Appendix F6

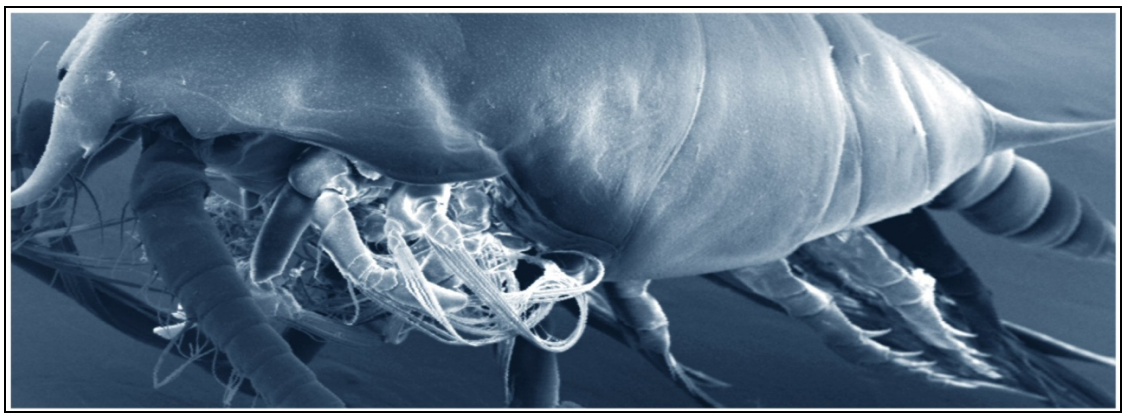
Brinkman et al. 2009b

Understanding Water Column and Pelagic Ecosystem Processes affecting the Lagoon of South Reef, Scott Reef – Annual Report, 2008-2009

BROWSE FLNG DEVELOPMENT
Draft Environmental Impact Statement

EPBC 2013/7079
November 2014

Understanding water column and pelagic ecosystem processes affecting the lagoon of South Reef, Scott Reef



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WOODSIDE ENERGY LIMITED
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PERTH 2009
Final Report

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Cover photo: A new species of Aetideid copepod collected from Scott Reef

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Preamble

Scope of Works

The Australian Institute of Marine Science (AIMS) entered into a contract (No. 4600001754) with Woodside Energy Limited (WEL), as agent for the Browse Joint Venture Partners (JVP), on 28 February 2008, to undertake a three year research program at Scott Reef. For the purpose of this report, this research program is known as the Scott Reef Research Project (SRRP).

The research within the SRRP is divided among three projects, and each project is required to submit an annual report to WEL and the Browse JVP as part of their contractual requirements. This annual report for 2009 summarises the research of Project 3: Understanding water column and pelagic ecosystem processes affecting South Reef Lagoon. The report specifically summarises the data collected from contiguous deployments of in-situ logging instrumentation spanning March 2008 – May 2009, and three inter-seasonal biological oceanography cruises in June/July and December 2008, and May/June 2009. This contemporary data is also discussed in the context of historical AIMS' oceanographic research undertaken at Scott Reef since 1994. The data presented in this report represents the first stages of a multi-year observational programme. For meaningful interpretation of the results of oceanographic studies a solid basis in actual field data is required, incorporating seasonal change in particular. Moreover, there is growing recognition that many changes in both physical and biological oceanography in the tropics are the result of episodic events that only repeated measurement can hope to capture. These results are therefore preliminary, and any conclusions made from them should take consideration of the early stage of this study.

The report follows a format agreed with WEL, and includes responses to particular questions of interest to WEL, presented in an informative manner suitable for a general, non-technical audience. These questions are as follows.

Project 3

Please describe the physical environment of the lagoon of South Reef, Scott Reef since March 2008, summarising:

- Photosynthetically Active Radiation (% reaching the substratum at different depths eg. 1% at 50 m?)
- Temperature (eg. Water cooling, anomalies)
- Salinity (higher salinity in the lagoon)
- Chlorophyll (spatial variability and potentially why)
- Turbidity (spatially variability)
- Sediment Deposition at monitoring sites (comparison to other reef locations)

Undertake a broad comparison of these data with other comparable reef locations in WA, Australia and elsewhere in the world.

Cool-water Intrusions

- Describe the periodicity and extent of thermocline water intrusion into the lagoon of South Reef.
- Include early thoughts on the drivers for these intrusions.
- Describe the biological consequences of these intrusions.
- Early thoughts on the origin of intrusion (ie. depth, direction of the water being pushed up from the channel).

Productivity of Scott Reef waters

- Describe the local and regional productivity at and around Scott Reef (and put into a global context).
- Describe the potential role of the intrusion as a food source for the deep water corals of South Reef lagoon.

Internal Waves

- Describe the characteristics (frequency, seasonality, direction etc) of the internal waves in the Scott Reef region.
- Describe how the structure of Scott Reef changes the characteristics of those waves.
- What is the role of internal waves in the cold water intrusions into the lagoon of South Reef?
- Could the internal waves potentially bring waters (and material) from 250-450 metres depth into the deep water lagoon of South Reef?

Specific Response to WEL Questions

The physical environment of Scott Reef

Oceanic conditions and internal waves

Scott Reef is an emergent reef structure on the edge of the continental shelf in water depths of >400 m. The surrounding oceanic environment is typical of the Timor Sea and North Eastern Indian Ocean, and is characterized by warm, highly transparent waters that are deficient in nutrients in the surface mixed layer (~ 0 – 100 m water depth). Immediately below the surface mixed layer, a strong thermocline exists down to ~ 300 m depth, with a rate of change of temperature of approximately 0.08°C m^{-1}. Prevailing ocean currents and seasonal atmospheric cycles introduce seasonal variability into the vertical structure of salinity and temperature and alter the depth of the surface mixed layer, which deepens during periods of persistent wind, and shallows during calm periods (Fig A.1).

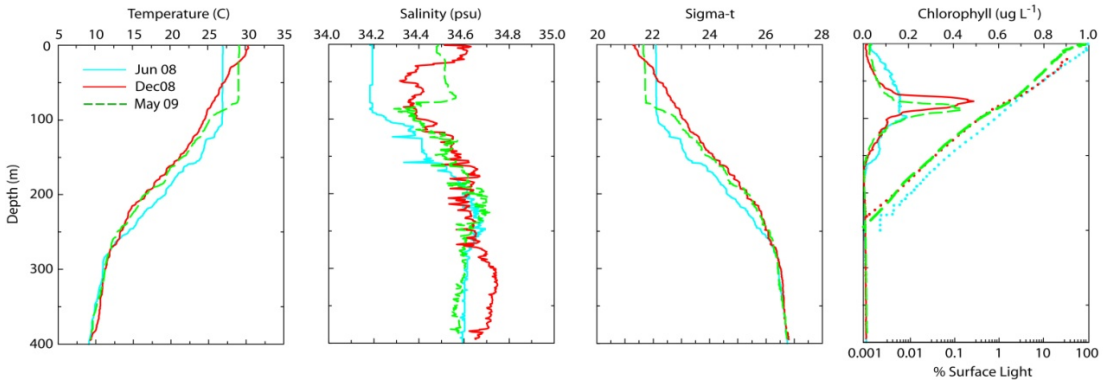

Fig. A1. Vertical profiles of water temperature, salinity, water density, chlorophyll and light penetration at an open water site in the vicinity of Scott Reef, during summer, winter and autumn conditions.

The vertical structure of density in the surrounding ocean supports the existence of internal tides and internal waves that appear as periodic vertical movements in the depth of the bottom of the surface mixed layer. Internal waves are produced as a response to surface tides moving water in a stratified ocean, and internal tides are internal waves at a tidal frequency. The vertical amplitude of internal waves is large compared to the generating surface movement.

At Scott Reef, the semi-diurnal internal tide in the surrounding ocean is modified by interaction with the local bathymetry (Wolanski and Deleersnijder, 1998) resulting in increased vertical displacement and frequency of motion of the thermocline within the channel between North and South Reef, compared to the adjacent open ocean (Fig. A2). The dominant internal wave amplitude range is 30-60 m, with peak amplitudes reaching 110 m. There is no clear seasonal variability evident in long-term observations of internal waves at Scott Reef undertaken between 1996 and 1999.

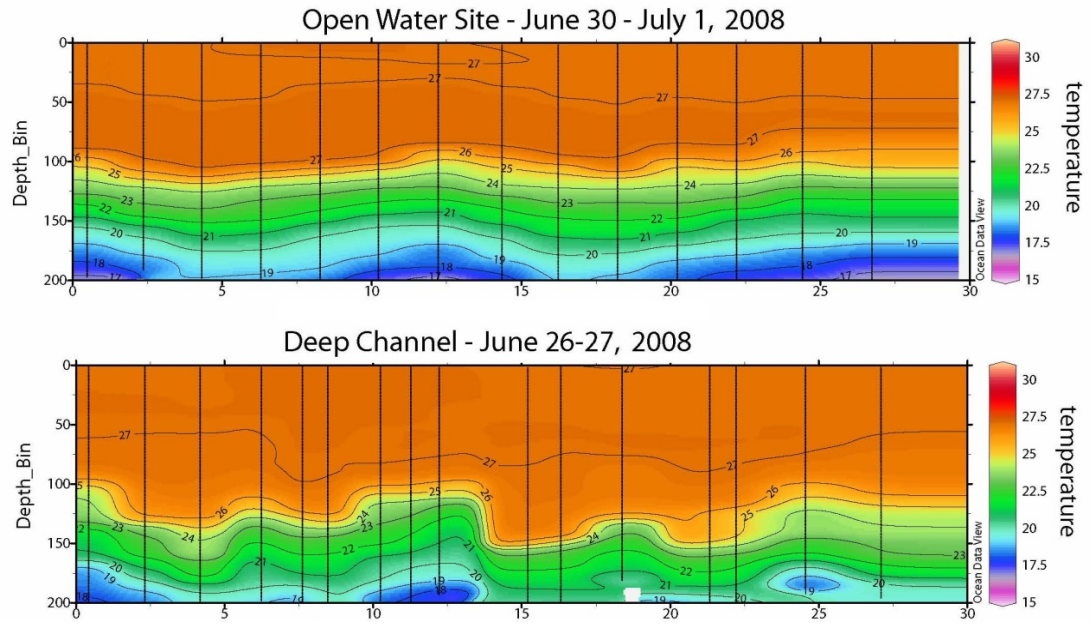

Fig. A2. Contoured time-series of water column temperature profiles over a 24hr period in the open ocean adjacent to Scott Reef (top) and within the deep channel between North and South Reef.

Cool water intrusions.

When the thickness of the surface mixed layer is equivalent to the depth of the South Reef lagoon, local internal wave/tidal dynamics episodically raise the bottom of the surface mixed layer above the sill depth, allowing cooler, nutrient-enriched water from the thermocline to move laterally into the deep lagoon of South Reef. These episodic events are evident in the temperature time-series data collected from the sea-bottom mounted water quality loggers deployed near the northern margin of South Reef lagoon. Intrusions are primarily semi-diurnal, driven by a combination of the strong semi-diurnal periodicity in the prevailing internal wave and tide regime and the horizontal shear due to the strong tidal currents that can entrain water from below the sill depth up into the lagoon. Due to the explicit link to tidal energy, intrusion of thermocline water into the lagoon of South Reef is also strongly modulated by the spring-neap tidal cycle.

Intrusions of cool water are evident at all sites close to the deep channel, suggesting some homogeneity of supply of cool water along the lagoon's northern margin (Fig. A3). Intrusion activity exhibits strong seasonal variability, with greater frequency and increased magnitude of cooling occurring through summer and autumn. This variability is linked to seasonal changes in the thickness of the surface mixed layer in response to atmospheric conditions. With a well mixed surface layer approximately 100 m thick (as shown in Fig A1, June08), vertical motions within the water column at the depth of the sill (~60m) will not be accompanied by significant changes in temperature.

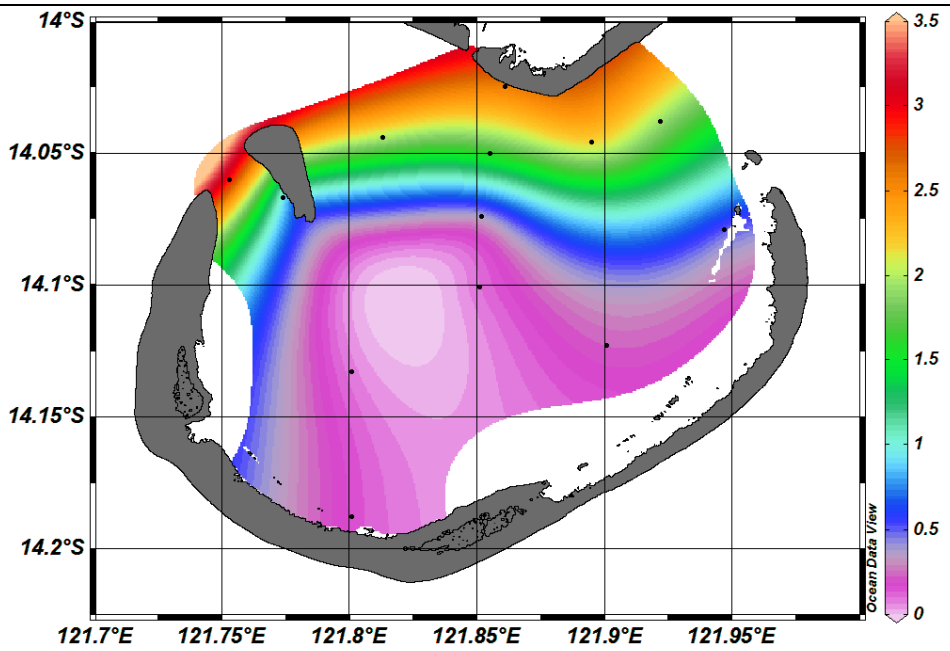

Fig. A3. Mean daily near-bottom temperature range for Autumn, as determined from bottom mounted water quality loggers. Logger locations are shown as dots. Colour scale shows temperature range in °C. Daily temperature range is an appropriate proxy for the intensity of cool water intrusions.

Because of the strong stratification of the water column below the surface mixed layer, the bulk of cool water mixed vertically into the surface layer or intruded laterally into the bottom of the South Reef lagoon will be derived from the upper portion of the thermocline. It is energetically more efficient for water masses to move and mix laterally along (near-) constant density surfaces than vertically against the significant density gradients that exist in and around Scott Reef. It is therefore highly unlikely that water masses from the deeper (>200 m) portions of the deep channel between North Reef and South Reef will be directly upwelled into the lagoon of South Reef.

Cool water intrusions into the South Reef lagoon originate from the thermocline region of the water column that characteristically has higher levels of dissolved inorganic nutrients compared to surface waters, and the introduction of these "new nutrients" in the form of nitrate and phosphate can support the growth of larger phytoplankton. Under these conditions diatoms in particular are able to outgrow the small cells typical of Scott Reef waters, potentially forming short-lived blooms. However, the strong tidal signal in temperature associated with intrusion events observed along the margin of the lagoon suggests that the majority of the volume of cool water and dissolved nutrients that intrude into the lagoon are advected out of the lagoon at the reverse of the tide. Our data show that a small proportion of the intruded water mixes with the lagoon water through processes associated with horizontal current shear and bottom boundary turbulence, and remains resident in the lagoon, resulting in locally enhanced productivity near the seabed of the lagoon (Fig A4). However, results from our biological process studies suggests that the majority of primary production is respired by the plankton, and that the proportion of water column productivity around Scott Reef available to deep water coral communities is likely to be small.

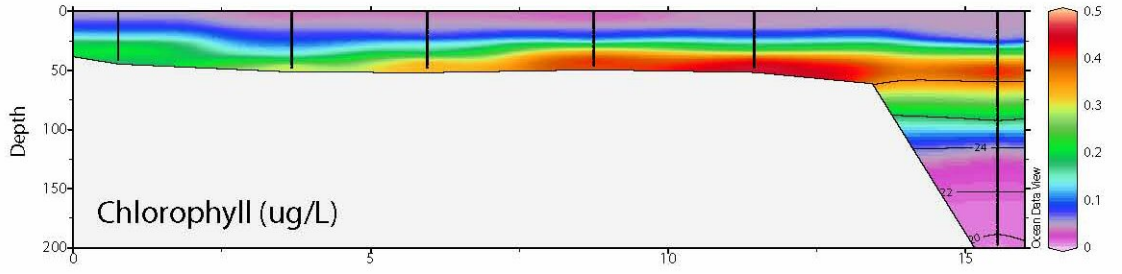

Fig. A4. Contoured longitudinal sections of chlorophyll along the central axis of the South Reef lagoon on 31 May 2009

The physical environment of South Reef lagoon

The physical environment of South Reef lagoon is primarily controlled by the seasonal characteristics of the surface layer of the surrounding ocean, and the interaction of these surface waters with the topography of the reef and lagoon. The lagoon environment mirrors the seasonal and inter-annual variability in temperature and salinity structure exhibited by the regional oceanic waters, with additional higher frequency variability due to the local process such as enhanced vertical mixing, modified horizontal advection and residence times and increased local evaporation.

The average daily water temperature within the lagoon between March 2008 – May 2009 ranged from 25.7°C to 30.0°C, with minimum and maximum observed temperatures of 24.4°C and 30.9°C. Average daily temperatures recorded from loggers within South Reef lagoon show a seasonal variability, with a maximum at each site in April followed by a minimum in late August The primary driver for local temporal and spatial variability of temperature within the South Reef lagoon is the intrusion of cool water originating from within the channel separating North and South Reef (Fig. A3). Near bottom environments close to the northern margin of the lagoon experience daily temperature ranges of up to 5°C during strong intrusion events; elsewhere daily temperature ranges were generally less than 1 °C. Within a particular season, the waters of the lagoon show a spatially consistent vertical temperature structure and are, in general, horizontally well mixed. The degree of temperature stratification shows a strong seasonal signal, as would be expected in a relatively shallow lagoon environment, with summer stratification destroyed through autumn as the water cools to become vertically and horizontally well mixed during winter.

Salinity within the lagoon is, in general, horizontally and vertically uniform, however there is evidence of transient episodes of salinity stratification due to local rainfall and evaporation. For example, a near-bottom salinity maximum layer was observed during May/June 2009 that covered much of the central lagoon. This subsurface layer was embedded in a water mass of uniform temperature and was discontinuous with the sub-surface salinity maximum in the adjacent deep channel and surrounding waters. The near-bottom salinity maximum layer was not observed when the lagoon was re-sampled 9 days later. The source of the higher salinity water was most likely due to evaporation in shallow parts of the lagoon, with subsequent sinking toward the centre of the lagoon rather than input from the deep channel as no temperature anomaly or nutrient signature was evident. Mean salinity within the lagoon was 34.43 PSU and ranged between 33.75 – 35.59 PSU during our observational period.

Chlorophyll concentration (as inferred from Chlorophyll fluorescence) within the lagoon exhibits some episodically driven spatial variability, driven by a local response to the delivery of new nutrients via intrusions of cool water. We have observed a persistent near-bottom

layer of enhanced chlorophyll concentration that covered much of the central lagoon (Fig. A4). The chlorophyll maximum within the lagoon was continuous with a chlorophyll maximum in the adjacent deep channel. This subsurface layer was not accompanied by cooler temperatures, indicating that the local water had been resident in the lagoon sufficiently long to mix with the surrounding water and was the result of local production. Background levels of chlorophyll fluorescence within the lagoon range from 0.18 to 1.42 mg/m^3.

Lagoon water is persistently low in suspended matter, with very limited spatial variability in the deeper sections of the lagoon. Mean daily turbidity levels recorded by near-bottom loggers are *ca* 0.15 NTU, with a maximum observed level of 6.10 NTU in the high current region between West Hook and the Sandy Islet. Mean sedimentation rates determined from in-situ sediment traps within the deeper sections of the lagoon are very low (< 0.5 mg cm^{-2} d^{-1}).

Water clarity within the lagoon is high, and the degree of light penetration shows little seasonality, suggesting no significant inter-seasonal difference in water transparency. The amount of Photosynthetically Active Radiation (PAR) reaching the benthos was >1% surface PAR at the deepest observational sites (~55 m water depth) and was within the range of 1%-10% for observational sites at depths between 55m and 35m. The light extinction coefficient of the lagoonal water was of the order of 0.07 m^{-1}.

Productivity of Scott Reef Waters

The productivity of Scott Reef waters has been measured at four locations which typify the regional environment: (i) the lagoon of South Reef; (ii) the deep channel between North and South Reef; (iii) an exposed site on the NE margin of North Reef; and (iv) a reference site in deep water to the SE of Scott Reef. As is typical of oligotrophic (low-nutrient, low-production) waters of the tropical ocean, phytoplankton cells (Fig A5), primarily photosynthetic bacteria, less than 2 microns in size are responsible for most photosynthetic carbon fixation. These tiny primary producers account for over 70% of the standing crop of chlorophyll and 80% of the primary production. Experiments with isotopic tracers and measurements of oxygen production indicate that regional primary producers typically fix between 0.5 and 2 g C m^{-2} day^{-1}. Because of their high intrinsic productivity, these tiny phytoplankton support a community of grazers of higher biomass than themselves (Gasol et al. 1997). High water temperatures also cause high rates of respiration by phytoplankton, their grazers and other micro-organisms such as bacteria. As a result, virtually all of the carbon fixed by phytoplankton is respired by the microbial plankton community of the upper 100 m rather than being transferred to higher trophic levels, resulting in negative net plankton community production, or heterotrophy.

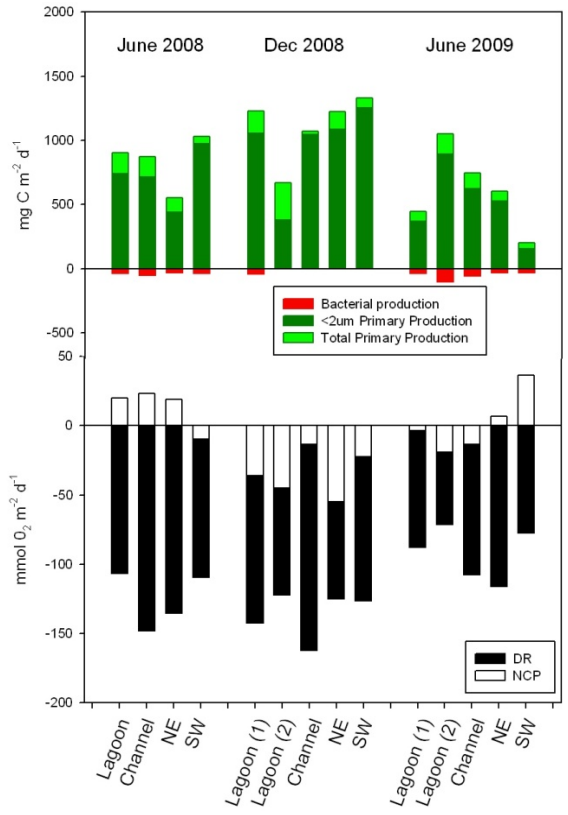

Fig. A5. Productivity of waters around Scott Reef. Top panel, carbon fixation in to particulate matter by the total phytoplankton community and phytoplankton less than 2µm in size, and secondary production by bacteria; Bottom panel, metabolism based upon oxygen flux measurements, contrasting oxygen production as a result of photosynthesis in light bottles (Net Community Production; NCP) and oxygen consumption in dark bottles (Dark Respiration; DR).

Fig. A6. The diverse microplankton community comprises both plants and animals, but their combined respiration is usually greater than phytoplankton production.

Production by phytoplankton in the vicinity of Scott Reef is similar to that near North West Cape (Furnas 2007), and to measurements made by AIMS on the NW shelf in 1993 and 1995. Concurrent bacterial production is at the low end of the range reported from similar environments. There are very few measurements of oxygen metabolism from tropical oceans, making the Scott Reef data set particularly valuable. The Scott Reef data align with the low end of earlier measurements made by AIMS in the Timor Sea, and are similar in magnitude to other areas of the tropical ocean (Equatorial Pacific, Arabian Sea, Banda Sea, Equatorial Atlantic).

Fig. A7 Preparing water samples for incubation to measure plankton production in water baths designed to simulate the light climate at discrete depths in the water column.

Intrusions of deep water introduce "new nutrients" in the form of nitrate and phosphate into the South Reef lagoon. These extra nutrients foster growth of larger phytoplankton such as diatoms, that can stimulate the production of "marine snow" – flocculated organic aggregates that are available to suspension-feeding benthic organisms. However, our data suggest that most production is respired by the plankton, and that the proportion of water column productivity around Scott Reef available to deep water coral communities is likely to be small. If this is the case, it suggests that deep-living corals are primarily dependent on autotrophy (primary production by symbiotic zooxanthellae) so that ensuring that water clarity at Scott Reef remains high is of critical importance to the health of these communities. Further, our data suggest that rapid utilisation and turn-over of nutrients by plankton in response to local nutrient-rich intrusions at Scott Reef is likely to have limited regional significance.

The oceanic region to the NW of Australia is known to be rich in subsurface ocean mixing processes, primarily internal waves and internal tides, that play a role in mixing vertically across ocean isopycnals (density levels). We have shown that at Scott Reef, the unique topography of the deep channel alters the prevailing internal wave climate and delivers cool water with enhanced nutrient concentration well into the euphotic zone where it supports primary production. The extent to which internal processes along the shelf break increase the delivery of nutrients to the euphotic zone at other areas throughout the region, either with or without emergent topography remains unknown.

Executive Summary

This report summarises preliminary findings on the physical and biological oceanography of Scott Reef based on the research by AIMS in 2008 and 2009 under the contract with WEL (No. 4600001754). The project builds on the significant oceanographic research undertaken by AIMS at Scott Reef since 1993. This report specifically summarises the data collected from contiguous deployments of in-situ logging instrumentation spanning March 2008 – May 2009, and three inter-seasonal biological oceanography cruises in June/July and December 2008, and May/June 2009. This contemporary data is also discussed in the context of historical AIMS' oceanographic research undertaken at Scott Reef since 1994. The data presented in this report represents the first stages of a multi-year observational programme. For meaningful interpretation of the results of oceanographic studies a solid basis in actual field data is required, incorporating seasonal change in particular. Moreover, there is growing recognition that many changes in both physical and biological oceanography in the tropics are the result of episodic events that only repeated measurement can hope to capture. These results are therefore preliminary, and any conclusions made from them should take consideration of the early stage of this study.

The general conclusions of this report are:

- The oceanic environment surrounding Scott Reef is typical of the Timor Sea and North Eastern Indian Ocean, and is characterized by warm, highly transparent waters that are deficient in nutrients in the surface mixed layer (~ 0 – 100 m water depth). Immediately below the surface mixed layer, a strong thermocline exists down to ~ 300 m depth, with a rate of change of temperature of approximately 0.08°C m^{-1}. Prevailing ocean currents and seasonal atmospheric cycles introduce seasonal variability into the vertical structure of salinity and temperature and alter the depth of the surface mixed layer, which deepens during periods of persistent wind, and shallows during calm periods
- At Scott Reef, the semi-diurnal internal tide in the surrounding ocean is modified by interaction with the local bathymetry resulting in increased vertical displacement and frequency of motion of the thermocline within the channel between North and South Reef, compared to the adjacent open ocean. The dominant internal wave amplitude range is 30-60 m, with peak amplitudes reaching 110 m.
- The primary driver for local temporal and spatial variability of temperature within the South Reef lagoon is the intrusion of cool water originating from within the channel separating North and South Reef. Intrusions are primarily semi-diurnal, driven by a combination of the strong semi-diurnal periodicity in the prevailing internal wave and tide regime and the horizontal shear due to the strong tidal currents that can entrain water from below the sill depth up into the lagoon. Due to the explicit link to tidal current energy, intrusions are strongly modulated by the spring-neap tidal cycle
- Intrusion activity, and therefore temperature and chlorophyll *a,* exhibits strong seasonal variability, with greater frequency and increased magnitude of cooling occurring through summer and autumn. This variability is linked to seasonal changes in the thickness of the surface mixed layer in response to atmospheric conditions.
- Near bottom environments close to the northern margin of the lagoon experience daily temperature ranges of up to 5°C during strong intrusion events; elsewhere in the lagoon daily temperature ranges were generally less than 1 °C.

- Cool water intrusions into the South Reef lagoon originate from the thermocline region of the water column less than 200 m in depth that characteristically has higher levels of dissolved inorganic nutrients compared to surface waters. The introduction of these "new nutrients" in the form of nitrate and phosphate results in locally enhanced productivity near the seabed of the lagoon, manifested as a persistent near-bottom layer of enhanced chlorophyll concentration that covered much of the central lagoon.
- Our data suggest that it is unlikely that water masses from the deeper (>200 m) portions of the deep channel between North and South Reefs will be directly upwelled into the lagoon of South Reef.
- Lagoon waters are low in suspended matter, water clarity is high and there is significant light penetration with >1% surface PAR reaching the seabed in the deepest sites surveyed (55 m).
- Concentrations of nitrate, phosphate and silicate increase steadily with depth below the mixed layer and decreasing temperature. Nitrate, phosphate and silicate concentrations are linearly correlated with temperature < 26.5 °C, indicating that concentration gradients within the thermocline were largely determined by physical mixing between nutrient depleted surface waters and high-nutrient deep waters. The linearity of these relationships indicate that temperature can be used as a proxy tracer for nutrient concentration in the upper thermocline and freshly intruded water masses before biological uptake commences.
- Over 70% of the standing crop of phytoplankton and 80% of the primary production was measured in the <2 µm size fraction (picoplankton), dominated by the marine cyanobacteria *Prochlorococcus* and *Synechococcus*. At the non-lagoon stations the picoplankton was dominated by *Prochlorococcus*.
- Regional primary producers were found to typically fix between 0.5 – 2.0 g C m^{-2} d^{-1}. High water temperatures also cause high rates of respiration by phytoplankton, their grazers and other micro-organisms such as bacteria. As a result, virtually all of the carbon fixed by phytoplankton is respired by the microbial plankton community of the upper 100 m rather than being transferred to higher trophic levels, resulting in the plankton community failing to achieve metabolic balance (i.e. it is net heterotrophic).
- Production by phytoplankton in the vicinity of Scott Reef phytoplankton is similar to that near North West Cape, and to measurements on the NW shelf in 1993 and 1995. Concurrent bacterial production is at the low end of the range reported from similar environments.
- Our data suggest that most production is respired by the plankton, and that the proportion of water column productivity around Scott Reef available to deep water coral communities is likely to be small. If this is the case, it suggests that deep-living corals are primarily dependent on autotrophy (primary production by symbiotic zooxanthellae) so that ensuring that water clarity at Scott Reef remains high is of critical importance to the health of these communities.
- During winter, depth-integrated estimates of phytoplankton biomass (as chlorophyll *a*) at the production stations within South Reef lagoon were similar to standing crop values recorded at deep water sites adjacent and away from Scott Reef. However, during summer depth-integrated estimates of phytoplankton biomass at the stations close to Scott Reef were approximately twice that recorded at the open water site.
- Pelagic processes in the vicinity of Scott Reef are typical of the oligotrophic open ocean, in that they are dominated by microbial food chains. Microbial food chains are inefficient in transferring nutrients to higher trophic levels (ultimately producing fish),

meaning that most energy is lost in respiration. The balance between net autotrophy (i.e. positive net carbon fixation) and net heterotrophy (losses of carbon due to respiration exceeding carbon fixation) is determined by episodic input of nutrients into the productive surface layers, increasing production and pushing the metabolic balance toward autotrophy. Our data suggest that the metabolic balance of waters around Scott Reef is finely balanced, consistent with the hypothesis that open ocean waters are frequently heterotrophic, and that overall metabolic balance is maintained by aperiodic net autotrophic events that can only be resolved by frequent sampling.

- Localized aggregations of large zooplankton occur within the mixed layer of the deep channel, and appear to be responsible for backscatterance signatures observed on the ship's echosounder.

Introduction

Large tides and strong thermal stratification in the Indian Ocean waters surrounding Scott Reef interact with regional bathymetry to form large and dynamic internal waves and internal tides. These underwater waves episodically lift nutrient-rich sub-thermocline water into the euphotic zone and enhance vertical mixing where there is shear. Locally, bottom topography can alter the amplitude and period of these waves. The net effect is to introduce cool nutrient-rich water from the thermocline into the low-nutrient near-surface layers of the Scott Reef ecosystem (Steinberg et al. 2003; Bird et al. 2004). These added nutrients have the capacity to support enhanced production of organic matter in this normally oligotrophic environment. The spatial extent and temporal variability of intrusion events linked to internal wave activity and topography is poorly understood as are their physical consequences, such as local sediment resuspension and increased turbidity. Nutrients introduced into the near-surface layer during enhanced mixing or upwelling events are likely to initiate higher plankton production, resulting in increased plankton biomass and detritus that becomes available to corals and fishes dwelling on the lagoon margin and floor. To the extent that topographic upwelling is a recurrent process at Scott Reef, this added production of organic matter and food resources is likely to influence the distribution, productivity and resilience of local benthic communities, particularly corals and other filter feeders. In general, deep-living coral communities are likely to be more dependent on heterotrophic nutrition (i.e. feeding on organic matter such as plankton) than shallow water corals, which derive most of their energy autotrophically (i.e. from the photosynthesis of organic matter by zooxanthellae).

This project has two major activity components: physical and biological oceanography. The focus of the physical oceanography component is to characterise: 1) the temporal and spatial dynamics of upwelling into South Reef lagoon; and 2) the temporal and spatial variability of bio-physical variables near the seabed at sites throughout both shallow and deep water environments in the lagoon of South Reef. The focus of the biological oceanographic component is to quantify the distribution, production and cycling of organic matter and nutrients in waters around Scott Reef and in particular the role of internal wave dynamics. Important goals include defining the major spatial fields of biogeochemical variables and significant ecosystem production and trophic processes that influence food availability and quality for deep-living benthic communities on Scott Reef. This component employs a range of technologies and approaches to quantify planktonic productivity and cycling of nutrients, plankton growth rates, the cycling of organic matter in the water column (e.g. respiration – direct consumption of organic material by the plankton), plankton standing stocks and the sedimentation of organic material from the water column.

This report specifically summarises the data collected from long-term deployments of in-situ observational instrumentation (T°C, S‰, PAR, Chl) and the first 3 (of 4 scheduled) inter-seasonal biological oceanographic research cruises. Deployments of in-situ observational instrumentation commenced in late March 2008, with loggers being serviced at ~2 monthly intervals. The most recent data presented in this report were retrieved from loggers serviced in May 2009. The biological oceanography cruises were undertaken from the RV Solander over both winter (June/July, 2008; May/June 2009) and summer (November 30 – December 12, 2008) periods.

Materials and Methods

Physical Oceanography

In-situ observational instrumentation

Time series of key bio-physical parameters are being collected through the deployment of sea-bottom mounted, self contained, multi-parameter water quality loggers. Seabird SBE16 Temperature, Conductivity and Depth loggers with integrated Wetlabs ECO FLNTU and ECO PAR optical sensors for fluorescence, turbidity, and PAR (www.Seabird.com, www.Wetlabs.com) have been deployed at a total of 13 sites within and adjacent to the lagoon of South Reef (see Fig. 1 and Table 1). Observational sites for moored instrumentation have been chosen to:

- provide good spatial coverage of the lagoon of South Reef, with a focus on the exchange of water between the deep channel and the lagoon.
- span a range of depths and habitat types
- complement other historic, current and proposed ecological, biological and environmental monitoring programs.
- provide sufficient local coverage in relation to development options.

Initial locations of observational sites were determined with input from the WEL Browse LNG Development Environmental Section, and reflected a particular geographic focus relevant to the development options at the time of the first deployment (March 2008). The locations of three observational sites were subsequently changed following a refinement of the Browse development plans, and three new instrumental observation sites were established. In May 2009, four shallow observational sites (Sites PE01- PE04) were removed on request from WEL. These sites may change again over the life of the project to reflect potential change in geographic focus for evolving development options.

The SBE16 systems, and integrated Wetlabs sensors are internally logging and powered by self contained batteries. The Wetlabs ECO FLNTU combines optical sensors for Fluorescence at an excitation wavelength of 470 nm with optical scattering measurement at 700 nm for simultaneous determination of turbidity. It is standard practice to use the concentration of material that fluoresces at this excitation wavelength as a proxy for Chlorophyll concentration. The ECO PAR utilizes an integrated Satlantic PAR sensor with a 400 – 700 nm bandpass. Biological fouling in the Seabird is controlled by internal chemical antifouling devices. The Wetlabs sensors employ an integrated anti-fouling bio-wiper to minimize biological growth near the sensor face and protective copper tape to prevent fouling on the instrument body.

Water column current velocities and waves have also been observed at a subset of observational sites (sites PE01, PE02, PE03, PE12, PE06 in Fig. 1 and Table 1) through the deployment of Nortek 600 kHz AWAC and Nortek 1MHz Aquapro Acoustic Doppler Current Profilers (ADCP) with wave capability. The current profilers are mounted adjacent to the water quality loggers and look vertically up through the water column.

Instrument sampling

Seabird SBE16 systems are programmed to integrate 20 samples @ 4Hz every 15 minutes for Conductivity, Temperature, Pressure, PAR, Turbidity, and Chlorophyll (fluorescence).

Nortek AWAC and Aquapro wave current meters are programmed to record a 5 minute average at 30 minute intervals. A 20 minute wave observation burst is undertaken every 4 hours.

Other non-digital observational techniques

In addition to internally logging instrumentation, fixed sediment traps have been attached to the water quality loggers at a number of deepwater sites, since July 2008. Sediment traps are constructed from cylindrical lengths of PVC tubing with an internal diameter of 110 mm. The traps are 700 mm long. An internal baffle system at the entrance of each trap composed of seven 150 mm lengths of PVC tube with an internal diameter of 30 mm is positioned such that the baffle is flush with the outer entrance of the trap. The baffle system is designed to prevent larger organisms from occupying the traps (e.g. fish, crustaceans and octopus), and therefore prevent their nitrogenous waste products and moult shell from contaminating the sediment load. The bottom of each trap is sealed with a screw type PVC cap. After recovery, the contents (sediment and water) of each trap are processed by gravimetric settling of particulate material from a known volume of water onto a pre-weighed membrane filter. Four replicate 60 ml sub-samples are measured from the trap contents. Membrane filters are stored frozen. Mean rates of sediment accumulation (mg cm^{-2} d^{-1}) and sediment size classes will be derived for each trap location for each successive period of deployment.

Instrument deployment frames are also utilised to deploy coral settlement tiles at a number of the deeper observational sites. Instrument deployment frames accommodate up to 6 settlement tiles attached to the frame structure. After retrieval, tiles are bleached, rinsed in freshwater, dried, packaged and transported to the laboratory for analysis by AIMS SRRP Projects 1. Recruits are surveyed using a dissection microscope and grid search and mapping technique. Analysis and reporting of results from settlement tiles will be undertaken by AIMS SRRP Projects 1 and 2.

Deployment summary

Initial deployment of in-situ observational instrumentation was undertaken during the period 18 to 24 March 2008. Subsequent recovery, downloading, servicing and redeployment has been undertaken on four occasions:

- 28 May 2008 – 03 June 2008;
- 20 – 30 July 2008;
- 23 September– 01 October 2008.
- 17 – 24 November 2008.
- 07 – 18 February 2009.
- 15 – 25 May 2009.

Observational sites PE10, PE11 and PE12 were discontinued and sites PE14, PE15 and PE16 (see **Fig. 1**) were established during the research cruise undertaken for the period 23 September – 01 October 2008. The new sites provided a better spatial resolution in the zone of interaction between lagoonal and deep channel waters. Observational sites PE01, PE02, PE03 and PE04 were removed in May 2009 following a request from WEL. Sites PE01, PE02, PE03 and PE04 were adjacent to coral monitoring sites occupied as part of AIMS SRRP Project 1 where temperature loggers and sediment traps remain deployed as part of that Project.

Sediment traps have been deployed on selected deep frames since July 2008. Trap contents for deployments up to May 09 have been analysed for daily sedimentation rate.

Coral settlement tiles were deployed in March 2008, recovered in July 2008, and deployed again in November 2008, and February 2009. Recovered tiles are currently being processed by AIMS SRRP Projects 1 staff.

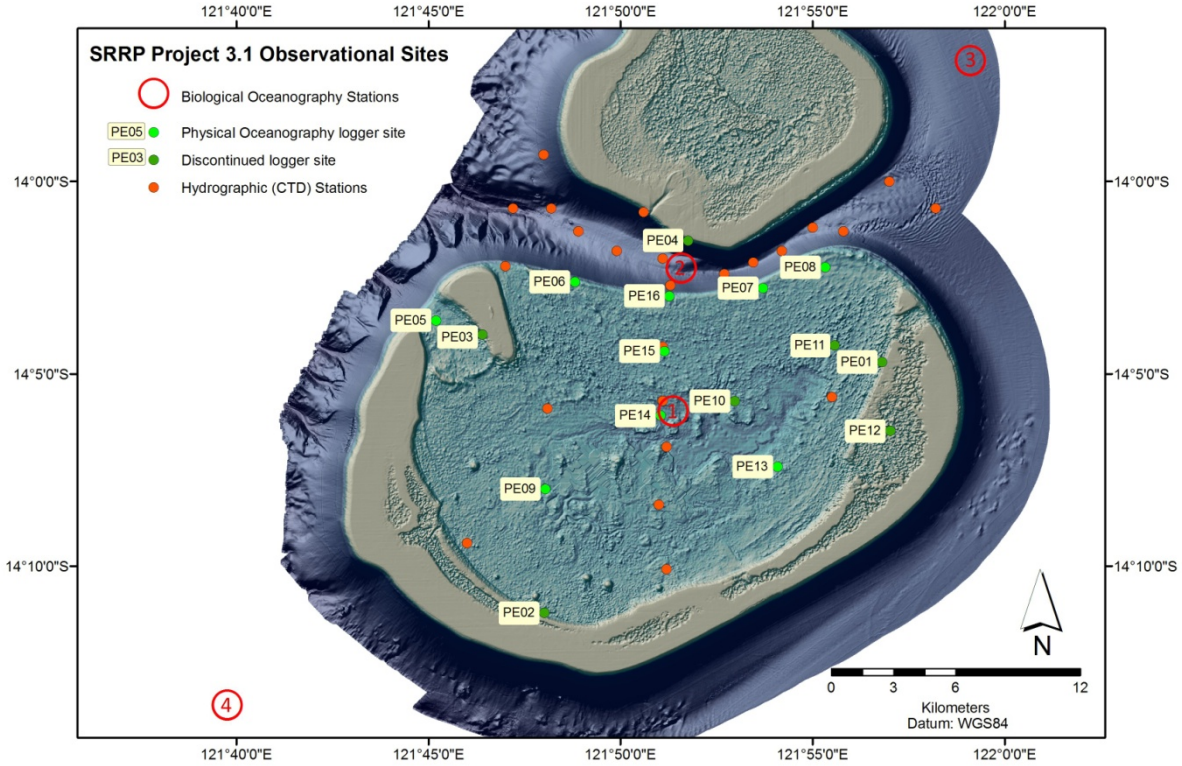

Fig. 1 Locations of biological oceanographic sampling stations, long-term logger sites and hydrographic stations. The four regions of interest for time-series sampling and productivity measurements during the biological oceanography cruises are indicated by the red circles. During September – October observational sites PE10, PE11 and PE12 were discontinued and new sites PE14, PE15 and PE16 were established. Sites PE01, PE02, PE03 and PE04 were removed in May 2009 and are no longer occupied.

Table 1 Nominal positions and depths of biological oceanographic sampling stations and long-term logger sites and instrument configuration (WQ = SBE16 water quality logger, CW = current and wave meter). Horizontal Datum: WGS 84. Depth datum: Approximate depth below surface at time of deployment. Not corrected to chart datum.

	Site name	Latitude (S)	Longitude (E)	Water Depth (m)	Instrument Configuration
Physical oceanographic logger sites	PE01[+]	14° 4.75'	121° 56.85'	24	SBE16 + CW
	PE02[+]	14° 11.29'	121° 48.06'	37	SBE16 + CW
	PE03[+]	14° 4.02'	121° 46.41'	25	SBE16 + CW
	PE04[+]	14° 1.48'	121° 51.60'	34	SBE16
	PE05	14° 3.60'	121° 45.18'	44	SBE16
	PE06	14° 2.65'	121° 48.80'	44	SBE16 (+ CW[#])
	PE07	14° 2.80'	121° 53.73'	44	SBE16
	PE08	14° 2.29'	121° 55.34'	43	SBE16
	PE09	14° 8.02'	121° 48.11'	49	SBE16
	PE10*	14° 5.71'	121° 52.98'	45	SBE16
	PE11*	14° 4.27'	121° 55.58'	47	SBE16
	PE12*	14° 6.48'	121° 57.02'	18	SBE16 +CW
	PE13	14° 7.40'	121° 54.08'	48	SBE16
	PE14[#]	14° 6.09'	121° 51.04'	54	SBE16
	PE15[#]	14° 4.41'	121° 51.15'	50	SBE16
	PE16[#]	14° 2.98'	121° 51.27'	46	SBE16
Biological oceanographic sampling stations	Site 1: Lagoon	14° 3.60'	121° 43.80'	53	
	Site 2: Deep Channel	14° 2.20'	121° 51.70'	456	
	Site 3: NE margin	14° 6.30'	121° 51.00'	450	
	Site 4: Open water reference site	13° 52.10'	121° 52.50'	784	

[+] Discontinued since May 2009
* Discontinued since September 2008
[#] Established in September 2008

Biological Oceanography

The biological oceanography component of the project is based around four (4) cruises over a 2-year period to Scott Reef and surrounding waters, with the rationale that two of the cruises will be undertaken during the winter [dry] season: May-July in 2008 and 2009 and two in the summer [pre-wet] season November-December in 2008 and 2009 to capture broad seasonal differences in wind forcing, insolation and temperature on pelagic biogeochemical processes. To date three of the four sampling cruises have been undertaken with cruises in Jun-Jul 2008, Nov-Dec 2008 and May-Jun 2009. The initial cruise (June/July 2008) followed a period of strong winds and likely enhanced mixing of surface waters within the upper thermocline. The December 2008 cruise took place during calm weather and the period of maximum annual insolation, prior to the extended cloud cover of the wet season. The May-Jun 2009 cruise was undertaken under calm conditions.

The biological and chemical oceanographic sampling are primarily structured around activities at four representative sites (see Fig. 1 and Table 1):

1) A lagoon site in the central part of the lagoon of South Reef (Lagoon – Site 1).
2) A site in the channel between North Reef and South Reef (Deep Channel – Site 2).
3) A reef-flank site (> 150 m depth) on an open margin of North Scott Reef away from the deep channel, but likely to be influenced by internal wave activity (NE Margin – Site 3).
4) A far-field site >10 km from Scott Reef which is likely to be representative of the general outer shelf pelagic environment (Open Water – Site 4).

In June-July 2008, a grid of hydrographic and optical sampling stations was occupied in and around the lagoon of South Reef to define the general field of oceanographic and optical characteristics of water masses in the lagoon. With the December 2008 cruise, the grid was replaced by hydrographic sampling transects down the central axes of South Reef Lagoon and east-west along the deep channel between North Reef and South Reef. These transects were sampled at the beginning and end of the cruise to determine the extent and structure of any intrusions into the lagoon.

At each of the experimental sites, a range of sampling and experimental activities was undertaken over a 48-hour period to resolve key ecosystem fluxes and temporal variability in the environment at these sites.

During the first 24-hour period on-site, conductivity, temperature and depth (CTD) casts were carried out at 2-hr intervals to profile vertical distributions of general water column parameters (T°C, S‰, PAR, NTU, beam transmittance, chlorophyll fluorescence) in response to local internal wave/tidal activity. In periods between CTD casts, at least two water bottle casts were made (day, night) to quantify vertical distributions of dissolved nutrients, organic matter, plant pigments, suspended particulate matter and small phytoplankton in relation to the vertical temperature, salinity and density fields. Four series of depth-stratified zooplankton tows were undertaken with towed multi-net systems to quantify vertical distributions of zooplankton.

