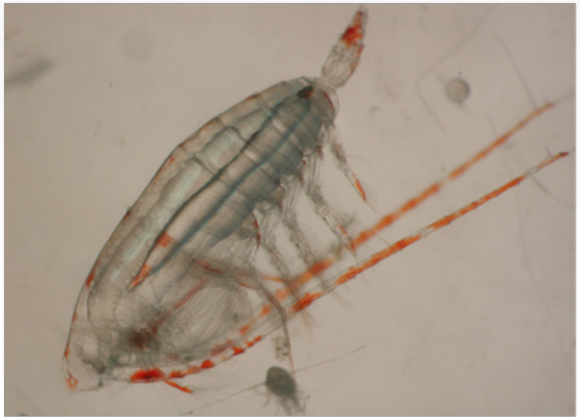
Ocean Conditions and Forecasting Salmon Returns: how variability in ocean conditions affects salmon survival

Bill Peterson
Senior Scientist
NOAA Fisheries
Hatfield Marine Science Center
Newport Oregon



See www.nwfsc.noaa.gov, "Ocean Conditions and Salmon Forecasting"

Some First Principles

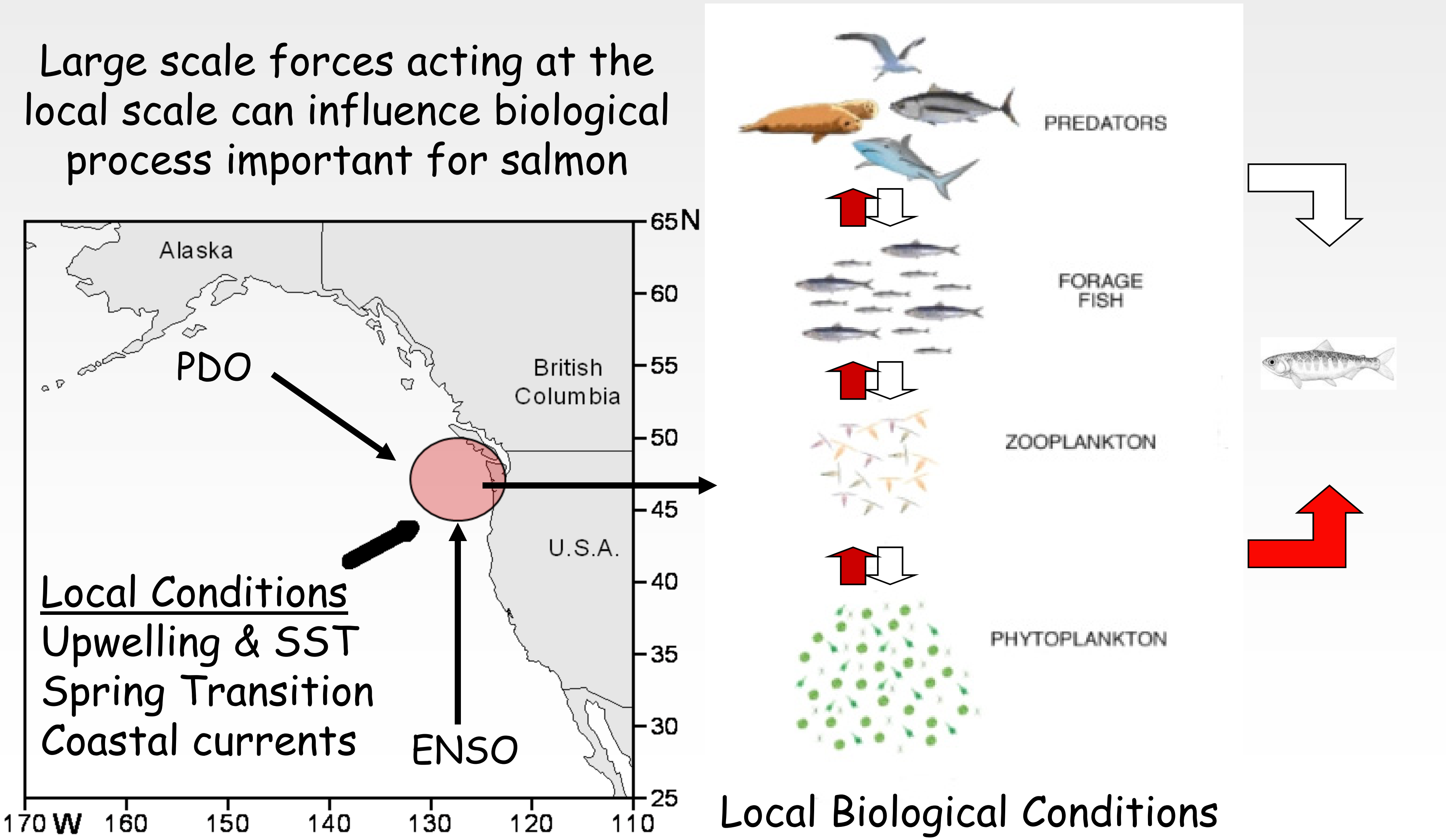
- A common perception is that salmon leave the rivers and enter a black box (the ocean) and magically (and luckily) they return after being away for a year or two (or more).
- Rates of return from the ocean are quite variable among years, and results are often filled with many surprises.
- After 14 years of research we think we have worked out what it is about ocean conditions that leads to variable returns.
- And, we have gone boldly where others have gone before, and now provide outlooks on the rates of returns of salmon to rivers.

Salmon are goal-oriented species with few needs

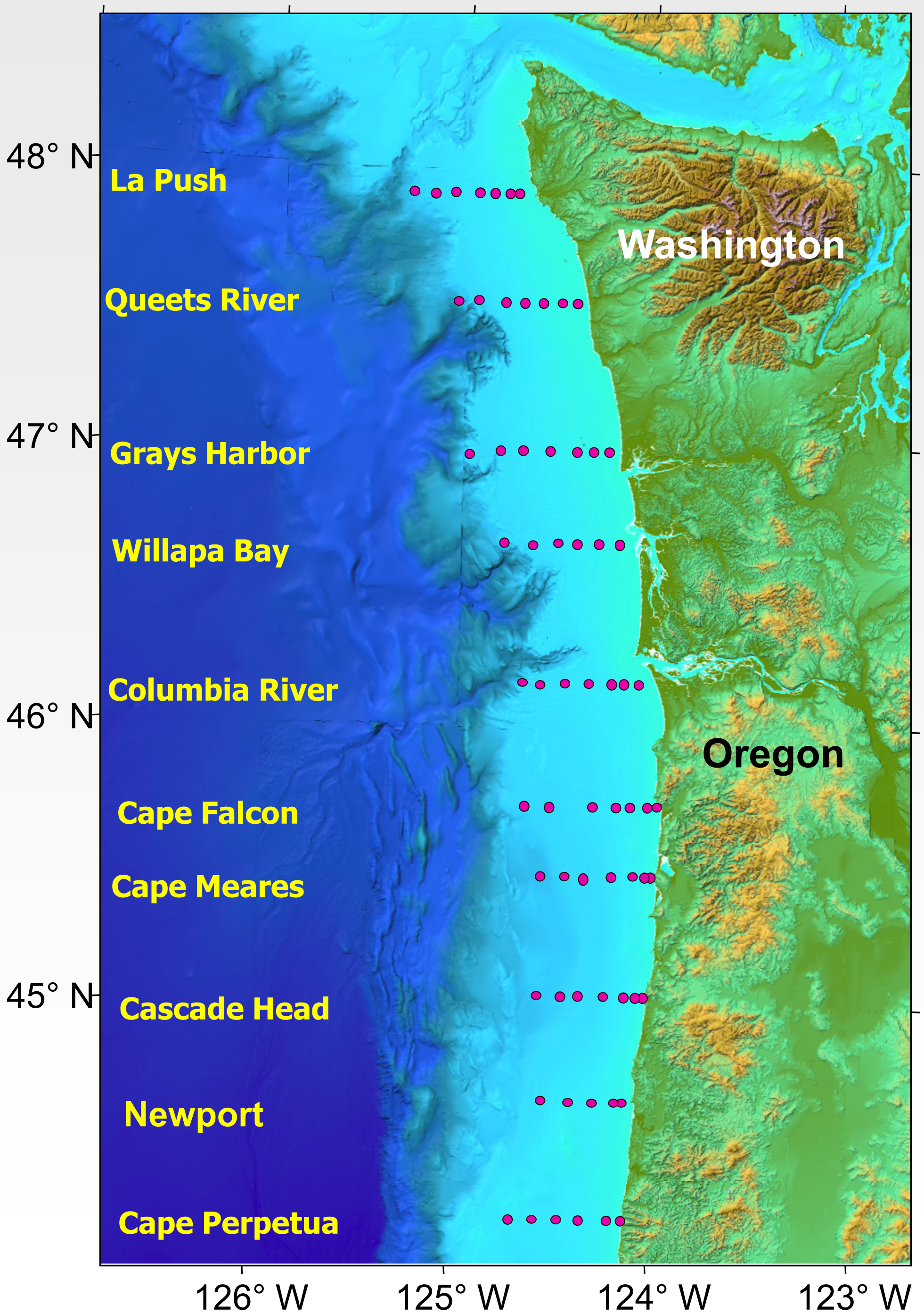
- They want to get to the ocean to fatten up
- They want to return home to spawn
- Along the way they have simple requirements…
  - Find something to eat
  - Avoid being eaten

We are contributing to salmon management by studying the ocean phase of their life history and by developing management advice based on a suite of physical, biological and ecological indicators of ocean conditions

Large scale forces acting at the local scale can influence biological process important for salmon



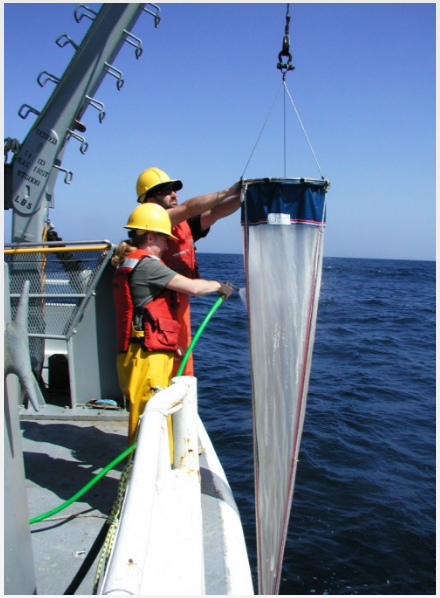
Observations

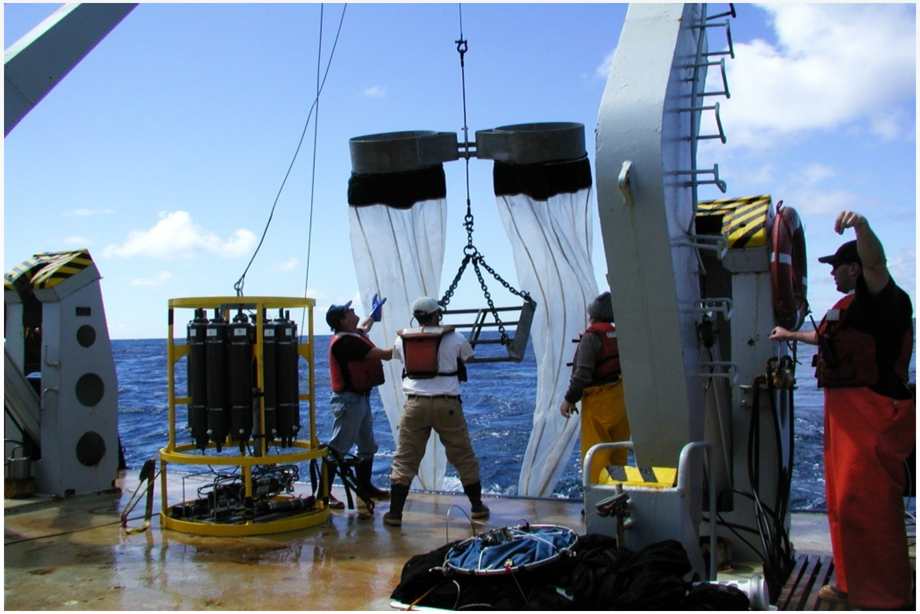


- Newport Line biweekly sampling since 1996 (15th year)
- Juvenile salmon sampling in June and September since 1998 (13th year)
- Historical data:
  - hydrography, 1960s;
  - plankton, 1969-1973; 1983, 1990-1992
  - juvenile salmon, 1981-1985

Sampling methods

- Copepods with ½ m diameter 200 μm mesh net towed vertically from 100 m
- Krill with 70 cm 333 μm mesh Bongo net towed obliquely
- Salmon with pelagic rope trawl, Nordic 264 from NET Systems





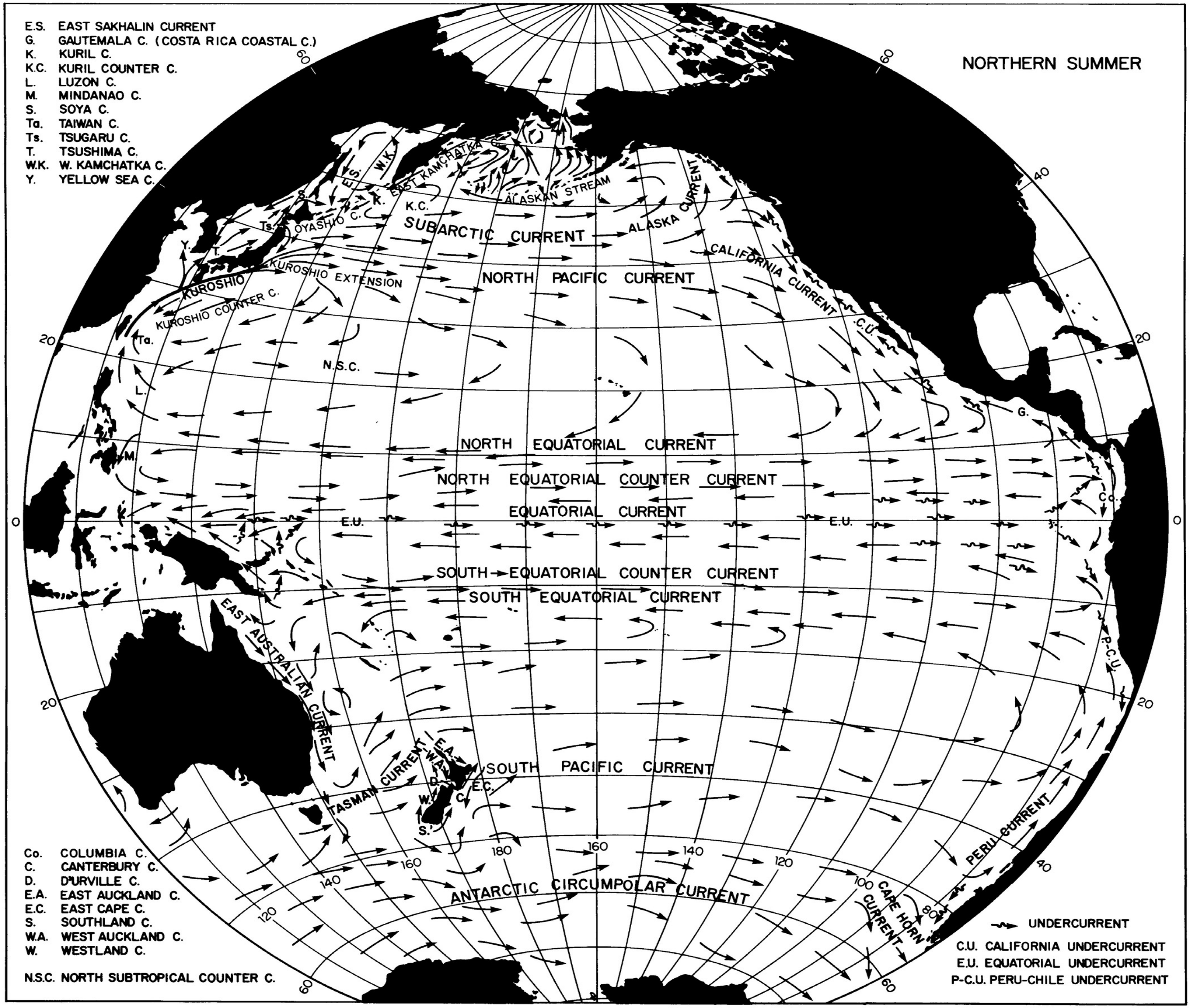
Here are some images of two types of plankton, copepods and krill, that play key roles in a salmon's food web

Four factors affect plankton, food chains, pelagic fish and the growth and survival of salmon in the northern California Current

