Ocean-time series as windows into scales of variability in the sea

Two things never to do with a time series: start one, end one

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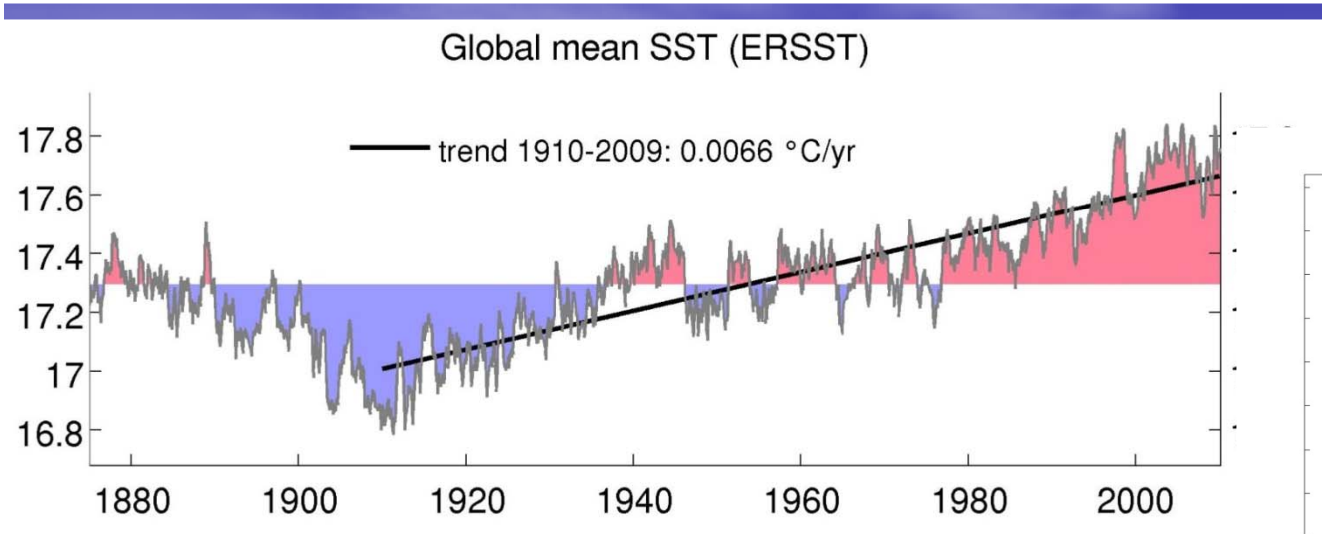
Monterey Bay Aquarium Research Institute (MBARI)

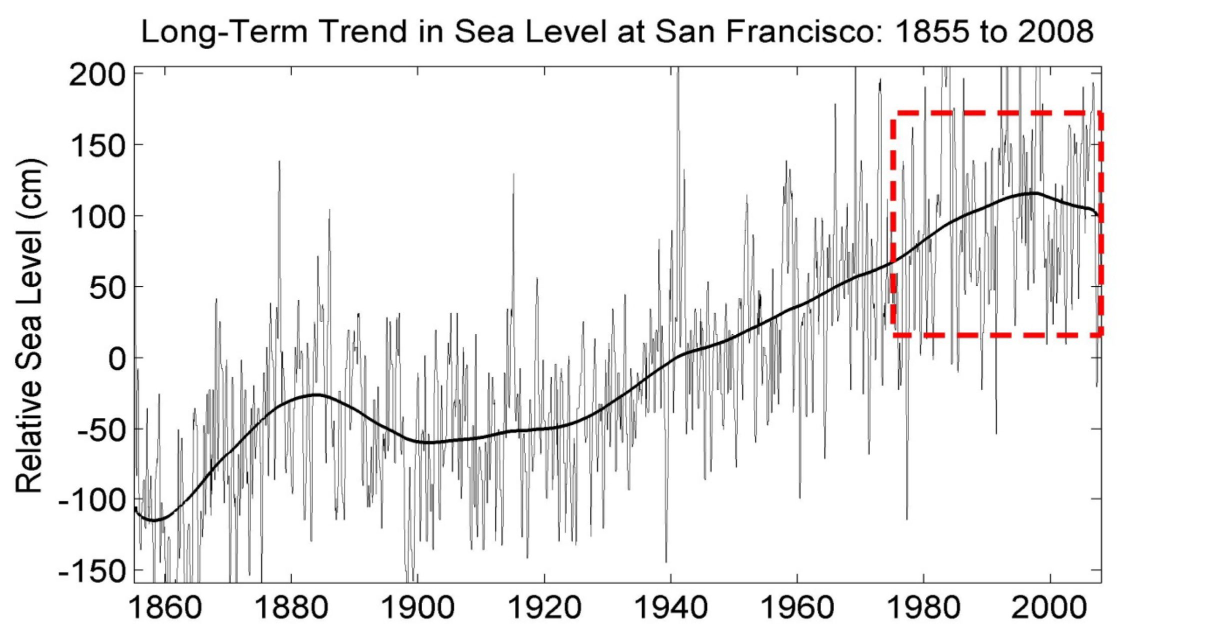
Founded in 1987 by David Packard
(www.mbari.org)

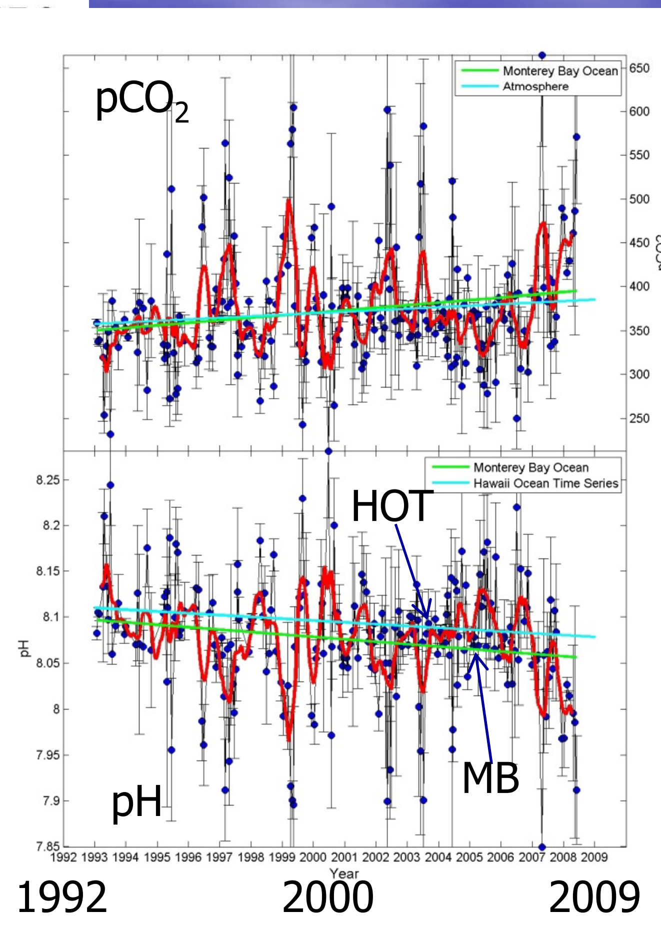
The mission of MBARI is to achieve and maintain a position as world center for advanced research and education in ocean science and technology, and to do so through the development of better instruments, systems and methods for scientific research in the deep waters of the ocean.

David Packard, November 1995

Executive Directors: R.T. Barber 1987-91
P.G. Brewer 1991-96
G.R. Heath 1996-1997
M. McNutt 1997-2009
Chris Scholin 2009-







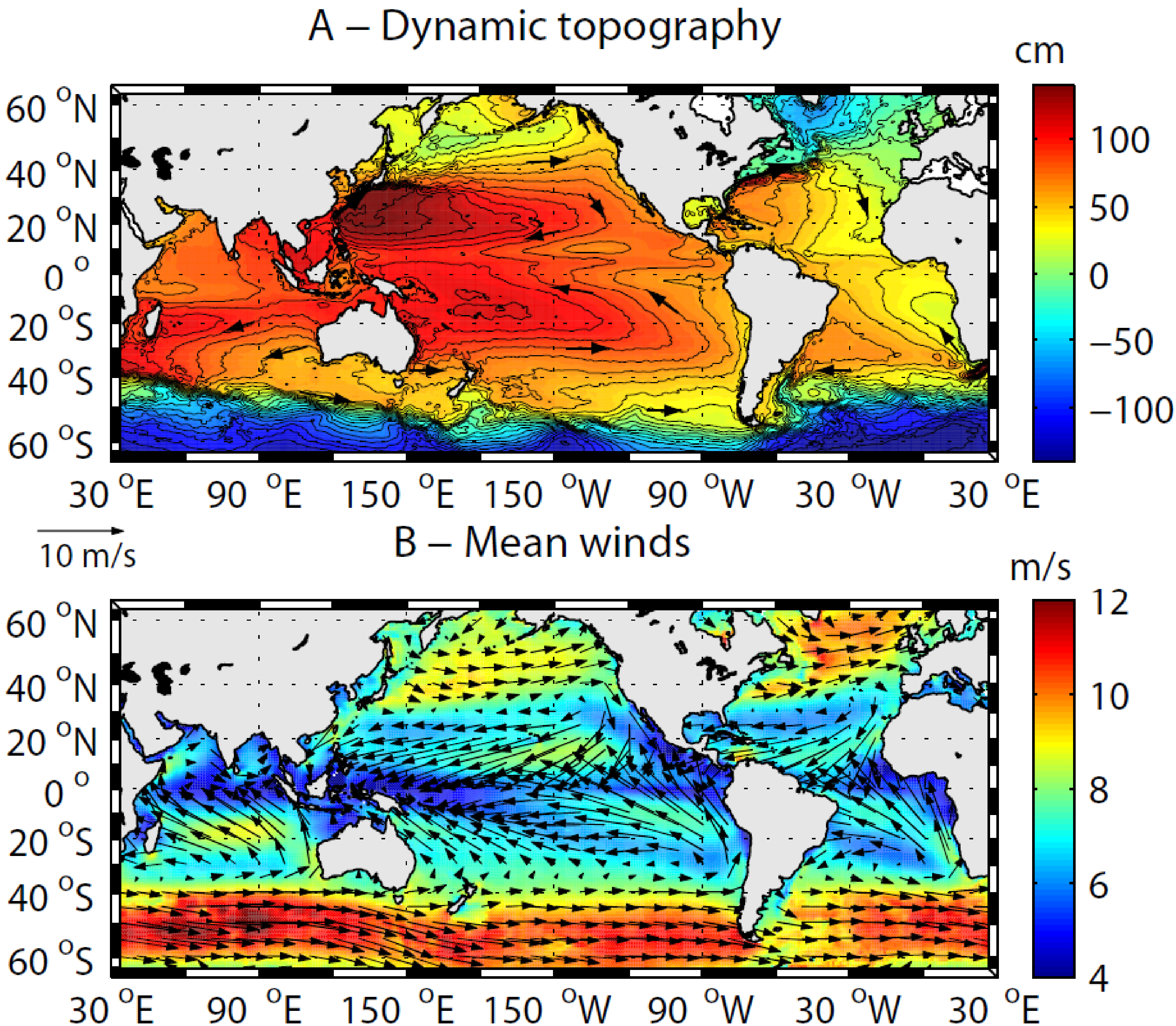
The societal drivers

Outline

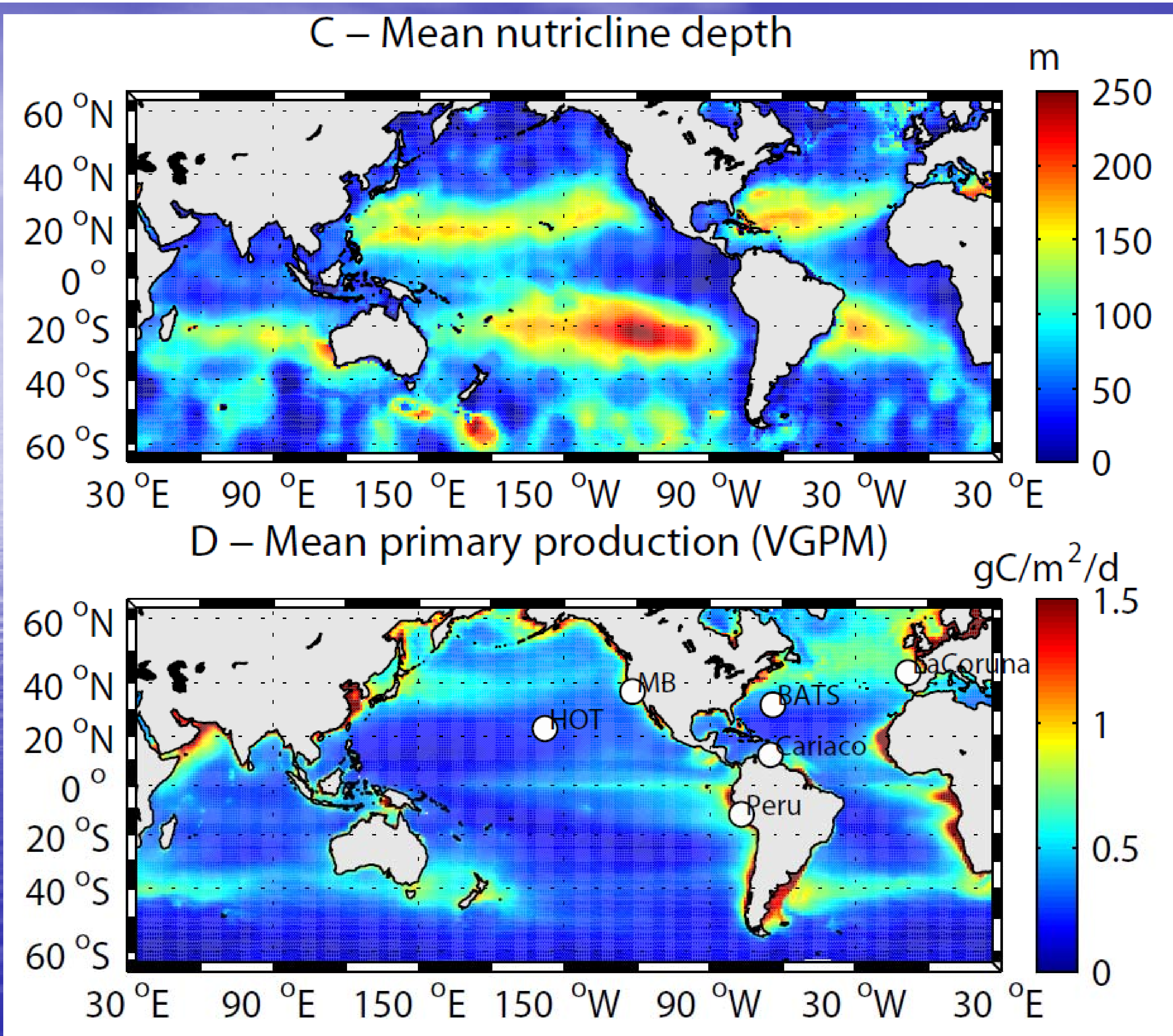
- Monterey Bay Time Series
- Global climate variability during the twentieth century from SST
- Primary production over the past 20 years from SeaWiFS, BATS, Cariaco, La Coruña (Spain), HOT, MB and Peru
- Looking to the past to learn something about future changes in climate
- Some thoughts about the future