During the following 24-hour period on station, experiments or sampling was undertaken to measure:

- Phytoplankton primary production by inorganic ^{14}C uptake
- Bacterial production by uptake of ^{3}H-labelled thymidine
- Plankton community respiration and net photosynthesis by oxygen uptake/production
- Vertical fluxes of particulate and organic matter out of the euphotic zone by drifting sediment traps

- Vertical distributions of downwelling radiance and inherent optical properties (IOP's) in the near-surface layer.
- Hyperspectral remote sensing reflectance (R_{rs}). [June-July 2009 only to date]

Instrumentation used on site consisted of:

- CTD casts – Seabird CTD (SBE19+) with chlorophyll fluorescence (Wetlabs Wetstar), PAR (Biospherical QSP-200), beam transmittance (Seastar), oxygen (Seabird SBE43)
- Underway temperature and salinity (2009) – Seabird SBE21 + Wetlabs FLNTU
- Spectral absorbance (a) – Wetlabs AC-9+ or AC-S + DH4 data concentrator
- Spectral backscatter (b) – Wetlabs BB9
- Downwelling PAR – Biospherical QSR-200 quantum sensor + data logger
- Remote sensing reflectance (Rrs) – DALEC 3-channel hyperspectral radiometer – AIMS/Curtin University – custom made with Zeiss MMS spectrometers
- Picoplankton and bacterial abundance – Becton Dickinson FACScan flow cytometer
- Zooplankton distribution – Hydro-Bios MultiNet – Laser Optical Plankton Counter [LOPC – May/June 2009 only]
- Microzoplankton distribution – Flowcam optical plankton imager [May/June 2009 only]

A detailed description of the experimental and analytical procedures applied during and subsequent to the Biological Oceanography cruise is given in Appendix 1.

Results and Discussion

The physical environment of Scott Reef

Oceanic conditions and internal waves

The oceanic environment surrounding Scott Reef is characterized by a stratified, oligotrophic water column exhibiting some seasonal and inter-annual variability in its temperature and salinity structure. During the winter (dry season), water column profiles at all four experimental sites are characterized by a clearly defined surface mixed layer of near uniform temperature (Fig. 2 and Fig. 3). In June/July 2008, following strong winds, the mixed layer (ca. 27.0°C) was approximately 100 m in thickness, while in June 2009, following calm conditions, the mixed layer was warmer (>28.5°C) and thinner (ca. 70 m). As a result, the thickness of the winter mixed layer exceeded the sill depth for the South Reef lagoon. In contrast during the December 2008 cruise, surface temperatures exceeded 30.0°C and there was no clearly defined surface mixed layer, with water temperature decreasing steadily with depth (Fig. 4).

Between 150 and 250 m, regardless of season, water temperatures decreased at a near uniform rate of 0.08°C m^{-1}. Below 300 m, the rate of temperature change was slower. Winter and summer temperature profiles were essentially similar. Concurrent salinity profiles and temperature salinity plots suggest a more complicated vertical structure of water masses with evidence for multiple interleaving layers within the mixed layer and thermocline to 300 m. While water temperatures below 300 m are relatively uniform, the December 2008 cruise was characterized by distinctly higher salinities at depth, indicating a different source water for this stratum. Salinity distributions within the upper 100 m were characterized by distinct cruise-to-cruise differences. In June 2009, the bottom of the surface mixed layer was characterized by a broad salinity maximum. The source of this higher salinity, but isothermal water is unknown.

The degree of light penetration at all deepwater hydrographic stations (Fig. 2) shows little seasonality, suggesting no significant inter-seasonal difference in water transparency. Red light is attenuated rapidly in the upper 5 m. Thereafter, downwelling irradiance levels exhibited a fairly steady exponential decline with depth. The small deviations from log-linearity between 50 and 150 m are related to slightly enhanced light attenuation by phytoplankton cells in the deep chlorophyll maximum.

On the initial cruise which closely followed an episode of strong winds, the Open Water site (Site 4) was characterized by a broad sub-surface chlorophyll maximum spanning the lower portion of the mixed layer and upper thermocline (Fig. 3). Under the strongly stable conditions of early summer (Dec 2008, Fig. 4) and the following winter (June 2009, Fig. 5) cruises, the subsurface chlorophyll fluorescence maximum was concentrated within a narrow depth band at the top of the thermocline. In some cases, multiple subsurface chlorophyll peaks were observed, likely as a result of the growth of phytoplankton in distinct depth (density) horizons due to the stability of the water column. The vertical confinement of the chlorophyll maximum persisted through the tidal cycle (Fig. 4). Sub-surface chlorophyll fluorescence (calibrated against discrete samples) increased over the course of the daylight hours and then fell during the night, reflecting both the strongly synchronized diel cell division dynamics of the dominant cyanobacteria, *Synechococcus* and *Prochlorococcus*, in these waters and grazing mortality over the course of the night when cyanobacteria were not growing.

At stations close to Scott Reef (Deep Channel and NE Margin sites), vertical profiles of chlorophyll were characterized by higher concentrations with broader vertical distributions within the surface mixed layer due to enhanced vertical mixing associated with the interaction

of the prevailing oceanic conditions and tidal motions with local topography to form large and dynamic internal waves and internal tides (Fig. 6). During summer, well defined, depth stratified peaks in chlorophyll persisted even within the deep channel, suggesting a reduction in vertical mixing during this period (Fig. 7).

Representative plots of temperature-salinity relationships in the upper 400 m for water masses at the open water site in June 2008, December 2008 and June 2009 (Fig. 8) exhibit higher salinities at the surface due to the combined effects of excess evaporation over precipitation and large scale advection of regional water masses. Surface salinities in May-June 2009 were between those in June and December 2008. AIMS research and other historical studies have demonstrated that the prevailing surface circulation in this region varies seasonally, flowing from the southwest between September – January, and from the east-southeast during March – April (Gilmour et al, 2008; Cresswell et al, 1993). The consistency of winter temperature-salinity relationships at sites outside of the lagoon during winter (Fig. 8) indicates a homogeneous water mass, with negligible horizontal density gradients in the vicinity of Scott Reef.

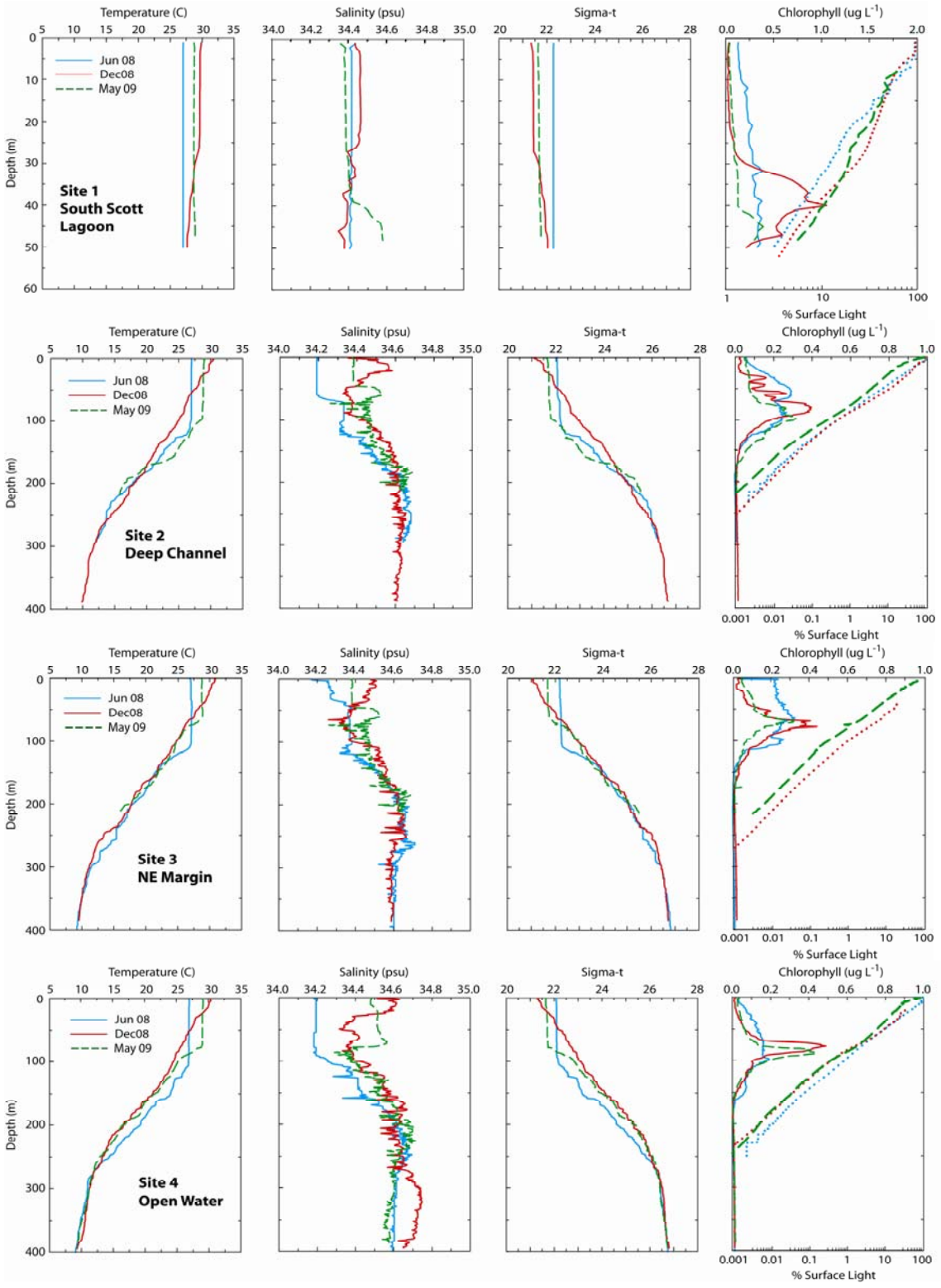

Fig. 2 Representative mid-day vertical profiles of water temperature (°C), salinity (‰), density (sigma$_t$), chlorophyll *a* (µg L^{-1}) and percent surface irradiance (%I$_o$). Rows of panels from top to bottom show Lagoon (Site 1), the deep channel between North Reef and South Reef (Site 2), the NE margin of North Reef (Site 3) and an open-water reference site SW of Scott Reef (Site 4).

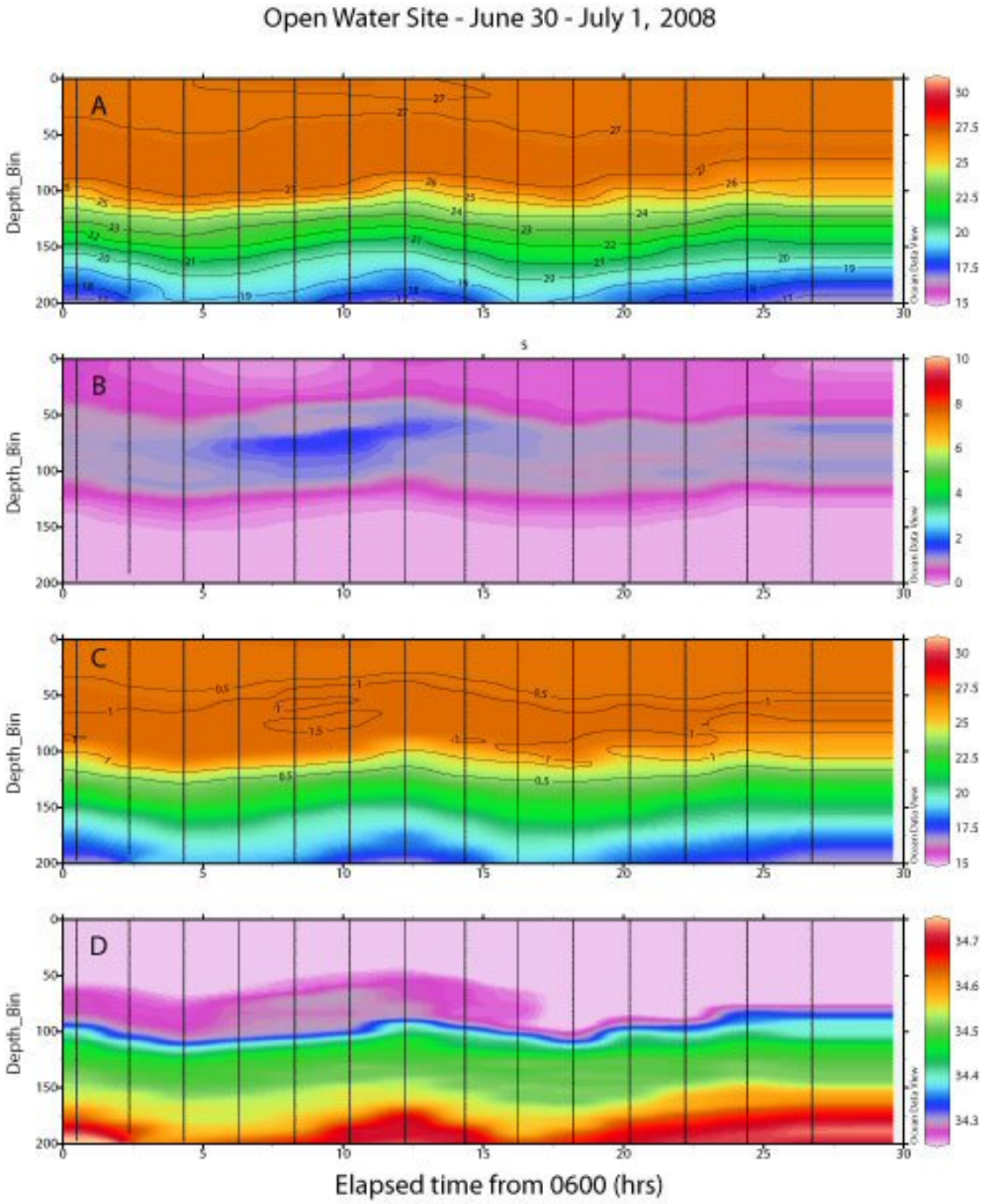

Fig. 3 A) Contoured time series of water temperature (°C) measured at the deep water site SW of South Reef (Site 4) from 0600 local time on 30 June 2008. B) Contoured time series of chlorophyll fluorescence (arbitrary fluorometer units) measured contemporaneously. C) Contoured time series of chlorophyll fluorescence (arbitrary units) overlain on contoured temperature. D) Contoured time series of contemporaneously measured salinity (‰)

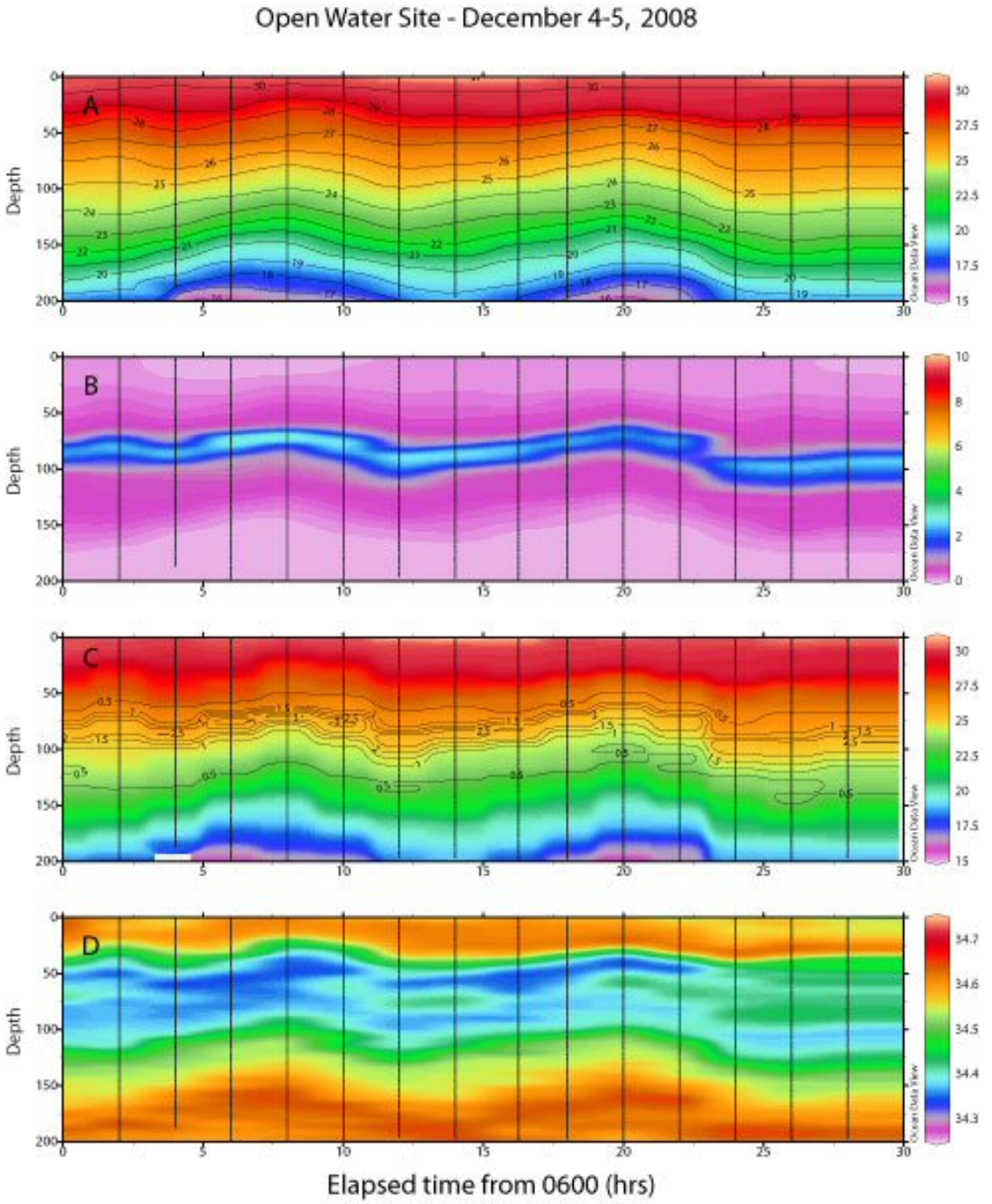

Fig. 4 A) Contoured time series of water temperature (°C) measured at the deep water site SW of Scott Reef (Site 4) from 0600 local time on 4 December 2008. B) Contoured time series of chlorophyll fluorescence (arbitrary fluorometer units) measured contemporaneously. C) Contoured time series of chlorophyll fluorescence (arbitrary units) overlain on contoured temperature. D) Contoured time series of contemporaneously measured salinity (‰)

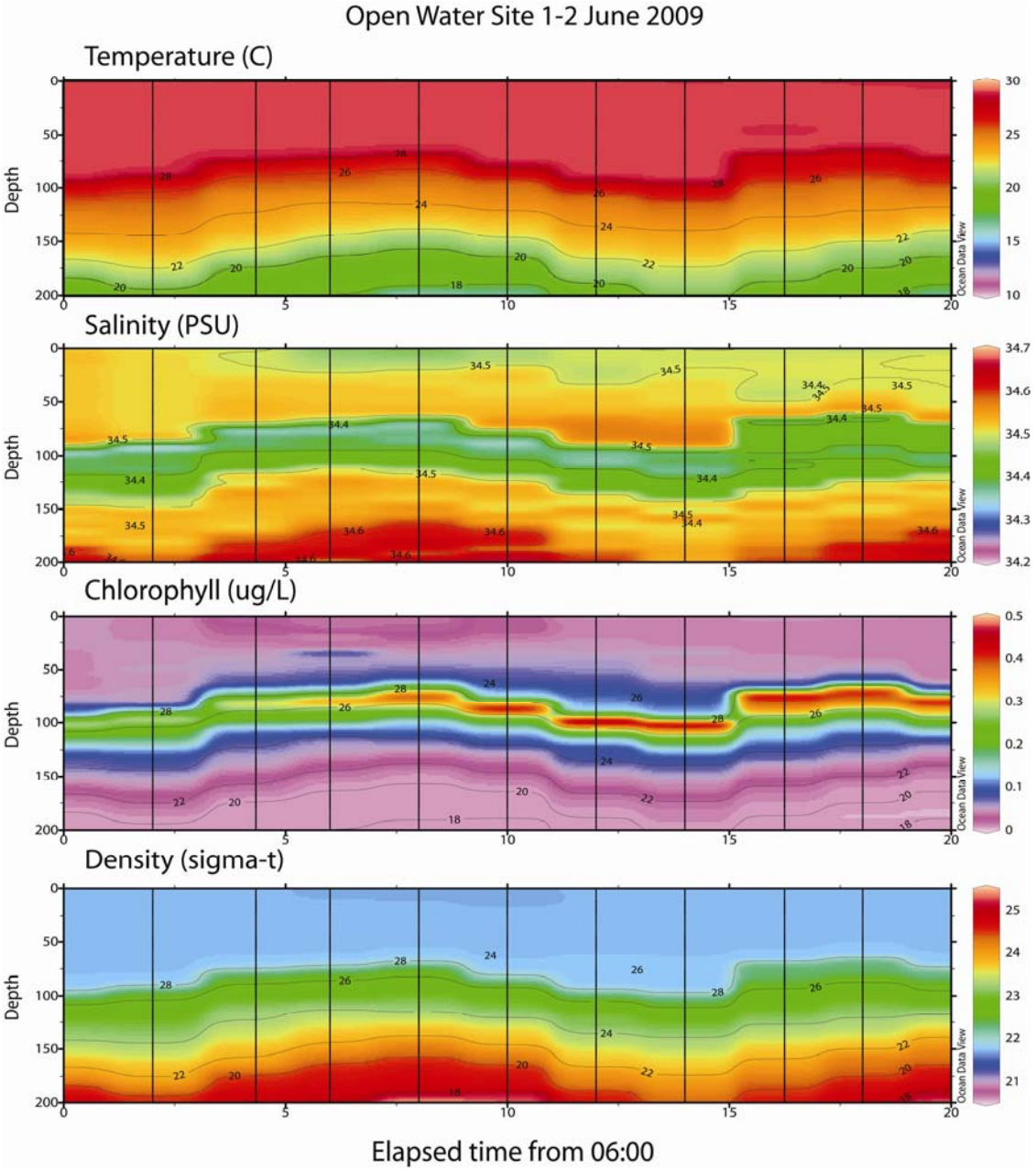

Fig. 5 A) Contoured time series of water temperature (°C) measured at the deep water site SW of Scott Reef (Site 4) from 0600 local time, 1-2 June 2009. B) Contoured time series of salinity (‰). C) Contoured time series of chlorophyll (from profiler fluorescence) with an overlay of temperature contours. D) Contoured time series of contemporaneously measured density (sigma-t) with an overlay of temperature contours

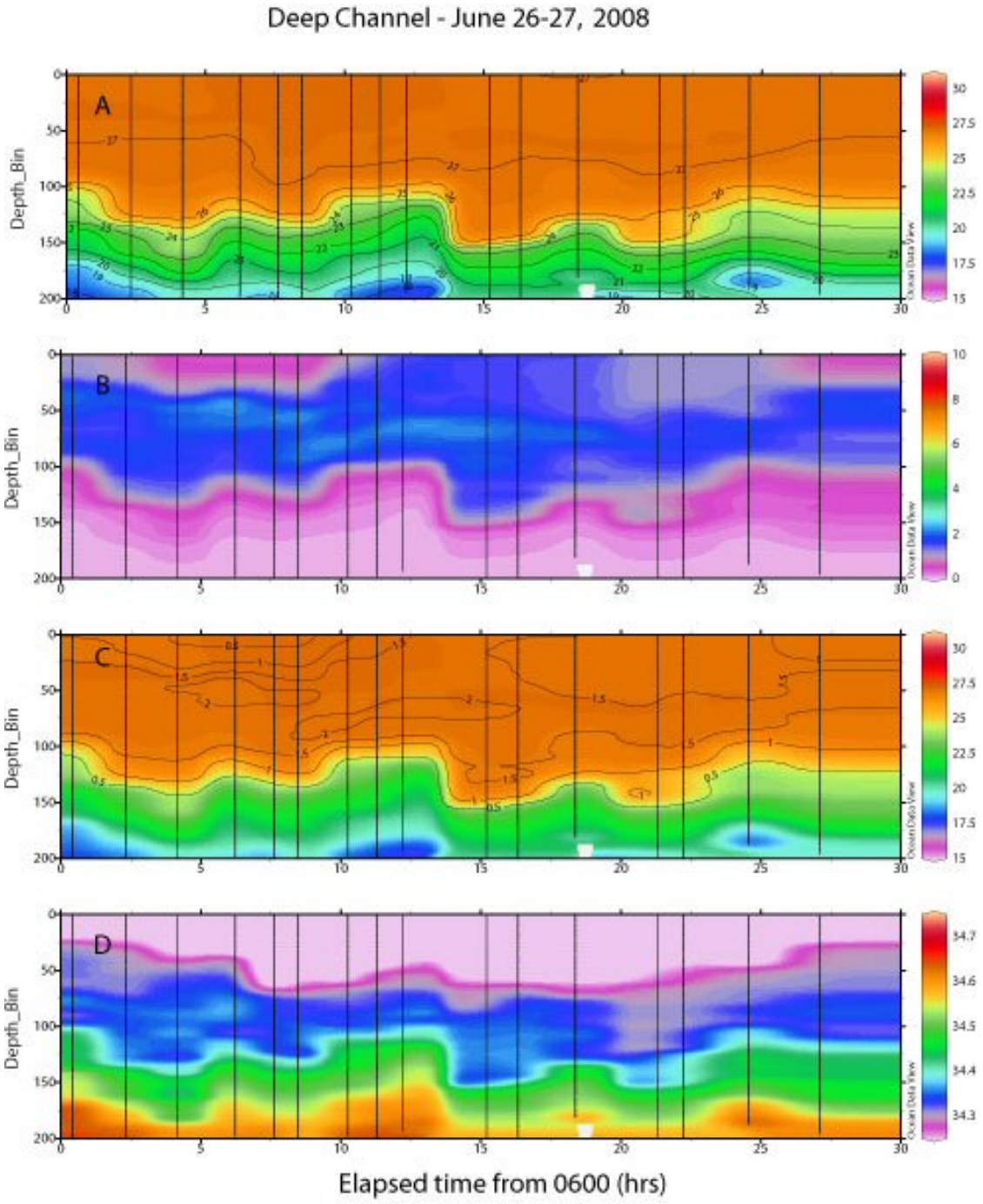

Fig. 6 A) Contoured time series of water temperature (°C) measured in the deep channel between North Reef and South Reef (Site 2) from 0600 local time on 26 June 2008. B) Contoured time series of contemporaneously measured chlorophyll fluorescence (arbitrary fluorometer units). C) Contoured time series of chlorophyll fluorescence (arbitrary units) overlain on contoured temperature. D) Contoured time series of salinity (‰) measured contemporaneously in the deep channel between North Reef and South Reef (Site 2)

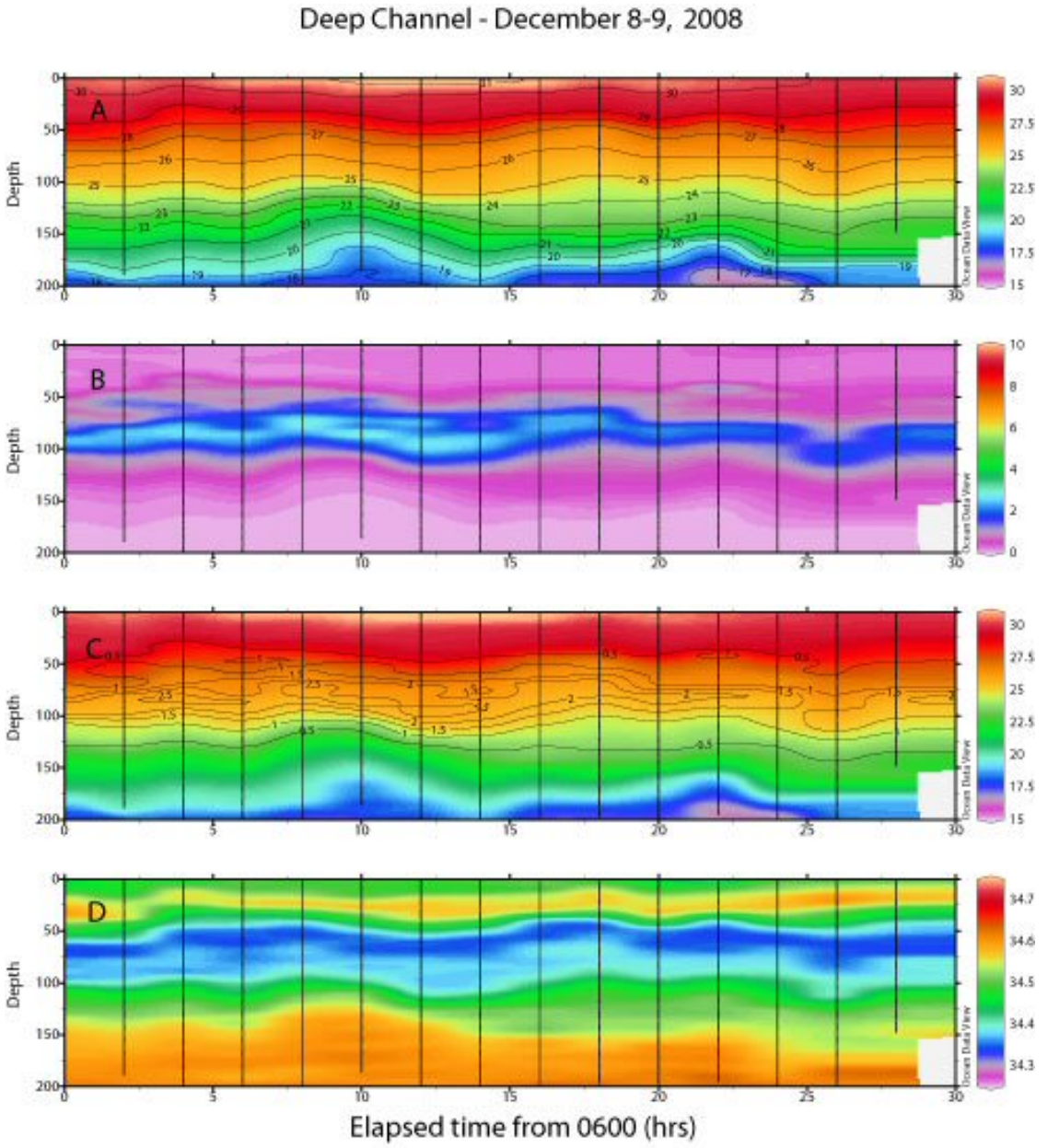

Fig. 7 A) Contoured time series of water temperature (°C) measured in the deep channel between North Reef and South Reef (Site 2) from 0600 local time on 4 December 2008. B) Contoured time series of contemporaneously measured chlorophyll fluorescence (arbitrary fluorometer units). C) Contoured time series of chlorophyll fluorescence (arbitrary units) overlain on contoured temperature. D) Contoured time series of salinity (‰) measured contemporaneously in the deep channel between North Reef and South Reef (Site 2)

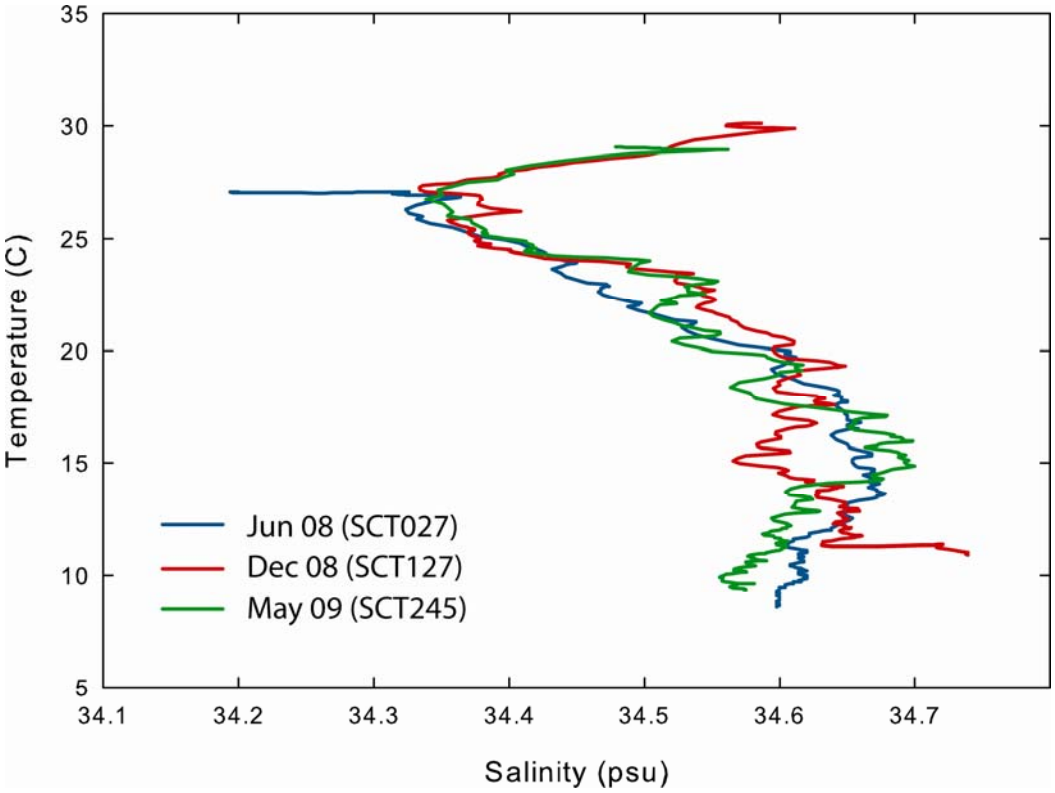

Fig. 8 Representative plots of temperature-salinity (T/S) relationships in the upper 400 m for water masses at the open water site (Site 4) in June 2008, December 2008 and June 2009.

Internal waves are a regular feature of the oceanographic environment at Scott Reef. Relatively less is known about the internal wave dynamics at Scott Reef than further south on the North West Shelf (Holloway, 1983; Holloway, 1994; Holloway, 1996) where the internal wave dynamics influence engineering structures constructed for the offshore oil and gas industry. Vertical mixing associated with internal wave activity is presumed to be a significant source of nutrients supporting biological productivity on the North West Shelf.

The internal waves at Scott Reef are primarily semi-diurnal in periodicity, and are generated by an interaction between the local internal tide and shelf bathymetry (Wolanski and Deleersnijder, 1998). Observed internal wave activity at Scott Reef is therefore a combination of local internal tides and internal waves. Away from Scott Reef or other large bathymetric features, water motions associated with internal wave activity have a dominant cross-shelf direction (Holloway, 1994). Wave activity has a spring-neap variation in intensity, most likely modulated by the internal tide. This variation is more pronounced to the south of Scott Reef (e.g. Figure 17, Rowley Shoals, Furnas and Steinberg, 1999) than has heretofore been observed at Scott Reef.

At the far-field, Open Water site to the southwest of Scott Reef (Fig. 3, Fig. 4, & Fig. 5), the local internal waves exhibited a regular, sinusoidal character that was most pronounced at depths > 100 m. In contrast, wave dynamics observed at the Deep Channel site during winter (Fig. 6, Fig. 7**)** were considerably more irregular due to interactions with the local bathymetry, and again, internal wave activity was most pronounced at depths > 100 m, within the thermocline. During summer, with a much more stable water column, internal wave activity within the channel was more regular (Fig. 7) and exhibited periodicity and amplitude similar to that observed at the Open Water site during the same period.

At Scott Reef, upwelling of thermocline water and contained nutrients occurs through two mechanisms. The first is through enhanced vertical mixing of thermocline waters into mixed layer due to enhanced horizontal shear at the top of the thermocline. This vertical mixing process is enhanced close to Scott Reef and in the deep channel due to topographic disruptions of the waves by local bathymetry.

The second type of upwelling occurs when the bottom of the surface mixed layer (nominally the 22.24 σ_t density surface during the June – July 2008 cruise) is shallower than the sill depth of the South Reef lagoon. This can be due to either a regional thinning of the surface mixed layer as a consequence of regional transport of surface waters and vertical mixing processes, or to local internal wave/tidal dynamics that raise the top of the thermocline above the sill depth. The former mechanism is likely to produce a situation where the top of the thermocline is shallower than the lagoon sill depth for an extended period of time, while the latter mechanism produces a situation where the thermocline top is shallower than the sill depth on an irregular or episodic basis. In both cases, cooler, nutrient-enriched water from the thermocline is able to move laterally into the deep lagoon of South Reef. These episodic events can be seen in some of the near-bottom temperature records from temperature loggers deployed on the northern margin of South Reef lagoon (see next section for discussion). During these intrusion events, the extent of lateral movement of thermocline waters into the lagoon depends upon both the length of time the thermocline is shallower than the sill depth and the thickness of the intruding layer (height of the thermocline top above the bottom).

Two studies have previously dealt with internal wave activity at Scott Reef. Firstly, Wolanski and Deleersnijder (1998) observed internal wave activity at Scott Reef using sub-surface temperature and current meter moorings on the western and north-eastern flanks of the reef

system, at depth between 100-200 m. The observed waves were mainly semi-diurnal in nature and modulated with the spring-neap tidal cycle, with amplitudes peaking at up to 60 m. during spring tides. Secondly, between 1993 and January 1999, a mooring with sub-surface temperature and pressure (depth) sensors was maintained at Scott Reef to monitor internal wave activity in the vicinity of the reef. The mooring was nominally located on the continental slope immediately to the west of South Reef (near 14 5.3'S 121 43.1'E). The mooring consisted of temperature-pressure loggers nominally deployed at 100 and 150 m in the upper thermocline. The objective of the mooring program was to record ranges of temperature variability within narrow depth strata associated with vertical movements of the thermocline in internal waves or tides.

Absolute fluctuations of temperature recorded by individual instruments at depth are related to four factors:

1. Regional-scale temperature variations associated with seasonal insolation and large-scale water movements.
2. Cross-shelf tidal oscillations of the horizontal temperature gradient past the mooring site
3. Vertical motions of the instruments in the thermocline due to mooring lean
4. Local vertical movements of the thermocline due to internal waves and internal tides.

Regional-scale temperature variations at Scott Reef associated with seasonal changes in insolation and large-scale water movements were found to be on the order of one to several °C per month. The largest *monthly* change in low-pass filtered (removing short-term variability, i.e. daily, tidal) temperature between 1993 and 1999 was 3.76°C (Furnas and Steinberg, 1999). The *median monthly* change in low-pass filtered temperature over this period was < 1.7°C. Measured ranges of water temperature within one-month periods at ~100 and 160 m were on the order of 3 times the range of low-pass filtered temperatures for those periods (Table 2). In the absence of temperature changes due to the passage of frontal boundaries, daily low-pass temperature fluctuations would most likely be less than 0.1°C (Furnas and Steinberg, 1999). Cross-shelf temperature gradients in the vicinity of Scott Reef at 0, 50 and 100 m were 0.001, 0.007 and 0.049°C, respectively (Furnas and Steinberg, 1997). For a nominal cross-shelf tidal current velocity of 1 kt (1.8 km hr^{-1}), the net horizontal displacement of water during one half-tidal cycle (6 hours) would be approximately 11 km which would lead to nominal temperature variations < 0.1°C in the upper 50 m and no greater than 0.5°C at 100 m. Vertical temperature gradients in the thermocline near Scott Reef are generally between 0.04 and 0.07°C m^{-1}. Recorded vertical movements of the moored instruments at Scott Reef due to local currents were almost always < 5 m. As a result, diel temperature fluctuations due to mooring lean would be on the order of 0.2 to 0.4°C. Taken together, maximum daily temperature fluctuations at depth associated with lateral water movements past the mooring and vertical mooring motion are most likely < 1°C. The largest part of temperature variability measured at depth within a relatively short (24 hour) period is therefore associated with vertical movements of the thermocline under the influence of internal waves and tides.

Temperature fluctuations associated with internal wave or internal tide activity in a given depth band can be calculated as the differences between the absolute temperature range for a monthly period and the range of low-pass filtered temperatures for that period. The maximum potential amplitude of internal waves within monthly periods were estimated by dividing the difference between the raw and low-pass filtered temperature by a conservative estimate of the mean temperature gradient in the thermocline (0.07°C m^{-1}). An alternative approach to estimating wave amplitude is to divide the average diel (24 hour) range of water temperatures at a particular depth by the vertical temperature gradient. These two approaches yield similar estimates of internal wave amplitude within monthly time bands (Table 2).

Table 2 Measured ranges of raw and low-pass filtered water temperatures within monthly periods at Scott Reef between November 1997 and January 1999 and estimated amplitudes of internal waves calculated from diel (24-hour) temperature ranges within monthly time frames. From Furnas and Steinberg (1999).

	Temperature Range				Internal wave amplitude			
	Shallow (100 m)		Deep (160 m)		Shallow (100 m)		Deep (160 m)	
	Raw	Low Pass	Raw	Low Pass	Max	Mean	Max	Mean
	°C	°C	°C	°C	M	m	m	m
1997								
Nov	5.04	1.11			56	48		
Dec	6.04	2.13			56	53		
1998								
Jan	5.23	1.70			50	48		
Feb	5.93	2.13			64	52		
Mar	6.03	2.03	4.54	1.01	57	50	50	45
Apr	8.18	2.65	5.95	2.33	79	64	52	56
May	8.25	2.43	7.08	1.73	83	76	76	63
Jun	6.91	1.81	8.04	2.52	73	69	79	67
Jul	5.00	1.75	5.76	2.32	46	49	49	52
Aug	5.76	2.07	7.60	1.34	53	52	79	66
Sep	5.45	1.67	5.58	1.45	54	55	59	50
Oct	4.78	1.17	6.33	1.31	52	43	72	57
Nov	6.04	1.29	6.02	1.45	68	56	65	61
Dec	5.44	1.54	6.83	1.64	56	45	74	57
1999								
Jan	4.73	0.83	5.91	0.88	56	43	72	51
Mean	5.92	1.71	6.33	1.63	60	54	67	57

Time series of diel temperature ranges recorded at 100 m for the period between August 1995 and January 1999 (Fig. 9) exhibit fluctuations between 2 and 4°C, with peak values approaching 8°C. For a conservative temperature gradient of 0.07°C m-1, this would translate to a dominant internal wave amplitude range of 30-60 m, with peak amplitudes reaching 110 m.

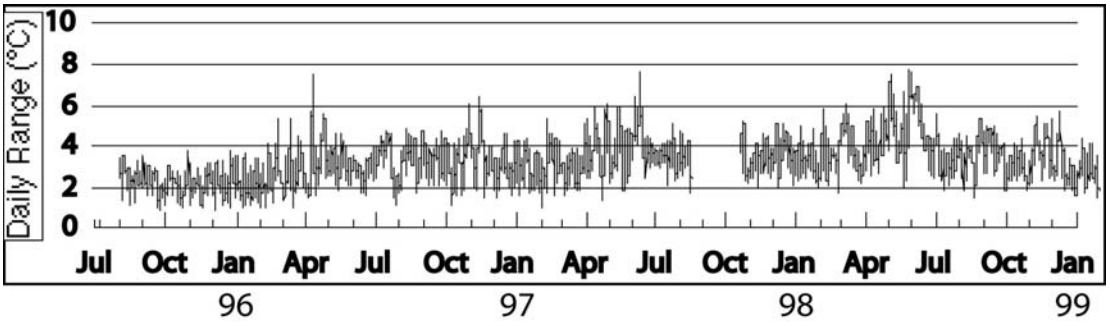

Fig. 9 Diel temperature ranges at 100 m depth between August 1995- January 1999.

During winter in 2008 and 2009, measured vertical fluctuations of the thermocline due to internal waves over one diel period at time series sites 2, 3 and 4 were ~ 60 m, 25-35 m and ~30 m, respectively (Fig. 10). During the strongly stable conditions of early summer (Dec 2008), the magnitudes of the vertical fluctuations of the thermocline due to internal waves over one diel period were ~35 m at time series sites 2, 3 and 4.

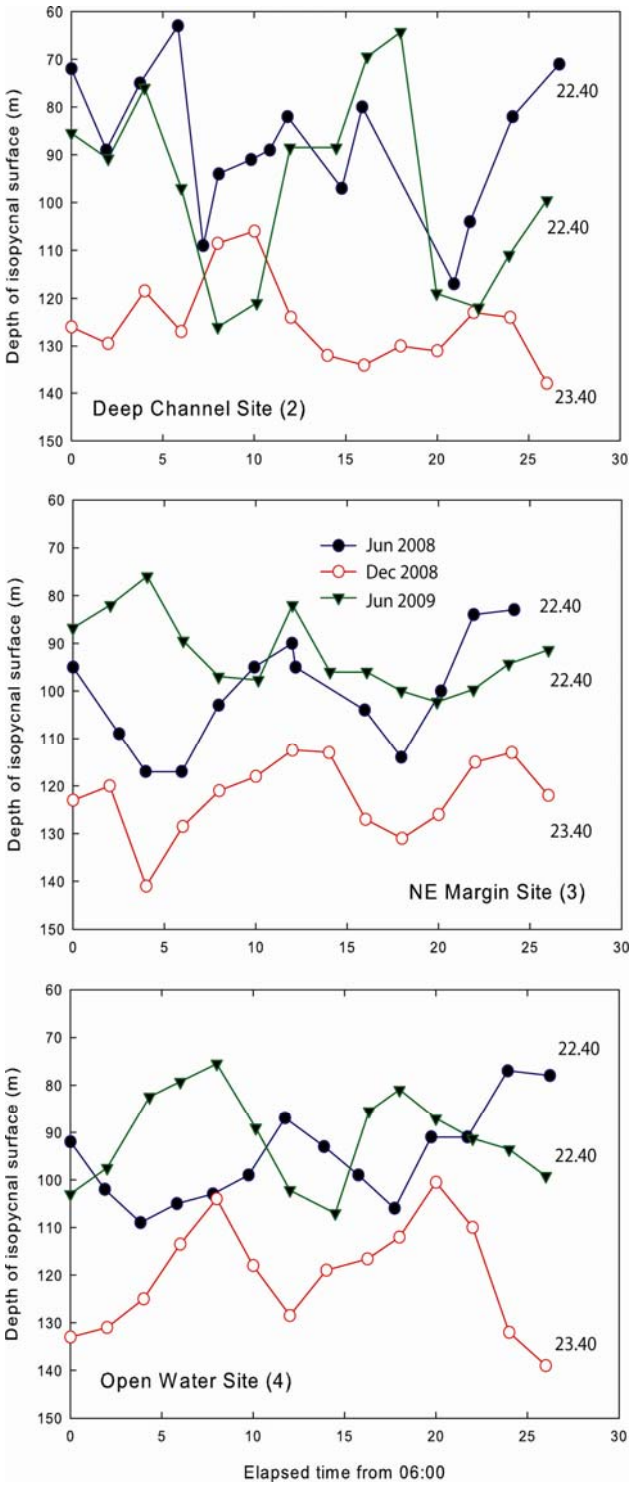

Fig. 10 Vertical excursions of selected density surfaces due to internal wave activity over diel time frames at Scott Reef deep water sites.

During the entirety of the June-July 2008 biological oceanography cruise to Scott Reef, the bottom of the mixed layer (90 – 150 m in the deep channel) lay significantly deeper than the sill depth of the South Reef lagoon. As a result, no evidence for upwelling was observed in the time series sampling for this period.

The physical environment of South Reef lagoon

The hydrographic environment of South Reef lagoon is primarily controlled by the seasonal characteristics of the surface layer (0 – 100 m water depth) of the surrounding ocean, and the interaction of these surface waters with the topography of the reef and lagoon. The lagoon environment mirrors the seasonal and inter-annual variability in temperature and salinity structure exhibited by the regional oceanic waters, with additional higher frequency variability due to the local process such as enhanced vertical mixing, modified horizontal advection and residence times and increased local evaporation.