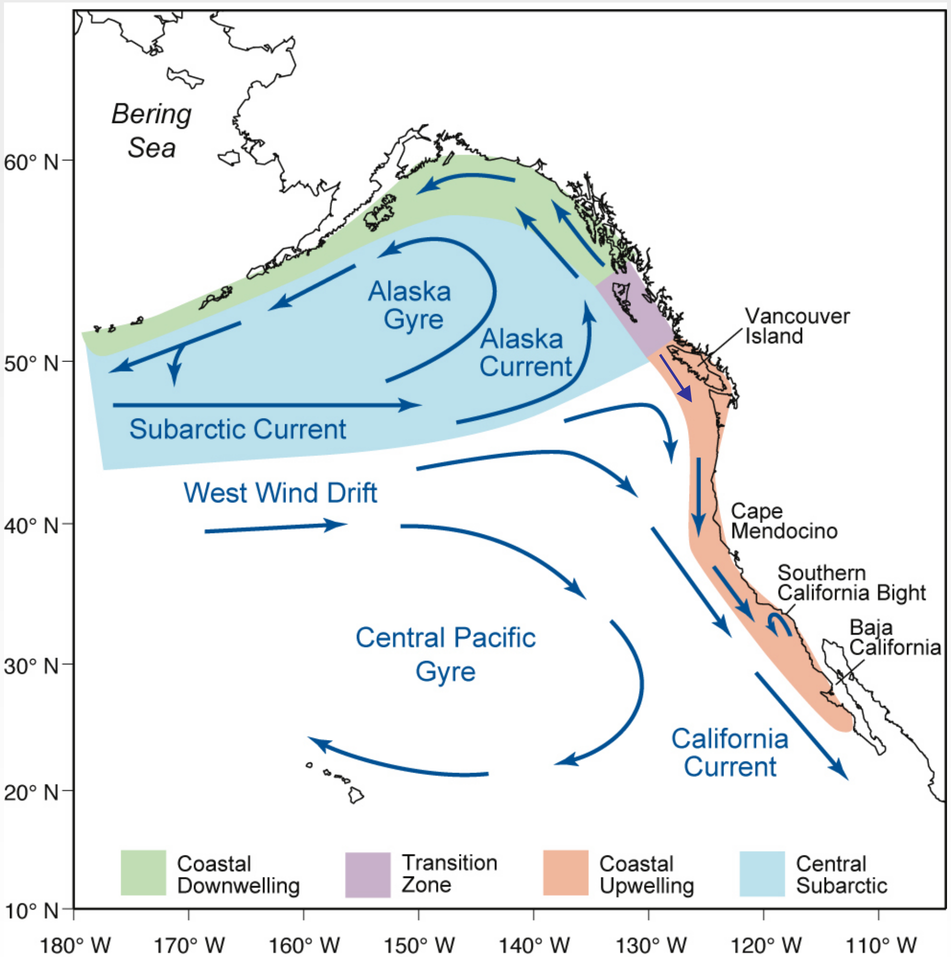
- Large-scale circulation patterns and the kinds of water that feed the California current
- Seasonal reversal of coastal currents: southward in summer – northward in winter
- Coastal Upwelling
- Phase of the Pacific Decadal Oscillation (PDO)

Everything is on the the web at:
http://www.nwfsc.noaa.gov
“Ocean Conditions and Salmon Forecasting”

Oceanography 101



Circulation off the Pacific Northwest

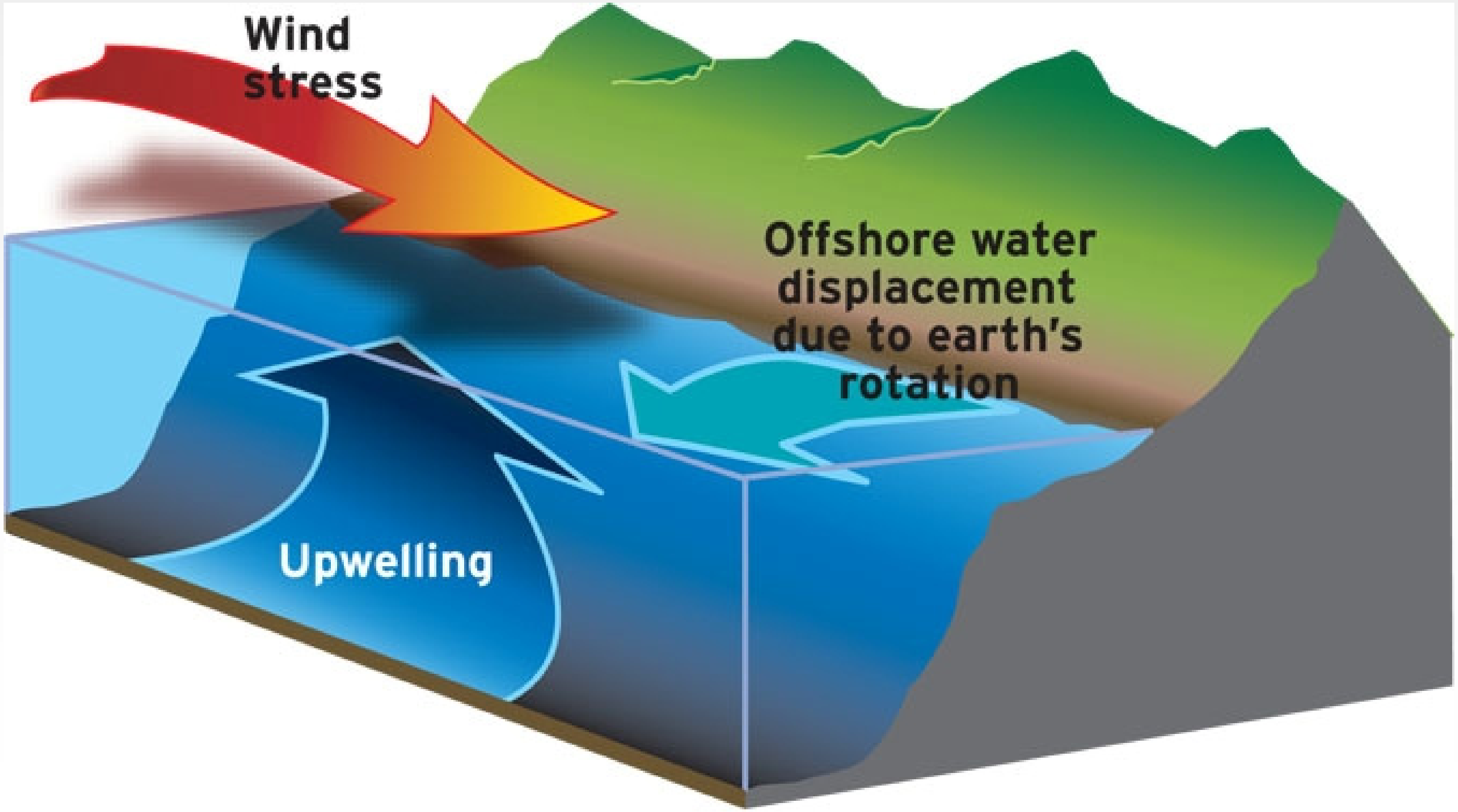


Subarctic Current brings cold water and northern species to the N. California Current;

The West Wind Drift brings subtropical water and subtropical species to the N. California Current

Therefore, ecosystem structure is affected by the source waters which feed the California Current.

Local winds drive currents and cause upwelling along the coasts of Washington, Oregon and California



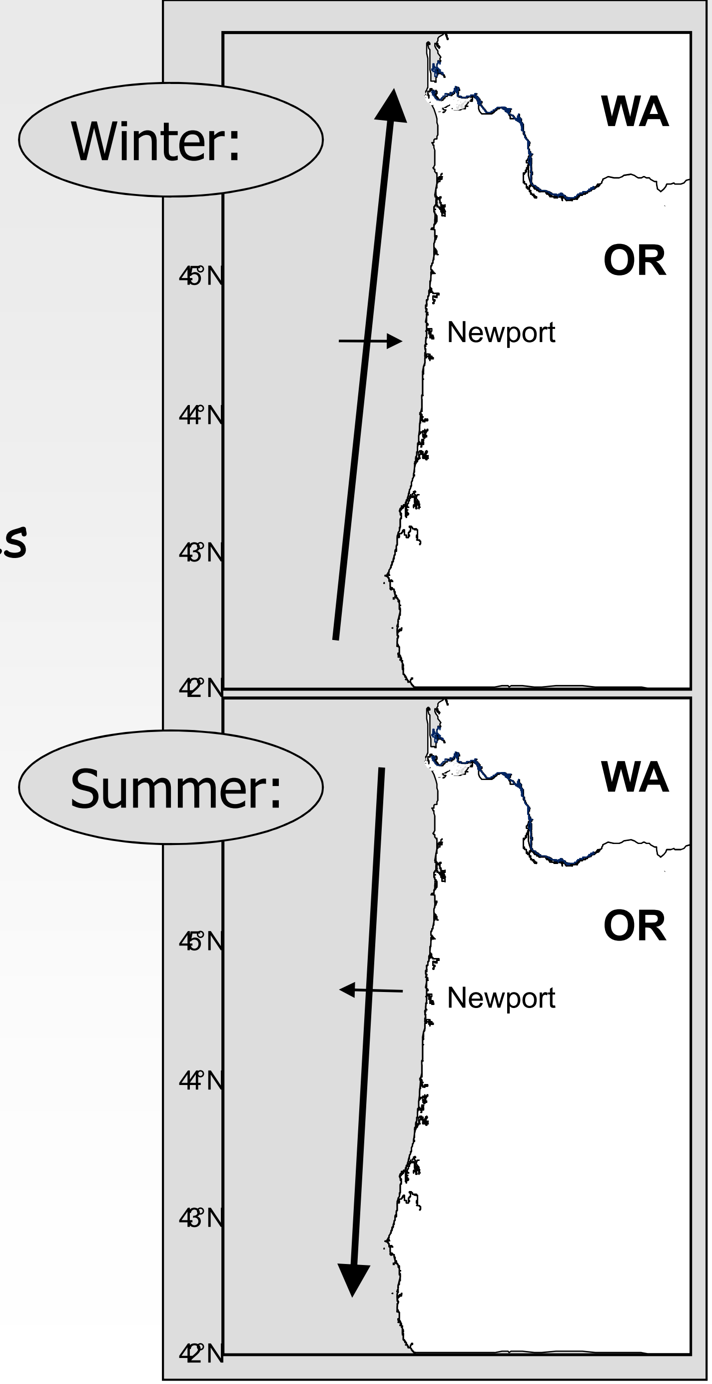
Winds and current structure off coastal Oregon:

- Winter:
  - Winds from the South
  - Downwelling
  - Poleward-flowing Davidson Current
  - Subtropical and southern plankton species transported northward & onshore
  - Many fish spawn at this time

•Spring Transition in April/May

- Summer:
  - Strong winds from the North
  - Coastal upwelling
  - Equatorward alongshore transport
  - Boreal/northern species transported southward

•Fall Transition in October

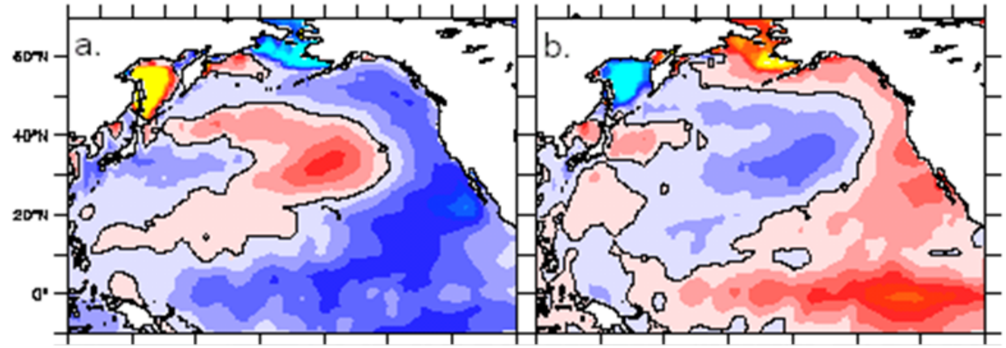


PDO & SST

The PDO has two phases, resulting from the direction from which winds blow in winter.

The SST anomaly patterns shown on the right results from basin scale winds: W'ly and NW'ly [negative phase] and SW'ly [positive phase]

Westerlies dominated during winter 07-08; SW'ly winter 09-10.



Negative Phase	Positive Phase
1948-1976	1925-1947
1998-2002	1976-1998
2006-	2003-2006

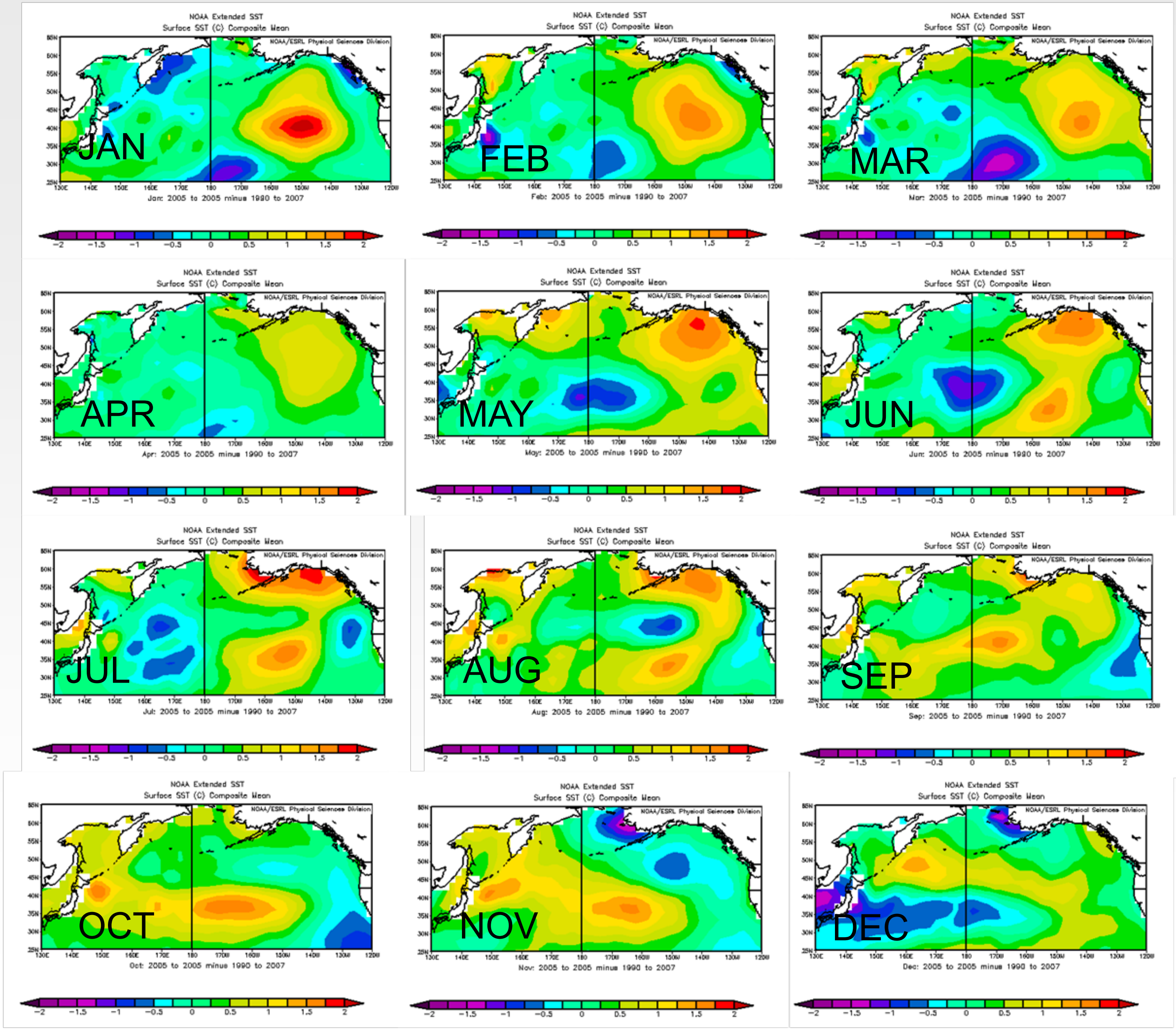
Blue is anomalously cold
Red is anomalously warm

PDO and SST
Two Recent and Contrasting Years

- 2005. The year that resulted in collapse of the Sacramento Fall Chinook run.

