stage III and IV. The findings show that *C. finmarchius* is likely to be negatively affected if chronically exposed to CO2-levels of 3300 or higher. Further studies employing more moderate levels are presently conducted to reveal if this species may also be vulnerable to the more moderate CO_2-levels relevant for near future ocean acidification scenarios.

[1] NTNU, Department of Biology, Høgskolerinen 5, N-7491 Trondheim, Norway
(Sindre.Pedersen@bio.ntnu.no)
[2] SINTEF Mat & Chem, Marine Environm Technol, N-7465 Trondheim, Norway
[3]BioTrix, N-7022 Trondheim, Norway

OCEAN ACIDIFICATION EFFECTS ON THE COMMUNITY METABOLISM AND BENTHIC PROCESS

Pereira, Camila O., Betina G. Rodrigues Alves, and Paulo Yukio .G. Sumida

Increased atmospheric CO_2 concentrations are causing greater dissolution of CO_2 into seawater, and are ultimately responsible for today's ongoing ocean acidification (OA). It is estimated that the oceans have taken up on the order of a third to one half of the CO_2 released to the atmosphere via anthropogenic activities since the industrial revolution. The function of this carbon sink is extremely important in the global carbon cycle. In coastal shallow areas, such as Ubatuba (Brazil), marine microphytobenthos is an important compartment, and is one of the principal agents responsible for carbon input into the entire system. The effect of short term exposure to acidified seawater on the community metabolism (primary production, respiration) was investigated. Intact sediment samples containing benthic microalgae and organisms were exposed to seawater acidified to a pH 7.7, 7.3 and 6.9. Control treatments were maintained in natural seawater (pH ≈ 8.1). During the experimented period, all treatments had similar results with a slight decrease in the concentration of chlorophyll *a* at the end of the experiment. Result from others experimental studies observed an increase in the rate of photosynthesis under increased CO_2 conditions. Changes in rates of primary production and subsequent availability of organic carbon can alter benthic communities. We conclude that the lowered seawater pH could cause changes in benthic process and could have indirectly impact on coastal sediment communities. However, more studies are needed to understand the effects of OA in the entire benthic system in Brazilian coastal areas.

Oceanographic Institute, University of São Paulo, Praça do Oceanográfico 191, 05508-120, São Paulo, Brasil (copereira@usp.br)

OBSERVED TRENDS IN ACIDIFICATION AND ALKALINTY INCREASE IN NORTH ATLANTIC WATER MASSES

Pérez, Fiz F.[1], Aida F. Ríos[1], Marcos Vázquez-Rodríguez[1], and Herle Mercier[2]

Models have predicted the acidification of the ocean due to the uptake of a large fraction of the carbon dioxide (CO_2) that is released to the atmosphere by mankind. The spatiotemporal sparseness of *in situ* measurements has made difficult assessing the recent rates of ocean acidification, particularly in the high latitudes. Here we show a time series of pH records in the northern North Atlantic that provides direct, quantifiable evidence for the development of unprecedented acidification rates in upper and intermediate North Atlantic waters since 1981. The highest acidification rates are associated to Subarctic Intermediate Water (SAIW; -0.0018 ± 0.0001 yr^{-1}) and to Subpolar Mode Water (SPMW; -0.0012 ± 0.0002 yr^{-1}). The Labrador Seawater (LSW) shows an unexpectedly fast acidification rate of -0.0015 ± 0.001 pH units per year. The deep convection and rapid subduction of well-ventilated waters in the North Atlantic subpolar gyre transports surface waters, loaded with anthropogenic CO_2, into intermediate waters faster than via downward diffusion and mixing alone.
Also recent biogeochemical models have shown that this acidification is likely to impact calcification rates of many pelagic organisms and predict trends of increase in total alkalinity (A_T). The recent biannual occupations of the Greenland-Portugal OVIDE section offers a unique opportunity to verify this prediction. The data set shows a positive trends in A_T for surface and in intermediate North Atlantic waters of ~0.14 ± 0.06 $umol\cdot kg^{-1}\cdot y^{-1}$ between 2002 and 2010.

[1] Department of Oceanography, Instituto de Investigaciones Marinas, IIM-CSIC, Eduardo Cabello, 6, E-36208 Vigo, Spain (fiz.perez@iim.csic.es)

[2] Laboratoire de Physique des Océans (LPO), CNRS Ifremer IRD UBO, IFREMER Centre de Brest, B.P. 70 29280 Plouzané, France

THE EFFECTS OF INCREASED pCO_2 ON MOLLUSCAN EARLY DEVELOPMENT: CRITICAL THRESHOLD AND ACCLIMATION

Picard, Manon[1], Christopher D.G. Harley[1], Erin K. McClelland[2], Ruth E. Withler[2], and Robert Saunders[3]

Ocean acidification has many negative effects on marine organisms, including economically important shellfish. Identifying the effects of OA on commercial bivalves is a priority for aquaculture and fishery managers, yet little is known about the effects at early developmental stages. Therefore, we investigated which early developmental stage of oyster (*Crassostrea gigas*), mussel (*Mytilus edulis*), and scallop (*Patinopecten yessoensis* x *P. caurinus* hybrids) is most vulnerable to high pCO_2 levels and whether larvae grown in high pCO_2 demonstrate signs of acclimation. Conducting this study under aquaculture setting, we measured growth and feeding rate as well as activity and condition of the individuals at four different pCO_2 levels. Preliminary results with the Pacific oyster (*Crassostrea gigas*) show that increasing pCO_2 decreases size of larval and juvenile oyster However, they also show that the larval pCO_2 conditions do not affect the growth of the juvenile. Our study could provide hatcheries with a better yield by determining the intake water pH levels at which chemical interventions must be employed. In the long term, a better insight in the effects of ocean acidification in the development of shellfish could provide managers with a tool for restoring stocks that are negatively impacted in the wild.

[1] University of British Columbia, 6270 University Blvd, Vancouver, BC, Canada, V6T 1Z4 (picard@zoology.ubc.ca)
[2] Fisheries & Oceans Canada, 4160 Hammond Bay Road, Nanaimo, BC, Canada, V9T 6N7
[3] Island Scallops ltd., 5552 West Island Hwy, Qualicum Beach, BC, Canada, V9K 2C8

PARENTAL EFFECTS ARE MODULATED BY CLIMATE CHANGE STRESSORS IN SPAWNING CORALS

Putnam, Hollie M. and Ruth D. Gates

Coral reefs are highly productive and diverse ecosystems that are under threat both locally and globally. Increasing seawater temperatures and ocean acidification (decreased pH and altered carbonate chemistry) are known to have profound detrimental effects on corals, and the severity of these stressors on reefs is predicted to increase in the future. To examine the simultaneous effect of these stressors on reproductively active corals and their eggs, adult *Montipora capitata* fragments (n=48) from Kaneohe Bay, Hawaii were exposed to ambient (26°C, ~400µatm), or high (29°C, ~850µatm) treatments for one month prior to spawning. Following the exposure, adult corals were assessed for spawning activity, time of release, egg size, number of eggs and egg biomass per coral. In addition, adult colonies were measured for photophysiological performance, *Symbiodinium* density, chlorophyll-a content, host biomass and skeletal density. Reproductive timing was shifted, with release of egg-sperm bundles occurring earlier in high treatment tanks. Egg size was reduced by ~23% in the high treatment, however, total reproductive biomass was maintained at statistically equal levels with higher numbers of smaller eggs released under high treatment, and fewer larger eggs released under ambient treatment. Together, these results suggest increased temperature and ocean acidification affect reproductively active corals by influencing the timing of release and size of eggs. The consequence of smaller eggs under increased climate change stressors have potential to carry over through development, and this may have profound

ramifications for reefs by magnifying the negative effects of global stressors through later life stages and future generations.

Hawaii Institute of Marine Biology, 46-007 Lilipuna Rd, Kaneohe HI 96744. hputnam@hawaii.edu

CONSTRAINING CARBONATE SYSTEM VARIABILITY ON THE CALIFORNIA MARGIN FROM LGM TO PRESENT

Quintana Krupinski, Nadine B.[1], Dorothy K. Pak[2], Ann. D. Russell[3], Tessa M. Hill[3], and Adina Paytan[1]

Today's ocean is experiencing rapid reductions in pH and changes in the carbonate saturation state due to the uptake of anthropogenic CO_2; impacts for calcifying organisms are unclear and could be severe. It is important to determine the natural variability of the carbonate system over timescales of thousands of years to provide long-term perspective on the current and expected future changes caused by increased anthropogenic CO_2 inputs, and to provide a basis for determining whether there is a critical threshold at which organisms may be negatively affected by changing carbonate saturation. The state, stability and natural variability of pre-anthropogenic marine carbonate systems can be reconstructed from carbonate system proxies in foraminiferal calcite. We constrain the long-term (post-LGM) natural variability of surface water carbonate system chemistry in the Southern California Borderland, a coastal region that experiences substantial pH fluctuations today. Additional temperature reconstruction allows comparison with other nearby Southern California temperature records.
We present trace metal (B/Ca, U/Ca and Mg/Ca) and stable isotope ($\delta^{18}O$, $\delta^{13}C$) values of planktonic foraminifera *G. bulloides* and *N. pachyderma* (d) from Santa Monica Basin to reconstruct the past surface ocean carbonate system and temperature for the past ~20ka. Initial results suggest that decadal-scale Holocene carbonate system and temperature variability are roughly within the range of modern seasonal variations. However, late Pleistocene values may be beyond this range. High-resolution windows in the early Holocene indicate some intervals of apparent stability in the carbonate system over multi-decadal timescales, but shorter timescales may show larger variations.

[1]University of California, Santa Cruz, USA., nadine@pmc.ucsc.edu,
[2]University of California, Santa Barbara, USA.
[3]University of California, Davis, USA.

COMPOSITION AND DIVERSITY OF INFAUNAL MACROBENTHIC ASSEMBLAGES UNDER INCREASED *P*CO_2 AND REDUCED PH

Range, P.[1], D. Piló[1], R. Ben-Hamadou[1], M. Chícharo[1], F. Leitão[1], D. Matias[2], S. Joaquim[2], T. Drago[2], A.P. Oliveira[3], and L. Chícharo[4]

Anthropogenic emissions of CO_2 are forcing atmospheric concentrations to unprecedented levels, leading to decreases in pH, carbonate ions and the related $CaCO_3$ saturation state of seawater. Investigating whether and how marine organisms will be affected by ocean acidification (OA) has been a priority for research in recent years. Despite most the observed effects of OA coming from experiments with single species, impacts on marine assemblages are frequently hypothesized. Some the perceived effects are the following: decreased diversity of marine assemblages (i.e. number and evenness of taxa and functional groups); increased abundance of non-calcifying organisms, in detriment of calcifying taxa and; decreased resistance of assemblages to predation. In the present study we used controlled CO_2 perturbation experiments to test these hypotheses in infaunal macrobenthic assemblages, under

realistic and locally relevant scenarios of seawater acidification. Two types of sediment (sand and mud) were collected from intertidal areas in the Ria Formosa coastal lagoon (South Portugal). Samples were sieved in 0.5 mm mesh and all macrofaunal organisms identified for initial characterization of the assemblages. Additional patches of live sediment samples were settled in 25l indoor mesocosms and gradually exposed to two levels of seawater acidification (pH reduced by −0.4 and−0.6 units), relative to one unmanipulated (control) level. The experiment lasted for 75 days and the response was measured in terms of changes in diversity (i.e. number and evenness of taxa and functional groups), composition and sediment characteristics (grain size, carbonate content, pH, organic content and mineralogical composition).

[1] Centro de Ciências do Mar, Universidade do Algarve. Faro, Portugal (prange@ualg.pt)
[2] Instituto Nacional de Recursos Biológicos, I.P./L-IPIMAR, Olhão, Portugal
[3] Instituto Nacional de Recursos Biológicos, I.P./L-IPIMAR, Lisboa, Portugal
[4] Faculdade de Ciências e Tecnologia, Universidade do Algarve, Faro Portugal

EFFECTS OF SEAWATER ACIDIFICATION BY CO_2 ON RNA/DNA RATIOS OF BIVALVES IN A COASTAL LAGOON ENVIRONMENT

Range, P.[1], M. Chícharo[1], D. Piló[1], R. Ben-Hamadou[1], E. Sá[2];, A. Amaral[1], and L. Chícharo[2]

The RNA/DNA ratio is a widely used indicator of nutritional condition, physiological state and recent growth in different groups of marine organisms. It is based on the assumption that the amount of DNA, the primary carrier of genetic information, is stable in a somatic cell under changing environmental situations, whereas the amount of RNA directly involved in protein synthesis, varies with age, life-stage, disease-state and with changing environmental conditions. In the present study, we manipulated the carbonate chemistry of seawater from the Ria Formosa lagoon (south Portugal), by diffusing pure CO_2, to achieve pH reductions varying between 0.3 and 0.7 pH units, relative to unmanipulated seawater. Standardized RNA:DNA ratios and protein content for *Mytilus galloprovincialis* and *Ruditapes decussatus* were determined using a spectrofluorometric method. After 3 months of exposure, no differences were detected for *M. galloprovincialis*. In contrast, for the clams *R. decussatus*, the ratio consistently decreased with pH, particularly for the smallest sizes. Despite shell growth of both species being unaffected by the treatments, reduced clearance, ingestion and respiration rates and increased excretion of ammonia have been reported for *R. decussatus* exposed to similar levels of acidification. Reduced ingestion combined with increased excretion is generally associated with a decreased energy input, which is consistent the pattern now reported for the RNA/DNA ratio. This reduced ecophysiological condition may constitute an important threat to survival of some bivalve populations, especially under cumulative anthropogenic stress (e.g. pollution). Nevertheless, our results also highlight the variable sensitivities of bivalves to ocean acidification.

[1] Centro de Ciências do Mar (CCMAR), Universidade do Algarve. Faro, Portugal (prange@ualg.pt)
[2] Faculdade de Ciências e Tecnologia, Universidade do Algarve, Faro Portugal

EFFECTS OF SEAWATER ACIDIFICATION BY CO_2 ON THE REPRODUCTION OF *MYTILUS EDULIS*

Range, P.[1], T. Casimiro[2], P. Moura[3], D. Piló[1], D. Matias[3], M. Gaspar[3], and L. Chícharo[2]

Ocean acidification is one of the most challenging large scale processes humankind is facing. The consequences to ecosystem functions and associated services are still not fully know or evaluated.

Major direct effects are expected on species with carbonate shells, like bivalves, which may be affected by dissolution of their calcified structures. Less visible and studied, however, are the indirect effects on species life cycles. In this study we analyzed the effects of seawater acidification – to levels predicted according to the IPCC scenarios for atmospheric concentrations of CO_2 – on the reproductive activity of the bivalve *Mytilus edulis*. The carbonate chemistry of seawater from the Ria Formosa lagoon (South Portugal) was manipulated, by diffusing pure CO_2, to attain two reduced pH levels, by -0.4 and -0.7 pH units. The experiment was done in an indoor flow-through system and covered one reproductive season, between May and August. The response of the mussels was measured in terms of gonad somatic- index, condition index, gametogenesis, oocyte diameter and sex ratio. The strongest pH reduction (-0,7 units) seems to have affected gametogenesis, causing delayed spawning in females. Such a desynchronized gametogenic development could reduce the reproductive success of *M. edulis* in some geographical areas, with consequences to the abundance and sustainability of local populations of mussels.

[1] CCMAR - Centro de Ciências do Mar, Universidade do Algarve, Campus de Gambelas 8005-139 Faro Portugal (prange@ualg.pt)
[2] Faculdade de Ciências e Tecnologia, Universidade do Algarve, Campus Gambelas, 8005- 139 Faro Portugal
[3] Instituto Nacional de Recursos Biológicos, L-IPIMAR, Av. 5 de Outubro s/n, 8700 305 Olhão, Portugal

THE COMBINED EFFECTS OF CO_2 AND TEMPERATURE ON ACID-BASE REGULATION DURING TIDAL EMERSION AND RE-IMMERSION IN *NECORA PUBER.*

Rastrick, S.P.S.[1], P. Calosi[1], R. Calder-Potts[2], G. Nightingale[1], S. Thomas[1], S. Widdicombe[2], and J.I. Spicer[1].

Changes in the distribution of marine crustaceans at different spatial scales affect assemblage structure, biodiversity and subsequently impact upon fisheries. Across an intertidal gradient the distribution of many economically and ecologically important crustacean species is, in part, determined by their ability to survive and recover from tidal emersion. During emersion they often experience gill-collapse impairing gas-exchange, resulting in hypercapnia-induced respiratory acidosis alongside systemic hypoxia leading to hyperlactaemia and metabolic acidosis. How such physiological responses to emersion are modified by prior exposure to CO_2 and temperature, together and in isolation, has not been investigated previously.
Consequently, we investigated selected physiological responses of the crab *Necora puber*, acclimated for 2weeks to one of four CO_2/temperature treatments (380ppm/9˚C, 750ppm/9˚C, 380ppm/15˚C, 750ppm/15˚C), during and after 3h emersion. Recovery of acid-base balance following emersion was 1h longer at elevated temperature (15˚C) and 2h longer at elevated temperature and CO_2 (750ppm). Recovery from hyperlactaemia, *via* gluco- and glyconeogenesis was also inhibited by increased CO_2 and temperature, possibly due to increased metabolic demand and lactate fermentation at high temperatures combined with the pH sensitivity of pyruvate carboxylase.
We suggest that important intertidal species, such as *N. puber*, considered to be relatively “tolerant” to climate change will show greater vulnerability to ocean acidification when experiencing ‘routine’ acid-base stress during emersion. If increases in environmental pCO_2 and temperature lead to a reduction in emersion resistance and recovery time then some intertidal species may be forced to shift their vertical distribution, affecting the structure, diversity and dynamics of intertidal assemblages.

[1] Marine Biology & Ecology Research Centre, Plymouth University, Drake Circus, Plymouth, Devon, PL4 8AA, UK (Samuel.Rastrick@plymouth.ac.uk)

[2] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth PL1 3DH, UK.

ANTICIPATED OCEAN ACIDIFICATION ON THE US NORTHEAST SHELF USING A COUPLED EARTH SYSTEMS MODEL AND REGIONAL CLIMATOLOGY

Rebuck, Nathan D., and Jonathan A. Hare

While global scale climate models provide the best estimates of future atmospheric and oceanic carbon dioxide concentrations over the coming decades, they are limited by a relatively coarse spatial resolution. The resultant estimates often lose the substantial variability inherent in nearshore and shelf regions. Results of a recent analysis of carbonate parameters on the US Northeast Shelf show variability across gradients of salinity and bathymetry, in addition to significant interannual variability in the average pH. To evaluate the potential magnitude and effects of ocean acidification, we integrate results from the coupled atmosphere/ocean GFDL ESM model with a regional climatology to identify localized areas and fisheries susceptible to changes in both the mean and extreme of carbonate chemistry. Using a "local delta" approach, where the changes represented in the global model output are superimposed on the more detailed shelf-wide climatology, the regional variation in carbonate chemistry is preserved while realistically anticipating future changes. This methodology is necessary to evaluate the impact of acidification on fisheries as it allows the retention of inshore-offshore gradients of factors influencing pH, such as salinity and primary productivity, in addition to the temporal variation in seasonal phenomena along a north-south gradient important to fisheries recruitment. This research suggests that offshore areas may be susceptible to a shift in the annual average pH, whereas inshore areas may be more at risk of drastic, shorter term events of low pH.

NOAA NEFSC Narragansett, 28 Tarzwell Dr., Narragansett, RI 02882 (Nathan.Rebuck@noaa.gov)

DEVELOPMENT OF A COLORIMETRIC MICRO-SENSOR FOR SEAWATER pH ANALYSIS

Rérolle, Victoire M. C.[1], Cedric F. A. Floquet[2], Matt C. Mowlem[2], Andy J. K. Harris[2], Richard R. G. J. Bellerby[3], and Eric P. Achterberg[1]

High quality carbonate chemistry measurements are required in order to fully understand the dynamics of the oceanic carbonate system. Seawater pH data with good spatial and temporal coverage are particularly critical to apprehend ocean acidification phenomena and their consequences.
The aim of our project is to develop an accurate and precise autonomous *in situ* pH sensor for long term deployment on remote platforms. The system is based on the spectrophotometric approach implemented on a simple micro-fluidic platform with low power and reagent consumption. A robust optical set up is achieved with the use of a custom-made polymeric flow cell coupled to a three wavelength LED. The measurement is made close to *in situ* temperature (+0.2 °C) in the sampling chamber which has a continuous flow of the ship's underway seawater supply.
The system features a short term precision better than 1 mpH unit (n=20) and an accuracy within the range of a certified Tris buffer (4 mpH units). The pH sensor has been deployed on RRS *Discovery* cruises D366 and D368 for a period of two months in summer 2011 and will be deployed in the Arctic in June 2012.
This work is supported by SENSEnet, a Marie Curie Initial Training Network (ITN) funded by the European Commission Seventh Framework Programme, Contract Number PITN-GA-2009-237868.

[1] University of Southampton, National Oceanography Centre, Southampton, Southampton SO14 3ZH, UK. Victoire.Rerolle@noc.soton.ac.uk
[2] National Oceanography Centre, Southampton SO14 3ZH, UK
[3] University of Bergen, Norway

Hg AND Ba AS BIOGEOCHEMICAL PROXIES TO IMPROVE THE UNDERSTANDING OF PROCESSES AT THE CONTINENT-OCEAN INTERFACE: CAMPOS BASIN - RIO DE JANEIRO, BRAZIL

Rezende, Carlos E.[1], Marcelo G. Almeida[1], Beatriz F. Araújo[1], Arizoli A. R. Gobo[1], Bianca T. L. Pires[1] , and Ana P. Falcão[2]

Marine biogeochemistry is a very stimulating scientific field where different disciplines are connected in order to improve the understanding on past and present processes and to model the future of ecosystems. At the present time, several changes are affecting the oceans such as pollution, overfishing, mining and petroleum extraction. More recently ocean acidification has been also highlighted as a significant issue. Ocean acidification has been better understood in its biological aspects; however, biogeochemical features are being studied at a slower pace. The aim of our investigation was to describe a large marine area (25 to 3,000m) using two elements, Ba and Hg as biogeochemical proxies for natural and anthropogenic sources, respectively, and their geochemical supports (Organic Carbon "OC", Carbonate, Ca, Fe, Al). Mercury concentration ranged from <0.5 to 55 $ng.g^{-1}$ and showed a clear trend which increased with deep. Total carbonate also showed a similar pattern to that observed for Hg with a range from 1 to 85%. Ba, OC, Fe, Al concentrations increased until the middle of Continental Margin (~1,300m) and, and decreased up to 3,000 m. The ratio between Hg and Ba, with different geochemical supports (Hg/Ca, Hg/OC, Ba/Ca, Ba/OC), showed clear signals of terrestrial contribution up to 100m isobaths, and then the internal oceanographic processes were dominant up to 3,000m. However, the Hg/Al and Hg/Fe ratios showed that terrestrial dust represent an important source of Hg for ocean biogeochemical cycles. Finally, a specific geochemical extraction showed that mobile phases can be their chemical equilibrium affected under ocean acidification, especially when the sediments are carbonate-rich.

[1]Universidade Estadual do Norte Fluminense, Centro de Biociências e Biotecnologia, Laboratório de Ciências Ambientais, Av. Alberto Lamego 2000, Campos dos Goytacazes, Rio de Janeiro, 28.013-600, Brazil. crezende@uenf.br
[2]Centro de Pesquisa da PETROBRAS S.A., Gerência de Avaliação e Monitoramento Ambiental, Av. Horácio de Macedo 950, Ilha do Fundão, Rio de Janeiro, 21941-915, Brazil.

CHANGING OCEANS EXPEDITION 2012: DEEP-SEA ECOSYSTEM FUNCTION AND THE IMPACTS OF OCEAN ACIDIFICATION ON COLD-WATER CORAL ECOSYSTEMS IN THE NORTHEAST ATLANTIC OCEAN

Roberts, J Murray and the shipboard party JC073

From mid-May to mid-June 2012 the RRS James Cook embarks on an ambitious expedition to study the functional ecology of cold-water coral ecosystems west of the UK and Ireland. Cold-water corals form amongst the most complex biogenic structures in the deep sea. Providing habitat to many other species, the aragonitic reef frameworks formed by scleractinian corals are believed to be particularly vulnerable to ocean warming and acidification. At sea, ship-board experiments examine coral biology and ecophysiology under both elevated temperature and pCO_2 treatments. In parallel the Changing Oceans Expedition uses a deep-sea remotely operated vehicle (ROV) to experiment *in situ* within coral habitats.

Seabed experiments include deployments of a novel aquatic eddy correlation lander to assess O_2 flux and benthic spreader chambers to examine uptake of dissolved organic matter in deep-sea reef organisms. A newly designed sampling apparatus allows us to sample and fix microbiological samples at depth, avoiding potential contamination or community changes between collection and recovery. A Sediment Profile Imaging (SPI) camera system allows studies of soft-sediment habitats *in situ* and box core sampling retrieves material for incubations on the vessel while at sea. This presentation will provide an overview of the initial results from this interdisciplinary expedition. It will also summarise the expedition's public outreach activities involving schoolchildren from the Hebridean Islands and their participation in debates on deep-sea conservation issues facilitated by Scotland's national geoscience outreach centre 'Our Dynamic Earth'.