Temperature and Salinity

The primary driver for local variability of temperature within the South Reef lagoon is the depth of the surface mixed layer within the channel separating North and South Reef, relative to the sill depth of the South Reef lagoon. When the depth of the surface mixed layer is equivalent to the sill depth, local internal wave/tidal dynamics episodically raise the bottom of the surface mixed layer above the sill depth, allowing cooler, nutrient-enriched water from the thermocline to move laterally into the deep lagoon of South Reef.

These episodic events are evident in the temperature time-series data collected from the sea-bottom mounted water quality loggers deployed near the northern margin of South Reef lagoon (Fig. 11). Intrusions are primarily semi-diurnal (Fig. 12), driven by a combination of the strong semi-diurnal periodicity in the prevailing internal wave and tide regime (see Fig. 6) and the horizontal shear due to the strong tidal currents that can entrain water from below the sill depth up into the lagoon. Due to the explicit link to tidal energy, intrusion of thermocline water into the lagoon of South Reef is strongly modulated by the spring-neap tidal cycle.

Intrusions of cool water are evident at all sites close to the deep channel, suggesting some broad homogeneity of supply of cool water along the lagoon's northern margin. The depth of the sill along this margin is relatively consistent (~40 m depth) and shoals with proximity to East Hook and the Sandy Islet, and any fine-scale variability in the timing and location of intrusions is likely to be due to the complex internal wave dynamics within the Deep Channel (Fig. 6). The strong tidal signal in the temperature records associated with intrusion events observed along the margin of the lagoon suggests that the majority of the volume of cool water that intrudes into the lagoon is advected out of the lagoon at the reverse of the tide. However, a proportion of the intruded water will mix with the lagoon water though mixing processes associated with horizontal current shear and bottom boundary turbulence, and remain resident in the lagoon to be advected by lower frequency (sub-tidal) processes. This propagation and subsequent mixing of intruded water within the interior of the lagoon is evident in temperature time-series data from instruments deployed along a North-South transect from the deep channel into the interior of the South Reef Lagoon (Fig. 12). At the northern margin of the lagoon (site PE16), temperature exhibits 1.0-2.0 °C fluctuations tied to the tidal frequency and modulated by the spring neap cycle. With increasing distance into the lagoon, there is a decrease in both the magnitude and frequency of cooling, and an increase in the time taken for temperature to return to the 'pre-cooling' conditions. At sites interior to the lagoon, the time between rapid cooling and return to pre-cooled temperatures is indicative of the residence time and mixing of the introduced cool water; short times indicate rapid flushing and limited mixing, extended times indicate reduced flushing and extended mixing. For sites PE15 and PE14, this time is approximately 1-2 days, and 2-5 days,

respectively, suggesting that nutrient-enriched cool water delivered into the system remains resident within the interior of the lagoon for up to 5 days, before it is thoroughly mixed with the greater surrounding waters.

Intrusion activity demonstrates strong seasonal variability, with greater frequency and increased magnitude of cooling occurring from April through to May (Fig. 13). During June, July and August, evidence of intrusions into the lagoon of South Reef is limited to low magnitude (< 1.0 °C temperature drop) episodes occurring between West Hook and Sandy Islet. Through September and into November the frequency, magnitude and extent of intrusions again increases, and is evident at all sites along the northern edge of South Reef. This seasonal variability of cool water intrusion activity is linked to seasonal changes in the depth of the surface mixed layer in response to atmospheric conditions. With a well mixed surface layer persisting down to a depth of approximately 100 m (as shown in Fig. 2: June 08,), vertical motions within the water column at the depth of the sill will not be accompanied by significant changes in temperature. In contrast, during late spring and early summer when the water column exhibits no clearly defined mixed layer (Fig. 2, Dec 08), vertical motion of the water column will result in temperature fluctuations when observed from a fixed depth reference level.

Daily temperature ranges from the sea-bottom mounted loggers (Fig. 13) show that during the autumn period of increased frequency of intrusion events, the daily temperature ranges fluctuated by only 2 – 4°C, with a maximum daily temperature range of > 4.5°C. Average daily temperatures at sites along the northern margin of the southern lagoon ranged between 28.0 and 29.0 °C. The temperature- salinity (T/S) relationship of the intruded water confirms its origin from ~160 m depth within the thermocline. During October and November, daily temperature ranges fluctuated by only 1.0 - 3.0 °C. During this early summer period, a reduction in temperature of this range is indicative of water originating from <100 m depth.

Daily statistics, aggregated monthly, have been calculated for all temperature time-series data (Appendix A - Table A. 1). During the period March 2008 – May 2009, the average daily water temperature within the lagoon ranged from 25.7°C to 30.0°C, with minimum and maximum observed temperatures of 24.4°C and 30.9°C. Average daily temperatures recorded from loggers within South Reef lagoon show a seasonal variability, with a maximum at each site in April followed by a minimum in late August. Higher temperature were recorded at loggers deployed at shallow sites (e.g. sites PE01, PE02, PE03, PE04, & site PE12), with the highest temperature (*ca* 30.9°C) recorded within the shallow reef edge site (site PE03), presumably due to local warmed water originating from the reef top flowing passed this logger site. Consistently lower average temperatures were recorded at sites close to the channel (sites PE05, PE06, PE07, PE08, PE16) due to the persistent cooling influence of the intrusions.

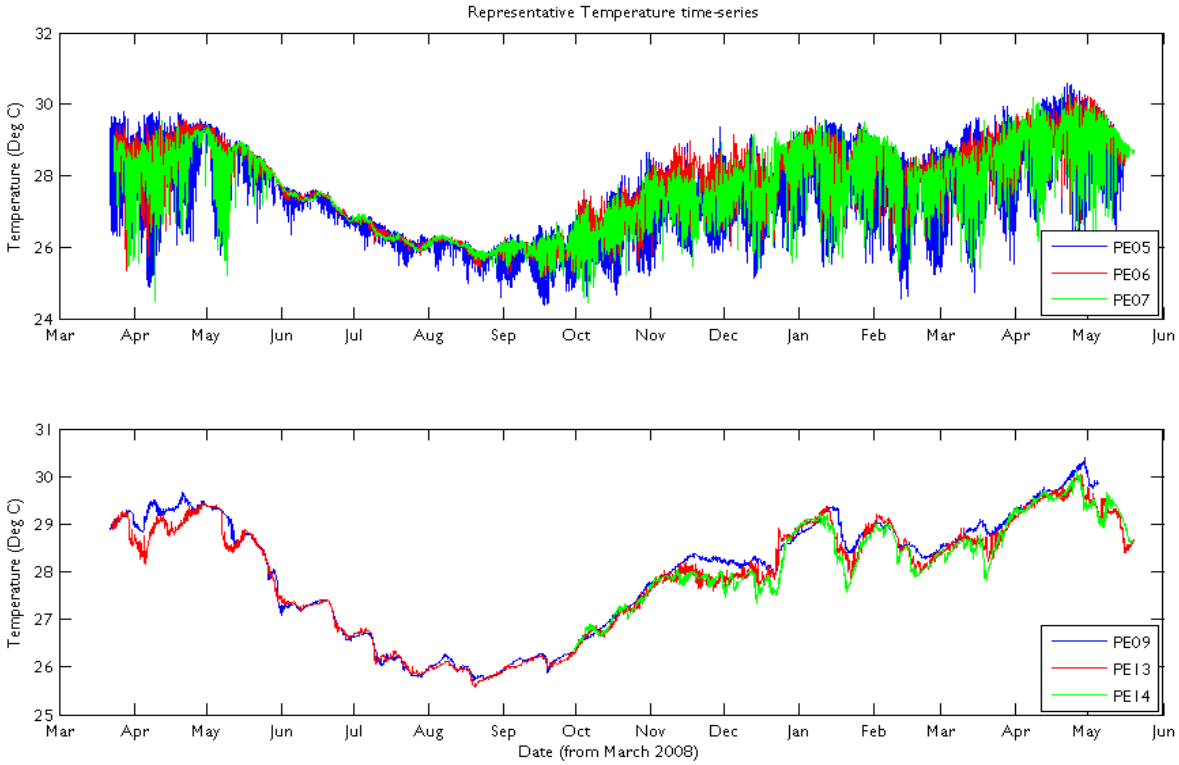

Fig. 11 Time series of temperature (@15 minute sampling) at in-situ logger sites. Top plot shows representative sites adjacent to the channel; bottom plot show sites in the interior or southern region of the lagoon.

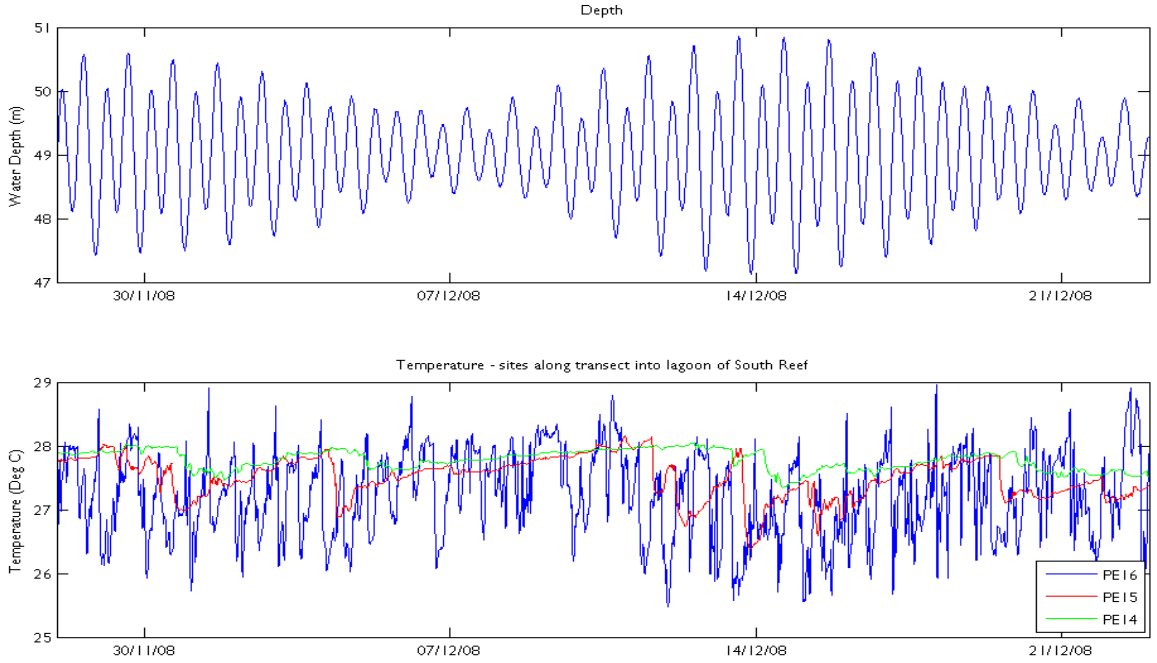

Fig. 12 Time series of water depth (at Site PE16) and temperature at sites PE16, PE15 and PE14 along a North-South transect from the deep channel into the interior of the South Reef Lagoon.

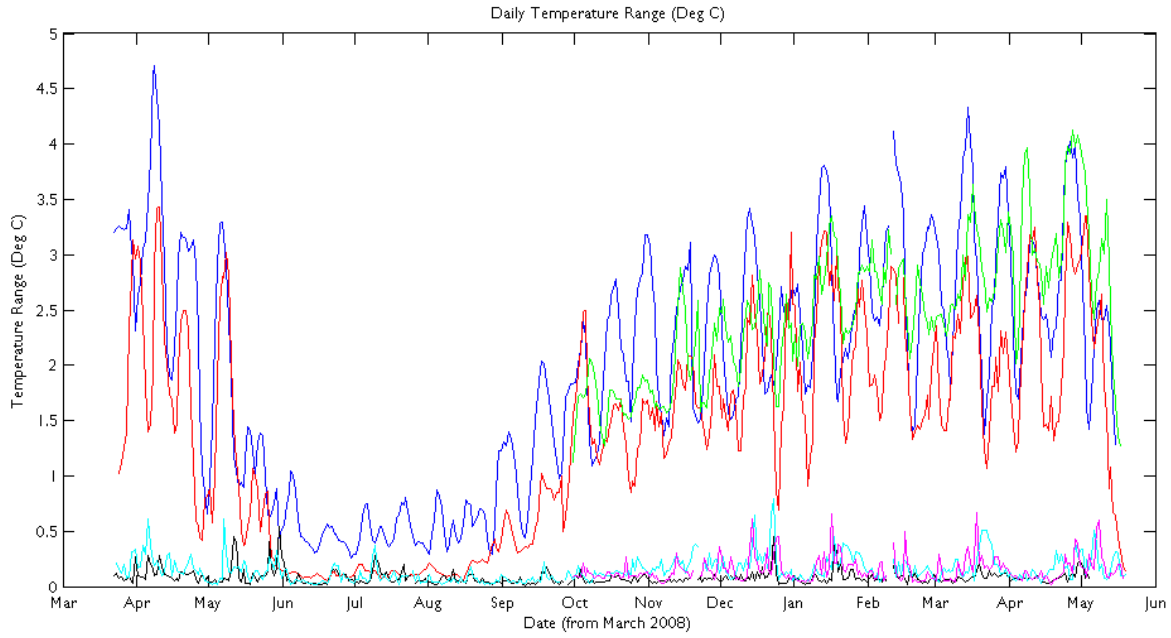

Fig. 13 Daily temperature ranges at in-situ logger sites. Sites shown are PE05 (blue), PE07 (red), PE16 (green), PE09 (black), PE13 (cyan), & PE14 (magenta).

Within a particular season, the waters of South Reef lagoon show a spatially consistent vertical temperature structure and are, in general, horizontally well mixed with limited horizontal variability (Fig. 14). The degree of temperature stratification shows a strong seasonal signal, as would be expected in a relatively shallow lagoon environment, with summer stratification destroyed through autumn as the water cools to become vertically and horizontally well mixed during winter (Fig. 15, Fig. 17).

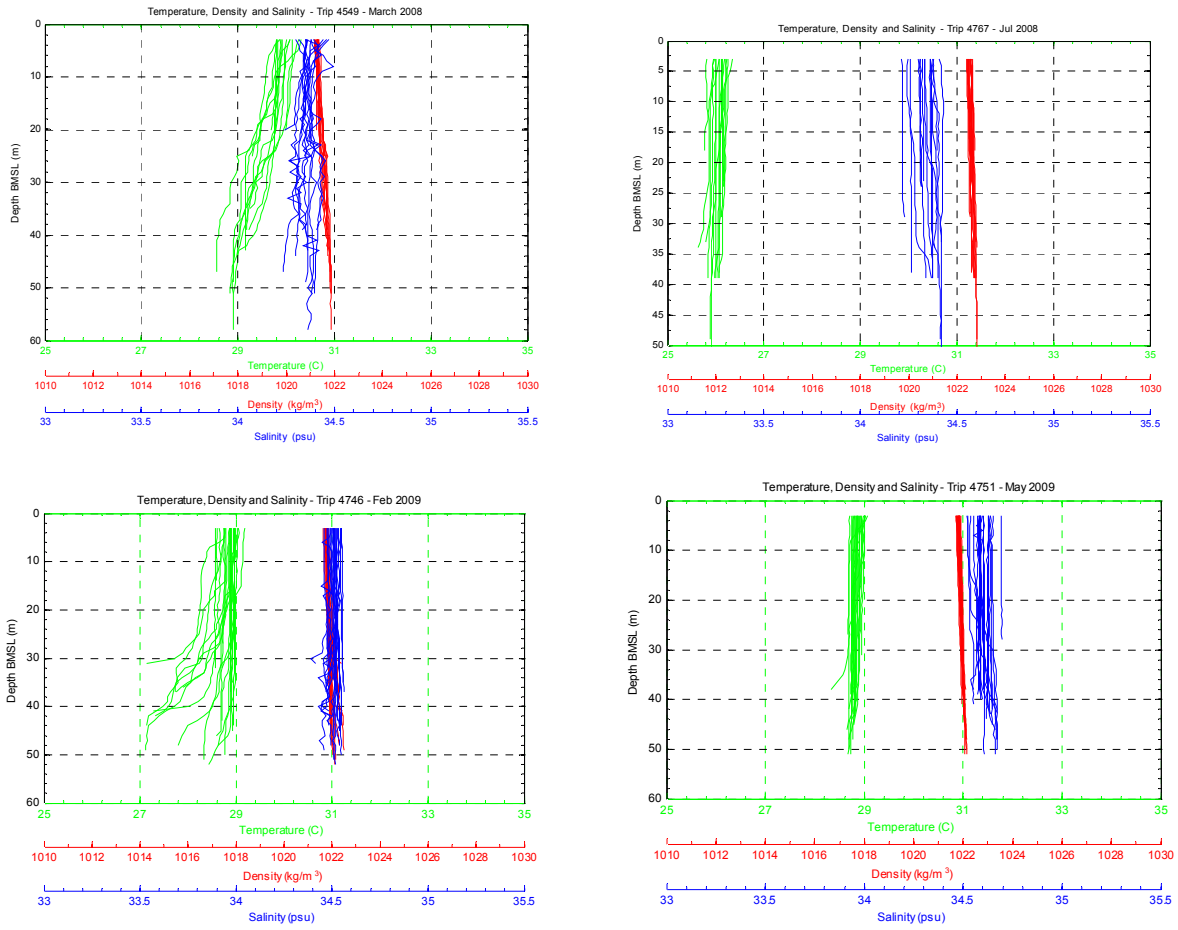

Fig. 14 Vertical profiles of temperature, salinity and density at all logger sites in March 2008 (top left), July 2008 (top right), February 2009 (bottom left) and May 2009 (bottom right).

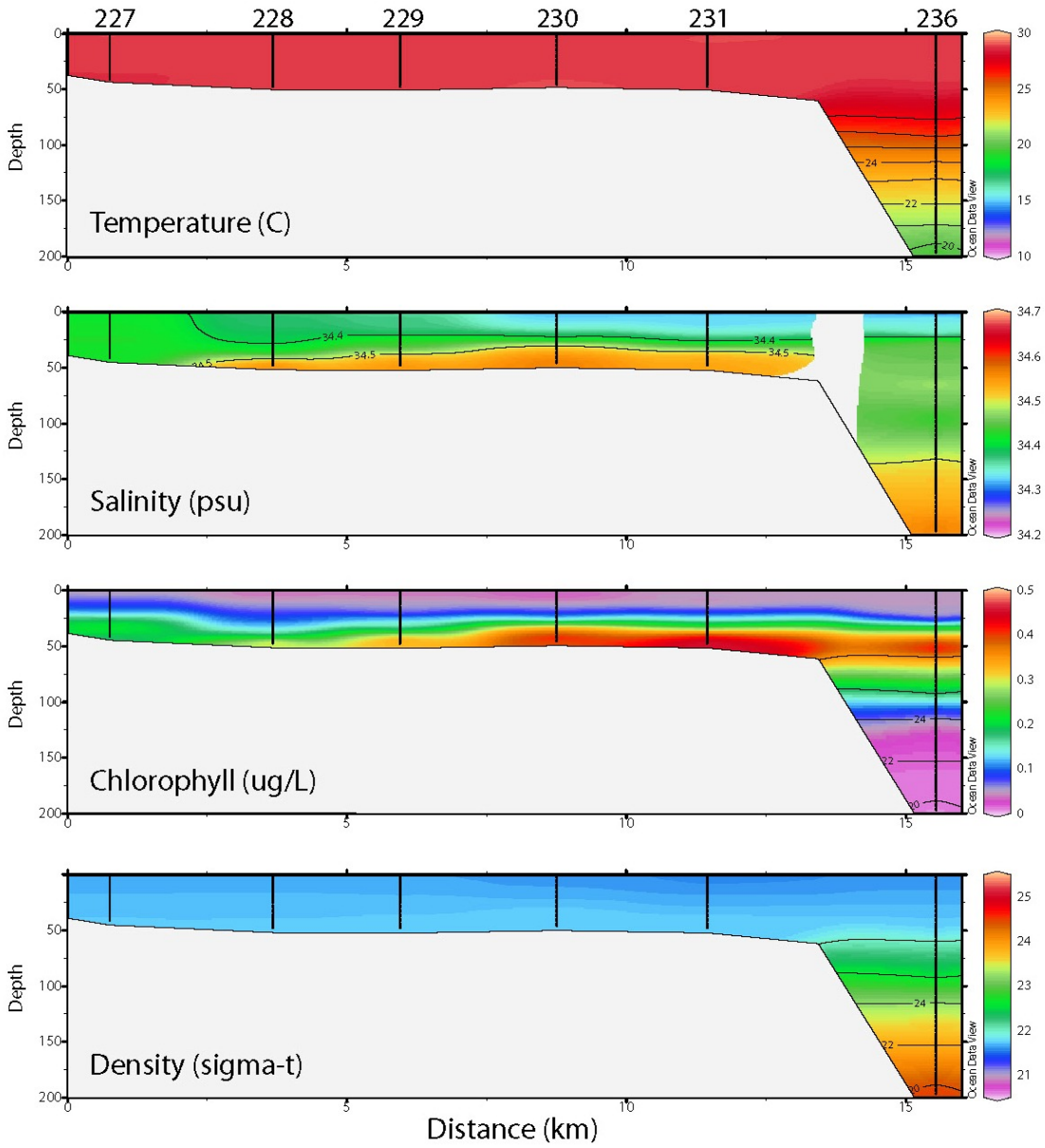

Fig. 15 Contoured longitudinal sections of water temperature, salinity, chlorophyll and density along the central axis of the South Reef lagoon on 31 May 2009. The stations contoured are SCT227 (left) to SCT231 and SCT236. Note – blank section in salinity plot is due to interpolated data being omitted in this area of large salinity gradients and depth change. In areas of large change, such as in this case where the depth of the 34.5 PSU contour changes by >100m, then the gridding method becomes unreliable, and the interpolated data are therefore omitted.

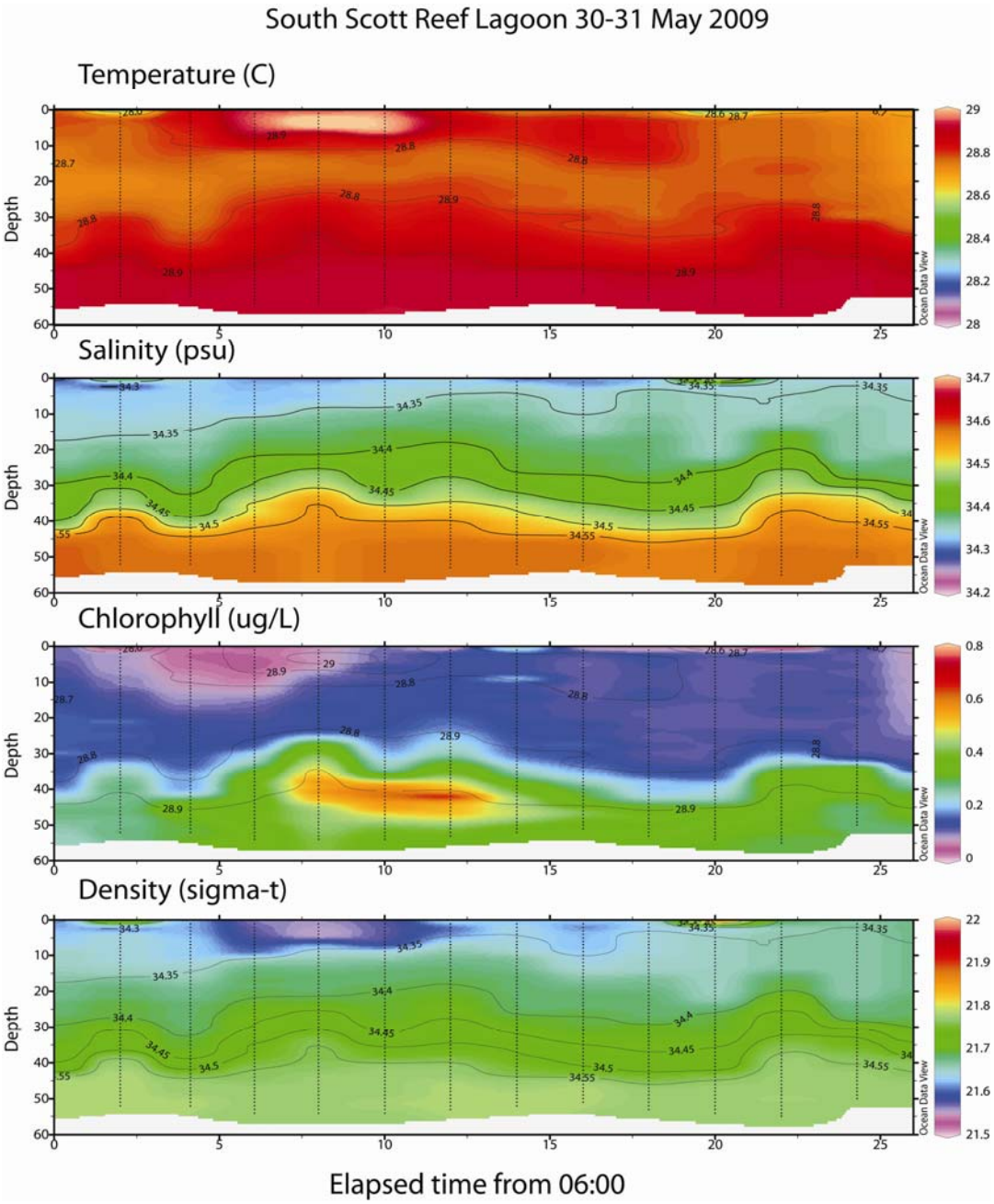

Fig. 16 Contoured time series profiles of temperature, salinity, chlorophyll and density in the centre of South Reef lagoon (Site 1) on 30-31 May 2009.

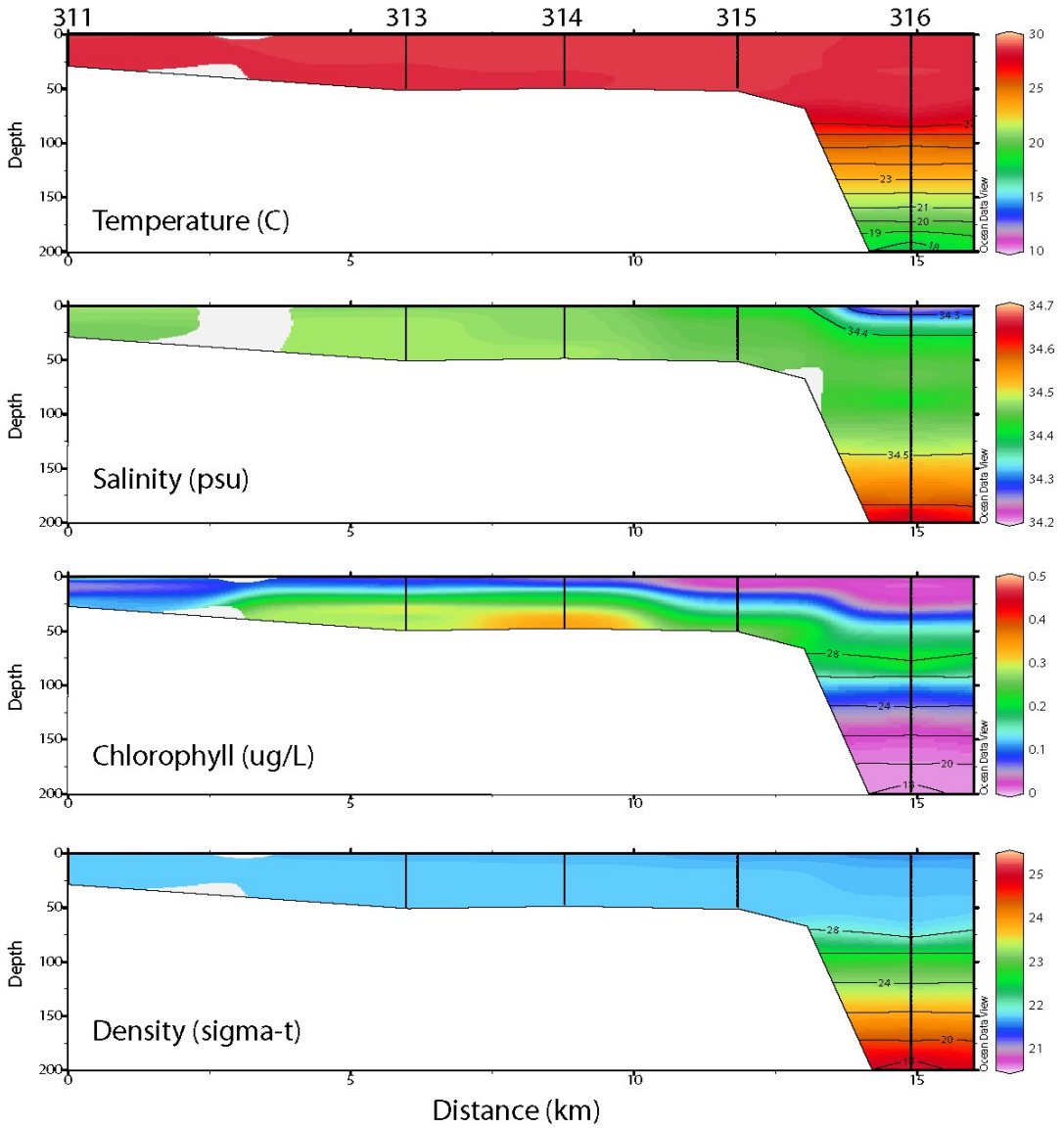

Fig. 17 Contoured longitudinal sections of water temperature, salinity, chlorophyll (by in vivo fluorescence) and density along the central axis of the South Reef lagoon on 10 June 2009. The stations contoured are SCT311 (left) to SCT317.

Daily statistics, aggregated to monthly, have been calculated for all salinity time-series data (Appendix A - Table A. 2). Mean salinity within the lagoon was 34.43 PSU and ranged between 33.75 – 35.59 PSU during the observational period.

Most vertical profiles of salinity in the South Reef lagoon were found to be virtually isohaline (e.g. Fig. 2), reflecting the water column characteristics of the surface mixed layer in surrounding deep waters. At the beginning of the May-June 2009, biological oceanography cruise, however, a persistent near-bottom salinity maximum layer was observed (Fig. 15) that covered much of the central lagoon. This subsurface layer was embedded in a largely isothermal lagoonal water mass (Fig. 16) and was discontinuous with the sub-surface salinity maximum in the adjacent deep channel and surrounding waters. The near-bottom salinity maximum layer was not observed when the lagoon was re-sampled on 9 June 2009 (Fig. 17). The source of the higher salinity water was un-resolved; however, we feel it would most likely be due to evaporation in shallow distal portions of the lagoon with subsequent sinking toward the centre rather than intrusive emplacement from the deep channel as no temperature anomaly or nutrient signature is evident.

Turbidity, Sedimentation rate and Photosynthetically Active Radiation (PAR)

Vertical profiles of turbidity within South Reef lagoon confirm that the lagoon waters are low in suspended matter and highly transparent and the degree of light penetration (Fig. 2) shows little seasonality, suggesting no significant inter-seasonal difference in water transparency. Mean daily turbidity levels within the lagoon were *ca* 0.15 NTU, and ranged between 0.04 and 6.10 NTU. Monthly aggregated mean levels of turbidity, as determined from the in-situ loggers are presented in Appendix A - Table A. 3. Levels of turbidity within the lagoon are in general spatially homogeneous, and this characteristic persists through time (Fig. 18).

There is little evidence of a sustained increase in turbidity near the seabed that could potentially result from resuspension of settled matter. Sites located on the margins of the reef slopes and in the channel between West Hook and the Sandy Islet show higher variability and slightly higher mean turbidity levels than that observed at the deeper lagoon sites. For sites located adjacent to shallow reef areas, this is likely a consequence of detritus and suspended material originating from the reef tops being advected from the reef flats past these sites. A snapshot of the maximum observed turbidity within a particular month (in this case January 2009) is representative of the general pattern of spatial variability in turbidity within the lagoon (Fig. 19).

Sedimentation rates reflect the general observation of high water clarity with little suspended matter. At all sites sampled with in-situ sediment traps, mean sedimentation rates were less than 0.5 mg cm^{-2} d^{-1} with the highest sedimentation rates observed in the channel between West Hook and the Sandy Islet (Site PE05). This observation supports the turbidity logger data from that location which shows elevated turbidity as a result of resuspension of settled material by the strong tidal currents that persist in this vicinity.

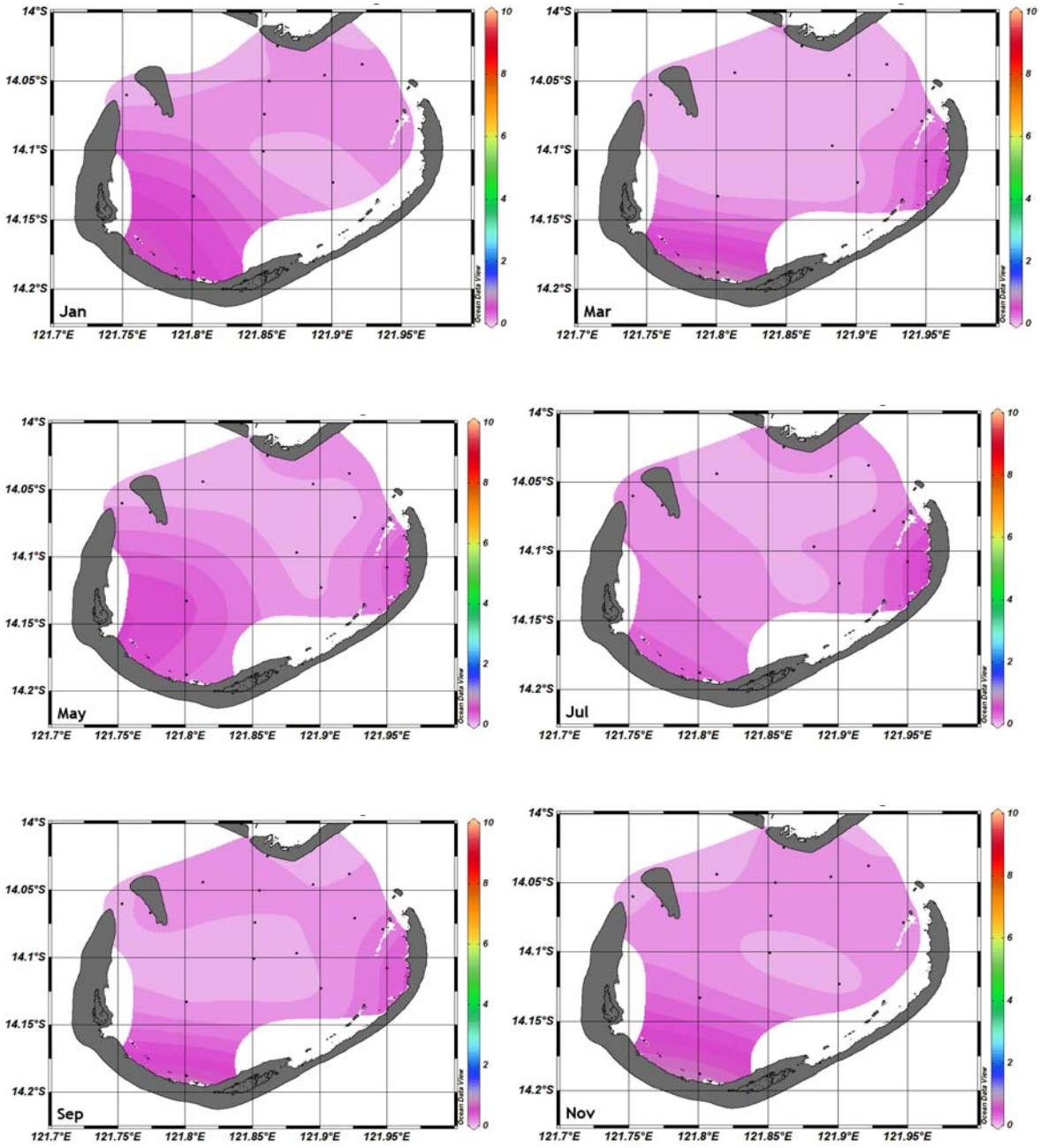

Fig. 18 Contoured mean monthly turbidity at in-situ logger sites. Only every second month (from January) is shown. Colour scale shows turbidity in NTU. Dots indicate logger sites.

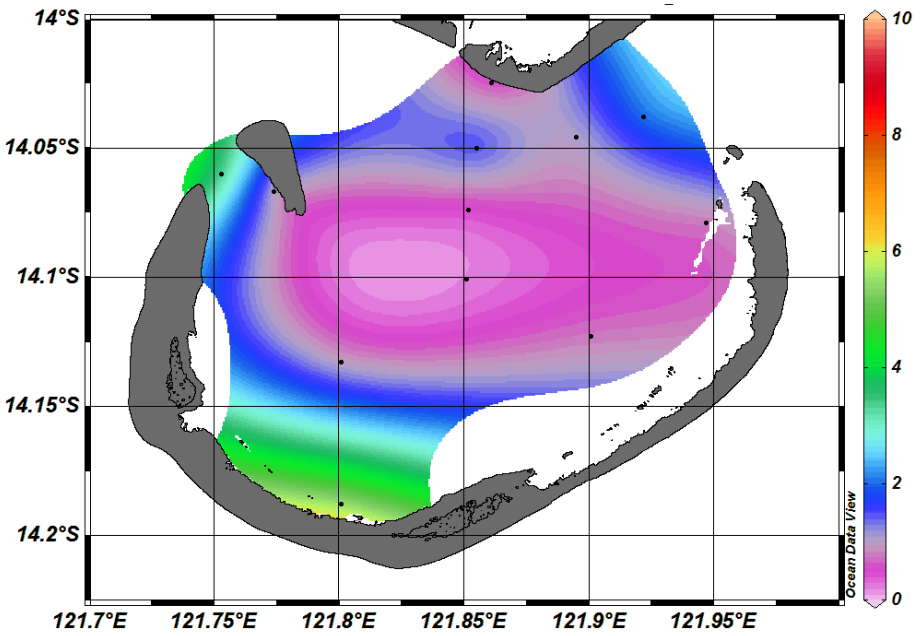

Fig. 19 Contoured maximum turbidity at in-situ logger sites during January 2009. Colour scale shows turbidity in NTU. Dots indicate logger sites.

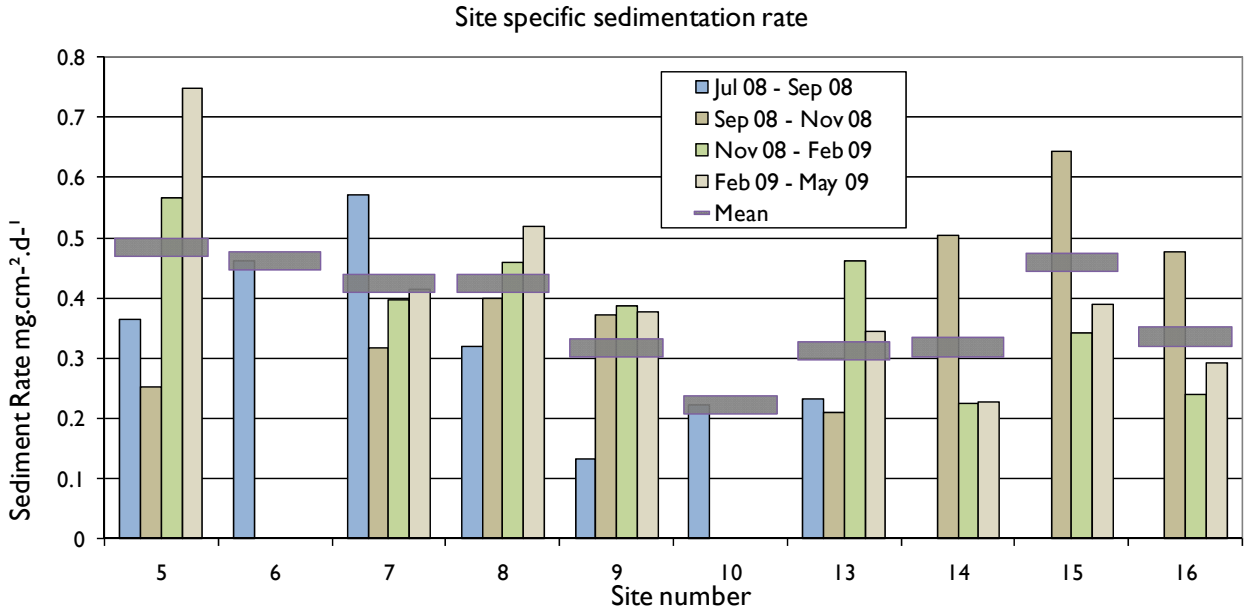

Fig. 20 Sedimentation rates from in-situ sediment traps deployed at logger locations within the South Reef lagoon.

Light levels within the lagoon are being monitored through both vertical hydrographic casts, and through the accumulation of PAR time series at the observation logger sites. Vertical water column profiles of PAR provide a good estimate of downwelling PAR from which to determine the light conditions at the seabed as a percentage of incident light at the surface.

The reporting of PAR as % reaching a particular depth level can be problematic as it relies on an accurate measurement of incident PAR. This is not always straightforward. For profiling instruments, PAR sensors often saturate at the high near surface light levels, requiring some extrapolation (from deeper observations where the sensor is not saturated) to estimate near

surface PAR. For in situ near bottom PAR loggers, surface incident PAR is not observed, and 'typical' values are employed to interpret the deep observations as '% of surface PAR'. With this in mind, we chose to report %PAR (particularly that recorded from our loggers) not as absolute values, but as greater than a meaningful threshold, such as >1% or less than 10%.

Downwelling PAR from hydrographic casts undertaken within the South Reef lagoon during the biological oceanographic cruises has been used to characterise the %PAR reaching the seabed. At all stations within the lagoon, %PAR reaching the seabed was >1% for the deepest sites surveyed (55m), and generally fell within the range of >1% and ≤10%, for seabed depths between 35 and 55m.

Using the relationship:

$$PAR_{depth} = PAR_{surface}\, e^{(-kD)},$$

Where PAR_{depth} is PAR at depth, $PAR_{surface}$ is incident value PAR at the surface, D is the depth and k is the light extinction co-efficient, extinction coefficients were found to be of the order of 0.07 m^{-1}.

Time series data of observed PAR at logger sites confirms the temporal consistency of significant light penetration (>1% surface PAR) to the benthos within South Reef lagoon. Maximum daily PAR at observational sites (Fig. 21) was generally in excess of 100 mmol ph/m^2/s, or equivalent to >5% surface PAR (maximum surface PAR is generally ~2000 mmol ph/m^2/s (Kirk, 1994)). Our data indicate that water clarity is consistently high, with significant and consistent light penetration to the benthos within South Reef lagoon. This supports the findings of AIMS SRRP Project 2.2.

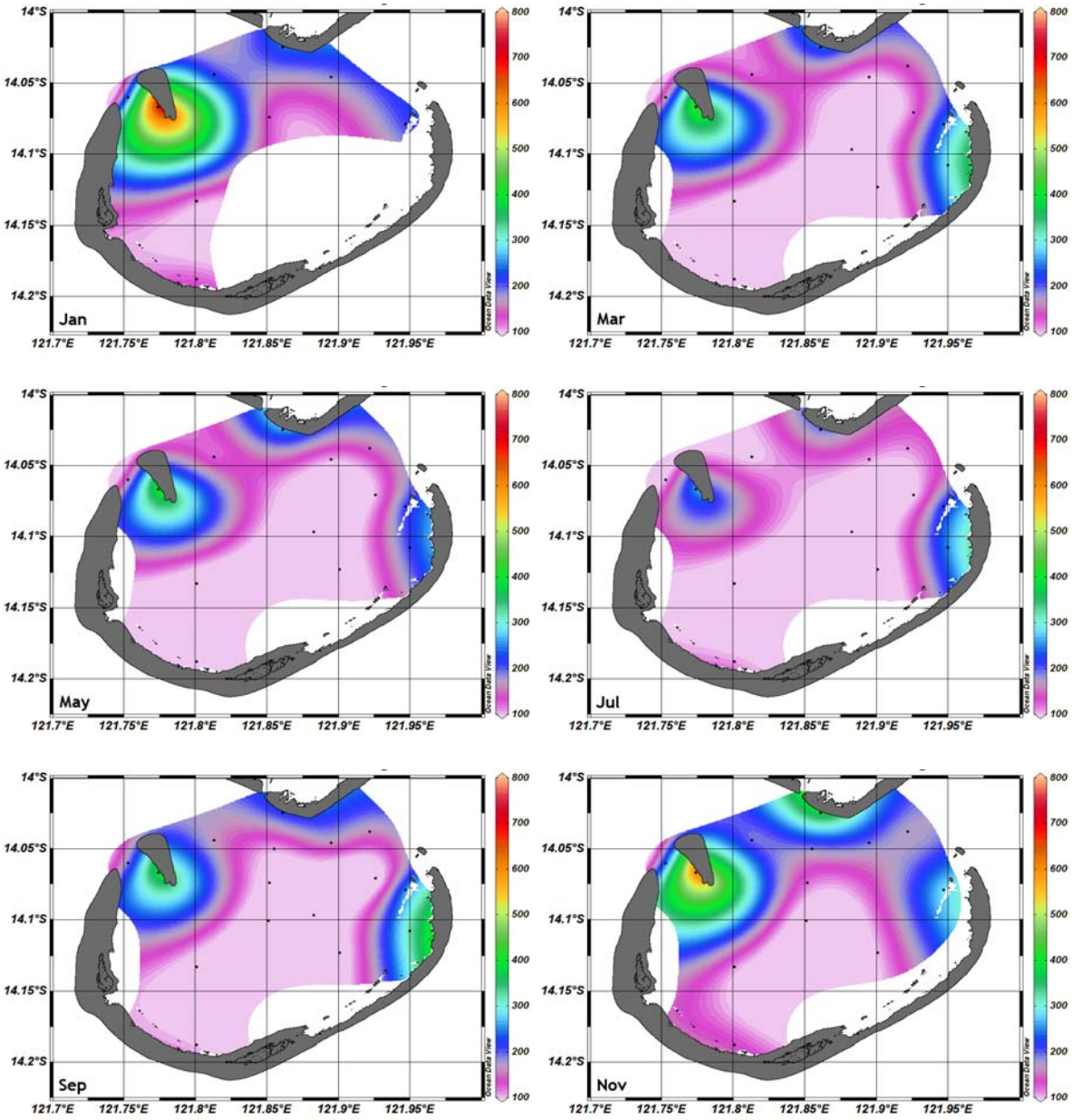

Fig. 21 Contoured maximum PAR at logger sites. Shown as maximum PAR at each site within the designated month, showing only every second month from January. Depths of logger sites are given in Table 1. Colour scale show PAR in units of mmol ph/m^2/s. Dots indicate logger sites.

Chlorophyll distributions

Mean levels of near-bottom chlorophyll fluorescence at in-situ logger sites show limited spatial variability throughout the southern lagoon, with mean values ranging from 0.18 to 1.42 mg/m^3. (Appendix A - Table A. 4). Note that these values are derived using the instrument supplied software and have not been calibrated against discrete samples. Background levels of chlorophyll fluorescence within the deep channel range from ~0.75 to 1.25 mg/m^3 from the surface to 40 m depth, respectively.

Despite a generally persistent spatial homogeneity of chlorophyll within the southern lagoon, there is evidence that cool water intrusions over the sill during spring tides drive enhanced productivity at sites within the lagoon. During May-June 2009, there was a persistent near-

bottom chlorophyll maximum layer was observed (Fig. 15) that covered much of the central lagoon. This subsurface layer was not accompanied by cooler temperatures, indicating that the local water had been resident in the lagoon sufficiently long to mix with the surrounding water (see previous section on Temperature in the South Reef lagoon). The chlorophyll maximum within the lagoon was not continuous with a chlorophyll maximum in the adjacent deep channel (Fig. 17), suggesting that the enhanced chlorophyll was the result of local production.