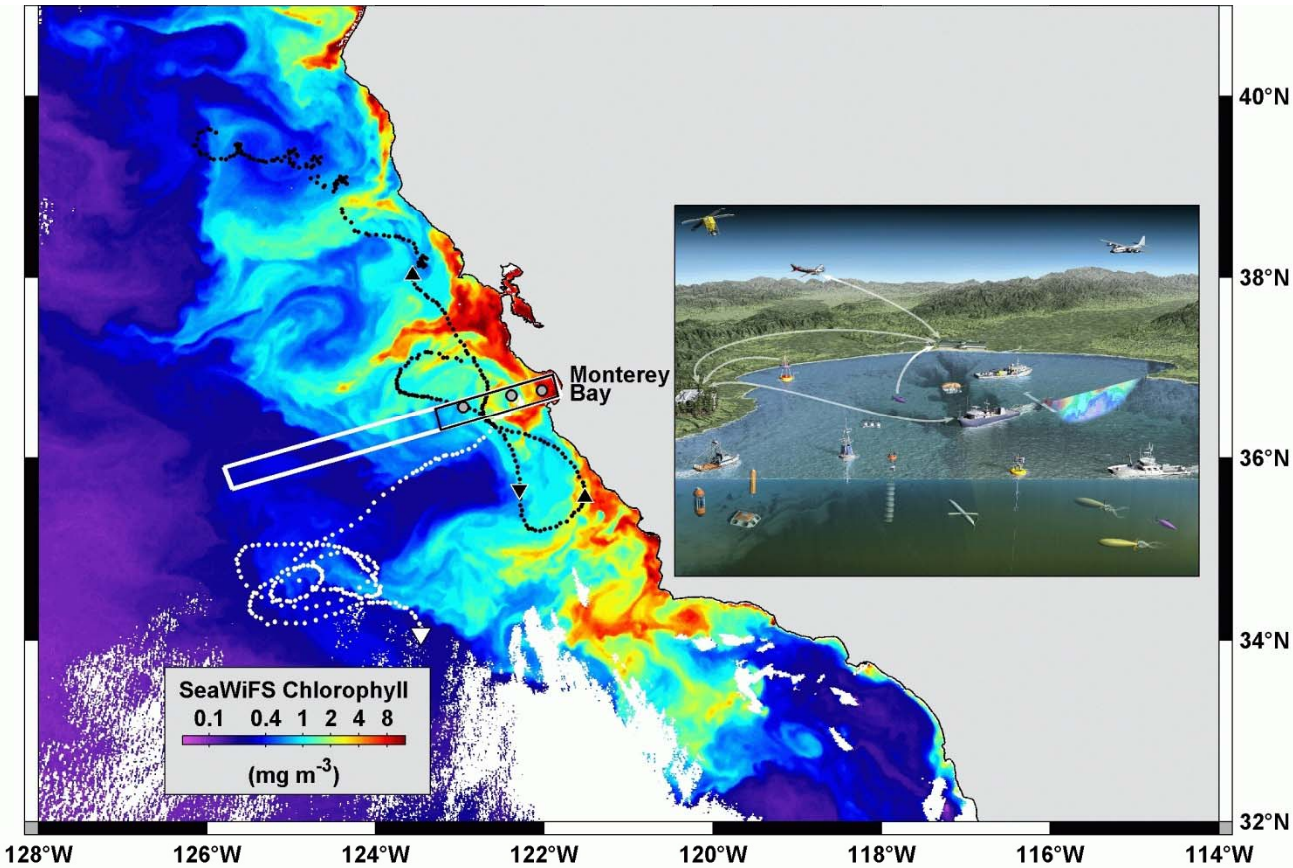
Monterey Bay Time Series

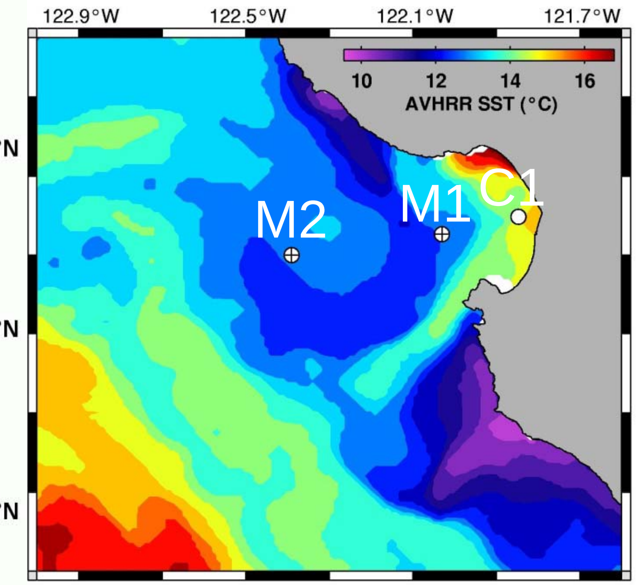
- Since 1989 combines ship, mooring, AUV, satellite and modeling
- Resulted in over 150 publications
- Generates new ideas and process studies
- Provides a natural laboratory for technology development
- Studies biological responses to climate variability and global change

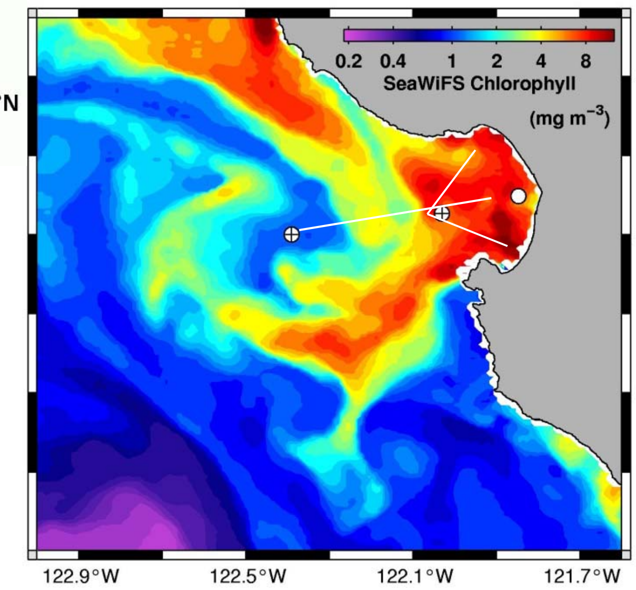


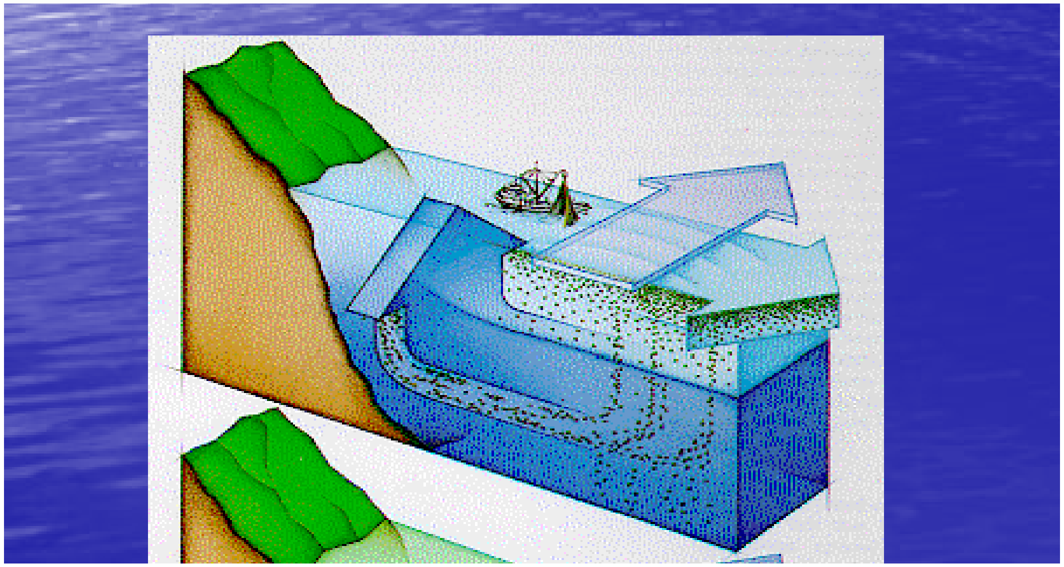
A – Dynamic topography
cm
100
50
0
−50
−100
60 °N
40 °N
20 °N
0 °
20 °S
40 °S
60 °S
30 °E
90 °E
150 °E
150 °W
90 °W
30 °W
30 °E
10 m/s
B – Mean winds
m/s
12
10
8
6
4
60 °N
40 °N
20 °N
0 °
20 °S
40 °S
60 °S
30 °E
90 °E
150 °E
150 °W
90 °W
30 °W
30 °E

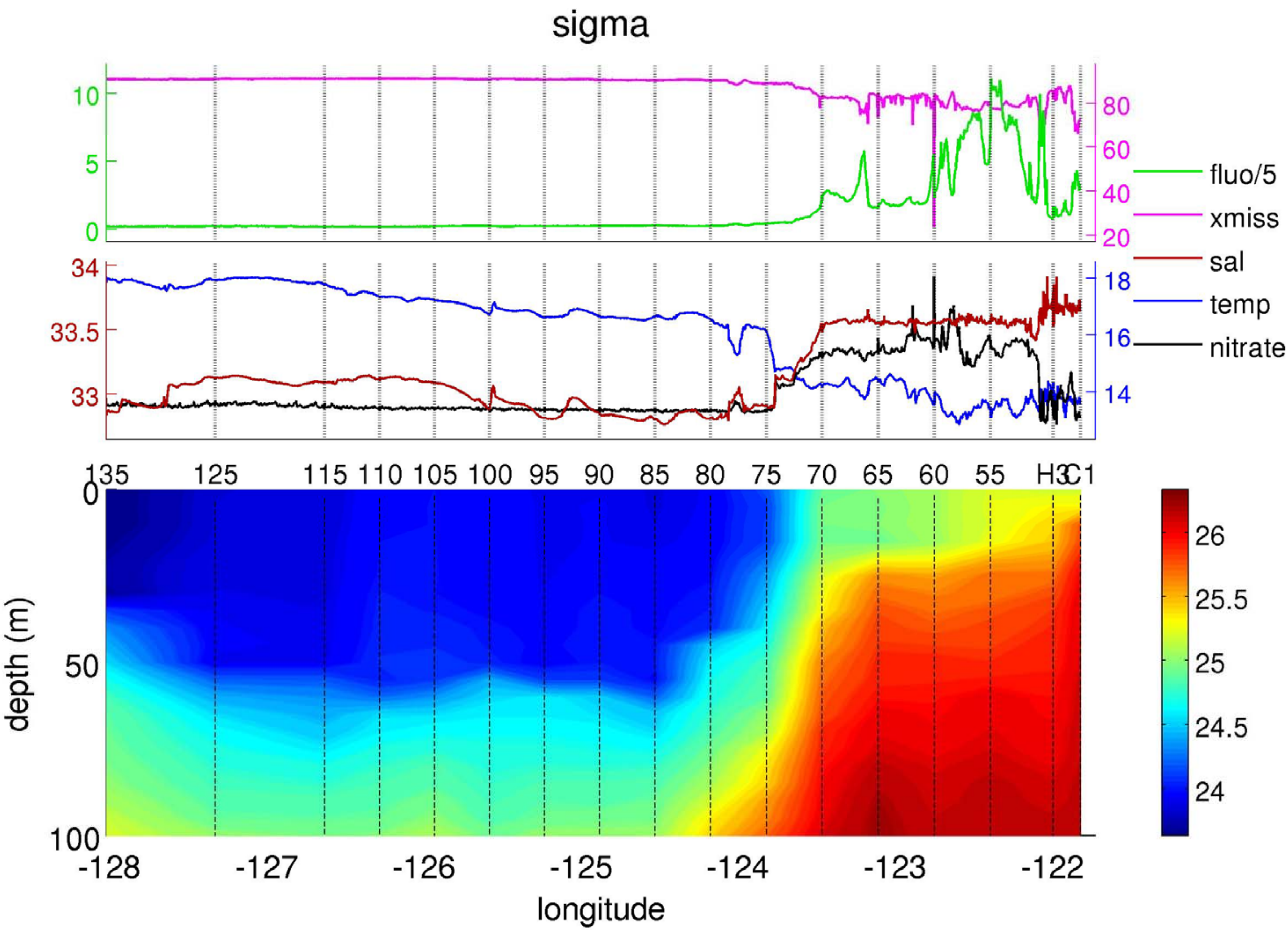

C – Mean nutricline depth
m
250
200
150
100
50
0
60 °N
40 °N
20 °N
0 °
20 °S
40 °S
60 °S
30 °E
90 °E
150 °E
150 °W
90 °W
30 °W
30 °E
D – Mean primary production (VGPM)
gC/m²/d
1.5
1
0.5
0
HOT
MB
BATS
Cariaco
Peru
LaCoruna


Monterey Bay
SeaWiFS Chlorophyll
0.1 0.4 1 2 4 8
(mg m^{-3})
40°N
38°N
36°N
34°N
32°N
128°W
126°W
124°W
122°W
120°W
118°W
116°W
114°W


122.9°W
122.5°W
122.1°W
121.7°W
10 12 14 16
AVHRR SST (°C)
M2
M1
C1

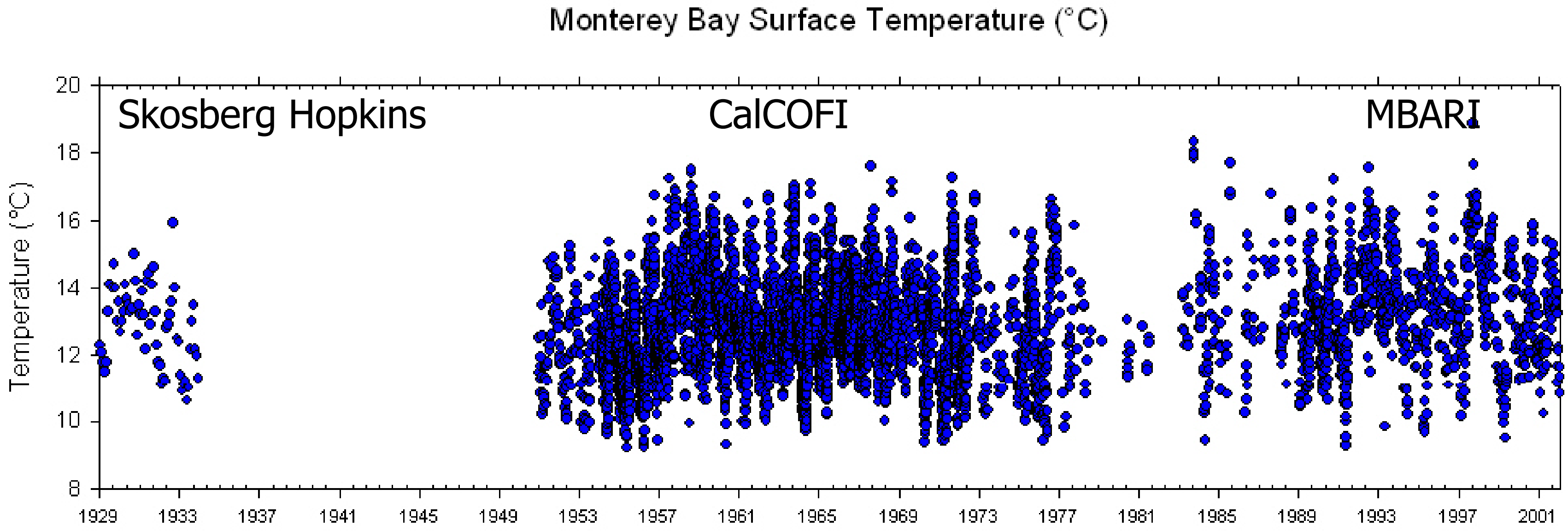

0.2 0.4 1 2 4 8
SeaWiFS Chlorophyll
(mg m^{-3})
122.9°W
122.5°W
122.1°W
121.7°W

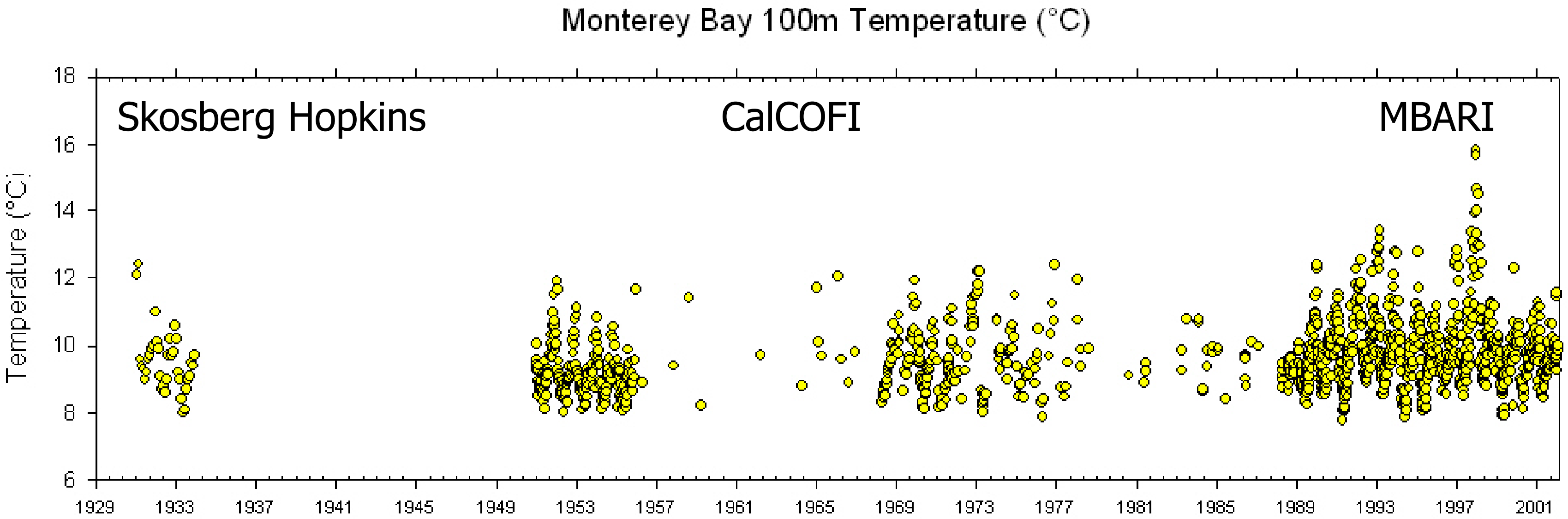




sigma
fluo/5
xmiss
sal
temp
nitrate
135
125
115
110
105
100
95
90
85
80
75
70
65
60
55
H3
C1
depth (m)
longitude
-128
-127
-126
-125
-124
-123
-122