Centre for Marine Biodiversity & Biotechnology, School of Life Sciences, Heriot-Watt University, Edinburgh, Scotland, EH14 4AS, UK. j.m.roberts@hw.ac.uk

A LOW-COST SENSOR FOR AUTONOMOUS FIELD MEASUREMENTS OF SEAWATER CARBONATE

Rockwell, Rachel[1], Jerry Breecher[2], Jia Wei[1], Sergio Granados-Focil[1], and Christina M. McGraw[1]

Spatial and temporal variability in CO_3^{2-} can be much larger than the expected near-term changes due to ocean acidification. However, these fluctuations are difficult to measure directly, so $[CO_3^{2-}]$ is usually calculated from measured values of at least two other carbon chemistry parameters (pH, pCO_2, dissolved inorganic carbon, alkalinity). Using solid-state fabrication techniques, a rugged, $2 carbonate ion-selective electrode has been developed which can measure CO_3^{2-} directly using a copolymer membrane doped with a carbonate-selective ion receptor. The chemical structures of both the copolymer and the carbonate-selective ion receptor have been tailored to yield optimal performance. The CO_3^{2-} sensor's linear response range encompasses relevant marine concentrations, with uncertainties consistent with other ion selective electrodes (10%). Although this relatively high uncertainty limits its use for constrained measurements of the marine carbon system, the accuracy and precision of the sensor is suitable for measuring the magnitude of natural carbonate variability. In order to use these sensors to measure localized variability, a low-cost (<$150) electronic platform was also developed. Laboratory validation indicates that the device is currently capable of collecting and logging data from four CO_3^{2-} electrodes every two minutes for up to two weeks.

[1] Carlson School of Chemistry and Biochemistry, Clark University, Worcester, MA, 01610, USA. cmmcgraw@clarku.edu
[2] Computer Science Department, Worcester Polytechnic Institute, Worcester, MA, 01609, USA

SOME MEDITERRANEAN CORALS, BUT ALSO BRYOZOANS, MOLLUSCS AND GASTROPODS KEEP CALCIFYING AT LOW CARBONATE IONS CONCENTRATIONS

Rodolfo-Metalpa, Riccardo, Jason M. Hall-Spencer, and coworkers*

Anthropogenic carbon dioxide emissions cause a decrease in surface ocean pH, lowering carbonate ions concentration ($[CO_3^{2-}]$). Although mechanisms of calcification in marine invertebrates are still poorly known, their calcification rates are projected to dramatically decrease with $[CO_3^{2-}]$. Six coral species (three shallow, and three deep-sea species), a bryozoan, a commercially important shellfish, and three gastropods have been studied near CO_2 vents and in laboratory experiments. Here we show that the net calcification (NC) rates of five of the seven calcifiers (corals and a bryozoan) exposed to projected end-

of-century pH values (pH_T 7.7-8.1) are not affected by a decrease in [CO_3^{2-}]. Decreases in NC measured on two coral species were likely related to: i) skeletal dissolution due to short exposures to corrosive waters undersaturated in aragonite during transplantation at CO_2 vents; ii) species morphology (no tissue or organic layer protecting them from dissolution); iii) high skeleton porosity. A key result is that all the species exposed to a gradient of pH (pH_T 7.4-8.1) always showed measurable gross calcification (GC), which is not affected by dissolution. GC rates generally were unaffected even at extremely low pH values and [CO_3^{2-}]. Therefore, species from different taxa may not rely on seawater [CO_3^{2-}] to build their shells and skeletons.
We propose that the dramatic decrease observed in coastal biodiversity at a range of CO_2 vent sites at pH_T values around 7.8 is due to a decrease in the benthic recruitment from the plankton and the combined deleterious effects of warming and acidification.

Marine Biology and Ecology Research Centre, School of Marine Science & Engineering, University of Plymouth, UK. PL4 8AA. (riccardo@rodolfo-metalpa.com)
*Aliani Stefano (CNR, Italy), Baggini Cecilia (University Plymouth, UK), Brusca Lorenzo (INGV, Italy), Descroix-Comanducci Florance (CSM, Monaco), Fine Maoz (Bar-Ilan University, Israel), Foggo Andy (University Plymouth, UK), Garilli Vittorio (APEMA, Italy), Gattuso Jean-Pierre (CNRS-UPMC, France), Gori Andrea (CSM, Monaco), Houlbrèque Fanny (IRD, New Caledonia), Milazzo Marco (University of Palermo, Italy), Montagna Paolo (CNR, Italy), Oberhänsli Francois (IAEA, Monaco), Sicari Roberto (University of Palermo), Scuderi Danilo (University of Palermo, Italy), Tambutté Eric (CSM, Monaco), Taviani Marco (CNR, Italy).

THE EFFECTS OF OCEAN ACIDIFICATION ON BENTHIC METABOLISM AND SEDIMENT NUTRIENT FLUXES

Rodrigues Alves, Betina G., Pereira, Camila O., and Sumida, Paulo Yukio G.

The majority of studies on ocean acidification encompass organism level and very little is known about the effects of acidification on the marine ecological processes. Among these, benthic remineralization and flux rates are fundamental, since marine sediments are the main depositories of organic matter (OM) in the ocean. Benthic organisms degrade OM and supply nutrients that stimulate benthic and planktonic primary production. Mesocosm experiments are being carried out to quantify the effects of acidified seawater on O_2 and CO_2 fluxes, dissolved organic carbon and nutrients in the sediment-water interface. The seawater was acidified by the use of a CO_2 gas system to pH 7.7, 7.3 and 6.9. Control treatments were maintained in natural seawater (pH ≈ 8.1). The results revealed a decrease in dissolved organic carbon concentrations. Nitrate and nitrite fluxes decreased in response to increased acidification while the ammonium efflux increased. A shift in the sediment procariont community composition has been found under lower pH (pH 6.9). Effects of acidification in nutrient availability and the related biogeochemical processes were identified in Brazilian coastal waters. We conclude that more studies are fundamental to understand how sediments, the organisms that live in the sediments, and the processes that occur in them will react to changes in the acidity of seawater.

Oceanographic Institute, University of São Paulo, Praça do Oceanográfico 191, 05508-120, São Paulo, Brazil betinaio@usp.br

IMPACT OF TEMPERATURE, NUTRIENTS AND THE CARBONATE SYSTEM ON THE MAIN SPECIES OF COCCOLITHOPHORES FROM THE GULF OF CALIFORNIA AND EASTERN TROPICAL NORTH PACIFIC WATERS

Rosas-Navarro, Anaid[1], Patrizia Ziveri[1], Gerald Langer [2], and Michael Grelaud[1]

The synergetic effect of multiple environmental stressors on organisms and ecosystems is key for understanding the impact of climate and global change on the marine systems. A clear knowledge of the environmental variables controlling the coccolithophore distribution and calcification, particularly in a region where ocean acidification may be very important in this context. The main aim of this study was 1. to identify the principle variables controlling target species distributions and their degree of calcification/morphology in the North eastern Pacific and 2. test/validate the effects on one of the identified key parameters in culture experiments. The study was performed on field samples collected in the Gulf of California and in the eastern tropical North Pacific in summer 2008, and on laboratory experiment samples. In the field samples, *Emiliania huxleyi* type A and type C cells were mainly found at higher nutrient concentrations and at lower temperatures, while *Gephyrocapsa oceanica* was mainly found at lower concentrations of dissolved inorganic carbon (DIC), bicarbonate ion and phosphate, and at higher temperatures. *Emiliania huxleyi* type A cells with higher degree of calcification were found at higher nutrient concentrations, lower temperatures and lower carbonate ion concentrations. Temperature and carbonate chemistry were identified as the main variables; hence a culture experiment was performed on strains of the two main species at temperatures ranging from 6.5 to 30 ºC. For all strains maximum growth rates were observed between 20 and 25 ºC with a sharp decline on either side of the optimum, showing a direct and important response to temperature. We are presenting the response of the coccolith morphogenesis in field and culture samples and consider the implication for calcite production.

[1] Institute of Environmental Science and Technology (ICTA), Autonomous University of Barcelona (UAB), 08193 Bellaterra, Spain (Anaid.Rosas@uab.cat)
[2] Alfred Wegener Institute for Polar and Marine Research (AWI), Am Handelshafen 12, 27570 Bremerhaven, Germany. Now at Department of Earth Sciences, Cambridge University, Downing St., Cambridge. CB2 3EQ. UK.

THE INFLUENCE OF UPWELLING-DRIVEN OCEAN ACIDIFICATION ON GROWTH OF THE CALIFORNIA MUSSEL, *MYTILUS CALIFORNIANUS*

Rose, Jeremy M.[1], Carol A. Blanchette[2], Eric Sanford[3], Rachael C. Williams[4], Peter T. Raimondi[4], and Bruce A. Menge[1]

Coastal upwelling systems can serve as natural laboratories for assessing biological responses to future global carbonate chemistry projections. These systems, including the California Current Large Marine Ecosystem (CCLME), are characterized by seasonal shoaling of deeper carbon-dioxide-rich waters that bathe nearshore biological communities in low-pH conditions. The goal of this study was to quantify the relative influence of pH on growth of the adult California mussel *Mytilus californianus* at 8 sites (2 in each of 4 regions) along the CCLME from central Oregon to southern California during the 2011 upwelling season. Mussel growth was measured both in the intertidal zone and subtidally on nearshore moorings. Coincident pH sensors at each location provided the context for comparing the relative influence of pH variation on mussel growth among a suite of other monitored environmental factors. To assess the potential underlying influence of genetic or persistent phenotypic differences (e.g. age or

prior exposure), mussels were transplanted to each site from both the local site population and a common population originating in Oregon.
Our study reveals both local and regional-scale variations in mussel growth. These variations are partially consistent with the hypothesis that growth is reduced in alongshore low-pH regions and confirm the previously documented importance of temperature and primary productivity. Growth did not differ between local-site and common-site mussels, suggesting that prior exposure does not influence the effects of further exposure. These combined results suggest that, despite a history of exposure to low-pH waters, mussel growth will be increasingly suppressed under forecasted ocean acidification.

[1] Department of Zoology, Oregon State University, 3029 Cordley Hall, Corvallis, OR 97331, USA. rosej@science.oregonstate.edu
[2] Marine Science Institute, University of California, Santa Barbara, CA 93106, USA
[3] Bodega Marine Laboratory, UC Davis, P.O. Box 247, Bodega Bay, CA 94923, USA
[4] Long Marine Laboratory, UC Santa Cruz, 100 Shaffer Road, Santa Cruz, CA 95060, USA

CORAL CALCIFICATION IN A REEF ENVIRONMENT CHARACTERIZED BY DAILY SWINGS IN pH
Ruiz-Jones, Guadalupe and Stephen Palumbi

As we seek to understand the stresses that corals will face due to ocean acidification, we can begin by studying coral communities that are already thriving in regions with variable environmental conditions. On Ofu Island in American Samoa, the back-reef is comprised of multiple pools that experience a range of environmental conditions. Data from continuous-recording pH sensors show that, during high tides, the pH in the back-reef is very close to the pH in the fore-reef due to constant water exchange. However, during low tides, the pH in the back-reef is higher during the day and lower during the night, likely due to an imbalance between CO_2 consumption (photosynthesis) and respiration. Temperature also rises and falls with the tide. We investigated linear extension growth rates between corals from a “highly-variable” pool (daily pH range from 8.31 to 7.78; 0.53 units) and a “moderately-variable” pool (daily pH range from 8.17 to 7.88; 0.29 units) and gene expression changes associated with large swings in pH and temperature during strong tides as compared to expression associated with smaller fluctuations during intermediate tides. Linear extension rates were measured using fluorescence microscopy and skeletal thin-sectioning of stained corals and gene expression analysis was conducted using high-throughput mRNA sequencing. These results are a first attempt at elucidating the impact that large, natural variation may have on coral physiology and fine-scale growth rates. Preliminary analysis suggests that the magnitude of daily environmental variability affects the amount of calcification as well as gene expression patterns over short time-scales.

Department of Biology, Stanford University, Hopkins Marine Station, 120 Oceanview Blvd., Pacific Grove, CA 93950, USA. gjrj@stanford.edu

RESPONSE OF A PLANKTONIC COMMUNITY TO OCEAN ACIDIFICATION IN THE OLIGOTROPHIC MEDITERRANEAN SEA
A. Sallon, C. Guieu, J.-M. Grisoni, F. Louis, J.-P. Gattuso, and F.Gazeau

A large-scale mesocosm experiment will be performed in the NW Mediterranean to investigate the response of key planktonic processes to ocean acidification. As a contribution to the European project “Mediterranean Sea Acidification in a Changing Climate” (MedSeA), this study will be carried out in

the oligotrophic waters of the Bay of Calvi (Corsica) in June and July 2012, thirty-seven researchers and students from eight countries will participate to this experiment.
Nine mesocosms (height 12 m, volume of ca. 52 m^3) will be deployed *in situ* for 4 weeks and subject to pCO_2 levels of 450, 550, 650, 750, 1000, 1250 µatm. The remaining three mesocosms will serve as controls. Many parameters and processes will be measured, among which the carbonate system, net and gross primary production (oxygen, ^{18}O, ^{14}C), community respiration (oxygen), nutrients, particle fluxes (sediment traps), physical speciation of chemical elements (P, N, Fe), nitrification, nitrogen fixation, bacterial production and respiration, POC – PON – POP, transparent exopolymeric particles (TEP), CDOM, zooplankton abundance, DMS, sea-air flux, impact on the microlayer. This poster will present an overview of this experiment as well as preliminary data.

Université Pierre et Marie Curie-Paris 6, Observatoire Océanologique de Villefranche-sur-Mer, France (sallon@obs-vlfr.fr) and CNRS-INSU, Laboratoire d'Océanographie Villefranche-sur-Mer, France

CARBON DIOXIDE IN A SUBTROPICAL BAY OF THE EASTERN PACIFIC OCEAN

Sámano-Rodríguez, Clara, Ramón Sosa-Ávalos, Aramis Olivos-Ortiz, Lidia Silva Iñiguez, and Juan Mimbela-López

Monthly samplings were carried out from December 2010 to December 2011 in seven stations in the Manzanillo Bay of Mexico. Carbon dioxide (CO_2) was calculated using the program CO_2 Sys in each station in four depths (surface, 10, 25 and 50 m). The highest averages in surface are observed of December 2010 to April, and the lowest of May to December 2011. The surface maximum was registers in April and the minimum in September with 2079.75 and 1668.28 µM/Kg, respectively. The vertical profiles show increase of CO_2 from the 10 m of depth of January to April, whereas of May to September is observed a slight increase through the water column. In June and July the CO_2 concentration is homogenous with the depth, as of September until December 2011 is observed a gradient concentration from 25m, having indicated stratification in the water column. The large changes with the depth are estimated in October and December 2011. In addition, the CO_2 presents temporal variation with significant differences ($P = 0.00$) between June, September and November with respect to the other months, as well as, the CO_2 has variation with the depth. The highest values of CO_2 are due to the shorts upwellings events of two or three days of duration, while the lowest values were estimated in summer when the temperature increase in the bay.

Facultad de Ciencias Marinas, Universidad de Colima. Km. 20 carretera Manzanillo-Barra de Navidad, Manzanillo. 28860, Mexico. rsosa@ucol.mx

JAPANESE PROJECT ON SOUTHERN OCEAN ACIDIFICATION - 1. PRESENT STATE ON THE VARIABILITY OF CO_2 AND CARBONATE PLANKTERS.

Sasaki, H.[1], F. Akiha[2], S. Suganami[3], S. Konno[4], H. Hattori[5], G. Hashida[6], T. Odate[7], A. Suzuki[8], W. Okoshi[9], and H. Yoshikawa[10]

The Southern Ocean is a substantial sink for atmospheric CO_2 to take up a large proportion of the anthropogenic carbon in global oceans. The extra CO_2 that dissolves in sea water reduces ocean pH. Ocean acidification also reduces saturation states (Ω) of calcium carbonate due to the decrease of the carbonate ion concentrations. Thus the fate of aragonite calcifiers in the Southern Ocean is of particular interest, because they are likely to respond to ocean acidification. We have made oceanographic studies focusing on responses of Antarctic marine ecosystems on ocean acidification as part of the JARE (Japanese Antarctic Research Expedition) in 2011/2012. The target sea area was primarily 40-65^{O}S along 110^{O}E in the Indian Sector of the Southern Ocean. Successive oceanographic observations were made from early December to March with the "Shirase" and "Umitaka-maru". We will show the outline of this study and the preliminary results on the present state on variations of CO_2 in sea water, and shelled (thecosomatous) pteropods which is one major group of aragonite producers. One of the present results shows that the biomass of shelled pteropods can be comparable to that of herviborous crustacean zooplankton during a short period in late summer. It suggests that they have an important role in carbon cycling in the Antarctic ecosystem more than expected.

[1] Department of Bioengineering, Senshu University of Ishinomaki, Ishinomaki, 985-8580, Japan (sasaki@isenshu-u.ac.jp)
[2] Graduate School of Science & Engineering, Senshu University of Ishinomaki, Ishinomaki, 985-8580, Japan
[3] Graduate School of Science & Engineering, Senshu University of Ishinomaki, Ishinomaki, 985-8580, Japan
[4] Graduate School of Science & Engineering, Senshu University of Ishinomaki, Ishinomaki, 985-8580, Japan
[5] Department of Biological Sciences, Tokai University, Sapporo, 005-8601, Japan
[6] National Institute of Polar Research, Tokyo, 190-8518, Japan
[7] National Institute of Polar Research, Tokyo, 190-8518, Japan
[8] Graduate School of Agriculture, Tohoku University, Sendai, 981-8555, Japan
[9] Graduate School of Agriculture, Tohoku University, Sendai, 981-8555, Japan
[10] Graduate School of Earth & Environmental Sciences, Hokkaido University, Sapporo, 060-0810, Japan

HIF-1A GENE EXPRESSION IN THE EMBRYO OF RED SEA BREAM, *PAGRUS MAJOR*, EXPOSED TO HYPOXIA AND HYPERCAPNIA DURING SOMITOGENETIC STAGE

Sawada, Yoshifumi, Yasuo Agawa, and Tomoki Honryo

Fish survival during early life, from embryos to juveniles, has a major impact on their natural population dynamics, and malformations during this period have a profound adverse effect on their survival and on their future biomass consequently. Large scale human-induced hypoxic and hypercapnic condition has a possibility of profound impact on fish population dynamics through malformation incidence in their early life. In fact, our previous study has revealed in several fishes that a short term exposure to extreme hypoxia and hypercapnia induces the same abnormalities in somite segmentation during embryonic stage, which advances to defects of centra in juveniles and adults. In this study, we investigated the common embryologic mechanism, especially the molecular one, of somitic disturbance in red sea bream, which is a representative fish in the Far Eastern coastal water, embryos exposed to hypoxia and hypercapnia. We examined the HIF-1α gene expression in embryos at somitegenesis exposed to these conditions, because HIF-1α protein is well known to increase in quantity in the tissues exposed to hypoxia as the defensive response to the hostile environment of it. In the embryos exposed to both conditions at somitegenesis, the HIF-1α gene expression did not increase at the absolute amount whereas it increased at the relative amount to that of β-actin gene. This suggests the relative increase of HIF-1α gene expression, which is responsible for its downstream major morphogenetic gene expressions, is a key factor in the common embryologic mechanism of fish somitic disturbance in embryos exposed to hypoxia and hypercapnia.

Fisheries Laboratory of Kinki University, Ohshima 1790-4, Kushimoto, Wakayama 649-3633, Japan (yoshifumi.sawada@kindaisuiken.jp)

LESSONS LEARNED FROM DATA-MODEL SYNTHESES OF MESOCOSM ACIDIFICATION PERTURBATION EXPERIMENTS

Schartau, Markus[1] and Tom van Engeland [2]

Field mesocosm experiments typically exhibit great variability in their response to different carbon dioxide (CO_2) concentrations. In our presentation we show model results of the first Pelagic Ecosystem CO_2 Enrichment Study (PeECE-I, 2001) and demonstrate that small variations in initial plankton composition can explain most of the variability observed. Our model results disclose difficulties in separating a CO_2-induced physiological effect from variations in plankton composition. From our data-model synthesis we learned that the modeled physiological calcification response to ocean acidification determines only a small fraction of the observed variability in biogenic calcium carbonate precipitation. This entails large uncertainties in model projections of changes in algal calcification due to ocean acidification. Thus, model results are required to be very well constrained, in order to improve the credibility of future scenario projections. Results from an extensive model sensitivity study, based on a Markov-Chain Monte-Carlo method, reveal that many model parameter values cannot be estimated with sufficient accuracy, given data typically available. We will discuss possibilities of reducing model complexity and we will provide feedback information for experimental scientists, as we summarize types of measurement needed as valuable constraints for modeling mesocosms.

[1] Helmholtz Zentrum Geesthacht (HZG), Centre for Materials- and Coastal Research, Max-Planck-Strasse 1, D-21502, Geesthacht, Germany (markus.schartau@hzg.de)
[2] NIOZ Yerseke, The Centre for Estuarine and Marine Ecology, Korringaweg 7, 4401 NT Yerseke, The Netherlands

REPRODUCTIVE SUCCESS AND INDIVIDUALITY IN AN ACIDIC OCEAN

Schlegel, Peter[1], Jon Havenhand[2], and Jane Williamson[1]

Due to rapid oceanic acidification, marine organisms are facing a strong selection pressure against susceptible genotypes, particularly during early life stages. This selection for resistant individuals is likely to drastically change population composition with unknown fitness consequences. The potential of inter-individual variation to mediate selection responses in changing environmental conditions, however, remains to be tested.
We investigated the impact of ocean acidification on fertilization kinetics of one sea urchin species and one polychaete species, focussing on response levels of single individuals rather than pooled group means. Acidification significantly decreased percentage sperm motility in both species, but sperm speed was only impacted in polychaetes. Fertilization was not significantly impacted, but both species displayed large, significant differences between individual responses, ranging from large decreased fertilization success to slightly increased fertilization. Thus, reproductive success will be enhanced for some individuals under acidified conditions. These results support the often proposed concept of 'winners' and 'losers' of climate change on an inter-individual level, yet fitness consequences remain unclear as traits that covary with acidification-resistance might not be beneficial across the entire life cycle.

[1] Department of Biological Sciences – Marine Ecology Group, Macquarie University, Sydney NSW 2109 (peter.schlegel@mq.edu.au)
[2] Department of Marine Ecology, Gothenburg University, S-40530 Goeteborg, Sweden

CORAL GROWTH AND METABOLIC RESPONSE TO NATURAL VARIATIONS OF ARAGONITE SATURATION AND TEMPERATURE DUE TO APERIODIC UPWELLING EVENTS

Schmidt, Gertraud M.[1], Marlene Wall[1], Carin Jantzen[1], Dirk de Beer[2], and Claudio Richter[1]

The structural complexity of tropical coral reefs derives from coral calcification which entails high energetic costs for the corals and is particularly vulnerable to ocean acidification (OA). The photosynthetic carbon dioxide fixation by zooxanthellae (symbiotic unicellular dinoflagellates) accounts for the high productivity of tropical corals and the energy needed to sustain high aragonite saturation levels at the sites of calcification. Increasing OA will enhance this imbalance and further rise energetic costs. Thresholds and tipping-points, where corals are no longer able to afford the energetic expenses for calcification in response to OA, are only poorly understood. Marginal reefs subjected to large amplitude internal waves (LAIW) provide a natural laboratory to study these processes at short temporal scales due to frequent, aperiodic upwellings of cold (drops of up to 10 °C), nutrient rich (up to 12-fold for nitrate and nitrite concentrations), and low-aragonite saturation waters (down to Ω_{AR} 1.77). Corals exposed to LAIW showed reduced calcification rates, despite a higher energetic status and enhanced pigment concentrations in their coral tissue. They were found to grow on basement rock in the absence of a three-dimensional carbonate framework. The massive coral *Porites lutea*, abundant at the high-LAIW impacted sites, served as the main study organism and was further investigated in the laboratory. LAIW conditions were simulated (i.e. drops of temperature, pH and Ω_{AR} respectively) while oxygen and pH dynamics were measured simultaneously on the coral surface with microsensors. The impact of LAIW on photosynthesis and respiration may then be related to calcification.

[1] Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, Germany
[2] Max-Planck-Institute for Marine Microbiology (MPI), Bremen, Germany

INFERENCES ON THE GLACIAL DEEP-OCEAN CARBON RESERVOIR BASED ON EXTRAPOLATION OF THE MODERN Δ^{14}C-DIC RELATIONSHIP TO PEAK GLACIAL VENTILATION AGES

Schneider, Birgit[1], Michael Sarnthein[1], and Pieter M. Grootes[2]

To effect a deglacial atmospheric CO_2 rise on the order of 100 ppm, paralleled by an increase in the terrestrial carbon reservoir, a transfer of 500-700 Gt C is required. This amount is usually attributed to carbon release from the deep ocean, although the actual mechanisms remained elusive, since an adequately old and carbon-enriched deep-ocean reservoir seemed unlikely. In the present study we use a new Δ^{14}C data set of peak glacial deep ocean reservoir ages, showing that during the Last Glacial Maximum (LGM) the Δ^{14}C age difference between ocean deep waters and the atmosphere exceeded the modern values by up to 1500 ^{14}C yr. Today, the Δ^{14}C ventilation appears directly linked to the concentration of dissolved inorganic carbon (DIC) below 2000 m depth. Using a range of modern Δ^{14}C-DIC relationships, derived from different ocean basins to extrapolate the deep ocean carbon reservoir to an average LGM aging by ~600 yr, results in an increased reservoir of 730-980 Gt DIC. This amount can also explain a reduction of carbon storage in the shallow to intermediate ocean caused by a lower atmospheric partial pressure of CO_2, without requiring major reorganizations of ocean circulation patterns.