Concurrent time-series of temperature, chlorophyll and sea level at sites along a North-South transect into the interior of the South Reef Lagoon (Fig. 22) show that following a strong intrusion event at the margin of the lagoon (site PE16), the intrusion propagates southwards and can be seen in temperature time series at sites PE15 and 14 within 24 hours. There is a decrease in the magnitude of cooling with distance into the lagoon and an increase in the time taken for temperature to return to the 'pre-cooling' conditions, presumable due to mixing of the intruded water. After a lag of 3-4 days following an intrusion observed at site PE15 (on 5/12/08), there is an increase in the chlorophyll fluorescence at both sites PE15 and PE14. This increase in chlorophyll fluorescence persists until a subsequent strong intrusion (*ca* 12/12/08) presumably displaces the otherwise resident local water mass. We speculate that this enhanced chlorophyll fluorescence within the deeper section of the lagoon is indicative of enhanced production following the supply of new nutrients in to the lagoon. A discussion regarding the productivity of lagoon waters is given in the next section.

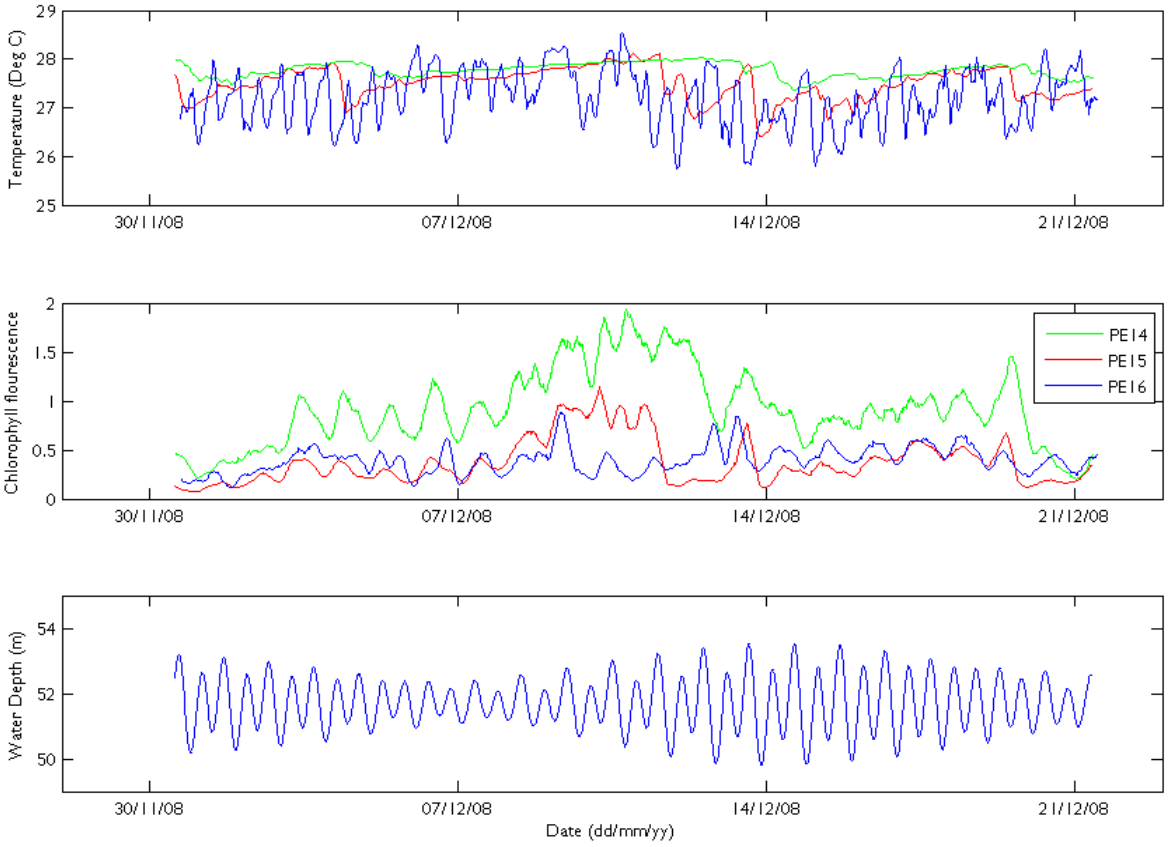

Fig. 22 Time series plots of temperature (top) and chlorophyll (middle) at sites PE16, PE15 and PE14, which lie along a North-South transect from the sill into the interior of the lagoon. Site PE14 is approximately 6 km south of site PE16. Sea level time series is shown in the bottom frame.

Productivity of Scott Reef waters

On each of the biological oceanography cruises to date, extensive sampling was carried out at 4 experimental sites in and around South Reef, Scott Reef. Upon arrival at each of these sites, hydrographic casts were made every 2 hours for 26 hours to document diel changes in water column structure. During this period, four zooplankton net hauls were taken to document vertical patterns in mesozooplankton community composition. On the day following, a drifting sediment trap was deployed, followed for the day and retrieved at sunset. A range of productivity and community food-web experiments were undertaken in parallel with the trap deployment. As time permitted, hydrographic (CTD) surveys in the South Reef lagoon and deep channel were also carried out in parallel with these activities.

In situ levels and vertical distributions of nutrients at Scott Reef

At this time, nutrient data is available for both 2008 Biological Oceanography cruises. Samples from the May-June 2009 cruise are still being analysed, although partial results are presented as appropriate.

Representative vertical profiles of nitrate (NO_3^-), phosphate (PO_4^{3-}), silicate ($Si(OH)_4$), dissolved organic carbon (DOC), particulate nitrogen (PN) and particulate organic carbon (PC) in June 2008 and December 2008 are presented in Fig. 23 and Fig. 24. Vertical profiles of dissolved organic N (DON), dissolved organic phosphorus (DOP) and particulate phosphorus (PP) exhibited limited vertical structure that did not show clear patterns with respect to depth, hydrographic structure or the subsurface distribution of chlorophyll.

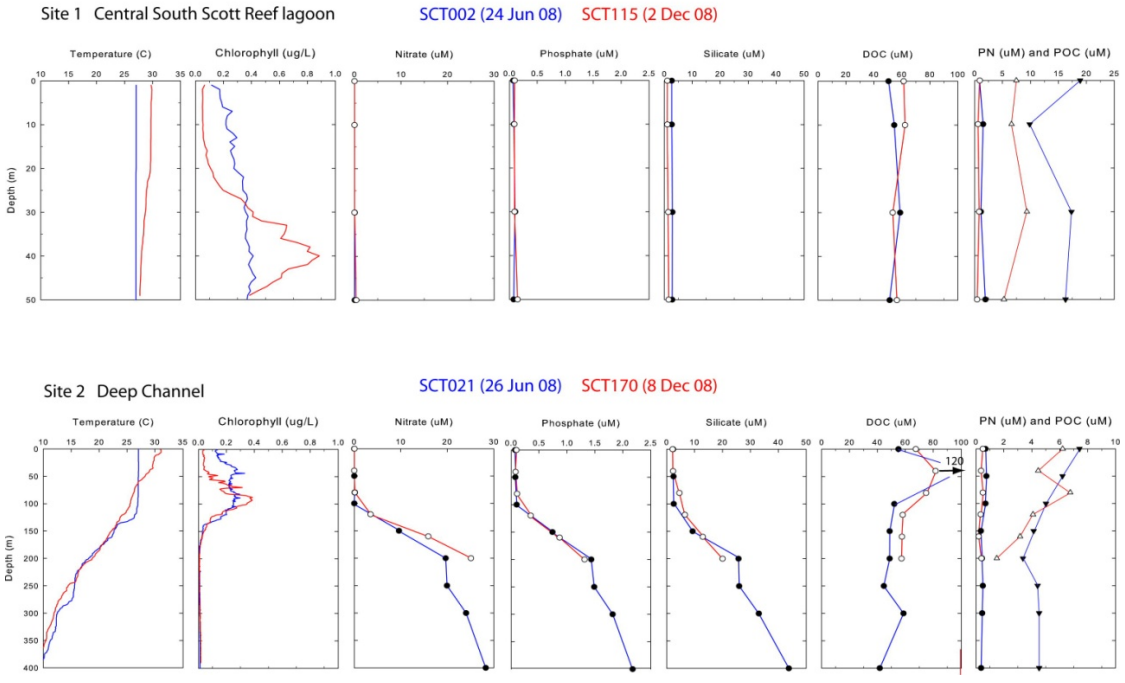

Fig. 23 Representative plots of temperature, chlorophyll fluorescence, NO_3^-, PO_4^{3-}, $Si(OH)_4$, dissolved organic carbon (DOC) and particulate nitrogen (PN) and particulate organic carbon (PC) in the central region of South Reef lagoon (Site 1, TOP) and the deep channel between North and South Reef (Site 2, BOTTOM) in July 2008 (winter - blue profiles) and December 2008 (summer – red profiles).

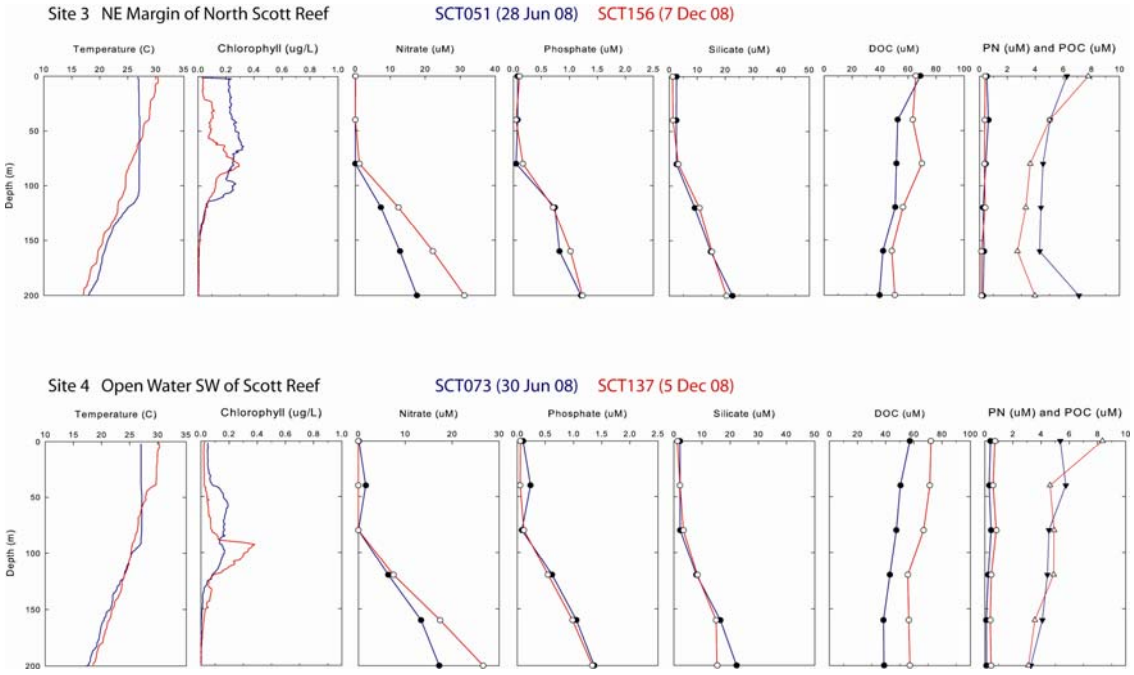

Fig. 24. Representative plots of temperature, chlorophyll fluorescence, NO_3^-, PO_4^{3-}, $Si(OH)_4$, dissolved organic carbon (DOC) and particulate nitrogen (PN) and particulate organic carbon (PC) along the NE margin of North Reef (Site 3, TOP) and at an open water site SW of Scott Reef (Site 4, BOTTOM) in July 2008 (winter - blue profiles) and December 2008 (summer – red profiles).

Mixed layer concentrations of dissolved inorganic N and P were very low at all four of the experimental sites. Within the South Reef lagoon, the full water column was characterized by very low nitrate and phosphate concentrations at all times. Nitrate concentrations, in particular, were near or below detection limits (<20 nM). Ammonium concentrations have not been measured with appropriate high sensitivity, low contamination methods (Holmes et al., 1999), but given the conditions, it is likely that ambient NH_4^+ concentrations are also very low (< 50 nM). While very low, ambient concentrations of phosphate were consistently measurable at all four sites (ca. 50-200 nM). In contrast, near-surface silicate concentrations were generally on the order of 2-3 μM, approximately 1-2 orders of magnitude more abundant than inorganic N and P. The observed concentration ranges and ratios of dissolved inorganic nutrients indicate that surface waters surrounding Scott Reef are most likely strongly N-limited (DIN:DIP < 16, DIN:Si << 1), with phytoplankton and bacterial demand for N and P being primarily met through rapid and continuous water column remineralisation of organic N and P. These conditions are typical of oligotrophic oceanic waters.

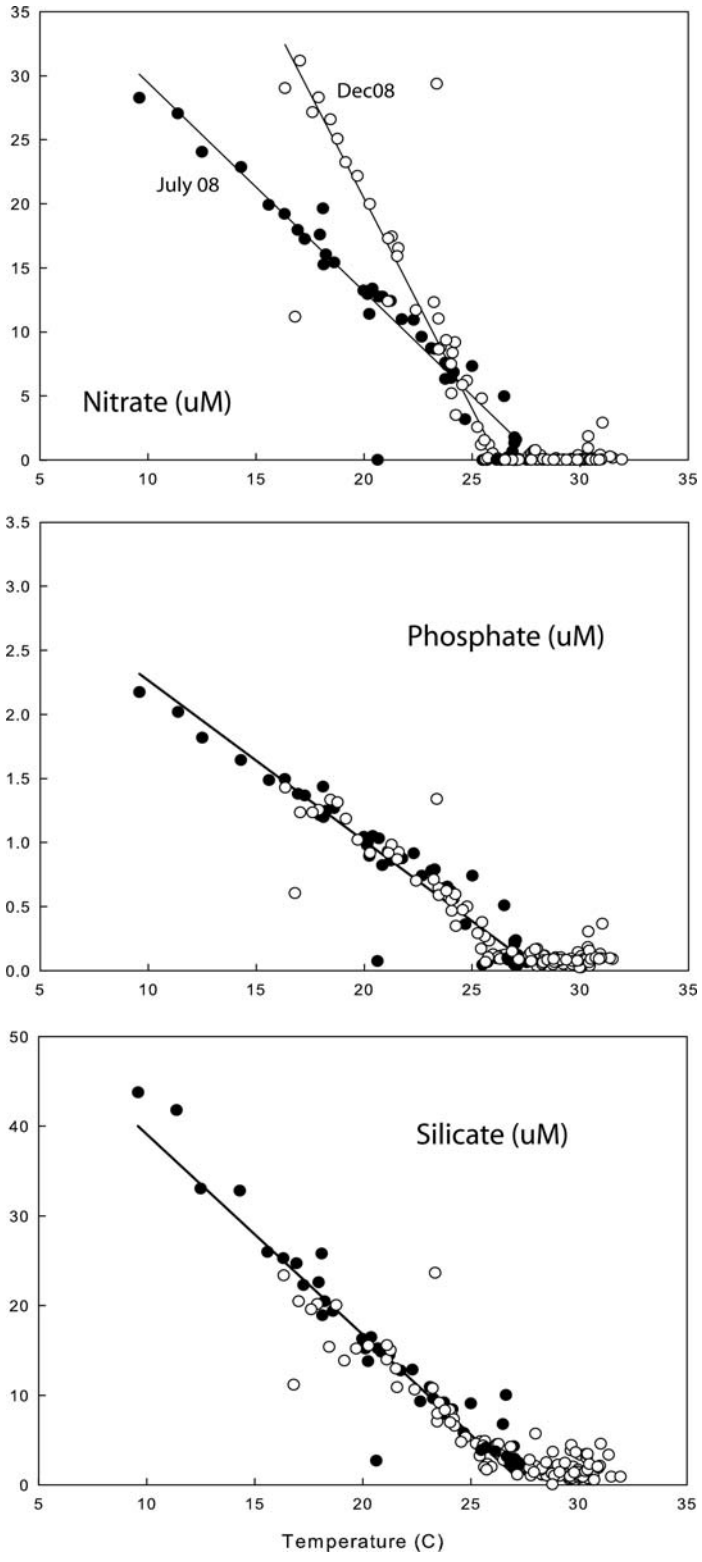

Fig. 25 Plots of relationships between temperature and concentrations of NO_3^- (TOP), PO_4^{3-} (MIDDLE), $Si(OH)_4$ (BOTTOM) at stations occupied at the open water site (Site 4) in June-July 2008 (closed symbols) and December 2009 (open symbols). Regression lines shown are derived for data collected at depths below the mixed layer and upper margin of the thermocline (temperature < 26.5°C). Obvious outlier values were also excluded from the calculation. Regression coefficients are given in Table 1.

From the base of the thermocline downward, concentrations of nitrate, phosphate and silicate increased steadily with depth and decreasing temperature. Plots of nitrate, phosphate and silicate concentrations versus temperature were strongly linear for temperatures < 26.5 °C (Fig. 25), indicating that concentration gradients within the thermocline were largely determined by physical mixing between nutrient depleted surface waters and high-nutrient deep waters. Table 3 presents the equations relating nutrient concentrations to temperature in the thermocline. The strength of these relationships indicate that temperature can be used as a proxy tracer for nutrient concentration in the upper thermocline and freshly intruded water masses before biological uptake get strongly underway.

Table 3 Regression equations for nutrient-temperature relationships shown in Fig. 25. Regressions are based on samples collected at the open water site (Site 4) in June-July 2008 and December 2008 at depth with temperatures < 26.5°C.

Jun-Jul 2008	NO_3^- (μM)	= -1.630 (T°C) + 45.7	r^2 = 0.95
Dec 2008	NO_3^- (μM)	= -3.281 (T°C) + 86.0	r^2 = 0.97
All cruises	PO_4^{3-} (μM)	= -0.425 (T°C) + 3.52	r^2 = 0.95
All cruises	Si $(OH)_4$ (μM)	= -2.234 (T°C) + 61.5	r^2 = 0.94

Dissolved organic carbon concentrations in South Reef lagoon waters ranged between 40 and 60 μM C, with little vertical structure in the thermocline, or seasonal variation. At deep water sites, DOC concentrations ranged from ca. 40 to ca. 120 μM C, with generally higher concentrations closer to the surface. This gradient, though weak, indicates that DOC produced in the productive surface layer is continuously being mixed downward from the surface layer into the thermocline where it supports bacterial production at depth. The upward mixing of inorganic nutrients to support autotrophic production in the euphotic zone therefore contrasts with the downward mixing of organic material to support heterotrophs at the base of the euphotic zone and below.

In the small amount of data available at present, vertical distributions of PN and PC exhibited no pronounced seasonal or depth-related distribution patterns. PN and PC concentrations were poorly correlated with chlorophyll concentrations, indicating that most water column organic matter is detrital in nature.

Abundance and distribution of picoplankton at Scott Reef

Picoplankton community composition

Picoplankton are the smallest size class of plankton (cells < 2 µm) and comprise both autotrophic and heterotrophic cells. The autotrophic picoplankton assemblage, which derive their energy from photosynthesis, are composed of photosynthetic unicellular cyanobacteria (*Prochlorococcus* ~ 0.6 µm, *Synechococcus* ~ 1-2 µm) and small photosynthetic unicellular eukaryotes (termed 'Picoeukaryotes' - cells of various groups with a more complicated cellular structure, more closely related to higher plants ~ 1-2 µm). In oligotrophic (low-nutrient) tropical waters such as those surrounding Scott Reef, autotrophic picoplankton dominate the phytoplankton biomass (~ 80% of total chlorophyll *a* biomass) and commonly contribute > 60% of primary production. The heterotrophic picoplankton (termed 'bacterioplankton'), are major consumers of organic matter (much of which is produced by the autotrophic picoplankton community via photosynthesis) and therefore play fundamental roles in the remineralisation and cycling of organic matter through marine food webs. Unlike the autotrophic picoplankton, which are restricted to the photic zone due to their dependence on light, bacteria can persist below the photic zone in response to relatively (compared to upper lit waters) high organic matter availability (due to e.g. dead sinking cells, marine snow).

The autotrophic picoplankton and bacterioplankton community are primarily preyed upon by very small planktonic organisms (nanoplankton, such as small unicellular flagellates and ciliates). Viruses, which are the smallest and most abundant organisms in marine waters, are also pathogens of picoplankton. Organic matter is also released via viral activity, through lysis of infected cells and as such, viral activity further enhances energy cycling through marine microbial food webs. While much of the productivity of the picoplankton is consumed and recycled within this 'microbial loop' (microbial loop = picoplankton, nanoplankton, viruses), consumption and leakage of organic matter from the microbial loop ultimately drives much of the pelagic ecosystem in oligotrophic tropical waters. Constituent species, strains and/or groups of picoplankton have differing growth potentials and responses to light, temperature and nutrient availability. As a result, differences in the absolute and relative abundances of different picoplankton groups, as well as the viruses which infect these groups, provide insight into the state of water quality and trophic relationships in different systems.

Using flow cytometry, three autotrophic picoplankton groups, *Prochlorococcus*, *Synechococcus* and a population of slightly larger picoeukaryotes, could be identified throughout the upper water column (to depths of ~ 120 m in Summer 2008 and Winter 2009, but down to 150 – 160 m in Winter 2008) in the Channel, North East margin and at the Open Water station, as well as in the lagoon (~ 50 m depth) at Scott Reef (Fig. 26). However for each of these groups, large variations in abundance often occurred between sites within the one sampling period and between sampling periods (three sampling periods to date; May/June 2008; November/December 2008 and May/June 2009) (discussed below).

Temporal and spatial variations in autotrophic picoplankton abundances

Overall, highest autotrophic picoplankton cell abundances occurred in Winter 2008 for all stations (Fig. 27). For example, when comparing the maximum cell abundance over the upper 100 m of the water column at all stations, cell abundances were 2.2 – 4.2-fold, 4.1 – 12.5-fold and 5.4 – 12.0-fold higher for *Prochlorococcus*, *Synechococcus* and picoeukaryotes respectively, in Winter 2008 than in Summer 2008 or Winter 2009 (Fig. 27). Furthermore, while water column structure was most similar between Winter 2008 (mixed layer down to ~ 100 m) and

Winter 2009 (mixed layer down to ~ 65 m), overall autotrophic picoplankton generally showed similar trends in cell abundances and distributions between Summer 2008 (when there was no defined mixed) and Winter 2009. Reasons for elevated picoplankton abundances during the Winter 2009 sampling period are not clear, however elevated picoplankton abundances coincided with elevated chlorophyll *a* biomass; particularly in the lagoon and Channel waters (Fig. 28). However in the few days prior to sampling, the weather was very rough, and it is possible that intense wind-driven mixing of the lagoon water column may have mobilised organic matter (i.e. from the benthos) leading to an increase in nutrient availability to the picoplankton community.

Diurnal shifts in picoplankton abundance were also evident; however, the magnitude of these changes were generally much smaller than the variation occurring between sites or seasons. Smallest changes in abundances over a 24-hr period at similar depths (sampling at ~ 08:00, 14:00 and 20:00 for most locations) for *Prochlorococcus*, *Synechococcus* and picoeukaryotes collectively, occurred in Winter 2008, with abundances shifting 1.4- to 3.0-fold over the first 100 m of the water column (50 m for Lagoon). The magnitude of change for picoplankton abundances over a 24-hr period was similar in Summer 2008 and Winter 2009, varying between 1.4- and 7.8-fold. Highest variations in picoplankton abundances usually occurred close to, or within the chlorophyll *a* maxima. *Prochlorococcus* and *Synechococcus* abundances were commonly highest at 20:00, suggesting cell division of these groups occurred at night. These results are in accordance with previous studies which have also shown in other oceanic locations, that cell division of *Prochlorococcus* and *Synechococcus* predominantly occurs at night.

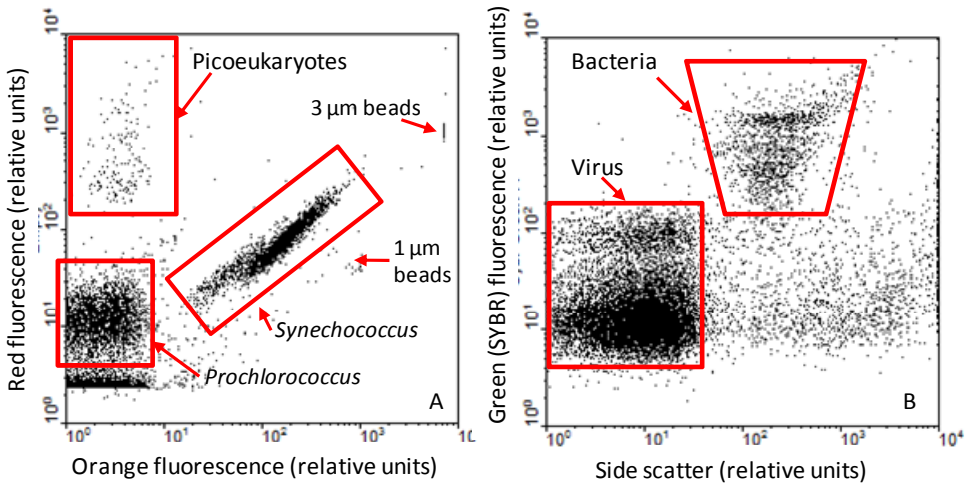

Fig. 26 Dot plots from flow cytometry analysis of a representative seawater sample showing (A) groups of autotrophic (photosynthesising) picoplankton, (B) Bacterioplankton and viruses. (A) Auto-fluorescing autotrophic (photosynthesising) picoplankton with individual groups represented by Prochlorococcus, Synechococcus and picoeukaryotes. Vertical (y) and horizontal (x) axes (log scales) are relative levels of blue-light (488 nm) stimulated orange (560 nm) and red (>640 nm) fluorescence due to individual cellular concentrations of the pigments phycoerythrin and chlorophyll, respectively. Cellular pigment levels are primarily related to cell size and degrees of physiological adaptation to in-situ light levels. Fluorescing 1 µm and 3 µm beads were added to samples as an internal reference to compare the relative fluorescence intensity and size of individual groups between samples. (B) Bacterioplankton and viruses. Vertical (y) axis (log scale) represents relative levels of blue-light (488 nm) stimulated green (500 nm) fluorescence due to the added DNA stain (SYBR Green) and the horizontal (x) axis (log scale) represents side scatter, an indicator of cell size and complexity.

Regardless of the sampling period, *Prochlorococcus* abundances were always slightly higher at the Open water station. However similar abundances also occurred in the Channel and in the

NE margin station. *Prochlorococcus* abundances were generally lowest in the Lagoon; and most so in winter 2008. In winter 2008 and summer 2008 *Prochlorococcus* abundances were positively correlated with chlorophyll *a* biomass at Channel and North East Margin sites only. There were no clear relationships between *Prochlorococcus* abundances and chlorophyll *a* biomass at any of the sites in winter 2009.

Synechococcus generally followed the opposite trend to *Prochlorococcus*. Highest *Synechococcus* abundances occurred in lagoon waters in winter 2008 and summer 2008, while in winter 2009, *Synechococcus* abundances were similarly low in waters at the Lagoon, Channel and NE margin stations. Relatively high *Synechococcus* abundances persisted down to depths of 100 m in winter 2008 in the Channel and NE margin, and closely followed the chlorophyll *a* distribution within the ~ 100 m mixed layer, which was more strongly defined during this period than on subsequent trips (Fig. 2). In contrast, in summer 2008 and winter 2009; *Synechococcus* abundances rapidly declined below ~ 50 m and showed no clear relationship with chlorophyll *a* biomass at any of the investigated sites.

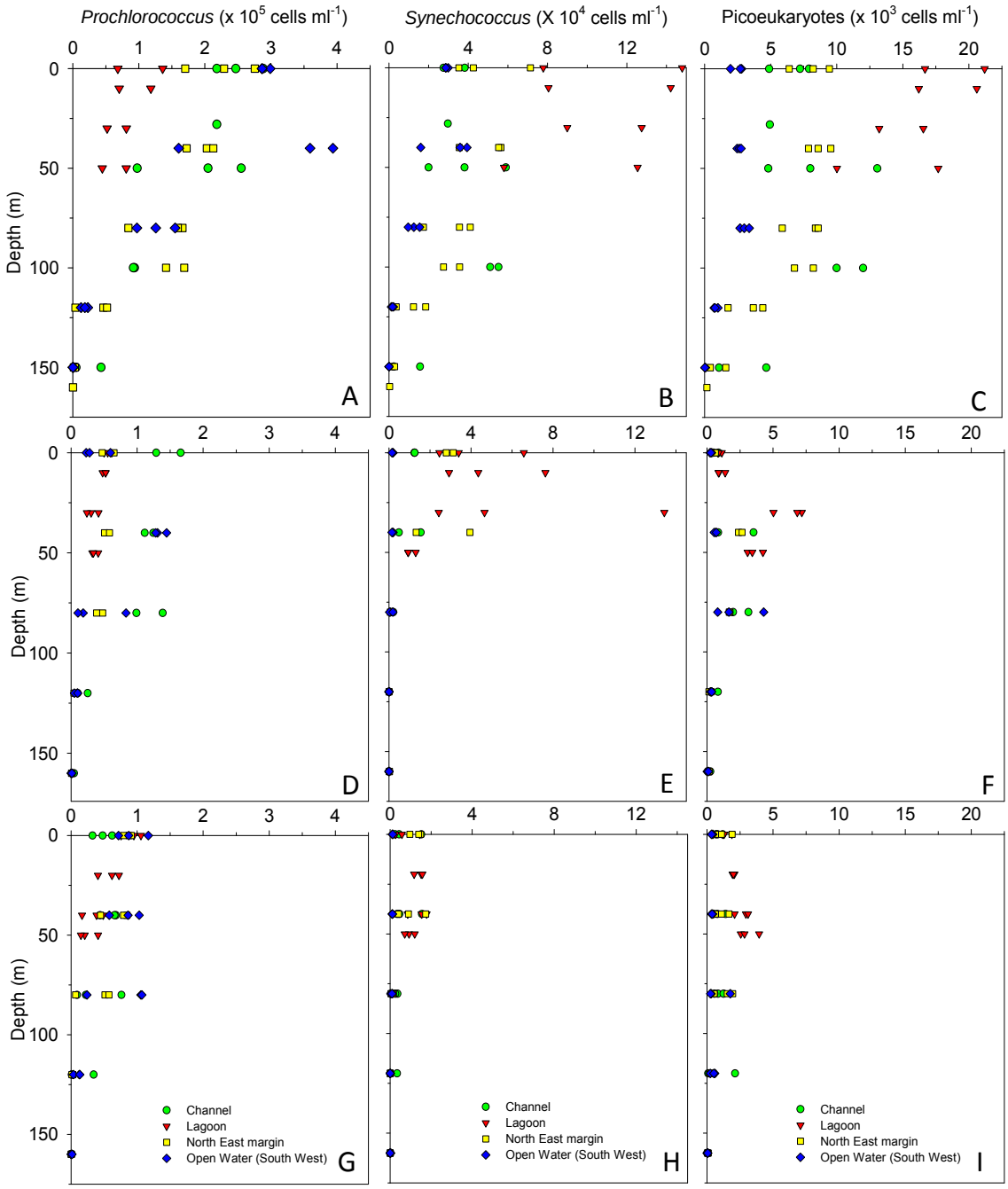

Fig. 27 Abundances of autotrophic picoplankton (*Prochlorococcus*, *Synechococcus* and Picoeukaryotes) at Scott Reef in Winter 2008 (A – C), Summer 2008 (D – F) and Winter 2009 (G – I). Data in these plots represent the combined time series data (two or three sampling periods per day, sampled at approximately 08:00, 14:00 and 20:00) for each of the four biological oceanography stations (Lagoon, Deep Channel, NE margin and Open Water). Values are means of duplicate or triplicate samples.

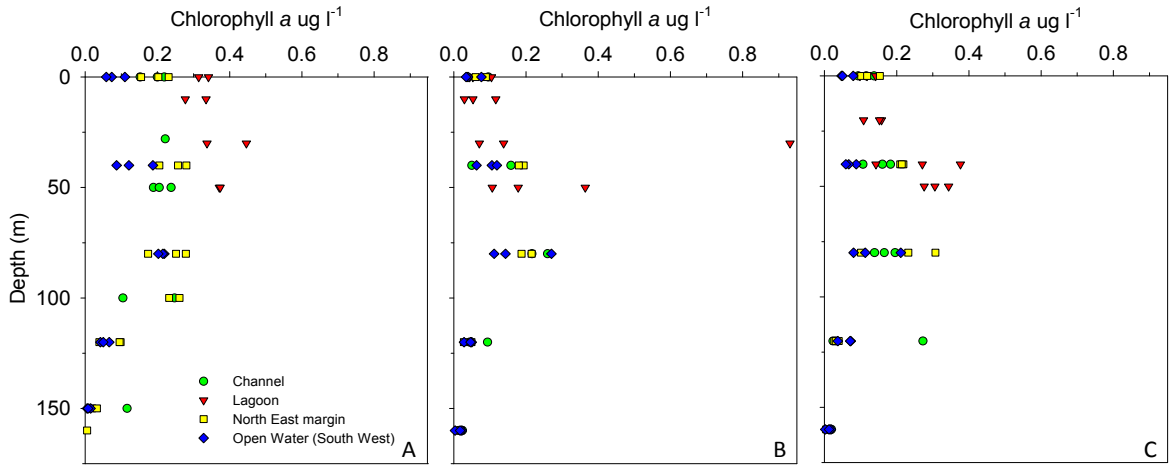

Fig. 28 Chlorophyll *a* biomass (µg l^{-1}) at Scott Reef in Winter 2008 (A), Summer 2008 (B) and Winter 2009 (C). Data in these plots represent the combined time series data (two or three sampling periods per day, sampled at approximately 08:00, 14:00 and 20:00) for each of the four biological oceanography stations (Lagoon, Deep Channel, NE margin and Open Water). Values are means of duplicates.

The distinct shifts between *Prochlorococcus* and *Synechococcus* between sites and between seasons, can best be determined by examining the ratio of *Prochlorococcus* to *Synechococcus* (*Pro:Syn* ratio). Lowest *Pro:Syn* ratios (< 1) occurred in lagoon waters in winter 2008 but lowest ratios (relative to all other sites in a given sampling period) also occurred in Lagoon waters in Summer 2008 (*Pro:Syn* ratio 0.3 – 4.38) and winter 2009 (2.0 – 40). Highest *Pro:Syn* ratios occurred in the Open water site in Summer 2008 and Winter2009 (*Pro: Syn* ratio 30 – 88). Shifts in the autotrophic picoplankton community in winter 2008, compared with summer 2008 and winter 2009 at the channel and NE margin sites could also clearly be seen using the *Pro:Syn* ratio, with *Pro:Syn* always less than 11 in winter 2008, and ranging from 8 – 82 in summer 2008/winter 2009.

The low *Pro:Syn* ratios in lagoon waters are an indicator of the higher nutrient status of this habitat in relation to the other observational sites, as is also shown by the slightly higher chlorophyll concentrations in lagoon waters. Lowest ratios occurring in winter 2008 in the lagoon, concomitant with generally highest chlorophyll *a* biomass at this time, may provide further evidence for weather driven mixing of lagoonal waters, leading to an increase in nutrient availability for picoplankton growth. In a range of tropical ecosystems, *Pro:Syn* ratios are highest in oligotrophic open oceanic waters and decrease as one moves along gradients from more nutrient-enriched parts of the ecosystem such as enclosed reef lagoons or inshore waters. Experimental studies in the Great Barrier Reef indicate *Prochlorococcus* is able to survive and grow rapidly in all these areas (Crosbie and Furnas, 2001); however, its maximum growth rate (2 doublings day^{-1}) is less able to support high population levels in the face of enhanced grazing mortality from larger populations of microbial predators with access to higher levels of food resources from faster-growing populations of *Synechococcus* (3 doublings day^{-1}) and picoeukaryotes. Some strains of *Prochlorococcus* are also unable to reduce and assimilate NO_3-N which is the primary form of 'new' nitrogen introduced in upwelled waters. Absolute and relative abundances of picoplankters can therefore provide a useful bio-indicator of ecosystem nutrient status, even when concentrations of dissolved nutrients are reduced to very low levels.

Like *Synechococcus*, picoeukaryote abundances were generally highest in lagoon waters regardless of the season however similar abundances also occurred in Channel and NE margin waters (Fig. 27), with their distribution closely following that of chlorophyll *a* (Fig. 28). While there was no clear relationship between picoeukaryote abundance and chlorophyll *a* biomass in the lagoon, they were positively correlated with chlorophyll *a* biomass in the Channel, NE margin and Open waters in winter 2008, summer 2008 and winter 2009.

Spatial variations in abundances of bacterioplankton and viruses

Bacterioplankton and virus abundances have so far only been analysed for summer 2009 (Fig. 29). Bacterioplankton abundances were generally highest in the upper 100 m of the water column and gradually decreased with depth. However, in contrast to autotrophic picoplankton which were present only down to a maximum depth of ~160 m, bacteria abundances occurred over similar ranges from 120 m down to 300 m (the deepest measurement made). Bacterioplankton abundances varied at most 2.1-fold between sites (when comparing the same depths) with highest variation, like autotrophic picoplankton, also occurring close to the chlorophyll *a* maxima. Bacterioplankton were positively correlated with *Prochlorococcus* abundances in Channel, Open waters and NE margin waters and with *Synechococcus* in lagoon and open water. Largest shifts which occurred when chlorophyll *a* biomass was highest, and the positive relationships occurring between the autotrophic picoplankton and bacterioplankton, imply that the bacterioplankton community are directly utilising organic matter produced by the photosynthesising picoplankton community. There were no clear diurnal trends evident for bacterioplankton abundances, varying at most, 1.5-fold over the 24-hr period, further suggesting consistent remineralisation of organic matter throughout day and night.

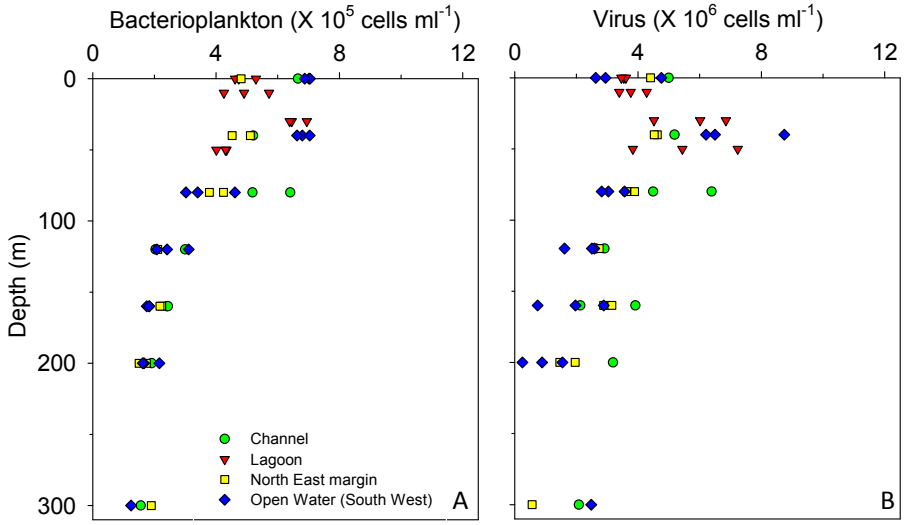

Fig. 29 Abundances of (A) Bacterioplankton and (B) Viruses at Scott Reef in Summer 2009. Data in these plots represent the combined time series data (two or three sampling periods per day, sampled at approximately 08:00, 14:00 and 20:00) for each of the four biological oceanography stations (Lagoon, Deep Channel, NE margin and Open Water). Values are means of duplicate or triplicate samples.

Viral abundances were an on average, an order of magnitude higher than bacterioplankton abundances for all investigated sites (Fig. 29). Highest virus abundances generally occurred between 40 and 80 m in the water column in Open water, NE Margin and Channel and 30 –

50 m in the Lagoon, coinciding with regions in the water column with highest chlorophyll *a* biomass. Like bacterioplankton abundances, virus abundance decreased gradually down to 300 m (deepest measurement made). Highest virus abundances occurred in the water column at both the Open Water and Lagoon sites, but abundances only slightly lower than these sites occurred in the water column at the Channel and NE Margin sites. As observed for bacteria, there were no clear diurnal trends observed for viral abundances. Viruses were positively correlated with bacterioplankton and *Prochlorococcus* at NE margin, Channel and Open water sites; with *Synechococcus* at NE margin and Open Water sites and with picoeukaryotes at all four sites. Since viruses have been shown in other locations to be pathogens of all groups comprising the picoplankton community, close coupling between viruses, bacterioplankton and autotrophic picoplankton as observed here at Scott Reef, suggest that viruses likely play important roles in the production and recycling of organic matter through the microbial food web. Further insights into the control viruses have on different groups within the picoplankton community at Scott reef will be revealed when samples from two separate experiments (conducted at all four stations in summer 2008 and winter 2009) have been analysed.

Comparisons between Scott Reef picoplankton and virus abundance data to other Australian tropical oceanic and reef locations

There have only been a few studies documenting autotrophic picoplankton abundances and/or bacterioplankton and virus distributions in tropical Australian waters. There are even fewer studies documenting the whole picoplankton community together with the virus community in tropical ocean and/or reef waters globally. However, if we are to gain information for how organic matter is produced, consumed and recycled within marine microbial food webs, it is important to document any changes in the picoplankton community, relative to the viral community. Ultimately this data can reveal any shifts in ecosystem functioning over different temporal and spatial scales. Most studies from the late 1990s onwards, have used flow cytometry to document autotrophic picoplankton abundances (allowing discrimination between *Prochlorococcus*, *Synechococcus* and picoeukaryotes), while both flow cytometry and epifluorescence microscopy has been employed to document bacterioplankton and virus abundances. A summary of picoplankton (*Prochlorococcus*, *Synechococcus*, picoeukaryote, bacterioplankton) and virus data for Scott Reef from the four stations (Lagoon, Channel, North East Margin and Open water) are provided and compared with other tropical ocean and reef locations around Australia and other locations (Table 4).

While the autotrophic picoplankton community composition at Scott Reef varies between locations and seasons, one of the major differences to that of other lagoonal reef locations such as the Great Barrier Reef, French Polynesia and New Caledonia, is that *Prochlorococcus* make up a significant proportion of picoplankton abundance. The dominance of *Prochlorococcus* over *Synechococcus* and other picoeukaryotes at Scott Reef can be explained by the very low nutrient concentrations in this region. Because of the small size of *Prochlorococcus* (~ 0.6 µm) and hence its high surface to volume ratio, *Prochlorococcus* has an advantage over *Synechococcus* or other larger Picoeukaryotes with respect to nutrient uptake. As such, these cells can flourish. However the shift from high to low *Pro:Syn* ratios from Open Water to Lagoonal even at Scott Reef, indicates spatial (and also temporal) variation in nutrient availability for picoplankton. For regions where bacterioplankton and viruses have been measured (See Table 4), the ranges in abundances are similar to that at Scott Reef. However, the relatively high bacteria and viral abundances occurring at Scott Reef, in a region where nutrient concentrations are extremely low (i.e. compared to other oceanic reef areas), highlights the important role that microbes play in the cycling of organic matter through microbial food webs in this ecosystem.

Table 4 Ranges in picoplankton and virus abundance at Scott Reef and other tropical ocean and reef locations.

Location	**Pro** x10^5 cells ml^{-1}	**Syn** x10^4 cells ml^{-1}	**Peuks** x10^3 cells ml^{-1}	**Bac** x10^5 cells ml^{-1}	**Virus** x10^6 cells ml^{-1}	**Reference**
Scott Reef						This study
Lagoon	< 1 – 2	< 1 - 15	1 - 20	4 - 7	3 – 7	
Channel	< 1 – 3	< 1 – 6	< 1 – 12	2 – 7	2 – 6	
NE Margin	< 1 – 3	< 1 – 7	< 1 – 10	2 – 5	1 – 5	
Open Water	< 1 - 4	< 1 - 4	< 1 - 4	2 - 5	4 – 5	
Great Barrier Reef (GBR)						
Lizard Island	Absent	4 - 10	-	6 - 8	1 - 2	Patten, unpublished
Heron Island	-	-	-	5 - 10	1 - 4	Patten et al.. 2008
South GBR	< 1	7 – 17	-	-	-	Crosbie & Furnas., 2001
Central GBR	≤ 1	≤ 1	-	-	-	Crosbie & Furnas., 2001
Ningaloo	< 1 - 3	< 1 - 7	< 1 - 9	1 - 9	1 - 7	Patten, unpublished
Kimberley coast	Absent	2 - 13	1 - 6	2 - 5	2 - 12	Patten, unpublished
French Polynesia						
Astrolabe reef/lagoon	< 1 – 7	2.5 - 15	1 – 4	-	-	Charpy & Blanchot 1999
New Caledonia						Jacquet et al. 2006
Lagoon	< 1	5 – 12	2 – 18	-	-	
Ocean reference	2	2	2			
Line Islands Atolls	-	-	-	< 1 - 8	< 1 - 5	Dinsdale et al. 2008

Scott reef data are combined from all three research cruises to date (Winter 2008, Summer 2008, Winter 2009). Ranges were determined in the upper 100 m of the water column (where depths exceeded 100 m).
'Absent' indicates these groups were not observed in samples at those locations. '-' indicates abundances not determined. Pro = *Prochlorococcus* (x10^5 cells ml^{-1}), Syn = *Synechococcus* (x10^4 cells ml^{-1}), Peuks = Picoeukaryotes(x10^3 cells ml^{-1}), Bac = Bacterioplankton (x10^5 cells ml^{-1}) and Virus = Viruses (x10^6 cells ml^{-1})

Abundance and distribution of nano and microplankton at Scott Reef

Nanoplankton and microplankton are the size classes of plankton with cells 2-20 µm and 20-200 µm respectively, and comprise both autotrophic and heterotrophic cells. On cruises 2 and 3 (December 2008 and June 2009) we used a FlowCam to enumerate cells larger than 5 µm (to minimise overlap with the flow-cytometry data collected for picoplankton). The FlowCam uses flow-cytometry principles to count cells in a larger size fraction than the flow-cytometer used for the picoplankton counts, but in addition takes photographic images of each particle to facilitate their identification (Fig. 30).

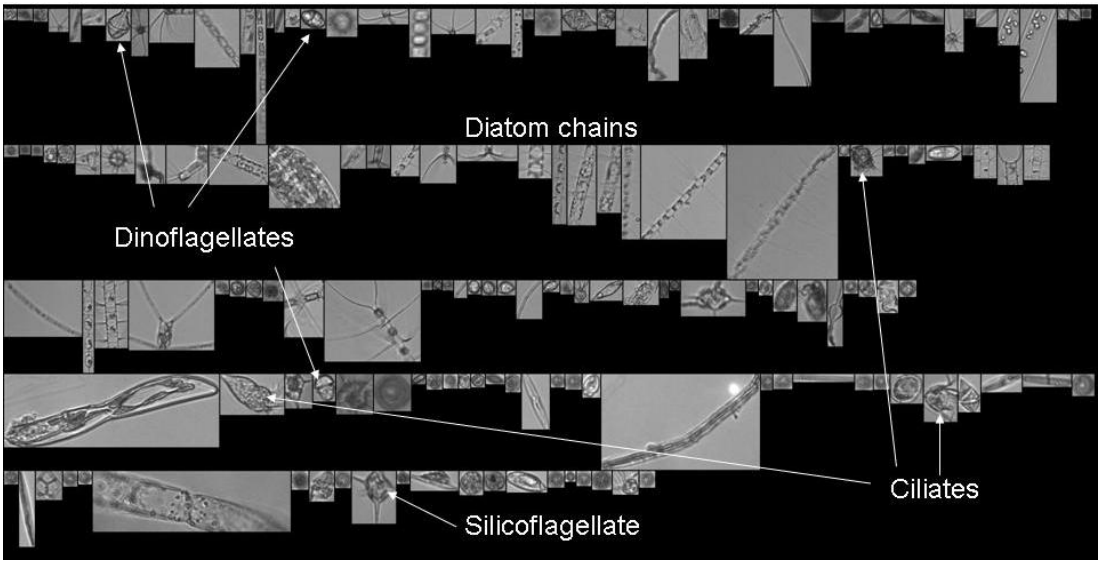

Fig. 30 Representative images of nano and microplankton taken by the FlowCam at Scott Reef on the December 2008 and June 2009 Biological Oceanography cruises.