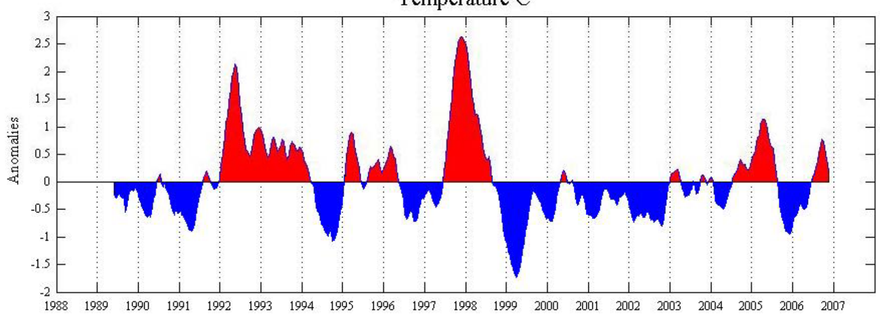
The history of Monterey Bay measurements at Station H3/M1



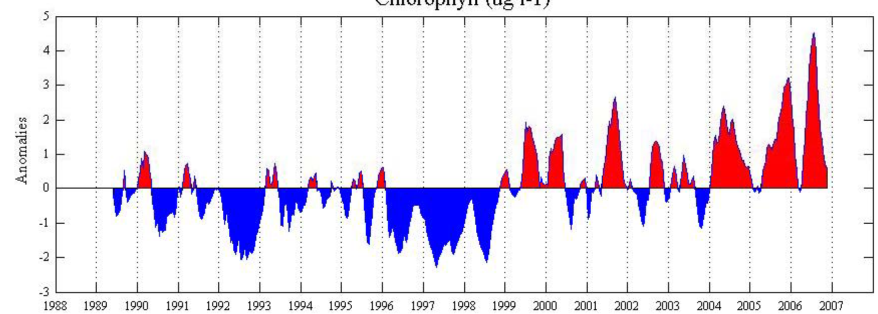


An Introduction to Anomalies

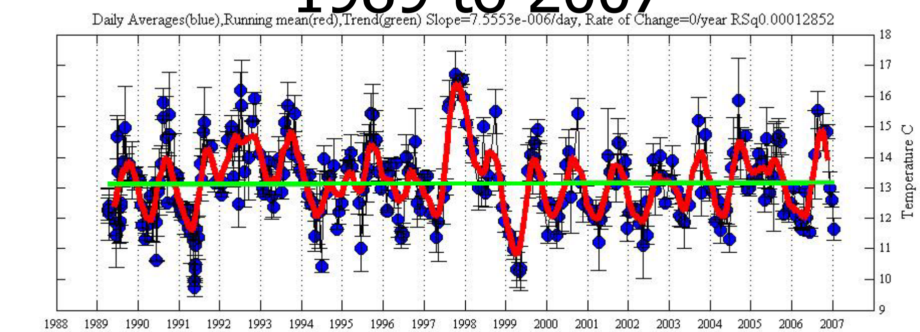
Temperature



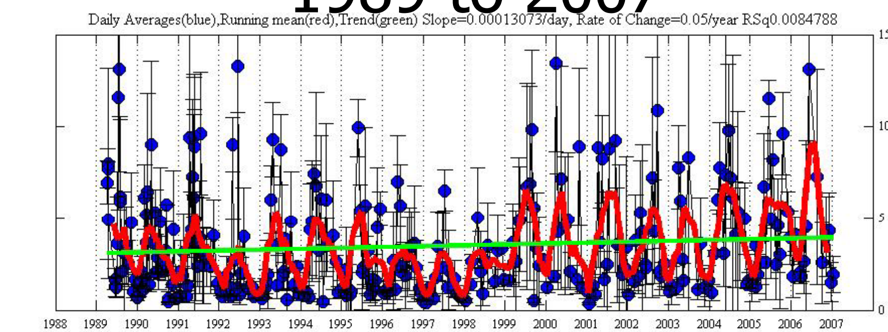
Chlorophyll



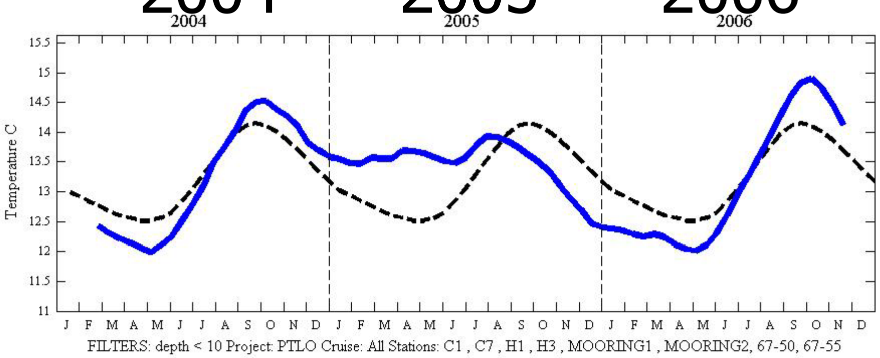
1989 to 2007



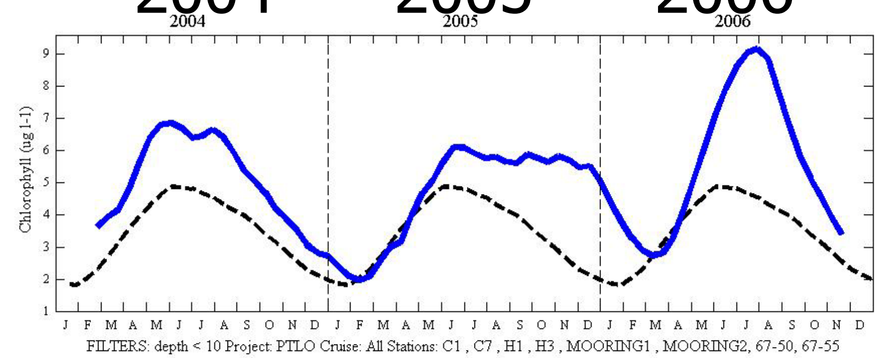
1989 to 2007

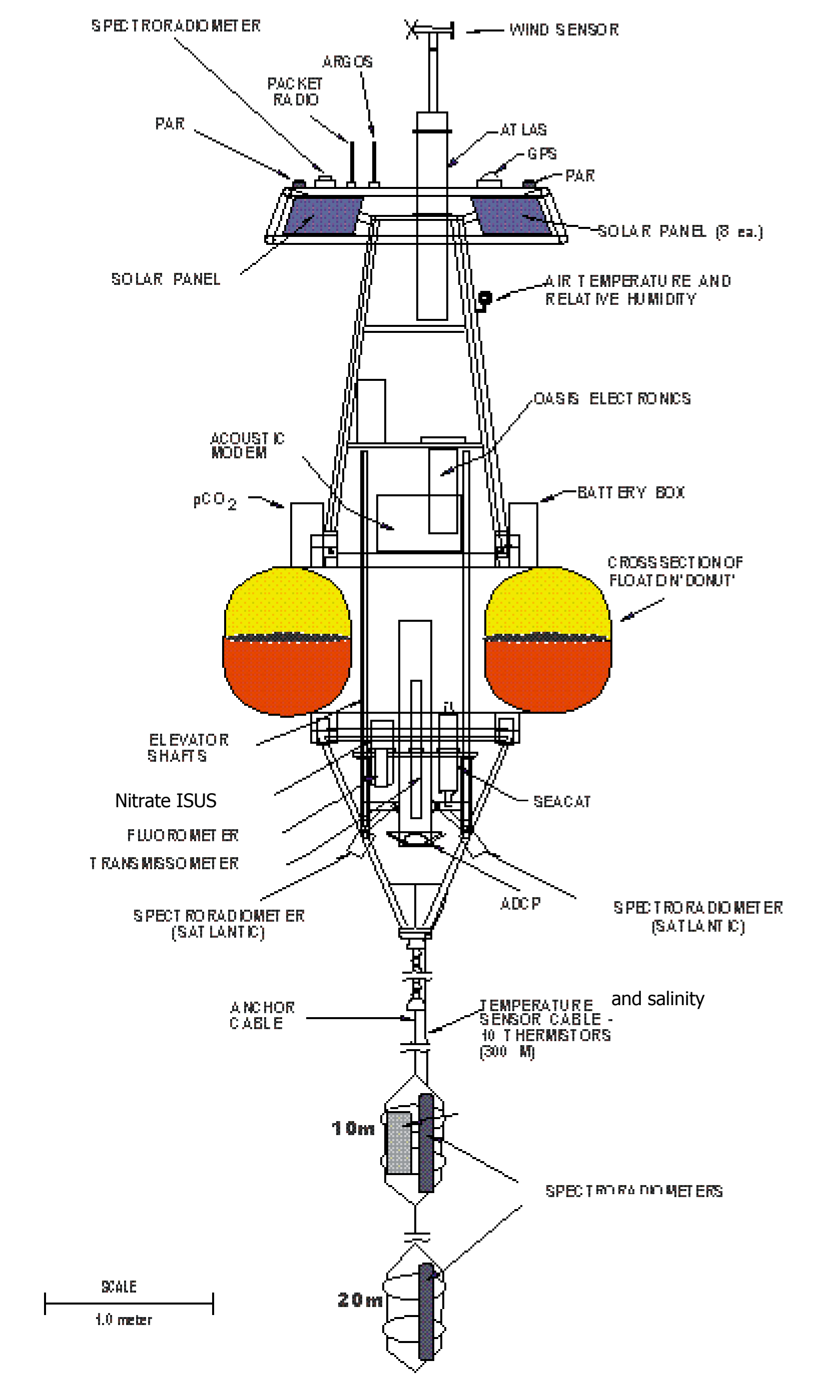


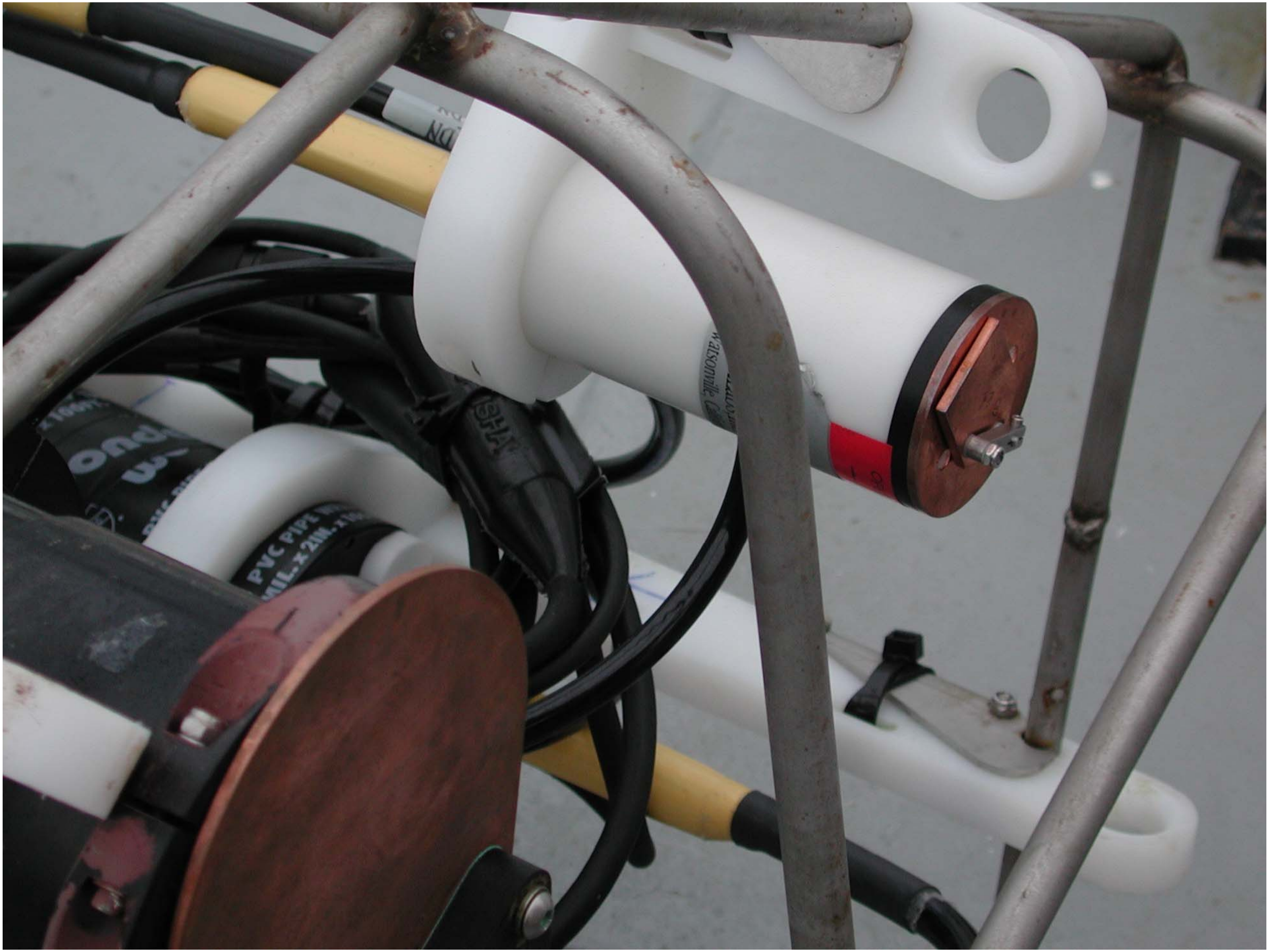
2004 2005 2006

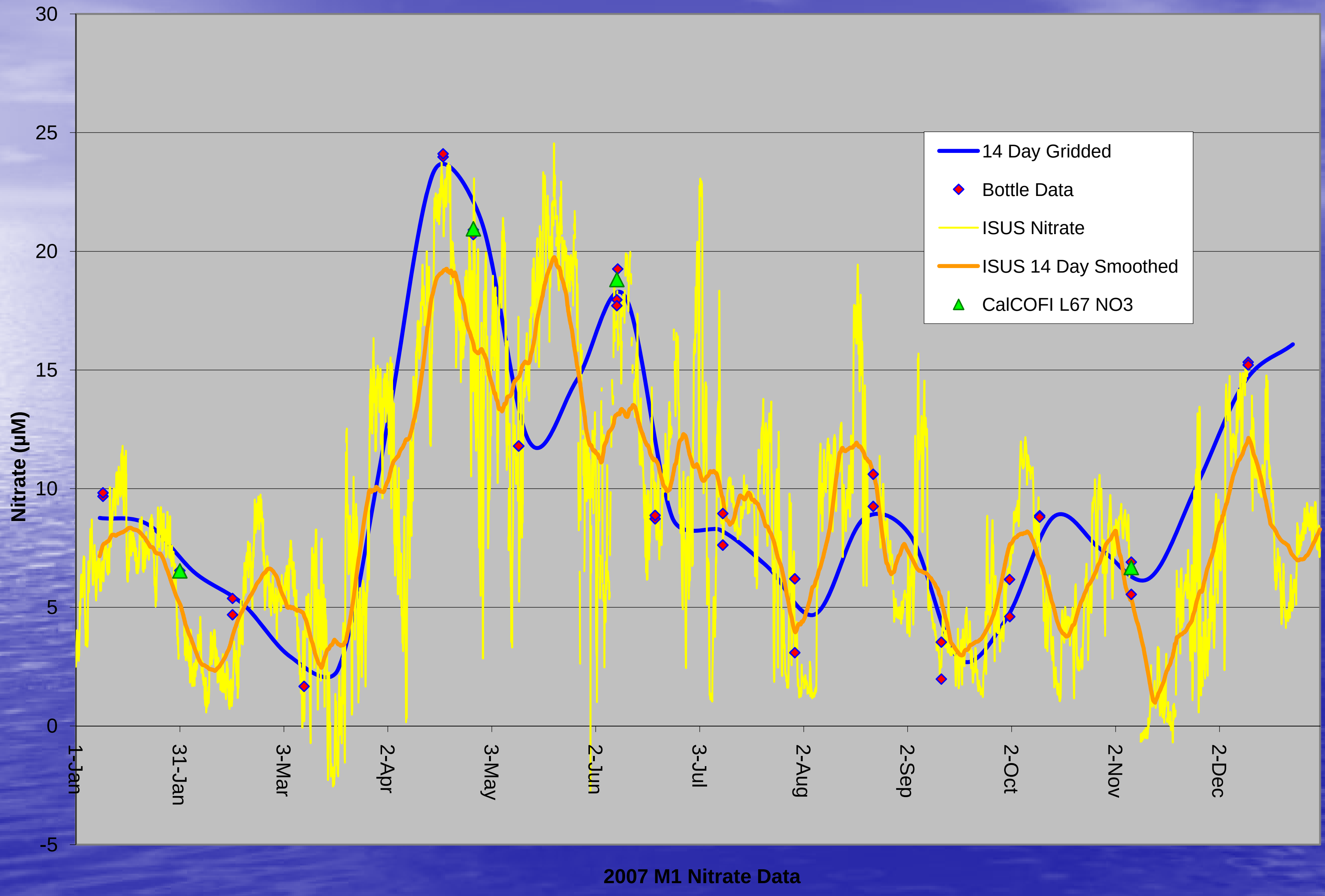


2004 2005 2006



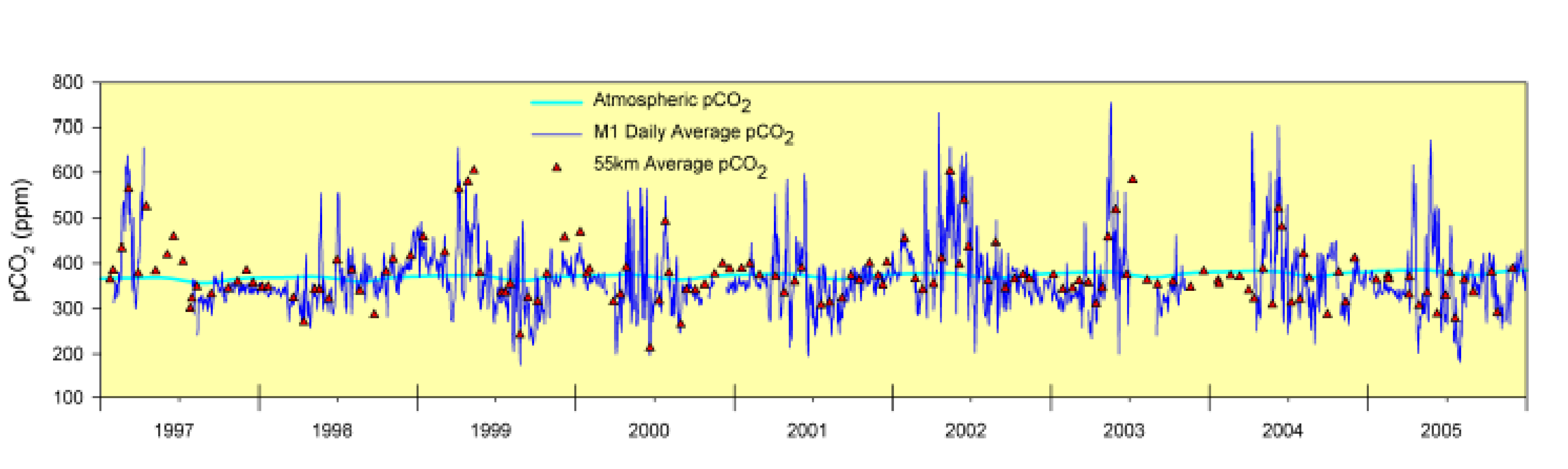

SPECTRORADIOMETER
WIND SENSOR
ARGOS
PACKET RADIO
PAR
ATLAS
GPS
PAR
SOLAR PANEL (8 ea.)
SOLAR PANEL
AIR TEMPERATURE AND RELATIVE HUMIDITY
OASIS ELECTRONICS
ACOUSTIC MODEM
pCO2
BATTERY BOX
CROSS SECTION OF FLOATIN' DONUT'
ELEVATOR SHAFTS
Nitrate ISUS
SEACAT
FLUOROMETER
TRANSMISSOMETER
SPECTRORADIOMETER (SATLANTIC)
ADCP
SPECTRORADIOMETER (SATLANTIC)