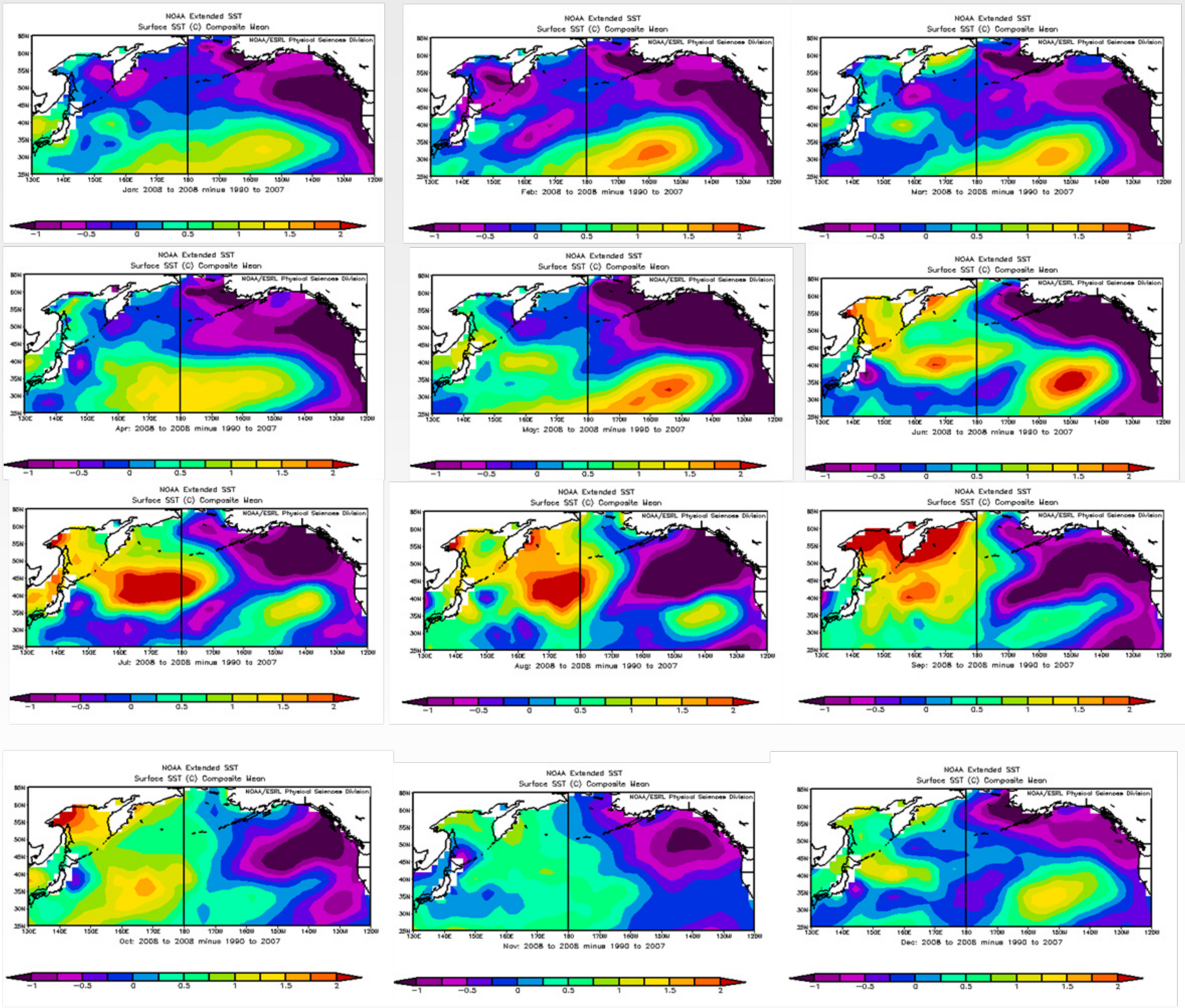
- 2008. The year that resulted in near-record returns of spring and fall Chinook, coho, steelhead and sockeye to the Columbia and other rivers of the Pacific Northwest this year (2010).

2005

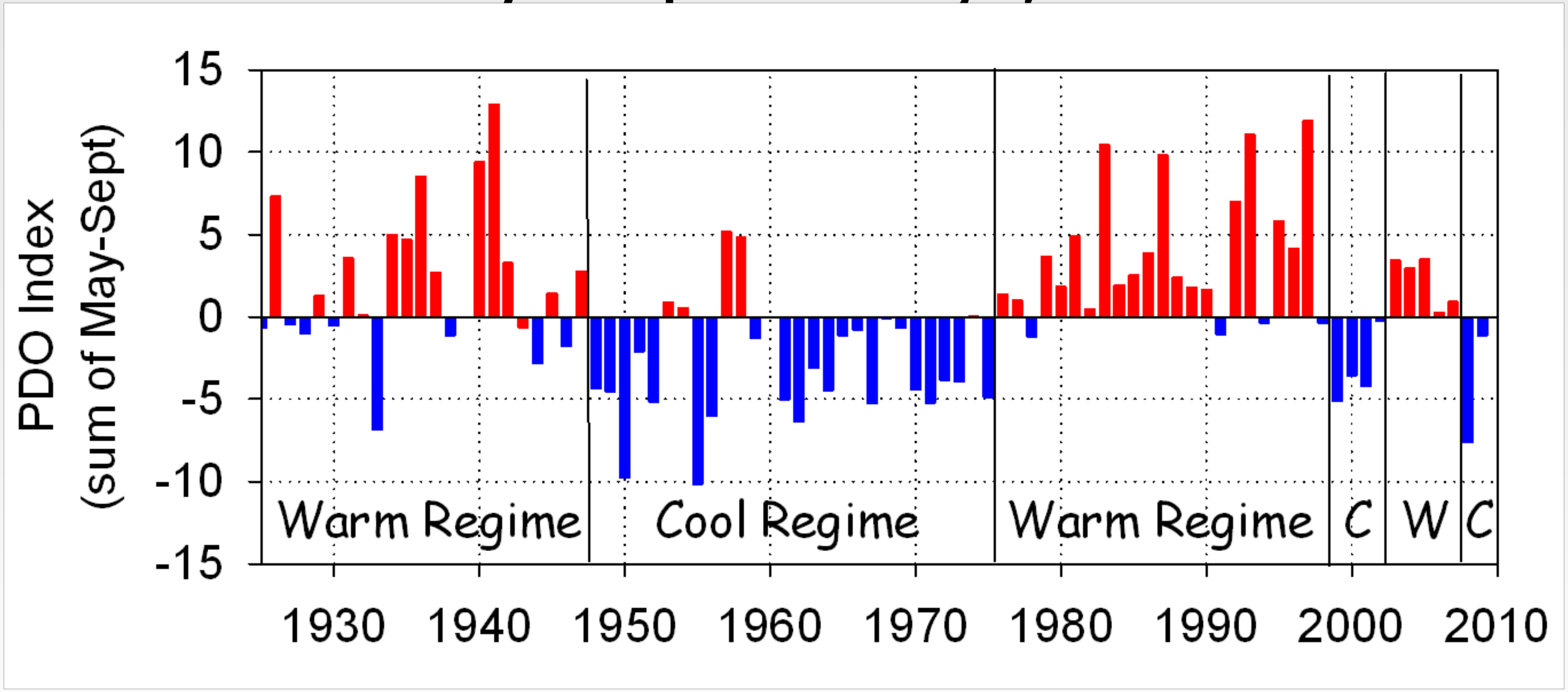

NOAA Extended SST
Surface SST (C) Composite Mean
NOAA/ESRL Physical Sciences Division
JAN
Jan: 2005 to 2005 minus 1990 to 2007
FEB
Feb: 2005 to 2005 minus 1990 to 2007
MAR
Mar: 2005 to 2005 minus 1990 to 2007
APR
Apr: 2005 to 2005 minus 1990 to 2007
MAY
May: 2005 to 2005 minus 1990 to 2007
JUN
Jun: 2005 to 2005 minus 1990 to 2007
JUL
Jul: 2005 to 2005 minus 1990 to 2007
AUG
Aug: 2005 to 2005 minus 1990 to 2007
SEP
Sep: 2005 to 2005 minus 1990 to 2007
OCT
Oct: 2005 to 2005 minus 1990 to 2007
NOV
Nov: 2005 to 2005 minus 1990 to 2007
DEC
Dec: 2005 to 2005 minus 1990 to 2007
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2

2008 – very cold throughout the California Current

2008



PDO: May-Sep Average, 1925-2009

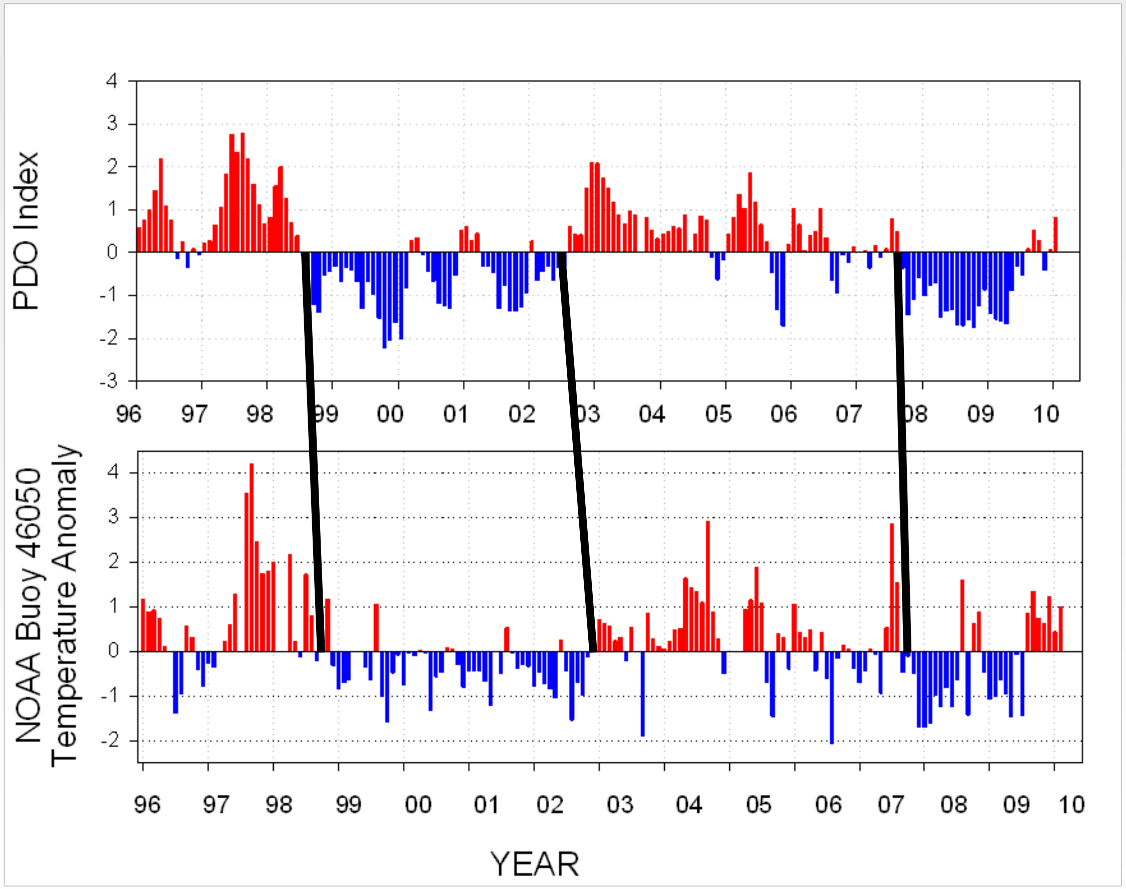


- From 1925-1998, PDO shifted every 20-30 years. Some refer to these as "salmon" regimes (cool) and "sardine" regimes (warm).
- However, we have had two shifts of four years duration recently: 1999-2002 and 2003-2006, and another shift in late 2007, thus we have a natural experiment to test the affects of PDO on marine food chains and salmon populations.
- Note 2008: most negative PDO since 1950s!!

Interannual variations

- Source waters: variations and their causes largely unknown
- Upwelling varies in terms of date of onset, length of season, and strength of winds
- Seasonal reversals in currents related to the upwelling/downwelling seasons
- Phase of the PDO – used to be decadal now more like semi-decadal

14 year time series of SST off Newport shows that PDO downscales to local SST

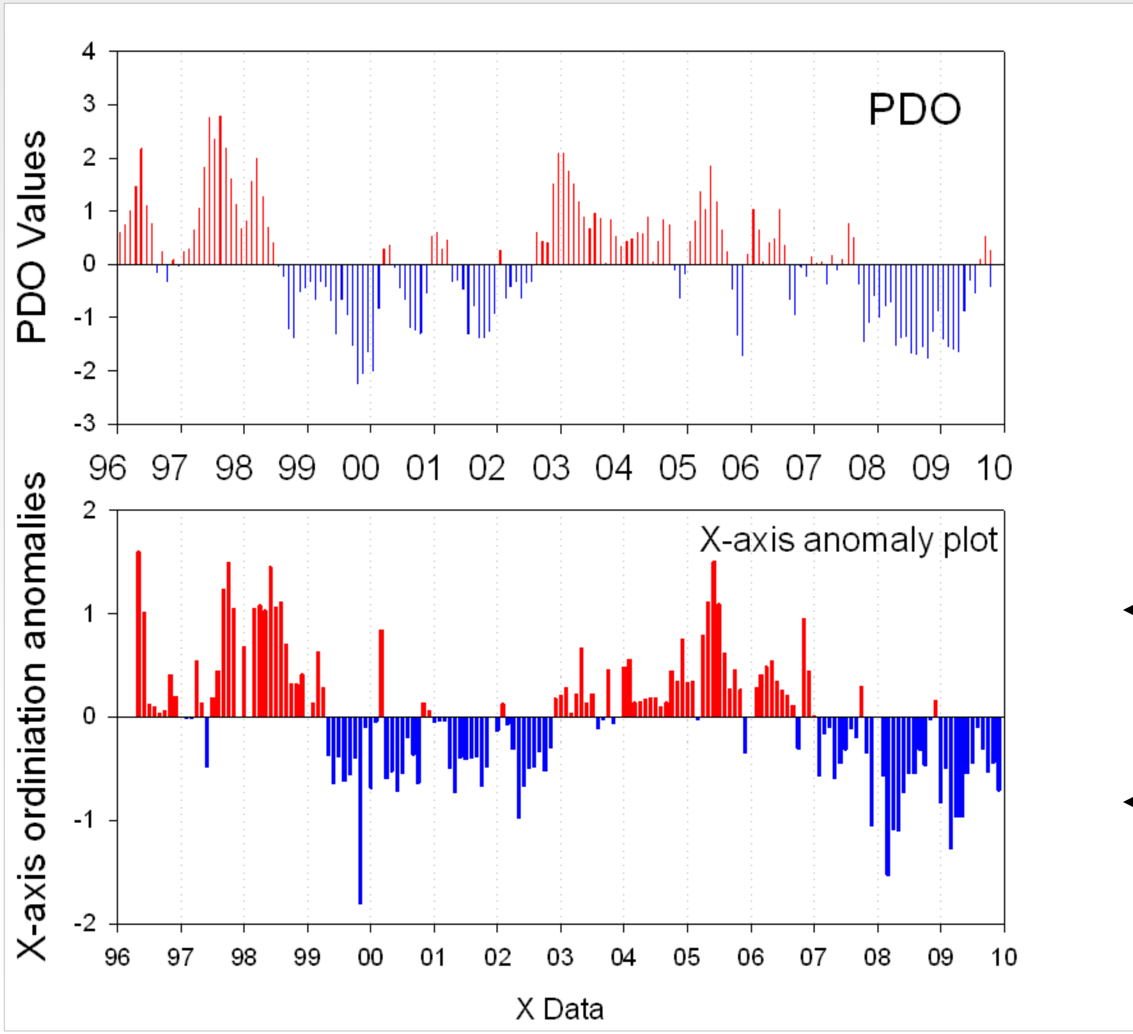


Temperature differences usually ± 1°C

- PDO and SST correlated, as they should be.
- Note the three recent periods of persistent sign changes: mid-1999, mid-2003 and mid-2007
- However there are time lags between PDO sign change and SST response of ~ 3-5 months, suggesting perhaps that the PDO is an advective signal along the Oregon coast

PDO and zooplankton: copepod community composition

As I said earlier, the sign of the PDO is associated with either warm or cold water being advected to the coast



As a consequence you get "warm" and "cold" water zooplankton communities in coastal waters in association with positive or negative phase of the PDO, but with a few months lag

Warm water community

Cold water community

Contrasting Communities

- **Negative PDO = "cold-water" copepod species.** These are dominants in Bering Sea, coastal GOA, coastal northern California Current
  - *Pseudocalanus mimus, Calanus marshallae, Acartia longiremis*
- **Positive PDO = "warm-water" copepods.** These are common in the Southern California Current neritic and offshore NCC waters
  - *Clausocalanus spp., Ctenocalanus vanus, Paracalanus parvus, Mesocalanus tenuicornis, Calocalanus styliremis*

Based on Peterson and Keister (2003)

Comparisons in size and chemical composition

- **Warm-water taxa** - (from offshore OR) are **small** in size and have minimal high energy wax ester lipid depots

- **Cold-water taxa** – (boreal coastal species) are **large** and store high-energy **wax esters** as an over-wintering strategy

Therefore, significantly different food chains may result from climate shifts;

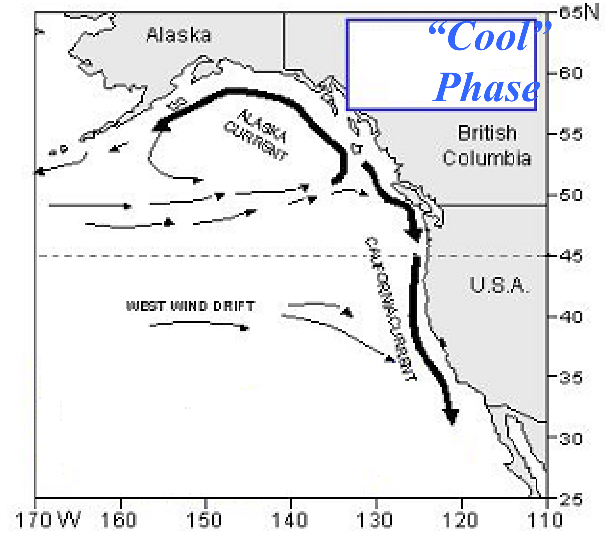
A working mechanistic hypothesis: source waters. . .