Diatom chains were amongst the most frequently imaged plankton. These phytoplankton are probably the most important contributors to primary production in the nano and microplankton size range, and are an important trophic link to zooplankton such as copepods and euphausiids. Dinoflagellates were common, but these cells can be autotrophic, heterotrophic or mixotrophic (both auto- and heterotrophic). Heterotrophic ciliates such as *Strombidium* and *Strobilidium* were also frequently imaged. Count data from June 2009 indicate that cells >5 µm in size are more common in the surface layers, but at times form layers at sub-surface depths (Fig. 31). The remaining FlowCam data is yet to be analysed.

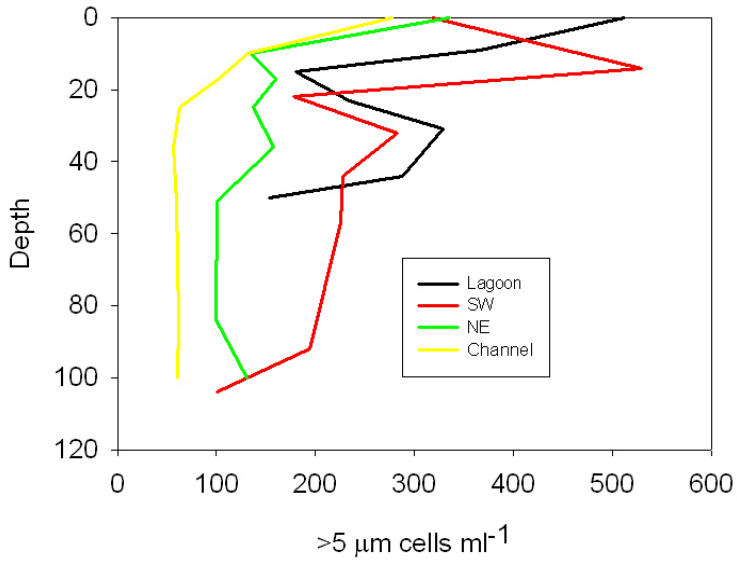

Fig. 31 Depth distribution of cells >5 µm in size at the Production stations occupied in June 2009.

Primary productivity and carbon turnover in Scott Reef waters

^{14}C uptake Experiments

To date, fourteen (14) primary production experiments based on ^{14}C tracer methods have been carried out at the four experimental sites (Table 5) in and around Scott Reef. At least one productivity experiment was carried out at each site on each biological oceanography cruise. Repeat productivity experiments were also carried out at the lagoon site (Site 1) at the end of the December 2008 and May-June 2009 cruises. Table 6 summarizes the results of these productivity experiments.

Table 5 Locations of primary production stations occupied at and near Scott Reef in June – July, 2008.

Site	Name	Latitude	Longitude	Depth (m)
1	Lagoon	14° 3.6'S	121° 43.8'E	53
2	Deep Channel	14° 2.2'S	121° 51.7'E	456
3	NE Margin	14° 6.3'S	121° 51.0'E	450
3	Open Water	13° 52,1'S	121° 52.5'E	784

The primary production experiments involved the size fractionation of natural populations (Total population, > 10 µm size fraction, 2 – 10 µm size fraction, < 2 µm size fraction) to partition daily production between important functional groups within the phytoplankton. This was done because different size classes of phytoplankton have differing fates within pelagic food webs and contribute differentially to potential material exports to benthic food webs.

Diatoms and dinoflagellates are the primary phytoplankton groups in the > 10 µm size fraction, while the dominant < 2 µm size fraction (picoplankton) is overwhelmingly characterized by very small unicellular photosynthetic cyanobacteria (formerly called blue-green algae, see previous section). The intermediate 2 – 10 µm size fraction contains a diverse

assemblage of microflagellates and small non-motile microalgae. Unicellular cyanobacteria smaller than 2 μm typically dominate phytoplankton biomass and production in oligotrophic tropical oceanic waters. In a wide range of ecosystems; however, short-term phytoplankton community and production responses to enhanced nutrient inputs such as upwelling are commonly manifested through the preferential growth of diatom populations until their slower-growing metazoan (e.g. copepod) grazers have time to reproduce and develop significant biomass.

In the present study, phytoplankton populations were collected from 6-8 depths through the euphotic zone and incubated under simulated *in-situ* light conditions matching the collection depths. Mid-day hourly photosynthesis rates (10:00 – 14:00 local time) were integrated to give an estimate of mid-day areal production (mg C m^{-2} hr^{-1}) which was then converted to an estimate of daily primary production (mg C m^{-2} d^{-1}). This estimate is based upon the observation that approximately 50% of total daily irradiance available for photosynthesis impinges on the ocean surface between 10:00 and 14:00. This estimate of production is generally equivalent to (though usually less than) estimates of gross primary production calculated from community oxygen fluxes (see discussion below).

Fig. 32 to Fig. 34 present illustrative vertical profiles of size-fractionated chlorophyll *a* concentration and mid-day primary production rates measured in the central South Reef lagoon (SCT121, SCT184), the deep channel between North and South Reef (SCT176, SCT287),and in open shelf-edge waters away from the topographic influence of Scott Reef (SCT253, SCT270). Profiles of chlorophyll and productivity at the NE margin site (not shown) are similar to those in the adjacent deep channel.

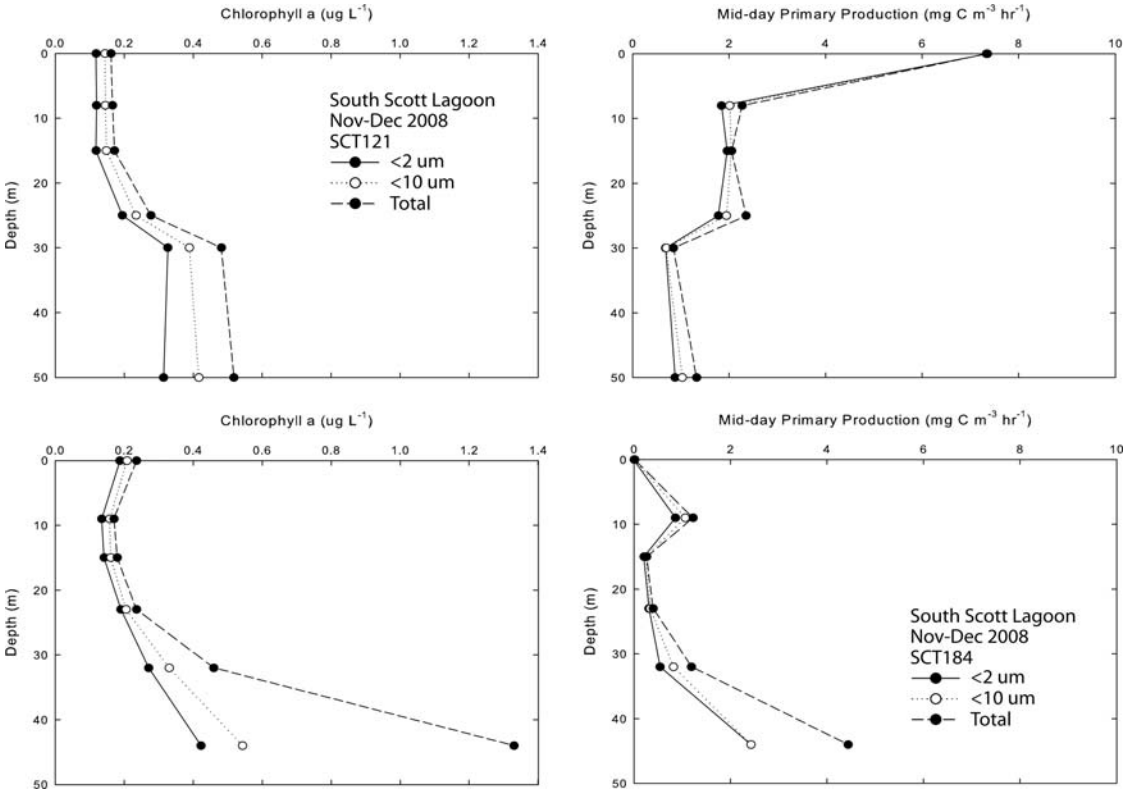

Fig. 32 Vertical profiles of size fractionated chlorophyll (Left) and primary production (Right) in the lagoon of South Reef in Nov-Dec 2008.

Two types of profiles were observed in the South Reef lagoon. Most commonly, the vertical distribution of chlorophyll in the lagoon is characterized by a near-bottom maximum. Larger phytoplankton (>10 μm) made a noticeable contribution to community biomass on a number of occasions. As noted above, a greater proportion of larger phytoplankton is often indicative of nutrient input processes. Within the lagoon setting, this might be either the result of upwelling and lateral intrusion of thermocline waters, or from enhanced mineralization of organic nutrients by benthic communities. Vertical productivity distributions were characterized by profiles with maxima either near the surface or bottom. Peak productivity rates (>4 mg C m^{-3} hr^{-1}) within profiles in the shallow, high-light environment of the lagoon were consistently higher than observed at nearby deep water sites.

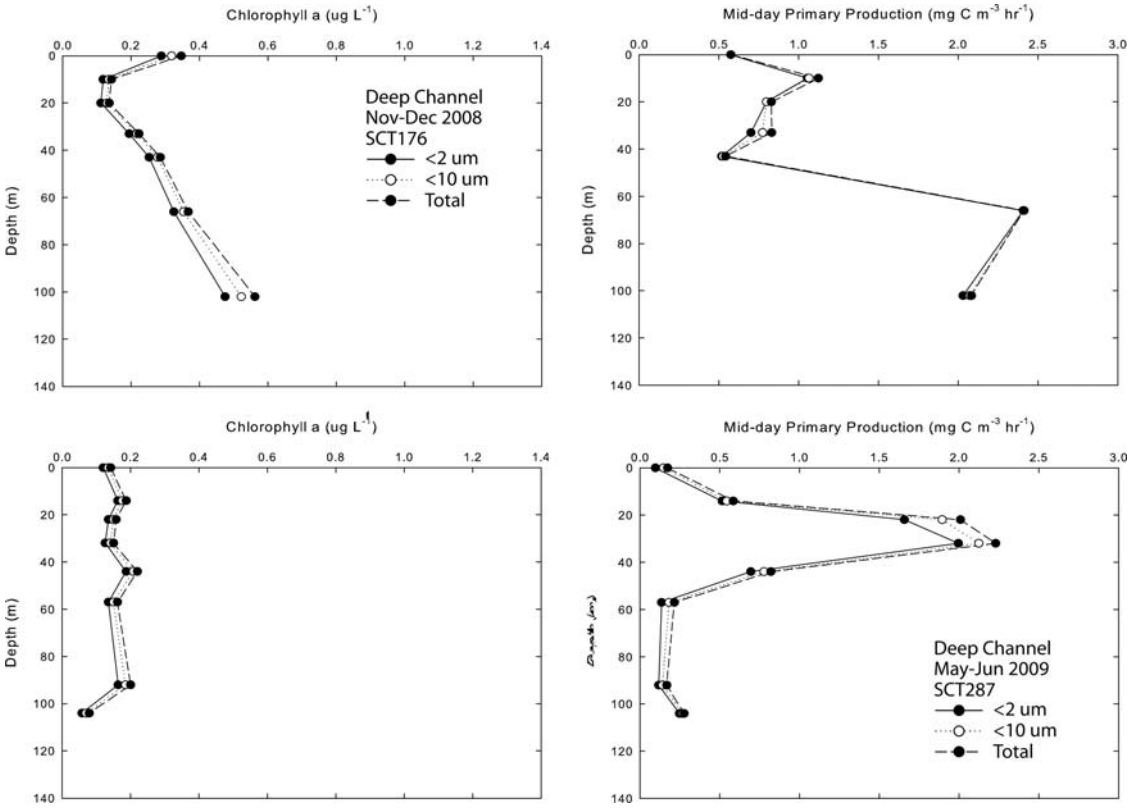

Fig. 33 Vertical profiles of size fractionated chlorophyll (Left) and primary production (Right) in the deep channel between North and South Reefs in Nov-Dec 2008 (Top) and May-June 2009 (Bottom)

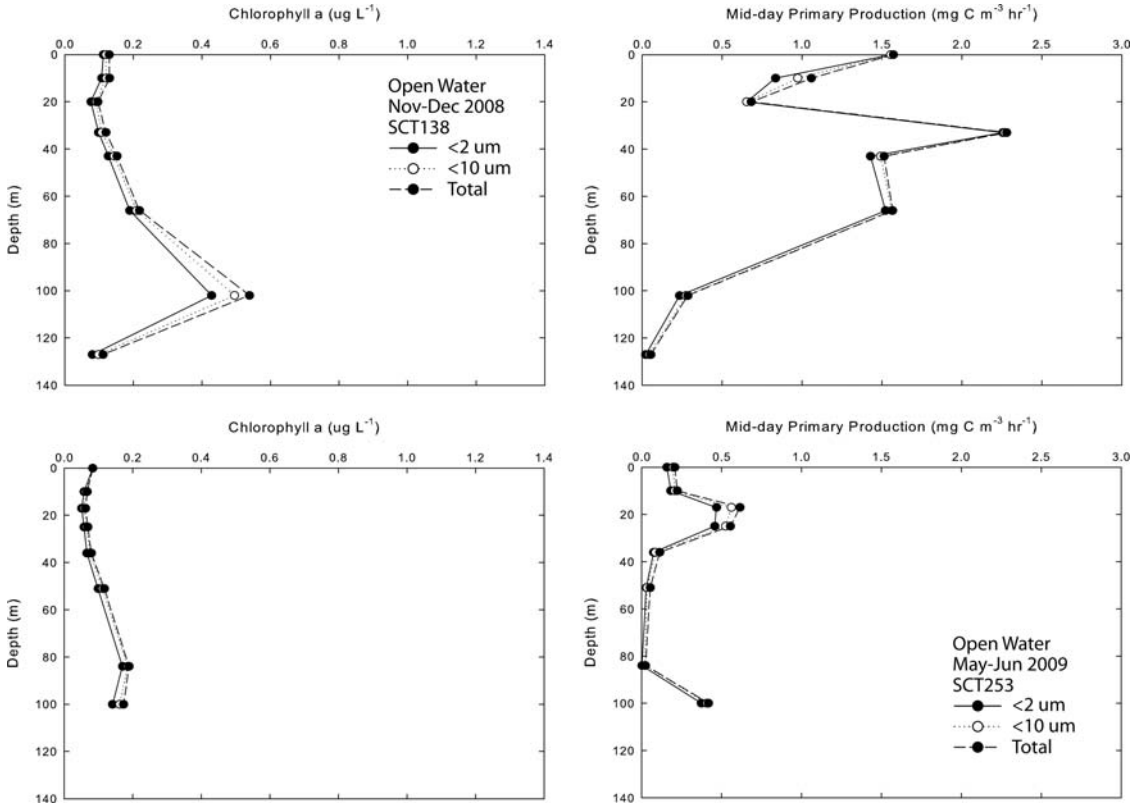

Fig. 34 Vertical profiles of size fractionated chlorophyll (Left) and primary production (Right) at the open water site southwest of Scott Reef in Nov-Dec 2008 (Top) and May-June 2009 (Bottom).

At the deep water sites (2-4), vertical distributions of phytoplankton biomass (as chlorophyll) and primary productivity differed. Vertical distributions of chlorophyll are most commonly characterized by a well defined sub-surface maximum at depths ranging between 40 and 100 m. In contrast, the highest primary production rates were most commonly measured in a shallower and narrow depth stratum between 20 and 40 m. This depth band is characterized by downwelling irradiance levels between approximately 20 and 5 percent of surface irradiance. Smaller secondary productivity maxima associated with the deep chlorophyll maximum layer were occasionally observed.

On all three biological oceanography cruises to date, phytoplankton biomass and primary production (by C uptake) at both lagoon and deep water sites were overwhelmingly dominated by picoplankton (< 2 μm size fraction). With only one exception, picoplankton chlorophyll and primary production exceeded 75 percent of total biomass and production at the three deep sites. In 13 of 14 cases, the picoplankton contribution exceeded 90 percent of total production.

Larger phytoplankton (> 10 μm size fraction) were only observed to make a significant contribution to biomass and productivity at the South Reef lagoon site (1) and only in experiments run during the December 2008 cruise (SCT184, 10-Dec-2008).

The average of depth-integrated estimates of phytoplankton biomass (as chlorophyll *a*) at the production stations during winter (dry season) within South Reef lagoon (11.2 mg m^{-2}, Table 6) were similar to standing crop values recorded at deep water sites adjacent and away from Scott Reef (dry season average 14.9 mg m^{-2}). Average daily dry season productivity (800 mg C m^{-2} day^{-1}), however was higher than recorded at dry season deep water sites (mean = 668, range 204-1,031 mg C m^{-2} d^{-1}). Estimates of chlorophyll standing crop during the one early summer cruise to date was approximately twice that measured during the dry season (average = 20.6 mg m-2 in the lagoon and 33.1 mg m^{-2} for the deep water sites). Average integral daily production in the lagoon averaged 948 mg C m^{-2} day^{-1} compared to 1,208 mg C m^{-2} d^{-1} at summer deep-water sites.

Table 6 Estimates of phytoplankton standing crop (as chlorophyll), daily primary production in functional group size fractions and daily bacterial production at Scott Reef sites. Chlorophyll and production values in parentheses give the percent of total standing crop or daily production in experimental size fractions. Bacterial production values in brackets indicate bacterial production as a percent of primary production

Site	Date	Station	Chl standing crop				Primary Production		Bacterial Production
			mg m^{-2}				mg C m^{-2} d^{-1}		mg C m^{-2} d^{-1}
			<2 μm	<10 μm	Total	<2 μm	<10 μm	Total	
Lagoon	25-06-08	SCT011	8.8 (73)	10.2 (85)	12.0	740 (82)	857 (95)	905	37.6 [4]
	03-12-08	SCT121	11.1 (66)	13.7 (82)	16.6	1,056 (86)	1,113 (91)	1,227	42.1 [3]
	10-12-08	SCT184	12.0 (49)	14.5 (59)	24.6	377 (56)	428 (64)	669	a
	31-05-09	SCT225	7.9 (82)	9.0 (94)	9.6	369 (83)	421 (94)	447	38.7 [9]
	08-06-09	STC296	9.8 (82)	10.7 (89)	12.0	893 (85)	951 (91)	1,049	101.9 [10]
Deep Channel	01-07-08	SCT079	2.8 (40)	6.3 (89)	7.1	976 (95)	1,034 (100)	1,031	37.4 [4]
	09-12-09	SCT176	29.2 (86)	32.2 (95)	33.9	1,045 (97)	1,058 (97)	1,073	a
	06-06-09	SCT287	15.0 (84)	16.7 (93)	17.9	621 (83)	695 (93)	746	57.7 [8]
NE Margin	29-06-08	SCT057	12.3 (79)	13.9 (90)	15.5	441 (79)	517 (93)	555	34.0 [6]
	07-12-09	SCT157	29.5 (81)	33.2 (90)	36.7	1,086 (89)	1,118 (92)	1,222	b
	04-06-09	SCT270	12.7 (83)	14.4 (94)	15.4	526 (88)	574 (95)	601	32.1 [5]
Open Water	27-06-09	SCT035	16.9 (78)	19.1 (88)	21.6	713 (82)	800 (92)	872	52.9 [6]
	05-12-08	SCT138	23.6 (82)	26.9 (93)	28.9	1,255 (94)	1,306 (98)	1,330	b
	02-06-09	SCT253	10.4 (87)	11.5 (96)	12.0	156 (76)	185 (90)	204	31.4 [15]

[a] All depths not sampled

[b] contaminated samples preclude integration

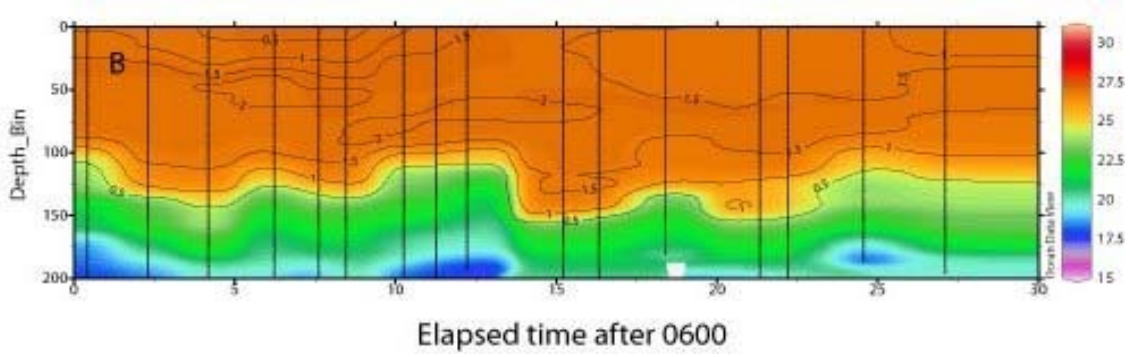

Fig. 35 Contour plot of subsurface chlorophyll *a* distributions overlaid on the temporal contour plot of water temperature at depths < 200 m in the deep channel between North and South Reef, 26 – 27 June, 2008

Pelagic metabolism

Pelagic processes in the vicinity of Scott Reef are typical of the oligotrophic open ocean, in that they are dominated by microbial food chains. Microbial food chains are inefficient in transferring nutrients to higher trophic levels (ultimately producing fish), meaning that most energy is lost in respiration. The balance between net autotrophy (i.e. positive net carbon fixation) and net heterotrophy (losses of carbon due to respiration exceeding carbon fixation) is determined by hydrological events that introduce pulses of nutrients into the productive surface layers, increasing production and pushing the metabolic balance toward autotrophy. Understanding the processes that determine this balance in the unperturbed environment and the frequency and amplitude of natural production events will allow any future potential anthropogenic perturbations to be placed in context.

At each of the four sites occupied during the Biological Oceanography cruises, production and respiration were measured by conducting incubations of water collected at the same stations and depths as for the ^{14}C experiments (except for the Open water site on the June 2008 cruise, which was sampled one day earlier). In these experiments, O_2 evolution as a result of photosynthesis was measured in samples exposed to the same light regime they would have experienced at the depth of collection. Since O_2 evolution in light bottles is proportional to carbon fixation, it is possible to use this measurement to make an additional estimate of the primary production rate by phytoplankton. A parallel set of samples was incubated in the dark. The consumption of O_2 in the dark is an index of water column respiration rate (metabolic activity by all microorganisms including bacteria, phytoplankton, and microzooplankton).

At all stations where surface incubations were conducted, surface production by phytoplankton was insufficient to compensate for community respiration and resulted in negative net oxygen flux (Fig. 36, Fig. 37 and Fig. 38), as a result of photoinhibition caused by the cells being exposed to full strength sunlight for a full day. Whether this effect occurs in the field or is a consequence of the bottle incubations is unclear, since in the field cells would be distributed through the water column by turbulence. To avoid this effect, we often omitted the surface incubation in our experiments. At depths approaching the bottom of the euphotic zone, production was light-limited and again respiration outweighed production. Consequently, phytoplankton production usually only exceeded respiration in the middle of the euphotic zone, if at all.

Mean dark respiration rates were 1.60 ± 0.69 (SD) mmol O_2 m^{-3} d^{-1} in June 2008, 1.80 ± 0.80 mmol O_2 m^{-3} d^{-1} in December 2008, and 1.26 ± 0.41 mmol O_2 m^{-3} d^{-1} in June 2009. The highest observed dark respiration rates (DR) occurred at the lagoon station in December 2008 (2.58 ± 0.52 mmol O_2 m^{-3} d^{-1}), compared to water column average DR at the same site of 1.77 ± 0.84 and 1.55 ± 0.29 mmol O_2 m^{-3} d^{-1} in June of 2008 and 2009 respectively. DR at the other stations occupied in December were 2 fold lower, and of the same magnitude as those observed in June.

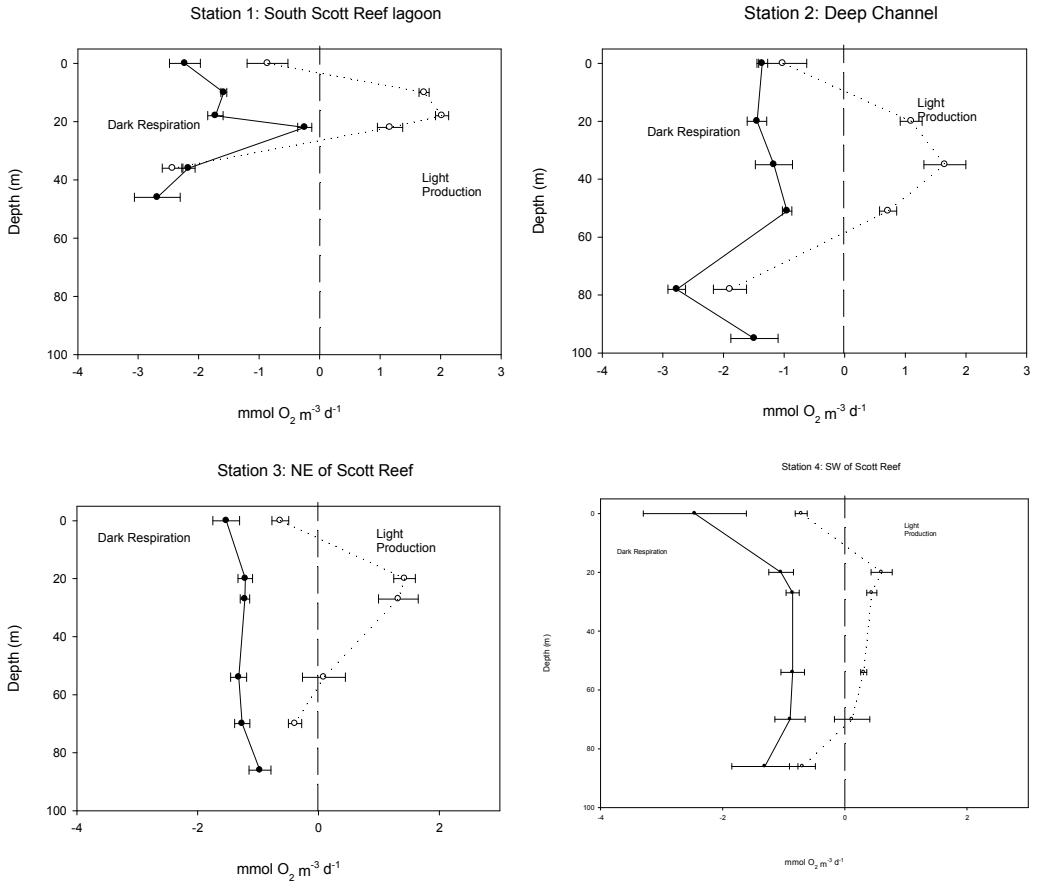

Fig. 36 Oxygen flux through the water column at lagoon, Deep Channel, NE Margin and Open Water sites, June 2008. Solid symbols indicate dark respiration; unfilled symbols indicate samples in the light. The compensation point, at which production = respiration (i.e. net O_2 flux is zero) is indicated by the vertical dotted line.

Production rates in the light bottle incubations usually only exceeded the compensation point (i.e. the point at which production of oxygen balances consumption) at depths of 20-40 m. At the lagoon station in December 2008, we observed a very strange pattern of layering of positive oxygen flux through the water column alternating with depths at which oxygen flux was negative. This prompted us to repeat the observations at the end of the cruise, and a broadly similar pattern was observed. It is unclear what could be causing these patterns, other than layers of microbes forming at distinct depths during the very calm weather.

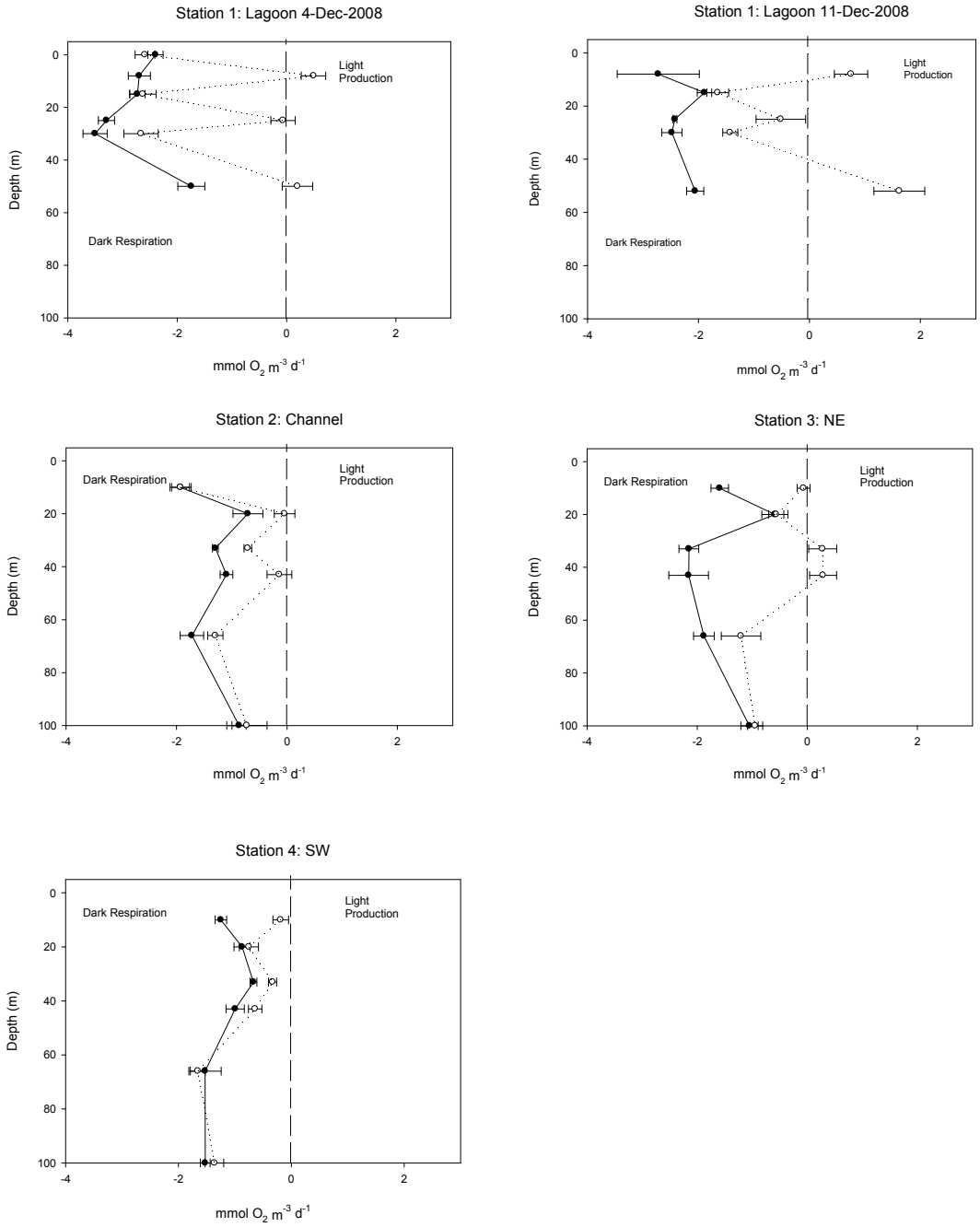

Fig. 37 Oxygen flux through the water column at lagoon, Deep Channel, NE Margin and Open Water sites, December 2008, as for Fig. 29. Measurements at the Lagoon station conducted at the start of the cruise (4 Dec 2008) were repeated on 11 Dec 2008.

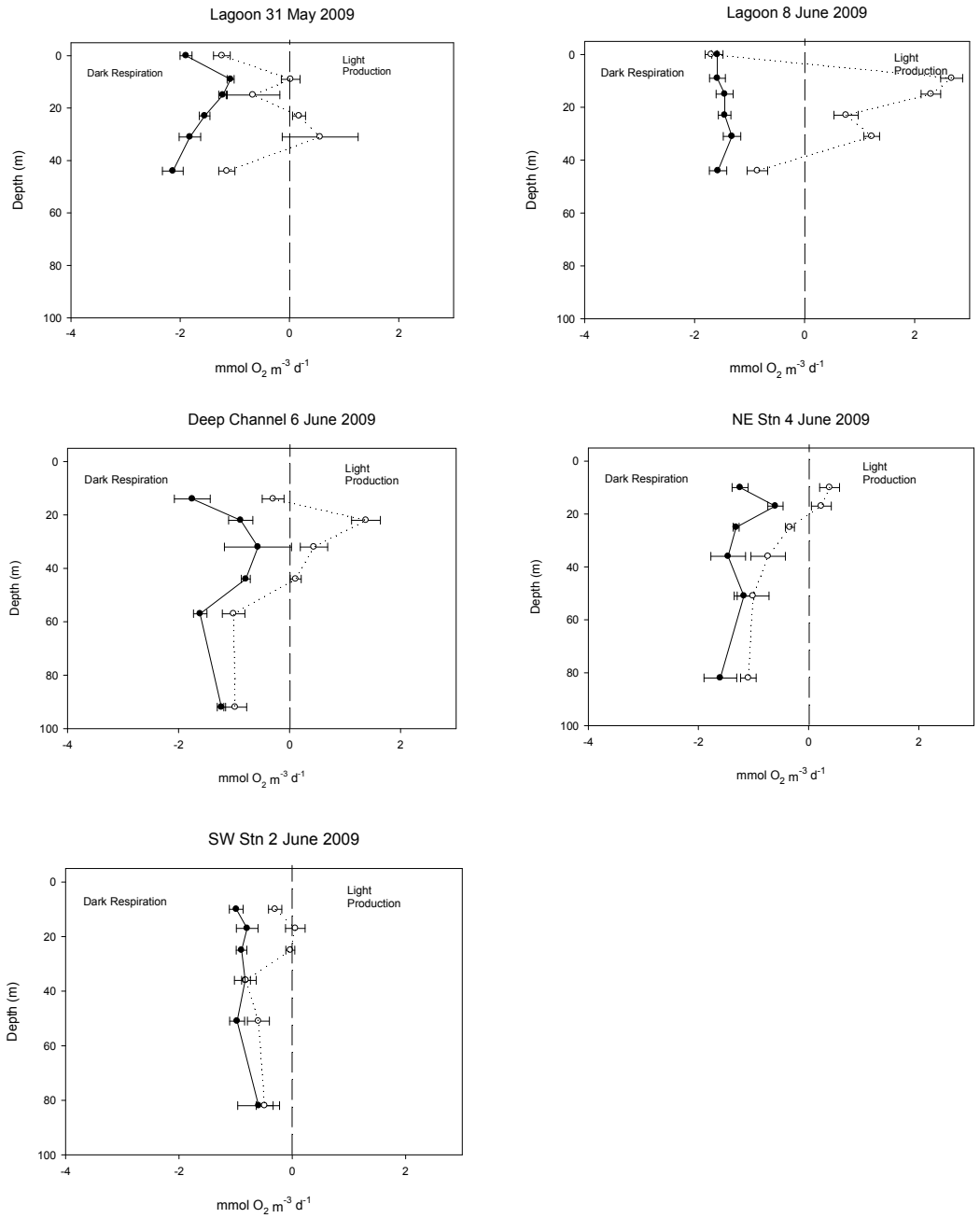

Fig. 38 Oxygen flux through the water column at lagoon, Deep Channel, NE Margin and Open Water sites, May-June 2009, as for Fig. 29. Measurements at the Lagoon station conducted at the start of the cruise (31 May 2009) were repeated on 8 June 2009.

By integrating oxygen fluxes measured at discrete intervals through the water column down to the 1% light level, generally taken as being the bottom of the euphotic zone, it is possible to estimate area-specific rates of production and respiration (Fig. 39). This analysis reveals the waters in and around Scott Reef are usually heterotrophic (phytoplankton production insufficient to offset water column respiration rates), with only 5 of the 14 stations measured achieving a P:R ratio > 1 (i.e. autotrophic).

In June 2008, the lagoon, Deep Channel and NE Margin sites were autotrophic, but the rates of production were low. Overall, the mean P:R ratio was 1.11 ± 0.15. There was little

difference in net production at the autotrophic stations, and while gross production was lower at the lagoon site, this probably reflects the shallower water column within the lagoon.

Heterotrophy was most pronounced on the December cruise (Fig. 39), where all stations failed to achieve metabolic balance and the mean P:R ratio was 0.69 ± 0.17. The reason for this heterotrophy is not yet clear, but may be related to the very stable water column observed during this period resulting in the euphotic zone being "burnt-out", with key micro-nutrients depleted and little introduction of new nutrients from sub-thermocline waters.

Interestingly, in June 2009 the lagoon and channel stations were heterotrophic, and the more oceanic NE and SW sites were autotrophic, almost the opposite of what was observed in June 2008. Overall, the mean P:R ratio in June 2009 was 1.02 ± 0.32.

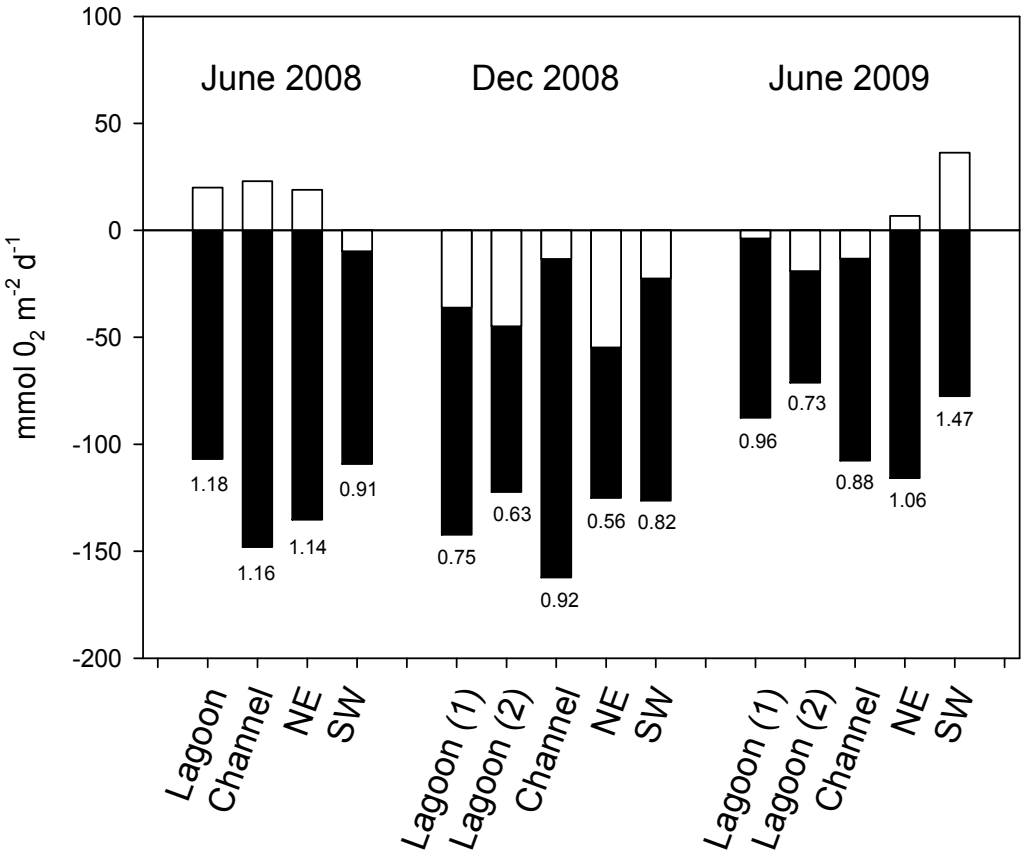

Fig. 39 Community respiration and net primary production at Scott Reef. The number under each bar is the P:R ratio i.e. the ratio of Gross Production (CR+NPP) to respiration (CR). When the P:R ratio is >1 the system is autotrophic, when it is <1 the system is heterotrophic.

Area-specific respiration far exceeded production at all sites. The bulk of pelagic respiration at Scott Reef is likely to be contributed by micro-heterotrophs, from bacteria to protists. Robinson and Williams (2005) have attributed 45% of respiration to bacteria, and Calbet and Landry (2004) suggest that microzooplankton contribute a similar amount.

Our data suggest that the metabolic balance of waters around Scott Reef is finely balanced. Recent oceanographic literature suggests that open ocean waters are frequently heterotrophic, and that overall metabolic balance is maintained by aperiodic net autotrophic

events that can only be resolved by frequent sampling (Marañón et al., 2000, Karl et al. 2003, Williams et al. 2004). The Scott Reef data set is consistent with this hypothesis. Mixing of nutrient rich deep water into the euphotic zone may have accounted for autotrophy at the lagoon, Deep Channel and NE Margin sites during June 2008 because of strong winds prior to the experiments, but cannot account for the autotrophy observed at the NE and SW sites during June 2009. However, the contrasting patterns observed on each of the biological oceanography cruises are intriguing, and the reasons for these patterns unclear.

Comparison of the Scott Reef metabolism data to other Australian locations

We have made measurements in a number of other locations in tropical Australia using the same techniques. These results can be compared by plotting the P:R ratio against gross primary production (Fig. 40). The data to hand from Scott Reef form a distinct cluster, characterised by very low values of gross primary production (GPP). To achieve autotrophy, our data suggest that GPP needs to exceed 119 mmol O_2 m^{-2} d^{-1}, or 2 g C m^{-2} d^{-1}, assuming a photosynthetic quotient of 1.4 (Bender et al., 1999). This compares with the global average of 80 mmol O_2 m^{-2} d^{-1}, (Williams et al., 1998)

The data from Scott Reef aligns with data from the Sahul Banks region of the Timor Sea, though the latter is more productive, and the Coral Sea. Measurements from the Great Barrier Reef are similar in GPP, but have higher P:R ratios because of the shallower water column and consequent lower values of areal respiration. In Exmouth Gulf, areal respiration rates were low, probably because of the shallow water column through which respiration was integrated, and there was high production in the surface. The highest production rates measured using the oxygen method have been on the shallow NW shelf en route to the Timor Sea.

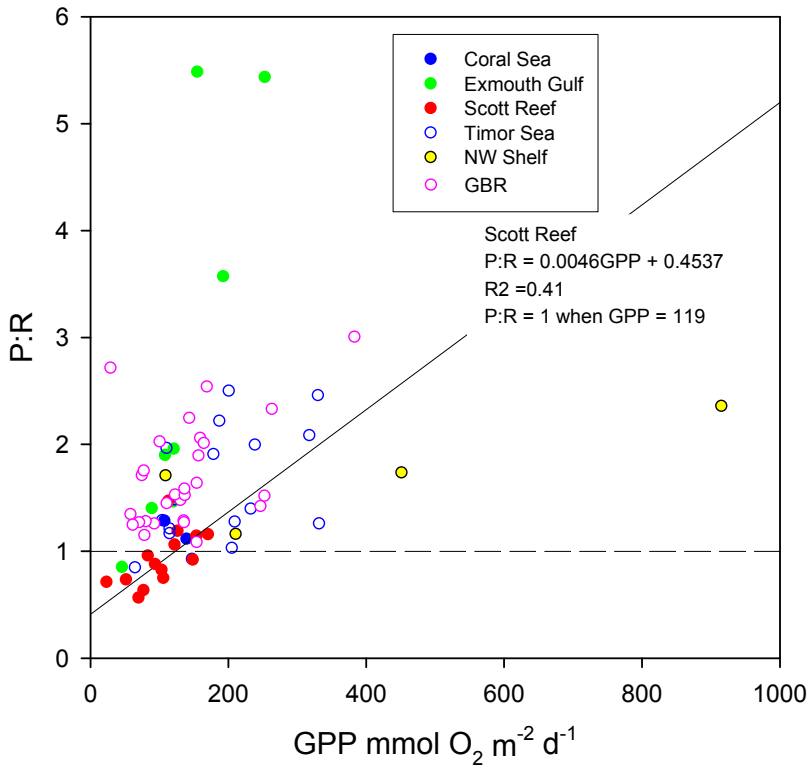

Fig. 40 The relationship of P:R ratio to Gross Primary Production, at Scott Reef compared to other locations where AIMS has made similar measurements.

Comparison of the Scott Reef data to other areas of the globe

Duarte and Regaudie-de-Gioux (2009) compiled all available data on the metabolic balance of marine planktonic communities, and concluded that, on average, a threshold GPP of 1-3 mmol O_2 m^{-3} d^{-1} was required for open ocean planktonic communities to achieve metabolic balance (i.e. a P:R ratio of 1). The relationship between volume-based measurements of NCP and GPP at Scott Reef is highly significant (Fig. 41) and indicates a threshold GPP of 1.57 mmol O_2 m^{-3} d^{-1} is required to achieve metabolic balance (Table 7). Of the 35 studies listed by Duarte and Regaudie-de-Gioux (2009), only 8 significant relationships are listed for subtropical areas of the ocean. It is worthy of note that there is only one other set of measurements available from the tropical ocean (that of Robinson and Williams 1999 from the NW Indian Ocean), making the Scott Reef data particularly valuable. The data of Robinson and Williams (1999) is from the Arabian Sea, an area with both coastal and open-ocean upwelling and consequent higher rates of primary production, in contrast to the predominately oligotrophic oceanographic regime at Scott Reef.

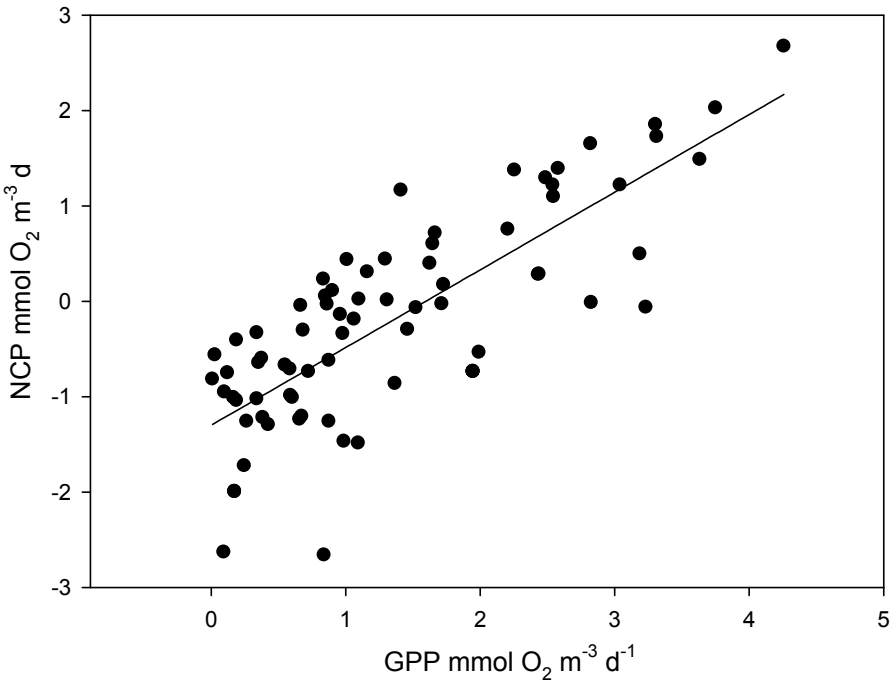

Fig. 41 Volumetric NCP vs GPP from Scott Reef. See Table 7 for regression statistics.

Table 7 Comparison of Reduced Major Axis (Model II) Regression statistics of the relationship between NCP and GPP (mmol O_2 m^{-3} d^{-1}) at Scott Reef with subtropical and tropical locations from Table 1 of Duarte and Regaudie-de-Gioux (2009).