[1] Institute of Geosciences, University of Kiel, Germany (bschneider@gpi.uni-kiel.de)
[2] Leibniz Laboratory for Radiometric Dating and Isotope Research, Kiel, Germany

THE EFFECT OF HOLOTHURIANS (SEA CUCUMBERS) ON $CaCO_3$ DISSOLUTION ON A CORAL REEF.

Schneider, Kenneth[1], Jacob Silverman[2], Ben Kravitz[1], Erika Woolsey[3], Aya Schneider Mor[4], Sergio Barbosa[5], Tanya Rivlin[6], Maria Byrne[5], and Ken Caldeira[1].

Holothurians (sea cucumbers) are among the largest and most important deposit feeder in coral reefs. They play a role in nutrient and $CaCO_3$ cycling within the reef structure. As a result of their digestive process they secrete alkalinity due to $CaCO_3$ dissolution and organic matter degradation forming ammonia. In a survey at station DK13 on One Three Reef we found that the population density of holothurians was > 1 individual m^{-2}. The dominant sea cucumber species *Holothuria leucospilota* was collected from DK13. The increase in alkalinity due to $CaCO_3$ dissolution in aquaria incubations was measured to be 47±7 mol kg^{-1} in average per individual. Combining this dissolution rate with the sea cucumbers concentrations at DK13 suggest that they may account for a dissolution rate of 34.9±17.8 mmol m^{-2} day^{-1}, which is equivalent to about half of night time community dissolution measured in DK13. This indicates that in reefs where the sea cucumber population is healthy and protected from fishing they can be important in the $CaCO_3$ cycle. Preliminary result suggests that the $CaCO_3$ dissolution rates are not affected by the chemistry of the sea water they are incubated in. The primary parameter determining the $CaCO_3$ dissolution by sea cucumber is the amount of carbonate send in their gut. This suggests that sea cucumber dissolution in the future is not expected to change due to ocean acidification, but as calcification diminishes the proportion of $CaCO_3$ dissolved by Holothurians in the coral reefs may increase.

[1]Carnegie Institution, Department of Global Ecology, 260 Panama Street, Stanford, CA 94305, USA (Kennysch@carnegie.stanford.edu).
[2]Israeli Limnology and Oceanography institute, Tel Shikmona, Haifa, 31080, Israel.
[3]Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia.
[4]Department of Geology and Environmental Sciences, Stanford University, 367 Panama street, Stanford, CA., 94305, USA.
[5]Schools of Medical and Biological Sciences, University of Sydney, New South Wales 2006, Australia.
[6]Inter University Institute for Marine Sciences, P. O. Box 469, Eilat 88103, Israel.

USING A RIM BETWEEN TWO LAGOONS TO ESTIMATE REEF COMMUNITY METABOLISM AT ONE TREE REEF, GREAT BARRIER REEF.

Schneider, Kenneth[1], Jacob Silverman[2], Ben Kravitz[1], Julia Pongratz[1], Kate Ricke[1], and Ken Caldeira[1]

Reef community metabolism has been estimate in several studies in the past, but with ocean acidification and increased sea surface temperatures there is a need to establish base line measurements that can be repeated to monitor the changes that are occurring and to build understanding that will allow us to predict the future of these reefs. We have identified an area of coral reef creating a boundary "border" between two lagoons in the One Tree Reef, Great Barrier Reef. At low tide the One Tree Reef lagoons are isolated from the open ocean. Due to physical barriers between the lagoons there are height differences between them imposing a unidirectional flow depending on whether the tide is incoming or outgoing. Three transects along this border were sampled during low

tide periods for 12 days, the water depth above the reef was on average ~12 cm, average water velocity was ~1.3 cm s^{-1} and the length of the transects were around 30 m enough to produce a measurable alkalinity change ranging between 20 and 90 µmol kg^{-1} between the station located on the rim near the two lagoons, depending on the part of the day the low tide occurred. The average calcification rates for the 3 different sites were between 141 and 254 µmol $CaCO_3$ m^{-2} d^{-1}. The predictability of the flow and the low water volume crossing this reef transect at low tide periods make it an attractive area to monitor reef calcification rates and conduct reef metabolism studies.

[1]Carnegie Institution, Department of Global Ecology, 260 Panama Street, Stanford, CA 94305, USA (Kennysch@carnegie.stanford.edu).
[2]Israeli Limnology and Oceanography institute, Tel Shikmona, Haifa, 31080, Israel.

CORAL CALCIFICATION UNDER ELEVATED *p*CO_2 AND TEMPERATURE: A COMPARISON OF THE BUOYANT WEIGHT AND ALKALINITY ANOMALY METHODS

Schoepf, Verena[1], Xinping Hu[2], Andrea G. Grottoli[1], Wei-Jun Cai[2], Mark E. Warner[3], Todd Melman[4], Hui Xu[2], Qian Li[2], Yongchen Wang[2], Kenneth Hoadley[3], D. Tyler Pettay[3], Justin Baumann[1], and Yohei Matsui[1]

Interactive effects of elevated *p*CO_2 and temperature on coral calcification are poorly understood. This is further complicated by the use of two different methods commonly used to measure coral calcification: the buoyant weight and alkalinity anomaly methods. Here, we provide the first direct comparison of both methods. *Acropora millepora, Montipora monasteriata, Pocillopora damicornis, Turbinaria reniformis* were reared under a total of six treatments for three weeks, representing three *p*CO_2 levels (400, 620,775 ppm) and two temperature regimes (26.5, 29.0°C) within each *p*CO_2 level. Calcification was measured for each fragment using both the buoyant weight method (BW) and total alkalinity (TA) incubations during day and night. System calcification, where all 4 species of one treatment were pooled, was calculated based on both BW and TA changes in the sump of each system. Results from our pilot study show that TA-based calcification was typically higher by ~20% than BW-based calcification but showed overall similar patterns. In contrast, system calcification based on TA changes in the sump overestimated calcification by one order of magnitude, indicating that other processes such as nutrient uptake and/or non-coral calcification influenced TA. The comparison of these methods will be repeated in a similar experiment using a more sophisticated method to get a better understanding of what caused the observed differences. Overall, calcification only decreased in one species, but increased or did not change in all other species in response to high temperature and high *p*CO_2, suggesting that some corals may be more resilient than previously thought.

[1] School of Earth Sciences, The Ohio State University, Columbus, OH 43210, USA (schoepf.4@osu.edu)
[2] Department of Marine Sciences, University of Georgia, Athens, GA 30602, USA
[3] School of Marine Science and Policy, University of Delaware, Lewes, DE 19958, USA
[4] Reef Systems Coral Farm, New Albany, OH 43054, USA

ON THE USE OF METABOLISM AS A MEASURE OF OCEAN ACIDIFICATION IMPACT

Seibel, Brad A.

Organismal metabolism, typically measured as a rate of oxygen consumption, is a complicated metric that includes the sum costs of all energy intensive processes and activities. It may be a sensitive indicator of organismal stress but the interpretation of changes in metabolism is not straightforward.

Here I provide information on the factors known to (and those known not to) influence metabolism, synergism between those factors, the direction of the expected response, and the mechanisms leading to a response. I review important methodological requirements for the measurement of metabolism. I provide examples of metabolic changes that result from synergistic effects of temperature, oxygen, feeding history, body size, environmental history and acidification.

Biological Sciences, University of Rhode Island, Kingston, RI 0289, USA. seibel@uri.edu

POTENTIAL BIOLOGICAL PH BUFFERING EFFECT AND REGIME SHIFT

Seto, Mayumi[1], Wada Shigeki[2], and Masao Ishii[3]

pH is one of the factors that influence the growth and photosynthesis of phytoplankton, whilst phytoplankton alter surrounding pH in many ways. For instance, photosynthesis increases pH due to the disturbance of chemical carbonate equilibrium, reaching pH above 9. Here we consider whether ocean acidification can affect not only the growth and/or species composition of phytoplankton but also its biological effect on pH.
We use a simple mathematical model in order to explore a feedback between phytoplankton and pH in response to a rise of partial pressure of carbon dioxide. pH of the model is mainly determined by carbonate species and photosynthesis and respiration of phytoplankton.
Photosynthesis can potentially moderate the sensitivity of average pH to changes in the partial pressure of carbon dioxide ($\Delta pH_{bio}/\Delta CO_2$), in comparison with the predicted sensitivity of average pH in chemical equilibrium ($\Delta pH_{abio}/\Delta CO_2$). We call this biological effect on pH "biological buffering effect". Biological buffering effect might not be observed when other factors (e.g., essential nutrients and/or light) limit the growth of phytoplankton. The strong biological buffering effect tends to be accompanied by bi-stability of the system, which implies that a stochastic change in phytoplankton population may trigger a regime shift and hysteretic response of pH. Possible species succession due to the acidification also can alter the biological pH buffering effect.

[1] G310, Nara Women 's University, Kita-Uoya Nishimachi, Nara 630-8506, Japan. (seto@ics.nara-wu.ac.jp)
[2] Shimoda Marine Research Center, Tsukuba University, Shimoda, Shizuoka 415-0025, Japan.
[3] Geochemical Research Department, Meteorological Research Institute, Nagamine 1–1, Tsukuba 305–0052, Japan.

STUDIES OF CARBON DIOXIDE AND RELATED VARIABLES IN RED SEA SURFACE WATER AND FIRST ESTIMATE FOR THE RED SEA ACIDIFICATION

Shaltout, Nayrah, Mohamed A. Sheradah, and Mamdouh A. Fahmy

Carbon dioxide system and related parameters were studied seasonally at 22 stations in Red Sea during 2010 and 2011. These samples represent Suez Gulf, Aqabah Gulf and Red Sea as a first studies for carbon system and air sea flux, to the best of our knowledge, in the Egyptian Red Sea coast. pH ranged between 8.16 at Suez Gulf to 8.20 at Red Sea and Aqaba Gulf. Alkalinity varied between 2242µmol.Kg^{-1} Sw during March 2011 to 2673 µmol.Kg^{-1} Sw. Red Sea surface water showed salinity fluctuated between 39.2 during March and 41.615 in July 2011. Carbonate saturation profile showed minimum value at March 6.87 for calcite and 4.5 for aragonite while the maximum was at July 8.12 for calcite and 5.42 for aragonite. Average Carbon dioxide Fugacity in surface water was ranged between 299.44 µtam in March

2011 and 353.78µatm in July while atmospheric carbon dioxide concentration was varied between 388.8 µatm in September 2010 and 393.28 µatm in March 2011.
In General Red Sea surface water showed under saturation of carbon dioxide with respect to the atmosphere and it act as a sink of carbon dioxide from atmosphere which varied seasonally and showed an average flux of carbon dioxide from the atmosphere to sea water about -39±12 $\mu mol.m^{-2}.d^{-1}$
Acidification was estimated for the study area using measurements of Salinity and Temperature by applying different models then estimating the acidification of Red Sea since 1970 corresponding to atmospheric carbon dioxide increase.

National Institute of Oceanography and Fisheries, Alanfoshi Quitbay, Alexandria, Egypt
(nshaltout@gmail.com)

EFFECTS OF OCEAN ACIDIFICATION ON CORAL COMMUNITIES OF ST. MARTIN'S ISLAND, BANGLADESH
Sharifuzzaman, S.M., S.R. Chowdhury, and M.S. Hossain

Carbon dioxide is releasing in the atmosphere at increasingly rapid rates since the industrial revolution. Ocean being the earth's largest carbon reservoir and a sink, this is directly changing the seawater chemistry toward more acidic state, a phenomenon called 'ocean acidification'. An increased acidity is particularly adverse for organisms using calcium carbonate to build their protective shells/skeletons, e.g. corals, calcareous plankton, etc. Ocean acidification coupled with elevated temperature regime acts as one of the most dreaded triggers for the infamous 'coral bleaching'. The coral communities of Bangladesh, representing 66 species of hard corals which are found only at St. Martin's Island, are currently stressed with pressure from resource exploitation, sedimentation and pollution. However, future ocean acidification will even worsen the situation by hampering the calcification, reducing the growth rates and reproductive capacity, and decreasing the structural strength of coral reefs. Such outcomes are anticipated to affect the species abundance, composition and distribution of corals. Consequently shifts may occur in the make-up of marine biodiversity as reefs provide habitats for numerous species by providing them spawning, nursery and feeding grounds. In particular, 86 reef fish species of the St. Martin's Island may face probable extinction. These untoward changes will have significant implications for food production and the livelihoods of thousands of islanders. Moreover, tourism dependent business enterprises of this unique coral island might come to cease. Altogether, loss of substantial direct ecosystem services and economic activities might become an immediate reality, if reefs disappear. Most of these issues are complex, poorly understood and difficult to predict, and virtually nothing has been studied in Bangladesh regarding the risks of ocean acidification and the fate of corals in the future.

[1] Institute of Marine Sciences and Fisheries, University of Chittagong, Chittagong 4331, Bangladesh
(sharifuzaman@yahoo.com)

EFFECTS OF LOWER pH ON THE GROWTH IN EARLY DEVELOPMENT STAGE OF PACIFIC OYSTER, *CRASSOSTREA GIGAS*
Shim, JeongHee and Jeongro Kwon

Lower pH environment induced by uptake of anthropogenic carbon dioxide (CO_2) threatens the viability of calcifying and young marine organisms due to decrease of calcification and increase of environmental stress. The Pacific oyster, *Crassostrea gigas* provides the largest mass/economic production among

industries of coastal aquaculture in Korea, with annual production of about 2.8×10^5 ton and 200 billion KW in 2011. The survival and growth of juvenile oyster is the keystone for an abundant harvest in oyster industry and has serious consequences on one of important marine food resources. To understand the impacts of ocean acidification on juvenile oyster, a circular culturing system is made with precise pH controlling by CO_2 injection and 3-steps of water tanks (activator, reservoir and incubator). Juvenile oysters sampled at Nulcha area in estuarine of Nakdong River, South coast of Korea, were incubated for 40 days at four different pH levels (7.6, 7.8, 8.0 and 8.2). The weight increasing rate was reduced when oyster was grown at lower pH with respect to normal pH. The growth rates at 7.6 and 7.8 were 6.5% and 34% lower as compared to pH 8.2. The declined growth rate in low pH was detected after 15days of incubation. These results indicate that the high-CO_2 world in future will negatively affect the population, production and thus, industry of oyster aquaculture. We will discuss in more detail on the impact of ocean acidification on growth and calcification of juvenile oyster through mesocosm culture experiments and monitoring shells with SEM techniques.

Marine Environment Research Div., NFRDI, Gijang, Busan, South Korea (jshim@nfrdi.go.kr).

VALIDATION OF AN INORGANIC CALCIFICATION RATE EQUATION FOR CORAL REEF COMMUNITY CALCIFICATION

Silverman, Jacob[1], Kenny Schneider[2], Jonathan Erez[3], Boaz Lazar[3], David Kline[4], and Ken Caldeira[2]

In a recent study it had been predicted that the calcification rate of most coral reefs around the world should have decreased already by 20-40% relative to their preindustrial rates. This prediction was made based on an inorganic calcification rate equation as a function of temperature and $\Omega_{arag.}$(G_i), which were shown to agree well with measurements of net community calcification (G_{net}) of a coral reef in the northern Red Sea.

During 2008-2009 we measured G_{net} on reef flats in Lizard Island and One Tree Island, GBR in order to validate the equation for G_i. Both sites had been the focus of previous reef metabolism studies during the 1960-70's that used the same geochemical approach used in the current study. In 2008 and 2009, G_{net} in the Lizard Island and One Tree Island sites were 31%-45% lower than the rates measured during the 1960-70's. The G_{net} values measured in this study correlated well with their corresponding G_i values estimated from the temperature and Ω_{arag} measured during each study. This result validates the application of the inorganic rate equation in other coral reefs around the world. In addition, the similarity between the predicted decrease and the measured decrease in G_{net} suggests that ocean acidification may already be significantly affecting $CaCO_3$ precipitation in coral reefs.

[1] Institute for Oceanographic and Limnological Research, Haifa, Israel
[2] Carnegie Institution, Department of Global Ecology, Stanford, CA, USA
[3] The Fredy and Nadine Herrman Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel (boaz.lazar@huji.ac.il)
[4] Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

IMPACT OF MEDIUM-TERM EXPOSURE TO CO_2 ENRICHED SEAWATER ON THE PHYSIOLOGICAL FUNCTIONS OF THE VELVET SWIMMING CRAB, *NECORA PUBER*

Small, Daniel[1,2], Samuel Rastrick[1,2], Nathan Atkinson[1], Lucy Turner[1], Steve Widdicombe[2], John Spicer[1], and Piero Calosi[1]

Ocean acidification (OA) is predicted to play a major role in shaping species biogeography and marine biodiversity over the next century. Moreover, potential leaks from Carbon Capture and Storage (CCS) pipes pose a threat to marine biota. In two studies we have tested the effect of medium-term exposure to OA and CCS leakage scenarios on the survival and physiological functions of the velvet swimming crab *Necora puber*.
A suit of physiological proxies (oxygen uptake, haemolymph acid-base balance and ionic regulation, activity, feeding rates, gill Na^+/K^+ATPase, carapace mineralisation, and upper thermal tolerance (UTT)) were measured after 30 d exposure to elevated pCO_2 conditions (pH 8.00, 7.70, 6.90). We only see an effect of OA as a decrease in feeding rates after 30 days. *Necora puber* was able to buffer extracellular pH, with no evidence of net shell dissolution, thus demonstrating that HCO_3^- is actively taken up from the surrounding water. However, haemolymph pH did decrease under CCS levels. Under CCS scenarios the energetics of *N. puber* appear compromised, with maintenance costs associated with buffering activity increasing (shown by elevated gill Na^+/K^+ATPase activity and increased haemolymph [Ca^{2+}] and [HCO_3^-]) despite a reduction in total energy availability (shown by decreased oxygen uptake and feeding). This decrease in energy availability is also associated with reduced activity and net weight loss that may impact on organism fitness and performance. *N. puber* can tolerate medium term exposure to OA with minimal changes in physiological function, however is severely compromised when exposed to CCS leakage scenarios.

[1] Marine Biology and Ecology Research Centre, Plymouth University, Drakes Circus, Plymouth, PL4 8AA, UK (daniel.small@plymouth.ac.uk)
[2] Plymouth Marine Laboratory, Prospect Place, West Hoe, Plymouth, PL1 3DH, UK

DOES OCEAN ACIDIFICATION SHOW ANY EFFECT ON SHELL GROWTH AND MICROSTRUCTURE OF THE LONG LIVING BIVALVE *ARCTICA ISLANDICA*?

Stemmer, Kristina, Gernot Nehrke, and Thomas Brey

The boreal bivalve *Arctica islandica* is an important tool for paleoclimate reconstruction; geneticists are interested in the longevity of the clam; and the Canadian clam chowder would not taste as good without it. The shell is made out of 100% aragonite, a less stable calcium carbonate polymorph besides calcite. We want to see weather ocean acidification will affect shell growth, microstructure and state of the $CaCO_3$ polymorph.
We incubated *A. islandica* at 380 μatm, 760 μatm and 1120 μatm pCO_2. Bivalves were marked with the fluorescent dye calcein at the start of the experiment. After 90 days shells were embedded, cut and polished. Growth was measured from the end of the calcein mark to the outer shell margin. Shell microstructure was analyzed by means of Scanning Electron Microscopy and $CaCO_3$ polymorphs were identified by Confocal Raman-Spectroscopy.
We find no significant effect of CO_2 exposition on shell growth in *A. islandica*. Furthermore, CO_2 exposition did neither affect calcium carbonate polymorph composition nor size, shape or distribution of the granulate biocrystals the shell is composed of.

[1] Alfred Wegener Institute for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany (kristina.stemmer@awi.de)

LONG TERM OCEAN ACIDIFICATION: FORECASTING THE FUTURE AND EXPERIMENTAL CONSIDERATIONS FOR LIFE-CYCLE APPROACHES

Suckling, Coleen C.[1,2], Melody S. Clark[1], and Lloyd S. Peck[1]

Our oceans are already acidifying yet we still know little about how this will affect marine biota, or the differences between species from different global regions. Much literature reports varying responses of organisms to ocean acidification (OA) but have largely utilized short exposure times and focussed on limited parts of the life-cycle. Early life-stage studies generally utilized gametes and/or offspring obtained from parents maintained in ambient conditions and then immediately introduced to altered seawater-pH. These therefore preclude the effects of altered seawater-saturation levels on gonad development and adult acclimation effects.
We challenge these early-life stage laboratory approaches by using temperate exemplified model-organisms. Here we will present our results of larval success to juvenile-stages arising from rapid or slow introduction to forecasted seawater-pH. We also present the short to long-term (weeks-years) physiological/reproductive impacts of exposing parent invertebrates to present and forecasted OA (~1000 ppm CO_2) for polar and temperate species. Some studies on fast developing temperate species have indicated room for plasticity. However slower development of polar organisms, almost paralleling the time process of OA, coupled with poor abilities to acclimate to small increases in temperature raise concern over polar organismal acclimative/adaptative abilities.
When approaching one of the biggest questions of this century, 'How will organisms respond to a changing climate?' we provide examples on whether: i) careful consideration is needed when studies report the responses of offspring, derived from ambient conditions, introduced directly to forecasted OA conditions; ii) there is room for acclimation and adaptation in the future.

[1] British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge, CB3 0ET, UK (colckl@bas.ac.uk; coleenclaire@yahoo.co.uk)
[2] Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, UK.

EFFECTS OF *P*CO_2 AND IRON ON ELEMENTAL COMPOSITION OF DIATOM *PSEUDO-NITZSCHIA PSEUDODELICATISSIMA*

Sugie, Koji and Takeshi Yoshimura

Partial pressure of CO_2 (pCO_2) and iron condition varies due to biological and anthropogenic activities. However, we have very little data about interactive effects of these factors on phytoplankton physiology and stoichiometry. Here we investigated the effects of pCO_2 and iron on the elemental composition of diatom *Pseudo-nitzschia pseudodelicatissima* using the dilute batch method under four pCO_2 (~180, ~380, ~600 and ~800 µatm) and five dissolved inorganic iron (Fe': ~5, ~10, ~20, ~50 and ~100 pmol L^{-1}) conditions. Net nutrient uptake rate per unit surface area increased with the increase in Fe' for all elements whereas it decreased with the increase in pCO_2 for C, P and Si. The C:N ratio decreased significantly with Fe' whereas C:P ratio increased significantly with pCO_2. The Si:C and Si:N ratios decreased with the increase in Fe' and pCO_2. Our results indicate that pCO_2 and iron availability can influence the biogeochemistry of nutrients in future high-CO_2 oceans and similarly for present

phytoplankton blooms and the past earth history in which pCO_2 and iron conditions dramatically change over seasonal and geological time scales.

Central Research Institute of Electric Power Industry, 1646 Abiko, Abiko, Chiba, 270-1194, Japan. (kojisugie@gmail.com)

EFFECTS OF LOW pCO_2 CONDITIONS ON SEA URCHIN LARVAL SIZE

Suwa, Ryota[1], Tomoyuki Nakano[1], Yukihiro Nojiri[2], Tsuneo Ono[3], and Yoshihisa Shirayama[4]

The phenomenon of ocean acidification is a result of the increase in atmospheric carbon dioxide (CO_2) concentrations, and its impact on marine species is predicted in the future. By the end of this century, atmospheric pCO_2 level will double relative to pre-industrial level (280 ppm). However, the effects of the pCO_2 concentrations such as pre-industrial and near-future levels (pCO_2 of less than 600 ppm) remain largely unexamined in marine organisms. In the present study, we examined the effects of those low pCO_2 levels on larvae of the sea urchins *Hemicentrotus pulcherrimus* and *Anthocidaris crassispina* using a high-accuracy CO_2 manipulation system.

The results showed that the larval size of both species was significantly larger when reared at the pre-industrial pCO_2 level relative to present and/or near future levels. In addition, pCO_2 increase of +200 ppm (500 ppm) from the preindustrial pCO_2 level (300 ppm) decreased *A. crassispina* larval size for 10.1% while pCO_2 increase of +200 ppm (600 ppm) from the present pCO_2 level (400 ppm) showed no effect.

Our findings suggest that predicted impacts of ocean acidification on the calcifiers in the future are already appearing in the present. It is also suggested that the observed effects of 200 ppm pCO_2 change between 300 and 500 ppm do not guarantee same effect on larval size when larvae were exposed to 200 ppm pCO_2 increase from 400 ppm. These suggestions may become important information for considering whether 550 ppm CO_2 stabilization scenario is appropriate.