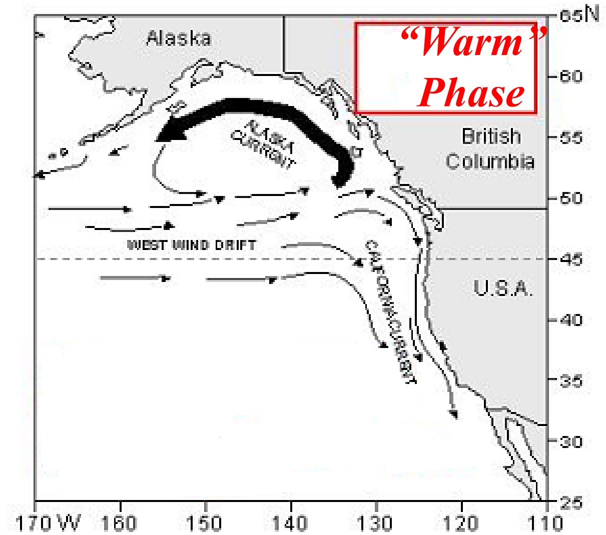
Cool Phase →

Transport of boreal coastal copepods into NCC from Gulf of Alaska

Warm Phase →

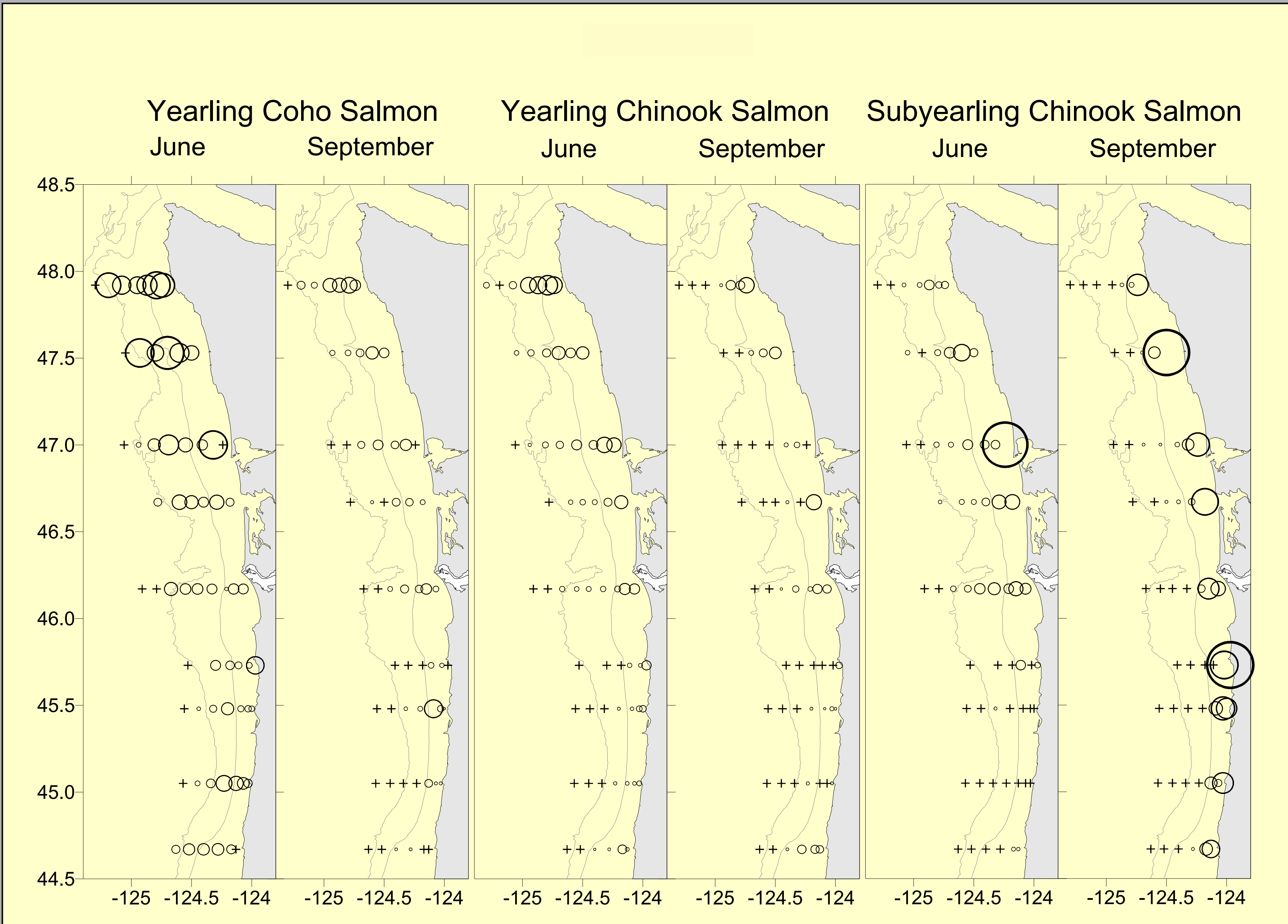
Transport of sub-tropical copepods into NCC from Transition Zone offshore

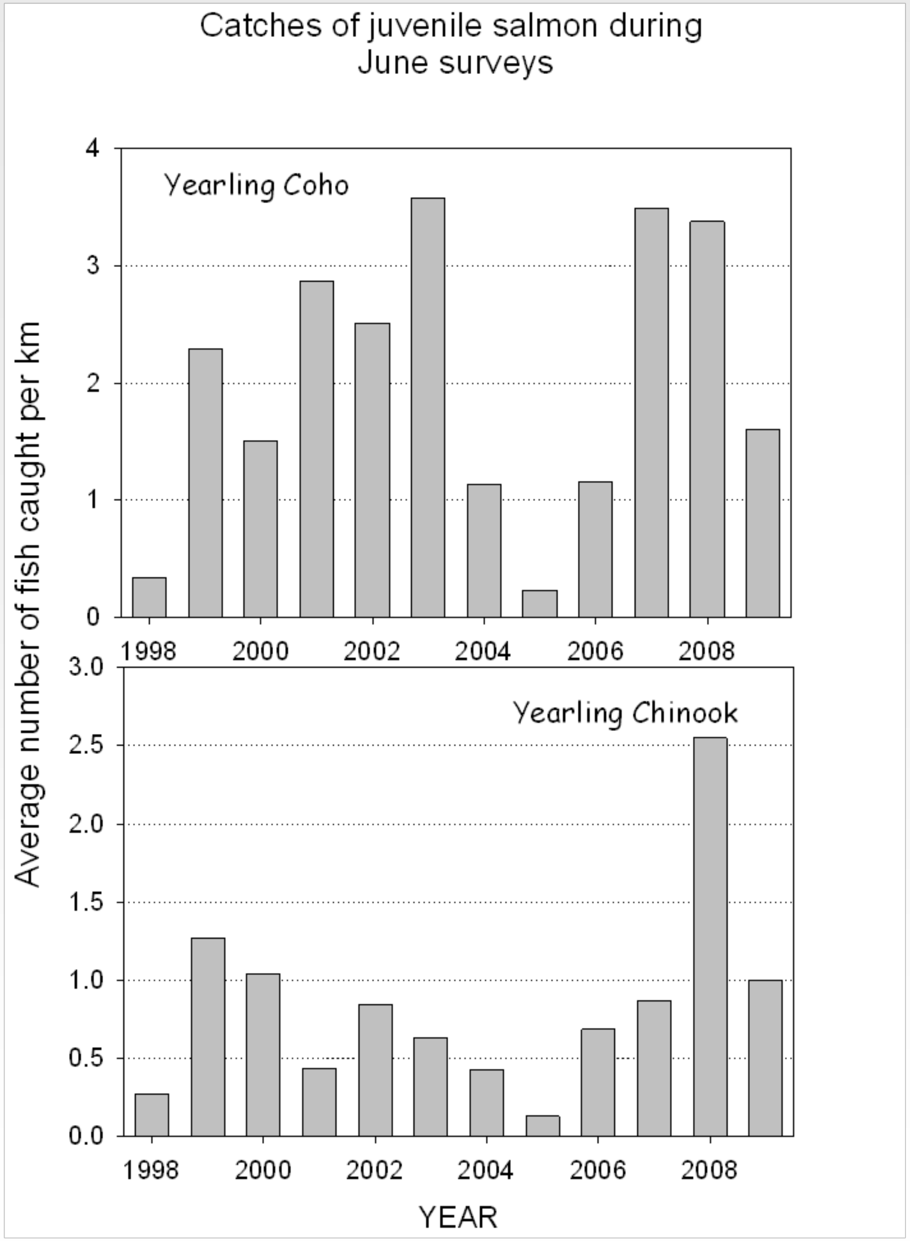




Salmon Habitat and Forecasting

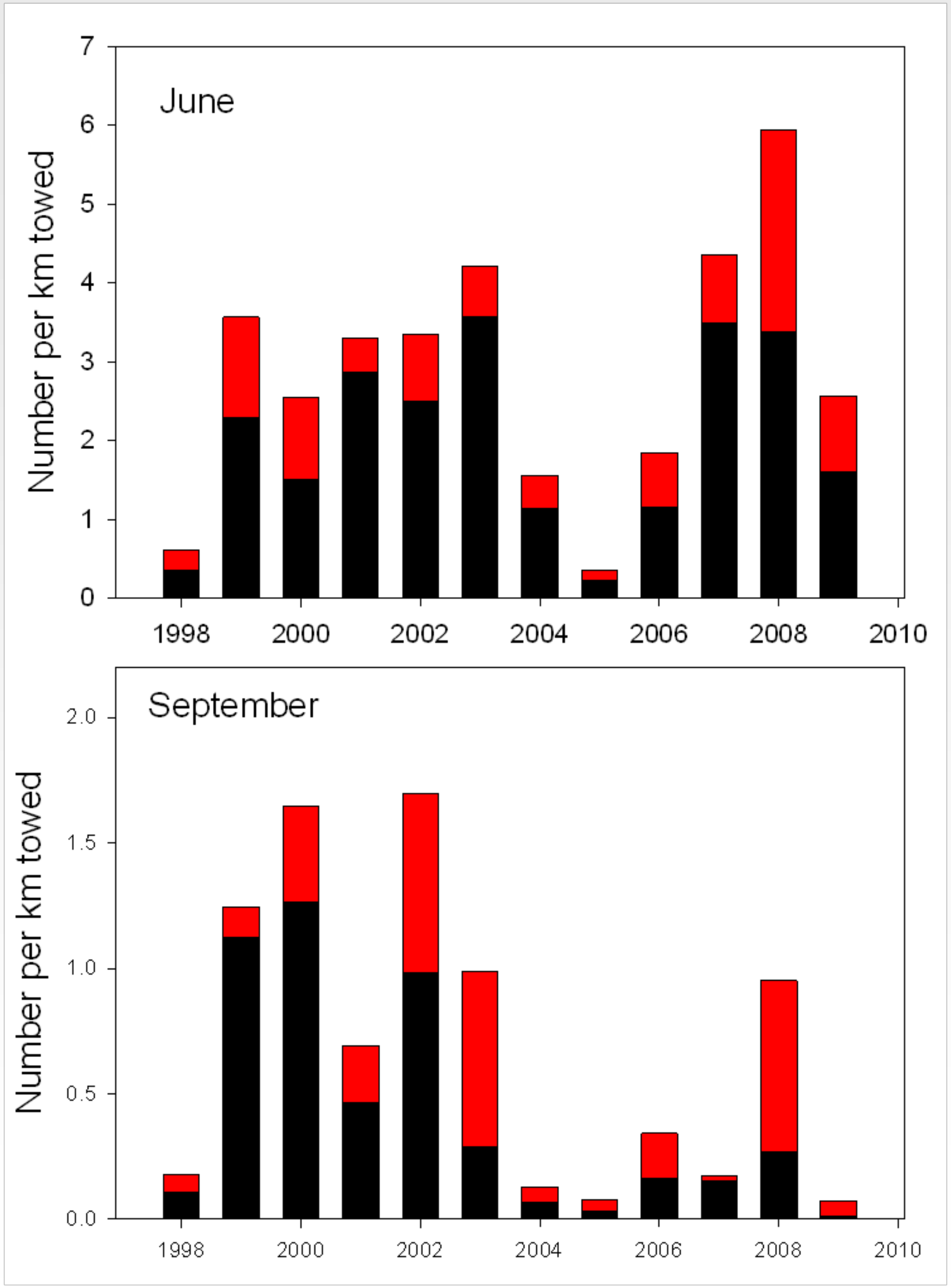
- In order to forecast returns of various salmon life history types, we must first establish where they live in the ocean.
- We have done this from our coastal surveys in May, June and September since 1998


Yearling Coho Salmon
Yearling Chinook Salmon
Subyearling Chinook Salmon
June
September
June
September
June
September
48.5
48.0
47.5
47.0
46.5
46.0
45.5
45.0
44.5
-125
-124.5
-124



Catches of juvenile salmon in rope trawl surveys

- Highest catches of spring Chinook in 2008, by a factor of 2.4; 2009 and 2010 were average
- High catches of coho in 2007 and 2008 but nothing special in 2009 and 2010



Salmon catches in pelagic trawl surveys: June & September

Forecasting -- since we know that juvenile salmon live in continental shelf waters, we use indices relevant to shelf waters

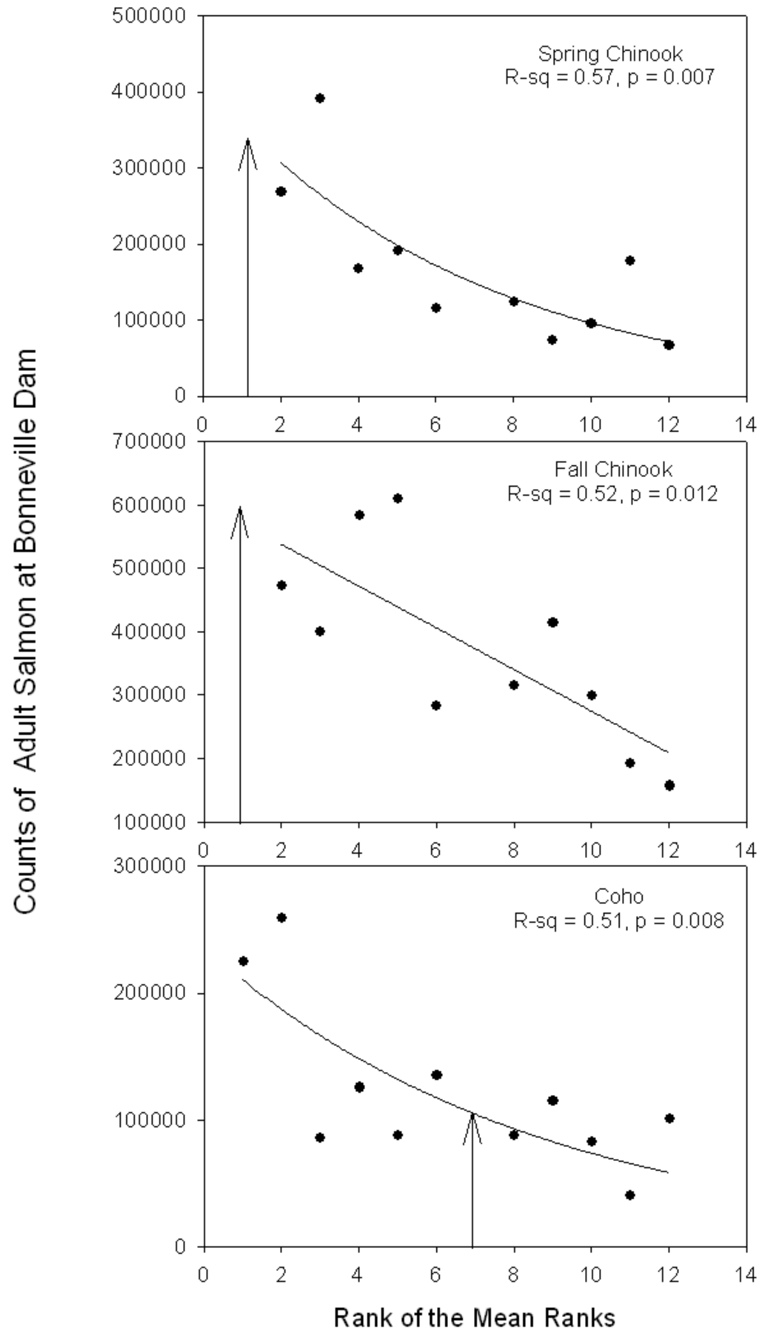
- Basin scale indicators
  - PDO
  - MEI
- Local indicators
  - SST
  - Upwelling
  - Date of spring transition
  - Length of upwelling season
- Biological indicators
  - Copepod biodiversity
  - N. copepod biomass anomaly
  - Copepod Community Structure
  - Catches of spring Chinook in June
  - Catches of coho in September