Region	Intercept	SE	Slope	SE	R^2 adj	Threshold GPP
NW Indian Ocean	-3.18	0.33	0.76	0.06	0.83	4.2
Subtropical Atlantic	0.99	1.22	1.14	0.16	0.65	1.01

Gyre							
Subtropical Atlantic	NE	-1.37	0.06	1.14	0.97	0.53	0.49
Subtropical Atlantic	E	-3.34	0.45	0.94	0.04	0.94	3.56
Subtropical Atlantic	NE	-1.16	0.26	0.8	0.06	0.63	1.45
Subtropical Atlantic		-3.32	0.32	2.02	0.22	0.21	1.65
Subtropical Atlantic	NE	-0.63	0.04	0.99	0.01	0.99	0.63
Subtropical Pacific	N	-0.56	0.05	0.66	0.08	0.23	0.84
Global Ocean		-1.37	2.09	1.3	0.14	0.46	1.06
This study		**-1.63**	**0.12**	**1.04**	**0.07**	**0.65**	**1.57**

Scott Reef is an extremely oligotrophic environment, as indicated by the comparison of locations in Fig. 40. Consequently, the threshold GPP required to achieve metabolic balance at Scott Reef is comparable to other oligotrophic regions of the subtropical ocean, but higher than the global average (Table 7). There are 3 possible reasons for the comparatively high threshold of GPP required for metabolic balance at Scott Reef:

1. Dissolved organic carbon release by phytoplankton is proportionally higher at low levels of primary production (Hessen and Anderson 2008), raising the GPP threshold for metabolic balance.
2. Intense light fields may increase photorespiration, also raising the GPP threshold (Hessen and Anderson 2008).
3. Oligotrophic planktonic communities tend to support a higher heterotrophic biomass per unit of autotrophic biomass than more productive systems (Gasol et al. 1997), raising respiration relative to GPP.

Overall, the Scott Reef metabolic data are similar to other areas of the tropical or subtropical ocean (Table 8). Areal rates of respiration and production were generally similar in the Timor Sea to those measured at Scott Reef, but there were a few episodes of very high productivity that lift the mean rates in the Timor Sea data. The Scott Reef respiration data are similar to data from other areas. There is a very wide range in the reported values of net primary production (NPP), as it appears that NPP establishes the metabolic balance of the ocean (Arístegui and Harrison, 2002). The frequent occurrence of heterotrophy at Scott Reef but overall positive NPP is most similar to the Atlantic (Serret et al., 2006). Station ALOHA off Hawaii (Williams et al., 2004) is consistently heterotrophic; these authors suggest that this may be the case in many areas of the open ocean.

Table 8 Comparison of Scott Reef rates with other areas of the globe. CR – average area-specific community respiration; NPP – average area-specific net primary production; DR – average volume-specific dark respiration; Max P – maximum observed O_2 flux in light bottles.

Location	**CR** mmol O_2 m^{-2} d^{-1}	**NPP** mmol O_2 m^{-2} d^{-1}	**DR** mmol O_2 m^{-3} d^{-1}	**Max P** mmol O_2 m^{-3} d^{-1}	**Reference**

Scott Reef					
June 2008	125	18	1.6	2.0	This study
Dec 2008	136	-3	1.8	1.5	
June 2009	92	1	1.3	2.7	
Timor Sea	224	198	1.6	5.6	McKinnon (unpub)
Equatorial Atlantic	71	80	0.6-2.6	3.5	Perez et al., 2005
South Atlantic Gyre	60	20	0.2	0.5	Serret et al., 2006
Stn. ALOHA (Hawaii)	86	-24	0.5 – 1.5	1.3	Williams et al., 2004
Arabian Sea	78 – 127	2.5 – 455	1.0 – 8.0	13	Dickson et al., 2001
Banda Sea	100 – 170	108 – 1350	1.0 – 1.7	?	Tijssen et al., 1990
Latitudinal average	~300	~40			Robinson and Williams, 2005

Bacterial Production (Thymidine uptake experiments)

Vertical profiles of bacterial biomass production (as carbon) were also measured at the four primary production stations using radio-labelled thymidine uptake (Fig. 42). Thymidine is one of the four organic bases that make up DNA in all living organisms. Eukaryotic phytoplankton and phototrophic cyanobacteria are unable to take up and assimilate free thymidine from the environment and must synthesise their own. The bacteria production estimate is based on empirically derived estimates of thymidine/DNA ratios, the average cellular DNA content and cellular carbon contents for pelagic marine bacteria (Furhman and Azam, 1980, 1982).

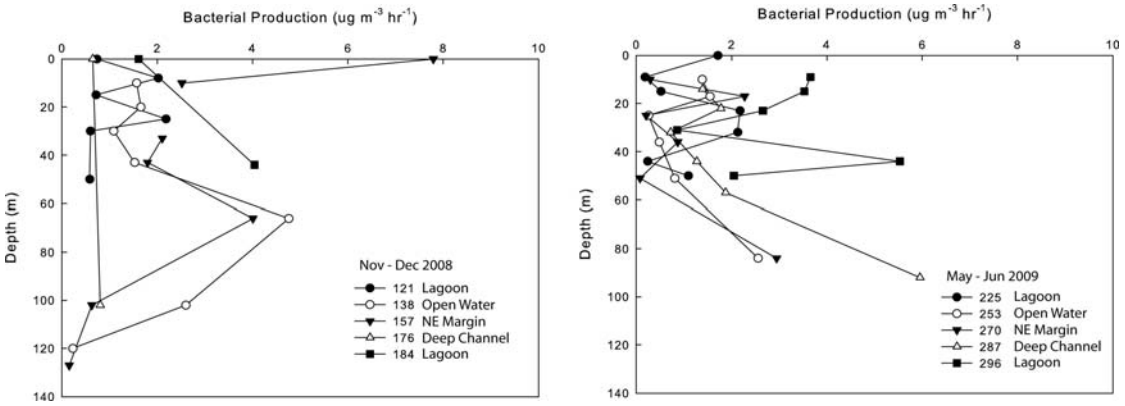

Fig. 42 Vertical profiles of daily bacterial carbon production (^{3}H-thymidine uptake) measured concurrently with phytoplankton primary production in the vicinity of Scott Reef during the Nov-Dec 2008 and May-June 2009 cruises.

Measured hourly bacterial production rates ranged from near nil to 8 mg C m^{-3} hr^{-1}. Two extremely high rates were recorded in December 2008, but are believed due to contamination of the samples with excess isotope. At the other production stations, bacterial carbon production rates generally ranged between 0.3 and 4 mg C m^{-3} hr^{-1}. Production maxima in individual depth profiles were variable, either coinciding with or lying somewhat below peaks in chlorophyll rather than primary production. The general coincidence between subsurface maxima in bacterial production and chlorophyll suggests that a significant portion of the organic matter supporting bacterial production may be coming from lysis of

algal/cyanobacterial cells through grazing or virus attack rather than direct excretion of organic matter from photosynthesising cells in the water column. This, however, remains to be confirmed experimentally.

Estimates of daily bacterial production (assuming growth over 24 hours) at the four production stations ranged from 31 (SCT253) to 102 (SCT296) mg C m^{-2} d^{-1} (Table 9). Estimated bacterial production rates ranged from 3.4% to 15.4% of concurrent phytoplankton production rates. This production is based upon the assimilation of low molecular weight organic compounds in the water which are derived from excretion by local phytoplankton, organic compounds released in the process of grazing on phytoplankton and lysis of bacteria and phytoplankton by viruses. Only a portion of the organic matter taken up by bacteria is converted to biomass. The remainder is metabolised and/or respired in the process of bacterial growth and metabolism. This is shown by the general correlation between primary production (^{14}C uptake) and dark-bottle respiration rates (above). The proportion of this organic matter that is converted into bacterial biomass, the Carbon Growth Efficiency (CGE) is known to be variable and is not well resolved in most ecosystems with values ranging from < 10 to 70 percent (summarised in Jones et al., 1996). Working in a comparable pelagic environment to Scott Reef, Jones et al. (1996) measured a mean CGE for pelagic bacteria of 23%.

Table 9 Estimates of bacterial biomass carbon production at Scott Reef as estimated from ^{3}H-thymidine uptake.

Station	Primary Production mg C m^{-2} d^{-1}	Bacterial Production mg C m^{-2} d^{-1}	Bacterial / Phytoplankton %
SCT011	905	37.6	4.2
SCT035	872	52.9	6.1
SCT057	555	34.0	6.1
SCT079	1,031	37.4	3.6
SCT121	1,227	42.1	3.4
SCT138	1,330	Contaminated	
SCT157	1,222	contaminated	
SCT225	447	38.7	8.7
SCT253	204	31.4	15.4
SCT270	601	32.1	5.3
SCT287	746	57.7	7.7
SCT296	1,049	101.9	9.7

Historical measurements of pelagic productivity at and near Scott Reef

On a global basis, the biological oceanography of the northern North West Shelf is relatively little studied; however, a significant number of primary production measurements have been made in NW Australia that can be usefully compared to those made in this project. Regional estimates of primary productivity have also been derived from ocean colour satellite estimates of near-surface chlorophyll concentrations, models of vertical phytoplankton biomass distributions and productivity-light relationships (e.g. Behrenfeld and Falkowski, 1997).

The first comprehensive set of productivity measurements in the NW Australian region were made by CSIRO oceanographers in the early 1960's (Jitts, 1969). These measurements are

based upon natural populations incubated in filtered artificial light. Because of methodological differences, it is difficult to directly compare these early rate measurements with modern productivity measurements, though reported vertical distributions of productivity generally follow more recent measurements. These early results show that phytoplankton productivity in the Indian Ocean to the west of Scott Reef varied seasonally and that the euphotic zone could often be quite deep. Daily primary production in oceanic were estimated to range between 80 and 130 mg C m^{-2}.

The AIMS Biological oceanography group made a number of productivity measurements at and near Scott Reef between 1993 and 1995 as part of other research activities using methods similar to those employed in this study. Measured production rates at deep-water stations near Scott Reef proper ranged between 544 and 1,109 mg C m^{-2} d^{-1} (mean - 765 ± 169 mg C m^{-2} d^{-1}). This range is comparable to that measured on the June – July cruises (204 – 1,049 mg C m^{-2} d^{-1}). Estimates of regional primary productivity based upon satellite ocean colour imagery are close to 670 mg C m^{-2} d^{-1} (~250 g C m^{-2} $year^{-1}$, e.g. Behrenfeld et al., 2006).

Early measurements of oceanic primary production suggested that much of the oligotrophic tropical ocean was characterised by low rates of primary production (50 – 100 g C m^{-2} $year^{-1}$ ~ 100 to 250 mg C m^{-2} d^{-1}; e.g. Ryther, 1969). This led to the view of oligotrophic oceanic regions as 'oceanic deserts'. Gradual improvements in sampling and experimental methodologies have led to a general increase in measured production rates in these systems to levels exceeding 500 mg C m^{-2} d^{-1}, even in the most oligotrophic oceanic systems (e.g. Laws et al., 1984, 1987; Jones et al., 1996). The carbon fixation rates measured in the vicinity of Scott Reef and along the continental margin of NW Australia average well above this value. Despite the apparent oligotrophy (low nutrient status) of surface waters along the seaward margin of the North West Shelf, primary production rates are reasonably high using modern techniques (Table 10). Measured primary production rates at continental margin sites bordering North West Cape and Ningaloo Reef range from 500 to 8,300 mg C m^{-2} day^{-1} (Furnas, 2007). This section of the shelf is characterised by intermittent upwelling activity due to strong wind stress from southwesterly winds, active vertical mixing due to internal wave activity and inter-annual variability in the thickness of the surface mixed layer due to changes in the strength of the Leeuwin Current. Under most conditions, oceanic primary production in the North West Cape region is dominated by picoplankton, though during the 1997 – 98 El Niño event, diatoms in the > 10 μm size fraction intermittently made significant contributions to total productivity (Furnas, 2007).

Measured bacterial production rates to date (31 – 102 mg C m^{-2} d^{-1}) are at the low end of the range of bacterial production rates (10 – 1,100 mg C m^{-2} d^{-1} 1997/98 median = 620 mg C m^{-2} d^{-1}; 1998/99 median = 110 mg C m^{-2} d^{-1}) measured in continental slope waters bordering the southern North West Shelf (Furnas, 2007). Where useful profiles of bacterial production could be integrated (average = 46.6 mg C m^{-2} d^{-1}) bacterial production averaged 7 percent of concurrent carbon fixation.

Table 10 A summary of historical primary production measurements (^{14}C-based) from the Great Barrier Reef, oceanic Coral Sea and outer shelf waters of NW Australia.

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Location	Range	Mean	Median	n	Source
	mg C m^{-2} d^{-1}				
Great Barrier Reef	32-5,564	784	631	186	Furnas and Mitchell, 1989, Furnas unpubl.
Coral Sea	117-3,033	599	356	35	Furnas and Mitchell, 1996
Continental Slope (Jan-Feb, 1995)	380-1,904	767	644	16	Furnas, unpubl.
NW Cape (Continental slope)	356-8,303	1,962	999	23	Furnas, 2007
Scott Reef (1993)	544-841	712	725	7	Furnas, unpubl.
Scott Reef	204-1,330	848	872	13	This study

Preliminary statistical analysis of biological oceanographic data

Most results pertaining to the nutrient and productivity status of waters around Scott Reef are to hand from Biological Oceanography cruises 1 and 2 (June and Dec 2008). Consequently, we have conducted a preliminary statistical analysis of the results to hand from the production stations only – i.e. those stations at which measurements of primary production and metabolism were undertaken.

Firstly, t-tests were used to determine which variables significantly discriminated between the cruises (Zar 1999). Of the 17 variables explored, there were significant differences in the cruise-station combination for eight (Table 11). Temperature was significantly higher in December than in June (means 28.44 and 26.93 respectively), as was salinity (34.45 and 34.28). Both <2 µm chlorophyll and <10 µm chlorophyll were significantly higher in December than in June (0.20 v 0.13 µg l^{-1} and 0.24 v 0.16 µg l^{-1}, respectively), and this was reflected by a significant difference in the total chlorophyll. There was no significant difference in < 2 µm production, < 10µm production and total production. Paradoxically, picophytoplankton abundance showed the opposite trend to both <2µm chlorophyll and production, with significantly higher abundance in June than December (223,100 vs 86,600 cells ml^{-1} respectively). Bacterial production was significantly higher in December than in June (4.9 v 0.48 µgC l^{-1} d^{-1}). Dissolved nutrient concentrations showed no significant difference.

Table 11 Results of t-test of data from the 2008 cruises.

Variables	***t-value***	***p-value***
Depth	-0.098	0.922
Temperature	-4.445	**>0.0001**
Salinity	-6.847	**>0.0001**
< 2µm chlorophyll	-2.906	**0.006**
< 10µm chlorophyll	-2.865	**0.006**
Total chlorophyll	3.858	**>0.0001**
< 2µm production	-1.005	0.320
< 10µm production	-0.775	0.442
Total production	-1.075	0.288
Bacterial production	-2.107	**0.045**
Dark Respiration	-0.488	0.628
Net Production (O_2)	1.034	0.310
Total Picoplankton	6.437	**>0.0001**
NO_3	0.500	0.622
Dissolved Inorganic P	0.502	0.621
Dissolved Organic C	-1.332	0.199

Principal components analysis of data from the production stations (Fig. 43) accounted for a total of 79% of the variance, 65% of which was on the first principal component. The results support those of the comparison between cruises, in which all variables except the counts of total picophytoplankton were higher in the December cruise than in the June cruise, as indicated by the temperature and salinity vectors. Furthermore, dissolved nutrients (NH_4, NO_3, DIP, DOC) were highly correlated with depth, as expected from depletion by phytoplankton in the well-lit surface layers. Samples from the June 2008 were strongly correlated with the vector indicating picophytoplankton abundance, in accordance with their anomalously high abundances on this cruise.

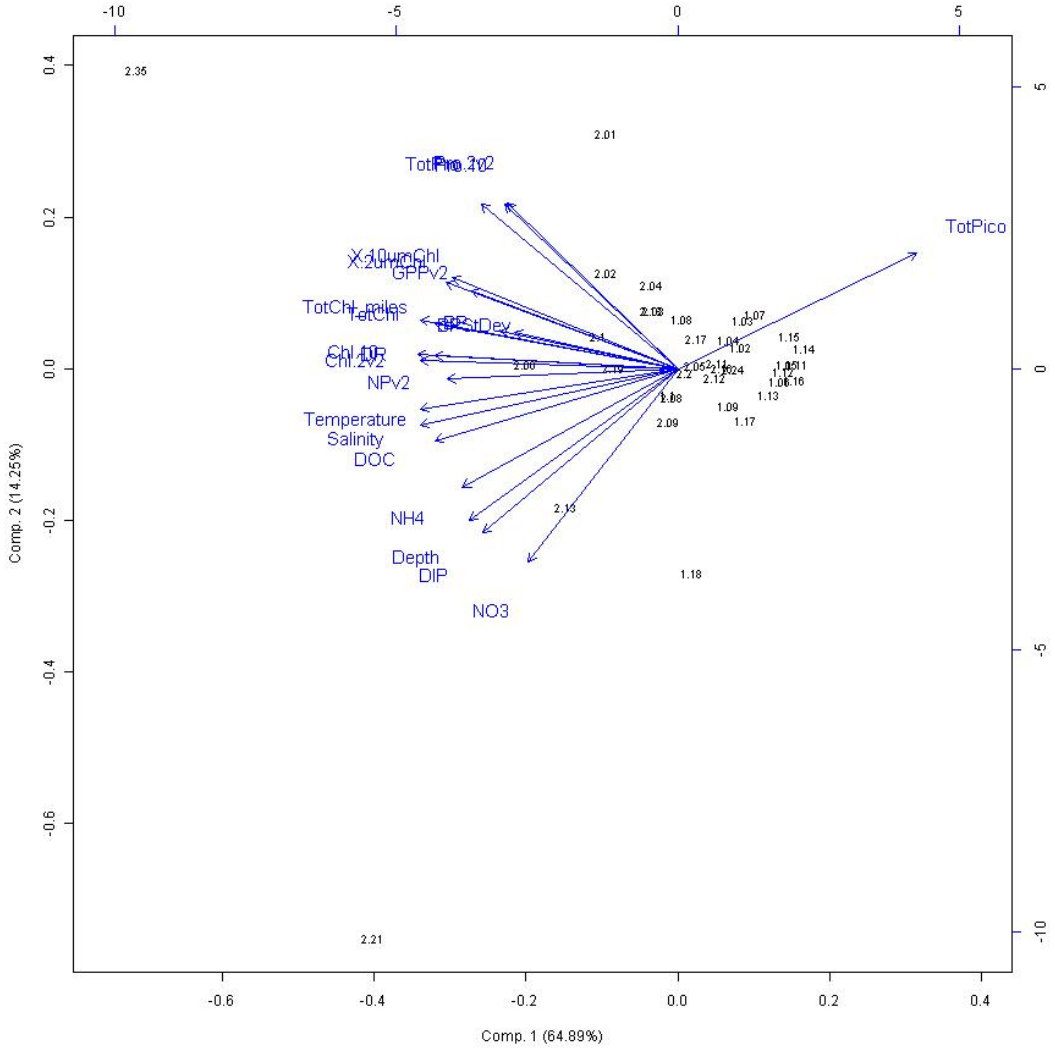

Fig. 43 Principal Components analysis of the data from Biological Oceanography cruises in June and December 2008; data as for Table t-test. Samples are indicated by numbers of the form Cruise.Observation number, i.e. 1.03 indicates the 3rd observation within Cruise 1.

Sedimentation Fluxes

At this time, samples from the Lagrangian sediment traps deployed at the productivity stations are still being analysed.

Zooplankton

At each of the four time series sites, zooplankton samples were taken 4 times per day with plankton nets made of 100 µm mesh. At the three deep sites (the Deep Channel, the NE margin and Open Water sites), stratified samples were taken with a Hydrobios multinet system, which has 5 nets that can be programmed to open at different depth intervals. For this series of samples, sampling depth intervals were set to be 400 – 300 m, 300 – 200 m, 200 – 100 m, 100 – 50 m, and 50 to the surface. Within the lagoon of South Reef the water depth was ~55 m, which was too shallow to obtain accurate stratified samples. In June 2008 we integrated the results of multinet samples from discrete depths, and subsequently in December 2008 and June 2009 we used a bongo net equipped with WP-2 nets to sample the

zooplankton in the lagoon. The bongo net proved to be more suitable for operation in shallow water.

The resultant samples were split into two fractions, one of which was filtered on to a pre-weighed mesh and frozen for later measurement of biomass, as dry weight. The other fraction was preserved in formalin so that the zooplankton community composition could be determined by microscopic analysis back in the laboratory. The average >100 μm zooplankton biomass within the lagoon was higher in December than in June of 2008 and 2009 (Table 12). At the three deep water stations, biomass in the mixed layer (~ the top 100 m) was lower than that of the lagoon (Fig. 44, Fig. 45, Fig. 46, Table 12), but below this, biomass dropped to < 3 mg m^{-3}. There is no indication of biomass change between day and night as a consequence of diurnal vertical migration, though the mixed layer biomass in the deep channel was elevated in the 0300 sample in December 2008 (Fig. 45). The reason for this is unclear; there is no indication of migration from deeper layers (i.e. of elevated biomass in deeper layers at other times of the day), but may be related to advection/retention of plankton around topographic features at this time.

To date, not all zooplankton samples have been counted. Over 90 taxonomic units have been enumerated within the copepod fraction alone (Table 13). Taxa identified to the level of family or genus are species groups that will take further time to resolve to species level. It is likely that the *Oncaeiidae* alone comprise >20 species. Deep water samples contain many small calanoids that have never been described from Australia, including members of the families *Tharybidae* and *Discoidae*. Other plankton have been identified to higher taxonomic units.

Table 12 Mean (± SD) >100μm plankton biomass at Scott Reef. Data represent samples taken from the lagoon, compared to the mixed layer and deeper water at Stations 2 (Deep Channel), 3 (NE) and 4 (SW) at 4 times during a 24h period.

	June 2008	December 2008	June 2009
Lagoon	18.2 ± 6.2	30.8 ± 8.7	18.1 ± 4.5
Stns 2-4, <100 m	8.5 ± 2.0	10.8 ± 4.0	6.7 ± 2.5
Stns 2-4, >100 m	1.7 ± 0.3	2.3 ± 1.1	1.7 ± 1.0

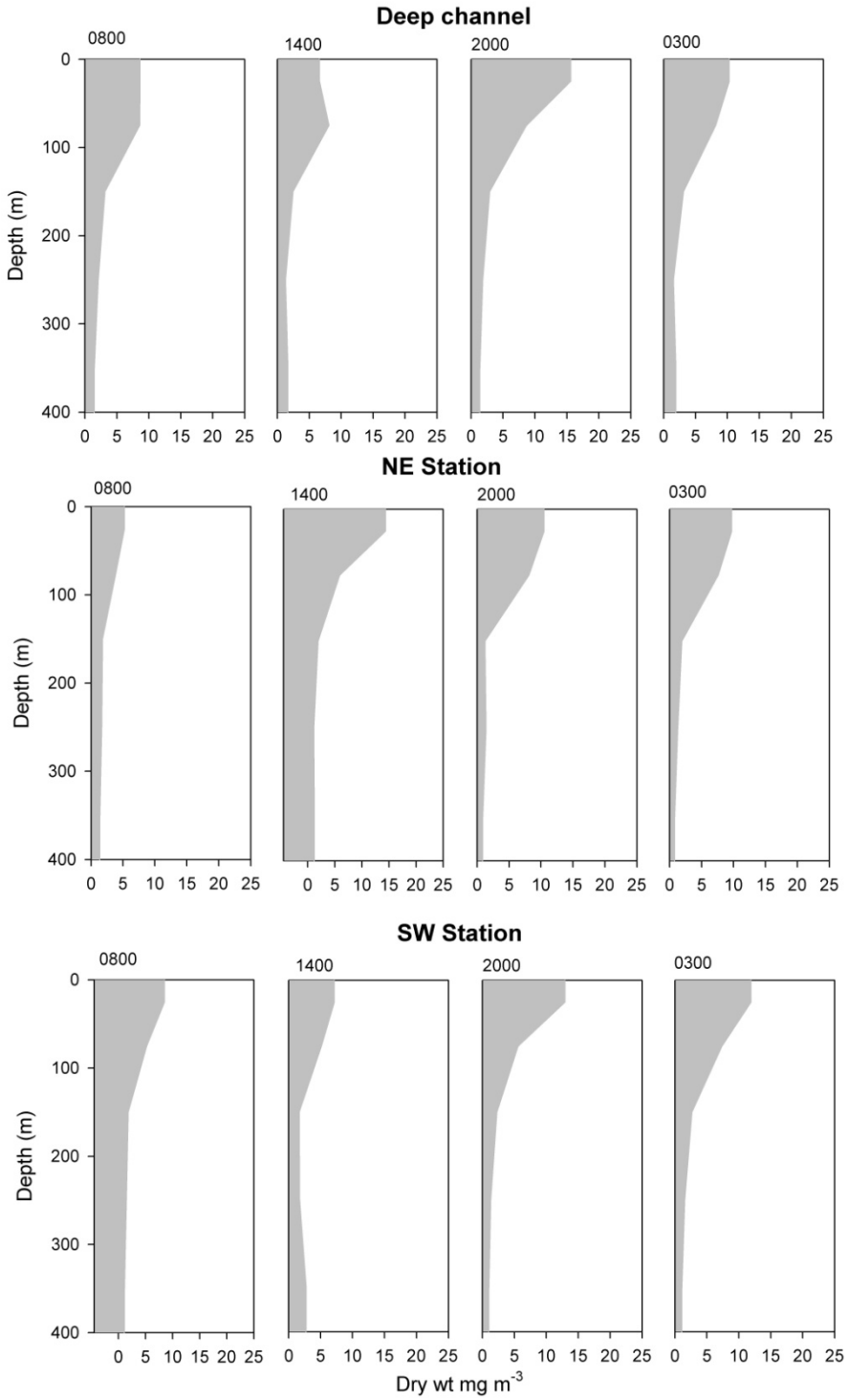

Fig. 44 Depth distribution of >100 µm zooplankton biomass during the June 2008 cruise. Hauls were taken four times per day at the time indicated at the top of each chart.

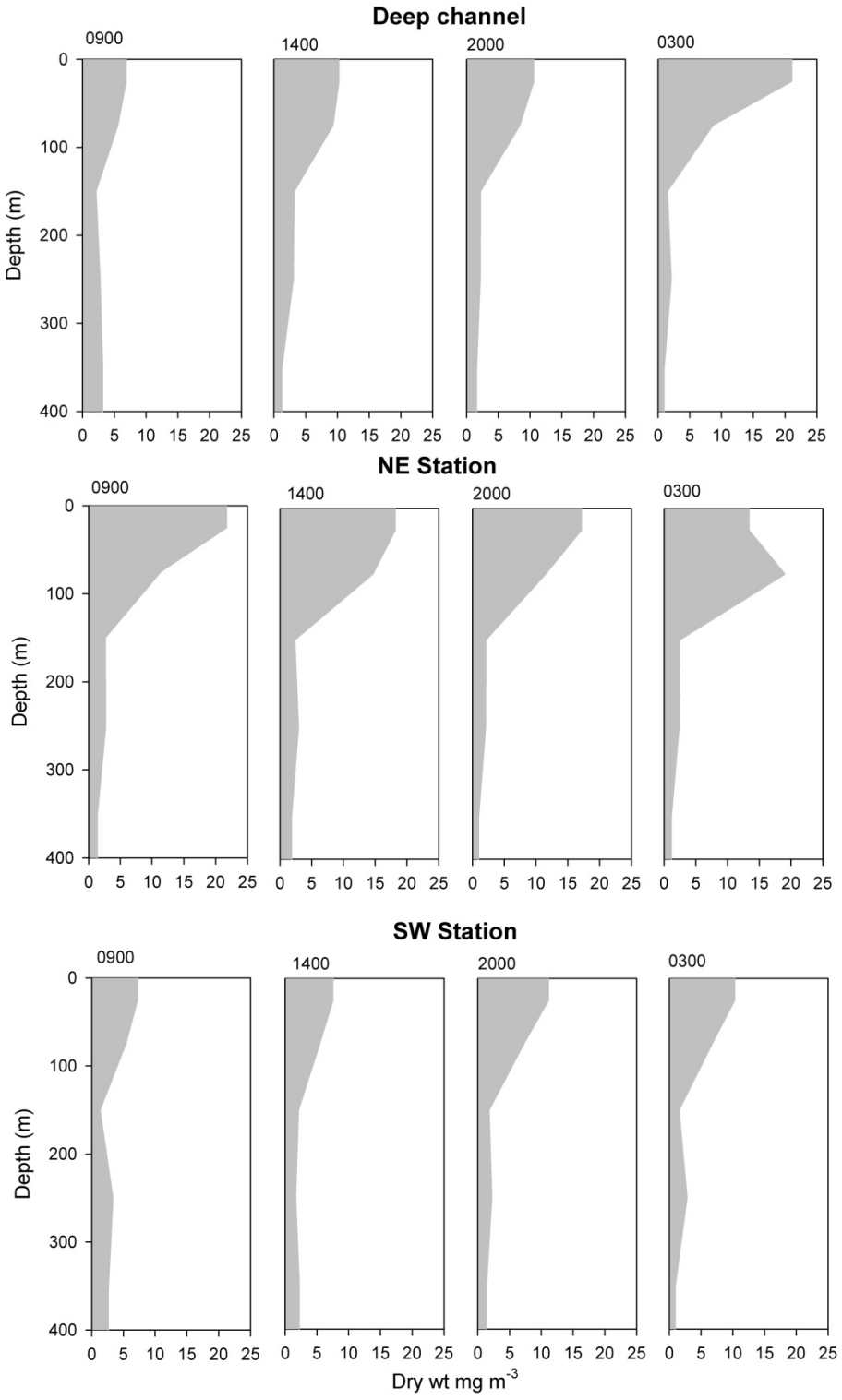

Fig. 45 Depth distribution of >100 µm zooplankton biomass during the December 2008 cruise as for Fig 44.

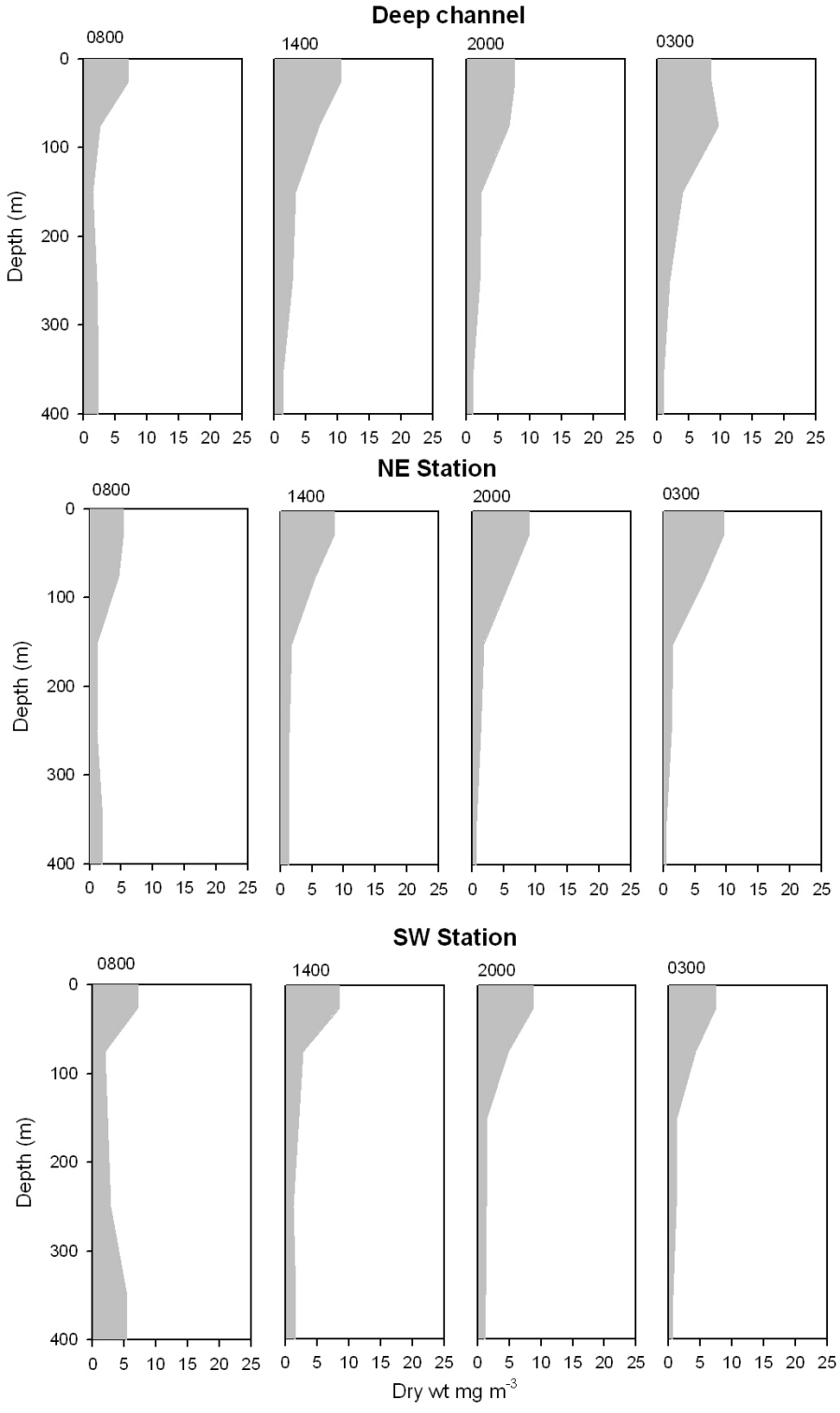

Fig. 46 Depth distribution of >100 µm zooplankton biomass during the June 2009 cruise as for Fig 44.

Table 13 Taxonomic units identified within the Copepoda.

Acartia erythraea
Acartia negligens
Aetideidae spp.
Bestiolina sp
Calanopia elliptica
Calocalanus pavo
Calocalanus sp. 1
Calocalanus sp. 3
Candacia catula
Centropages furcatus
Clausocalanus arcuicornis
Clausocalanus furcatus
Clausocalanus sp.
Copilia spp
Corycaeus asiaticus
Corycaeus clausi
Corycaeus dahli
Corycaeus flaccus
Corycaeus longistylis
Corycaeus pacificus
Corycaeus spp
Delius sp.
Euchaeta indica
Euchaeta rimana
Farranula carinata
Farranula curta
Haloptilus longicornis
Labidocera laevidentata
Lucicutia clausi
Mecynocera clausi
Mormonilla phasma
Oithona attenuata
Oithona nana
Oithona rigida
Oithona simplex
Oithona sp 2
Oithona sp 4
Oithona tenuis
Oncaeiidae spp
Paracalanus aculeatus
Paracalanus indicus
Paracalanus sp
Parvocalanus crassirostris
Pleuromamma abdominalis
Pleuromamma gracilis
Pleuromamma piseki
Rhincalanus rostrifrons
Scottocalanus farrani
Undinula vulgaris
Unidentified Harpacticoida
Acartia fossae
Acartia pacifica
Bestiolina similis
Calanopia aurivilli
Calanus minor
Calocalanus sp 4
Calocalanus sp. 2
Candacia bipinnata
Canthocalanus pauper
Clausocalanidae spp.
Clausocalanus farrani
Clausocalanus paululus
Conaea rapax
Corycaeus andrewsi
Corycaeus catus
Corycaeus crassiusculus
Corycaeus dubius
Corycaeus furcifer
Corycaeus ovalis
Corycaeus speciosus
Cosmocalanus darwini
Eucalanidae spp
Euchaeta marina
Euterpina acutifrons
Farranula concinna
Farranula gibbulus
Haloptilus spp
Labidocera pseudocuta
Lucicutia flavicornis
Microsetella spp.
Oithona (Paroithona) sp.
Oithona fallax
Oithona plumifera
Oithona setigera
Oithona sp 1
Oithona sp 3
Oithona spp
Oncaea venusta
Paracalanidae spp
Paracalanus aculeatus minor
Paracalanus nanus
Pareuchaeta russelli
Parvocalanus dubia
Pleuromamma borealis
Pleuromamma indica
Pleuromamma xiphias
Scolecithrix danae
Subeucalanus subtenuis
Unidentified Calanoida

The abundance of total >100 μm zooplankton in the lagoon was 3,632 organisms m^{-3} in June 2008, and 6,625 organisms m^{-3} in December 2008. By comparison, the abundance of >63 μm zooplankton in the 0 – 60 m stratum at a shelf break station near NW Cape was ~10,000 m^{-3} (McKinnon and Duggan, 2003). The lower abundance at Scott Reef reflects the more oceanic conditions experienced by this atoll. Mixed layer (0-100 m) abundances at the deep stations during June 2008 were of similar magnitude to those observed in the lagoon (Fig. 47), but lower in December 2008. As was the case with the biomass samples, zooplankton numerical abundance was noticeably higher within the mixed layer than below it at the three deep stations (Fig. 47). There were quite marked differences in mixed layer abundance at the Deep Channel station at different times of the day, and these were especially high at 20:00 in June 2008. At the NE station, temporal differences were less marked, and at the SW station there was virtually no differences at all.

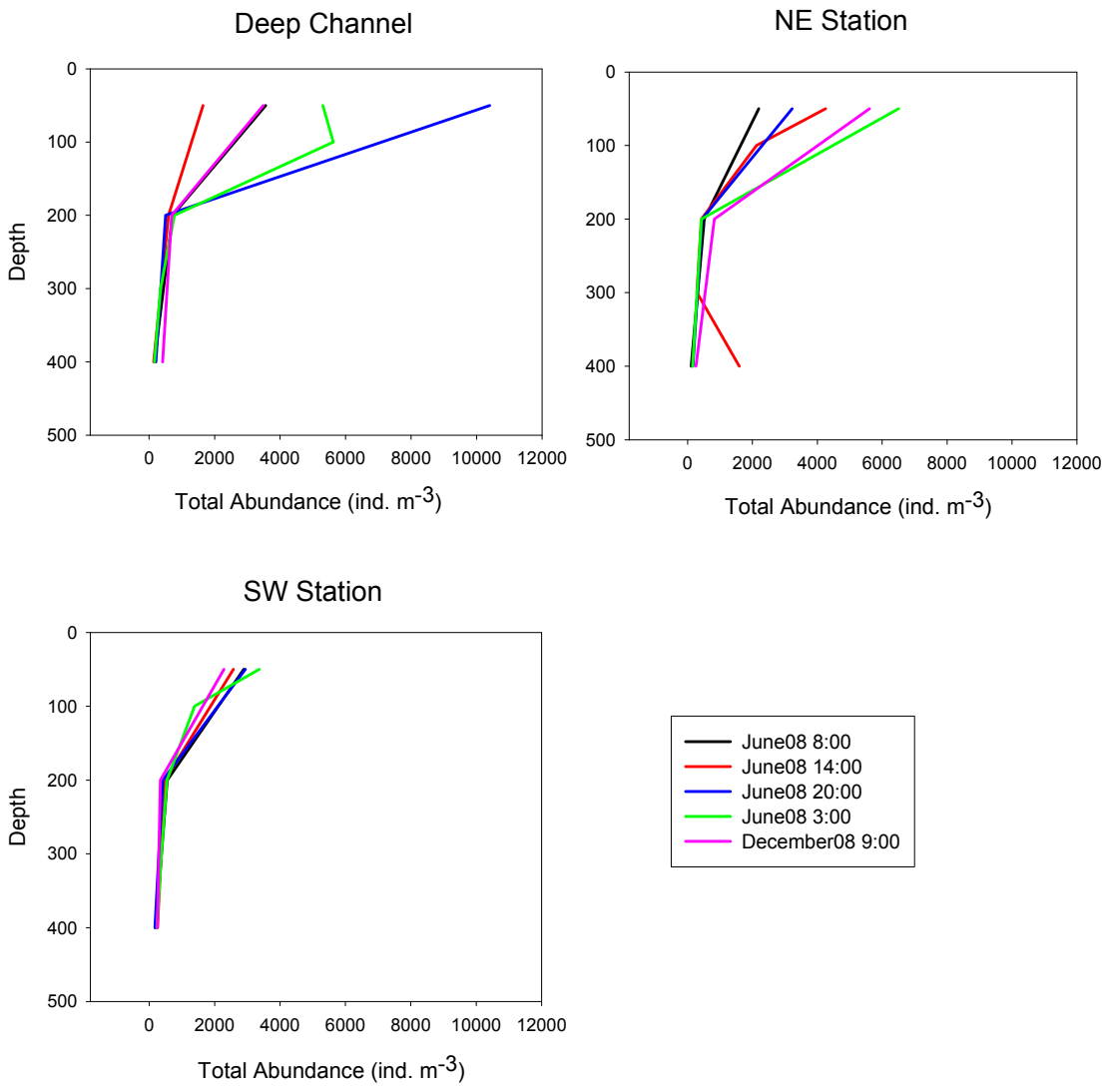

Fig. 47 Total >100 μm zooplankton abundance at the 3 deep Scott Reef stations at depth intervals sampled by the multinet sampler, at 4 times of day in June 2008, and at 0900 in December 2008. Sample analyses from December 2008 are not yet complete.

The >100 µm size range of zooplankton is dominated by copepods. At the lagoon station, Calanoid and Cyclopoid (excluding Oncaeidae) copepods dominated the plankton (Fig. 48), and there was a ~2-fold difference in plankton abundance over the 24 hour period, which may be related to the tides. The family Oncaeidae only contributed a small percentage of the total plankton. Larvaceans were the most important of the non-copepod plankton.

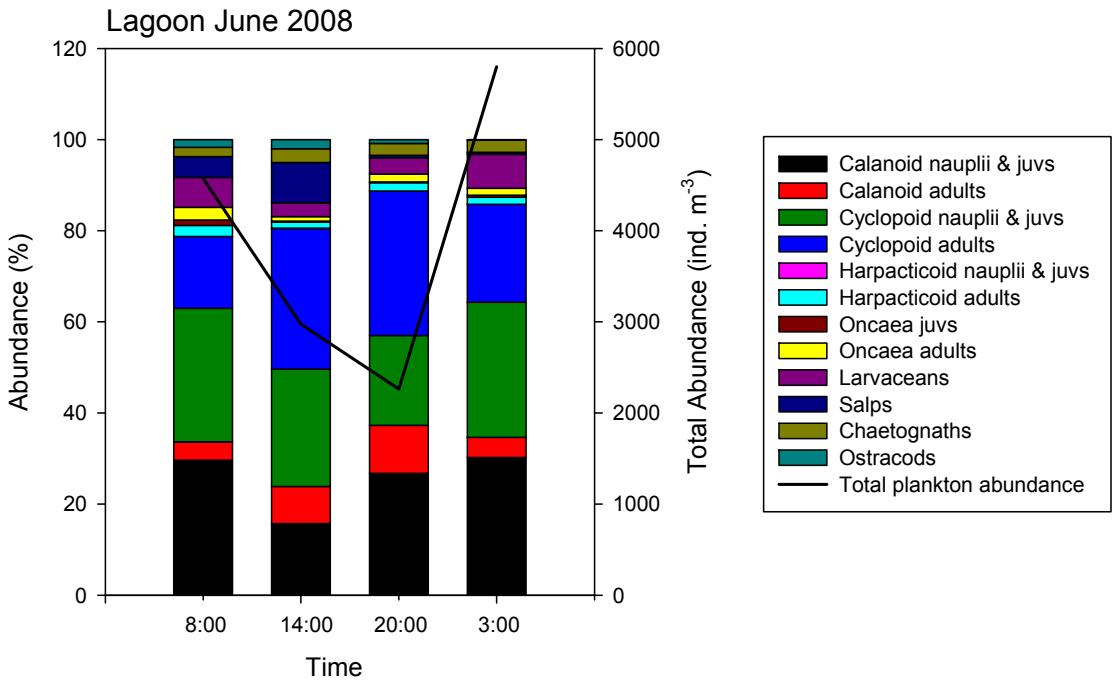

Fig. 48 Composition and total abundance of >100 µm zooplankton within South Reef lagoon in June 2008.

At the deep water stations the plankton composition changed markedly with depth (Fig. 49, Fig. 50 & Fig. 51). The most striking change was the increasing dominance of the family Oncaeidae with depth. The community composition of the mixed layer resembled that observed at the lagoon, and the proportionally higher contribution of larvaceans to the plankton in the surface layers are also noticeable. Larvaceans are pelagic tunicates that are capable of feeding on picoplankton, and are known to have some of the highest growth rates of any metazoan. Consequently these animals may have a disproportionately high contribution, in terms of total community secondary production. At this level of taxonomic resolution, there does not seem to be great differences with time of day, or between stations. However, our ongoing refinement of taxonomic resolution may reveal more subtle differences.

One of our goals with the zooplankton work is to detect past intrusion events into the lagoon by using zooplankton indicator species. As expected, the oncaeid copepods are likely to provide the best chance of achieving this goal, since they are small, comparatively non-motile and are much more abundant in sub-thermocline waters adjacent to Scott Reef. However, the taxonomy of this group is extremely complex, and we are currently working on resolving the species composition in collaboration with the world expert on the group, Dr. Ruth Böttger-Schnack. Previous experience at NW Cape leads us to believe that this family will prove extremely species rich, and that each species will have defined depth preferences. For instance, *Oncaea venusta* and *O. mediterranea* are known to be epipelagic (i.e. confined to surface layers) whereas other species only occur in sub-thermocline waters. Once we have better constrained the depth preferences of the species at the deep water stations, the

occurrence of those with sub-thermocline preferences in the waters of the lagoon may be able to be used as an indicator of past intrusion of cool, nutrient rich waters.

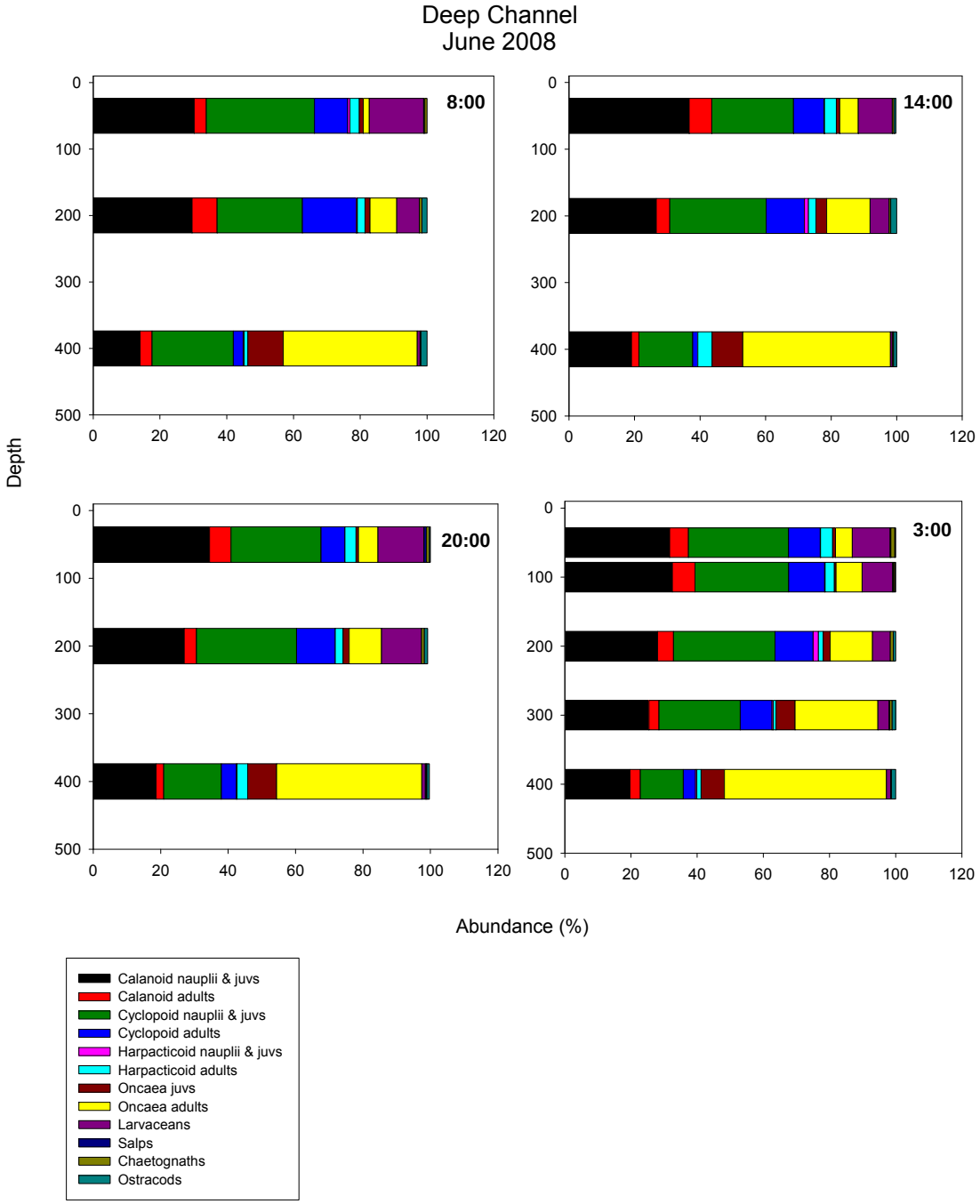

Fig. 49 Composition of >100 µm zooplankton in the deep channel in June 2008.