[1] Seto Marine Biological Laboratory, Field Science Education and Research Center, Kyoto University, 459 Shirahama, Wakayama 649-2211, Japan (ryota@zenno.jp)

[2] Center for Global Environment Research, National Institute for Environmental Studies, 16-2, Onogawa, Tsukuba, Ibaraki 305-8506, Japan

[3] Stock Enhancement and Fisheries Oceanography Division, Hokkaido National Fisheries Research Institute, Fisheries Research Agency, 116 Katsurakoi, Kushiro, Hokkaido 085-0802, Japan

[4] Japan Agency for Marine-Earth Science and Technology, Headquarters, 2-15 Natsushima, Yokosuka, Kanagawa 237-0061, Japan

SYMBIOSIS INCREASES TOLERANCE OF ACROPORA CORAL TO OCEAN ACIDIFICATION

Suzuki Atsushi[1], Shun Ohki[2], Takahiro Irie[2], Mayuri Inoue[3], Takashi Nakamura[4], Kazuhiko Sakai[2], Hodaka Kawahata[3], Yukihiro Nojiri[5], and Robert van Woesik[6]

Increasing the acidity of ocean waters will directly threaten calcifying marine organisms such as reef-building scleractinian corals, and the myriad of species that rely on corals for protection and sustenance. Ocean pH has already decreased by around 0.1 pH units since the beginning of the industrial revolution, and is expected to decrease by another 0.2 – 0.4 pH units by 2100. This study mimicked the pre-industrial, present, and near-future levels of pCO_2 using a precise control system (± 5% pCO_2), to assess the impact of ocean acidification on the calcification of recently-settled primary polyps of *Acropora*

digitifera, both with and without symbionts, and adult fragments with symbionts. The increase in pCO_2 of 100 µatm between the pre-industrial period and the present had more effect on the calcification rate of adult *A. digitifera* than the anticipated future increases of several hundreds of micro-atmospheres of pCO_2. The primary polyps with symbionts showed higher calcification rates than primary polyps without symbionts, suggesting that (i) primary polyps housing symbionts are more tolerant to near-future ocean acidification than organisms without symbionts, and (ii) corals acquiring symbionts from the environment (i.e. broadcasting species) will be more vulnerable to ocean acidification than corals that maternally acquire symbionts.

[1]Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8567, Japan (a.suzuki@aist.go.jp)
[2]Tropical Biosphere Research Center, University of the Ryukyus, Okinawa 905-0227, Japan
[3]Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa 277-8564, Japan [4]Faculty of Science, University of the Ryukyus, Nishihara, Okinawa 903-0213, Japan
[5]Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan
[6]Department of Biological Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA.

COMPARISON WITH CARBON DATA SYNTHESES IN THE PACIFIC OCEAN

Suzuki, Toru, Masao Ishii, Tsuneo Ono, Takeshi Kawano, Masahide Wakita, Lisa Miller, Akihiko Murata, Ken-ichi Sasaki, James Christian, and Robert M. Key

The PACIFICA, Pacific Ocean interior carbon, is carbon data synthesis as one of activities of Section on Carbon and Climate of PICES in order to clarify the distribution and several decadal changes of both natural and anthropogenic inorganic carbon and the related parameters in the Pacific Ocean. The PACIFICA consists of WOCE and CLIVAR hydrographic cruise, Line P and other time series cruises in the Western North Pacific since 1990's mainly, and recommended adjustment values for dissolved inorganic carbon, alkalinity, salinity, nutrients and dissolved oxygen for each cruises. Although WOCE cruises are overlapped with GLODAP, their adjustment values were re-estimated by secondary quality control procedures in according with CARINA. From comparison with the result of GLODAP and PACIFICA, the distribution and variation of inorganic carbon and progress of ocean acidification in the Pacific Ocean were updated.

Marine Information Research Center, Japan Hydrographic Association, 1-6-6-6F, Hanedakuko, Ota-ku, Tokyo 144-0041, Japan, suzuki@mirc.jha.jp
Meteorological Research Institute, Japan
National Research Institute of Fisheries Sciences, Fisheries Research Agency, Japan
Japan Agency for Marine-Earth Science and Technology
Mutsu Institute for Oceanography, Japan Agency for Marine-Earth Science and Technology
Institute of Ocean Sciences, Fisheries and Oceans Canada
Japan Agency for Marine-Earth Science and Technology
Mutsu Institute for Oceanography, Japan Agency for Marine-Earth Science and Technology
Canadian Centre for Climate Modelling and Analysis, Fisheries and Oceans Canada
Department of Geosciences, Princeton University

EVOLUTION ALONG A VARIABLE COASTLINE: DO DIFFERENCES IN LIFE HISTORY, PHENOTYPIC PLASTICITY, AND LOCAL ADAPTATION DRIVE ORGANISMAL RESPONSE TO INCREASING CONCENTRATIONS OF CO_2?

Swezey, Daniel S., Eric D. Sanford, and Brian P. Gaylord

Recent studies in the marine environment have found that phenotypic plasticity and local adaptation play important roles in the dynamics of marine invertebrate populations. The way in which these phenomena act to shape marine species' responses to global change stressors is largely unknown. Bryozoans, a group of predominantly calcifying colonial invertebrates found in abundance along the temperate coasts of North America, provide an ideal study system for investigating the impacts of ocean acidification (OA). Many west coast bryozoan species occur along a gradient of persistent variation in upwelling intensity, which may impose selection pressures on populations in terms of sensitivity to elevated pCO_2. With a newly constructed CO_2 injection apparatus that uses digital mass flow controller technology, we are testing several hypotheses with species of west coast bryozoans:

1. Populations of the bryozoans *Celleporella sp.* and *Membranipora sp.* will show reduced survival, growth, and calcification in response to future OA.
2. Bryozoans will exhibit variable degrees of plasticity in the form of $CaCO_3$ incorporated into their colonial skeletons under future OA.
3. Reductions in growth will be variable among different populations of bryozoans. This difference results from local adaptation to upwelling conditions.
4. OA "starves" bryozoans by increasing proton pumping demands at the site of calcification, which increases organismal energetic demand.
5. OA will alter interspecific space competition hierarchies among bryozoan species.

Bodega Marine Laboratory and Department of Evolution and Ecology, University of California at Davis, 2099 Westshore Road, Bodega Bay, CA 94923, USA (dsswezey@ucdavis.edu)

THE EFFECT OF NEAR FUTURE OCEAN ACIDIFICATION SCENARIOS ON FECUNDITY AND FERTILITY OF THE COPEPOD *CALANUS FINMARCHICUS*

Tagliati, Alice[1], Iurgi Salaberria[2], Ole Jacob Håkedal[2], Liv Marie Gustavson[2], Dag Altin[3], Anders J. Olsen[2], and Sindre A. Pedersen[2]

The present research focuses on the potential effects of near future ocean acidification scenarios on the copepod *Calanus finmarchicus*. Given the key role of this species in North Atlantic food webs, any negative effects of elevated CO_2 levels could have a significant impact on the entire ecosystem. Previous studies have focused predominantly on the effects of acute short term exposure on adult copepods. Thus, there is a need to investigate the effects of more realistic CO_2 concentrations on all life stages and on consecutive generations. In the present study, pregnant *C. finmarchicus* females exposed for two subsequent generations to different CO_2 regimes were incubated individually to investigate egg laying and hatching success on a daily basis. The CO_2 exposure levels included 380 ppm: present day scenario; 1080 and 2080 ppm: predicted respectively at the end of the century and in a worst-case scenario in the year 2300; and 3080 ppm: positive control treatment. In a parallel experiment, eggs of females with the same CO_2 exposure histories were incubated for 72 hours under different CO_2 conditions to reveal potential acclimation and adaption to elevated partial pressure of CO_2 in seawater. Preliminary results suggest that the reproductive performance of *C. finmarchicus* is affected by elevated CO_2 levels, showing reduced egg laying rates at higher CO_2 concentrations. The results will be incorporated into a state of the art model tool to predict population level effects using different CO_2 emission scenarios.

[1]Deparment of Life Sciences and Environment, Università Politecnica delle Marche, via Brecce Bianche, 60131, Italy (alice.tagliati@gmail.com)
[2]Department of Biology, Norwegian University of Science and Technology, N-7491 Trondheim, Norway
[3]BioTrix, N-7022 Trondheim, Norway

INVESTIGATING THE IMPACT OF OCEAN ACIDIFICATION ON BIOFILM FORMATION AND LARVAL RECRUITMENT IN THE FIELD

Tait, Karen, Tom Vance, Helen Parry, and Steve Widdicombe

Settlement panels that incorporate gas permeable membranes were designed to study the impact of increased CO_2 on biofilm formation and succession in the field. Each panel consisted of a 3 mm thick PVC backing panel, 5 mm gas space, 5 mm reinforced silicone polymer membrane and a 3 mm thick PVC gasket to seal the layers of the unit. The exact pressure required to produce a drop of 0.3 pH units was carefully calibrated in laboratory experiments under varying hydrodynamic regimes. The panels were immersed in a fully marine tidal embayment at a depth of 1 meter and randomly assigned one of three treatments: ambient pH (not supplied with gas), ambient pH (supplied with ambient atmospheric air) and 0.3 pH units below ambient (supplied with CO_2 at pressure). At 2, 4, 6, 8 and 12 weeks after deployment, 5 replicate panels of each treatment type were randomly selected and the microbial component analysed. Measurements of biofilm wet weight, biofilm coverage and 16S rDNA gene copies mm^{-2} were all significantly lower on panels supplied with CO_2 than the panels receiving no gas and air. T-RFLP analysis also indicated changes to the bacterial community exposed to CO_2. The impact of each treatment on invertebrate larval recruitment is currently being investigated using combinations of microscopy and molecular biology.
Plymouth Marine Laboratory, Prospect Place, Plymouth, PL1 3DH (ktait@pml.ac.uk)

IMPACT OF OCEAN ACIDIFICATION ON EARLY DEVELOPMENT OF ECONOMICALLY VALUABLE GASTROPODS

Takami, Hideki[1], Toshihiro Onitsuka[2], Ryo Kimura[3], and Tsuneo Ono[4]

Commercially valuable shellfish species will be affected more seriously by ocean acidification (OA) in conjunction with overfishing. Here we investigated the effects of OA on fertilization, larval development, metamorphosis, and post-larval growth of valuable gastropods; Ezo abalone *Haliotis discus hannai*, small abalone *H. diversicolor* and turban shell *Turbo cornutus*, using a highly accurate CO_2 manipulation system. There were no effect of exposure to <1000 ppm pCO_2 seawater observed in fertilization, malformation, or mortality rates in *H. discus hannai* and *T. cornutus.* However, fertilization and hatching rates decreased with exposure to >1500 ppm pCO_2 seawater. The malformation rates at >1000 ppm increased significantly, and the diameter of larval shells from >800 ppm was significantly smaller compared to those in control seawater (400-450 ppm pCO_2) in both species. The elevated pCO_2 did not affect the percentage of larvae metamorphosing into post-larvae in *H. discus hannai* and *H. diversicolor*. Shell growth rates of post-larval *H. discus hannai* at >1500 ppm were significantly reduced compared with those at <1000 ppm. Scanning electron microscope images of post-larval shells from >1000 ppm showed abnormal development suggesting problems with shell deposition and/or increased shell dissolution. These results indicate that pCO_2 >1000 ppm reduced developmental performance of these gastropods in early life stages.

[1] Tohoku National Fisheries Research Institute, Fisheries Research Agency, 3-27-5, Shinhama, Shiogama, Miyagi 985-0001, Japan (htakami@affrc.go.jp)
[2] Hokkaido National Fisheries Research Institute, Fisheries Research Agency, 116, Katsurakoi, Kushiro, Hokkaido 085-0802, Japan.
[3] Fisheries Research Agency, 15F Queen's Tower B, 2-3-3, Minato Mirai, Nishi-ku, Yokohama, Kanagawa 220-6115, Japan.
[4] National Research Institute of Fisheries Science, Fisheries Research Agency, 2-12-4, Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648, Japan.

EFFECTS OF ACIDIFICATION ON THE CALCIFICATION PROCESS OF THE CORAL *STYLOPHORA PISTILLATA*

Tambutté, Eric[1], Michael Holcomb[1*], Alexander Venn[1], Didier Zoccola[1], Silke Ruffing[2], Cédric Patapy[2], Denis Allemand[1], and Sylvie Tambutté[1]

Coral reefs are among the most biologically diverse and economically important ecosystems on the planet. Coral reefs are being affected by the rapid increase in the atmospheric carbon dioxide concentration which drives ocean acidification. Calcification of the main reef builders, the scleractinian corals, is one of the physiological processes that can be affected by ocean acidification. When looking at the literature, it now appears that the response of corals varies depending on the species. The reason for this variability is yet unknown certainly because the process of calcification itself is still poorly understood. By applying defined scenarios of acidification, we aimed to identify mechanisms causing changes at cellular to organismic levels of biological organization related to the calcification process. The study was performed in the laboratory on the tropical scleractinian coral *Stylophora pistillata*. This experiment was a long term experiment which lasted one year during which we have regularly monitored the seawater chemistry under 4 different pH conditions and different aragonite saturation states with increasing levels of pCO_2. All the coral nubbins survived the experiment and grew skeleton even at aragonite saturation states < 1. We have analyzed different parameters which are known to be linked to the calcification process: tissue biomass, morphology and porosity of skeletons, rates of calcium incorporation and photosynthesis, organic matrix content and composition. Our results show the physiological response of corals at different scales of observation.

[1] Centre Scientifique de Monaco, Avenue Saint-Martin, 98000 Monaco. etambutte@centrescientifique.mc
[2] Laboratory of Construction Materials, Ecole Polytechnique Fédérale de Lausanne, CH-1015, Lausanne, Switzerland
[3] Centre Commun de Microscopie Appliquée, Faculté des Sciences, Parc Valrose, 06208 Nice Cedex 2, France
*present address: ARC Centre of Excellence in Coral Reef Studies, School of Earth and, Environment & Oceans Institute, The University of Western Australia, 35 Stirling Highway , M004, Crawley, WA 6009

METABOLIC BALANCE OF A PLANKTON COMMUNITY IN ARCTIC COASTAL WATERS IN RESPONSE TO INCREASED PCO_2

Tanaka, T.[1,2], S. Alliouane[1,2], K. G. Schulz[3], and J.-P. Gattuso[1,2]

The effect of ocean acidification on the balance between gross community production (GCP) and community respiration (CR) (i.e. net community production, NCP) of Arctic plankton communities was investigated in summer 2010 at Ny-Ålesund, Spitsbergen. Coastal surface water, which was

characterized by low concentrations of nutrients and chlorophyll, was enclosed in 9 mesocosms and subjected to 8 pCO_2 levels (2 replicated controls and 7 enhanced pCO_2 treatments) for one month. Nutrients were added to all mesocosms on day 13 of the experiment. No clear trend in response to increasing pCO_2 was found in the daily values of NCP, CR, and GCP. The cumulative NCP significantly decreased with increasing pCO_2 after the nutrient addition. CR was relatively stable throughout the experiment in all mesocosms. As a result, the cumulative GCP (the difference between NCP and CR) significantly decreased with increasing pCO_2 after the nutrient addition. While the nutrient addition on day 13 induced an increase in phytoplankton biomass in all mesocosms, the ratios of NCP to NO_3 consumption tended to be smaller at higher pCO_2 levels, suggesting alterations of stoichiometric C and nutrient coupling in response to increasing pCO_2 levels. The results suggest that elevated pCO_2 reduced the capacity of the plankton community to use the nutrient consumed for increasing NCP, and ocean acidification may reduce planktonic NCP and GCP in Arctic coastal waters.

[1] CNRS-INSU, Laboratoire d'Océanographie de Villefranche, BP 28, 06234 Villefranche sur Mer cedex, France (gattuso@obs-vlfr.fr)
[2] Université Pierre et Marie Curie-Paris 6, Observatoire Océanologie de Villefranche, 06230 Villefranche sur Mer cedex, France
[3] GEOMAR, Düsternbrooker Weg 20, 24105 Kiel, Germany

COMBINED EFFECTS OF OCEAN ACIDIFICATION AND TEMPERATURE ON THE PRODUCTION OF DISSOLVED ORGANIC MATTER BY PHYTOPLANKTON AND ITS UTILIZATION BY BACTERIA

Taucher, J.[1], A. James[2], U. Riebesell[1], and U. Passow[2]

Dissolved organic matter (DOM) plays a major role in marine biogeochemical cycles, with more than 90% of organic carbon in the ocean occurring as dissolved organic carbon (DOC). However, little is known about potential impacts of sea surface warming and ocean acidification – and especially their combined effects - on production and degradation processes of DOC.
To address these questions, we are conducting experiments where the effects of temperature and increasing pCO_2 concentrations on the build-up of DOC and its utilization by bacteria are investigated. Since these two processes are usually tightly coupled, our goal is to experimentally separate production of DOC by phytoplankton and its utilization by bacteria.
The presented DOC build-up experiment was carried out with diatom cultures under pCO_2 levels of 400 and 1000 µatm, each at temperatures of 10, 15, 20, and 25 °C. The experimental design minimized bacterial activity and DOC contamination. Phytoplankton cultures were acclimatized to the respective environmental conditions in semi-continuous batch cultures for at least a week. Afterwards, the cultures were incubated in translucent polyethylene bags (20 L) under target temperature and pCO_2 conditions with no headspace. Phytoplankton cultures in all treatments were run into nitrogen limitation (initial NO_3: 20 µmol), where the most pronounced build-up of DOC occurs. We monitored phytoplankton abundance and fluorescence, build-up of DOM and POM and their respective composition, accumulation of transparent exopolymer particles (TEP), the carbonate system and bacterial activity. The bioavailability of the generated DOM for natural bacteria populations was investigated in a follow-up experiment.

[1]Helmholtz Centre for Ocean Research Kiel (GEOMAR), jtaucher@geomar.de
[2]Marine Science Institute, University of California Santa Barbara

THE UTILITY OF SPECTROPHOTOMETRIC PH DETERMINATION FOR PIGMENTED BIOLOGICAL FLUIDS

Taylor, Josi R., Eric F. Pane, Kurt R. Buck, and James P. Barry

Studies of acid-base physiology in aquatic animals require accurate methods for measuring pH of intracellular and extracellular fluids, often in small (ca. 200 µl) volumes. Spectrophotometric pH determination is precise and accurate for analyses of water samples, compared to traditional potentiometric methods, but may be unsuitable for analysis of biological fluids due to interference by suspended or dissolved pigmentation. We determined the threshold absorbance for 3 wavelengths (434, 578, 750 nm) where spectrophotometric pH measurements were biased by sample pigmentation. Using the pH indicator dye *m*-cresol purple, 578 nm was the most sensitive wavelength to sample pigmentation, and must not exceed background absorbance (i.e., 0.01 AU or 1%) to achieve pH precision of 0.01 units using micro-modified spectrophotometry. Precision of 0.02 pH units requires absorbance <0.034 at 578 nm. Only two species tested, the brachiopod *Laqueus californianus*, and fragile pink sea urchin *Strongylocentrotus fragilis*, had extracellular fluids sufficiently unpigmented to meet the most stringent criteria (0.01 unit precision) for extracellular pH (pH_e) measurement via spectrophotometry. Intracellular pH (pH_i) determination by spectrophotometry was appropriate only for samples prepared from poorly vascularized, negligibly pigmented tissue including molluscan foot, and fish white muscle. We recommend great care be taken in using spectrophotometry to measure fine-scale changes in pH_e and pH_i, ensuring samples meet absorbance criteria to achieve the desired precision. A background scan of sample absorbance must be conducted to determine suitability of a sample for spectrophotometric pH determination.

Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039, USA.
josi@mbari.org

STRUCTURAL PROPERTIES OF SOUTHERN OCEAN PTEROPODS

Teniswood, C.[1], D. Roberts[2], W. Howard[3], and J. E. Bradby[1]

Many sea creatures, including pteropods (marine snails), form carbonate mineral shells. The strength of such structures is predicted to be affected by changes in ocean chemistry caused by the increasing uptake of carbon dioxide from fossil-fuel emissions.

This study aims to determine the impact of ocean acidification on Southern Ocean pteropods via a detailed understanding of the structural properties of their shells. A set of pteropod samples collected under identical conditions is characterized to establish a baseline of mechanical properties.

The current mechanical strength of Southern Ocean pteropod shells is determined through nanoindentation – a process whereby the shells' mechanical properties, including the hardness and modulus, are calculated. Electron microscopy techniques assist in building a comprehensive understanding of the aragonite shell structure as well as the effects of sample preparation techniques. For example, the bleaching and drying process that is often used in the analysis of shells and other calcifying marine organisms appears to have a dramatic impact on the mechanical integrity of the calcareous structure, while the microstructure remains largely intact.

By creating a baseline of pteropod shell structural properties, the effect of ocean acidification can be measured on populations collected from water masses with changing chemical properties (including from different regions, the past and the future).

[1]Department of Electronic Materials Engineering, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 0200, Australia (clara.teniswood@anu.edu.au)

[2]Antarctic Climate and Ecosystems Cooperative Research Centre, Private Bag 80, Sandy Bay, Hobart, TAS 7001, Australia
[3]Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia.

$CaCO_3$ SATURATION STATE OF CHILEAN COASTAL WATERS: "$CaCO_3$ CORROSIVE WATER" IN COASTAL SYSTEMS

Torres, Rodrigo[1], Jorge Navarro[2], Patricio Manriquez[2], Silvio Pantoja[3], Maximo Frangopulos[5], Peter von Dassow[5], Carlos Duarte[6], Cristian Duarte[6], Nelson Lagos[7], Cristian Vargas[8], Marco Lardies[8], and Nolasca Valdez[1]

Carbon system parameters measured during several expeditions along the coast of Chile (23°S–56°S) in last decade are used to show the main spatial and temporal trends of $CaCO_3$ saturation state in the coastal waters of the eastern South Pacific. Chilean coastal waters are characterized by high variability in $CaCO_3$ saturation state, both in time and space. We found $CaCO_3$ corrosive waters (or almost corrosive water) in both upwelling and mesohaline coastal waters. However, both corrosive water masses present contrasting levels of DIC (maximum in recently upwelled waters and minimum in mesohaline coastal waters) and variable pCO_2 levels. We suggest that the ratio between $CaCO_3$ saturation state and pCO_2 could be an appropriate parameter to assess the vulnerability of these coastal systems due to rising of atmospheric CO_2.

[1] Centro de Estudios en Ecosistemas de la Patagonia, Universidad Austral de Chile, Ignacio Serrano 509, Coyhaique, Chile (rtorres@ciep.cl)
[2] Instituto de Ciencias Marinas y Limnológicas, Universidad Austral de Chile, Valdivia, Chile
[3] Departamento de Oceanografía, Universidad de Concepción, Concepción, Chile.
[4] Centro de Estudios del Cuaternario Fuego-Patagonia (CEQUA), Punta Arenas, Chile.
[5] Departamento de Ecología, Pontificia Universidad Católica de Chile, Santiago Chile.
[6] Departamento de Cambio Climatico, IMEDEA, Instituto Mediterráneo de Estudios Avanzados, Esporles, Mallorca, España.
[7] Universidad Santo Tomas, Santiago, Chile
[8] Centro EULA, Universidad de Concepción, Concepción, Chile.
[9] Facultad de Artes Liberales, Universidad Adolfo Ibañez, Santiago, Chile.

THE COPEPOD AND THE ACIDIFYING SEA: ROLE OF FOOD QUALITY AND ACIDIFICATION ON THE STRENGTH OF COPEPOD MATERNAL EFFECTS

Vehmaa, Anu[1], Andreas Brutemark[1,2], Anna-Karin Sandbacka[1], and Jonna Engström-Öst[1]

Organisms inhabiting a fluctuating environment (e.g. boreal coastal upwelling region) have to cope with both seasonal and sudden changes in pH; therefore they are probably, to some extent, able to cope with climate change induced pH changes. We have shown that copepod eggs develop faster if they are hatching in the same pH conditions as they were produced. This adaptive maternal effect implies that the mothers are able to adjust their eggs to perform better in the environment that they experience themselves. However, there are indications that the effect is dependent on the condition of the mother and the quantity and quality of her diet, which is also influenced by acidification. We hypothesized that copepod offspring development in a low pH environment is better when the mothers are provided with a balanced diet. Also, an increasing temperature can induce a stronger acidification effect, and thus increase the importance of maternal investments. We tested the hypothesis on a weekly basis in a

mesocosm experiment with 8 CO_2 treatments, ranging from ~180-1250 µatm. The study was executed in the Gulf of Finland, Baltic Sea in summer 2012.

[1] ARONIA Coastal Zone Research Team, Novia University of Applied Sciences and Åbo Akademi University, FI-10600 Ekenäs, Finland (anu.vehmaa@novia.fi)
[2] Tvärminne Zoological Station, FI-10900 Hanko, Finland.

OCEANOGRAPHIC MECHANISMS MEDIATING CHANGES IN BASELINE OCEAN ACIDITY OF FINE WATER LAYERS OFF WESTERN AUSTRALIA

Waite, Anya M.[1], Bronte Tilbrook[2], John Akl[2], Lars Stemman[3], Gaby Gorsky[3], Peter A. Thompson[2], Vincent Rossi[4,1], Andy Hogg[5], and Moninya Roughan[4]

Here we investigate the biogeochemical mechanisms driving creation of low pH layers in vertically interleaving water masses in the Eastern Indian Ocean off Australia. These water masses have been shown to impact directly the ecological function of Ningaloo Reef and other iconic coastal habitats. In particular, we describe the role of large (0.5 – 2 mm) sedimenting particles in creating fine low-pH (high pCO_2) layers, and the alignment of dissolved oxygen and nitrate profiles with ocean acidity. Mechanisms involve water mass dynamics and in-situ biogeochemical processes in three dimensions on and off the continental shelf. These are the first measurements of their kind in this region.