Indicator Values

		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
PDO (December-March)		5.07	-1.75	-4.17	1.86	-1.73	7.45	1.85	2.44	1.94	-0.17	-3.06	-5.41
PDO (Sum May-September)		0.9	-5.54	-3.23	-2.95	-0.47	3.42	2.21	3.94	0.28	0.18	-6.08	-1.11
MEI Annual		0.87	-0.85	-0.51	-0.18	0.59	0.46	0.38	0.40	0.22	-0.20	-0.65	0.32
MEI Jan-June		2.28	-0.80	-0.63	-0.28	0.32	0.55	0.27	0.65	-0.42	0.49	-0.84	-0.23
SST 46050	deg C	13.70	13.14	12.54	12.56	12.30	12.92	14.59	13.43	12.60	13.88	12.5	13.02
SST NH 05 Summer	deg C	11.34	10.89	10.62	10.91	11.14	11.2	12.99	12.24	11.02	11.55	10.9	12.00
SST NH 05 Winter Before	deg C	12.11	10.52	10.26	10.31	10.01	10.81	11.32	11.07	10.92	9.96	9.03	9.63
SST NH 05 Winter After E	deg C	10.52	10.26	10.31	10.01	10.81	11.32	11.07	10.92	9.96	9.03	9.63	
Physical Spring Trans Log	Day of Year	105	91	72	61	80	112	110	145	112	74	89	82
Upwelling Anomaly (April-May)		-14	19	-36	2	-12	-34	-27	-55	-14	9	0	-5
NH 05 Deep T	deg C	8.58	7.51	7.52	7.50	7.39	7.75	7.88	7.91	7.92	7.55	7.46	7.83
NH 05 Deep S		33.51	33.87	33.83	33.87	33.87	33.7	33.66	33.79	33.82	33.88	33.9	33.68
Length of upwelling seaso	days	191	205	208	173	218	168	178	132	194	200	180	201
Copepod richness	no. of speci	5.49	-2.46	-3.03	-0.41	-0.72	1.52	0.57	5.02	3.67	-0.39	-0.53	-0.35
Northern Copepod Bioma	log biomass	-1.97	0.084	0.717	0.486	0.834	-0.08	0.262	-1.74	0.163	0.617	0.87	0.662
Biological Transition	Day of Year	187	119	96	129	120	156	131	206	150	81	63	83
Copepod Community stru	X-axis ordin	0.726	-0.82	-0.82	-0.78	-0.98	-0.18	-0.14	0.541	0.15	-0.66	-0.96	-0.8
June-Chinook Catches	fish per km	0.26	1.27	1.04	0.44	0.85	0.63	0.42	0.13	0.69	0.86	2.55	1.00
Sept-Coho Catches	fish per km	0.11	1.12	1.27	0.47	0.98	0.29	0.07	0.03	0.16	0.15	0.27	0.01

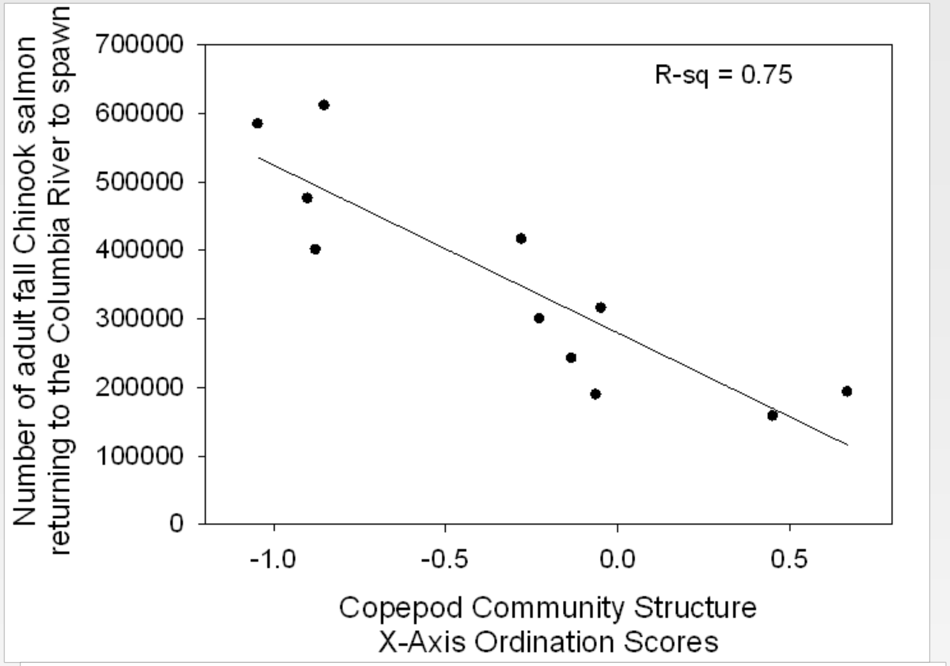
1998, 2003-2005 = warm & unproductive; poor salmon returns
1999-2002 and 2008 = cold & productive; record returns

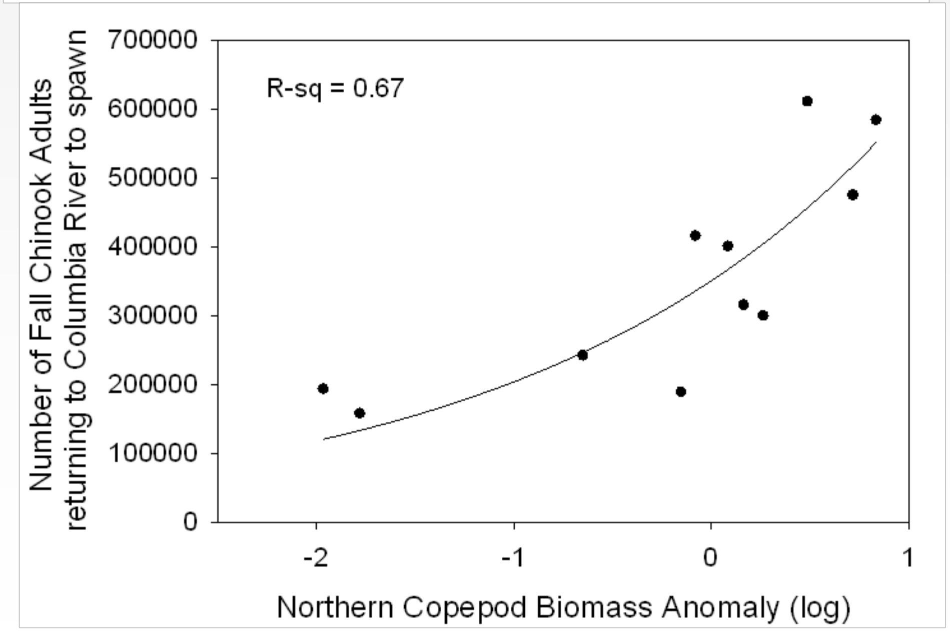
Environmental Variables	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
PDO (December-March)	11	5	2	8	4	12	7	10	9	6	3	1
PDO (May-September)	9	2	3	4	6	11	10	12	8	7	1	5
MEI Annual	12	1	3	5	11	10	8	9	6	4	2	7
MEI Jan-June	12	2	3	5	8	10	7	11	4	9	1	6
SST at 46050 (May-Sept)	10	8	4	5	1	6	12	9	2	11	3	7
SST at NH 05 (May-Sept)	8	2	1	4	6	7	12	11	5	9	3	10
SST winter before going to sea	12	7	5	6	4	8	11	10	9	3	1	2
Physical Spring Trans (Logerwell)	8	7	2	1	4	10	9	12	10	3	6	5
Upwelling (Apr-May)	7	1	11	3	6	10	9	12	7	2	4	5
Deep Temperature at NH 05	12	4	5	3	1	7	9	10	11	6	2	8
Deep Salinity at NH05	12	3	6	2	5	9	11	8	7	1	4	10
Length of upwelling season	7	3	2	10	1	11	9	12	6	5	8	4
Copepod richness	12	2	1	5	3	9	8	11	10	6	4	7
N.Copepod Anomaly	12	9	3	6	2	10	7	11	8	5	1	4
Biological Transition	11	5	4	7	6	10	8	12	9	2	1	3
Copepod Community structure	12	3	4	6	1	8	9	11	10	7	2	5
Catches of salmon in surveys												
June-Chinook Catches	11	2	3	9	6	8	10	12	7	5	1	4
Sept-Coho Catches	9	2	1	4	3	5	10	11	7	8	6	12
Mean of Ranks of Environmental Da	10.4	3.8	3.5	5.2	4.3	8.9	9.2	10.8	7.5	5.5	2.9	5.8
RANK of the mean rank	11	3	2	5	4	9	10	12	8	6	1	7



A simple approach to forecasting

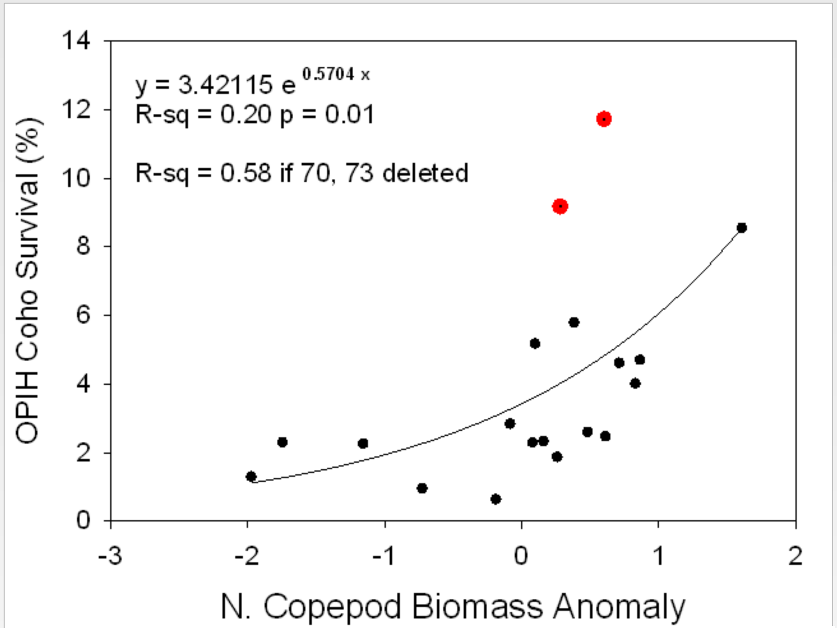
- Regression of salmon counts at Bonneville Dam with the rank of all variables.
- Spring Chinook (2008 ocean entry) returned in 2010 at 2nd or 3rd highest in history.
- Fall Chinook (2008 ocean entry) are expected to return in 2010 at near-record numbers (records were 604,200 in 2003 (fall) and 414,628 in 2001 (spring)
- Of the Coho that went to sea in 2008, 224,592 passed Bonneville Dam in 2009 (2nd highest on record); Coho that went to sea in 2009 are expected to only reach about half that value.

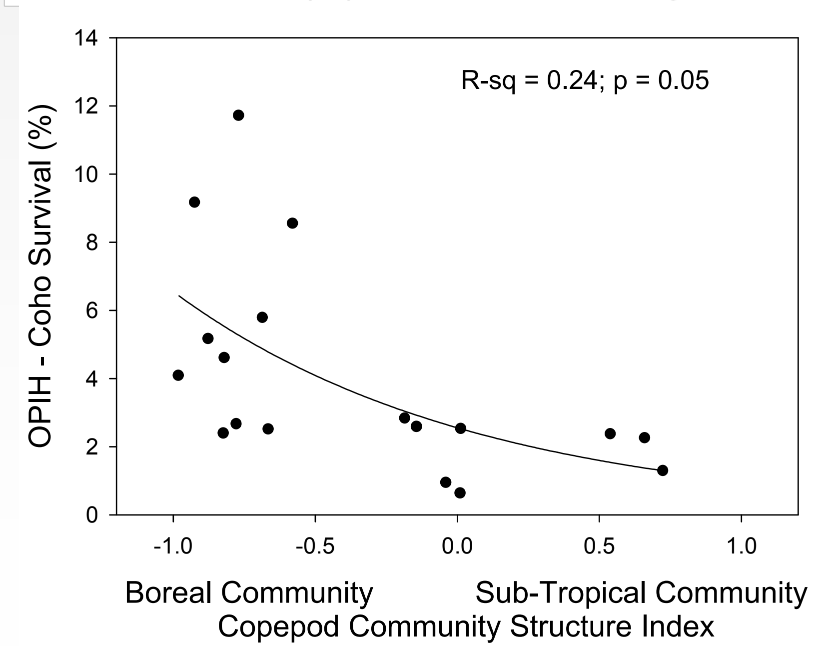




Fall Chinook

- Regressions with copepods alone work nicely
- Community structure
- Biomass of lipid-rich species

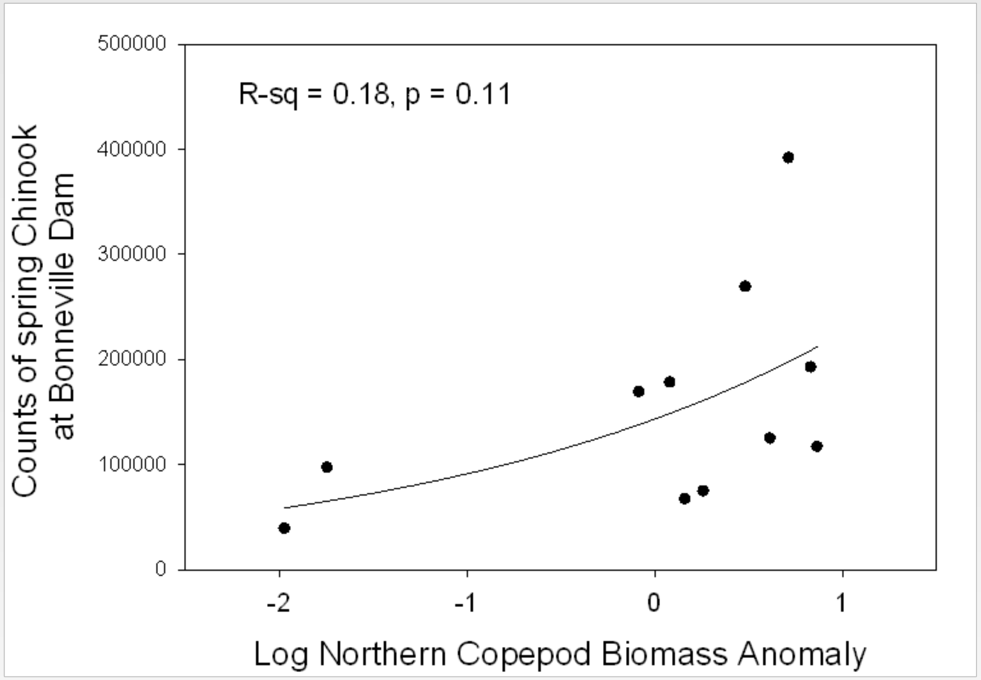


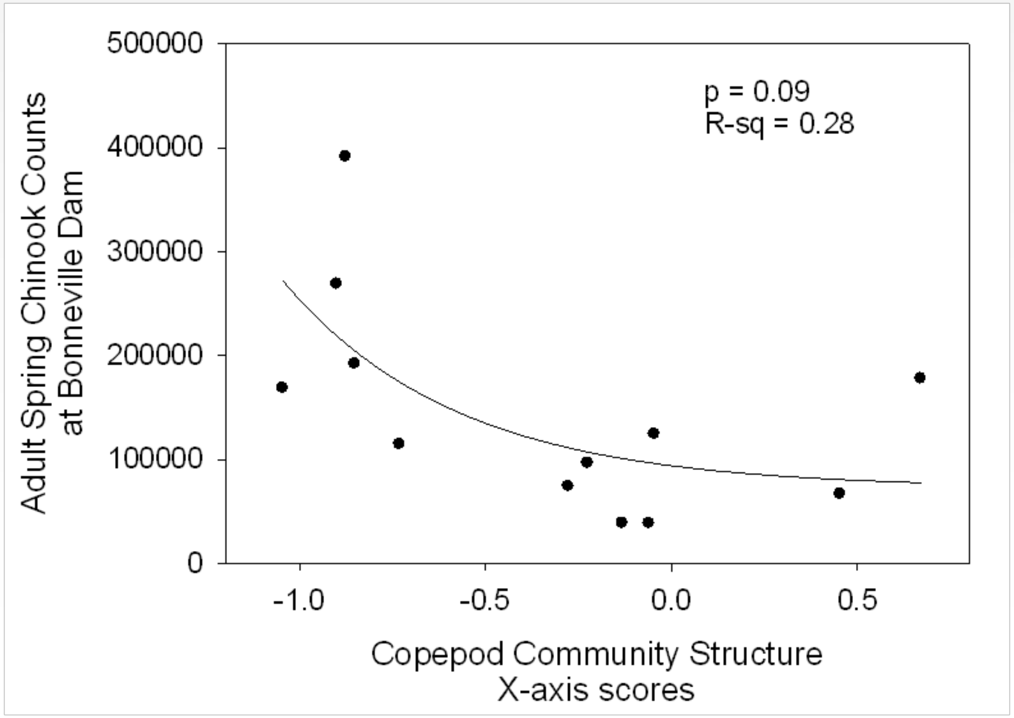


Coho

- When poor ocean conditions prevail (negative copepod biomass anomalies) coho do poorly; when ocean conditions are good, coho returns can be both good and poor.