ANCHOR CABLE
TEMPERATURE and salinity SENSOR CABLE - 10 THERMISTORS (300 M)
10m
SPECTRORADIOMETERS
20m
SCALE
1.0 meter


PVC PIPE



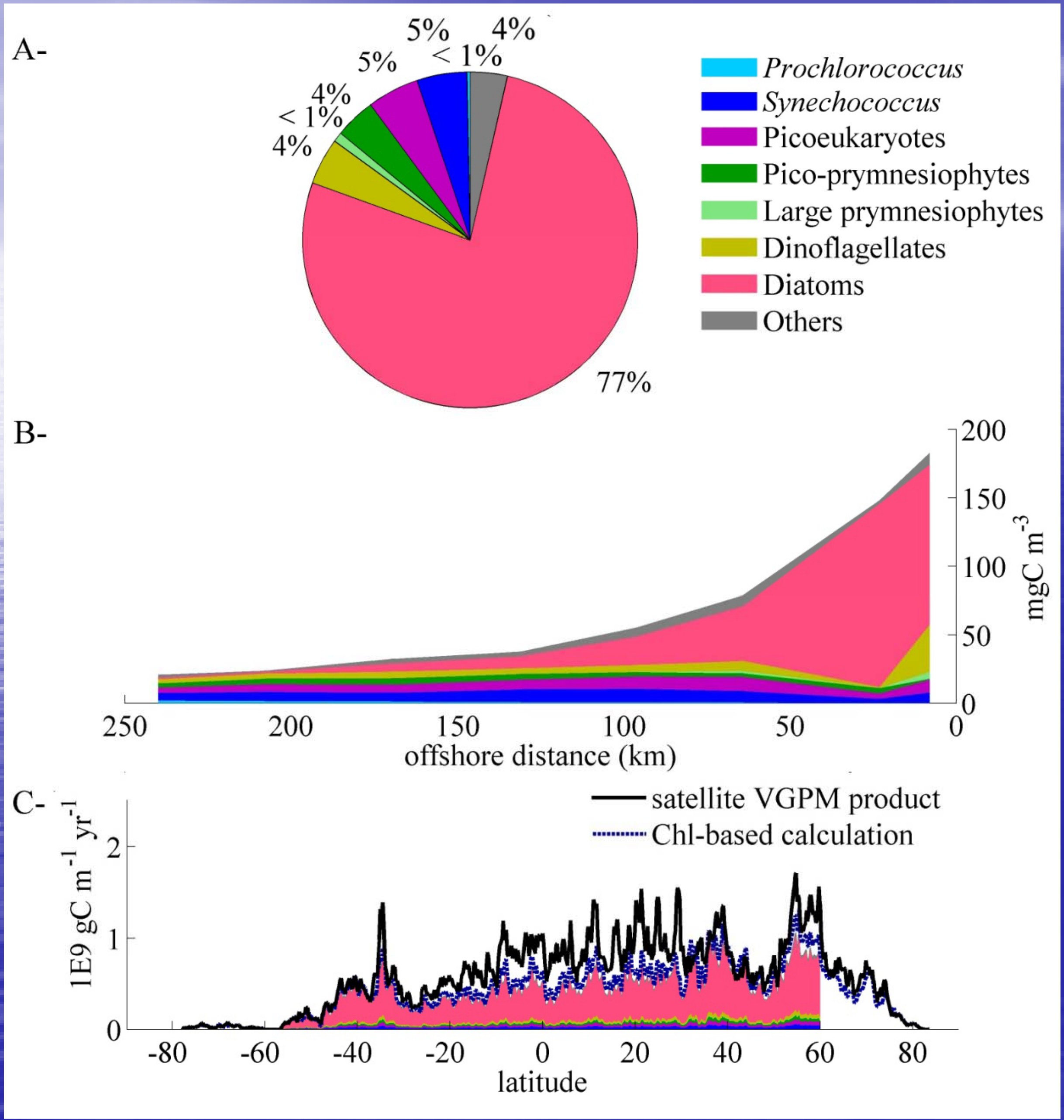
Nitrate (µM)
30
25
20
15
10
5
0
-5
1-Jan
31-Jan
3-Mar
2-Apr
3-May
2-Jun
3-Jul
2-Aug
2-Sep
2-Oct
2-Nov
2-Dec
14 Day Gridded
Bottle Data
ISUS Nitrate
ISUS 14 Day Smoothed
CalCOFI L67 NO3
2007 M1 Nitrate Data

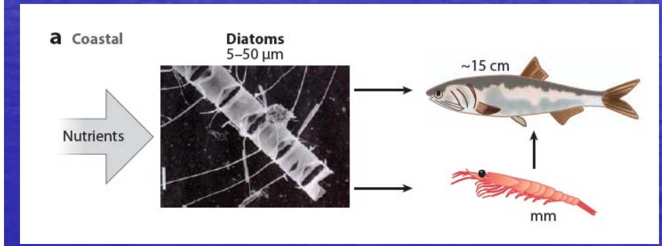
M1 and ship section average



Slope between M1 and ship = 1

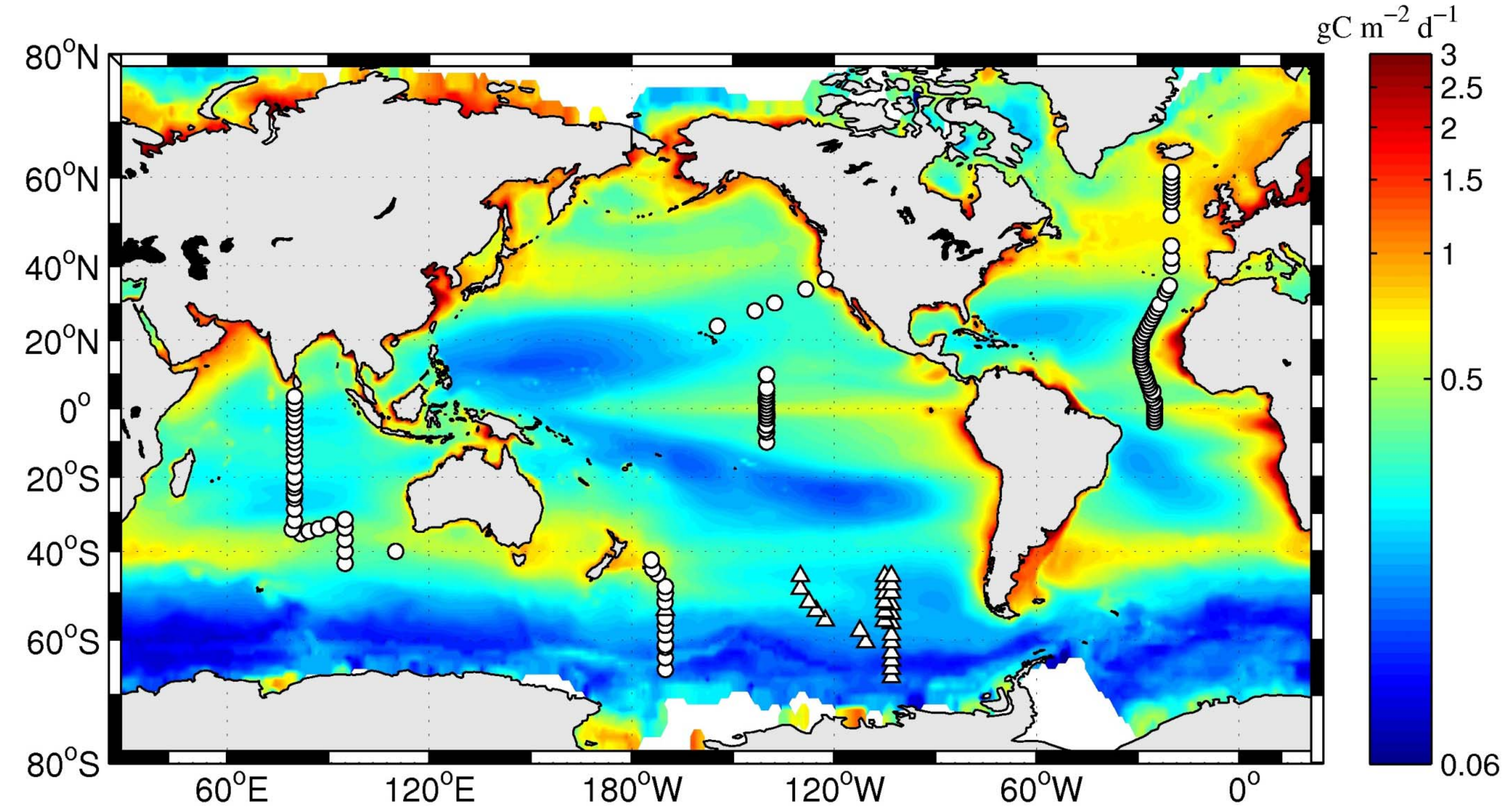
Diatom domination that transitions to pico-dominated offshore





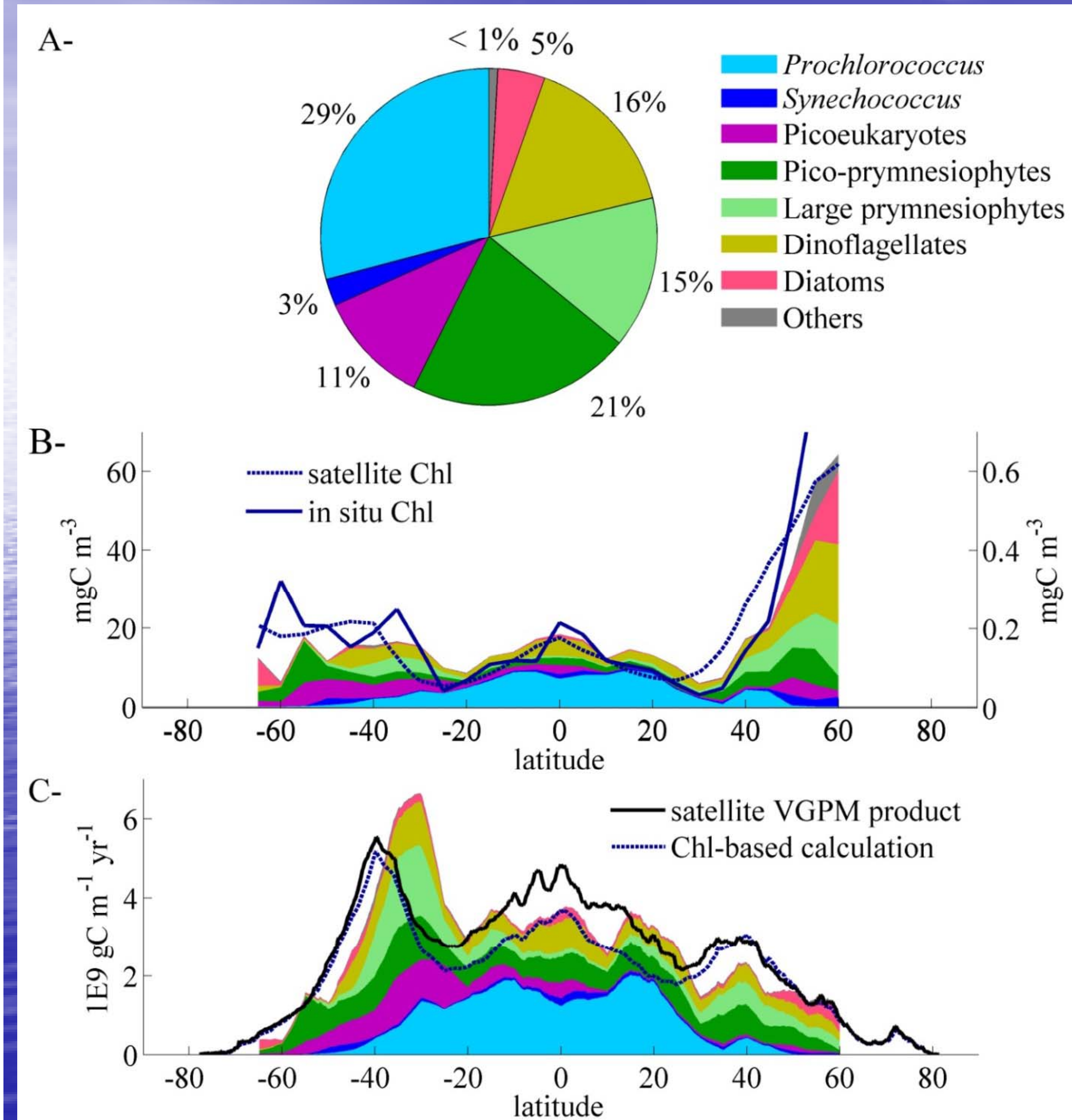
Coastal out to 150 km ~16% of global NPP

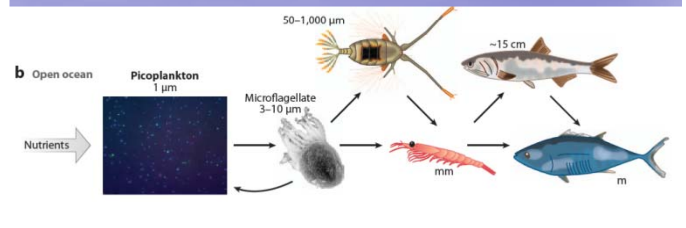
Locations where the full photosynthetic plankton community was enumerated and sized by flow cytometry and microscopy



All stations collapsed into a single latitudinal profile and the same done with SeaWiFS chlorophyll