[1] The Oceans Institute, M047 University of Western Australia, Crawley 6009 WA, Australia (Anya.Waite@uwa.edu.au)
[2] CSIRO Wealth from Oceans National Research Flagship, Hobart, TAS Australia 7001
[3] Station Zoologique BP 28, 06234 Villefranche sur Mer, France
[4] Department of Mathematics and Statistics, University of New South Wales, Sydney, NSW Australia
[5] Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia

OCEAN ACIDIFICATION FROM 1997 TO 2011 IN THE SUBARCTIC WESTERN NORTH PACIFIC OCEAN

Wakita, Masahide[1,2], Shuichi Watanabe[1], Katsunori Kimoto[1], Makio Honda[1], Kazuhiko Matsumoto[1], Hajime Kawakami[1,2], Tetsuichi Fujiki[1], Kenichi Sasaki[1, 2], and Akihiko Murata[1]

Rising atmospheric CO_2 contents have led to greater CO_2 uptake by the oceans, lowering both pH and $CaCO_3$ saturation states due to declining carbonate ion (CO_3^{2-}). Here we found that pH in winter mixed layer calculated from total alkalinity (TA) and dissolved inorganic carbon (DIC) was decreasing at −0.0010 ± 0.0004 $pH_{in\ situ}$/yr from 1997 to 2011 in the western subarctic gyre; this region is a source of atmospheric CO_2 in winter due to vertical mixing of deep waters rich in DIC. This rate was lower than that expected from oceanic equilibration with increasing atmospheric CO_2 (−0.0021 pH/yr) and those in the subtropical regions (−0.0017 pH/yr; ALOHA, BATS, ESTOC), which is caused by the reduction of CO_2 emission in winter due to the increase of TA. Below the mixed layer, the calcite saturation horizon ($\Omega_{calcite}$= 1, ~185 m) only has shoaled at −2.9± 0.9 m/yr induced by declining CO_3^{2-} (−0.03 ± 0.01 µmol/kg/yr). Between 200 m and 300 m, the acidification (−0.0050 ± 0.0010 pH/yr) was the maximum in the open North Pacific (-0.004 $pH_{25°C}$/yr; NPIW, -0.003 $pH_{in\ situ}$/yr; ALOHA 250m). This enhanced acidification occurred below $\Omega_{calcite}$= 1 is influenced by oceanic CO_2 uptake and the increase of biological carbon remineralization due to AOU increase, which suggests the increase of dissolution of $CaCO_3$ particles.

[1] Mutsu Institute for Oceanography, Japan Agency for Marine-Earth Science and Technology, Mutsu, Aomori 035-0022, Japan (mwakita@jamstec.go.jp)
[2] Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Kanagawa 237-0061, Japan

THE INFLUENCE OF FRESHWATER-SALINE WATER MIXING ON PHYTOPLANKTON GROWTH AND SEAWATER ACIDIFICATION IN THE CHANGJIANG RIVER ESTUARY

Wang, Kui[1,2], Jianfang Chen[1], Jie Xu[3], Haiyan Jin[1], Hongliang Li[1] , Shengquan Gao[1], Yong Lu[1], and Daji Huang[1]

The distribution of nutrients, chlorophyll-a, pH, DO and salinity recorded in the June 2009 in the Changjiang Estuary indicated that the fresh-saline water mixing were the main factor controlling nutrient behavior. However, episodic algae bloom (maximum 7.16 mg/m^3) lead to oxygen super-saturation (maximum 120%) and pH anomaly (maximum 8.35) at the plume. To better understand the influence of freshwater-saline water mixing on phytoplankton growth and hence the implication on nutrients and pH, two water samples were collected from the stations C1 and I10 which were from the freshwater and saline water end-members, then incubated in-situ with diluting portions by 100%, 75%, 50%, 25% and 0% for about 3 days. The results were as follows: (1) The lower the percentage of freshwater, the lower the growth rate and pH increase rate of phytoplankton during the exponential growth period, (2) Macronutrients were apparently consumed. PO_4^{3-} in the 100%, 75% and 50% dilution treatments were depleted within 48 h, suggesting that PO_4^{3-} limit phytoplankton growth below salinity of 26. (3) For the 100% treatment the DIN/P ratio doubled as PO_4^{3-} was consumed rapidly, while DIN decreased slowly. The DIN/Si ratio decreased to about 0.7 times the original level during the first 48 h, reflecting the lower initial DIN/Si value compared to the diatom uptake ratio (?DIN/?Si) during the incubation period. The results demonstrated the mixing processes may cause algae blooms which episodically change nutrient structure, biological DIC uptake and pH increase, hence will improve the estuarine seawater buffer capacity for ocean acidification.

[1] Laboratory of Marine Ecological Systems and Biogeochemistry, Second Institute of Oceanography, State Oceanic Administration, Hangzhou, 310012, China (wang.kui@msn.com)
[2] Department of Geoscience, Zhejiang University, Hangzhou, 310012, China
[3]Atmospheric, Marine and Coastal Environmental Program, the Hong Kong University of Science and Technology, Kowloon, Hong Kong

OCEAN ACIDIFICATION IN THE NORTHWEST ATLANTIC BETWEEN 2003 AND 2011

Wang, Zhaohui Aleck[1], Katherine Hoering[1], and Gareth Lawson[2]

Water-column carbonate chemistry was measured comprehensively during a recent ocean acidification (OA) cruise in August 2011 along the WOCE/CLIVAR A20 transect in the Northwest Atlantic. This study is a part of a larger OA project to use natural differences in carbonate chemistry between the North Atlantic and North Pacific Oceans to investigate potential effects of ocean acidification on the in-situ distribution and behavior of pteropods. Discrete samples of dissolved inorganic carbon (DIC), total alkalinity (TA), and pH samples from depths up to 3000m were collected and analyzed. The data were de-seasonalized and then compared to the data from the 2003 WOCE/CLIVAR A20 cruise to directly assess the ocean acidification rate. The decreasing rate of pH in the upper 200 m between 36 and 39°N has a mean value of ~0.001 pH units yr^{-1} (0 – 0 .003 pH units yr^{-1}). This rate is consistent with the

measurements at the Bermuda Atlantic Time-Series Study (BATS) station. However, the corresponding decrease of aragonite saturation state (Ω_A) is averaged at ~0.017 yr^{-1}, which is nearly 3 times of the decreasing rate observed at BATS. The shoaling of Ω_A horizon at a given value (e.g. Ω_A = 3.5) is also dramatic (>100 m) between 2003 and 2011. Efforts were taken to determine how much of these observed changes in carbonate chemistry are due to anthropogenic CO_2 invasion. The higher decreasing rate of Ω_A in the Northwest Atlantic is consistent with the strong CO_2 sink of the region.

[1] Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA, USA (email: zawang@whoi.edu)
[2] Biology, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA, USA

TRACE GAS CONCENTRATIONS UNDER HIGH CO_2 AND OCEAN ACIDIFICATION

Webb, Alison[1], Peter Liss[1], Frances Hopkins[2], Gill Malin[1], Claire Hughes[3], Roland von-Glasow[1], Phil Nightingale[2], and Stephen de Mora[2]

The human-induced increase in atmospheric carbon dioxide has led to an increase in oceanic carbon uptake and changes in seawater carbonate chemistry, resulting in lowering of surface water pH. Since the beginning of the industrial revolution, surface ocean acidity has increased by 30%. Dimethylsulphide (DMS) is a climatically important gas in the marine system. A product of marine algae, particularly the coccolithophores and dinoflagellates, it is the major natural route of sulphur into the atmosphere and therefore a major influence on biogeochemical climate feedbacks such as particle and cloud formation. Another important suite of trace gases with a marine biogenic source are the halocarbons. These act as greenhouse gases and undergo photochemical reactions with atmospheric ozone, as well as acting as an important part of the halogen cycling to the land from the sea. Previous studies have suggested a direct relationship between lowered seawater pH and changes in the production of these trace gases. This study aims to investigate this link further, through the use of both large-scale high CO_2 field experiments and laboratory culture studies. Our current data shows a reduction in DMS and greater variability in some halocarbon concentrations. Further research is planned to determine the trace gas concentrations in cyanobacterial-dominated environments under increased CO_2 and acidity, where it is hypothesised that halocarbon emissions will be more significant than in previous investigations. Any changes to these gas concentrations are likely to have a significant impact on the atmospheric cycling of these elements and on climatically important atmospheric reactions.

[1] University of East Anglia, Norwich, NR5 7TJ UK (alison.l.webb@uea.ac.uk)
[2] Plymouth Marine Laboratory, Plymouth, PL1 3DH, UK
[3] University of York, York, YO10 5DD, UK

ACCLIMATION OF THE COLD WATER CORAL *LOPHELIA PERTUSA* TO PREDICTED RISES IN ATMOSPHERIC CO_2 AND SEA TEMPERATURES

Wicks, Laura, Sebastian Hennige, and J. Murray Roberts

Cold-water corals are amongst the most three-dimensionally complex deep-sea habitats known and are associated with high local biodiversity. Despite their importance, little is known about how these communities will fare in the face of predicted future climate change in terms of their eco-physiology and functionality. Projected rises in atmospheric $p CO_2$ will reduce the oceanic pH and the availability of carbonate ions, and increased sea temperatures may perturb cold-water coral systems beyond their thermal limits. Currently, the single and synergistic effects of projected increases in atmospheric pCO_2 and sea temperatures upon the cold-water coral *Lophelia pertusa* are unknown. Studies to date have only examined *L. pertusa* response to either increased temperature or increased pCO_2 on short time scales. However, short-term studies may not reflect *L. pertusa* acclimation to synergistic stressors. Here, we present data on the effects of increased sea temperatures (by 3°C) and increased pCO_2, (750 and 1000ppm) upon the metabolism and growth of cold-water coral *Lophelia pertusa*, collected from the Mingulay Reef Complex, Scotland, UK. Results from short-term exposure to increased temperature and pCO_2 on freshly collected corals will be contrasted with current data from an ongoing 18-month experiment. Comparison of short and long-term data will help define the impact of ocean acidification and increased temperatures upon the growth, physiology and structural integrity of the reef framework forming coral, *Lophelia pertusa.*

Centre for Marine Biodiversity and Biotechnology, Heriot-Watt University, Edinburgh, EH14 4AS, UK
(l.wicks@hw.ac.uk)

BENTHIC INVERTEBRATES IN A HIGH CO_2 WORLD: WHAT DOES THE FUTURE HOLD?

Wicks, Laura and J. Murray Roberts

Ocean acidification has emerged as one the major drivers of 21st Century marine scientific research. Here we describe the current understanding of OA on benthic marine invertebrates, in particular the calcifiers thought to be most sensitive to altered carbonate chemistry. We describe the responses of benthic invertebrates to OA conditions predicted up to the end of the century, examining individual organism response through to ecosystem-level impacts. Research over the past decade has found great variability in the physiological and functional response of different species and communities to OA, with further variability evident between life stages. Over both geological and recent timescales, the presence and calcification rates of marine calcifiers have been inextricably linked to the carbon chemistry of the oceans. Under short-term experimentally enhanced CO_2 conditions, many organisms have shown trade-offs in their physiological responses, such as reductions in calcification rate and reproductive output. Additionally, carry-over effects from fertilisation, larval and juvenile stages, such as enhanced development time and morphological changes, highlight the need for broad-scale studies over multiple life stages. These organism-level responses may propagate through to altered benthic communities under naturally enhanced CO_2 conditions, evident in studies of upwelling regions and at shallow water volcanic CO_2 vents. Only by establishing which benthic invertebrates have the ability to acclimate or adapt, via natural selection, to changes from OA in combination with other environmental stressors can we begin to predict the consequences of future climate change for these communities.

Centre for Marine Biodiversity and Biotechnology, Heriot-Watt University, Edinburgh, EH14 4AS, UK.
(l.wicks@hw.ac.uk)

EXPERIMENTAL EXPOSURE SYSTEM DESIGNED TO STUDY THE EFFECT OF MULTIPLE VARIABLES ASSOCIATED WITH OCEAN ACIDIFICATION ON THE EARLY LIFE STAGES OF FEDERAL MANAGED MARINE FISH SPECIES.

Wieczorek, D., B. Phelan, R.C. Chambers, M. Poach, and Jennifer Samson

Conducting ocean acidification research in a laboratory setting can present many unique obstacles associated with facility location, water supply, water quality, ambient conditions, and experimental variables. These obstacles are often compounded when attempting to create ecologically/biologically relevant experimental conditions while still achieving standardized pH/pCO2 levels proposed by the ocean acidification research community. The NOAA/NMFS/JJ Howard Marine Lab at Sandy Hook NJ has designed a system for exposing a variety of fish species at different early life stages that is customizable to many different variables, in many different combinations. We have designed and implemented an experimental system that can accommodate a wide range of distinct values for multiple variables. Our large scale system utilizes a flow through design and has the ability to manipulate carbonate chemistry, temperature, salinity, flow rates, dissolved oxygen, as well as biogeochemicals like ammonium and sulfide. The system is continuously monitored by National Instruments LabVIEW™ software using Li-Cor (pCO2), Honeywell Durafet® probes (pH) and Omega® thermocouples (temp). Initial trials of this system successfully accommodated a five pH by five temperature experimental design, as well as a three by three design, both in triplicate. These trials utilized between 50 to 150 exposure containers with 50 to 400 eggs or larvae per container with additional capacity available. Throughout the trials, the system maintained distinct pH values ranging from 7.1(~500 ppm pCO_2) to 7.8 (~ 4000 ppm pCO_2) and temperatures ranging from 4 to 21 degrees C.

Northeast Fisheries Science Center, NOAA Fisheries Service, Highlands, NJ 07732.
Daniel.Wieczorek@noaa.gov),

THE PELAGIC RECORD OF OCEAN ACIDIFICATION

Williams, Maria C[1], Morten Andersen[1], Paul Bown[2], and Daniela N Schmidt[1]

The current rise in atmospheric pCO_2 and its subsequent dissolution in seawater is reducing the pH and $[CO_3^{2-}]$ of the oceans. Anthropogenic ocean acidification is widely expected to affect the ability of marine calcifying organisms to precipitate their $CaCO_3$ exoskeletons, though species specific responses are documented. The aim of this study is to determine whether historical changes in seawater $[CO_3^{2-}]$ and pH since the beginning of industrialisation have already had discernible impacts on two groups of calcifying plankton, coccolithophores and foraminifers in high latitude environments. We aim to document trends in both plankton groups at the same location to improve our understanding of response to ocean acidification in different species and groups of plankton.
The focus of the study is a marine sediment core from the Erik Drift, a drift deposit off the south coast of Greenland. $^{230}Th_{xs}$ was applied to identify changes in sediment drift as a result of regional dynamic bottom water currents and hence redeposition of the coccolithophores and alteration of their historical record of calcification. Lateral sediment transport can be determined by normalising the activity of ^{230}Th in the sediments to its production rate in the water column. We present down core analysis of plankton measurements for both the industrial record and the natural variability throughout the Holocene.

[1]School of Earth Science, University of Bristol, Wills Memorial Building, Queens Road, Clifton, Bristol, BS8 1RJ (Maricel.Williams@bristol.ac.uk)
[2] Earth Science, University College London, Gower Street, London WC1E 6BT

OVERVIEW OF THE UK OCEAN ACIDIFICATION RESEARCH PROGRAMME

Williamson, Phillip[1], Carol M. Turley[2], and the UKOA research community

The £12m UKOA research programme (2010-2015) involves over 120 scientists in 26 research laboratories across the UK, working closely with European partners and other relevant international activities. Seven multi-institute consortium projects address: variability in oceanic CO_2 uptake and trends for the future; ocean acidification feedback on the carbon cycle and climate; effects of palaeo-ocean acidification events; impacts of ocean acidification on upper ocean biogeochemistry, benthic ecosystems, and commercially important species; and socio-economic implications. Fieldwork is focussed on European shelf seas (research cruise in 2011), the Arctic (2012) and the Southern Ocean (2013), with associated modelling. Preliminary results will be presented on upper ocean pH variability, high-resolution modelling of carbonate chemistry in the Arctic, and longterm OA experiments on benthic invertebrates. UKOA is funded by the UK Natural Environment Research Council, the Department for Environment, Food and Rural Affairs, and the Department of Energy and Climate Change.

[1]UKOA Science Coordinator; NERC/University of East Anglia, Norwich, UK (p.williamson@uea.ac.uk)
[2]UKOA Knowledge Exchange coordinator; Plymouth Marine Laboratory, Plymouth, UK)

CHLOROPHYLL TIMESERIES IN THE CALIFORNIA CURRENT SYSTEM MEASURED THROUGH WAVELENGTH-SPECIFIC OPTICAL ATTENUATION

Wilson, Samuel, Uwe Send, and Mark Ohman

Measurements of phytoplankton taken in tandem with biogeochemical variables in the California Current System (CCS) can provide an understanding of the influence rising CO_2 levels have on the region's ecosystem dynamics. Studies show that increased pH can sometimes negatively affect calcifying organisms (e.g., coccolithophores), while increased CO_2 concentrations can be beneficial to other phytoplankton; the combined effects on chlorophyll concentrations are less known. Multidisciplinary mooring deployments in the CCS off Pt. Conception since November, 2008, provide measurements useful for such studies; at present, two multidisciplinary moorings CCE1 and CCE2 are being operated in the low salinity core of the California Current and the coastal upwelling regime, respectively. Wavelength-specific light attenuation between the surface and a depth below the deep chlorophyll maximum at five wavelengths provides a technique for differentiating the attenuation due to chlorophyll, Chromophoric Dissolved Organic Matter, and sea water. This technique arrives at a timeseries of vertically integrated chlorophyll concentrations in the upper water column. Direct comparisons with CalCOFI measurements and moored fluorometers show the validity of this method. Single-depth measurements are also made of pCO_2, pH, O_2, and NO_3 on the moorings.
These measurements provide connections between phytoplankton biomass, nutrient availability, and carbon parameters. While an understanding of the context of chlorophyll-bloom events is gained through the frequency of such measurements, the magnitude and sign of the influence carbon cycle parameters have on chlorophyll levels is most important. In an ocean with rising CO_2 concentrations, this is gained only through the use of long timeseries.

Scripps Institution of Oceanography, 9500 Gilman Dr., La Jolla, CA 92093, USA. (sjwilson@ucsd.edu)

B/CA IN *CIBICIDODES PACHYDERMA*: EXTENDING THE GLOBAL CALIBRATION TO DEPTHS SHALLOWER THAN 1000 METERS.

Wojcieszek, Dominika E.[1], Benjamin P. Flower[1], and Ryan P. Moyer[2]

The oceans uptake much of the anthropogenic carbon emitted to Earth's atmosphere, resulting in the acidification of ocean waters. Reliable paleo-reconstructions of seawater chemistry provide geologic context and insight into possible consequences of ongoing ocean acidification. Changes in seawater pH are balanced by the carbonate and borate buffer systems. Decreasing pH causes carbonate ($[CO_3^{2-}]$) and borate ($[B(OH)^-_4]$) ion concentrations to decrease. Because calcifying organisms uptake $B(OH)^-_4$, the relative abundance of B in marine calcite reflects the carbonate ion saturation state ($\Delta[CO_3^{2-}]$) and pH of the water in which calcification occurred. Recent studies indicate a linear relationship between benthic foraminifer B/Ca and $\Delta[CO_3^{2-}]$ at depths >1000 m. Because ocean acidification most immediately affects upper 1000 m of the water column, a reliable shallow water (<1000 m) carbonate chemistry proxy is required. We test the application of B/Ca in the epibenthic foraminifera *Cibicidoides pachyderma* as a shallow water $\Delta[CO_3^{2-}]$ proxy. Nine surface sediment samples were collected from a 150-1400 m depth transect along the West Florida Shelf (Panama City, FL to DeSoto Canyon). Bottom water pH values along the transect range between 7.82 and 8.12, corresponding to $\Delta[CO_3^{2-}]$ values between 35 and 200 μmol kg^{-1}. Preliminary data will establish the relationship between *C. pachyderma* B/Ca and measured $\Delta[CO_3^{2-}]$ variations along the depth transect. Our results will extend global benthic foraminifer B/Ca calibrations to depths shallower than1000 m, allowing important insights into ocean acidification in shallow (0-1000m) marine environments.

[1]College of Marine Science, University of South Florida, 140 7th Avenue South, St. Petersburg, FL 33701(dewojcieszek@mail.usf.edu).
[2]Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute, 100 8th Ave SE, St. Petersburg FL 33701 USA.

CARBON SYSTEM MEASUREMENTS AND POTENTIAL CLIMATIC DRIVERS AT A SITE OF RAPIDLY DECLINING OCEAN PH

Wootton, J. Timothy and Catherine A. Pfister

We explored changes in ocean pH in coastal Washington state, USA, by extending a decadal-scale pH data series, by reporting independent measures of dissolved inorganic carbon (DIC), spectrophotometric pH, and total alkalinity (TA), by exploring pH patterns over larger spatial scales, and by probing for long-term trends in environmental variables reflecting potentially important drivers of pH. We found that pH continued to decline in this area at a rapid rate, that our measurements of pH corresponded well to spectrophotometric pH measures and expected pH calculated from DIC/TA, and that TA estimates based on salinity predicted well actual alkalinity. Multiple datasets reflecting upwelling, including water temperature, nutrient levels, phytoplankton abundance, the NOAA upwelling index, and data on local wind patterns showed no consistent trends over the period of our study. Multiple datasets reflecting precipitation change and freshwater runoff, including precipitation records, local and regional river discharge, salinity, nitrate and sulfate in rainwater, and dissolved organic carbon (DOC) in rivers also showed no consistent trends over time. Dissolved oxygen did not decline over time, indicating that long-term changes did not result from shifts in contributions of respiration to pH levels. These tests of multiple potential drivers of the observed rapid rate of pH decline indicate a primary role for inorganic carbon and suggest that geochemical models of coastal ocean carbon fluxes need increased investigation.

Dept. Ecology & Evolution, University of Chicago, Chicago, IL, USA (twootton@uchicago.edu)

OBSERVING CYCLES, HYSTERESIS AND BUFFER IN OCEAN ACIDIFICATION PROCESSES.

Wouters, Noémie[1,2], P.J. Valayer[2], and H.N. Cabral[1]

In many fields the representation of response to stress is used to investigate possible hysteresis phenomena. Hysteresis research is important for management as a lag in response often differentiate a resilient from a brittle system. The ocean's natural capability to buffer CO_2 is a resilient system property that might be altered by the current rate of CO_2 emissions. When expressed in response-to-stress terms, the investigation of paleontological events such as PETM and MECO, might provide crucial understandings on buffer hysteresis related to altered carbonate chemistry. Moreover PETM and MECO are characterized by CO_2 increase at different rates, possibly influencing the shape of hysteresis curves. This paper therefore examined both evidence in carbonate chemistry and fossil life in the settings of response-to-stress graphics. Carbon-13 and carbonate content from published data of cores of PETM and MECO are compared in the light of this representation. It was found that rates indeed influenced the shape of hysteresis curves. Next harmonic analysis, previously applied as spectral analysis in more recent settings to corals and glaciations, are extended here to evidence lags in response to cyclic or multicyclic stressors. The tool of response-to-stress representations provided a simple, yet striking element of comparison between paleo-events, particularly in terms of lasting impact, and as a comparative perspective for the current CO_2 emission-related ocean acidification. It is proposed that harmonic analysis be systematically extended to climate related carbonate time series, revealing time responses to pH changes of various systems and calciferous taxa.

[1] Centro de Oceanografia, Faculdade de Ciências de Lisboa, Campo Grande, Lisboa, Portugal. nwouters@fc.ul.pt
[2] Biomim-Greenloop, Aalstraat 11-12, 1000 Brussels.

INFLUENCE OF CO_2 ON THE SIZE SCALING OF GROWTH RATE AND ELEMENTAL COMPOSITION IN MARINE DIATOMS

Wu, Yaping[1], Douglas A. Campbell, and Zoe V. Finkel

Physiological differences across species responses to changing pCO_2 and pH will lead to changes in the size and taxonomic composition of phytoplankton communities. We measured the growth enhancement and elemental stoichiometry (C:N:Si:P) of 5 marine diatoms ranging over six orders of magnitude in cell volume, growing under 3 pCO_2 levels: 190, 380, and 750 ppmv. Growth rates increased with $pCO_2$from 5-33%, with no significant changes in chlorophyll content. Growth enhancement due to pCO_2 increases with cell size. As a result the size-scaling exponent associated with mass-normalized growth rate decreases with increasing pCO_2. Elemental stoichiometry, C:N:Si:P, varies with $pCO_2$and cell size. With increasing pCO_2 the larger species show no systematic change in elemental stoichiometry but the three smaller species examined show increases in C:P, N:P, and C:Si. These results confirm that increasing pCO_2can alter both the elemental stoichiometry of phytoplankton biomass and increase phytoplankton growth rates, especially of larger diatoms.