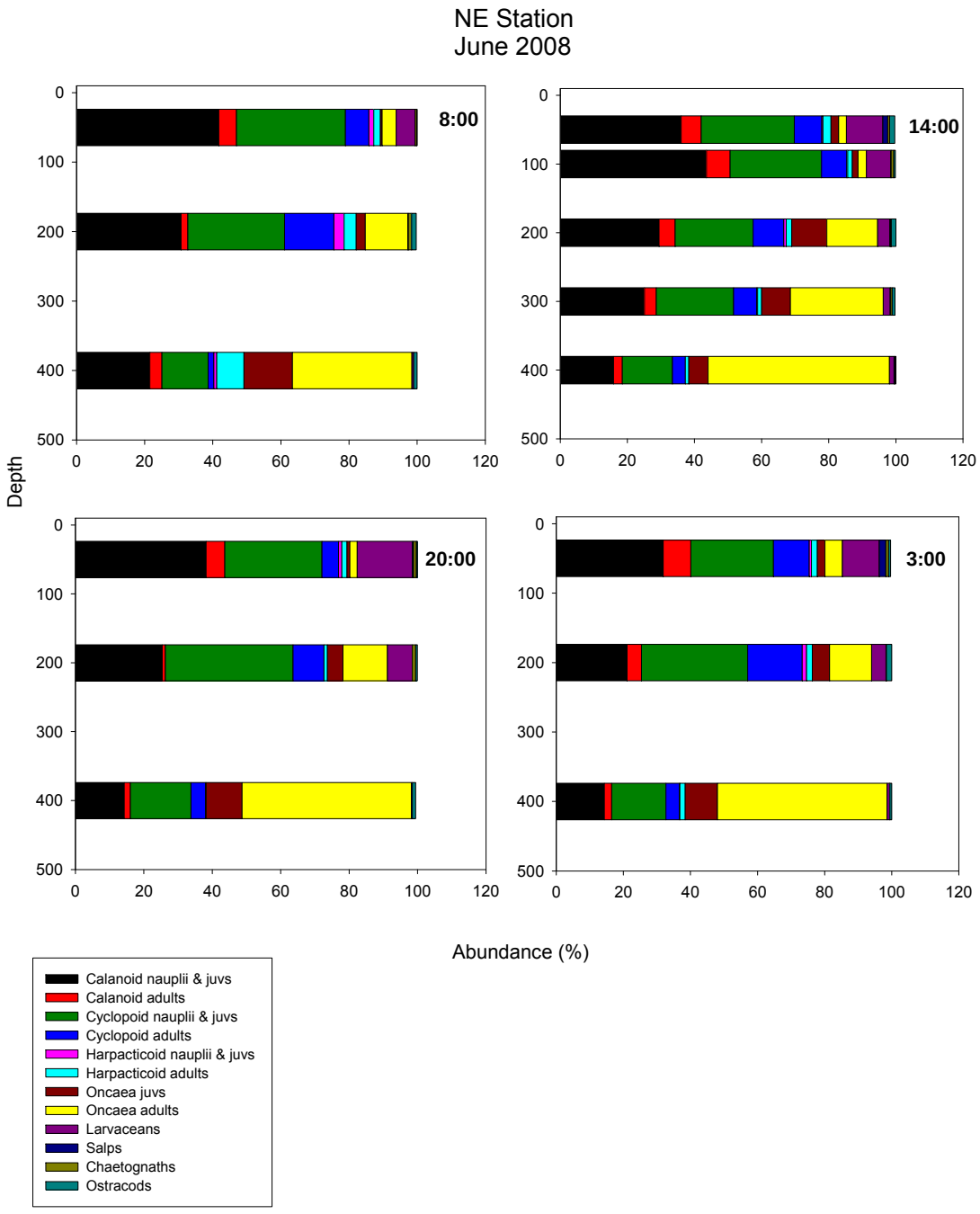

Fig. 50 Composition of >100 µm zooplankton at the NE station in June 2008.

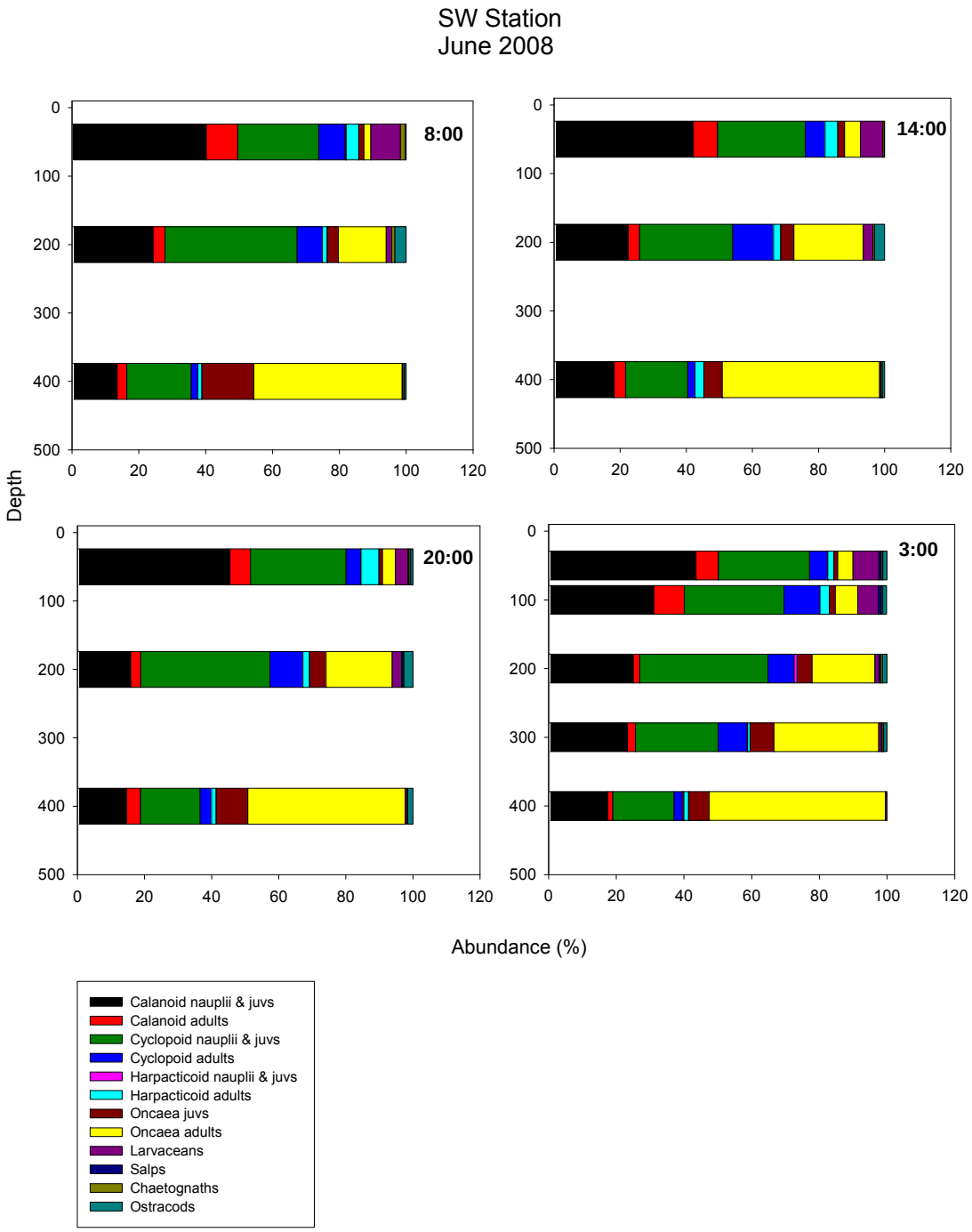

Fig. 51 Composition of >100 µm zooplankton at the SW station in June 2008.

Analysis of the zooplankton from the December 2008 cruise is in its early stages, and only some of the samples have been counted – all from the 09:00 sampling period at each of the 4 stations (Fig. 52). Interestingly, larvaceans comprised a much greater proportion of the plankton at the NE station and within the lagoon of South Reef than we have seen before. In a recent publication, Jaspers et al (2009) also found that larvaceans comprised a large proportion of the summer plankton in the Indian Ocean, and suggest that in terms of total production these animals will exceed the contribution of copepods.

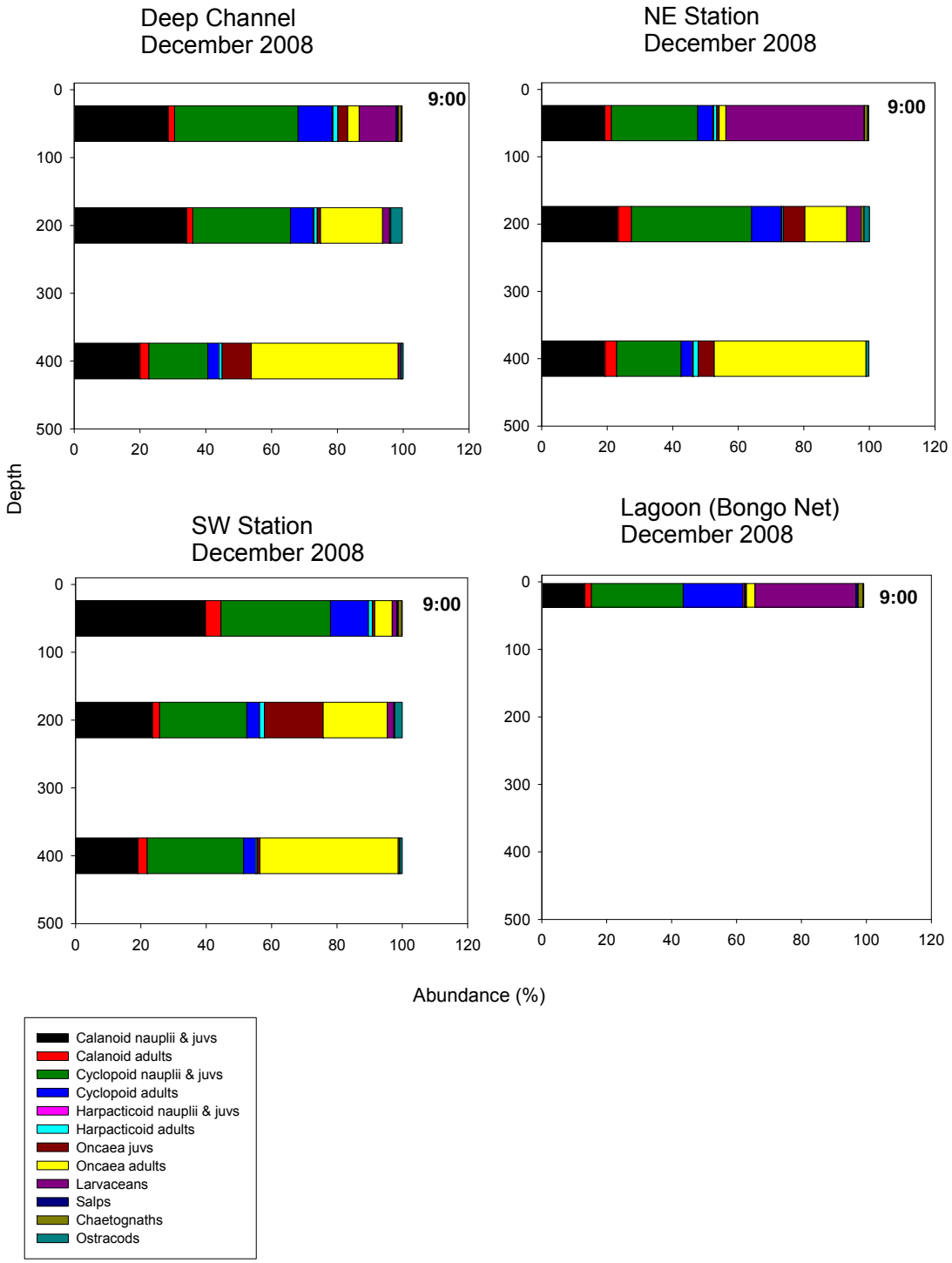

Fig. 52 Composition of >100 µm zooplankton in December 2008.

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Appendices

Methods used on Biological Oceanography Cruises.

Sampling

Vertical Profiling (T°C, S‰, Chlorophyll fluorescence, Beam transmittance, PAR)

Vertical profiles of temperature (T°C), salinity (S‰), chlorophyll fluorescence (Wetlabs Wetstar), photosynthetically available radiation (PAR: 400-700 nm Biospherical QSP-200), and beam transmittance (Seatech 25 cm path length) were determined at all sampling stations with a Seabird SBE19+ CTD profiler. The instrument was operated according to the manufacturer's directions. The SBE19+ samples at 4 Hz, and was lowered/raised at ca. 1m sec^{-1} during profiles. After casts, the raw data was downloaded to disk and converted to engineering values using manufacturer's software (DATCNV) and supplied instrument coefficients, filtered to remove bad scans (FILTER, WILDEDIT and binned (BINAVG)) at 1m intervals for further analysis and plotting.

Temperature and salinity profile data was checked against discrete temperature and salinity values measured in parallel water bottle casts. Temperatures were measured with RTM digital reversing thermometers and discrete salinity samples were collected from Niskin bottles. The salinity samples were analysed with a Guildline AutoSal laboratory salinometer calibrated against IAPSO standard seawater.

Chlorophyll fluorescence values were initially calculated with the software provided by Seabird (DATCNV). Profile fluorescence values were compared to chlorophyll concentrations in discrete samples collected in parallel Niskin bottle casts.

Discrete Water Samples

Discrete water samples were collected by hydrocasts using Niskin bottles closed at depth. Two of the bottles were fitted with reversing thermometers for CTD profile validation. The number of bottles in a cast was determined by the sampling requirements and water column depth. In deep waters, up to 6 depths were sampled and as few as 2 depths in the shallowest part of the South Reef lagoon.

Sub-samples of water were drawn from the Niskin bottles in order of priority: dissolved oxygen (when run), dissolved nutrients, chlorophyll, picoplankton abundance, total suspended solids (TSS), particulate nutrients (PN, PP, PC) and salinity.

Water Clarity (Secchi Disk)

At some stations occupied between approximately 0900 and 1500, estimates of water clarity were determined using a Secchi disk (Preisendorfer, 1986). The Secchi disk is a 30cm weighted white disk with a line marked at 1m intervals which was lowered through the water until it just disappeared from view and the depth was then recorded. Deployment of the Secchi disk depended upon sea and light conditions at the station being suitable for making reliable measurements. In rough seas, the hard chine of the R.V. Solander created significant surface spray and bubbles that made it difficult to make accurate Secchi disk disappearance measurements. When done properly, this measure gives a general index of the depth of the euphotic zone (ca. 1% of surface irradiance – I_o) and the diffuse attenuation coefficient ($K_d \approx 1.7/depth_{Secchi}$).

Zooplankton sampling (Multinet)

Vertically stratified tows were taken four times over a day at each process site with a multinet (Midi model, 50 cm mouth size, Hydro-Bios, Kiel) equipped with five 100µm-mesh nets. Each of the five nets was equipped with a calibrated Hydro-Bios flowmeter, to allow for individual estimates of filtered volume for each sample. Depth strata sampled by each net was selected to span three layers of sub-thermocline water, mixed layer water and the surface layer.

Each net sample was split into equal portions, one of which was preserved in formaldehyde for analysis of community composition, and the other filtered onto a pre-weighed disk of 73µm mesh and frozen.

Zooplankton sampling (Bongo net)

Oblique bottom to surface tows were taken four times over a day at the lagoon site with a bongo net equipped with 2 WP-2 100µm-mesh nets. Each of the nets was equipped with a calibrated Hydro-Bios flowmeter, to allow for individual estimates of filtered volume for each sample. For sampling larger plankton, such as krill, the nets were replaced with 500µm-mesh nets.

Each net sample was split into equal portions, one of which was preserved in formaldehyde for analysis of community composition, and the other filtered onto a pre-weighed disk of 73µm mesh and frozen.

Organic sedimentation (Lagrangian Sediment Traps)

Downward fluxes of particulate matter from the euphotic zone were measured using Lagrangian surface-tethered particle interceptor trap arrays (Knauer et al., 1979). The trap arrays consist of twelve (12) 75 x 600 mm polycarbonate tubes standing vertically in a fixed submerged array that acts as a drogue. The individual traps were fitted with a baffle at the top end to prevent intrusion of turbulence into the trap during retrieval or from current shear, and a near-bottom drain to allow removal of most water within, without disturbing the sedimented material resting at the bottom of the trap tubes.

Lagrangian surface-tethered traps were deployed to drift freely with the current to "tag" a particular water mass and minimise cross-trap current shear. During deployments, the trap array was suspended from a linear string of surface floats that served to dampen vertical array movements due to surface wave motion. A dan buoy with radar reflector and flashing light was used to track the movement of the array. The depth of trap deployment depended upon the sampling location. In open ocean waters, traps were generally deployed at the base of the euphotic zone (ca. 100 m). In shallow reef waters, shorter tethers were used so that the trap floated approximately 5m above the bottom. Trap deployments were ~12 hours (shelf waters with reefs) (Furnas and Mitchell, 1999). Because of the short duration of the deployments, no preservatives were used in the traps, making all available for chemical analysis.

Upon recovery, the traps were visually inspected to determine which were affected by undue in-trap turbulence and mixing. The trap contents were then allowed to settle for ca. 1 hr. Relatively little suspended matter was usually seen in individual traps. After settlement, overlying water in the individual trap tubes was carefully drained away to reduce trap contents to the sedimented material in the bottom water (ca. 350 ml) of the tubes. After the traps were drained, the contents were swirled to mix them up and the remaining water in individual

tubes filtered onto a pre-weighed and pre-combusted glass fibre filter (Whatman GF/F, 47mm). The filtered material from individual traps was then frozen for later analysis.

CTD and water bottle casts were undertaken immediately next to the deployed trap array at the time of deployment and recovery to establish water column concentrations and distributions of materials collected in the traps.

Primary Production (^{14}C uptake)

Estimates of primary production in intact and size fractionated water samples were made using the uptake of radioactive ^{14}C-bicarbonate into particulate matter (Steeman Nielsen, 1952). This method has been in general use within biological oceanography groups over the last 25 years (Furnas, 2007; Furnas and Mitchell, 1996, 1999).

Water samples for primary production measurements were collected between 0800 and 0900 local time from multiple depths in the water column using Niskin bottles with well-aged rubber closures. The sampling depths (between four and eight at a given station depending on water depth) were selected to have nominal mid-day in situ irradiance levels (100, 50, 30, 20, 8, 4, 1.6 and 0.6 percent of surface irradiance) close to those simulated in an on-deck incubator. Nominal isolume depths were estimated from mid-day underwater light profiles made at or near the production measurement site with an underwater irradiance sensor. Where a pre-experiment light profile could not be made, isolumes depths were estimated from previous light casts made in waters of similar optical characteristics.

In most cases, primary production was measured using the total population and two size classes: > 10 µm and > 2 µm. In these experiments, aliquots to be size fractionated were filtered after the incubations onto polycarbonate membrane filters. Photosynthesis rates in size fractions not directly measured (e.g. 2 to 10µm, <2 µm) were calculated by difference.

Production incubations were carried out in 250 ml clear polycarbonate bottles (Nalgene). The bottles were acid-soaked (10% trace metal grade HCl), deionised water soaked, deionised water rinsed and dried between cruises. Nine sub-samples were taken from the Niskin bottle at each sampling depth. Care was taken throughout to minimise contamination by metals or organic materials (Fitzwater et al., 1982). Filled sample bottles were stored in closed deck boxes between filling and the start of incubations and between the end of incubations and filtration.

Water samples were spiked under dim light conditions with 5 µCi (0.9 MBq) of ^{14}C-bicarbonate (GE Life Sciences). Isotope stocks were stored refrigerated in Teflon bottles. All plasticware used for isotope handling and spikes was cleaned, soaked in trace-metal grade HCl and rinsed with deionised water (MilliQ). After spiking, three incubation bottles from each sampling depth and size fraction were wrapped in aluminium foil to serve as dark bottles. The incubation bottles were then transferred to a multi-tank deck incubator filled with running surface seawater. Surface-to-bottom temperature gradients in shelf waters were <5°C. Individual tanks were screened with one or more layers of black plastic shadecloth to simulate in-situ light levels. The spiked samples were incubated for 4 hours, nominally 1000 to 1400 local time.

Following incubation, sample bottles were retrieved from the incubator tanks and stored in a dark deck box. The contents of each bottle were filtered under low vacuum (0.5 atm) and dim light onto either a Whatman GF/F glass fibre filter (25 mm – whole population) or polycarbonate membrane filters (2 or 10 µm pores – 25 mm diameter). After filtration, the

filters were placed in a scintillation vial and blotted with 100 µl of 10% HCl to remove residual inorganic carbon.

Radioactivity remaining on the filters was counted by liquid scintillation spectrometry. After appropriate quench and blank corrections, hourly carbon uptake (photosynthesis) rates (mg C m^{-3} hr^{-1}) were calculated according to Strickland and Parsons (1972).

Estimates of areal primary production (mg C m^{-2} hr^{-1}) were calculated by trapezoidal integration of measured rates over the depth profile. Daily primary production (g C m^{-2} day^{-1}) was estimated by dividing the calculated production during the incubation period (nominally 4 hours) by the proportion of daily surface irradiance (nominally about half) during that period. During experiments, surface irradiance was measured at 1 minute intervals from pre-dawn to after dark with a logging quantum sensor (Biospherical QSR-240) located in the ship's superstructure.

Bacterial Production (^{3}H-thymidine uptake)

Bacterial secondary production in the water column was estimated from the assimilation of radio-labelled thymidine (methyl-^{3}H-thymidine) into trichloroacetic acid (TCA) insoluble macro-molecules, nominally DNA (Fuhrman and Azam, 1980, 1982).

Triplicate sub-samples (10 ml) of water from each production sampling depth were dispensed into clean plastic screw-cap test tubes (12ml). The tubes were spiked with 10µCi (1.8 MBq) of methyl-^{3}H-thymidine (GE Life Sciences) and incubated at ambient water temperature for 1 hour. At the end of the incubation period, the samples were killed by the addition of 2ml of 10% (w/w) TCA. After a short period, the samples were filtered onto polycarbonate membrane filters (0.2µm pore size). Thymidine not incorporated into TCA-insoluble macro-molecules was rinsed from the filters with 3 x 2ml washes with ice-cold 3% TCA. The filters were then stored in scintillation vials until the particulate phase radioisotopes were counted by liquid scintillation spectrometry. A parallel set of formalin-killed water samples were run in parallel with each sample batch to blank for abiotic absorption of thymidine.

Bacterial secondary production was calculated from the assimilated thymidine assuming that 1.7 x 10^9 bacterial cells were produced from 1 nmol of thymidine free-living bacterial cells have an average carbon content of 2.0 x 10^{-14} gm C per cell (Fuhrman and Azam, 1980, 1982).

Pelagic metabolism

Production and respiration experiments were conducted on water samples taken from the same station as the ^{14}C production measurements. Immediately after retrieval on board, seawater from the Niskin bottles was used to fill calibrated acid-washed iodine flasks with a nominal volume of 125ml. Nine flasks were filled from each depth at every station; three were fixed for Winkler titrations immediately (zero-time samples), three were placed in a lightproof deck incubator (dark respiration), and three were placed in deck incubators with appropriate neutral density mesh to simulate the light climate at the depth of collection. Incubations were conducted for 24hr, after which the incubated flasks were fixed. The entire set of flasks from each experiment was then titrated as a single batch as soon as possible after completion of the experiment.

Dissolved oxygen concentration was determined with an automated precision Winkler titration system developed at the Oceanographic Data Facility, Scripps Institution of Oceanography, University of California, San Diego, and which uses the absorption of 365nm UV light for endpoint detection. Net community production (NCP) and community

respiration (CR) were estimated as the change in oxygen concentration during a 24 h period in iodine flasks incubated in the light and dark respectively.

Gross primary production (GPP) is calculated as the sum of NCP and CR, and the P:R ratio calculated as the ratio GPP:CR. Area-specific community rates are computed by trapezoidal integration of volumetric data to the sea bottom or to the 1% isolume, whichever comes first.

ANALYTICAL PROCEDURES (LABORATORY)

Chlorophyll (Fluorometry)

Replicate subsamples of water from Niskin bottles or surface buckets were filtered through Whatman GF/F (nominal pore size – 0.7 mm: total community) or polycarbonate membrane filters (2 mm pore, 10 mm pore - > 2 and > 10 mm size fractions). After filtration under subdued light, the samples were folded, stored in pre-combusted foil packet envelopes and frozen (<-10°C) until analysis.

In the laboratory, the filtered samples were ground in a tissue grinder with a 90% acetone: water mixture and extracted in the dark for ca. 1hr. After centrifugation to remove suspended matter, chlorophyll fluorescence in the supernatant extract was determined using a Turner Designs Model 10 fluorometer with a red-sensitive photomultiplier. Following the initial reading, the sample was acidified with 1 drop of 10% HCl and the fluorescence re-measured.

Chlorophyll and phaeophytin concentrations were calculated according to Parsons et al. (1984). Chlorophyll concentrations in size fractions not directly measured (2 – 10 mm, <2 mm) were calculated by difference between measured size fraction.

Dissolved inorganic nutrients (NO_2^-, NO_3^-, PO_4^{3-}, $Si(OH)_4$)

Duplicate water sub-samples (10 ml) were syringe filtered (0.45mm) into acid-washed screw-capped plastic test tubes (12ml) and stored frozen (ca. -20°C) until analysis ashore.

Dissolved inorganic nutrient concentrations in the filtered samples were determined by standard colorimetric methods (Parsons et al., 1984) implemented on a Braune and Lubbe segmented flow analyser (SFA: Ryle et al., 1981).

Duplicate water sub-samples (10 ml) for dissolved silicate analyses were stored at room temperature prior to analysis to prevent polymerisation of the silicic acid monomers during frozen storage.

Dissolved organic nutrients (DON, DOP)

Dissolved organic nutrient concentrations were estimated as the difference between measured total dissolved nutrient (TDN, TDP) concentrations in oxidised water samples and summed inorganic nitrogen (DIN = NH_4^+ + NO_2^- + NO_3^-) and phosphorus (PO_4^{3-}) concentrations in parallel sets of un-oxidised samples.

The organic matter in 10 ml filtered water samples were oxidised by alkaline persulfate digestion under high temperature (110°C) and pressure in an autoclave. After oxidation, the total inorganic nutrient (TDN, TDP) concentrations were determined by segmented flow analysis as above.

Dissolved organic carbon (DOC)

Water sub-samples (10 ml) for DOC analysis were syringe filtered (0.45μm) into duplicate, acid-washed screw-cap plastic test tubes. The tube contents were acidified with 100 ml of AR-grade HCl and stored at 4°C until analysis ashore.

In the laboratory, DOC in the sample water was determined by high temperature (1000°C) combustion (HTC) using a Shimadzu TC-5000 carbon analyser. Prior to analysis, CO_2 remaining in the sample water is removed by sparging with O_2 carrier gas.

Particulate carbon (PC)

The particulate carbon content of material collected on filters was determined by high temperature combustion (HTC) using a Shimadzu TC-5000 carbon analyser fitted with a solid sample inlet.

Filters containing sampled material were placed in pre-combusted (450°C) ceramic sample boats. After the sample inlet was purged of atmospheric CO_2, inorganic C on the filters (e.g. $CaCO_3$) was removed by addition of concentrated phosphoric acid and quantified by non-dispersive infra-red gas analysis (IRGA). After this quantification is completed, the filter was introduced into the sample oven (1000°C) where the remaining organic carbon was combusted in an oxygen stream and again quantified by IRGA. The analyses were standardised using certified reference materials (e.g. MESS-1).

Particulate nitrogen (PN)

Total particulate carbon (PC) and nitrogen (PN) measurements was made by filtering 250 ml sub-samples through pre-combusted Whatman GF/F glass fibre filters, which were subsequently analysed for C and N content on an Antek chemi-luminescent nitrogen analyser with a Beckman 880 NDIR carbon analyser mounted in series. The instrument was standardised with acetanilide.

Particulate phosphorus (PP)

Particulate phosphorus (PP) was determined by filtering 250 ml sub-samples through pre-combusted Whatman GF/F glass fibre filters and then refluxing these filters and their associated organic matter to dryness with acid persulfate (5%), redissolving the digest in deionised water and colorimetrically determining the PO_4^{3-} content of the supernatant (Parsons et al., 1984). The analysis was standardised with potassium phosphate and an organic sugar phosphate (e.g. fructose-6-phosphate).

Zooplankton analysis

In the laboratory, the frozen mesh was dried (65°) and re-weighed to estimate zooplankton community biomass. The preserved zooplankton sample was washed to remove formaldehyde and diluted to a known volume with water. A Stempel pipette was used to provide a subsample containing approximately 500 organisms that were then enumerated in a Bogorov tray under a Wild stereomicroscope. All taxa were counted to convenient taxonomic categories, and all nauplii and copepodites of calanoid and cyclopoid copepods counted. Adult copepods were identified to species and sex.

Organic sedimentation (Lagrangian Sediment Traps)

In the laboratory, 10 of the 12 filters from each deployment were dried to constant weight and weighed to establish the mass of material collected. After the weighing, pairs of dried filters were haphazardly assigned for analysis: PC, PN, PP, protein, carbohydrate. The pair of filters not dried and weighed was kept frozen until analysed for phytoplankton pigments.

Vertical fluxes were estimated as the mass of material or constituent sedimenting per m^2 over a 24 hr period.

Phytoplankton counts (Flow cytometry)

Small (< 10 μm), auto-fluorescent phytoplankton were counted live using a Becton Dickinson FACScan flow cytometer aboard the research vessel. Seawater sub-samples were collected directly from the Niskin bottles into clean plastic centrifuge tubes and processed immediately or stored at 4°C until they were processed (within 2 hr). Duplicate or triplicate seawater samples were run for 1 – 2 minutes at a flow rate of 45 μl $minute^{-1}$, with yellow-green fluorescent beads added as an internal reference (1 μm, Polyscience Inc.) and the threshold set to red fluorescence. Data for individual sub-samples were collected in list-mode files and data analysed using CYTOWIN (freely downloadable). Discrimination of living autotrophic phytoplankton cells was based upon their respective side scatter, orange (560nm) and red (>680nm) fluorescence after excitation with blue (488nm) laser light (15mW in a 40 x 60μm spot). The algal pigments chlorophyll *a* and phycoerythrin (PE) were fluorescent in the red and orange, respectively. Three types of small phytoplankters, the prochlorophyte *Prochlorococcus* (low side scatter, red fluorescence only), the cyanobacterium *Synechococcus* (larger size/higher side scatter, red and orange fluorescence) and small autotrophic eukaryotes (larger size/higher side scatter still, red fluorescence only) could be distinguished.

Seawater samples for enumeration of bacteria and viruses were also taken in Nov/Dec 2008 and May/June 2009. Seawater was collected from niskin bottles as above and 1 ml sub-samples were fixed in electron microscope grade glutaraldehyde (0.5% final concentration) for 15 minutes in the dark and frozen in liquid nitrogen until analysis. Samples were analysed within 2 – 4 months of collection. Samples were diluted 1:5 in 0.02 μm filtered Tris EDTA buffer (Sigma, pH = 8), stained with SYBR I Green (5 x 10^{-5} dilution) and incubated at 80°C for 10 minutes in the dark. Flow cytometric analysis was conducted on a Becton Dickinson FACSCanto II flow cytometer with the discriminator set to green fluorescence.. Duplicate sub-samples were run for 2 minutes at a flow rate of 30 μl second-1, with yellow green fluorescent beads (0.75 or 1μm diameter) added as an internal reference. Data for individual sub-samples were collected in list-mode files and data analysed using CYTOWIN. Two virus populations (V1 and V2) and 3 bacterial populations (low DNA, high DNA 1 and HDNA 2) could be distinguished according to their different side scatter (indicative of cell size/complexity) and Green (SYBR) fluorescence (indicative of nucleic acid content) signals. Virus populations (V1 and V2) exhibit lower side scatter and green fluorescence intensity than all bacterial populations. Low DNA and high DNA bacterial populations show similar side scatter signals but high DNA1 population exhibited higher green fluorescence. High DNA2 population exhibited highest side scatter and green fluoresce signals.

Glossary

Autotroph (ic): Organisms that produces complex organic compounds from simple inorganic molecules using energy from light or inorganic chemical reactions.

Bacterioplankton: single-celled microorganism with no nucleus of membrane bound organelles. In aquatic waters, bacterioplankton are composed of phylogenetically and metabolically diverse members. In marine waters in the euphotic zone, the majority of bacterioplankton are heterotrophic; that is they obtain their energy requirements from organic substrates.

Biogeochemistry: the scientific study of the chemical, physical, geological, and biological processes and reactions that govern the composition of the natural environment (including the biosphere, the hydrosphere, the pedosphere, the atmosphere, and the lithosphere), and the cycles of matter and energy that transport the Earth's chemical components in time and space.

Chlorophyll: a green pigment found in most plants, algae, and cyanobacteria. Its name is derived from Greek: χλωρός (chloros "green") and φύλλον (phyllon "leaf"). Chlorophyll absorbs light most strongly in the blue and red but poorly in the green portions of the electromagnetic spectrum, hence the green colour of chlorophyll-containing tissues. Chlorophyll is vital for photosynthesis, which allows plants to obtain energy from light.

Conductivity: a measure of a material's ability to conduct an electric current.

Cyanobacteria: blue-green algae, blue-green bacteria or Cyanophyta, is a phylum of aerobic bacteria that obtain their energy through photosynthesis. They are a significant component of the marine nitrogen cycle and an important primary producer in many areas of the ocean.

Diatom: a major group of eukaryotic algae, and are one of the most common types of phytoplankton. Most diatoms are unicellular, although they can exist as colonies in the shape of filaments or ribbons (e.g. Fragillaria), fans (Meridion), zigzags (Tabellaria), or stellate colonies (Asterionella). Diatoms are primary producers. A characteristic feature of diatom cells is that they produce a cell wall made of silica (hydrated silicon dioxide) called a frustule.

Diel: Pertaining to a 24-hour period

Dinoflagellate: a large group of flagellate protists. About half of all dinoflagellates are photosynthetic.

Downwelling: the process of accumulation and sinking of higher density material beneath lower density material, such as cold or saline water beneath warmer or fresher water or cold air beneath warm air. It is the sinking limb of a convection cell. Upwelling is the opposite process and together these two forces are responsible in the oceans for the thermohaline circulation.

Eukaryotes: organisms whose cells are organized into complex structures enclosed within membranes. The defining membrane-bound structure that differentiates eukaryotic cells from prokaryotic cells is the nucleus. The presence of a nucleus gives these organisms their name.

Euphotic zone: the near-surface layer of water receiving sufficient sunlight for photosynthesis to occur. The depth of the euphotic zone can be greatly affected by turbidity. In general practice, the euphotic zone is taken to extend from the surface to a depth where in situ light intensity falls to 1% of that at the surface, so its thickness depends on the extent of light attenuation in the water column. In clear tropical waters, dark-adapted phytoplankton at depth may still have limited photosynthesis to the 0.1% light depth. Since the euphotic zone is the only zone of water where primary productivity occurs, an exception being the productivity connected with abyssal hydrothermal vents along mid-oceanic ridges, the depth of the photic zone is generally proportional to the level of primary productivity that occurs in that area of the ocean. About 90% of all marine life lives in this region.

Femtoplankton: The size fraction of plankton organisms smaller than 0.2 μm. This primary organisms in this size fraction are viruses, but a few types of free-living bacteria are also this small.

Flagellates: cells with one or more whip-like organelles called flagella. Some flagellates are autotrophic (with chlorophyll) and are members of the phytoplankton, while others are wholly or partly heterotrophic and feed on bacteria, detritus and other small phytoplankton.

Fluorescence: llight emission that is mostly found as an optical phenomenon in cold bodies, in which the molecular absorption of a photon triggers the emission of another photon with a longer wavelength.

Gross production: see primary production

Heterotroph (ic): Organisms that require organic substrates to obtain energy for growth and development. This contrasts with autotrophs such as plants which are able to directly use sources of energy such as light to produce organic substrates from inorganic carbon dioxide.

Hydrography: the measurement of physical characteristics of waters and marginal land. In the generalized usage, "hydrography" pertains to measurement and description of any waters. With that usage oceanography and limnology are subsets of hydrography.

Internal waves: gravity waves that oscillate within, rather than on the surface of, a fluid medium. They arise from perturbations to hydrostatic equilibrium, where balance is maintained between the force of gravity and the buoyant restoring force. A simple example is a wave propagating on the interface between two fluids of different densities, such as oil and water. Internal waves typically have much lower frequencies and higher amplitudes than surface gravity waves because the density differences (and therefore the restoring forces) within a fluid are usually much smaller than the density of the fluid itself. Internal wave motions are ubiquitous in both the ocean and atmosphere. Nonlinear solitary internal waves are called solitons.

Metabolism: the set of chemical reactions that occur in living organisms in order to maintain life.

Metazoa(n): eukaryotic multicellular animals.

Microalgae: microscopic, usually uni-cellular algae typically found in freshwater and marine systems. They are unicellular species which exist individually, or in chains or groups. Depending on the species, their sizes can range from a few micrometers (µm) to a few hundreds of micrometers.

Microzooplankton: zooplankton between 20 and 200 micrometres in size.

Net production: see primary production

Nutrient: chemical that an organism needs to live and grow that must be taken in from its environment.

Oceanography: the branch of Earth science that studies the ocean. It covers a wide range of topics, including marine organisms and ecosystem dynamics; ocean currents, waves, and geophysical fluid dynamics; plate tectonics and the geology of the sea floor; and fluxes of various chemical substances and physical properties within the ocean and across its boundaries. These diverse topics reflect multiple disciplines that oceanographers blend to further knowledge of the world ocean and understanding of processes within it: biology, chemistry, geology, meteorology, and physics.

Oligotrophic: an ecosystem or environment that offers little to sustain life. The term is commonly utilised to describe bodies of water with very low nutrient levels.

PAR (Photosynthetically Active Radiation): the spectral range of solar light from 400 to 700 nanometers that is useful to plants in the process of photosynthesis.

Pelagic: water in the sea that is not close to the bottom is in the pelagic zone. The word pelagic comes from the Greek πέλαγος or pélagos, which means open sea.

Photosynthetic quotient: in photosynthesis, the moles of oxygen produced, divided by the moles of carbon dioxide assimilated

Phytoplankton: the autotrophic component of the plankton community. Most phytoplankton are too small to be individually seen with the unaided eye.

Picoplankton: the size fraction of plankton composed by cells between 0.2 and 2 micrometers. Important members of the picoplankton size fraction include: heterotrophic and autotrophic bacteria, cyanobacteria, very small eukaryotic cells (autotrophic and heterotrophic).

Primary production: the production of organic compounds from atmospheric or aquatic carbon dioxide, principally through the process of photosynthesis, with chemosynthesis being much less important. All life on earth is directly or indirectly reliant on primary production. The organisms responsible for primary production are known as primary producers or autotrophs, and form the base of the food chain. In aquatic ecoregions algae are primarily responsible. Primary production is distinguished as either net or gross, the former accounting for losses to processes such as cellular respiration, the latter not.

Protists: a diverse group of eukaryotic microorganisms. Historically, protists were treated as the kingdom Protista but this group is no longer recognized in modern taxonomy. The protists do not have much in common besides a relatively simple organization -- either they are unicellular, or they are multicellular without specialized tissues.

Respiration: the set of the metabolic reactions and processes that take place in organisms' cells to convert biochemical energy from nutrients into adenosine triphosphate (ATP), and then release waste products.

Thermocline: a thin but distinct layer in a large body of water, such as an ocean or lake, in which temperature changes more rapidly with depth than it does in the layers above or below. In the ocean, the thermocline may be thought of as an invisible blanket which separates the upper mixed layer from the calm deep water below. Depending largely on season, latitude and

turbulent mixing by wind, thermoclines may be a semi-permanent feature of the body of water in which they occur, or they may form temporarily in response to phenomena such as the radiative heating/cooling of surface water during the day/night. Factors that affect the depth and thickness of a thermocline include seasonal weather variations, latitude, and local environmental conditions, such as tides and currents.

Topography: relief or terrain of the ocean bottom, the three-dimensional quality of the surface.

T-S plots: Plots of salinity as a function of temperature, called T-S plots, are used to delineate water masses and their geographical distribution, to describe mixing among water masses, and to infer motion of water in the deep ocean. Water properties, such as temperature and salinity, are formed only when the water is at the surface or in the mixed layer. Heating, cooling, rain, and evaporation all contribute. Once the water sinks below the mixed layer, temperature and salinity can change only by mixing with adjacent water masses.

Turbidity: the cloudiness or haziness of a fluid caused by individual particles (suspended solids) that are generally invisible to the naked eye, similar to smoke in air. The measurement of turbidity is a key test of water quality.

Upwelling: wind-driven motion of dense, cooler, and usually nutrient-rich water towards the ocean surface, replacing the warmer, usually nutrient-depleted surface water. There are at least five types of upwelling: coastal upwelling, large-scale wind-driven upwelling in the ocean interior, upwelling associated with eddies, topographically-associated upwelling, and broad-diffusive upwelling in the ocean interior.

Virus: Infectious micro-organisms that cannot reproduce outside host cells. In aquatic waters, native viruses predominantly infect bacterioplankton and picoplankton. Through cell lysis, viral activity promotes nutrient cycling through the microbial food web.

Zooplankton: the heterotrophic (sometimes detritivorous) type of plankton. Plankton are organisms drifting in the water column of oceans, seas, and bodies of fresh water. Many zooplankton are too small to be seen individually with the naked eye.