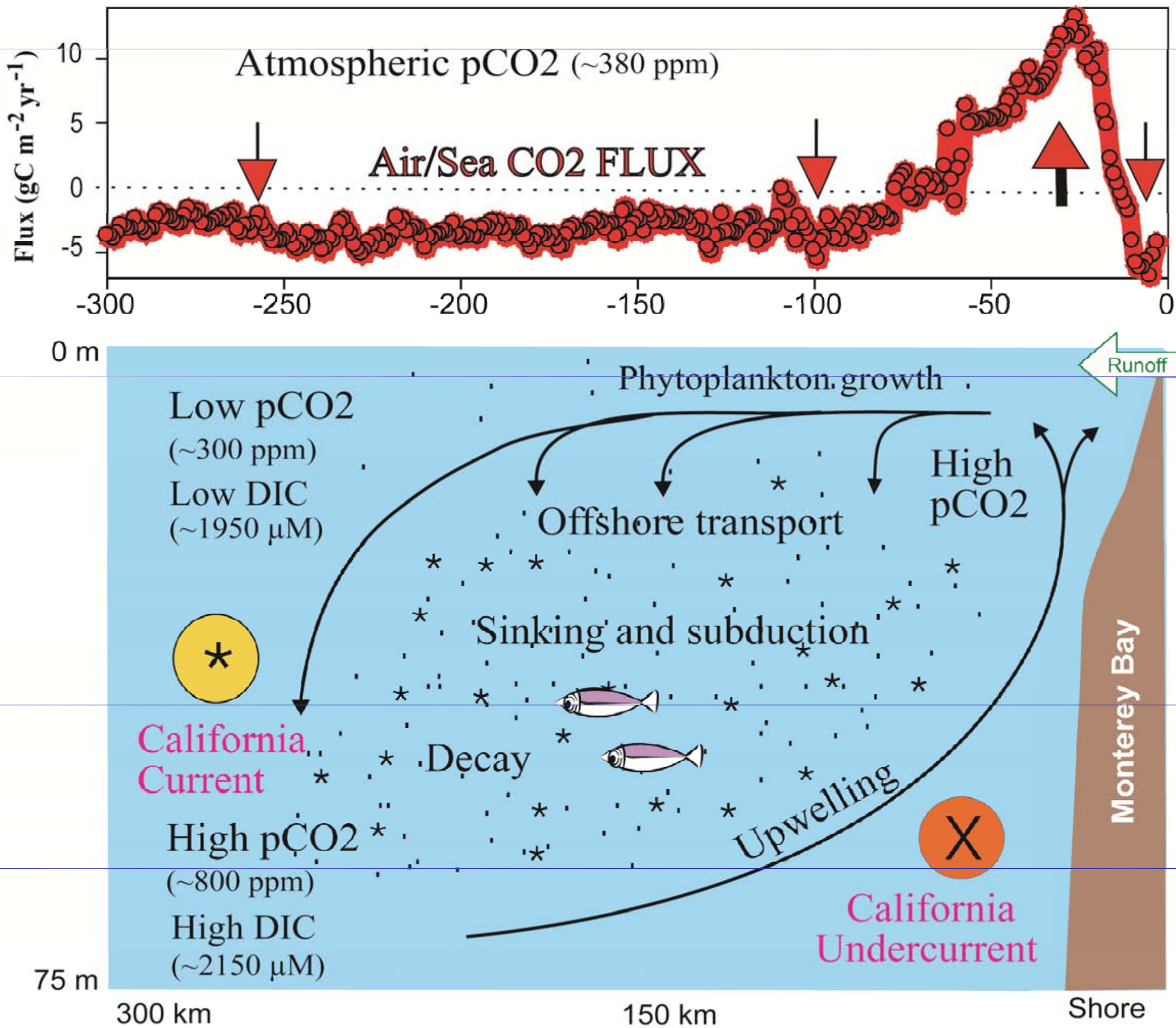
$$PP = 0.66125 * PAR / (PAR+4.1) * Z_{eu} * B_0 * \mu * DL$$



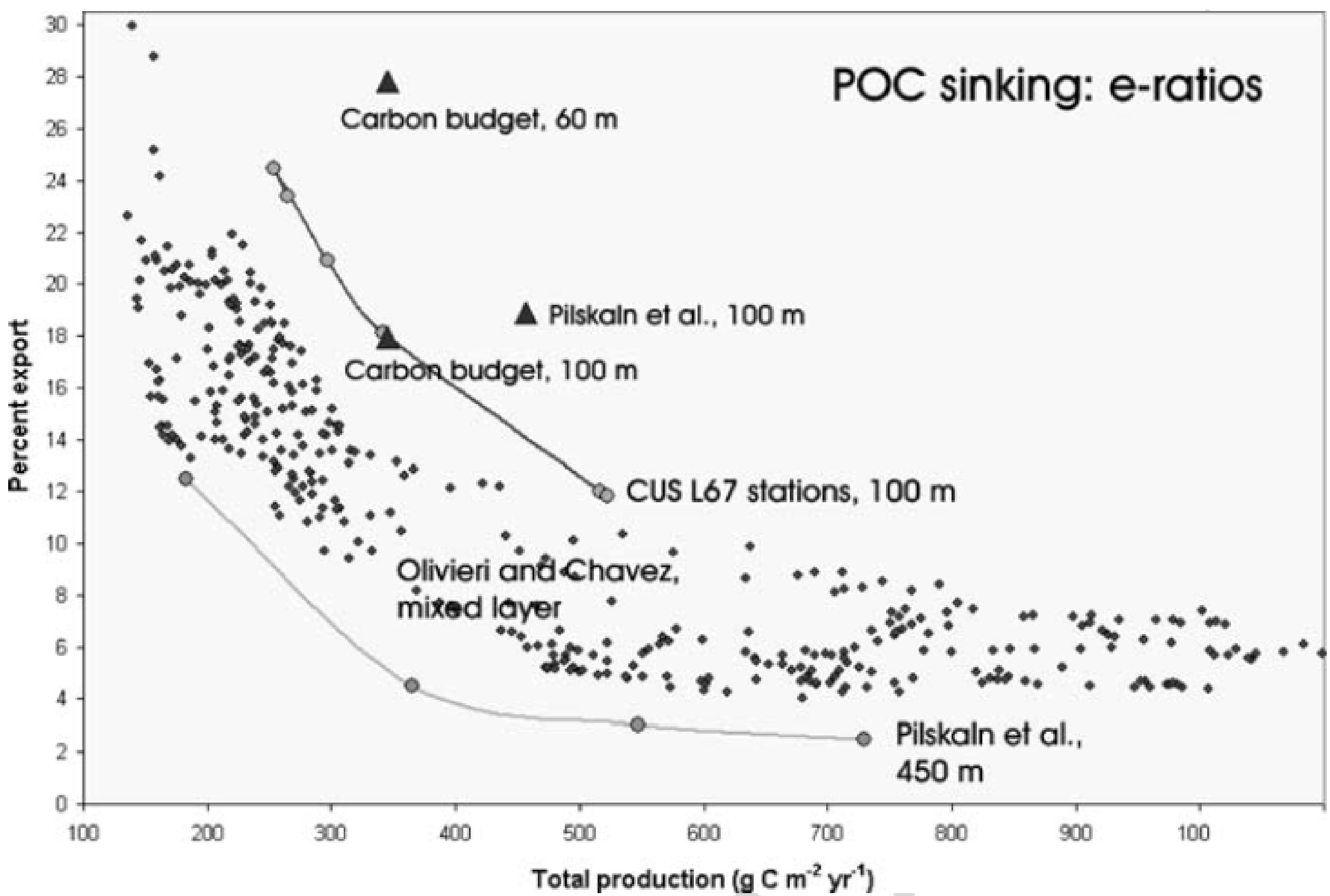


R=0.91 between cruise data and composite satellite chlorophyll

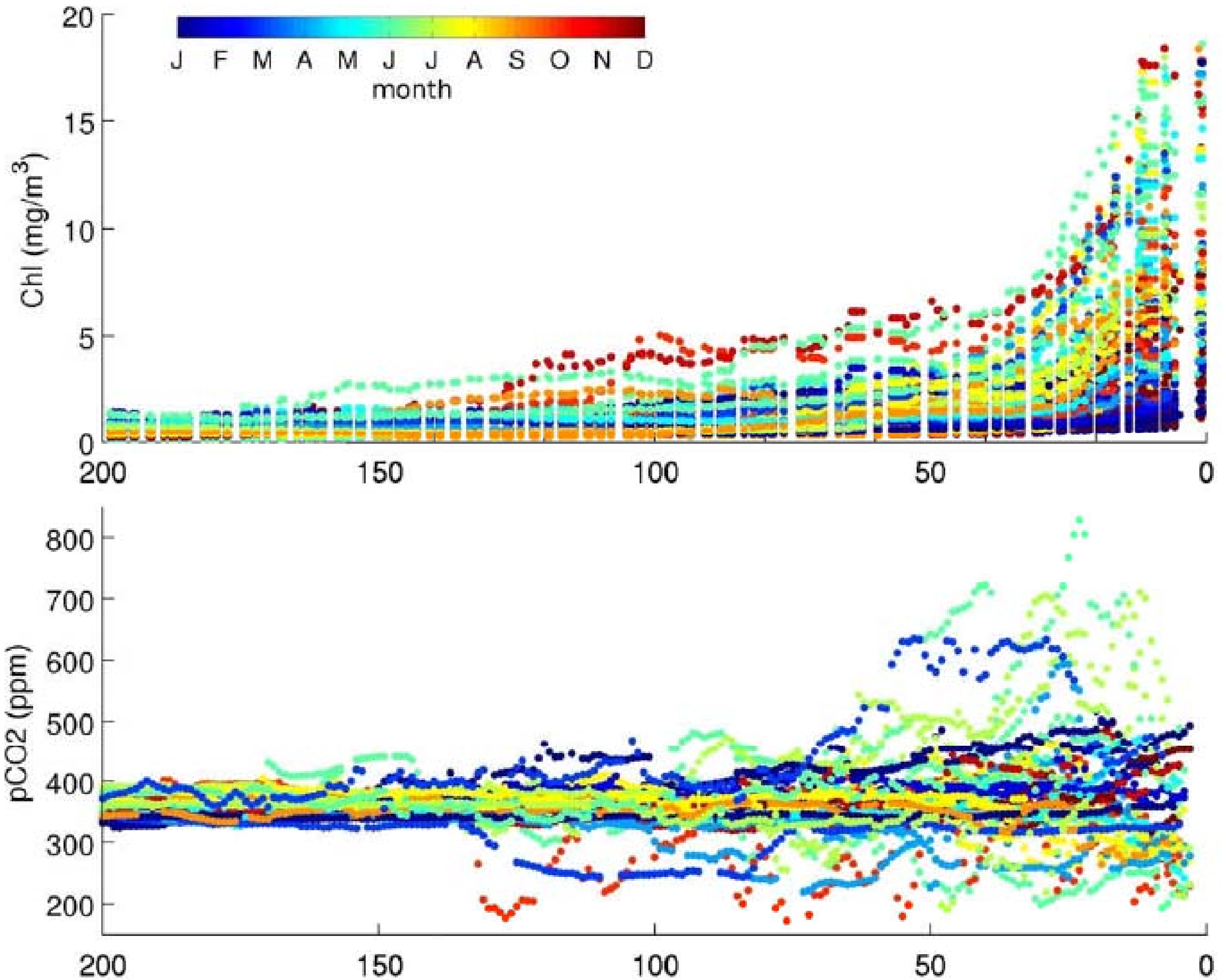
Sum all of the groups and estimate ~50 Petagrams carbon per year



Chavez et al. 2006

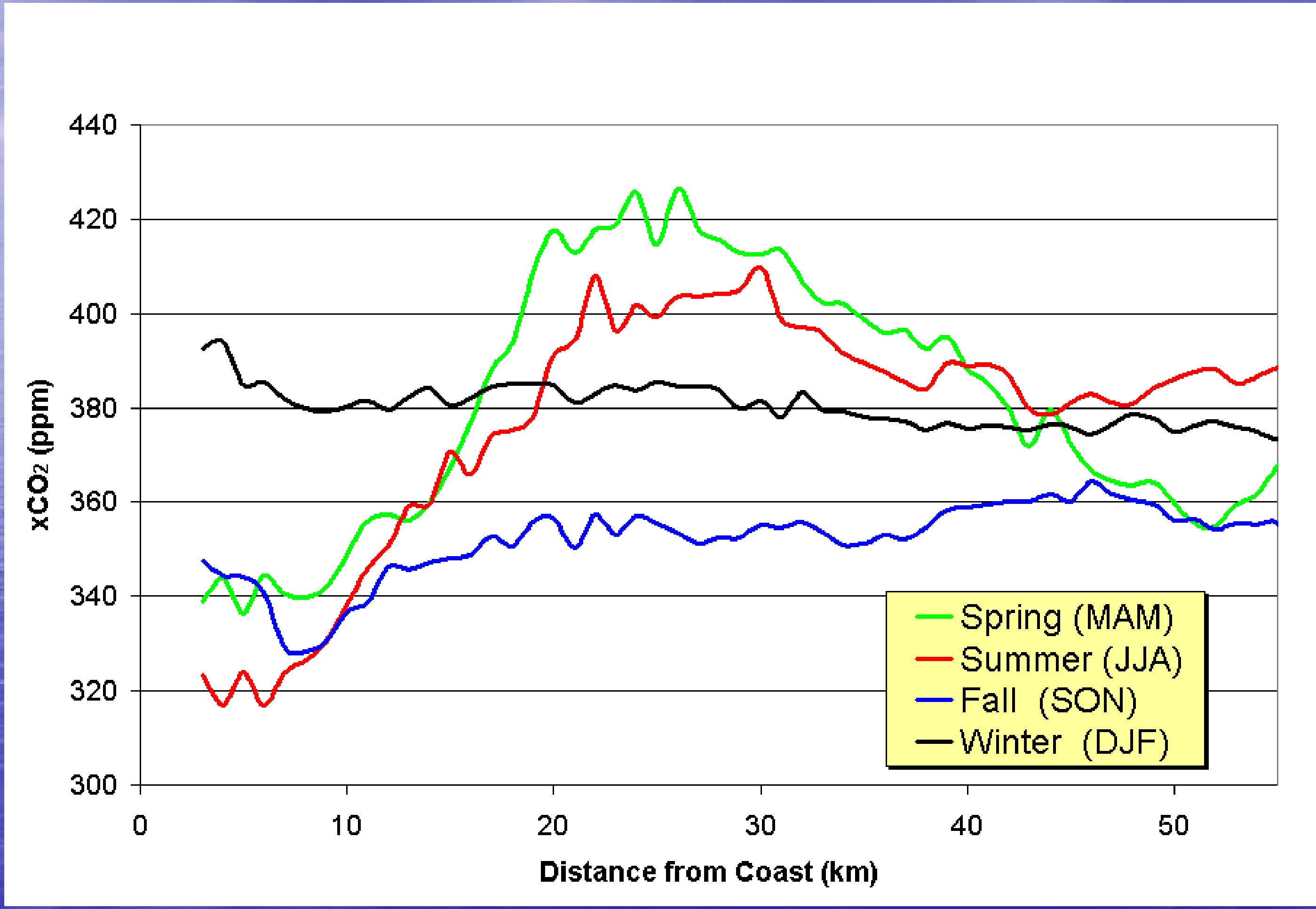


Pennington et al. (2009)



Chavez and Messie, 2009

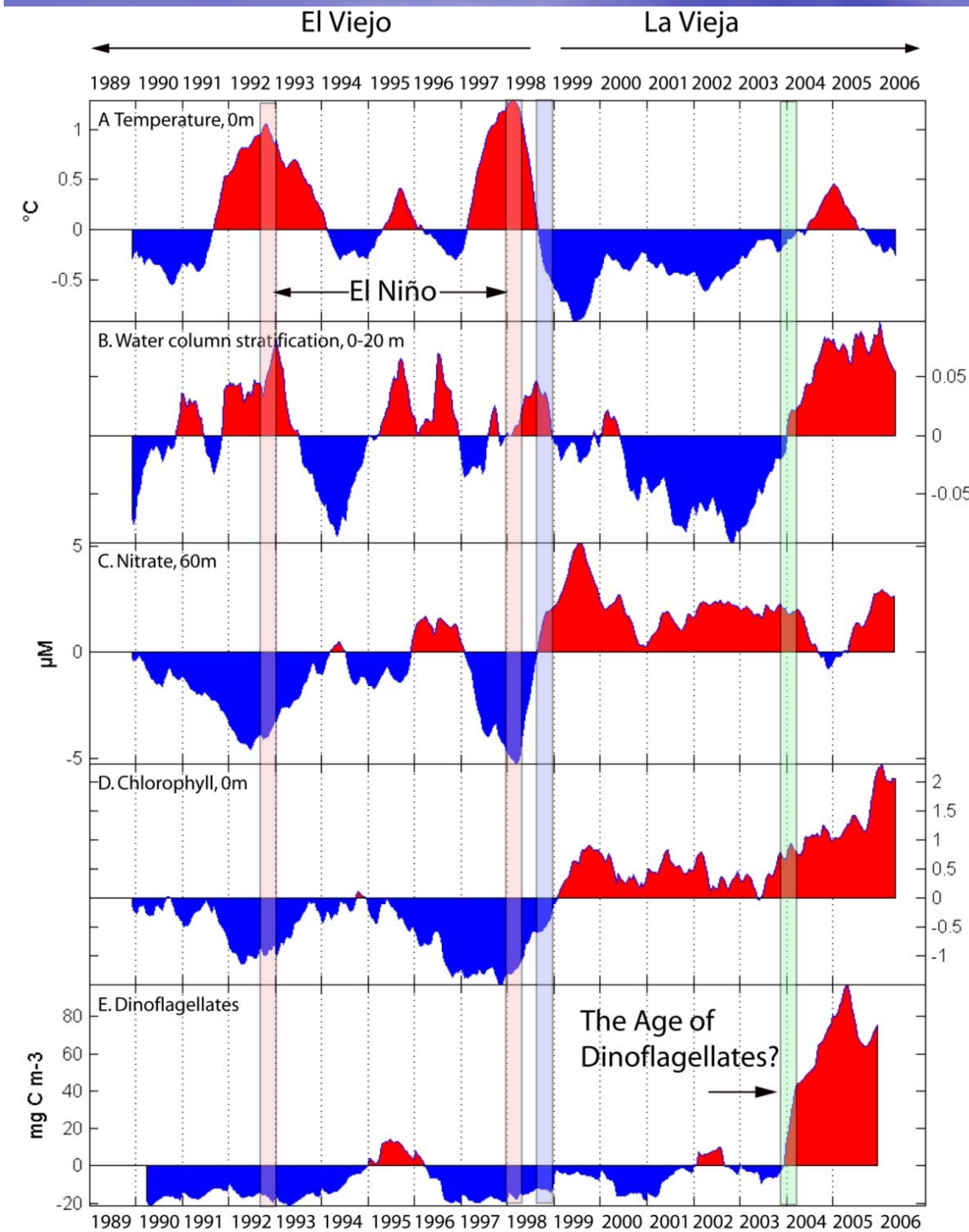
Drawdown of CO_2 driven by seasonal cycle of light, temperature and productivity