Spring Chinook

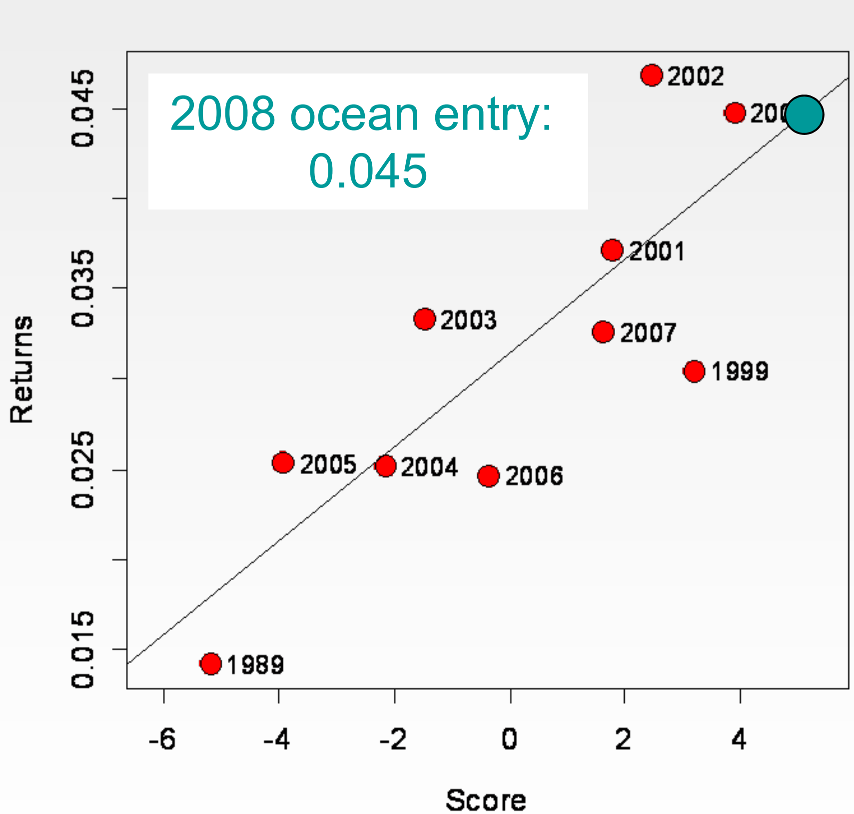




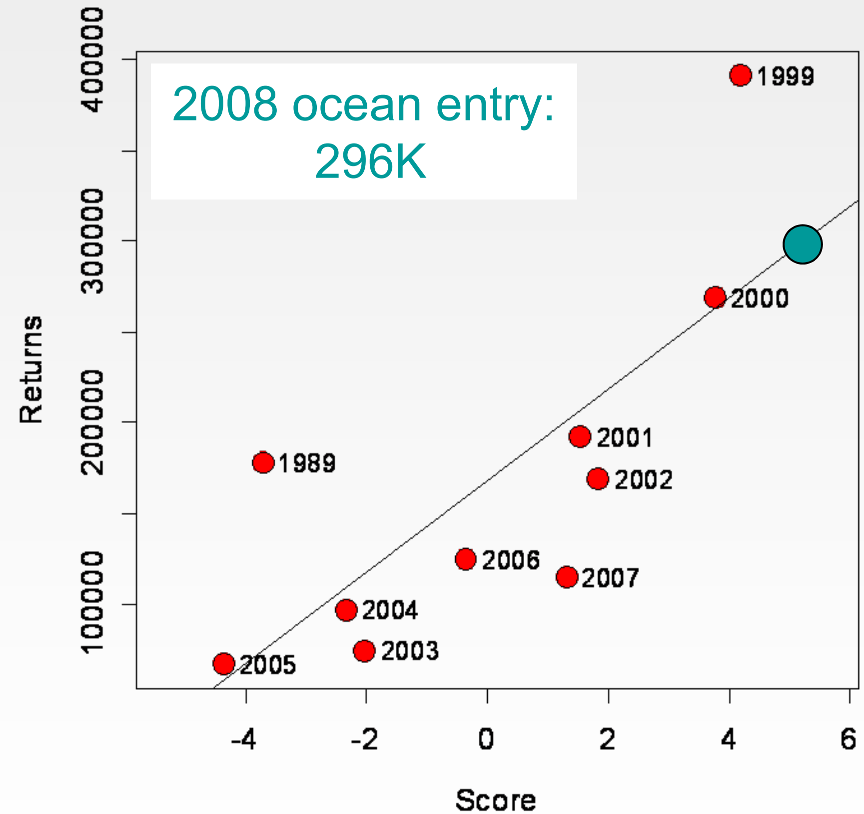
- Counts at Booneville don't seem to match up well with the northern copepods.
- Community structure works better
- But spring Chinook may not spend enough time off OR and WA for adult recruitment to be set in the first 4-8 weeks of local residence

Maximum Covariance Analysis
(Brian Burke)

Coho salmon



Spring Chinook salmon



A chain of events (in a perfect year)

	Negative	Positive
• Changes in basin-scale winds lead to sign changes in PDO		
• SST changes as do water types off Oregon	Cold/salty	Warm/fresh
• Spring transition	Early	Late
• Upwelling season	Long	Short
• Zooplankton species	Cold species	Warm species
• Food Chain	Lipid-rich	Lipid-deplete
• Forage Fish	Many	Few
• Juvenile salmonids	Many	Few

But time lags can complicate interpretations!

Is it this simple for all taxa?

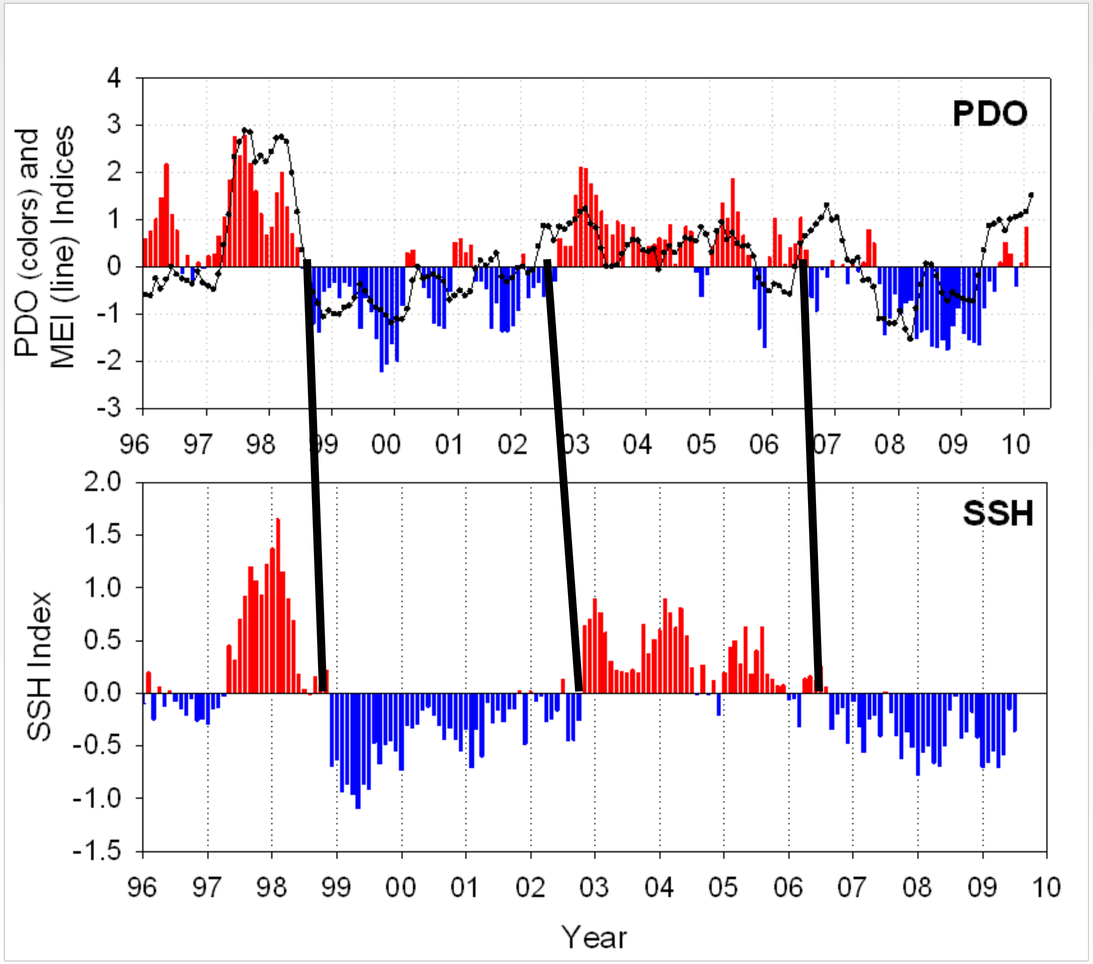
- For the Columbia, tremendous effort in improving freshwater habitat as well as fish passage through the hydropower system, and these seem to be working since a greater proportion of fish seem to be getting downstream past Bonneville
- The same is true for other streams/rivers due to the efforts of numerous Watershed Councils
- We don't know where steelhead or Snake River and Upper Columbia spring Chinook live in the ocean which makes it difficult to provide reliable forecasts.

Acknowledgements

- Bonneville Power Administration
- U.S.GLOBEC Program (NOAA/NSF)
- NOAA Stock Assessment Improvement Program (SAIP)
- Fisheries and the Environment (FATE-NOAA)
- National Science Foundation
- Office of Naval Research
- NASA

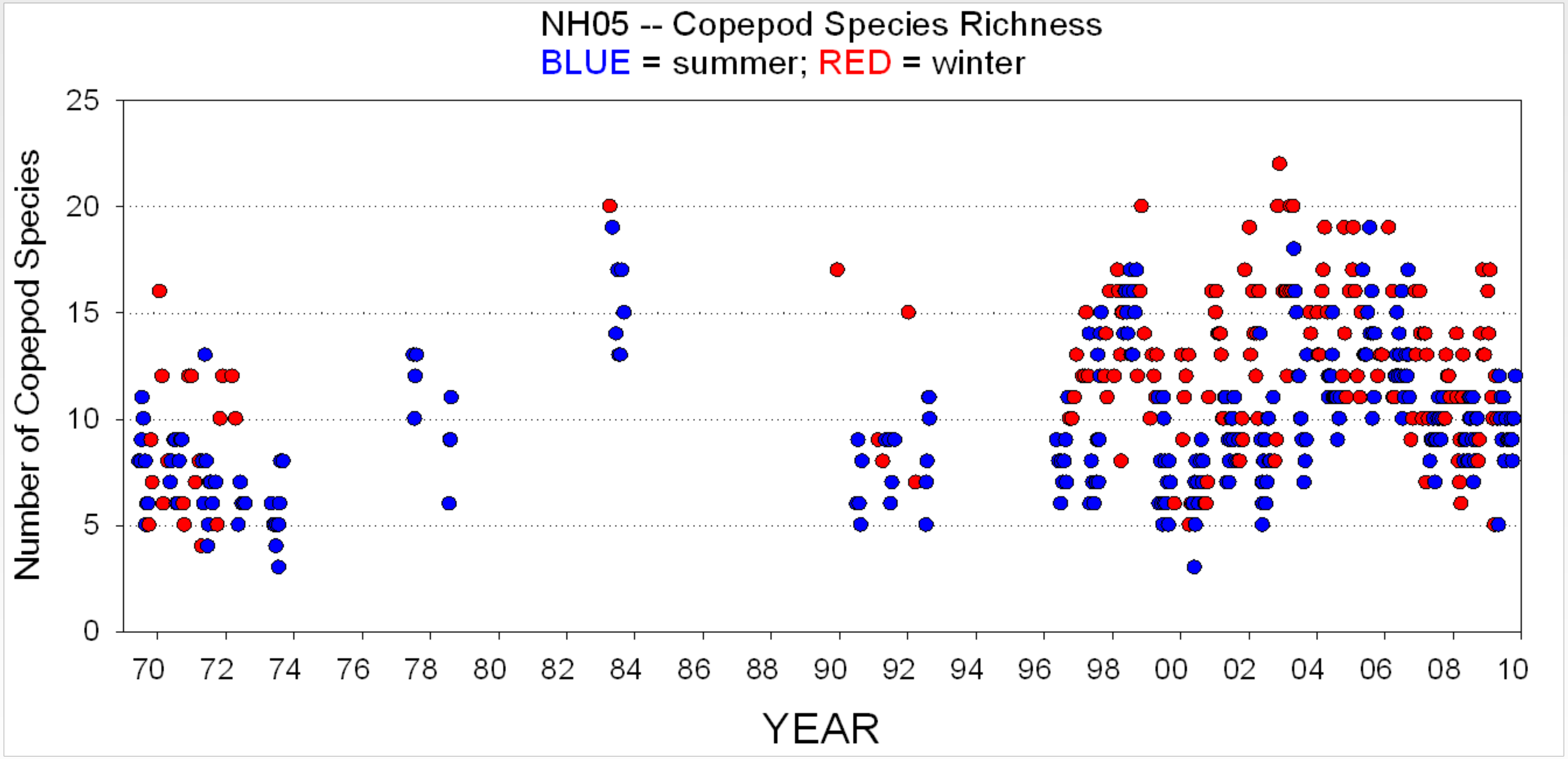
- See www.nwfsc.noaa.gov, "Ocean Conditions and Salmon Forecasting"

Analysis of Altimeter Data: SSH tracks the PDO; as with SST there can be a lag of a few months



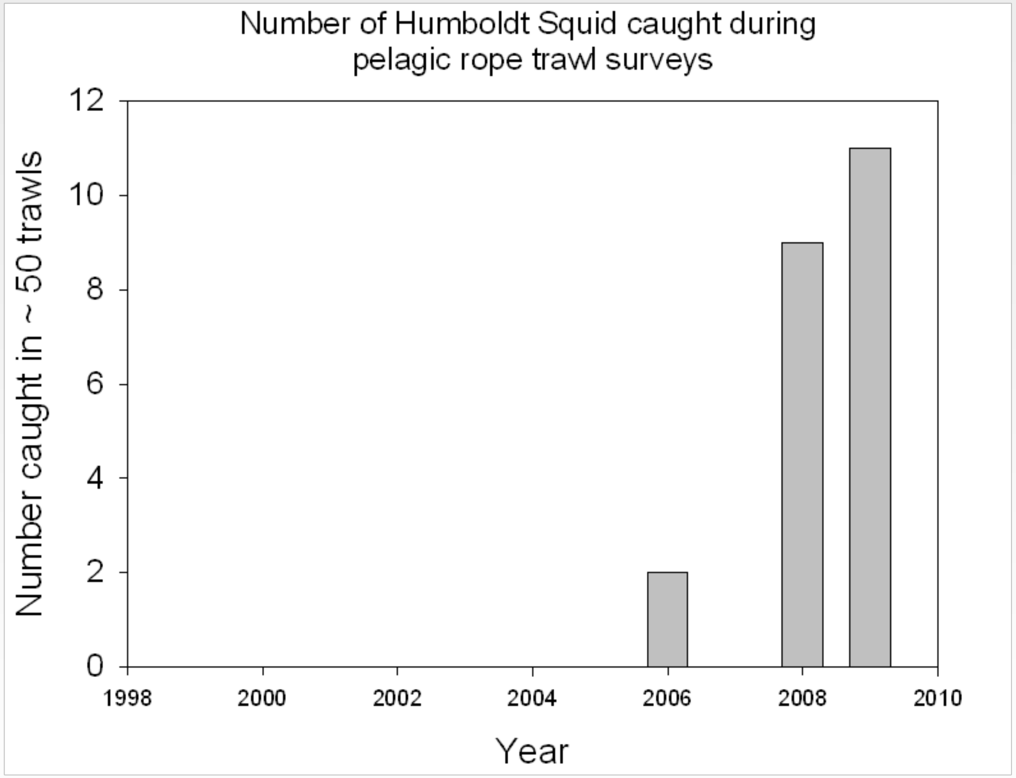
- PDO change points
  - July 98
  - Aug 02
  - Sep 07
- SSH change points
  - Dec 98
  - Nov 02
  - Sep 07

Are we seeing any indication of changes in copepods over the past 40 years?