Appendix A: Water quality parameter statistics

Table A. 1 Monthly aggregated daily statistics for water temperature time series collected by in-situ loggers. Unless otherwise indicated, all units are in °C.
% of month indicates temporal data coverage, Min = minimum of all data for that month, Max = maximum of all data for month, Std Dev = standard deviation of all data for month, Median = median of all data for month, Mean Daily Max = arithmetic mean of the daily maximum temperatures, Mean Daily Min = arithmetic mean of the daily minimum temperatures, Mean Daily Range = arithmetic mean of the daily temperature ranges (daily max – daily min),

	Jan									Feb									Mar								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	100	28.89	29.47	29.86	0.20	29.44	29.62	29.31	0.31	93	28.45	28.89	29.51	0.26	28.88	29.01	28.78	0.24	65	28.73	29.44	30.29	0.31	29.44	29.74	29.08	0.66
PE02	100	28.88	29.19	29.59	0.17	29.16	29.27	29.12	0.15	93	28.43	28.76	29.15	0.18	28.79	28.82	28.68	0.14	66	28.65	29.16	29.8	0.23	29.2	29.28	29.02	0.26
PE03	100	28.35	29.42	30.12	0.24	29.44	29.72	28.98	0.74	93	27.73	28.67	29.34	0.30	28.66	28.94	28.24	0.70	66	27.13	29.35	30.57	0.45	29.38	29.89	28.53	1.36
PE04	100	26.37	29.15	30.17	0.64	29.32	29.78	27.37	2.40	93	26.02	28.43	29.55	0.60	28.56	28.98	26.88	2.10	63	25.34	29.06	30.79	0.7	29.13	29.92	27.12	2.8
PE05	100	25.45	28.00	29.63	0.94	28.15	29.26	26.64	2.61	89	24.55	27.27	29.01	0.95	27.37	28.50	25.85	2.65	66	24.74	27.97	29.94	1	28.14	29.3	26.21	3.09
PE06	100	26.53	28.44	29.48	0.53	28.55	29.12	27.52	1.60	87	25.97	27.98	28.93	0.51	28.08	28.55	26.91	1.64	63	25.35	28.43	29.6	0.57	28.51	29.04	27.25	1.79
PE07	100	25.57	28.14	29.59	0.80	28.29	29.12	26.88	2.24	94	25.29	27.92	29.16	0.68	27.95	28.57	26.72	1.85	63	25.41	28.11	29.65	0.73	28.26	28.89	26.64	2.25
PE08	100	26.51	28.38	29.72	0.64	28.39	29.09	27.63	1.46	94	25.87	27.99	29.19	0.74	28.05	28.63	27.26	1.36	65	25.97	28.19	29.55	0.63	28.22	28.91	27.21	1.7
PE09	100	28.40	28.90	29.36	0.28	28.86	28.95	28.85	0.09	93	28.28	28.60	29.03	0.26	28.53	28.65	28.58	0.07	66	28.51	28.92	29.31	0.22	28.92	28.92	28.8	0.12
PE10																			13	28.15	28.89	29.21	0.31	29.04	29	28.72	0.27
PE11																			15	28.37	28.93	29.53	0.25	28.94	29.22	28.58	0.64
PE12																			15	29.56	29.99	30.22	0.13	30.03	30.11	29.85	0.26
PE13	100	27.87	28.77	29.36	0.38	28.91	28.89	28.69	0.20	93	28.01	28.53	29.20	0.39	28.40	28.62	28.49	0.13	65	28.22	28.74	29.26	0.25	28.68	28.84	28.54	0.3
PE14	100	27.58	28.65	29.21	0.46	28.81	28.74	28.57	0.17	93	27.89	28.43	29.02	0.36	28.40	28.51	28.38	0.12	50	27.81	28.57	29.33	0.31	28.56	28.66	28.47	0.19
PE15	100	26.68	28.35	29.18	0.60	28.48	28.57	28.03	0.54	90	27.21	28.20	28.99	0.40	28.17	28.39	27.97	0.42	50	26.93	28.31	29.48	0.51	28.31	28.53	27.96	0.57
PE16	100	25.49	27.91	29.29	0.80	28.04	29.00	26.37	2.63	90	25.00	27.57	28.99	0.75	27.70	28.48	25.83	2.64	50	24.6	27.88	29.48	0.8	27.99	28.85	26.04	2.81

Table A. 1 (cont'd)

	Apr									May									Jun								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	100	29.02	29.9	30.81	0.41	29.86	30.42	29.35	1.08	78	27.19	28.88	30.43	0.62	28.94	28.98	28.27	0.71	100	26.35	27.20	27.70	0.31	27.35	27.34	26.95	0.39
PE02	100	28.83	29.72	30.4	0.36	29.7	30.07	29.32	0.75	75	26.56	28.84	30.25	0.69	28.9	28.96	28.2	0.77	100	25.74	27.03	27.41	0.34	27.21	27.13	26.79	0.34
PE03	100	28.04	29.82	30.86	0.4	29.76	30.44	29.01	1.44	73	27.19	28.94	30.48	0.64	28.97	29.02	28.16	0.87	100	26.42	27.27	27.69	0.29	27.39	27.43	27.02	0.41
PE04	100	24.86	29.46	30.72	0.66	29.48	30.44	26.89	3.55	77	25.48	28.82	30.39	0.7	28.87	29.07	27.24	1.83	83	25.98	27.20	27.71	0.35	27.32	27.41	26.74	0.67
PE05	100	24.86	28.58	30.59	1	28.73	30.03	26.35	3.69	72	25.79	28.48	30.06	0.75	28.53	29.01	27.08	1.93	100	26.36	27.22	27.74	0.28	27.31	27.39	26.88	0.50
PE06	100	25.73	28.9	30.29	0.67	29.08	29.87	27.15	2.72	75	27.02	28.72	30.2	0.55	28.71	28.99	27.97	1.02	100	26.72	27.30	27.70	0.25	27.39	27.36	27.21	0.15
PE07	100	24.48	28.61	30.28	0.77	28.72	29.81	26.76	3.05	81	25.21	28.49	29.95	0.72	28.64	28.96	27.34	1.62	100	26.72	27.29	27.76	0.26	27.36	27.34	27.24	0.10
PE08	100	25.91	28.8	30.19	0.8	29.01	29.77	27.32	2.45	81	26.29	28.69	29.81	0.55	28.75	28.92	27.89	1.03	100	26.73	27.30	27.77	0.26	27.36	27.35	27.24	0.11
PE09	100	28.83	29.53	30.38	0.33	29.45	29.79	29.25	0.55	57	27.08	28.82	29.99	0.64	28.78	28.84	28.62	0.22	100	26.54	27.15	27.43	0.27	27.27	27.18	27.11	0.07
PE10	50	27.62	28.82	29.39	0.41	28.9	28.93	28.68	0.25	50	27.49	28.55	29.42	0.46	28.51	28.62	28.46	0.16	100	26.65	27.21	27.61	0.25	27.30	27.23	27.18	0.05
PE11	50	27.92	28.98	29.7	0.32	29.02	29.22	28.74	0.48	50	27.64	28.65	29.42	0.45	28.69	28.75	28.53	0.22	100	26.61	27.22	27.72	0.26	27.31	27.27	27.18	0.09
PE12	50	29.16	29.77	30.32	0.32	29.84	29.84	29.68	0.17	50	27.19	28.55	29.39	0.68	28.81	28.63	28.45	0.19	100	26.41	27.12	27.55	0.34	27.22	27.20	27.02	0.18
PE13	100	28.16	29.26	30.03	0.4	29.31	29.65	28.86	0.79	81	27.38	28.8	29.78	0.54	28.75	28.88	28.47	0.4	100	26.59	27.16	27.48	0.27	27.31	27.20	27.12	0.07
PE14	50	29.22	29.56	30.1	0.2	29.55	29.63	29.5	0.13	29	28.6	29.21	29.68	0.26	29.26	29.28	29.09	0.19									
PE15	50	28	29.31	29.81	0.27	29.37	29.47	29.07	0.41	28	27.88	28.98	29.7	0.43	29	29.16	28.79	0.38									
PE16	50	25.06	28.59	30.18	0.83	28.78	29.7	26.45	3.25	28	25.5	28.65	29.88	0.75	28.77	29.35	26.79	2.56									

Table A. 1 (cont'd)

	Jul									Aug									Sep								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	94	25.53	26.34	27.02	0.32	26.28	26.46	26.02	0.45	100	25.18	25.99	26.34	0.20	26.00	26.09	25.81	0.28	97	25.93	26.45	27.11	0.23	26.43	26.69	26.28	0.41
PE02	91	25.30	26.19	26.84	0.33	26.16	26.30	25.95	0.36	100	25.41	25.90	26.27	0.16	25.93	25.98	25.78	0.20	97	26.01	26.30	26.56	0.11	26.33	26.32	26.27	0.06
PE03	97	25.27	26.40	27.00	0.29	26.37	26.56	26.06	0.50	100	25.27	26.04	26.46	0.18	26.05	26.17	25.78	0.40	96	25.19	26.31	27.48	0.28	26.25	26.76	25.96	0.80
PE04	97	25.31	26.38	27.05	0.33	26.38	26.55	25.84	0.70	100	25.35	26.01	26.41	0.20	26.02	26.15	25.74	0.41	93	25.18	26.15	27.80	0.35	26.10	26.73	25.65	1.08
PE05	98	25.45	26.33	26.94	0.29	26.32	26.50	26.00	0.50	100	24.58	25.90	26.33	0.26	25.94	26.10	25.48	0.62	97	24.39	25.70	26.69	0.45	25.72	26.35	25.06	1.29
PE06	97	25.77	26.34	26.86	0.27	26.30	26.42	26.24	0.19	100	25.39	26.01	26.29	0.20	26.03	26.08	25.89	0.19	96	25.16	25.88	27.03	0.21	25.89	26.22	25.57	0.65
PE07	97	25.87	26.35	26.93	0.29	26.27	26.39	26.27	0.12	100	25.46	26.02	26.35	0.18	26.03	26.09	25.90	0.19	95	25.11	25.98	26.77	0.23	25.99	26.27	25.55	0.72
PE08	97	25.61	26.39	26.97	0.30	26.35	26.47	26.26	0.21	100	25.15	25.99	26.34	0.19	26.03	26.08	25.86	0.22	96	25.00	25.94	26.63	0.30	25.99	26.26	25.53	0.72
PE09	97	25.79	26.22	26.73	0.31	26.17	26.25	26.17	0.08	100	25.71	25.95	26.27	0.14	25.94	25.97	25.92	0.05	97	25.88	26.16	26.40	0.10	26.17	26.19	26.14	0.05
PE10	97	25.83	26.26	26.78	0.31	26.17	26.27	26.21	0.06	100	25.62	25.92	26.17	0.15	25.95	25.94	25.89	0.05	84	25.88	26.06	26.20	0.07	26.07	26.10	26.03	0.08
PE11	73	25.86	26.32	26.87	0.35	26.26	26.39	26.25	0.13	100	25.65	25.96	26.23	0.14	25.99	26.02	25.91	0.11	80	25.40	26.09	26.45	0.17	26.15	26.23	25.90	0.34
PE12	97	25.62	26.20	26.91	0.36	26.14	26.27	26.08	0.19	100	25.32	26.00	26.78	0.33	25.91	26.09	25.87	0.22	80	26.35	26.91	27.40	0.22	26.92	27.03	26.79	0.25
PE13	97	25.83	26.25	26.82	0.32	26.19	26.29	26.20	0.09	100	25.58	25.90	26.15	0.14	25.94	25.93	25.87	0.06	94	25.93	26.11	26.34	0.10	26.11	26.15	26.08	0.06
PE14																			3	26.33	26.38	26.41	0.02	26.38	26.41	26.33	0.09
PE15																			3	26.25	26.30	26.35	0.03	26.30	26.35	26.25	0.10
PE16																			3	25.50	26.06	26.62	0.34	26.03	26.62	25.50	1.12

Table A. 1 (cont'd)

	Oct									Nov									Dec								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	100	26.64	27.72	29.63	0.59	27.68	28.31	27.30	1.01	94	28.20	29.01	30.41	0.43	28.92	29.69	28.51	1.19	100	28.12	29.06	30.02	0.38	29.12	29.41	28.71	0.70
PE02	100	26.51	27.20	28.02	0.41	27.14	27.28	27.13	0.14	94	27.87	28.39	28.69	0.18	28.44	28.50	28.32	0.18	100	28.15	28.56	29.06	0.22	28.49	28.67	28.49	0.18
PE03	100	25.42	27.38	29.52	0.66	27.42	28.47	26.58	1.89	94	26.95	28.90	30.77	0.71	28.81	29.89	27.80	2.09	100	27.62	29.20	30.33	0.42	29.23	29.73	28.47	1.27
PE04	100	24.68	27.70	29.79	0.86	27.72	28.75	26.13	2.62	94	26.25	28.86	30.61	0.81	28.93	30.04	27.20	2.84	100	26.04	28.87	30.22	0.71	28.99	29.71	27.12	2.59
PE05	100	24.63	26.37	28.66	0.75	26.32	27.50	25.36	2.14	94	25.42	27.17	29.35	0.72	27.15	28.44	26.19	2.25	100	25.12	27.37	29.21	0.81	27.33	28.58	26.26	2.32
PE06	100	25.23	26.68	28.22	0.56	26.72	27.43	25.96	1.47	94	25.77	27.79	28.96	0.42	27.85	28.48	27.01	1.47	100	25.97	27.84	29.16	0.63	27.92	28.68	27.02	1.67
PE07	100	24.45	26.59	28.48	0.57	26.60	27.23	25.73	1.50	94	25.45	27.25	28.93	0.49	27.31	28.01	26.42	1.59	100	25.37	27.73	29.26	0.74	27.74	28.61	26.66	1.95
PE08	100	24.40	26.55	28.00	0.62	26.63	27.15	25.86	1.29	94	26.20	27.60	28.86	0.42	27.66	28.11	26.98	1.12	100	25.90	27.96	29.35	0.66	27.97	28.55	27.24	1.31
PE09	100	26.40	27.05	27.78	0.37	27.05	27.08	27.01	0.06	94	27.72	28.12	28.38	0.19	28.21	28.15	28.09	0.06	100	27.95	28.28	28.80	0.21	28.21	28.33	28.24	0.09
PE10																											
PE11																											
PE12																											
PE13	100	26.35	26.98	27.68	0.33	26.92	27.05	26.93	0.12	94	27.59	27.88	28.20	0.12	27.86	28.00	27.79	0.22	100	27.54	28.16	28.92	0.38	27.98	28.28	28.06	0.22
PE14	100	26.41	27.02	27.73	0.32	27.04	27.07	26.96	0.11	94	27.64	27.87	28.04	0.07	27.88	27.93	27.80	0.13	100	27.34	27.96	28.95	0.41	27.85	28.06	27.87	0.19
PE15	100	26.04	26.87	27.84	0.38	26.84	27.01	26.68	0.34	94	26.99	27.60	28.03	0.18	27.61	27.78	27.43	0.35	100	26.38	27.77	29.01	0.58	27.64	27.98	27.53	0.44
PE16	100	24.63	26.50	28.29	0.54	26.53	27.24	25.54	1.70	94	25.56	27.23	28.79	0.56	27.25	28.18	26.25	1.93	100	25.44	27.51	29.18	0.80	27.54	28.54	26.22	2.32

Table A. 2 Monthly aggregated daily statistics for salinity time series collected by in-situ loggers. Unless indicated otherwise, all units are in PSU
% of month indicates temporal data coverage, Min = minimum of all data for that month, Max = maximum of all data for month, Std Dev = standard deviation of all data for month, Median = median of all data for month, Mean Daily Max = arithmetic mean of the daily maximum salinities, Mean Daily Min = arithmetic mean of the daily minimum salinities, Mean Daily Range = arithmetic mean of the daily salinity ranges (daily max – daily min),

	Jan									Feb									Mar								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	100	34.46	34.58	34.66	0.03	34.58	34.60	34.56	0.04	93	34.38	34.49	34.63	0.05	34.46	34.50	34.47	0.03	65	34.31	34.41	34.47	0.04	34.43	34.45	34.40	0.05
PE02	100	34.54	34.58	34.64	0.02	34.57	34.59	34.56	0.03	93	34.44	34.54	34.64	0.04	34.54	34.55	34.52	0.03	66	34.38	34.46	34.53	0.03	34.47	34.49	34.44	0.05
PE03	100	34.46	34.60	34.71	0.04	34.60	34.64	34.55	0.09	93	34.26	34.45	34.60	0.08	34.42	34.49	34.40	0.09	66	34.26	34.37	34.56	0.03	34.38	34.43	34.33	0.11
PE04	100	34.28	34.55	34.70	0.06	34.56	34.63	34.42	0.22	93	34.28	34.46	34.80	0.06	34.44	34.53	34.38	0.14	63	34.20	34.41	34.60	0.04	34.42	34.49	34.34	0.15
PE05	100	34.28	34.50	34.66	0.07	34.50	34.60	34.41	0.19	89	34.33	34.45	34.58	0.04	34.44	34.51	34.38	0.12	66	34.25	34.41	34.53	0.05	34.42	34.47	34.36	0.11
PE06	100	34.34	34.46	34.56	0.04	34.46	34.52	34.40	0.12	87	34.32	34.44	34.55	0.03	34.45	34.48	34.39	0.09	63	34.27	34.41	34.53	0.04	34.43	34.47	34.37	0.10
PE07	100	34.37	34.51	34.71	0.04	34.51	34.59	34.44	0.15	93	34.36	34.47	34.66	0.05	34.45	34.52	34.42	0.10	63	34.28	34.40	34.49	0.04	34.41	34.45	34.35	0.10
PE08	100	34.36	34.51	34.64	0.05	34.51	34.57	34.45	0.12	94	34.37	34.49	34.62	0.05	34.47	34.53	34.46	0.07	65	34.28	34.42	34.49	0.05	34.44	34.46	34.38	0.08
PE09	100	34.52	34.56	34.63	0.02	34.54	34.56	34.55	0.01	93	34.48	34.52	34.60	0.03	34.51	34.53	34.51	0.01	66	34.33	34.46	34.49	0.04	34.47	34.48	34.45	0.04
PE10																			13	34.33	34.37	34.39	0.02	34.37	34.38	34.35	0.03
PE11																			15	34.30	34.34	34.39	0.02	34.35	34.36	34.32	0.04
PE12																			15	34.31	34.34	34.36	0.01	34.34	34.35	34.33	0.02
PE13	100	34.52	34.56	34.61	0.02	34.57	34.57	34.56	0.01	93	34.45	34.51	34.61	0.05	34.47	34.52	34.50	0.01	65	34.33	34.44	34.47	0.04	34.45	34.46	34.43	0.03
PE14	100	34.50	34.56	34.60	0.03	34.56	34.57	34.55	0.01	93	34.42	34.48	34.58	0.06	34.46	34.49	34.48	0.01	50	34.41	34.43	34.44	0.01	34.43	34.43	34.42	0.01
PE15	100	34.45	34.53	34.60	0.04	34.53	34.55	34.51	0.04	90	34.49	34.57	34.83	0.07	34.56	34.59	34.56	0.03	50	34.48	34.62	34.71	0.07	34.66	34.63	34.60	0.02
PE16	100	34.31	34.48	34.85	0.11	34.45	34.57	34.40	0.16	90	34.37	34.61	35.85	0.23	34.46	34.67	34.52	0.15	50	34.34	34.43	34.65	0.02	34.44	34.49	34.39	0.11

Table A. 2 (cont'd)

	Apr									May									Jun								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	100	34.31	34.44	34.59	0.05	34.43	34.49	34.39	0.11	78	34.35	34.50	34.69	0.09	34.46	34.56	34.41	0.16	100	34.23	34.38	34.52	0.06	34.37	34.43	34.35	0.08
PE02	100	34.35	34.45	34.61	0.06	34.46	34.51	34.39	0.12	75	34.26	34.47	34.74	0.14	34.42	34.56	34.35	0.21	100	34.24	34.36	34.49	0.06	34.34	34.38	34.33	0.05
PE03	100	34.23	34.39	34.51	0.05	34.40	34.45	34.33	0.12	73	34.22	34.41	34.61	0.08	34.44	34.47	34.34	0.13	100	34.16	34.33	34.48	0.07	34.34	34.39	34.28	0.11
PE04	100	34.23	34.42	34.73	0.05	34.41	34.53	34.31	0.22	77	34.19	34.46	34.76	0.12	34.44	34.57	34.31	0.26	83	34.18	34.31	34.45	0.07	34.32	34.41	34.26	0.15
PE05	100	34.26	34.41	34.58	0.04	34.41	34.49	34.35	0.14	72	34.26	34.43	34.64	0.10	34.40	34.51	34.33	0.18	100	34.18	34.34	34.50	0.06	34.35	34.38	34.29	0.09
PE06	100	34.28	34.41	34.57	0.04	34.41	34.48	34.35	0.13	75	34.26	34.43	34.65	0.10	34.41	34.48	34.35	0.13	100	34.21	34.38	34.46	0.03	34.38	34.41	34.35	0.06
PE07	100	34.27	34.41	34.57	0.04	34.41	34.47	34.34	0.13	81	34.25	34.45	34.66	0.10	34.43	34.53	34.33	0.20	100	34.26	34.40	34.47	0.04	34.40	34.42	34.37	0.05
PE08	100	34.33	34.42	34.56	0.05	34.41	34.48	34.37	0.11	81	34.28	34.47	34.68	0.11	34.44	34.55	34.37	0.18	100	34.28	34.40	34.47	0.04	34.40	34.42	34.37	0.05
PE09	100	34.33	34.43	34.57	0.05	34.45	34.48	34.39	0.08	55	34.32	34.43	34.60	0.06	34.42	34.45	34.39	0.05	100	34.34	34.42	34.50	0.04	34.42	34.43	34.41	0.01
PE10	50	34.35	34.39	34.45	0.03	34.39	34.40	34.39	0.02	50	34.34	34.43	34.48	0.03	34.44	34.44	34.42	0.03	100	34.35	34.44	34.48	0.03	34.44	34.44	34.43	0.01
PE11	50	34.33	34.39	34.44	0.02	34.38	34.40	34.38	0.03	50	34.35	34.42	34.48	0.03	34.43	34.44	34.41	0.04	100	34.31	34.42	34.47	0.04	34.43	34.43	34.40	0.03
PE12	50	34.27	34.44	34.54	0.06	34.43	34.46	34.43	0.03	50	34.39	34.45	34.52	0.03	34.45	34.46	34.44	0.03	100	34.30	34.41	34.50	0.05	34.42	34.42	34.39	0.03
PE13	100	34.34	34.43	34.55	0.04	34.43	34.47	34.39	0.08	81	34.39	34.52	34.71	0.09	34.47	34.57	34.44	0.13	100	34.34	34.43	34.48	0.04	34.45	34.44	34.42	0.02
PE14	50	34.40	34.45	34.54	0.04	34.43	34.45	34.44	0.01	29	34.52	34.59	34.69	0.05	34.61	34.61	34.59	0.02									
PE15	50	34.67	34.89	35.35	0.22	34.76	34.91	34.87	0.03	28	35.32	35.42	35.59	0.06	35.43	35.45	35.42	0.03									
PE16	50	34.33	34.44	34.62	0.04	34.44	34.50	34.39	0.11	28	34.43	34.57	34.69	0.05	34.58	34.61	34.49	0.12									

Table A. 2 (cont'd)

	Jul									Aug									Sep								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	94	34.21	34.31	34.52	0.06	34.31	34.36	34.29	0.07	100	34.29	34.38	34.47	0.03	34.39	34.40	34.37	0.04	97	34.32	34.38	34.45	0.01	34.38	34.40	34.36	0.04
PE02	91	34.17	34.33	34.48	0.07	34.34	34.37	34.31	0.06	100	34.33	34.39	34.46	0.03	34.41	34.41	34.39	0.02	97	34.36	34.39	34.41	0.01	34.40	34.40	34.39	0.01
PE03	97	34.12	34.30	34.40	0.05	34.31	34.34	34.25	0.09	100	34.28	34.37	34.44	0.04	34.39	34.40	34.35	0.06	90	34.28	34.37	34.51	0.03	34.36	34.40	34.34	0.07
PE04	97	34.14	34.29	34.42	0.06	34.30	34.37	34.25	0.12	100	34.26	34.38	34.48	0.04	34.39	34.43	34.35	0.07	94	34.21	34.37	34.53	0.04	34.37	34.43	34.33	0.10
PE05	98	34.18	34.32	34.40	0.04	34.32	34.36	34.28	0.08	100	34.25	34.35	34.42	0.03	34.35	34.39	34.31	0.07	98	34.24	34.35	34.52	0.05	34.34	34.40	34.29	0.11
PE06	97	34.23	34.33	34.40	0.04	34.34	34.35	34.30	0.05	100	34.29	34.39	34.46	0.03	34.40	34.41	34.37	0.04	96	34.23	34.37	34.47	0.05	34.37	34.40	34.34	0.06
PE07	97	34.20	34.32	34.41	0.05	34.33	34.34	34.31	0.04	100	34.29	34.38	34.42	0.02	34.39	34.40	34.36	0.04	97	34.26	34.37	34.50	0.04	34.38	34.41	34.34	0.07
PE08	97	34.21	34.32	34.48	0.05	34.33	34.35	34.29	0.06	100	34.32	34.38	34.43	0.02	34.38	34.40	34.36	0.03	97	34.24	34.38	34.46	0.04	34.38	34.41	34.34	0.07
PE09	97	34.25	34.35	34.44	0.05	34.36	34.36	34.34	0.02	100	34.30	34.35	34.37	0.02	34.34	34.35	34.34	0.01	97	34.30	34.35	34.37	0.02	34.35	34.35	34.34	0.01
PE10	97	34.26	34.36	34.43	0.05	34.36	34.37	34.35	0.02	100	34.35	34.40	34.44	0.01	34.40	34.40	34.39	0.02	84	34.32	34.38	34.42	0.02	34.39	34.39	34.37	0.01
PE11	73	34.22	34.34	34.42	0.05	34.34	34.36	34.31	0.05	100	34.35	34.40	34.44	0.01	34.40	34.41	34.39	0.02	80	34.33	34.39	34.45	0.02	34.38	34.41	34.37	0.04
PE12	97	34.24	34.36	34.47	0.07	34.38	34.37	34.34	0.03	100	34.37	34.41	34.48	0.03	34.40	34.42	34.40	0.02	80	34.37	34.41	34.48	0.03	34.40	34.42	34.40	0.02
PE13	97	34.26	34.38	34.46	0.05	34.41	34.39	34.36	0.03	100	34.38	34.41	34.45	0.02	34.41	34.42	34.40	0.02	94	34.36	34.39	34.42	0.02	34.41	34.40	34.39	0.01
PE14																			3	34.36	34.37	34.38	0.01	34.37	34.38	34.36	0.02
PE15																			3	34.28	34.30	34.33	0.02	34.30	34.33	34.28	0.06
PE16																			3	34.33	34.38	34.43	0.02	34.38	34.43	34.33	0.10

Table A. 2 (cont'd)

	Oct									Nov									Dec								
Site	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range	% of month	Min	Mean	Max	Std Dev	Median	Mean Daily Max	Mean Daily Min	Mean Daily Range
PE01	100	34.35	34.42	34.53	0.03	34.42	34.47	34.39	0.08	94	34.38	34.47	34.58	0.04	34.46	34.52	34.43	0.09	100	34.38	34.47	34.61	0.06	34.45	34.50	34.45	0.04
PE02	100	34.36	34.38	34.41	0.01	34.38	34.39	34.38	0.01	94	34.39	34.41	34.43	0.01	34.41	34.42	34.41	0.02	100	34.35	34.44	34.62	0.08	34.39	34.46	34.43	0.03
PE03	100	34.31	34.42	34.55	0.04	34.43	34.48	34.38	0.11	94	34.25	34.47	34.65	0.05	34.47	34.56	34.38	0.18	100	34.35	34.52	34.64	0.05	34.52	34.58	34.46	0.12
PE04	100	34.20	34.39	34.63	0.05	34.39	34.51	34.27	0.24	94	34.22	34.43	34.65	0.07	34.42	34.55	34.29	0.26	100	34.29	34.48	34.71	0.07	34.50	34.57	34.37	0.21
PE05	100	34.27	34.41	34.53	0.04	34.42	34.46	34.37	0.09	94	34.26	34.38	34.48	0.04	34.37	34.44	34.33	0.11	100	34.32	34.42	34.58	0.06	34.42	34.48	34.37	0.11
PE06	100	34.25	34.39	34.53	0.04	34.40	34.45	34.35	0.10	94	34.23	34.38	34.57	0.06	34.40	34.43	34.33	0.10	100	34.23	34.38	34.54	0.06	34.37	34.44	34.33	0.11
PE07	100	34.34	34.41	34.56	0.03	34.40	34.45	34.37	0.08	94	34.24	34.37	34.47	0.04	34.38	34.42	34.34	0.08	100	34.31	34.43	34.59	0.06	34.41	34.49	34.38	0.11
PE08	100	34.29	34.37	34.47	0.03	34.37	34.40	34.34	0.06	94	34.28	34.36	34.45	0.03	34.36	34.39	34.33	0.07	100	34.35	34.44	34.63	0.06	34.42	34.48	34.40	0.08
PE09	100	34.36	34.38	34.41	0.01	34.38	34.38	34.38	0.01	94	34.40	34.41	34.43	0.01	34.41	34.42	34.41	0.01	100	34.38	34.43	34.53	0.05	34.40	34.43	34.42	0.01
PE10																											
PE11																											
PE12																											
PE13	100	34.37	34.40	34.43	0.02	34.40	34.41	34.40	0.01	94	34.34	34.41	34.45	0.02	34.42	34.42	34.40	0.02	100	34.38	34.44	34.56	0.06	34.42	34.45	34.43	0.01
PE14	100	34.33	34.40	34.44	0.02	34.40	34.41	34.39	0.02	94	34.26	34.41	34.44	0.03	34.41	34.41	34.40	0.02	100	34.36	34.43	34.57	0.06	34.42	34.44	34.43	0.01
PE15	100	34.28	34.39	34.45	0.03	34.40	34.41	34.38	0.03	94	34.31	34.38	34.43	0.03	34.38	34.40	34.37	0.03	100	34.34	34.43	34.57	0.06	34.41	34.45	34.42	0.02
PE16	100	34.31	34.41	34.53	0.03	34.41	34.46	34.37	0.09	94	34.23	34.36	34.48	0.06	34.37	34.41	34.32	0.09	100	34.24	34.36	34.54	0.06	34.35	34.41	34.31	0.10

Table A. 3 Monthly aggregated daily statistics for Turbidity time series collected by in-situ loggers. Unless indicated otherwise, all units are in NTU
% of month indicates temporal data coverage, Min = minimum of all data for that month, Max = maximum of all data for month, Std Dev = standard deviation of all data for month, Median = median of all data for month,

	Jan						Feb						Mar					
Site	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median
PE01	100	0.05	0.17	0.75	0.07	0.15	92	0.07	0.2	1.36	0.1	0.18	64	0.06	0.19	1.2	0.08	0.17
PE02	100	0.05	0.52	5.5	0.31	0.47	93	0.06	0.53	5.86	0.5	0.4	66	0.07	0.63	6.12	0.46	0.55
PE03	100	0.04	0.09	0.98	0.04	0.08	33	0.04	0.29	1.36	0.3	0.16	16	0.04	0.08	0.48	0.03	0.08
PE04	100	0.05	0.1	0.53	0.04	0.09	92	0.03	0.11	0.9	0.08	0.09	63	0.04	0.08	0.79	0.04	0.08
PE05	100	0.03	0.06	3.43	0.09	0.06	74	0.03	0.08	2.34	0.09	0.07	66	0.04	0.08	2.01	0.08	0.07
PE06							54	0.04	0.08	0.31	0.02	0.08	63	0.04	0.08	0.29	0.02	0.08
PE07	100	0.08	0.12	1	0.04	0.12	93	0.07	0.11	0.52	0.03	0.1	63	0.05	0.1	0.36	0.02	0.1
PE08	76	0.05	0.1	2.05	0.06	0.09	57	0.04	0.08	0.61	0.04	0.07	64	0.04	0.07	0.53	0.03	0.07
PE09	100	0.16	0.38	0.97	0.09	0.38	92	0.04	0.21	1.91	0.19	0.09	63	0.05	0.12	1.84	0.09	0.1
PE10													13	0.05	0.08	0.41	0.03	0.08
PE11													15	0.04	0.08	0.82	0.04	0.08
PE12													14	0.11	0.31	1.22	0.12	0.28
PE13	100	0.05	0.07	0.76	0.03	0.07	93	0.03	0.11	0.76	0.06	0.1	64	0.05	0.11	0.48	0.03	0.11
PE14	99	0.03	0.06	0.2	0.01	0.05	93	0.02	0.05	0.5	0.03	0.04	50	0.03	0.05	0.58	0.03	0.05
PE15	100	0.11	0.14	0.43	0.02	0.14	90	0.06	0.11	1.23	0.05	0.1	50	0.06	0.1	1.1	0.05	0.1
PE16	77	0.05	0.09	1.53	0.04	0.08	57	0.05	0.09	0.94	0.04	0.08	50	0.05	0.09	1.85	0.05	0.08

Table A. 3 (cont'd)

	Apr						May						Jun					
Site	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median
PE01	100	0.08	0.19	2.45	0.09	0.17	77	0.07	0.23	2.03	0.12	0.2	100	0.06	0.23	2	0.13	0.2
PE02	99	0.06	0.52	5.85	0.36	0.46	74	0.06	0.32	5.22	0.24	0.28	100	0.06	0.26	2.81	0.16	0.24
PE03	50	0.04	0.09	2.75	0.08	0.08	48	0.04	0.11	2.8	0.13	0.08	100	0.03	0.1	1.97	0.09	0.08
PE04	100	0.02	0.08	1.34	0.05	0.07	77	0.03	0.1	2.02	0.06	0.08	74	0.04	0.1	1.04	0.08	0.07
PE05	100	0.04	0.08	1.44	0.06	0.07	70	0.04	0.08	2.24	0.06	0.07						
PE06	100	0.02	0.06	0.31	0.02	0.06	75	0.01	0.05	0.31	0.02	0.05	100	0.02	0.05	0.32	0.02	0.05
PE07	100	0.05	0.09	0.66	0.03	0.09	81	0.05	0.09	0.62	0.04	0.09	100	0.05	0.08	0.67	0.03	0.07
PE08	100	0.04	0.08	1.1	0.04	0.08	81	0.04	0.1	2.12	0.07	0.09	100	0.03	0.08	1.98	0.04	0.07
PE09	50	0.05	0.18	1.4	0.08	0.18	50	0.29	0.39	1.41	0.06	0.38	100	0.24	0.4	1.37	0.06	0.4
PE10	50	0.03	0.06	0.95	0.04	0.06	50	0.03	0.07	2.69	0.09	0.06	99	0.04	0.09	2.77	0.13	0.08
PE11	50	0.03	0.07	0.4	0.02	0.07	50	0.02	0.07	1.03	0.06	0.05	100	0.02	0.07	0.91	0.04	0.07
PE12	50	0.09	0.3	1.27	0.12	0.28	50	0.1	0.3	1.23	0.13	0.28	99	0.14	0.39	1.32	0.16	0.36
PE13	100	0.04	0.1	0.53	0.04	0.1	81	0.03	0.12	0.53	0.06	0.1	100	0.05	0.1	0.55	0.04	0.09
PE14	3	0.03	0.05	0.13	0.01	0.05												
PE15	50	0.06	0.12	0.93	0.04	0.11	28	0.06	0.12	0.72	0.05	0.11						
PE16	50	0.05	0.08	1.81	0.06	0.07	28	0.05	0.08	1.3	0.04	0.08						

Table A. 3 (cont'd)

	Jul						Aug						Sep					
Site	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median
PE01	94	0.07	0.23	1.98	0.12	0.2	99	0.07	0.22	0.84	0.09	0.2	96	0.07	0.21	0.78	0.08	0.2
PE02	91	0.06	0.29	2.24	0.17	0.26	100	0.15	0.41	2	0.14	0.41	97	0.34	0.64	3.54	0.18	0.61
PE03	97	0.04	0.13	3.37	0.19	0.09	100	0.05	0.11	0.99	0.06	0.1	96	0.05	0.12	3.54	0.19	0.09
PE04	13	0.04	0.11	0.72	0.07	0.09	100	0.05	0.1	1.98	0.07	0.08	94	0.04	0.09	1.99	0.08	0.07
PE05	16	0.04	0.15	0.45	0.09	0.13	100	0.05	0.14	0.47	0.12	0.08	98	0.04	0.07	0.45	0.02	0.07
PE06	97	0.03	0.07	0.3	0.03	0.06	100	0.09	0.12	0.27	0.02	0.12	96	0.07	0.11	0.28	0.02	0.11
PE07	97	0.05	0.09	0.7	0.03	0.09	100	0.05	0.08	0.24	0.02	0.08	97	0.04	0.09	0.26	0.03	0.09
PE08	96	0.04	0.09	1.04	0.05	0.08	100	0.06	0.09	0.37	0.02	0.08	97	0.05	0.09	0.65	0.03	0.09
PE09	97	0.06	0.17	1.31	0.07	0.17	100	0.05	0.1	0.45	0.03	0.09	97	0.05	0.09	0.44	0.03	0.09
PE10	97	0.04	0.1	2.05	0.11	0.08	100	0.04	0.07	1	0.03	0.07	84	0.04	0.08	0.61	0.03	0.08
PE11	73	0.03	0.09	0.92	0.05	0.08	100	0.08	0.13	1.34	0.05	0.12	80	0.1	0.14	0.86	0.03	0.13
PE12	97	0.13	0.39	1.29	0.15	0.36	99	0.15	0.36	1.02	0.14	0.34	80	0.14	0.3	1.02	0.1	0.28
PE13	97	0.05	0.1	1.46	0.05	0.09	100	0.05	0.09	2.1	0.05	0.08	93	0.03	0.09	2.53	0.07	0.08
PE14													3	0.05	0.07	0.16	0.02	0.06
PE15													3	0.06	0.08	0.17	0.02	0.08
PE16													3	0.1	0.12	0.21	0.02	0.12

Table A. 3 (cont'd)

	Oct						Nov						Dec					
Site	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median	% of month	Min	Mean	Max	Std Dev	Median
PE01	100	0.05	0.16	1.71	0.07	0.15	94	0.04	0.17	1.88	0.09	0.15	100	0.05	0.18	0.74	0.09	0.16
PE02	100	0.23	0.68	6.06	0.33	0.62	92	0.1	0.78	8.14	0.87	0.51	98	0.09	0.77	8.17	0.9	0.55
PE03	100	0.04	0.1	1.12	0.05	0.08	93	0.04	0.12	4.29	0.19	0.09	100	0.04	0.11	1.01	0.06	0.09
PE04	100	0.06	0.11	1.75	0.05	0.1	93	0.05	0.11	2.93	0.12	0.09	100	0.06	0.11	0.57	0.05	0.09
PE05	100	0.03	0.06	0.29	0.02	0.06	94	0.03	0.06	0.96	0.03	0.06	100	0.03	0.06	1.45	0.05	0.06
PE06	100	0.05	0.08	0.37	0.02	0.07	60	0.06	0.08	0.59	0.02	0.07						
PE07	100	0.09	0.12	1.54	0.04	0.12	94	0.1	0.14	2.05	0.07	0.13	100	0.09	0.12	0.71	0.03	0.12
PE08	99	0.05	0.09	1.35	0.04	0.09	94	0.05	0.1	0.98	0.04	0.1	100	0	0.09	1.24	0.04	0.08
PE09	100	0.06	0.16	0.78	0.05	0.15	94	0.11	0.23	1.22	0.08	0.24	100	0.09	0.18	0.97	0.08	0.15
PE10																		
PE11																		
PE12																		
PE13	100	0.05	0.08	0.42	0.02	0.07	94	0.05	0.08	0.74	0.03	0.07	100	0.04	0.09	0.76	0.05	0.08
PE14	100	0.05	0.08	0.26	0.02	0.07	94	0.04	0.07	0.24	0.02	0.07	99	0.04	0.07	0.21	0.02	0.06
PE15	100	0.04	0.09	1.15	0.04	0.08	94	0.06	0.11	1.51	0.05	0.11	100	0.1	0.14	0.44	0.03	0.14
PE16	100	0.09	0.12	1.12	0.04	0.12	94	0.05	0.11	1.29	0.05	0.11	100	0.05	0.08	1.4	0.04	0.08

Table A. 4 Monthly aggregated daily statistics for Chlorophyll fluorescence time series collected by in-situ loggers. Unless indicated otherwise, all units are notionally in mg/m^3
% of month indicates temporal data coverage, Min = minimum of all data for that month, Max = maximum of all data for month, Std Dev = standard deviation of all data for month,

	Jan					Feb					Mar				
Site	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev
PE01	100	0.05	0.29	0.86	0.13	92	0.12	0.45	1.71	0.2	65	0.05	0.46	1.18	0.18
PE02	100	0.04	1.01	5.89	0.51	0					0				
PE03	100	0.01	0.19	0.92	0.14	36	0.02	0.24	0.77	0.14	16	0.08	0.37	0.94	0.18
PE04	100	0.07	0.22	0.64	0.1	92	0.02	0.27	0.76	0.14	63	0.04	0.28	0.97	0.13
PE05	100	0.1	0.41	2.17	0.18	74	0.11	0.38	3.36	0.16	66	0.09	0.47	1.2	0.17
PE06						53	0.12	0.45	1.25	0.16	63	0.1	0.49	1.28	0.17
PE07	100	0.17	0.46	1.45	0.13	93	0.15	0.46	1.37	0.14	63	0.17	0.48	1.28	0.16
PE08	76	0.23	0.5	15.63	0.44	57	0.18	0.49	1.53	0.16	65	0.13	0.42	1.76	0.17
PE09	100	0.14	0.51	3.08	0.2	93	0.13	0.93	10.38	0.89	63	0.34	1.42	8.81	0.83
PE10											13	0.16	0.69	1.38	0.27
PE11											15	0.18	0.43	0.96	0.16
PE12											15	0.04	0.26	0.74	0.12
PE13	100	0.18	0.58	2.65	0.23	93	0.13	0.47	3.04	0.26	64	0.19	0.61	1.73	0.19
PE14	100	0.13	0.48	2.05	0.2	93	0.12	0.52	8.16	0.41	50	0.24	0.66	7.35	0.29
PE15	100	0.09	0.31	1.22	0.17	90	0.14	0.42	2.36	0.2	50	0.19	0.61	2.08	0.22
PE16	77	0.07	0.36	1.7	0.15	57	0.13	0.43	1.02	0.12	50	0.1	0.45	1.04	0.13

Table A. 4 (cont'd)

	Apr					May					Jun				
Site	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev
PE01	100	0.02	0.42	1.69	0.24	77	0.03	0.41	1.71	0.31	100	0.03	0.23	0.96	0.12
PE02	0					0					0				
PE03	50	0.09	0.44	1.36	0.22	48	0.07	0.4	2.66	0.24	100	0.11	0.45	1.61	0.21
PE04	100	0.02	0.28	1.22	0.14	77	0.03	0.25	1.67	0.16	74	0.07	0.32	1.69	0.13
PE05	100	0.13	0.52	1.96	0.23	70	0.12	0.47	3.33	0.2					
PE06	99	0.05	0.41	1.3	0.18	75	0.06	0.38	1.19	0.15	100	0.18	0.41	1	0.13
PE07	100	0.12	0.49	1.66	0.21	80	0.13	0.49	1.58	0.22	100	0.22	0.52	1.65	0.16
PE08	100	0.06	0.45	1.32	0.19	80	0.09	0.53	1.79	0.29	100	0.15	0.4	1.39	0.13
PE09	50	0.18	0.61	1.56	0.26	50	0.13	0.44	1.54	0.21	100	0.13	0.36	1.1	0.12
PE10	50	0.22	0.6	3.28	0.2	50	0.19	0.53	6.13	0.27	99	0.25	0.63	11.12	0.55
PE11	50	0.16	0.51	1.36	0.19	50	0.1	0.44	1.5	0.17	100	0.14	0.44	1.29	0.15
PE12	50	0.02	0.25	0.88	0.13	50	0.07	0.35	0.95	0.15	100	0.09	0.37	0.97	0.16
PE13	100	0.15	0.74	1.66	0.26	81	0.13	0.47	1.76	0.17	100	0.25	0.59	1.39	0.17
PE14	3	0.6	0.91	1.68	0.17						100	0.03	0.23	0.96	0.12
PE15	50	0.14	0.58	2.68	0.29	28	0.14	0.41	1.83	0.16	100	0.04	0.29	3.13	0.17
PE16	50	0.08	0.37	1.04	0.17	28	0.14	0.32	1.04	0.11	100	0.11	0.45	1.61	0.21

Table A. 4 (cont'd)

Site	Jul					Aug					Sep				
	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev
PE01	93	0.06	0.32	1.17	0.17	100	0.02	0.36	1	0.2	97	0.16	0.51	1.17	0.17
PE02	91	0.06	0.34	2.9	0.22	100	0.03	0.38	1.22	0.26	96	0.19	0.81	9.4	0.84
PE03	97	0.11	0.51	7.73	0.41	100	0.1	0.51	1.48	0.2	97	0.03	0.46	1.88	0.23
PE04	13	0.16	0.46	1.06	0.17	100	0.13	0.53	1.2	0.18	94	0.05	0.44	1.13	0.17
PE05	16	0.06	0.18	0.44	0.05	100	0.02	0.34	0.84	0.14	97	0.14	0.45	1.08	0.14
PE06	97	0.15	0.4	0.98	0.12	100	0.16	0.44	0.96	0.14	96	0.13	0.4	0.94	0.14
PE07	97	0.16	0.44	1.35	0.14	100	0.18	0.55	1.06	0.15	97	0.14	0.49	1.06	0.15
PE08	96	0.15	0.46	1.33	0.18	100	0.2	0.53	1.04	0.12	96	0.14	0.52	0.96	0.15
PE09	97	0.11	0.33	1.38	0.11	100	0.15	0.47	1.19	0.16	96	0.2	0.65	1.38	0.19
PE10	96	0.13	0.57	6.79	0.29	100	0.18	0.56	1.4	0.18	83	0.23	0.74	1.43	0.17
PE11	73	0.2	0.5	1.53	0.14	100	0.17	0.6	1.38	0.2	80	0.22	0.71	1.41	0.19
PE12	97	0.15	0.45	1.15	0.19	100	0.12	0.44	1.19	0.17	80	0.11	0.37	0.96	0.13
PE13	97	0.22	0.56	1.97	0.17	100	0.18	0.64	3.15	0.23	93	0.36	0.85	2.93	0.25
PE14	93	0.06	0.32	1.17	0.17	100	0.02	0.36	1	0.2	3	0.19	0.39	0.83	0.11
PE15	91	0.06	0.34	2.9	0.22	100	0.03	0.38	1.22	0.26	3	0.38	0.7	1.22	0.19
PE16	97	0.11	0.51	7.73	0.41	100	0.1	0.51	1.48	0.2	3	0.23	0.44	0.71	0.12

Table A. 4 (cont'd)

Site	Oct					Nov					Dec				
	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev	% of month	Min	Mean	Max	Std Dev
PE01	100	0.07	0.42	1.23	0.18	94	0.04	0.54	1.71	0.25	99	0.05	0.42	1.21	0.24
PE02	100	0.51	1.37	7.02	0.55	91	0.49	4.13	23.24	3.57	98	0.01	4.19	23.37	3.98
PE03	100	0.03	0.36	1.34	0.2	94	0.01	0.35	1.36	0.21	99	0.01	0.27	1.2	0.22
PE04	100	0.04	0.24	0.68	0.11	94	0.03	0.18	0.69	0.07	100	0.05	0.18	0.64	0.09
PE05	100	0.11	0.45	1.09	0.15	94	0.15	0.43	1.13	0.15	100	0.08	0.42	4.74	0.24
PE06	100	0.09	0.53	1.27	0.19	60	0.2	0.62	1.91	0.25					
PE07	100	0.17	0.47	1.32	0.14	94	0.14	0.48	4.97	0.26	100	0.12	0.48	1.52	0.19
PE08	99	0.04	0.32	0.96	0.13	94	0.11	0.4	1.5	0.17	100	0	0.48	2.2	0.2
PE09	100	0.21	0.62	1.32	0.18	94	0.2	0.57	2.49	0.18	97	0.19	0.98	3.11	0.59
PE10															
PE11															
PE12															
PE13	100	0.35	0.78	1.83	0.21	94	0.28	0.88	2.51	0.29	98	0.23	1.14	3.21	0.64
PE14	100	0.14	0.42	0.88	0.12	94	0.19	0.51	1.43	0.15	98	0.15	0.79	2.3	0.41
PE15	100	0.17	0.71	2.69	0.26	94	0.06	0.58	2.27	0.32	99	0.04	0.34	1.26	0.21
PE16	100	0.08	0.41	1.02	0.13	94	0.09	0.38	1.04	0.15	100	0.08	0.38	2.11	0.17

Table A. 5 Monthly aggregated daily statistics for PAR time series collected by in-situ loggers.

Unless indicated otherwise, all units are notionally in mmol/ ph/m^2/s

% of month indicates temporal data coverage, Max = maximum of all data for month, Mean Daily Range = arithmetic mean of the daily temperature ranges (daily max – daily min),

	Jan			Feb			Mar			Apr			May			Jun		
Site	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max
PE01	100	207.92	132.01	39	164.85	92.37	15	245.7	186.04	50	251.9	173.86	50	212.19	153.63	100	244.39	166.61
PE02	99	124.54	81.43	29	94.25	51.01	16	69.33	51.68	50	73.49	48.7	50	73.98	47.58	100	58.05	42.85
PE03	100	714.1	545.17	93	610.12	280.61	66	444.52	301.48	100	430.19	341.48	73	418.64	273.99	100	222.22	159.57
PE04	100	239.61	173.73	93	263.41	159.67	63	264.22	198.29	100	264.83	201.73	77	263.61	189.25	83	227.09	161.36
PE05	100	218.72	143.11	89	201.49	108.94	66	169.37	126.88	99	169.3	120.33	72	144.4	97.62	100	91.02	71.51
PE06	100	207.61	133.34	33	152.45	74.73	13	114.44	100.68	50	118.01	89.76	50	116.77	80.37	100	84.31	63.99
PE07	100	183.92	127.27	94	197.1	99.35	63	149.67	109.69	99	167.14	119.15	81	100.05	73.44	100	66.85	54.22
PE08				57	168.72	106.8	64	192.61	145.15	99	193.76	146.65	81	149.07	92.75	100	99.77	75.47
PE09	99	106.18	77.12	29	86.59	59.91	16	75.4	60.29	49	82.57	74.01	50	57.19	35.29	100	45.4	34.32
PE10							13	70.12	61.36	49	70.18	56.29	50	58.3	36.84	100	50.22	35.97
PE11							14	115.21	89.6	50	115.28	92.86	50	95.12	60.29	100	88.76	65.29
PE12							14	291.91	267.67	50	286.15	208.14	50	209.28	169.73	100	239.93	159.41
PE13				64	80.88	57.58	63	84.65	66.56	100	80.92	54.91	81	80.09	34.14	100	43.93	30.69
PE14																		
PE15	100	125.91	87.91	33	110.88	63.54												
PE16				56	117.02	77.86	50	118.39	82.6	11	119.3	105.51						

Table A. 5 (cont'd)

Site	Jul			Aug			Sep			Oct			Nov			Dec		
	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max	% of month	Max	Mean Daily Max
PE01	94	224.36	157.96	100	260.7	155.01	96	258.21	171.13	100	277.56	185.25	94	287.14	194.65	99	208.68	158.54
PE02	91	106.92	54.98	100	101.41	75.91	97	98.49	60.67	100	134	94.13	94	137.22	77.21	99	126.27	73.89
PE03	97	262.9	172.73	100	311.15	236.6	97	418.96	299.45	100	351.56	261.87	94	629.24	364.95	100	724.86	505.08
PE04	97	194.54	136.76	100	102.19	74.73	94	219.01	106.11	100	375.09	269.16	94	389.6	269.12	100	249.45	185.53
PE05	98	92.72	66.35	100	93.31	72.25	98	177.92	97.54	100	213.42	153.56	94	220.44	137.35	99	218.72	158.25
PE06	97	88.1	58.49	100	112.27	79.67	83	156.57	123.17				33	185.83	125.86	100	208.24	154.24
PE07	97	106.32	52.82	100	130.7	94.74	96	170.48	124.51	100	157.23	121.97	94	193.13	132.29	99	197.25	140.2
PE08	97	109.66	67.37	100	133.08	86.65	97	158.62	114.5	100	194.47	128.91	68	167.69	125.18			
PE09	97	58.69	41.09	100	67.7	38.39	97	70.16	46.88	100	98.47	72.4	94	108.01	66.24	100	107.26	63.76
PE10	97	66.29	42.22	100	61.77	36.45	84	66.27	46.75									
PE11	73	81.34	48.05	100	45.37	31.48	80	52.66	37.62									
PE12	97	252.48	164.28	100	220.4	157.94	80	319.49	229.8									
PE13	97	54.31	37.54	100	60.55	42.79	94	70.81	47.03	100	83.61	66.26	71	99.63	73.49			
PE14							3	49.8	49.8	100	64.73	45.47	93	60.22	44.93	92	60.73	52.67
PE15							3	78.45	78.45	100	118.51	78.46	94	120.59	76.94	100	125.86	85.17
PE16							3	99.79	99.79	100	168.49	125.09	67	184.17	108.42			