[1] Xiamen University, B-606, Daxue Road 182, Xiamen,Fujian,China 361005. YapingWu@xmu.edu.cn
No address information provided for the co-authors

A MODEL STUDY OF LONG-TERM VARIABILITY OF OCEANIC CO_2 IN THE PACIFIC OCEAN

Xiu, Peng and Fei Chai

The ocean plays an important role in regulating global carbon cycle by taking up and releasing CO_2 from and to the atmosphere simultaneously. One challenge to understand the mechanisms regulating oceanic CO_2 is that the contemporary variability of CO_2 flux consists of an oceanic component and an anthropogenic component from the atmosphere. To evaluate these components, we propose a coupled modeling study in the Pacific Ocean. The physical model is based on the ROMS and the biogeochemical model is based on the CoSINE model. Two modeling studies were conducted. The first one is the control run forced with measured atmospheric CO_2 at Mauna Loa Observatory. The other one is a case run forced with the constant atmospheric CO_2 in 1958. Both of the runs are integrated from 1958 to 2010 with the same initial condition and wind, heat, and freshwater forcings. The results from the control run were compared with available in-situ measurements. Further analysis of the model results indicate the carbonate system in the Pacific Ocean has strong spatial and temporal variations in terms of sea pCO_2, pH, and aragonite saturation state. Long-term trends of these variables were also analyzed, which show conspicuous spatial variability that could be related to the local physical and biogeochemical conditions. We separated the total carbonate variations (control run) into the internal one (case run) and the forced one (anthropogenic) to investigate the pathway and penetration depths of the anthropogenic CO_2, as well as the individual contributions from the oceanic and the anthropogenic components.

School of Marine Sciences, University of Maine, Orono, Maine, USA 04469
peng.xiu@maine.edu

PHYSIOLOGICAL AND BIOCHEMICAL RESPONSES OF THE DIATOMS *THALASSIOSIRA PSEUDONANA* AND *SKELETONEMA COSTATUM* TO FUTURE PROJECTED OCEAN CHANGES

Xu, Juntian[1], Kunshan Gao[1], and David A. Hutchins[2]

Combined or interactive effects of multiple stressors or future climate change variables on phytoplankton are important to understand ecological influences of future ocean changes. We investigated the growth rates, chlorophyll and biogenic silicate, particulate organic carbon and nitrogen contents while growing two diatoms, *Thalassiosira pseudonana* and *Skeletonema costatum*, under different regimes of solar radiation and different levels of nutrients and pCO_2 (pH), to simulate reduced thickness of upper mixing layer that leads to increased light exposures and decreased transport of nutrients, CO_2 rise and pH decline. Present (claster 1), mid-(cluster 2) and end-century (cluster 3) scenarios were simulated following future projections based on IPCC A1F1 senario. Our results showed that the growth rates decreased by 8-18% under cluser 2 and by 79-82% under cluster 3; chl a contents by 44-58% and 73-83% correspondingly. Cellular particulate organic carbon (POC) significantly increased in both species, being 1.3-1.4 times and 1.4-2.1 times higher under cluster 2 and cluster 3, respectively, compared with the cells grown under cluster 1. But no significant difference was found in cellular particulate organic nitrogen (PON), leading to increased C/N ratio. The Bsi contents showed no significant difference in *T. pseudonana* but increased by 40% and 100% in *S. costatum* under cluster 2 and cluster 3, respectively. It appeared that enhanced stratification with ocean warming and ocean acidification can interact to influence the diatoms-related biogeochemical processes via affecting their growth and biochemical compositions, though ocean warming was not incorporated and species-specific differences were observed.

[1] State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, 361005, China (jtxu@xmu.edu.cn)
[2] Marine Environmental Biology, Department of Biological Sciences, University of Southern California, Los Angeles, USA

DISTRIBUTION AND TEMPORAL EVOLUTION OF THE MEDITERRANEAN SEA ANTHROPOGENIC CO_2 (C_{ant}) OVER THE PAST TWO DECADES

Yao, Koffi Marcellin[1], Olivier Marcou[2], Catherine Goyet[2], Véronique Gugielmi[2], Jean-Philippe Savy[2], and Franck Touratier[2]

Understanding the distribution and the temporal evolution of the oceanic anthropogenic CO_2 (C_{ant}) is of great importance in establishing changes in the ocean chemical and biological processes and predicting their potential environmental impacts. Using C_{ant} estimations in the Mediterranean Sea, Touratier and Goyet have shown that the concentration of C_{ant}, a fraction of the total inorganic carbon C_T, is increasing with respect to time for intermediate and deep waters in the eastern basin but is decreasing in the western basin, although C_T is increasing. They also revealed that the impact of the regional and large-scale pressures on the Mediterranean Sea modifies rapidly the distribution of the oceanic carbonate system key properties (pH; total alkalinity, A_T; C_T and CO_2 partial pressure, pCO_2).
An effort made to understand the temporal evolution of C_T from 1995 to 2011 at the DYFAMED site (north-western Mediterranean) showed that C_{ant} absorption is the key factor that governs the distribution of C_T in the upper seawater layer. The Western Mediterranean Sea surface waters are accumulating C_{ant} at a rate of 3.6 µmol kg^{-1} y^{-1}, inducing a significant annual pH drop of 0.002 units. In the context of invasion of C_{ant} and increasing acidification of the Mediterranean Sea, increasing the number of medium to long-term monitoring stations and including pH, C_T and A_T as core parameters for the next oceanographic campaigns are required for accurate estimates of the future acidification rates in the Mediterranean Sea.

[1] Centre de Recherches Océanologiques, BP V 18 Abidjan 01, COTE D'IVOIRE (ykmarco21@yahoo.fr)
[2] Université de Perpignan via Domitia, Laboratoire IMAGES EA 4218, 52 avenue Paul Alduy, 66860 Perpignan cedex, FRANCE

OCEAN ACIDIFICATION LIMITS TEMPERATURE-INDUCED POLEWORD EXPANSION OF CORAL HABITATS

Yara, Yumiko[1, 2], Meike Vog[3], Masahiko Fujii[1], Hiroya Yamano[2], Claudine Hauri[3], Marco Steinacher[4, 5], Nicolas Gruber[3], and Yasuhiro Yamanaka[1]

Increasing atmospheric CO_2 concentrations change the distribution of corals in various ways via global warming and ocean acidification. Poleward expansion of coral habitats is caused by rising sea surface temperatures in response to global warming. Lowered aragonite saturation states due to ocean acidification, on the other hand, presumably affect at first corals in colder waters at higher latitudes. Therefore, the future distribution of coral habitats is determined by the combined effects of global warming and ocean acidification. In this study, we estimated future potential effects of global warming and ocean acidification on coral distribution in seas close to Japan using four coupled global carbon cycle-climate models along with simplified indicators for coral habitats. The model results suggest that future coral habitats will be sandwiched between high temperature regions, where the frequency of coral bleaching is predicted to increase, and low aragonite saturation states, which will reduce calcification rates. Given the combined effects of global warming and ocean acidification, tropical-

subtropical coral communities around Japan are projected to experience conditions far outside their present range, and the area of tropical-subtropical coral habitats in Japan will reduce by half by the 2020s.

[1] Faculty of Environmental Earth Science, Hokkaido University, N10W5, Kita-ku, Sapporo, Hokkaido 060-0810, Japan (mfujii@ees.hokudai.ac.jp)
[2] Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
[3] Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, Zurich, Switzerland
[4]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[5]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

RELATIONSHIP BETWEEN AN INCREASE IN PH DUE TO UPTAKE OF CO_2 AND NITROGEN CONCENTRATION: PHYTOPLANKTON SPECIES DIFFERENCES

Yin, Kedong[1,2], Jianzhang He[1], Bin Gou[3], Siru Wang[3], and Wei-Jun Cai[4]

Ocean acidification is an emerging threat to ocean ecosystems. As atmospheric CO_2 is dissolved in seawater at the surface, dissolved CO_2 needs to go through phytoplankton before going to the deeper ocean. Phytoplankton take up CO_2 and raise pH, serving a buffering filter against effects of ocean acidification in the surface layer. As CO_2 is the chemical form taken up by phytoplankton, an increase in pH due to photosynthesis decreases the CO_2 concentration and thus, may limit phytoplankton uptake of carbon. We hypothesize that there are species differences among phytoplankton in the maximum pH that limits C uptake. As carbon uptake is coupled to nitrogen uptake, nitrogen concentrations also regulate the maximum pH. *Skeletonema costatum* and *Phaeodactylum tricornutum* were grown in batch culture to study the effects of different inorganic nitrogen concentrations on the change in pH. The results showed that the concentration of chlorophyll a and final pH of the two algae's media increased with the medium N concentration from 10 to 200μmol·L^{-1}. A significant linear relationship was observed between the change of pH and the consumption of inorganic N and a linear significant relationship was also found between the change of pH and the consumption of inorganic carbon.
[1] School of Marine Sciences, Sun Yat-Sen University, Guangzhou, China, 510275, (yinkd@mail.sysu.edu.cn)
[2] Environmental Futures Centre, Griffith University, Nathan QLD 4111, Australia
[3] State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, CAS, Guangzhou, China
[4] Department of Marine Sciences, The University of Georgia, Athens, GA 30602 USA

IMPACTS OF OCEAN ACIDIFICATION ON IRON-DEFICIENT PHYTOPLANKTON ASSEMBLAGES AND ORGANIC MATTER PRODUCTION IN OPEN SUBARCTIC WATERS

Yoshimura, Takeshi [1], Koji Sugie [1], Hisashi Endo [2], and Koji Suzuki [2]

Marine ecosystems will be exposed to rapid increase in seawater pCO_2 and corresponding acidification of the water. Ocean acidification can affect the physiology and ecology of phytoplankton including non-calcifying species. Their response to ocean acidification is a key criterion for understanding the future ecosystem. Here, we compiled data from CO_2 manipulation experiments using iron-deficient natural

phytoplankton assemblages in the Bering Sea and subarctic Pacific in summers of 2007–2009 conducted in the framework of the Japanese research project, the Plankton Ecosystem Response to CO_2 Manipulation Study (PERCOM). During the 5 to 14 day incubations under different pCO_2 conditions, no critical but minor changes in the size composition of the Chl-*a* biomass and in the relative contributions of diatoms and haptophytes to the Chl-*a* biomass were observed among the treatments in all experiments. On the other hand, we found some CO_2-dependent changes in particulate and dissolved organic matter production, and elemental ratios, although their trends were not consistent among the four experiments. The projected ocean acidification appears to induce complex responses of iron-deficient plankton ecosystems with spatiotemporal variations.

[1] Central Research Institute of Electric Power Industry, Abiko, Chiba 270-1194, Japan (ytakeshi@criepi.denken.or.jp)
[2] Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan

OCEAN ACIDIFICATION AND OCEANIC CHANGES OVER THE PAST 30,000 YEARS: PLANKTIC FORAMINIFERA AND CALCIUM CARBONATE PRESERVATION IN THE FRAM STRAIT

Zamelczyk, Katarzyna and Tine L. Rasmussen

Planktic foraminifera constitute a major group of the calcareous marine microplankton. Due to their high sensitivity to varying sea surface conditions, carbonate chemistry changes and preservation of their calcareous shells in sedimentary archives, they are one of the most prominent sources of knowledge on past changes in climate and ocean circulation. However, their shells are vulnerable to dissolution. Dissolution can alter the distribution patterns of the planktic foraminiferal species and change the trace element composition of foraminiferal calcite. The Fram Strait is one of the main oceanographic connections between the Arctic and the rest of the world ocean. The eastern Fram Strait is occupied by the warm and saline Atlantic waters, whereas the western Fram Strait is dominated by cold and fresher Polar water and sea-ice. The two different water masses generate two oceanic fronts, the Polar and the Arctic front, characterized by high primary production and abundances of planktic foraminifera. Three high time resolution sediment cores located below the Atlantic water masses reveal details of oceanographic and carbonate preservation changes in the Fram Strait from the Late Weichselian to the Present. The extent of dissolution was quantified using the mean shell weight of planktic foraminifera specimens, % of fragmentation, and $CaCO_3$ content. The results indicate that fossil planktic foraminifera in the Fram Strait are affected by selective dissolution. Very poor preservation occurs within highly productive areas along oceanic fronts. The reliability of paleoreconstructions based on planktic foraminiferal assemblages in this region is considerably reduced.

University of Tromsø, Department of Geology, Tromsø, Norway. katarzyna.zamelczyk@uit.no

RESEARCH TURNS TO ACIDIFICATION AND WARMING IN THE MEDITERRANEAN SEA

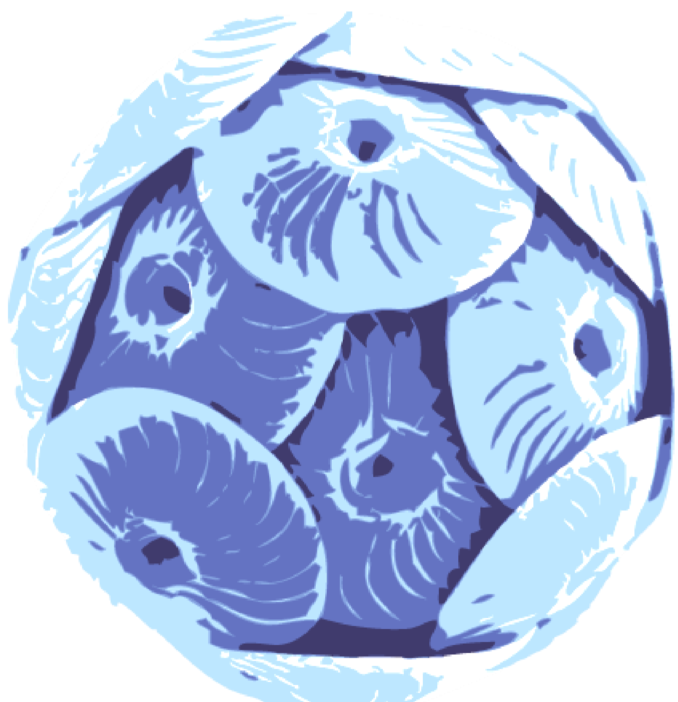
Ziveri, Patrizia, Rahiman Abdullah, and the MedSeA Consortium

The *Mediterranean Sea Acidification in a changing climate* (MedSeA) is a recently funded project of the European Commission (7th Framework Programme). It assesses uncertainties, risks and thresholds related to Mediterranean acidification and warming at organism, ecosystem and economic scales. Eighteen institutions from 11 countries, mainly bordering the Mediterranean, are collaborating in order to identify where the impacts of acidification on Mediterranean waters will be more severe, taking into

account the complete chain of causes and effects, from ocean chemistry through marine biology to socio-economic costs. As a practical outcome, it will propose policy measures for adaptation and mitigation that may geographically vary and at the same time require coordination between regions or countries. The total project budget is about € 6 M and it is co-financed by the European Community for € 3.5 M.
This project is the first one that aims to offer a comprehensive view on the physical, biological and socio-economic impacts of ocean acidification in the Mediterranean area using a so-called basin-scale approach. In addition, the results will allow us to identify particularly sensitive spots in the area and formulate effective and cost-effective adaptation policies and strategies at different scale levels. In MedSeA we are conveying acquired scientific knowledge to a wider audience of policy-makers, decision-makers, marine managers and other stakeholders through the formation of the Mediterranean Reference User Group (MRUG) (http://medsea-project.eu/mrug).

The main project strategy of this European initiative on ocean acidification and initial project results will be presented here. Further information is available at medsea-project.eu.

Universitat Autònoma de Barcelona (UAB), Institute of Environmental Science and Technology (ICTA), Barcelona, Spain (patrizia.ziveri@uab.cat / pr.medsea@uab.cat)



THIRD INTERNATIONAL SYMPOSIUM ON THE OCEAN IN A HIGH CO_2 WORLD
MONTEREY, CALIFORNIA, USA – SEPTEMBER 24-27, 2012
LIST OF PARTICIPANTS

Abeles	Adina	Center for Ocean Solutions, Stanford University	USA	abeles@stanford.edu
Achterberg	Eric	University of Southampton, National Oceanography Centre	UK	eric@noc.soton.ac.uk
Adams	Lisa	Kennesaw State University, Biology Department	USA	ladams@kennesaw.edu
Agnalt	Ann-Lisbeth	Institute of Marine Research	Norway	ann.lisbeth.agnalt@imr.no
Ahmed	Md. Kawser	University of Dhaka, Department of Fisheries	Bangladesh	kawser@univdhaka.edu
Aksissou	Mustapha	Faculty of Science, Biology Department	Morocco	aksissoum@hotmail.com
Albright	Rebecca	Australian Institute of Marine Science	Australia	r.albright@aims.gov.au
Alin	Simone	NOAA, Pacific Marine Environmental Laboratory	USA	simone.r.alin@noaa.gov
Anderson	Leif	University of Gothenburg	Sweden	leifand@chem.gu.se
Anderson	John	New England Aquarium	USA	janderson@neaq.org
Andersson	Andreas	Scripps Institution of Oceanography, UCSD	USA	aandersson@ucsd.edu
Anthony	Kenneth	Australian Institute of Marine Science	Australia	k.anthony@aims.gov.au
Armstrong	Claire	University of Tromsø	Norway	claire.armstrong@uit.no
Arnberg	Maj	IRIS - International Research Institute of Stavanger	Norway	maj.arnberg@iris.no
Artioli	Yuri	Plymouth Marine Laboratory	UK	yuti@pml.ac.uk
Arzayus	Krisa	NOAA/NODC	USA	krisa.arzayus@noaa.gov
Asnaghi	Valentina	University of Genoa	Italy	valentina.asnaghi@unige.it
Avril	Bernard	IMBER International Project Office	Norway	bernard.avril@imr.no
Azetsu-Scott	Kumiko	Bedford Institute of Oceanography	Canada	Kumiko.Azetsu-Scott@dfo-mpo.gc.ca
Bach	Lennart	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	lbach@geomar.de
Baker	Daniel	University of Auckland, School of Biological Sciences	New Zealand	dan.baker@auckland.ac.nz
Balestreri	Cecilia	Marine Biological Association of the United Kingdom	UK	cecbal@mba.ac.uk
Barcelos e Ramos	Joana	University of the Azores	Portugal	joanabr@uac.pt
Barott	Katie	Scripps Institution of Oceanography	USA	katiebarott@gmail.com
Barron	Megan	Scripps Institution of Oceanography	USA	meb3pm@gmail.com
Barry	James	Monterey Bay Aquarium Research Institute	USA	barry@mbari.org
Bartal	Roy	San Francisco State University	USA	bartal@mail.sfsu.edu

Bartl	Simona	Moss Landing Marine Laboratories	USA	sbartl@mlml.calstate.edu
Baussant	Thierry	IRIS - International Research Institute of Stavanger	Norway	thierry.baussant@iris.no
Bednarsek	Nina	University of Nova Gorica	Slovenia	nina.bednarsek@gmail.com
Bellerby	Richard	Norwegian Institute for Water Research	Norway	richard.bellerby@niva.no
Bénard	Robin	Université Laval, Biology Department	Canada	robin.benard.1@ulaval.ca
Bendtrsen	Jacob	Alphafilm	USA	jacob@alphafilm.dk
Benner	Ina	Romberg Tiburon Center (SFSU)	USA	ibenner@sfsu.edu
Bennett	Jennifer	NOAA Ocean Acidification Program (OAP)	USA	jennifer.bennett@noaa.gov
Bermúdez Monsalve	Jorge Rafael	Helmholtz Centre for Ocean Research Kiel (GEOMAR),	Germany	jrbermudez@geomar.de
Bernstein	Whitney	MIT-WHOI Joint Program, Marine Chemistry & Geochemistry	USA	wbernstein@whoi.edu
Bignami	Sean	RSMAS, University of Miami (FL)	USA	sbignami@rsmas.miami.edu
Birchenough	Silvana	Cefas	UK	silvana.birchenough@cefas.co.uk
Birney	Kristi	Environmental Defense Center	USA	KBirney@EnvironmentalDefenseCenter.org
Biswas	Haimanti	National Institute of Oceanography	India	bhaimanti@hotmail.com
Blackford	Jerry	Plymouth Marine Laboratory	UK	jcb@pml.ac.uk
Blanchette	Carol	University of California, Santa Barbara	USA	blanchette@msi.ucsb.edu
Blanco-Ameijeiras	Sonia	Univ. of Azores, Climate, Meteorology & Global Change	Portugal	sbameijeiras@uac.pt
Bock	Christian	Alfred-Wegener-Institute for Polar and Marine Research	Germany	Christian.Bock@awi.de
Bockmon	Emily	Scripps Institution of Oceanography	USA	ebockmon@ucsd.edu
Bögner	Desislava	Alfred Wegener Institute for Polar and Marine Research	Germany	dboegner@awi.de
Bopp	Laurent	IPSL / LSCE	France	Laurent.Bopp@lsce.ipsl.fr
Børsheim	Knut Yngve	Institute of Marine Research	Norway	yngve.borsheim@imr.no
Bown	Paul	University College London, Department of Earth Sciences	UK	p.bown@ucl.ac.uk
Bramanti	Lorenzo	ICM CSIC, Department of Oceanography and Marine Biology	Spain	philebo@gmail.com
Brander	Luke	VU University Amsterdam, Institute for Environmental Studies	Hong Kong	lukebrander@gmail.com
Brewer	Peter	Monterey Bay Aquarium Research Institute	USA	brpe@mbari.org
Bridges	Christopher	Heinrich Heine Univ., Metabolic Physiology - Ecophysiology	Germany	bridges@uni-duesseldorf.de
Broadgate	Wendy	IGBP Secretariat	Sweden	wendy@igbp.kva.se
Browman	Howard	Institute of Marine Research, Ecosystem Processes	Norway	howard.browman@imr.no
Brown	Keith	Satlantic LP	Canada	keith.brown@satlantic.com
Bulbul	Afroza	University of Otago, Chemistry Department	New Zealand	bafroza@chemistry.otago.ac.nz
Bursek	Julie	NOAA Channel Islands National Marine Sanctuary	USA	julie.bursek@noaa.gov
Busch	Shallin	NOAA Northwest Fisheries Science Center	USA	shallin.busch@noaa.gov

Bush	Eva	UC Davis	USA	eebush@ucdavis.edu
Bychkov	Alexander	PICES (North Pacific Marine Science Organization)	Canada	bychkov@pices.int
Byrne	Maria	University of Sydney, Medical and Biological Sciences	Australia	maria.byrne@sydney.edu.au
Caldeira	Ken	Carnegie Institution, Global Ecology	USA	kcaldeira@stanford.edu
Caldwell	Meg	Center for Ocean Solutions, Stanford University	USA	megc@stanford.edu
Calosi	Piero	Plymouth Univ., Marine Biology & Ecology Research Centre	UK	piero.calosi@plymouth.ac.uk
Candelmo	Allison	NOAA Fisheries	USA	allison.candelmo@noaa.gov
Carbonnel	Vincent	Peking University, Beijing, China	China	carbonnel.vincent@gmail.com
Carlson	Robert	Honeywell, Advanced Technology	USA	bob.j.carlson@honeywell.com
Carpenter	Robert	California State University, Northridge	USA	robert.carpenter@csun.edu
Carrington	Emily	University of Washington, Friday Harbor Laboratories	USA	ecarring@uw.edu
Carter	Hayley	San Francisco State University, Romberg Tiburon Center	USA	hacarter@sfsu.edu
Ceballos	Lina	San Francisco State University / Romberg Tiburon Center	USA	linaco@sfsu.edu
Chambers	Christopher	NOAA Fisheries Service	USA	chris.chambers@noaa.gov
Chandler	Cynthia	Woods Hole Oceanographic Institution	USA	cchandler@whoi.edu
Chavanich	Suchana	Chulalongkorn University, Department of Marine Science	Thailand	suchana.c@chula.ac.th
Chen	Jianfang	Second Institute of Oceanography, SOA	China	jfchen@sio.org.cn
Chierici	Melissa	Univ. of Gothenburg, Marine Ecosystem & Biogeochemistry	Sweden	melissa@chem.gu.se
Chilton	Linda	USC Sea Grant	USA	lchilton@usc.edu
Chou	Lei	Univ. Libre de Bruxelles, Sciences de la Terre et de l'Environ't.	Belgium	Lei.Chou@ulb.ac.be
Chrystal	Abbey	Univ. of California Santa Cruz, Earth and Planetary Sciences	USA	abbey.chrystal@gmail.com
Cigliano	John	Cedar Crest College, Biological Sciences	USA	jaciglia@cedarcrest.edu
Clemmesen	Catriona	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	cclemmesen@geomar.de
Collard	Marie	Université Libre de Bruxelles, Marine Biology Laboratory	Belgium	marie.collard9@gmail.com
Cooley	Sarah	Woods Hole Oceanographic Institution	USA	scooley@whoi.edu
Cornwall	Christopher	University of Otago	New Zealand	chris.cornwall@botany.otago.ac.nz
Covel	Jim	Monterey Bay Aquarium	USA	jcovel@mbayaq.org
Cripps	Gemma	Swansea University, Biosciences	UK	581604@swansea.ac.uk
Crona	Beatrice	Stockholm University, Stockholm Resilience Center	Sweden	beatrice.crona@stockholmresilience.su.se
Crook	Elizabeth	Univ. of California, Santa Cruz, Environmental & Planetary Sc.	USA	ederse@ucsc.edu
Cross	Jessica	Univ. of Alaska, Fairbanks, Ocean Acidification Rsrch. Center	USA	Jncross@alaska.edu
Crowder	Larry	Center for Ocean Solutions/Stanford University	USA	lbcrowd@stanford.edu
Currie	Kim	NIWA	New Zealand	kim.currie@niwa.co.nz