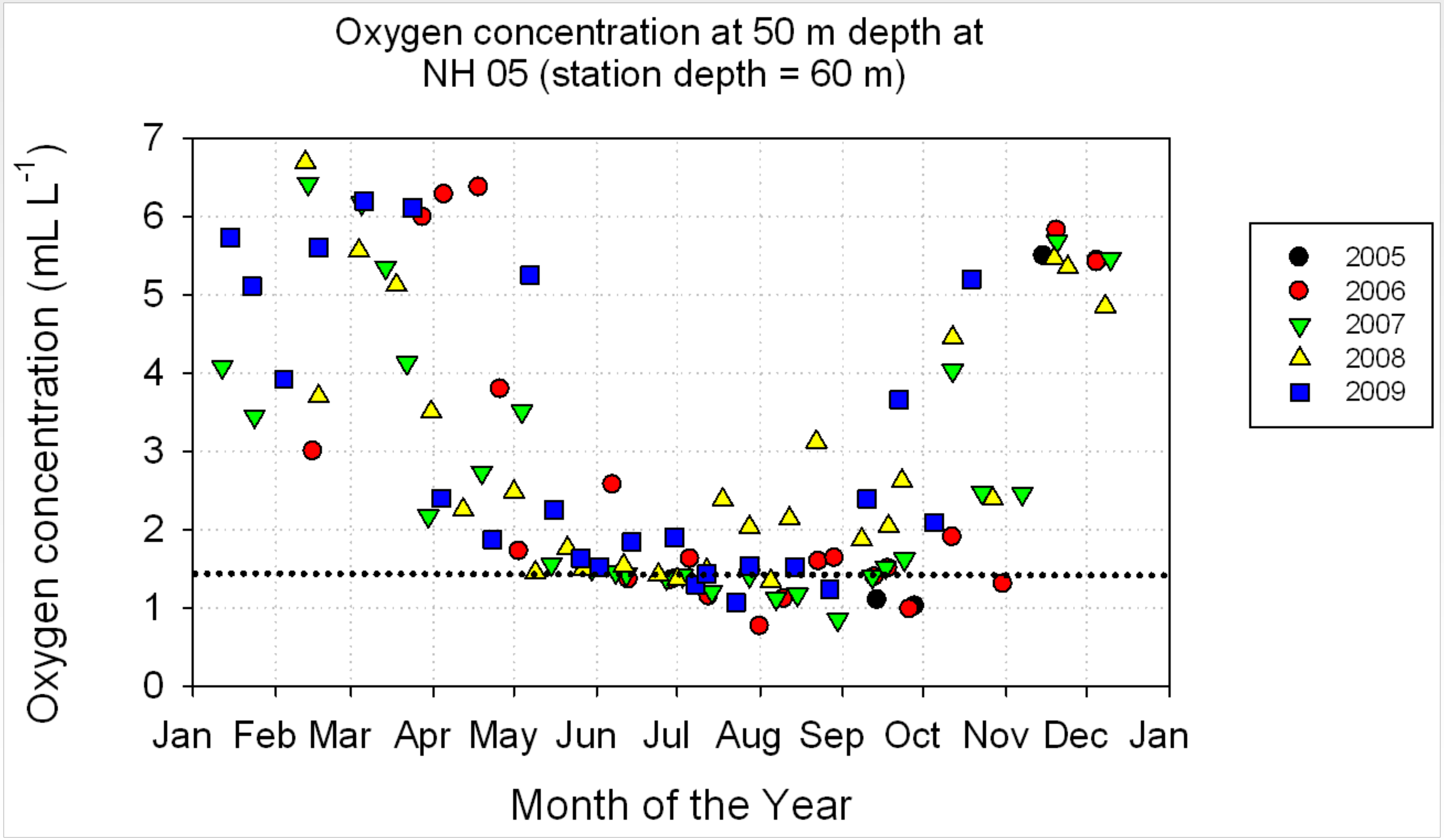
- 69-73 = 6.68 species
- 96-08 = 10.24 species
- Despite recent cold ocean conditions we still see high species richness
- Over the same time period, the surface waters of the NCC shelf have warmed by 0.53°C. and 0.43 °C in deep waters 0.43 °C

Squid caught in juvenile salmonid surveys, in Nordic 264 Rope Trawl



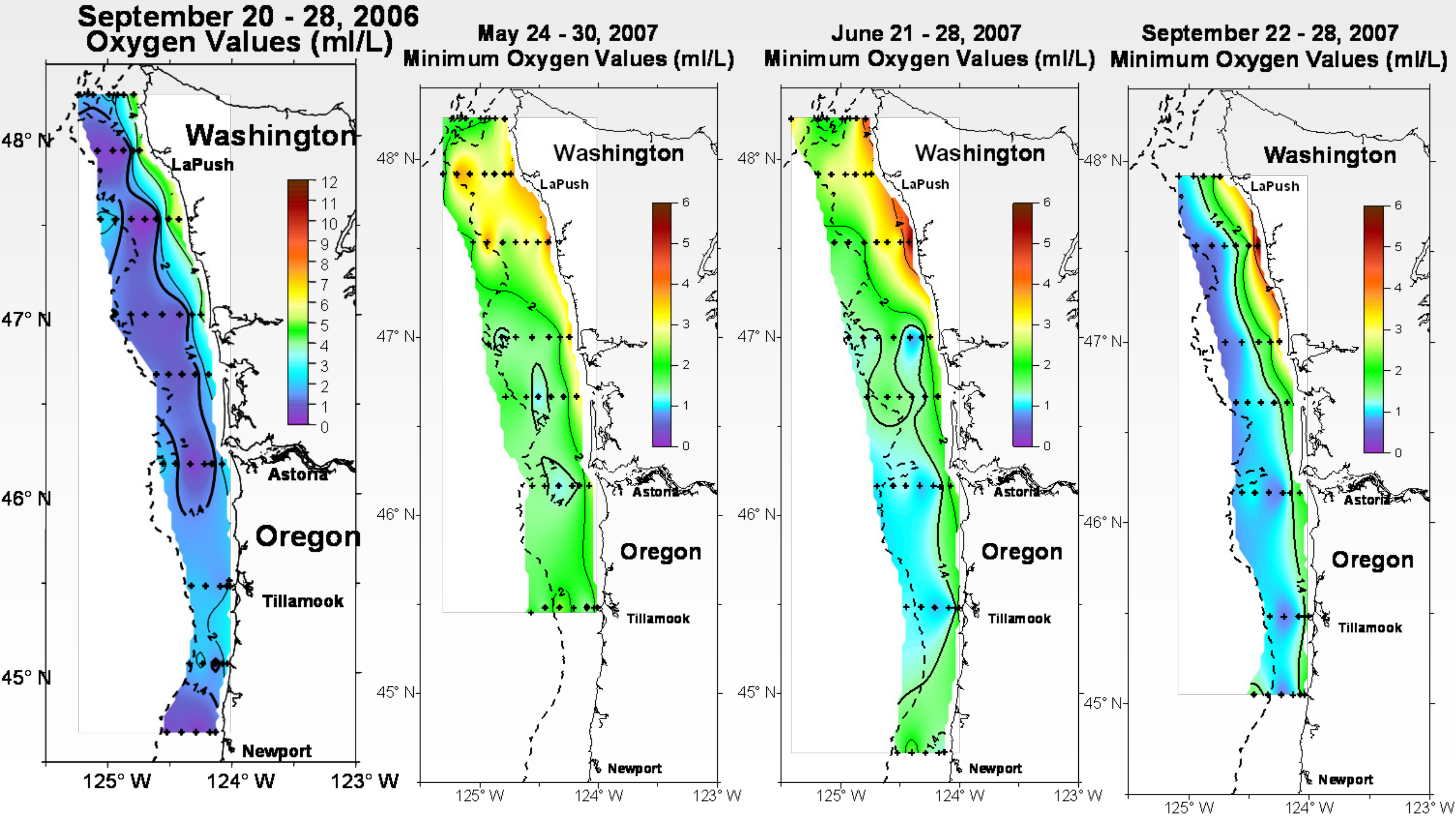
Surveys conducted from La Push south to Newport along 8 transect lines
Across the shelf, in May, June and September.
Humboldt squid caught only in September

Oxygen concentrations at a mid-shelf station off Newport

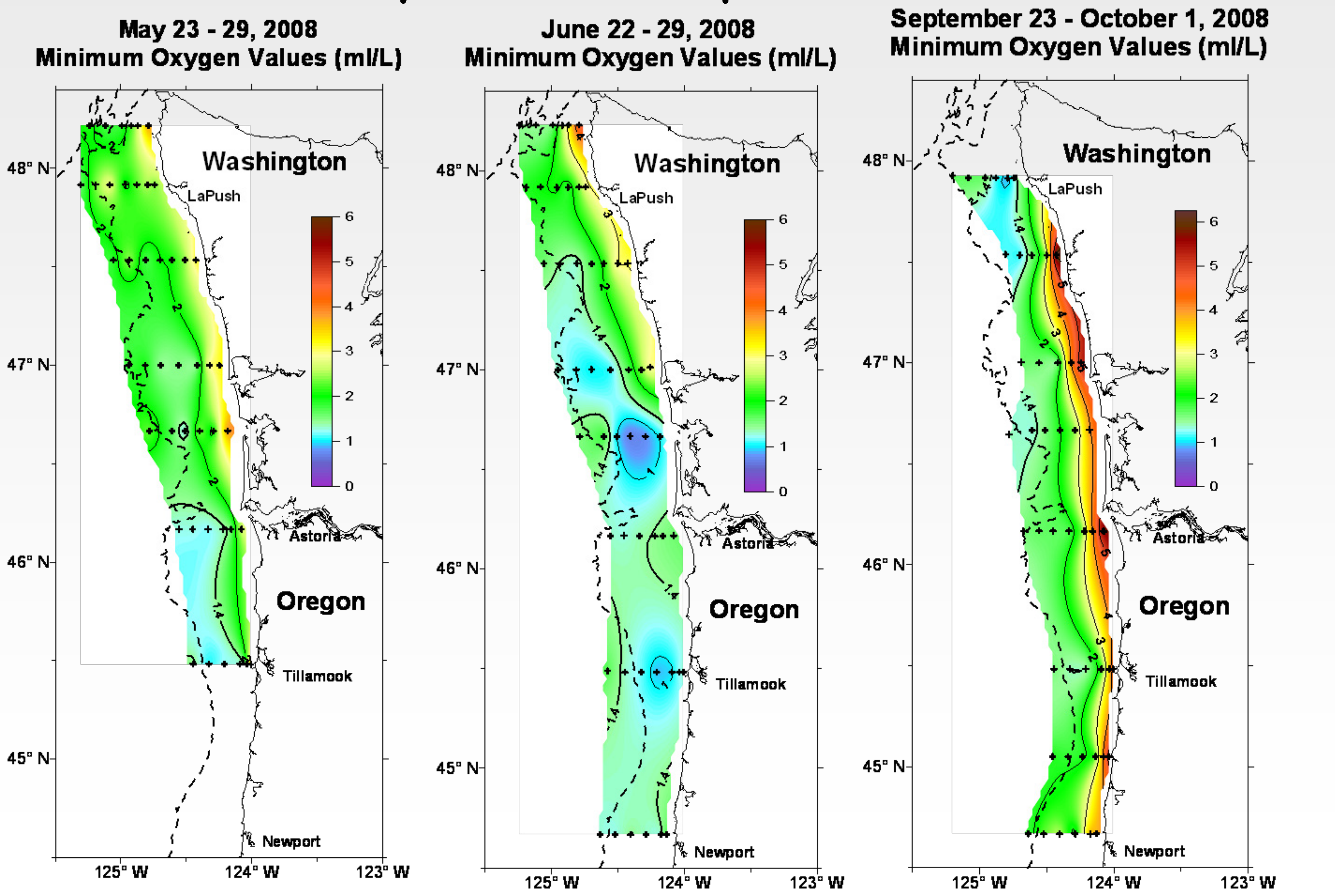


Area of hypoxia during summer 2006 equaled that of the Gulf of Mexico

Hypoxia off WA and OR May, June, Sept 2007



Hypoxia off WA and OR
May, June, Sept 2008

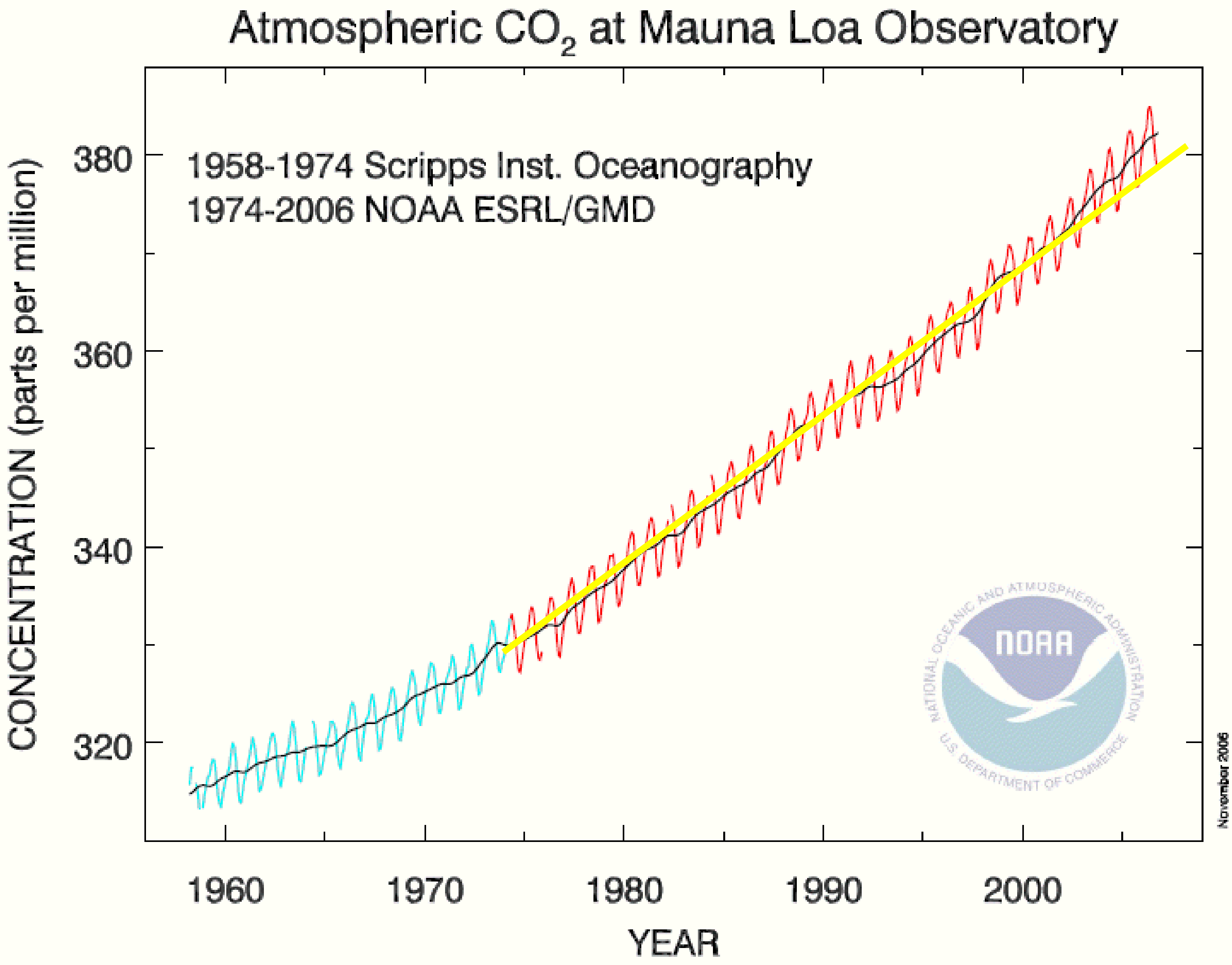


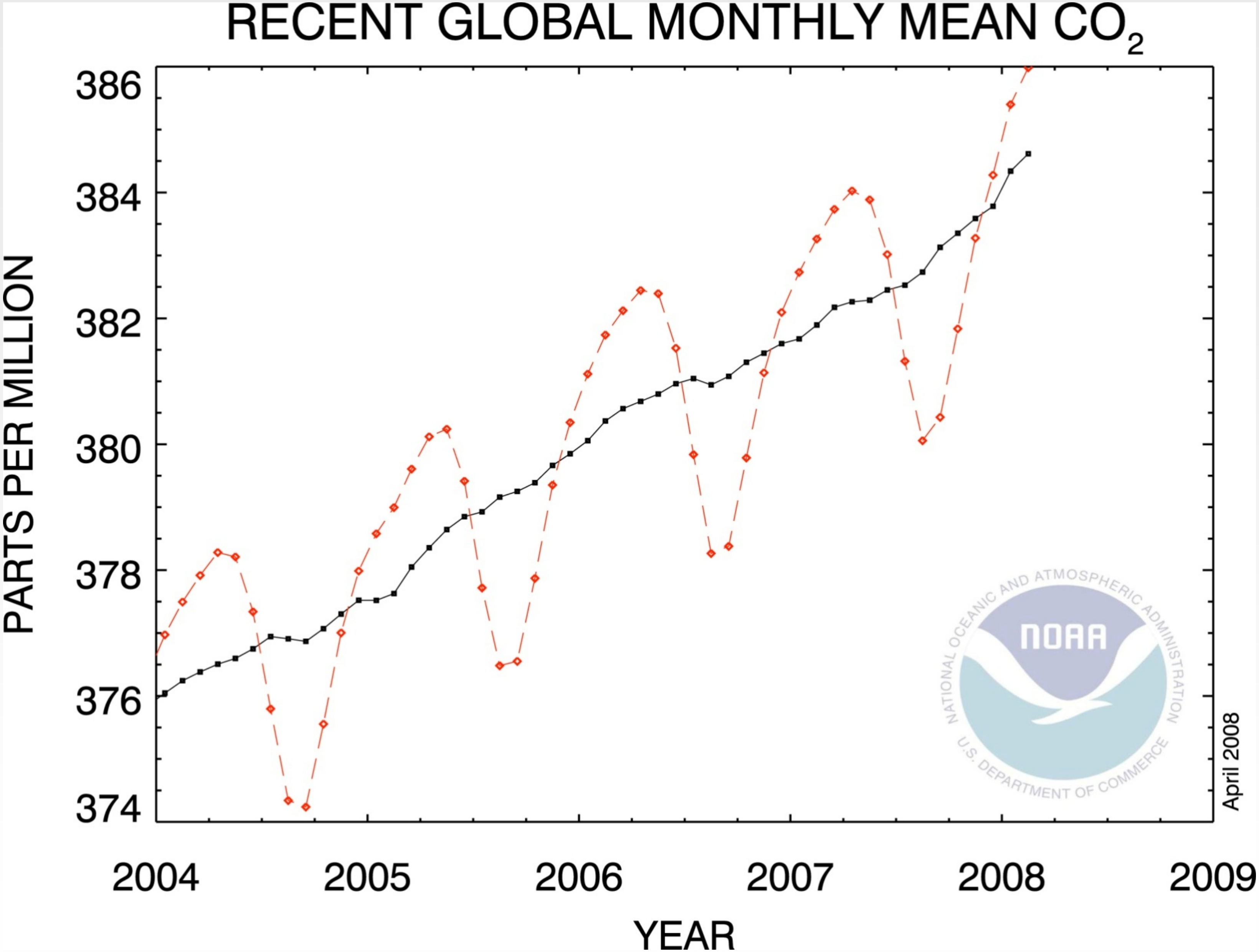
Climate is what you expect; weather is what you get!