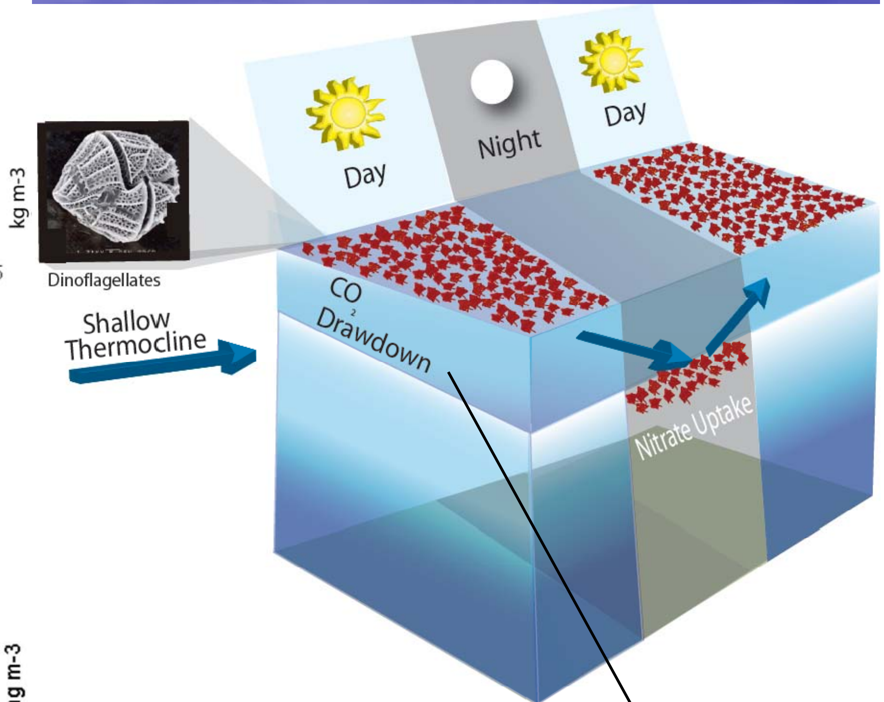


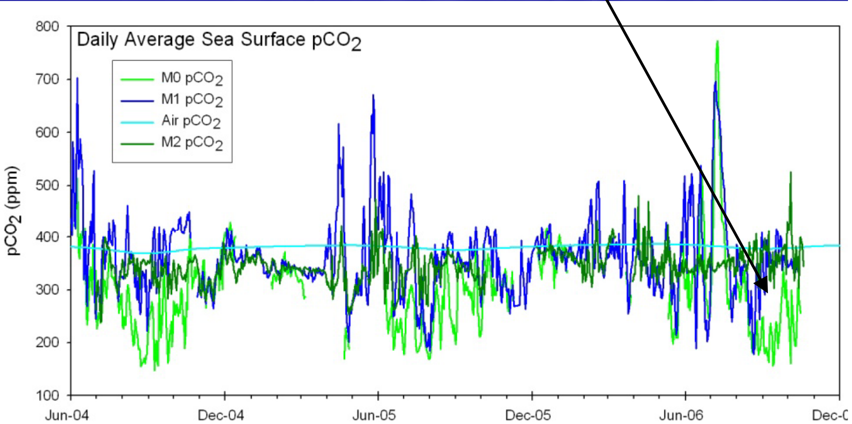
Offshore exactly opposite due to warming

Monterey Bay Time Series

- El Niños during 92-93 and 97-98
- Transition from El Viejo to La Vieja
- The age of dinoflagellates?

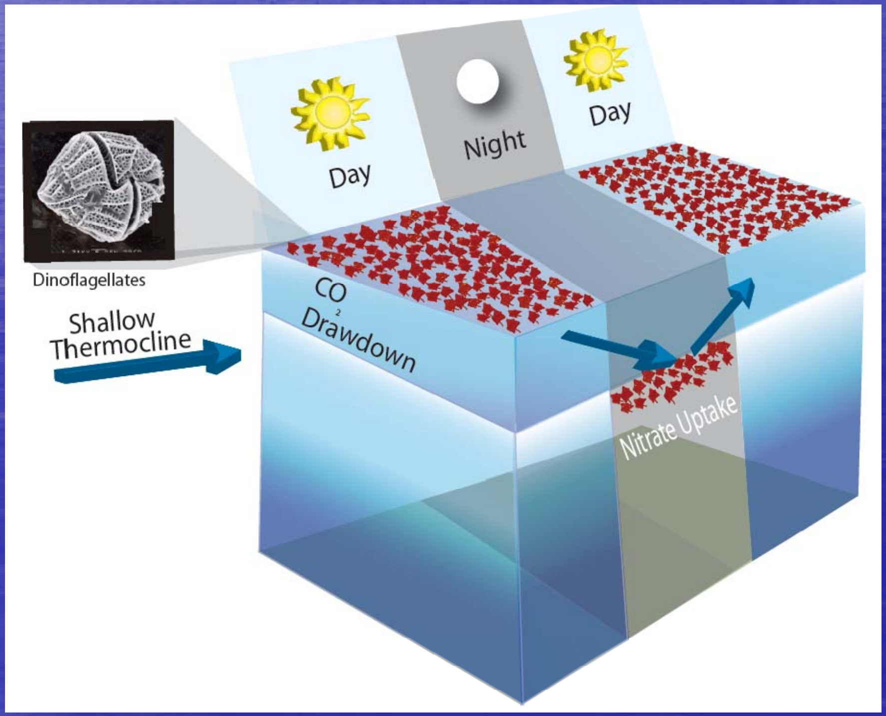






We see this CO_2 drawdown pattern in upwelling shadows:

- Monterey Bay
- Southern California Bight, Baja
- Peru

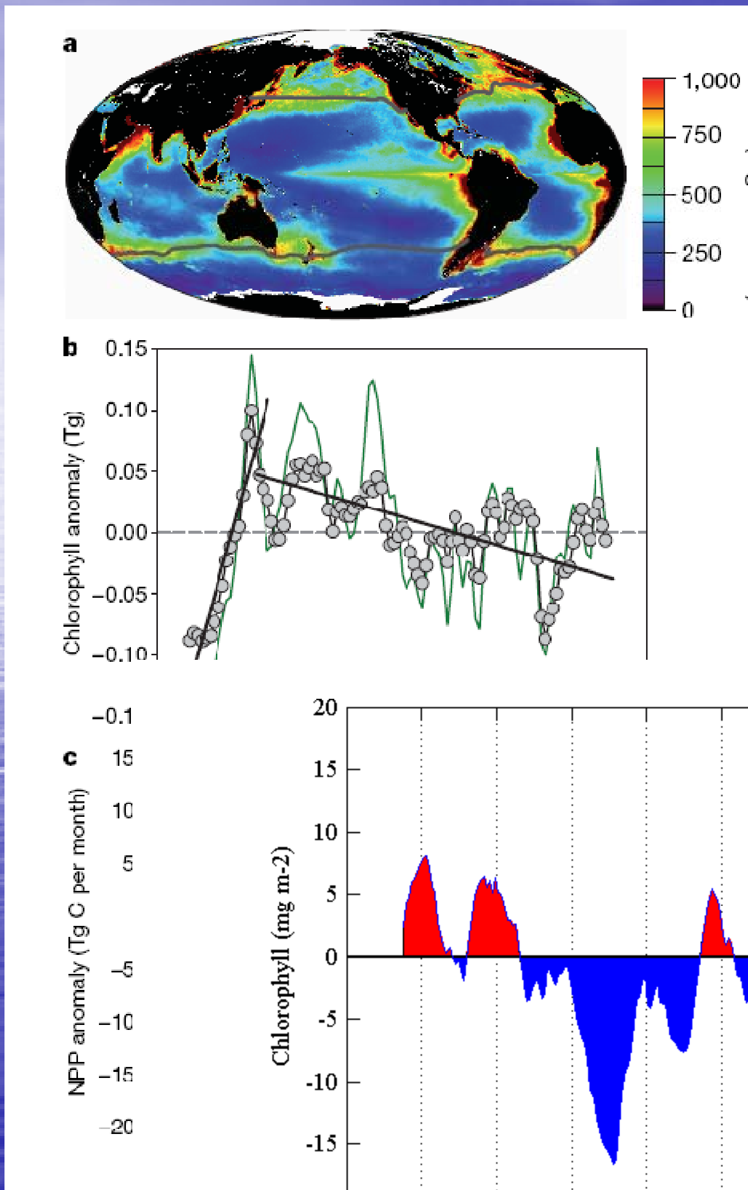


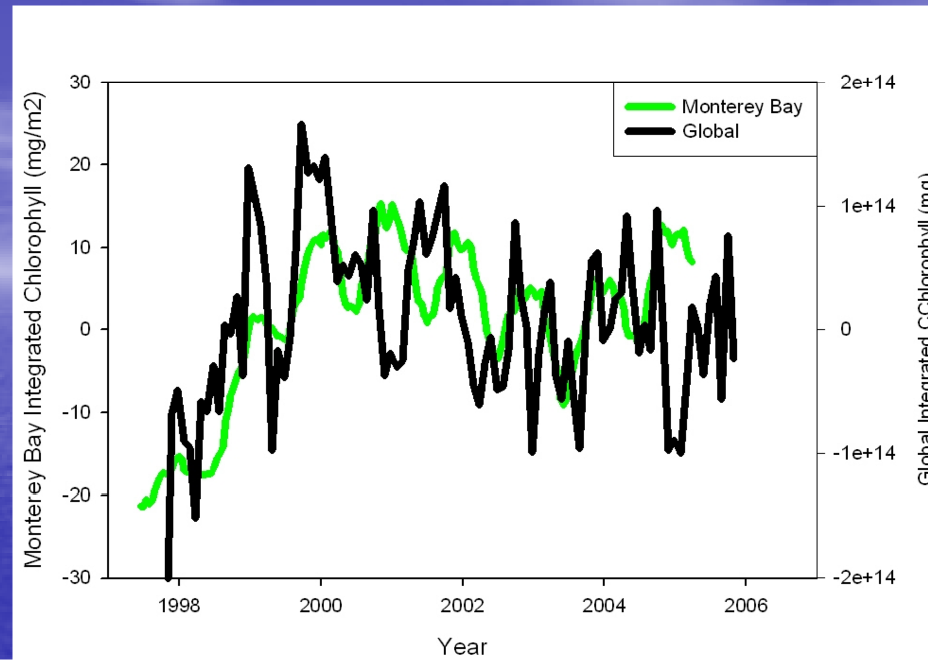
Dinoflagellates solution to CO_2 problem!

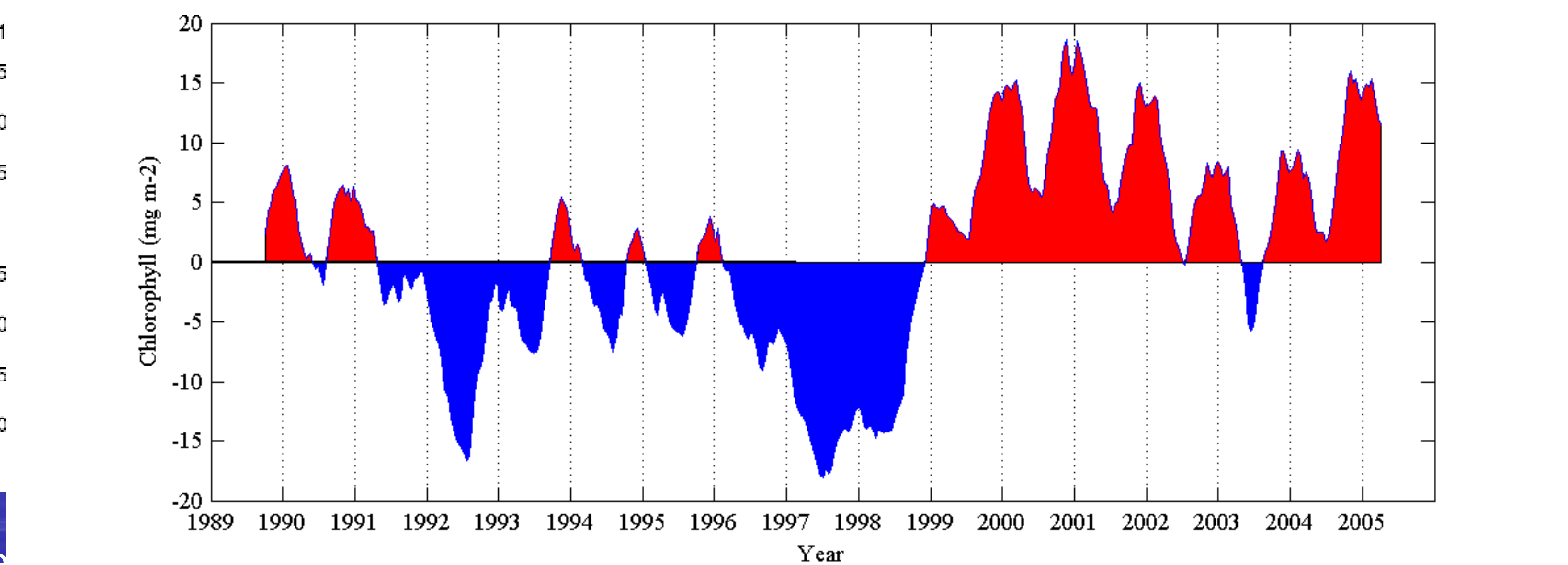
The Paleocene

- Dinoflagellates were prominent globally along coastal margins 55 million years ago when there was a rapid carbon release into the atmosphere and oceans, rivaling the present anthropogenic release of CO_2, and the world was significantly warmer