Currie	Ashleigh	Scottish Association for Marine Science	UK	Ashleigh.Currie@sams.ac.uk
Curry	Brad	Curry Kayaks	USA	Bcur@pacbell.net
Cyr	Ned	NOAA Fisheries	USA	ned.cyr@noaa.gov
Czerny	Jan	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	jczerny@geomar.de
Dalpadado	Padmini	Institute of Marine Research	Norway	padmini.dalpadado@imr.no
Danielson	Kathryn	San Francisco State University, Biology Department	USA	kdaniels@mail.sfsu.edu
Das	Surajit	National Institute of Technology Rourkela, Life Science	India	surajit@nitrkl.ac.in
Davis	Kate	University of California, Davis	USA	cvdavis@ucdavis.edu
De Carlo	Eric Heinen	University of Hawaii at Manoa, Department of Oceanography	USA	edecarlo@soest.hawaii.edu
de Francisco-Mora	Beatriz	Scottish Association for Marine Science, Ecology	UK	beatriz.defrancisco@sams.ac.uk
Denman	Ken	University of Victoria, School of Earth and Ocean Sciences	Canada	denmank@uvic.ca
Dery	Aurélie	Université Libre de Bruxelles, Marine Biology	Belgium	auredery@gmail.com
Dickson	Andrew	Scripps Institution of Oceanography	USA	adickson@ucsd.edu
Dilger	Linda	Monterey County Office of Education	USA	ldilger@monterey.k12.ca.us
Doney	Scott	Woods Hole Oceanographic Institution	USA	sdoney@whoi.edu
Donohue	Penelope	Univ. of Glasgow, School of Geographical & Earth Sciences	UK	p.donohue.1@research.gla.ac.uk
Dorey	Narimane	Univ. of Gothenburg, Biological and Environmental Sciences	Sweden	narimane.dorey@gu.se
Dorfman	Rachel	San Francisco State University, Romberg Tiburon Center	USA	racheld@mail.sfsu.edu
Drupp	Patrick	University of Hawaii, Department of Oceanography	USA	drupp@hawaii.edu
Duarte	Cristian	Facultad de Ecología y Recursos Naturales	Chile	cristian.duarte@unab.cl
Dubois	Philippe	Université Libre de Bruxelles	Belgium	phdubois@ulb.ac.be
Duffy	Allyn	Coastal Carolina University	USA	aeduffy@g.coastal.edu
Dunne	John	NOAA/GFDL	USA	john.dunne@noaa.gov
Dupont	Sam	The Sven Lovén Centre for Marine Sciences - Kristineberg	Sweden	sam.dupont@marecol.gu.se
Eberlein	Tim	Alfred Wegener Institute, Marine Biogeosciences	Germany	tim.eberlein@awi.de
Egilsdottir	Hronn	Marine Research Institute / University of Iceland	Iceland	hronn@hafro.is
Eichner	Meri	Alfred Wegener Institute, Marine Biogeosciences	Germany	meri.eichner@awi.de
Ellis	Robert	University of Exeter, College of Life & Environmental Science	UK	R.P.Ellis@exeter.ac.uk
Enge	Thorger	Plymouth University	UK	thorger.enge@students.plymouth.ac.uk
English	Chad	COMPASS	USA	cenglish@compassonline.org
Enyo	Kazutaka	Japan Meteorol. Agency, Global Environment & Marine Dept.	Japan	kenyo@met.kishou.go.jp
Epel	David	Stanford University, Hopkins Marine Station	USA	depel@stanford.edu
Evans	Tyler	Univ. of California Santa Barbara, Ecol., Evol’n & Marine Biol.	USA	tyler.evans@lifesci.ucsb.edu

Eyre	Bradley	Southern Cross University	Australia	bradley.eyre@scu.edu.au
Fabricius	Katharina	Australian Institute of Marine Science	Australia	k.fabricius@aims.gov.au
Fackler	Claire	NOAA Office of National Marine Sanctuaries	USA	claire.fackler@noaa.gov
Fangue	Nann	Univ. of California, Davis, Wildlife, Fish, & Conserv'n. Biology	USA	nafangue@ucdavis.edu
Fauville	Geraldine	University of Gothenburg	Sweden	geraldine.fauville@loven.gu.se
Feely	Richard	NOAA Pacific Marine Environmental Lab., Ocean Climate	USA	Richard.A.Feely@noaa.gov
Findlay	Helen	Plymouth Marine Laboratory	UK	hefi@pml.ac.uk
Fine	Maoz	Bar-Ilan University,	Israel	maoz.fine@biu.ac.il
Finzi-Hart	Juliette	University of Southern California, Sea Grant Program	USA	jahart@usc.edu
Fitzer	Susan	Univ. of Glasgow, School of Geographical and Earth Sciences	UK	susan.fitzer@glasgow.ac.uk
Foster	Laura	University of Bristol, Earth Sciences	UK	l.c.foster@bristol.ac.uk
Francis	Laura	NOAA Channel Islands National Marine Sanctuary	USA	laura.francis@noaa.gov
Fransson	Agneta	Norwegian Polar Institute	Norway	agneta.fransson@npolar.no
Frieder	Christina	Scripps Institution of Oceanography, Integrative Oceanogr.	USA	ctanner@ucsd.edu
Friederich	Gernot	Monterey Bay Aquarium Research Institute	USA	frge@mbari.org
Frommel	Andrea	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	afrommel@ifm-geomar.de
Fujii	Masahiko	Hokkaido University, Faculty of Environmental Earth Science	Japan	mfujii@ees.hokudai.ac.jp
Fulton	Elizabeth	CSIRO, Marine and Atmospheric Research	Australia	beth.fulton@csiro.au
Gable	Jill	EPA, Office of Water and Watersheds, Watershed Unit	USA	gable.jill@epa.gov
Gaffney	Owen	International Geosphere-Biosphere Programme	Sweden	owen.gaffney@igbp.kva.se
Gagnon	Alexander	Lawrence Berkeley National Laboratory, Earth Science Division	USA	acgagnon@lbl.gov
Gao	Kunshan	Xiamen Univ., State Key Lab of Marine Environmental Science	China	ksgao@xmu.edu.cn
Garcia	Hernan	NOAA, National Oceanographic Data Center	USA	Hernan.Garcia@noaa.gov
Garland	Michael	California Polytechnic State Univ., San Luis Obispo, Biol. Sci.	USA	mgarland@calpoly.edu
Garrison	David	National Science Foundation, Division of Ocean Sciences	USA	dgarriso@nsf.gov
Gaskill	Tom	South Slough National Estuarine Research Reserve	USA	tom.gaskill@state.or.us
Gattuso	Jean-Pierre	CNRS, Laboratoire d'Océanographie	France	gattuso@obs-vlfr.fr
Gaylord	Brian	University of California, Davis, Bodega Marine Laboratory	USA	bpgaylord@ucdavis.edu
Gazeau	Frédéric	Laboratoire d'Océanographie de Villefranche CNRS/UPMC	France	f.gazeau@obs-vlfr.fr
Giani	Michele	Istituto Nazionale di Oceanografia e Geofisica Sperimentale	Italy	mgiani@inogs.it
Gibbs	Samantha	University of Southampton, National Oceanography Centre	UK	sxg@noc.soton.ac.uk
Gledhill	Dwight	NOAA, Ocean Acidification Program	USA	dwight.gledhill@noaa.gov
Gobler	Christopher	Stony Brook University, Marine & Atmospheric Sciences	USA	christopher.gobler@stonybrook.edu

Godbold	Jasmin	University of Southampton, National Oceanography Centre	UK	j.a.godbold@soton.ac.uk
Goldberg	Stuart	The Consortium for Ocean Leadership	USA	sgoldberg@oceanleadership.org
Graham	Helen	Newcastle University, Marine Science and Technology	UK	helen.graham@ncl.ac.uk
Grefsrud	Ellen Sofie	Institute of Marine Research	Norway	ellens@imr.no
Gregoire	Lauren	University of Bristol, School of Geographical Sciences	UK	lauren.gregoire@bristol.ac.uk
Grosell	Martin	RSMAS, University of Miami, Marine Biology and Fisheries	USA	mgrosell@rsmas.miami.edu
Gross	Elizabeth	E & G Associates, LLC	USA	egross@scor-int.org
Grottoli	Andrea	The Ohio State University, School of Earth Sciences	USA	grottoli.1@osu.edu
Gustavson	Liv Marie	Norwegian University of Science & Technology, Biology Dept.	Norway	gustavso@stud.ntnu.no
Gutierrez-Magness	Angelica	Univ. of Maryland / NOAA, Civil and Environ'l. Engineering	USA	agutierr@umd.edu
Gutowska	Magdalena	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	mgutowska@geomar.de
Haakedal	Ole Jacob	Norwegian University of Science and Technology (NTNU)	Norway	olejah@stud.ntnu.no
Hagens	Mathilde	Utrecht University, Earth Sciences - Geochemistry	Netherlands	m.hagens@uu.nl
Hale	Rachel	University of East Anglia, Environmental Sciences	UK	r.hale1@uea.ac.uk
Hammer	Karen	SINTEF	Norway	karen.hammer@bio.ntnu.no
Hanshumaker	William	Oregon State University, Fisheries and Wildlife	USA	bill.hanshumaker@oregonstate.edu
Hansson	Lina	Laboratoire d'Océanographie de Villefranche, CNRS-LOV	France	hansson@obs-vlfr.fr
Harboe	Torstein	Institute of Marine Research	Norway	torsteinh@imr.no
Harms	Lars	Alfred Wegener Institute	Germany	Lars.Harms@awi.de
Harrold	Chris	Monterey Bay Aquarium	USA	charrold@mbayaq.org
Harrould-Kolieb	Ellycia	University of Melbourne, Resource Management & Geography	Australia	ellycia.harrould@unimelb.edu.au
Hartman	Susan	National Oceanography Centre	UK	suh@noc.ac.uk
Hattori	Hiroshi	Tokai University, Department of Marine Biology and Sciences	Japan	hattori@tspirit.tokai-u.jp
Hauck	Judith	Alfred Wegener Institute for Polar and Marine Research	Germany	judith.hauck@awi.de
Hauri	Claudine	University of Alaska, Fairbanks	USA	claudinehauri@gmail.com
Havenhand	Jon	University of Gothenburg, Biological & Environmental Sciences	Sweden	jon.havenhand@bioenv.gu.se
Headley	Kent	Monterey Bay Aquarium Research Institute	USA	headley@mbari.org
Heinze	Mathias	Max Planck Institute for Meteorology	Germany	mathias.heinze@zmaw.de
Hettinger	Annaliese	University of California Davis, Bodega Marine Laboratory	USA	ahettinger@ucdavis.edu
Heuer	Rachael	University of Miami, RSMAS, Marine Biology and Fisheries	USA	rheuer@rsmas.miami.edu
Hewlett	James	Finger Lakes Community College, Science and Technology	USA	hewletja@flcc.edu
Hicks	Natalie	Scottish Association for Marine Science, Biogeochemistry	UK	natalie.hicks@sams.ac.uk
Higgason	Kelley	NOAA Gulf of the Farallones National Marine Sanctuary	USA	kelley.higgason@noaa.gov

Hikami	Mana	Atmosphere and Ocean Research Inst., Ocean Floor Geosci.	Japan	hikami@aori.u-tokyo.ac.jp
Hildebrandt	Nicole	Alfred Wegener Institute for Polar and Marine Research	Germany	Nicole.Hildebrandt@awi.de
Hill	Tessa	University of California Davis, Bodega Marine Laboratory	USA	tmhill@ucdavis.edu
Hodin	Jason	Sanford University. Hopkins Marine Station	USA	seastar@stanford.edu
Hoegh-Guldberg	Ove	University of Queensland, Global Change Institute	Australia	oveh@uq.edu.au
Hofmann	Gretchen	UC, Santa Barbara, Ecology, Evolution & Marine Biology	USA	hofmann@lifesci.ucsb.edu
Hohn	Sönke	ZMT Bremen, Ecological Modelling	Germany	soenke.hohn@zmt-bremen.de
Holen	Silje	Norwegian Institute for Water Research	Norway	silje.holen@niva.no
Hopkins	Frances	Plymouth Marine Laboratory	UK	fhop@pml.ac.uk
Hoppe	Clara Jule Marie	Alfred Wegener Institute for Polar and Marine Research	Germany	Clara.Hoppe@awi.de
Hosfelt	Jessica	Bodega Marine Laboratory	USA	jdhosfelt@ucdavis.edu
Hossain	M. Shahadat	Univ. of Chittagong, Institute of Marine Sciences and Fisheries	Bangladesh	hossainms@yahoo.com
Hossain	Mohammad	Noakhali Science and Technology Univ., Biology Department	Brunei	mbhnstu@gmail.com
Howard	Dan	NOAA, Office of National Marine Sanctuaries	USA	dan.howard@noaa.gov
Howes	Ella	Université Pierre et Marie Curie/Jacobs University	France	ella.howes@obs-vlfr.fr
Huelsenbeck	Matthew	Oceana, Climate and Energy	USA	mhuelsenbeck@oceana.org
Hurst	Thomas	NOAA-NMFS, Alaska Fisheries Science Center	USA	thomas.hurst@noaa.gov
Hutchins	David	University of Southern California, Marine Environmental Biol.	USA	dahutch@usc.edu
Hutto	Sara	Channel Islands National Marine Sanctuary	USA	sara.hutto@noaa.gov
Ilyina	Tatiana	Max Planck Institute for Meteorology	Germany	tatiana.ilyina@zmaw.de
Inbakandan	Dhinakarasamy	Sathyabama University, Center for Ocean Research	India	inbakandan@gmail.com
Isensee	Kirsten	University of Oviedo, Department of Biology, Ecology	Spain	isenseekirsten@uniovi.es
Ishii	Masao	Meteorological Research Inst., Geochemical Research	Japan	mishii@mri-jma.go.jp
Ishimatsu	Atsushi	Nagasaki University, Institute for East China Sea Research	Japan	a-ishima@nagasaki-u.ac.jp
Ivanina	Anna	University of North Carolina, Charlotte, Biology Department	USA	aivanina@uncc.edu
Jahncke	Jaime	PRBO Conservation Science, California Current Group	USA	jjahncke@prbo.org
Jakubowska	Magdalena	University of Gdansk	Poland	ocemja@ug.edu.pl
Jansson	Anna	Åbo Akademi University, Environmental and Marine Biology	Finland	anna.jansson@abo.fi
Jeffers	Emily	Center for Biological Diversity	USA	ejeffers@biologicaldiversity.org
Jennions	Suzanne	University of Bristol	UK	sj9731@bristol.ac.uk
Jensen	Lisa	California State University Monterey Bay	USA	lijensen@csumb.edu
Jewett	Libby	NOAA Ocean Acidification Program	USA	Libby.Jewett@NOAA.gov
Jiang	Zong-Pei	National Oceanography Centre, Southampton	UK	zongpei.jiang@noc.soton.ac.uk

Johnson	Kevin	UC Santa Barbara, Ecology, Evolution & Marine Biology	USA	kejohnson@csumb.edu
Kamennaya	Nina	Lawrence Berkeley National Lab., Earth Sciences Division	USA	nkamennaya@lbl.gov
Kamenos	Nicholas	Univ. of Glasgow, School of Geographical & Earth Sciences	UK	nick.kamenos@glasgow.ac.uk
Kapsenberg	Lydia	UC Santa Barbara, Ecology, Evolution & Marine Biology	USA	lydia.kapsenberg@lifesci.ucsb.edu
Karlberg	Maria	University of Gothenburg, Biological & Environmental Sciences	Sweden	maria.karlberg@gu.se
Karlson	Bengt	Swedish Meteorol. & Hydrological Inst., Oceanographic Lab.	Sweden	bengt.karlson@smhi.se
Kawaguchi	So	Australian Antarctic Division	Australia	So.Kawaguchi@aad.gov.au
Kelly	Ryan	Stanford University, Center for Ocean Solutions	USA	rpk@stanford.edu
Khanna	Nikki	University of St Andrews, School of Biology	UK	nk274@st-andrews.ac.uk
Kim	Kyungsu	Pukyong National University, Department of Marine Biology	South Korea	ks-kim@pknu.ac.kr
Kim	Taewon	Monterey Bay Aquarium Research Institute	USA	ktwon@mbari.org
Kim	Hey-Jin	Scripps Institution of Oceanography	USA	hjkim@ucsd.edu
Kimoto	Katsunori	JAMSTEC, Research Institute for Global Change	Japan	kimopy@jamstec.go.jp
King	Andrew	NOAA/NMFS, Northeast Fisheries Science Center, Milford Lab.	USA	andrew.king@noaa.gov
Kippen	Rachel	The California Academy of Sciences	USA	rkippen@calacademy.org
Kleypas	Joanie	Nat'l. Center for Atmos. Rsrch, Climate & Global Dynamics	USA	kleypas@ucar.edu
Klinger	Terrie	University of Washington	USA	tklinger@uw.edu
Koch	Marguerite	Florida Atlantic University, Biological Sciences	USA	mkoch@fau.edu
Koeve	Wolfgang	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	wkoeve@geomar.de
Kontradowitz	Stefan	SOLAS, International Project Office	Germany	skontradowitz@geomar.de
Kostyleva	Anna	Southern Branch of P.P.Shirshov Institute of Oceanology	Russia	ventis-ire@yandex.ru
Kosugi	Naohiro	Meteorological Research Inst., Geochemical Research Dept.	Japan	nkosugi@mri-jma.go.jp
Kreiss	Cornelia	Alfred Wegener Institute for Marine and Polar Research	Germany	Cornelia.Kreiss@awi.de
Kroeker	Kristy	Hopkins Marine Station, Stanford University	USA	kkroeker@stanford.edu
Kuchinke	Mareva	CSIRO	Australia	mareva.kuchinke@csiro.au
Kurihara	Haruko	University of the Ryukyus	Japan	harukoku@e-mail.jp
Laffoley	Dan	International Union for the Conservation of Nature	UK	danlaffoley@btinternet.com
Lagos	Nelson	Univ. Santo Tomás, Ctr de Invest. en Ciencias Ambientales	Chile	nlagoss@ust.cl
Lane	Ackley	The University of Hong Kong, Swire Institute of Marine Science	Hong Kong	ackleylane@gmail.com
Langdon	Chris	Rosenstiel School of Marine and Atmospheric Science	USA	clangdon@rsmas.miami.edu
Lannig-Bock	Gisela	Alfred Wegener Institute, Integrative Ecophysiology	Germany	Gisela.Lannig@awi.de
Lara-Lara	Ruben	CICESE, Department of Oceanography	Mexico	rlara@cicese.mx
Lardies	Marco	Universidad Adolfo Ibanez	Chile	marco.lardies@uai.cl

Laverdure	Jacqueline	NOAA, Olympic Coast National Marine Sanctuary	USA	jacqueline.laverdure@noaa.gov
Leblud	Julien	University of Mons, Numerical Ecology of Aquatic Systems	Belgium	julien.leblud@umons.ac.be
Lenton	Andrew	CSIRO, Marine and Atmospheric Research	Australia	andrew.lenton@csiro.au
Leonard	George	Ocean Conservancy	USA	gleonard@oceanconservancy.org
Levasseur	Maurice	Université Laval, Biologie (Québec-Océan)	Canada	maurice.levasseur@bio.ulaval.ca
Levin	Lisa	Scripps Institution of Oceanography	USA	llevin@ucsd.edu
Lewis	Ceri	University of Exeter, Biosciences	UK	c.n.lewis@exeter.ac.uk
Lewis	Staci	Consortium for Ocean Leadership	USA	slewis@oceanleadership.org
Li	Hongliang	The Second Institute of Oceanography, SOA	China	gambooli@hotmail.com
Lipski	Danielle	NOAA Channel Islands National Marine Sanctuary	USA	danielle.lipski@noaa.gov
Lischka	Silke	Helmholtz Centre for Ocean Research Kiel (GEOMAR),	Germany	slischka@geomar.de
Litvin	Steven	Stanford University	USA	litvin@stanford.edu
Logan	Cheryl	California State University, Monterey Bay	USA	clogan@csumb.edu
Lohbeck	Kai	Helmholtz Centre for Ocean Research Kiel (GEOMAR))	Germany	klohbeck@geomar.de
Long	Dennis	Monterey Bay Sanctuary Foundation	USA	dennis@mbnmsf.org
Lovera	Christopher	Monterey Bay Aquarium Research Institute	USA	lovera@mbari.org
Lucey	Noelle	University of Plymouth	USA	nlucey@whoi.edu
Ludwig	Claudia	Institute for Systems Biology	USA	cludwig@systemsbiology.org
Lui	Hon-Kit	Nat'l. Sun Yat-Sen University, Inst. of Marine Geology & Chem.	Taiwan	m955030005@student.nsysu.edu.tw
Lyon	Paul	Fisheries and Oceans Canada	Canada	paul.lyon@dfo-mpo.gc.ca
Maas	Amy	Woods Hole Oceanographic Institution, Department of Biology	USA	amaas@whoi.edu
Mach	Katharine	Stanford Univ., Carnegie Institution for Science, Global Ecology	USA	mach@stanford.edu
Mahacek	Paul	Laboratoire d'Océanographie de Villefranche	France	mahacek@obs-vlfr.fr
Maloy	Carol	Washington State Dept. of Ecology	USA	carol.maloy@ecy.wa.gov
Maneja	Rommel	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	rmaneja@geomar.de
Mangor-Jensen	Anders	Institute of Marine Research, Austevoll Research Station	Norway	amj@imr.no
Manriquez	Patricio	Univ. Austral de Chile, Inst. de Ciencias Marinas y Limnológicas	Chile	pmanriquez@uach.cl
Manzello	Derek	NOAA, Atlantic Oceanographic & Meteorological Laboratory	USA	derek.manzello@noaa.gov
Marcou	Olivier	University of Perpignan	France	marcou@univ-perp.fr
Mark	Felix	Alfred Wegener Institute, Integrative Ecophysiology	Germany	fmark@awi.de
Marks	Corina	Stanford (COS) and CSU Monterey Bay	USA	cmarks@csumb.edu
Marshall	Brittney	University of South Carolina, Earth and Ocean Sciences	USA	brittneyj.marshall@gmail.com
Martínez Fernández	Ana	Univ. of California Santa Cruz, Earth and Planetary Sciences	USA	amarti43@ucsc.edu

Matear	Richard	CSIRO	Australia	richard.matear@csiro.au
Mathis	Jeremy	Univ. of Alaska Fairbanks, School of Fisheries and Ocean Sci.	USA	jtmathis@alaska.edu
Matoo	Omera	University of North Carolina at Charlotte, Biology	USA	obashir@uncc.edu
Matsumoto	George	Monterey Bay Aquarium Research Institute	USA	mage@mbari.org
Matsumoto	Karen	Seattle Aquarium, Conservation Education	USA	k.matsumoto@seattleaquarium.org
Matsumoto	Kirsten	Stevenson School	USA	kmatsumoto@stevensonschool.org
Maugendre	Laure	Laboratoire d'océanographie de Villefranche	France	maugendre@obs-vlfr.fr
McAfee	Skyli	Ocean Science Trust	USA	skyli.mcafee@calost.org
McClelland	Erin	Fisheries and Oceans Canada, Molecular Genetics Lab	Canada	Erin.McClelland@dfo-mpo.gc.ca
McClelland	Harry	University of Oxford, Department of Earth Sciences	UK	HarryM@earth.ox.ac.uk
McCorkle	Daniel	Woods Hole Oceanographic Institution	USA	dmccorkle@whoi.edu
McCoy	Sophie	The University of Chicago, Dept. of Ecology and Evolution	USA	mccoy@uchicago.edu
McElhany	Paul	NOAA - Northwest Fisheries Science Center	USA	paul.mcelhany@noaa.gov
McGrath	Triona	National University of Ireland, Galway	Ireland	triona_mcgrath@hotmail.com
McGraw	Christina	Clark University, Chemistry	USA	cmcgraw@clarku.edu
Medina-Rosas	Pedro	UdeG / UNCW	Mexico	pedromedinarosas@gmail.com
Melzner	Frank	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	fmelzner@geomar.de
Mengelt	Claudia	Ocean Studies Board/National Academy of Sciences	USA	cmengelt@nas.edu
Michael	Katharina	Alfred Wegener Institute for Polar and Marine Research	Germany	Katharina.Michael@awi.de
Micheli	Fiorenza	Stanford University, Biology	USA	micheli@stanford.edu
Mieszkowska	Nova	Marine Biol. Ass'n of the UK, Marine Biodiv. & Climate Change	UK	nova@mba.ac.uk
Miller	Gabrielle	James Cook Univ., Centre of Excellence for Coral Reef Studies	Australia	gabrielle.miller1@my.jcu.edu.au
Miller	Seth	Bodega Marine Laboratory, UC Davis	USA	shmiller@ucdavis.edu
Miller	Pamela	Stanford University, Hopkins Marine Station	USA	pam.miller@stanford.edu
Miller	Whitman	Smithsonian Environmental Research Center	USA	Millerw@si.edu
Miller	Kristi	Pacific Biological Station	Canada	Kristi.Miller@dfo-mpo.gc.ca
Millero	Frank	RSMAS, University of Miami, Marine & Atmospheric Chemistry	USA	fmillero@rsmas.miami.edu
Minnich-Bucksbaum	April	The Baum Foundation	USA	april@thebaumfoundation.org
Mongin	Mathieu	CSIRO	Australia	mathieu.mongin@csiro.au
Monteiro	Fanny	University of Bristol, School of Geographical Sciences	UK	f.monteiro@bristol.ac.uk
Moulin	Laure	Université Libre de Bruxelles, Laboratoire de biologie marine	Belgium	lmoulin@ulb.ac.be
Muehllehner	Nancy	University of Miami, RSMAS, Marine Biology & Fisheries	USA	nancymuehllehner@gmail.com
Muller	Erik	University of California, Santa Barbara	USA	bpbleus@yahoo.com