Climate change means that the weather will change but in ways that we may not expect!

Changes in marine food chains

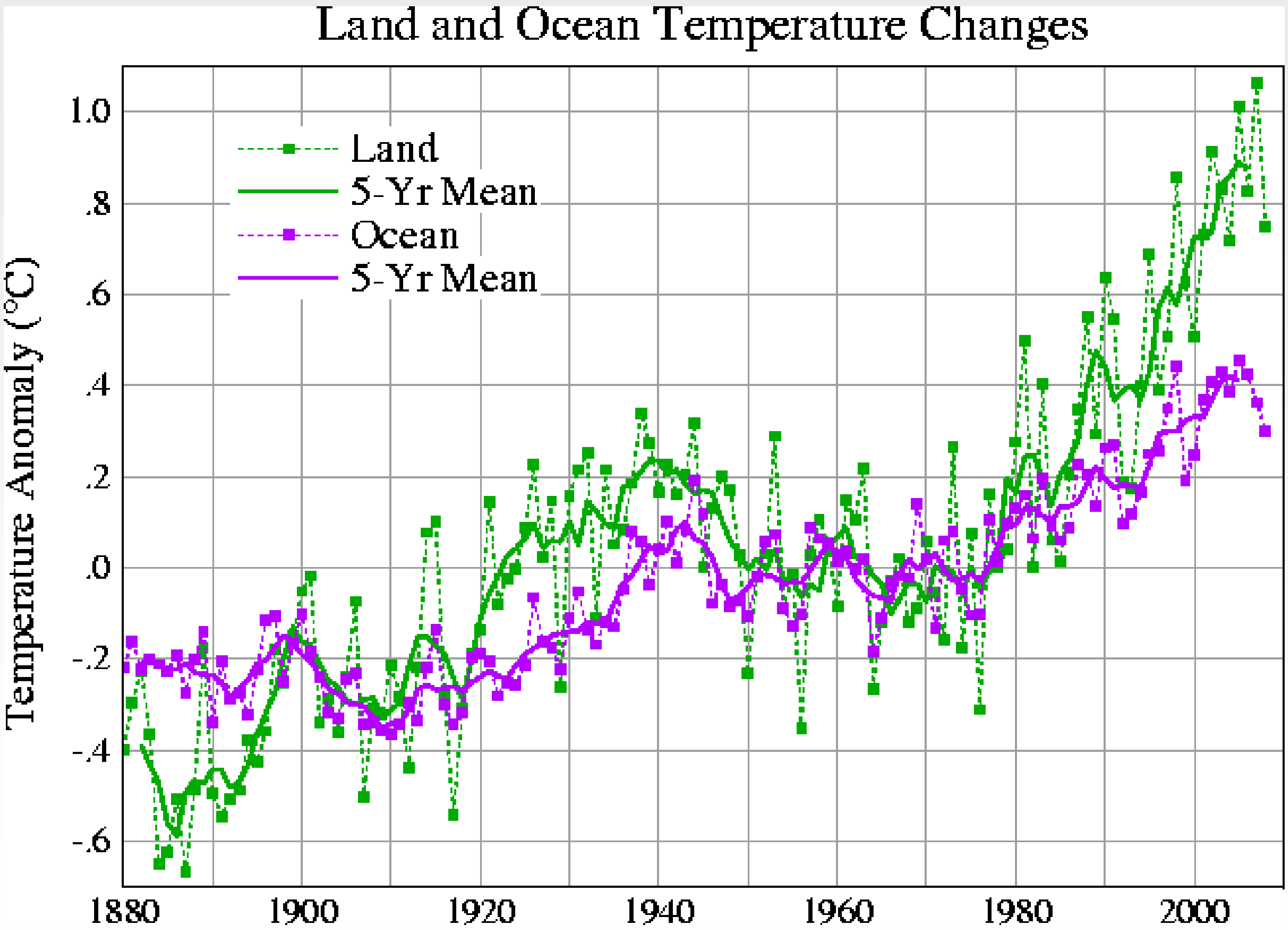
Photo taken just outside Ucluelet near Tofino BC…
Published in <www.westcoaster.ca>


Atmospheric CO_2 at Mauna Loa Observatory
1958-1974 Scripps Inst. Oceanography
1974-2006 NOAA ESRL/GMD
CONCENTRATION (parts per million)
380
360
340
320
1960
1970
1980
1990
2000
YEAR
NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
November 2006

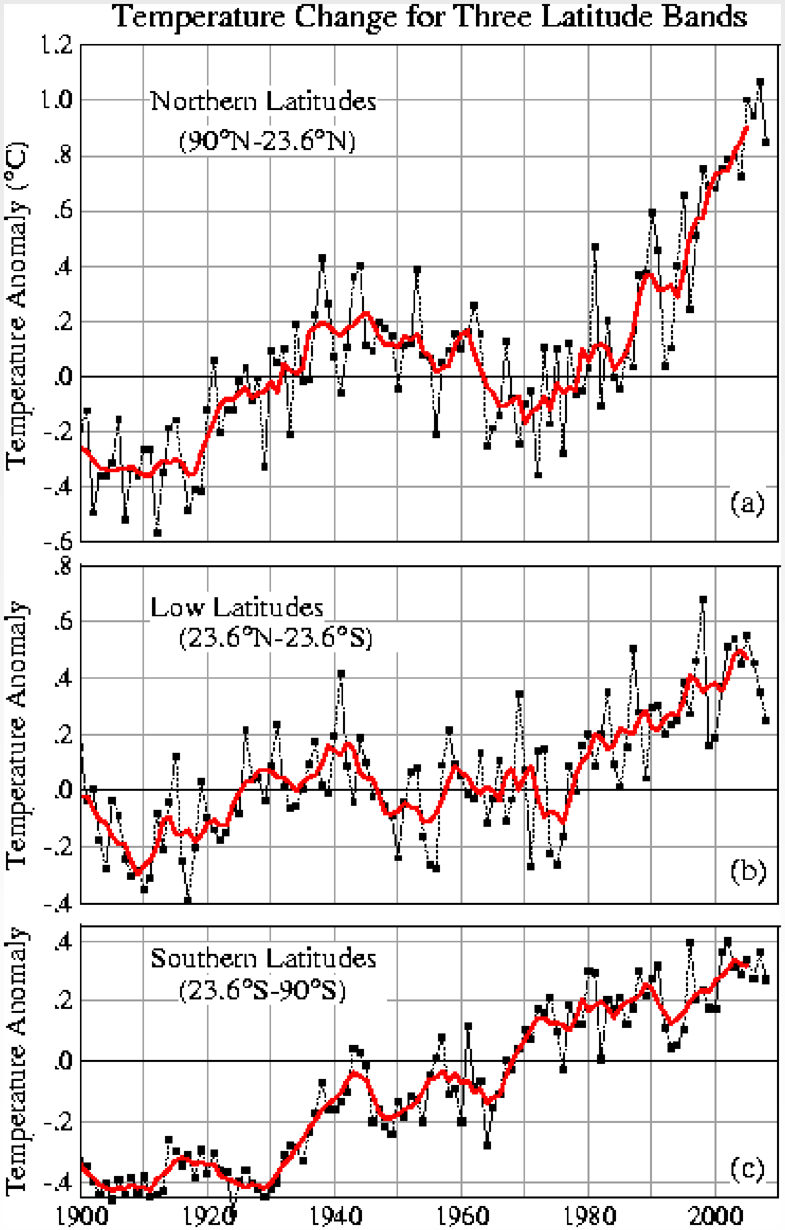


RECENT GLOBAL MONTHLY MEAN CO_2
PARTS PER MILLION
386
384
382
380
378
376
374
2004
2005
2006
2007
2008
2009
YEAR
April 2008

Land vs Ocean Temperatures



Goddard Institute for Space Studies



UPPER: 23-90° North
MIDDLE: Tropics
LOWER: S. 23-90° South

- Note greater warming in northern hemispere
- Note lesser warming in tropics and in southern latitudes.

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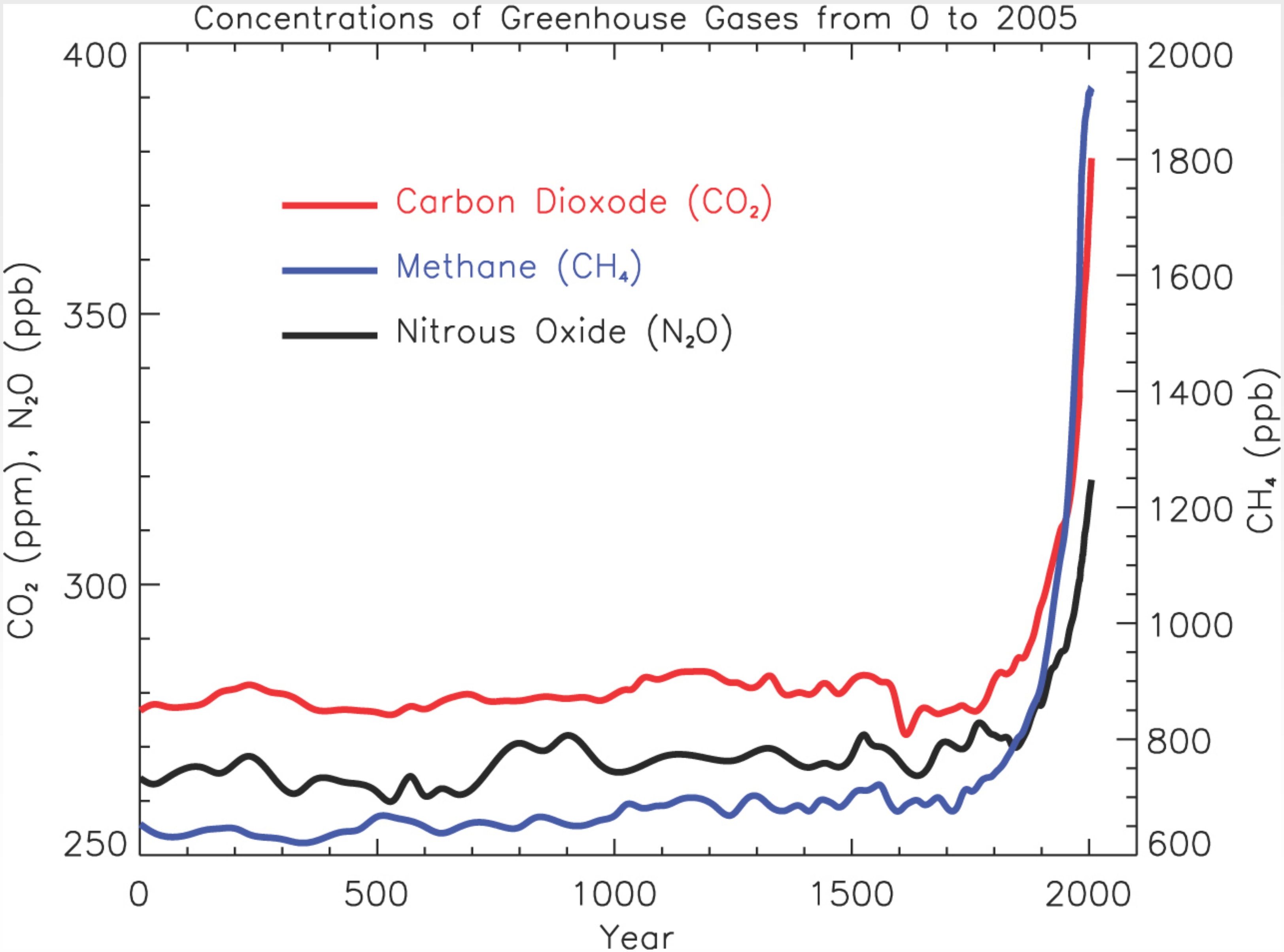

Concentrations of Greenhouse Gases from 0 to 2005
Carbon Dioxode (CO_2)
Methane (CH_4)
Nitrous Oxide (N_2O)
CO_2 (ppm), N_2O (ppb)
CH_4 (ppb)
Year
400
350
300
250
2000
1800
1600
1400
1200
1000
800
600
0
500
1000
1500
2000

Three issues to keep in mind

- The rate of warming is very slow….you will hardly notice that the globe is warming
- Variability in the weather is the problem
- There are huge uncertainties in any forecasts of future climate states, largely because this is all very new territory
- Regardless, "change" is all around us

To track some of the global impacts of climate change you need to become more familiar with geography

- Indus
- Brahmaputra
- Mekong
- Salween
- Yangtze
- Yellow

Changes to “expect”

- Greater variability (hot one day, snow the next)
- Earlier start to spring (but if you are a gardener, watch out for a late frost!)
- Northward and up-slope movement of “normal” biogeographic boundaries
- More rain, less snow pack in the Pacific Northwest
- Ice-free Arctic Ocean during summer months
- Loss of habitat of ice-dependent predators (polar bears)
- Melting of permafrost in Alaska and Canadian far-north disrupting communities; will need to rebuild entire villages/towns
- **Sea level rise** as the ice caps on land melt (Greenland and Antarctica)
- Warmer lakes, rivers, and streams

Changes to “expect” that are marine related

- Estuaries
  - Sea level rise and changes in river hydrographs
- Oceans
  - Increased or decreased upwelling?…that is the question
    - Associated with upwelling is acidification and hypoxia
  - Increased stratification due to warming and more FW
  - Northward shifts in distributions of animals that are capable of moving (reptiles, sea birds, mammals) resulting in altered food chain structure
  - Changes in phenology (timing of seasonal events e.g., spring)
  - Changes in size and strength of gyres leading to changes in source waters which feed eastern boundary currents (NCC)
  - Changes in magnitude and duration of natural climate cycles such as ENSO and PDO
  - sub-tropicalization of temperate pelagic ecosystems

But….the scariest thing will be the surprises – those unanticipated events that may leave us breathless

- Ocean acidification (now less of a surprise)
- Waters of low oxygen content are shoaling in CC
- Summer of 2005 – no upwelling until mid-July

- Humboldt squid appearing in increasingly large numbers
- Fish Kills in 2006 + nearly anoxic waters on Heceta Bank
- Winter of 2007-2008 – summer plankton species dominated
- Buried in *Neocalanus (*a Gulf of Alaska species) in 07/08; 08/09
- Collapse of Sacramento River fall Chinook salmon runs in 2007, 2008 and 2009 but record runs of salmon to the Columbia River
- Record runs of steelhead everywhere.
- Massive bloom of *Akashiwo sanguinea* resulting in deaths of large numbers of seabirds off the coast of Washington
- *Mola mola* everywhere in September 2009.