Müller	Marius	Institute for Marine and Antarctic Studies (IMAS)	Australia	marius.muller@utas.edu.au
Munday	Philip	James Cook Univ., Centre of Excellence for Coral Reef Studies	Australia	philip.munday@jcu.edu.au
Murata	Akihiko	JAMSTEC, Research Institute for Global Change	Japan	murataa@jamstec.go.jp
Murray	James	University of Washington, School of Oceanography	USA	jmurray@u.washington.edu
Naik	Sushant	National Inst. of Oceanogr., Geological Oceanography Division	India	sushant@nio.org
Nam	SungHyun	Scripps Institution of Oceanography	USA	sunam@ucsd.edu
Nash	Merinda	Australian National University, Research School of Physics	Australia	merinda.nash@anu.edu.au
Navarro	Michael	Scripps Inst. of Oceanography, Integrative Oceanogr. Division	USA	monavarr@ucsd.edu
Navarro Azócar	Jorge	Univ. Austral de Chile, Instituto Ciencias Marinas y Limnol.	Chile	jorgenavarroa@gmail.com
Nelson	Sarah-Mae	Monterey Bay Aquarium	USA	snelson@mbayaq.org
Neuer	Susanne	Arizona State University, School of Life Sciences	USA	susanne.neuer@asu.edu
Newton	Jan	University of Washington, Applied Physics Laboratory	USA	newton@apl.washington.edu
Noh	Jaehoon	KORDI, Marine Biology and Living Resources Research	South Korea	jhnoh@kordi.re.kr
Noisette	Fanny	CNRS - UPMC, Station Biologique of Roscoff	France	fanny.noisette@sb-roscoff.fr
Nojiri	Yukihiro	National Institute of Environmental Studies	Japan	nojiri@nies.go.jp
Norberg	Sarah	NOAA-NWFSC,	USA	sarah.norberg@noaa.gov
Normant	Monika	The Univ. of Gdansk, Experim'l Ecology of Marine Organisms	Poland	ocemn@univ.gda.pl
Nunes	Paulo A.L.D.	The Mediterranean Science Comm., Economics Research Prog.	Monaco	pnunes@ciesm.org
OBrien	Helen	Univ. of California, Santa Cruz, Ecology and Evolutionary Biol.	USA	hobrien@ucsc.edu
O'Dea	Sarah	University of Southampton	UK	sarah.odea@noc.soton.ac.uk
O'Donnell	Michael	University of Washington, Friday Harbor Laboratories	USA	mooseo@uw.edu
Okimura	Kristine	Romberg Tiburon Center for Environmental Studies, SFSU	USA	kokimura@sfsu.edu
Olafsdottir	Solveig	Marine Research Institute	Iceland	solveig@hafro.is
Olafsson	Jon	University of Iceland, Faculty of Earth Sciences	Iceland	jon@hafro.is
Orellana	Monica	University of Washington, Institute for Systems Biology	USA	morellana@systemsbiology.org
Orr	James	LSCE/IPSL	France	james.orr1@lsce.ipsl.fr
Osgood	Kenric	NOAA Fisheries Service	USA	kenric.osgood@noaa.gov
Oviedo Sabogal	Angela	Universität Autònoma de Barcelona	Spain	angela_mobula@yahoo.com
Padilla-Gamino	Jacqueline	UC Santa Barbara, Ecology, Evolution & Marine Biology	USA	jacqueline.padilla.gamino@lifesci.ucsb.edu
Paganini	Adam	RTC	USA	paganini@mail.sfsu.edu
Page	Tessa	Romberg Tiburon Center for Environmental Studies, SFSU	USA	tpage@sfsu.edu
Pajusalu	Liina	Estonian Marine Institute, University of Tartu	Estonia	liina.pajusalu@ut.ee
Palanisamy	Murugan	Central Institute of Brackishwater Aquaculture	India	mgn.bch@gmail.com

Palumbi	Stephen	Stanford University, Department of Biology	USA	spalumbi@stanford.edu
Pansch	Christian	Helmholtz Centre for Ocean Research Kiel (GEOMAR) Kiel	Germany	cpansch@geomar.de
Parker	Laura	University of Western Sydney, School of Science and Health	Australia	l.parker@uws.edu.au
Parsons	Christina	Word Craft	USA	cp@word-craft.com
Pasquer	Benedicte	Univ. of New South Wales /CSIRO, Climate Change Rsrch. Ctr.	Australia	benedicte.pasquer@csiro.au
Passow	Uta	Marine Science Institute, UC Santa Barbara	USA	passow@lifesci.ucsb.edu
Paytan	Adina	University of California, Santa Cruz	USA	apaytan@ucsc.edu
Pedersen	Sindre	Norwegian Univ. of Science and Technology, Dep't. of Biology	Norway	sindre.pedersen@bio.ntnu.no
Pelejero	Carles	Institut de Ciències del Mar, CSIC, Mar. Biol. & Oceanography	Spain	carles.pelejero@icrea.cat
Peltzer	Edward	Monterey Bay Aquarium Research Institute	USA	etp3@mbari.org
Penman	Donald	University of California, Santa Cruz, Earth & Planetary Sciences	USA	dpenman@ucsc.edu
Perez	Fiz	Institut de Ciències del Mar	Spain	fiz.perez@iim.csic.es
Phelan-Hill	Beth	NOAA, National Marine Fisheries Service	USA	beth.phelan@noaa.gov
Piatkowski	Uwe	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	upiatkowski@geomar.de
Picard	Manon	University of British Columbia, Zoology Department	Canada	picard@zoology.ubc.ca
Pillay	Kamleshan	University of KwaZulu-Natal, Environmental Sciences	South Africa	pillay.kamleshan@gmail.com
Pleschner-Steele	Diane	C-CAN	USA	dplesch@gmail.com
Podymov	Oleg	Southern Branch of P.P.Shirshov Institute of Oceanology	Russia	huravela@yahoo.com
Pope	Aaron	California Academy of Sciences	USA	apope@calacademy.org
Pope	Edward	Swansea University, Centre for Sustainable Aquatic Research	UK	e.c.pope@swansea.ac.uk
Pörtner	Hans	Alfred-Wegener-Institute, Integrative Ecophysiology	Germany	hans.poertner@awi.de
Preston	Carol	Gulf of the Farallones National Marine Sanctuary	USA	carol.a.preston@noaa.gov
Putnam	Hollie	Hawaii Institute of Marine Biology	USA	hputnam@hawaii.edu
Quintana Krupinski	Nadine	University of California Santa Cruz, Earth & Planetary Sciences	USA	nadine@pmc.ucsc.edu
Ragazzola	Federica	University of Bristol	UK	f.ragazzola@bristol.ac.uk
Rahman	Mohammad S.	Projonma Academy, Climate Change and Environment	Bangladesh	projonmaacdy@yahoo.com.au
Ramadoss	Dineshram	Hong Kong University, Biological Sciences	Hong Kong	dinbiot@gmail.com
Range	Pedro	CCMAR - Centro de Ciências do Mar	Portugal	prange@ualg.pt
Rasmussen	Tine	University of Tromsø, Geology	Norway	tine.rasmussen@uit.no
Rastrick	Samuel	Plymouth Univ., Marine Biology and Ecology Research Centre	UK	samuel.rastrick@plymouth.ac.uk
Rau	Greg	University of California, Santa Cruz, Institute Marine Sciences	USA	ghrau@sbcglobal.net
Rebuck	Nathan	NOAA NEFSC Narragansett	USA	nathan.rebuck@noaa.gov
Rerolle	Victoire	National Oceanography Centre Southampton	UK	Victoire.Rerolle@noc.soton.ac.uk

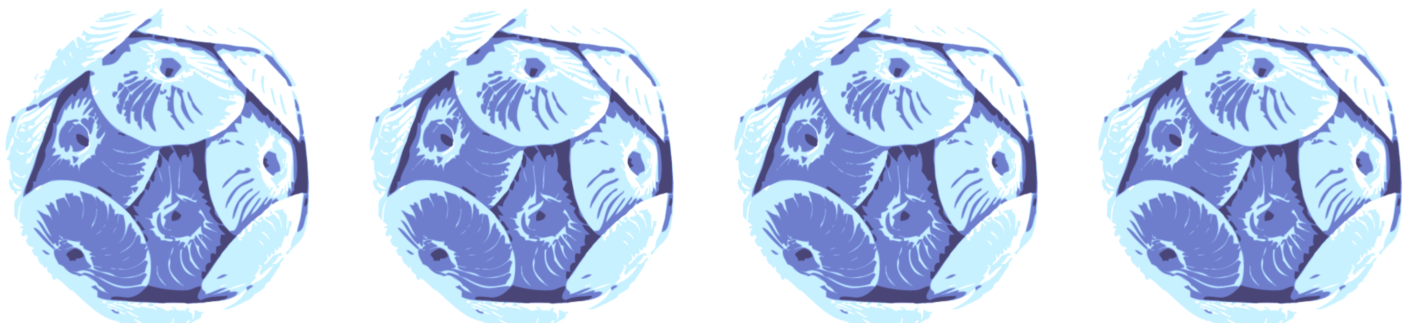
Rezende	Carlos	Univ. Es. do Norte Fluminense, Lab. de Ciências Ambientais	Brazil	crezende@uenf.br
Rice	Donald	National Science Foundation, Division of Ocean Sciences	USA	drice@nsf.gov
Richier	Sophie	National Oceanography Centre	UK	s.richier@noc.soton.ac.uk
Ridgwell	Andy	University of Bristol	UK	andy@seao2.org
Riebesell	Ulf	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	uriebesell@geomar.de
Rivest	Emily	University of California, Santa Barbara	USA	emily.rivest@lifesci.ucsb.edu
Roberson	Julia	The Ocean Conservancy	USA	jroberson@oceanconservancy.org
Roberts	Donna	Antarctic Climate & Ecosystem CRC	Australia	d.roberts@acecrc.org.au
Roberts	Murray	Heriot-Watt Univ., Centre for Marine Biodiversity & Biotech.	UK	j.m.roberts@hw.ac.uk
Roberts	Susan	National Academy of Sciences, National Research Council	USA	sroberts@nas.edu
Rodolfo-Metalpa	Riccardo	Plymouth Univ., Marine Biology and Ecology Research Centre	New Caledonia	riccardo@rodolfo-metalpa.com
Rodrigues Alves	Betina	University of São Paulo, Oceanographic Institute	Brazil	begralves@gmail.com
Rokitta	Sebastian	Alfred-Wegener-Institute, Biogeosciences	Germany	Sebastian.Rokitta@awi.de
Roleda	Michael	University of Otago, Department of Botany	New Zealand	michael.roleda@botany.otago.ac.nz
Rose	Jeremy	Oregon State University, Department of Zoology	USA	rosej@science.oregonstate.edu
Ross	Pauline	University of Western Sydney, School of Science and Health	Australia	pm.ross@uws.edu.au
Ruiz-Jones	Guadalupe	Stanford University, Hopkins Marine Station	USA	gjrj@stanford.edu
Sadorus	Lauri	International Pacific Halibut Commission	USA	lauri@iphc.int
Sharifi Rayeni	Sadriyeh	ICCN	South Korea	sadry.sharifi@gmail.com
Saenz	Dianne	Climate Nexus	USA	diannes@climatenexus.org
Sahlsten	Elisabeth	Swedish Agency for Marine and Water Management	Sweden	elisabeth.sahlsten@gmail.com
Sakas	Cathy	NOAA, Grays Reef National Marine Sanctuary	USA	cathy.sakas@noaa.gov
Sakashita	Miyoko	Center for Biological Diversity	USA	miyoko@biologicaldiversity.org
Sallon	Amélie	Laboratoire d'Océanographie de Villefranche, CNRS-UPMC	France	sallon@obs-vlfr.fr
Sams	Erin	NOAA	USA	erin.sams@noaa.gov
Sasaki	Hiroshi	Senshu University of Ishinomaki, Biological Engineering	Japan	sasaki@isenshu-u.ac.jp
Saunders	Robert	Island Scallops Ltd	Canada	robs@islandscallops.com
Sawada	Yoshifumi	Kinki University, Fisheries laboratory	Japan	yoshifumi.sawada@kindaisuiken.jp
Sawyer	Terry	Hog Island Oyster Co.	USA	terry@hogislandoysters.com
Schartau	Markus	Helmholtz Zentrum Geesthacht (HZG), Inst. of Coastal Rsrch.	Germany	markus.schartau@hzg.de
Schiffer	Melanie	Alfred Wegener Institute	Germany	melanie.schiffer@awi.de
Schlegel	Peter	Macquarie University, Biological Sciences	Australia	peter.schlegel@mq.edu.au
Schlining	Kyra	Monterey Bay Aquarium Research Institute	USA	schlin@mbari.org

Schmidt	Daniela	University of Bristol, Earth Science	UK	d.schmidt@bristol.ac.uk
Schneider	Birgit	University of Kiel, Institute of Geosciences	Germany	bschneider@gpi.uni-kiel.de
Schneider	Kenneth	Carnegie Institution, Global Ecology	USA	Kennysch@carnegie.stanford.edu
Schoepf	Verena	The Ohio State University, School of Earth Sciences	USA	schoepf.4@osu.edu
Scholin	Chris	Monterey Bay Aquarium Research Institute	USA	scholin@mbari.org
Schulz	Kai	Helmholtz Centre for Ocean Research Kiel (GEOMAR)	Germany	kschulz@geomar.de
Seibel	Brad	University of Rhode Island, Biology	USA	seibel@uri.edu
Selz	Virginia	National Science Foundation, Division of Ocean Sciences	USA	vselz@nsf.gov
Seto	Mayumi	Nara Women's Univ., Dept. Information & Computer Sciences	Japan	seto@ics.nara-wu.ac.jp
Sewell	Mary	University of Auckland	New Zealand	m.sewell@auckland.ac.nz
Shadwick	Elizabeth	Antarctic Climate & Ecosystems CRC	Australia	elizabeth.shadwick@utas.edu.au
Shaltout	Nayrah	National Inst. of Oceanography and Fisheries, Marine Chem.	Egypt	nshaltout@gmail.com
Sharifi Rayeni	Sadriyeh	ICCN	South Korea	sadry.sharifi@gmail.com
Sharifuzzaman	S.M.	Univ. of Chittagong, Institute of Marine Sciences and Fisheries	Bangladesh	sharifuzaman@yahoo.com
Shaw	Emily	University of New South Wales	Australia	e.shaw@student.unsw.edu.au
Shi	Dalin	Xiamen University, College of the Environment and Ecology	China	dshi@xmu.edu.cn
Shim	JeongHee	National Fisheries Research and Development Institute	South Korea	jshim@nfrdi.go.kr
Silbiger	Nyssa	Hawaii Institute of Marine Biology, Zoology Department	USA	silbiger@hawaii.edu
Six	Katharina	Max Planck Institute for Meteorol., Ocean in the Earth System	Germany	katharina.six@zmaw.de
Skiftesvik	Anne Berit	Institute of Marine Research, Ecosystem Processes	Norway	anne.berit.skiftesvik@imr.no
Skinder	Carolyn	Monterey Bay National Marine Sanctuary	USA	carolyn.skinder@noaa.gov
Small	Daniel	Plymouth Univ., Marine Biology and Ecology Research Centre	UK	daniel.small@plymouth.ac.uk
Solan	Martin	University of Southampton, School of Ocean and Earth Science	UK	m.solan@soton.ac.uk
Sosa Avalos	Ramón	Universidad de Colima, Facultad de Ciencias Marinas	Mexico	rsosa@ucol.mx
Spalding	Mark	The Ocean Foundation	USA	mspalding@oceanfdn.org
Spector Atkins	Fran	SpectorDance	USA	spectordance@earthlink.net
Stark	Jonathan	Australian Antarctic Div., Terrestrial & Nearshore Ecosys. Prog.	Australia	jonny.stark@aad.gov.au
Steele	Bruce	C-CAN	USA	dplesch@gmail.com
Steelquist	Robert	NOAA Olympic Coast National Marine Sanctuary	USA	robert.steelquist@noaa.gov
Stemmer	Kristina	Alfred Wegener Institute for Polar and Marine Research	Germany	kristina.stemmer@awi.de
Stillman	Jonathon	San Francisco State University, Romberg Tiburon Center	USA	stillmaj@sfsu.edu
Stock	Jennifer	NOAA/Cordell Bank National Marine Sanctuary	USA	jennifer.stock@noaa.gov
Stojkovic	Slobodanka	CSIRO, CMAR	Australia	slobodanka.stojkovic@monash.edu

Strobel	Anneli	Alfred Wegener Institute, Integrative Ecophysiology	Germany	anneli.strobel@awi.de
Suatoni	Lisa	Natural Resources Defense Council, Oceans	USA	lsuatoni@nrdc.org
Suckling	Coleen	British Antarctic Survey and Cambridge University	UK	colckl@bas.ac.uk
Sugie	Koji	Central Research Institute of Electric Power Industry	Japan	kojisugie@gmail.com
Suwa	Ryota	Kyoto University, Seto Marine Biological Laboratory	Japan	ryota@zenno.jp
Suzuki	Toru	Marine Information Research Center	Japan	suzuki@mirc.jha.jp
Suzuki	Atsushi	Geological Survey of Japan (AIST)	Japan	a.suzuki@aist.go.jp
Swezey	Daniel	University of California, Davis, Bodega Marine Laboratory	USA	dsswezey@ucdavis.edu
Tagliati	Alice	Università politecnica delle Marche	Italy	alice.tagliati@gmail.com
Tait	Karen	Plymouth Marine Laboratory	UK	ktait@pml.ac.uk
Takami	Hideki	Tohoku National Fisheries Research Institute, Japan	Japan	htakami@affrc.go.jp
Tambutte	Eric	Centre Scientifique de Monaco	Monaco	etambutte@centrescientifique.mc
Tatters	Avery	University of Southern California	USA	tatters@usc.edu
Taucher	Jan	Helmholtz-Centre for Ocean Research Kiel (GEOMAR)	Germany	jtaucher@geomar.de
Taylor	Josi	MBARI	USA	josi@mbari.org
Teniswood	Clara	Australian Nat'lUniv., Rsrch. School of Physics and Engineering	Australia	clara.teniswood@anu.edu.au
Thresher	Ronald	CSIRO	Australia	Ron.Thresher@csiro.au
Tilbrook	Bronte	CSIRO	Australia	bronte.tilbrook@csiro.au
Todgham	Anne	Biology, San Francisco State University	USA	todgham@sfsu.edu
Tomanek	Lars	California Polytechnic State University, Biological Sciences	USA	ltomanek@calpoly.edu
Torres	Rodrigo	Centro de Investigación en Ecosistemas de la Patagonia	Chile	rtorres@ciep.cl
Torstensson	Anders	Univ. of Gothenburg, Biological and Environmental Sciences	Sweden	anders.torstensson@bioenv.gu.se
Tracey	Dianne	NIWA, Deepsea	New Zealand	di.tracey@niwa.co.nz
Tresguerres	Martin	Scripps Institution of Oceanography	USA	mtresguerres@ucsd.edu
Turley	Carol	Plymouth Marine Laboratory	UK	ct@pml.ac.uk
Turner	Beth	NOAA, National Centers for Coastal Ocean Science	USA	elizabeth.turner@noaa.gov
Tynan	Eithne	National Oceanography Centre, Ocean and Earth Science	UK	e.tynan@soton.ac.uk
Tyrrell	Toby	National Oceanography Centre, Ocean and Earth Science	UK	tt@noc.soton.ac.uk
Urban	Ed	Scientific Committee on Oceanic Research	USA	Ed.Urban@scor-int.org
Valayer	Pierre Jean	Greenloop S.A. (Belgium)	France	p.jean.valayer@greenloop.eu
VALDES	LUIS	IOC-UNESCO	France	jl.valdes@unesco.org
Van Colen	Carl	Ghent University, Marine Biology Section	Belgium	carl.vancolen@ugent.be
Vanaverbeke	Jan	Ghent University, Marine Biology Research Group	Belgium	jan.vanaverbeke@ugent.be

Vargas	Cristian	Univ. de Concepción, Ecosystem Functioning Laboratory	Chile	crvargas@udec.cl
Vehmaa	Anu	Åbo Akademi University/Novia University of Applied Sciences	Finland	anu.vehmaa@novia.fi
Venn	Alexander	Centre Scientifique de Monaco	Monaco	alex@centrescientifique.mc
Waite	Anya	University of Western Australia	Australia	Anya.Waite@uwa.edu.au
Wakita	Masahide	JAMSTEC, Mutsu Institute for Oceanography	Japan	mwakita@jamstec.go.jp
Walker	Richard	Stevenson School	USA	rwalker@stevensonschool.org
Walkup	Sara	Scripps Institution of Oceanography, Biological Oceanography	USA	swalkup@ucsd.edu
Walz	Peter	Monterey Bay Aquarium Research Institute	USA	wape@mbari.org
Wang	Kui	Second Institute of Oceanography, Biogeochemistry	China	wang.kui@msn.com
Wang	Zhaohui Aleck	Woods Hole Oceanographic Institution	USA	zawang@whoi.edu
Wanninkhof	Rik	NOAA, Atlantic Oceanographic & Meteorological Laboratory	USA	rik.wanninkhof@noaa.gov
Warren	Brad	Global Ocean Health Program, SFP/NFCC	USA	brad.warren@sustainablefish.org
Watson	Sue-Ann	James Cook Univ., Centre of Excellence for Coral Reef Studies	Australia	sueann.watson@jcu.edu.au
Webb	Alison	University of East Anglia, School of Environmental Science	UK	alison.l.webb@uea.ac.uk
Weigelt-Krenz	Sieglinde	Bundesamt für Seeschifffahrt und Hydrographie	Germany	sieglinde.weigelt@bsh.de
Westerbeck	Jennifer	Salinas Union High School District, Alisal High School	USA	Jennifer.Westerbeck@salinasuhsd.org
Whiteley	Nia	Bangor University, School of Biological Sciences	UK	n.m.whiteley@bangor.ac.uk
Wicks	Laura	Heriot-Watt Univ., Centre for Marine Biodiversity and Biotech.	UK	l.wicks@hw.ac.uk
Widdicombe	Steve	Plymouth Marine Laboratory	UK	swi@pml.ac.uk
Widmer	Chad	University of St. Andrews	UK	cw647@st-andrews.ac.uk
Wieczorek	Daniel	NOAA-National Marine Fisheries Service	USA	daniel.wieczorek@noaa.gov
Williams	Maria	University of Bristol, School of Earth Science	UK	Maricel.Williams@bristol.ac.uk
Williams	Rachael	University of California, Davis	USA	Rachael.c.w.s@gmail.com
Williamson	Phillip	Natural Environment Research Council/Univ. of East Anglia	UK	p.williamson@uea.ac.uk
Williamson	Jane	Macquarie University, Department of Biological Sciences	Australia	jane.williamson@mq.edu.au
Williamson	Christopher	Natural History Mus. / Cardiff Univ., Earth & Ocean Sciences	UK	williamsoncj@cardiff.ac.uk
Wilson	Samuel	Scripps Institution of Oceanography, Physical Oceanography	USA	sjwilson@ucsd.edu
Wisshak	Max	SENCKENBERG am Meer, Marine Research Department	Germany	max.wisshak@senckenberg.de
Wojcieszek	Dominika	University of San Francisco, College of Marine Science	USA	dewojcieszek@gmail.com
Wong	Wei Ying	The Ocean Project	USA	wywong@theoceanproject.org
Woodson	C. Brock	Stanford University, Center for Ocean Solutions	USA	bwoodson@stanford.edu
Wootton	Tim	The University of Chicago, Ecology and Evolution	USA	twootton@uchicago.edu
Wouters	Noemie	Oceanographic Center of Lisbon, Portugal	Portugal	nwouters@fc.ul.pt

Wu	Yaping	Xiamen Univ., State Key Lab. of Marine Environmental Science	China	YapingWu@xmu.edu.cn
Wu	Jiawei	National Oceanography Centre, Southampton, UK	UK	wujiawei37@gmail.com
Wulff	Angela	Univ. of Gothenburg, Biological and Environmental Sciences	Sweden	angela.wulff@bioenv.gu.se
Wynn-Edwards	Cathryn	Institute for Marine and Antarctic Studies	Australia	cathryn.wynn-edwards@aad.gov.au
Xiu	Peng	University of Maine	USA	peng.xiu@maine.edu
Xu	Juntian	Xiamen University	China	jtxu@xmu.edu.cn
Yamamoto	Akitomo	Hokkaido University	Japan	akitomo@ees.hokudai.ac.jp
Yin	Kedong	Sun Yat-Sen University	China	k.yin@griffith.edu.au
Yoshimura	Takeshi	Central Research Institute of Electric Power Industry	Japan	ytakeshi@criepi.denken.or.jp
Zamelczyk	Katarzyna	Univ. of Tromsø, Environmental Science Research Laboratory	Norway	katarzyna.zamelczyk@uit.no
Zeebe	Richard	Univ. of Hawaii, School of Ocean and Earth Science & Tech.	USA	zeebe@hawaii.edu
Zhao	Yumei	National Ocean Technology Center	China	phsensorzym@yahoo.com.cn
Zimmerman	Richard	Old Dominion Univ., Ocean, Earth & Atmospheric Sciences	USA	rzimmerm@odu.edu
Zittier	Zora	Alfred Wegener Institute, Integrative Ecophysiology	Germany	Zora.Zittier@awi.de
Ziveri	Patrizia	Institute of Environmental Science and Technology (ICTA)	Spain	patrizia.ziveri@uab.cat



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