The Length of the Record is Important

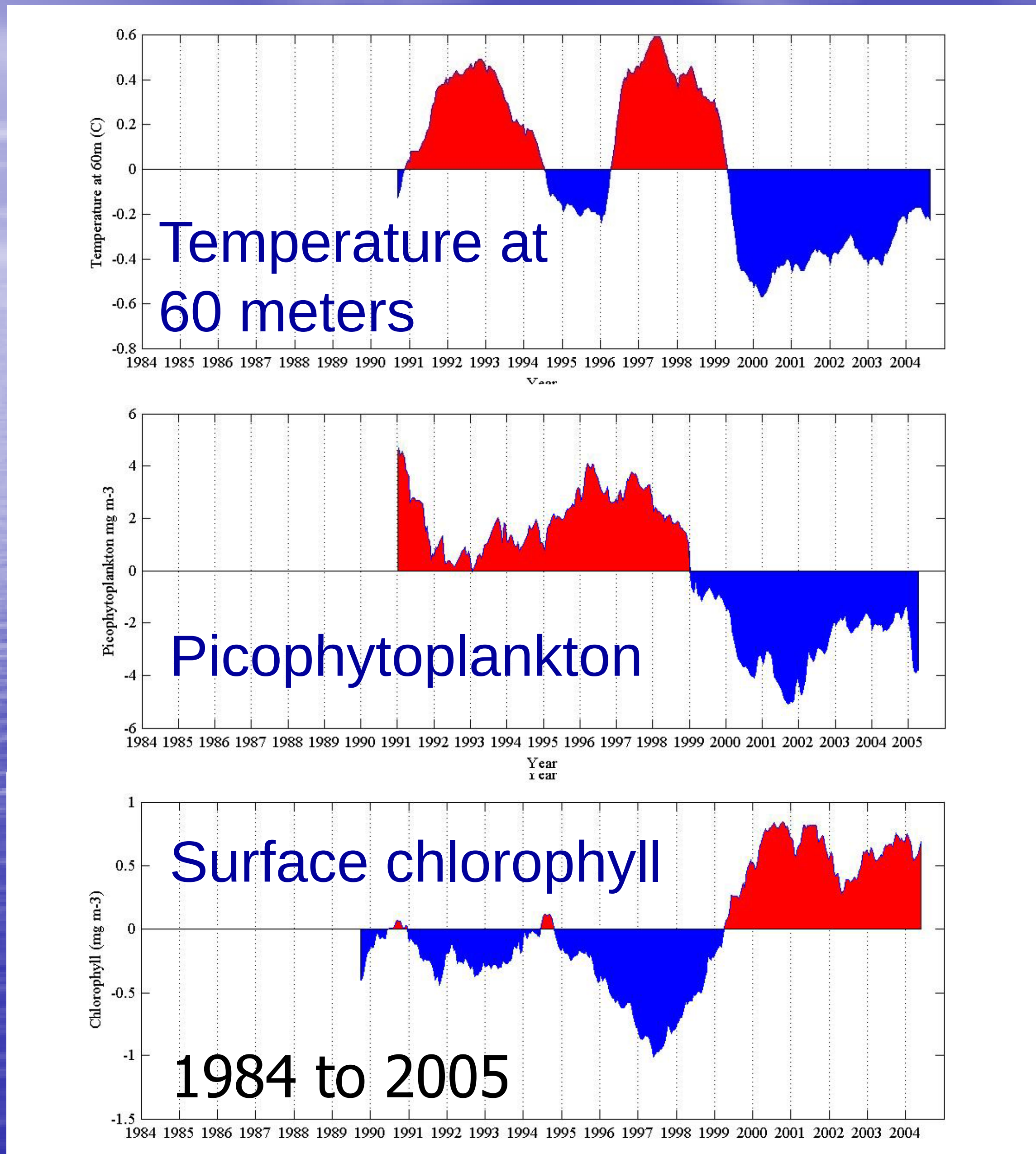






Behrenfeld et al., Nature 2007

Greening correlated with cooling and increase of nutrients at depth



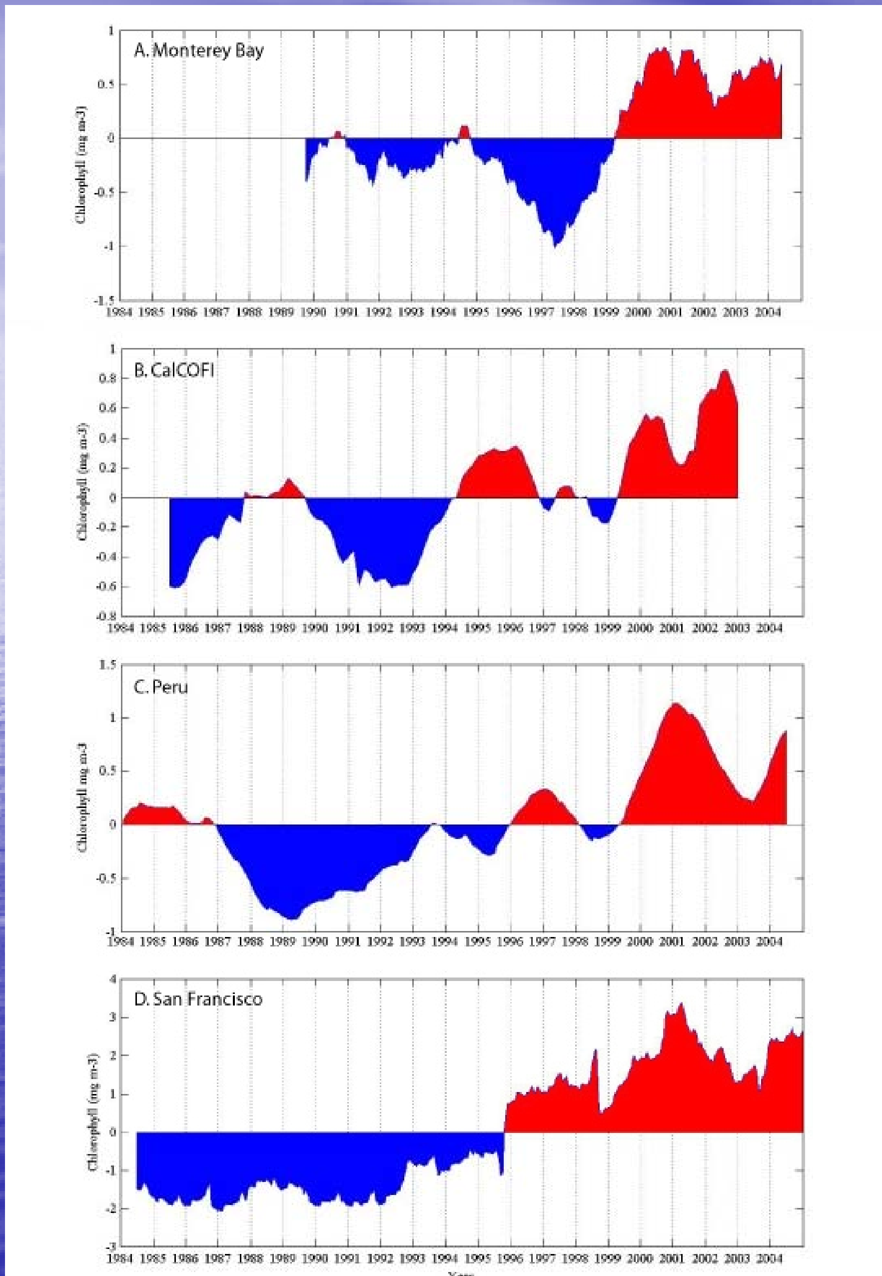
1985 1990 1995 2000 2005

Monterey Bay Temperature at Depth

Monterey Bay Nitrate at Depth

Monterey Bay Surface Chlorophyll

What is responsible for greening of California coastal waters?



1985 1990 1995 2000 2005

Monterey Bay chlorophyll

Southern California chlorophyll

Peru chlorophyll

San Francisco Bay chlorophyll

Global data sets

- Sea surface temperature (SST) - >100 y
- Sea surface height ~ 18 y
- Sea surface chlorophyll ~ 12 y

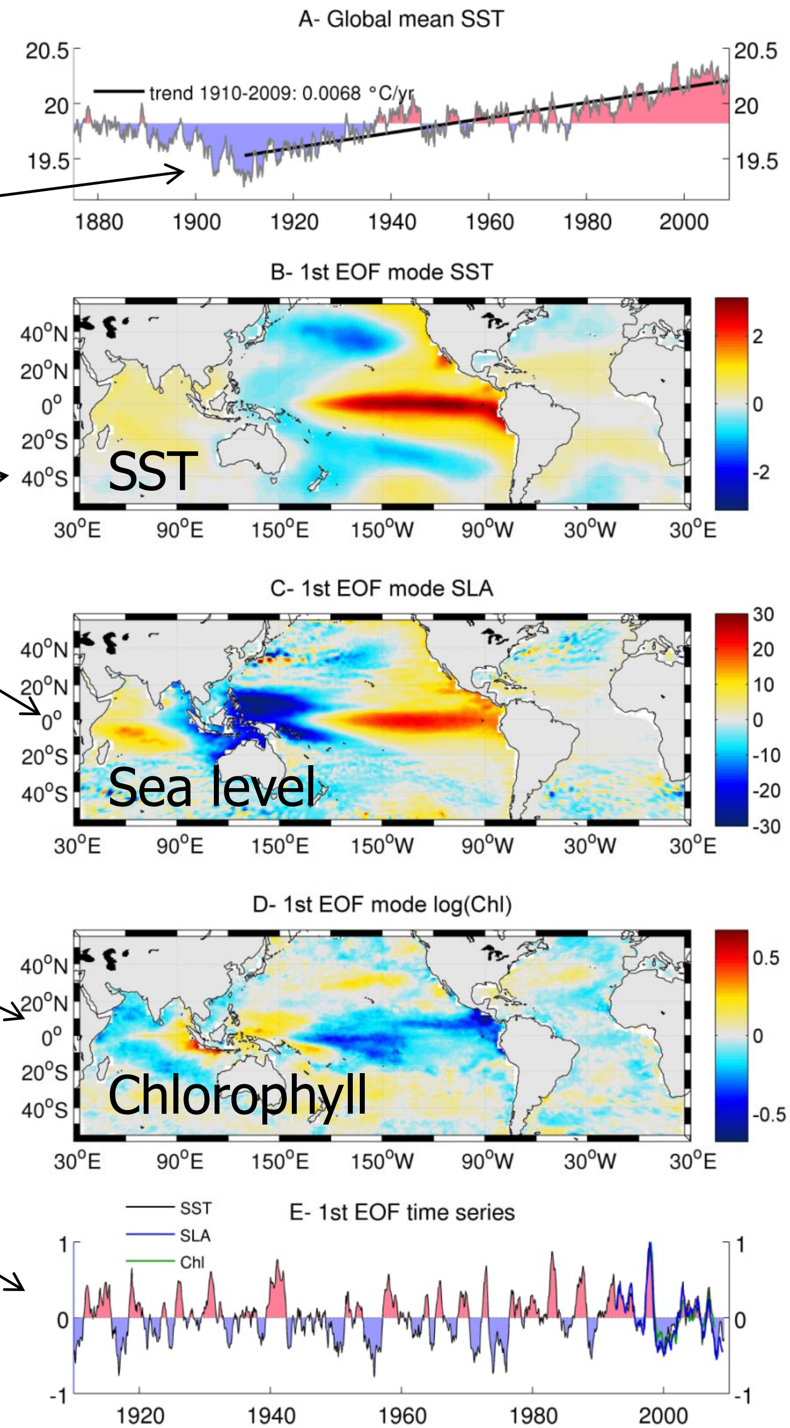
- Strong coherence

Scales of variability

- Past century – ENSO, AMO, PDO, NPGO, El Niño Modoki
- Past 400-500 years – Medieval Warm Period, Little Ice Age, the present
- THE Ice ages – not treated here
- Global warming – which of the above is the most likely analog?

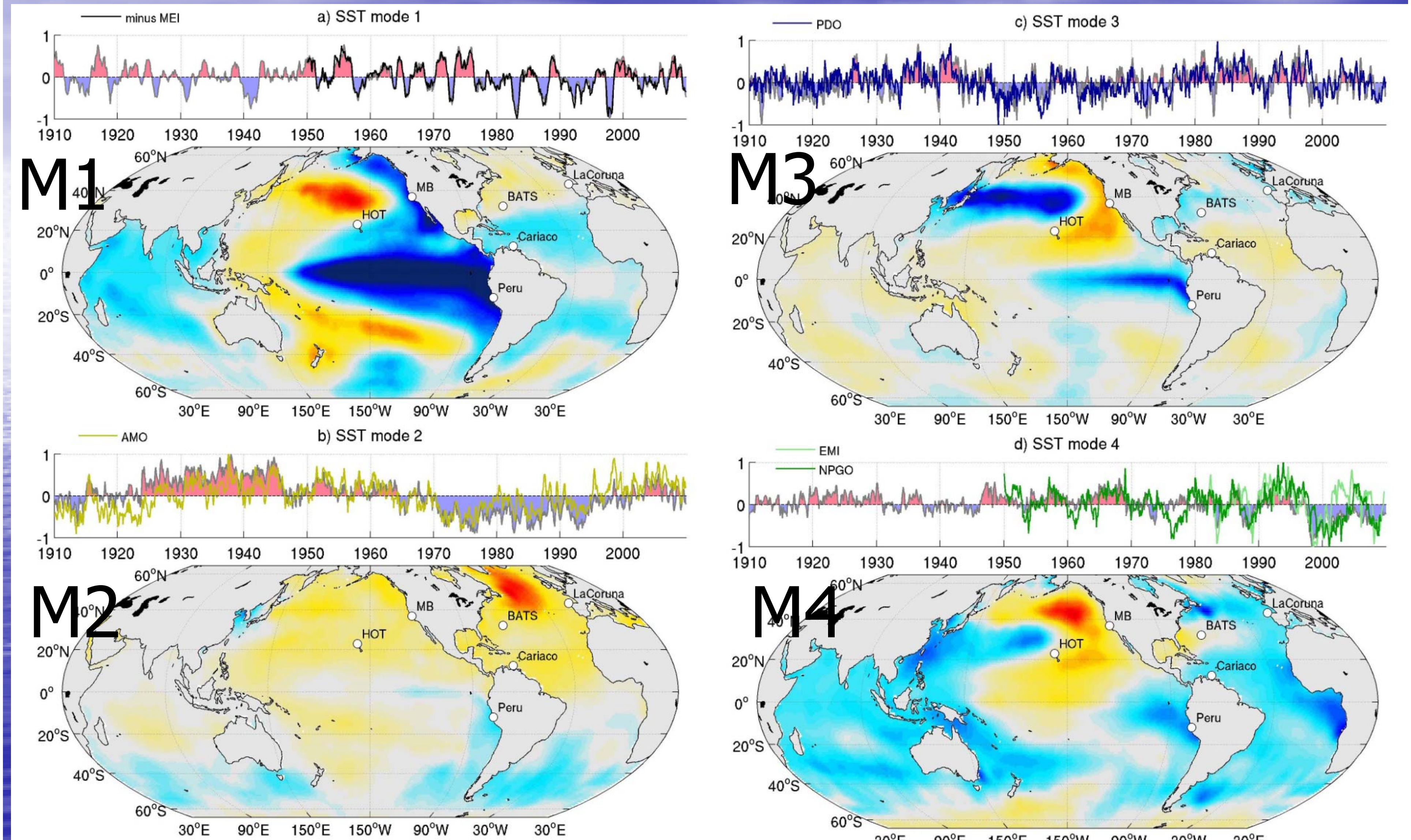
In the following series of SST maps the global trend from 1910 to 2009 and seasonal cycle has been removed and an EOF analysis performed. The first mode captures ENSO. Many other properties, like sea level, chlorophyll, sea level pressure (next slide), PAR or sunlight, winds, currents (last not shown) also display ENSO as their dominant mode.

The principal component time series are identical and correlated with the Multivariate ENSO Index (MEI)



The first four global modes of SST variability (Messie and Chavez, sub)

El Niño/ La Niña   Pacific Decadal Oscillation



Atlantic Multidecadal Oscillation   El Niño Modoki/North Pacific Gyre

GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L08607, doi:10.1029/2007GL032838, 2008

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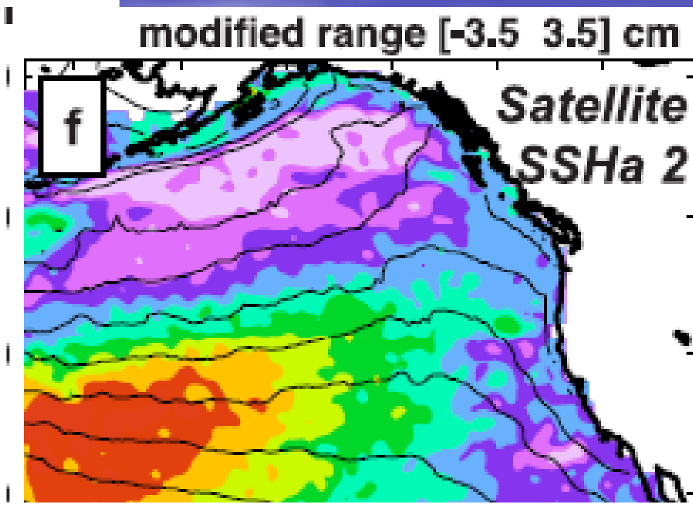
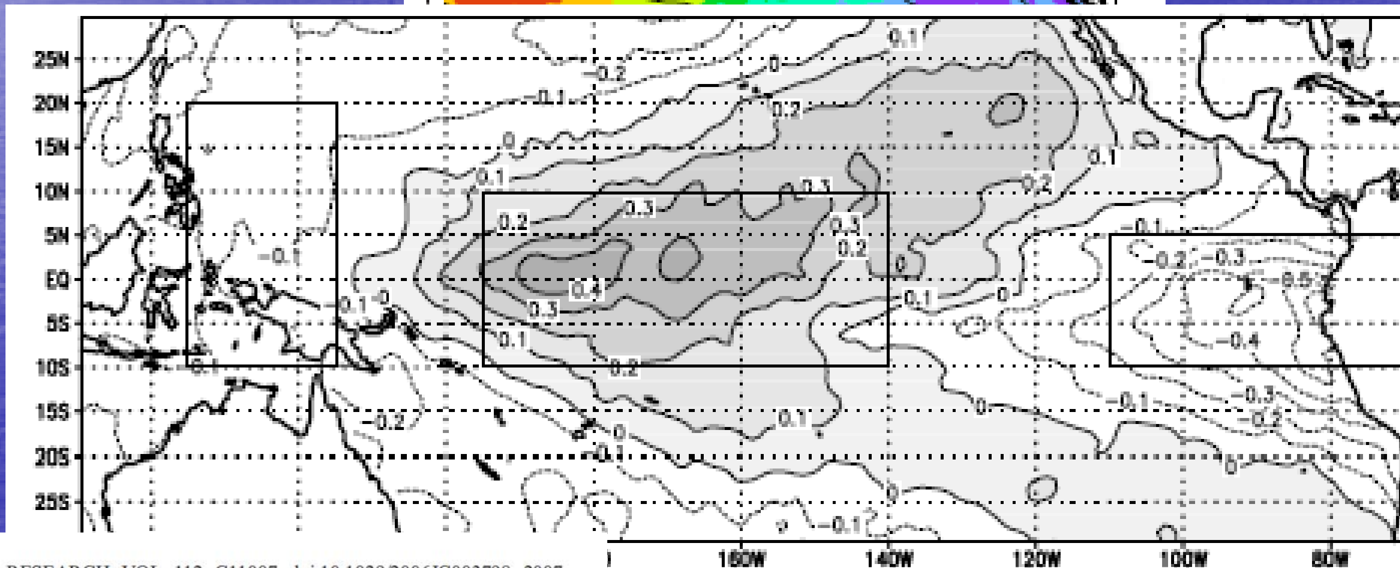
North Pacific Gyre Oscillation links ocean climate and ecosystem change

E. Di Lorenzo,[1] N. Schneider,[2] K. M. Cobb,[1] P. J. S. Franks,[3] K. Chhak,[1] A. J. Miller,[4] J. C. McWilliams,[5] S. J. Bograd,[6] H. Arango,[7] E. Curchitser,[7] T. M. Powell,[8] and P. Rivière[9]

Received 29 November 2007; revised 31 January 2008; accepted 19 February 2008; published 30 April 2008.





JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, C11007, doi:10.1029/2006JC003798, 2007

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El Niño Modoki and its possible teleconnection

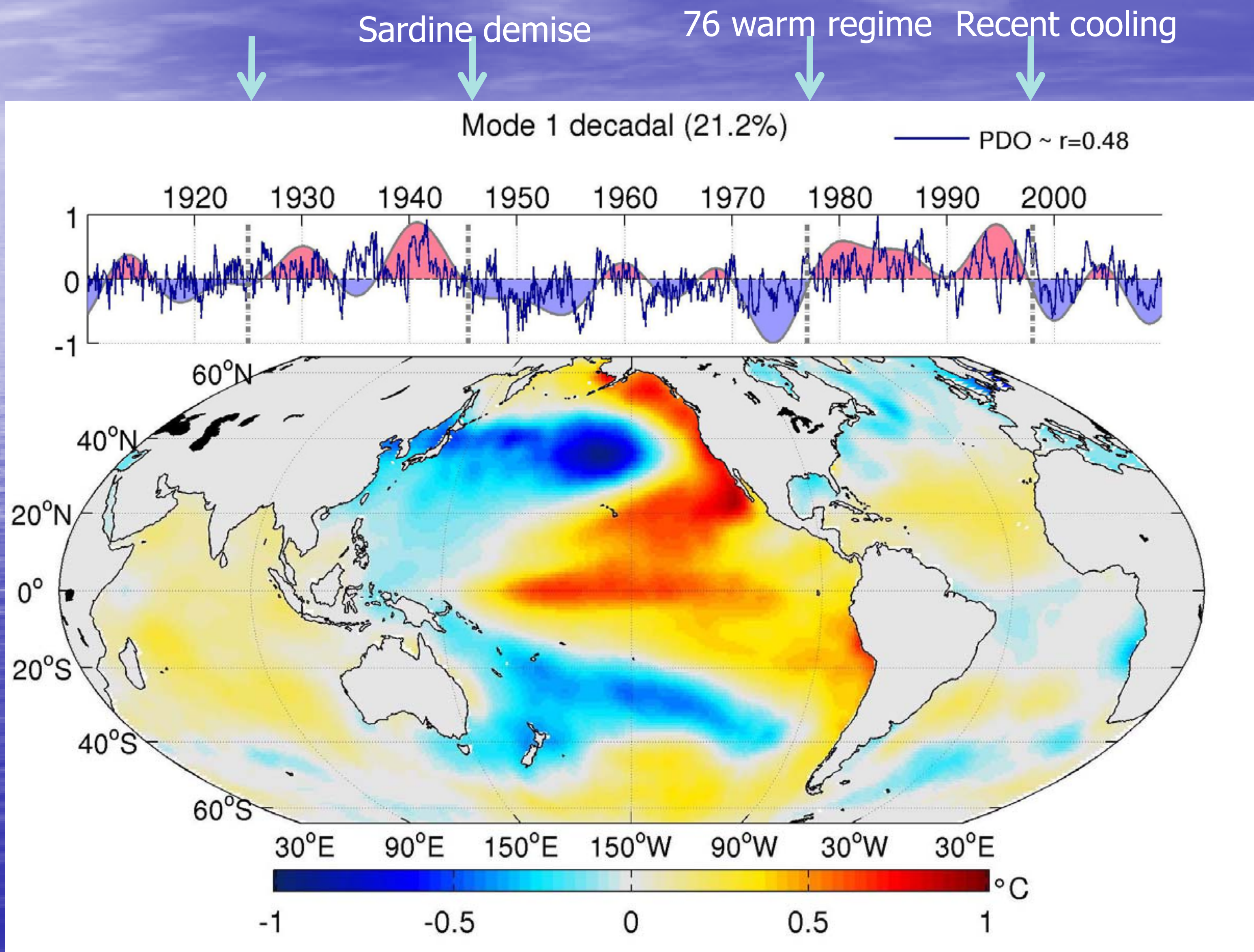
Karumuri Ashok,[1,2] Swadhin K. Behera,[1] Suryachandra A. Rao,[1] Hengyi Weng,[1] and Toshio Yamagata[1,3]

Received 4 July 2006; revised 2 March 2007; accepted 13 June 2007; published 8 November 2007.

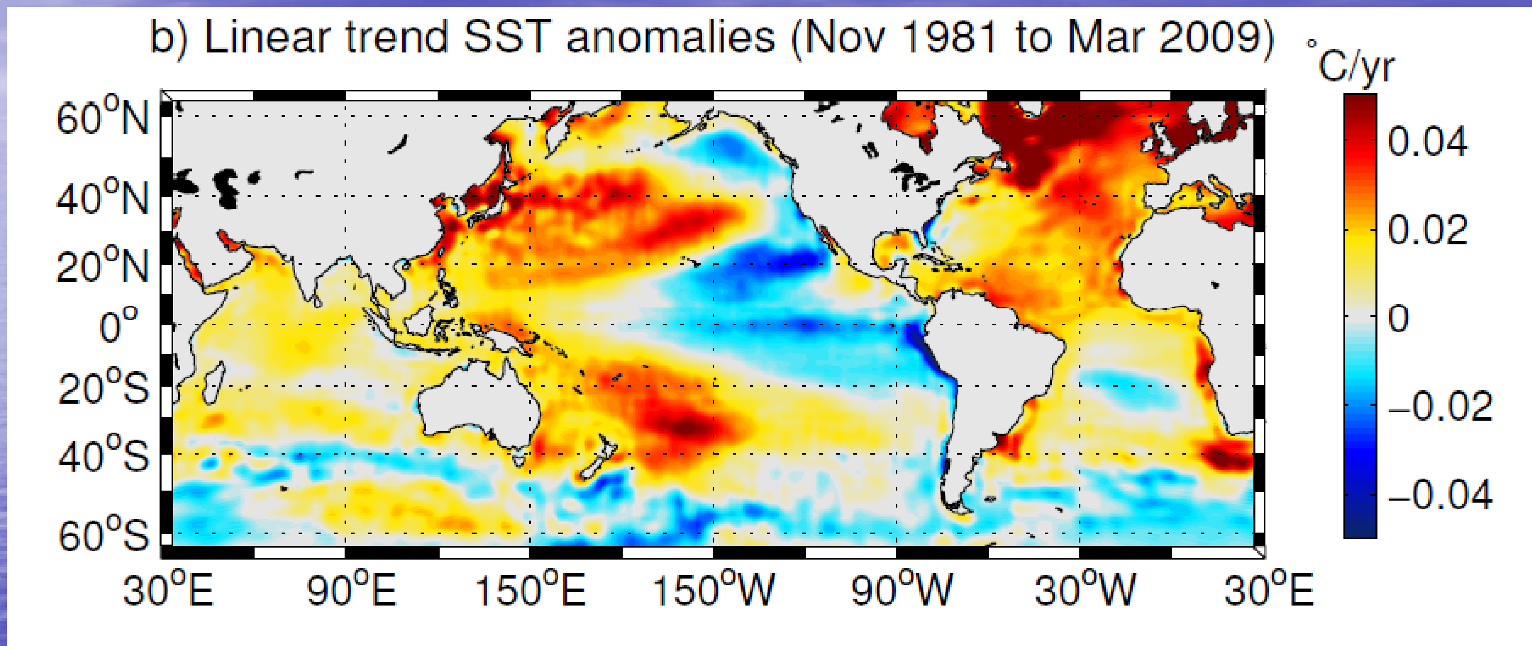
Past century in the Pacific

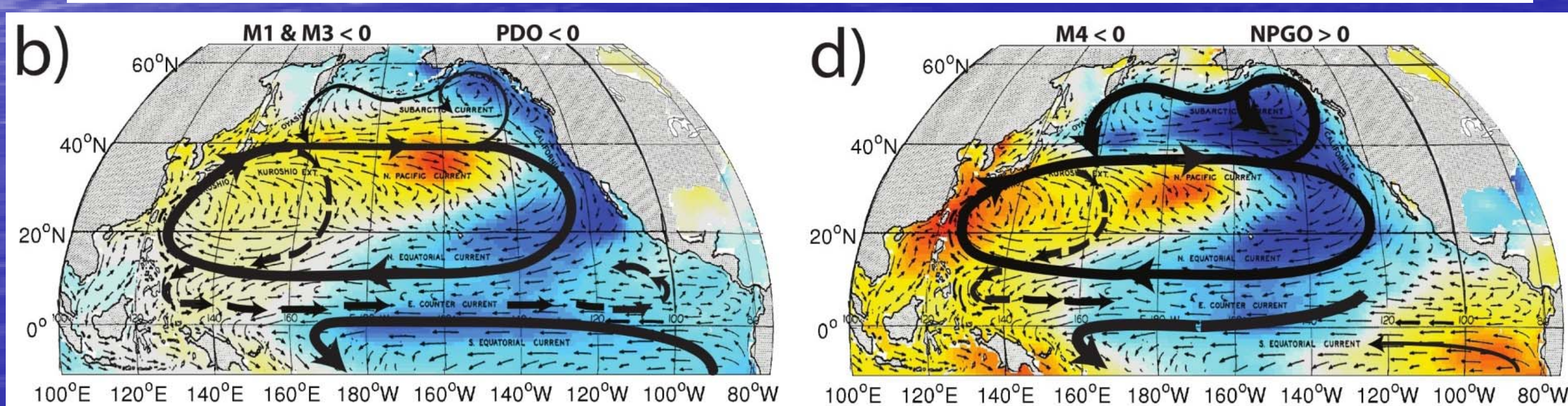
- M1 = ENSO (high interannual and some multidecadal energy)
- M3 like but not the same as PDO
- PDO = M1 + M3
- M4 associated with the North Pacific Gyre Oscillation and El Niño Modoki (one and the same; Modoki is Japanese for like but not the same) – increasing in amplitude, negative recently, recent El Niño events more western than eastern.

Pacific multidecadal variability and regime shifts, same pattern as recent cooling



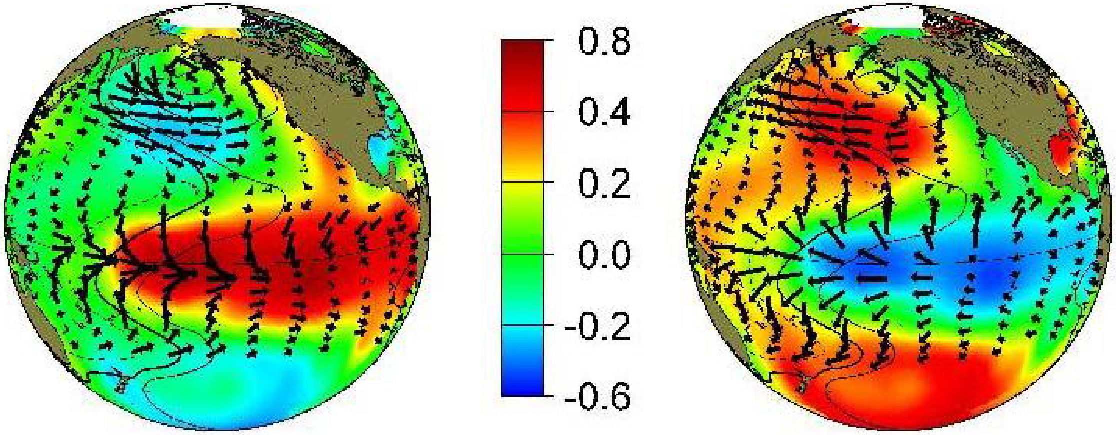
The recent shift in the mid 1990s "bigger" than others because M1 (ENSO), M3 (PDO) and M4 (NPGO, Modoki) are in phase (negative) –coincidence?



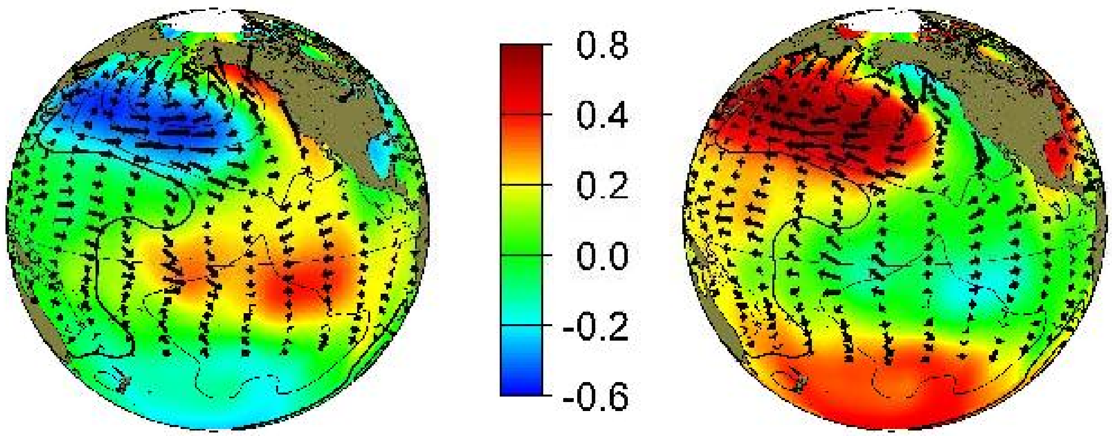


It is a familiar story

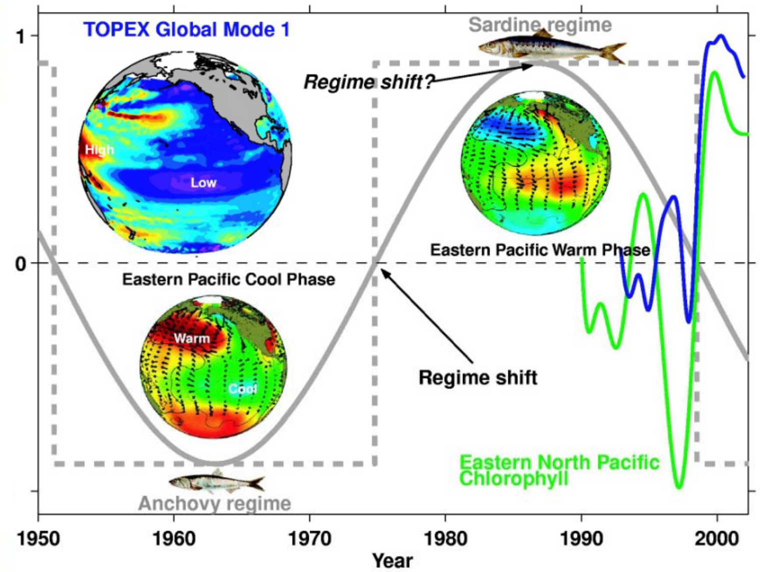
El Niño Child **La Niña**



El Viejo Parent **La Vieja**

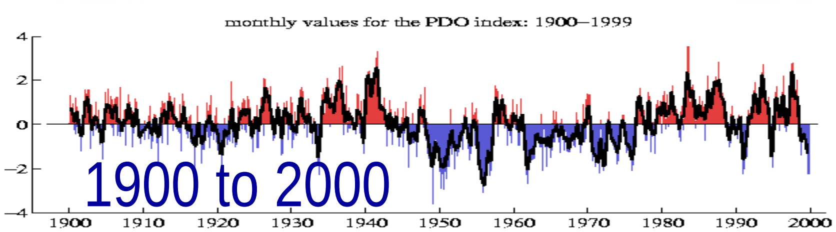


El Viejo

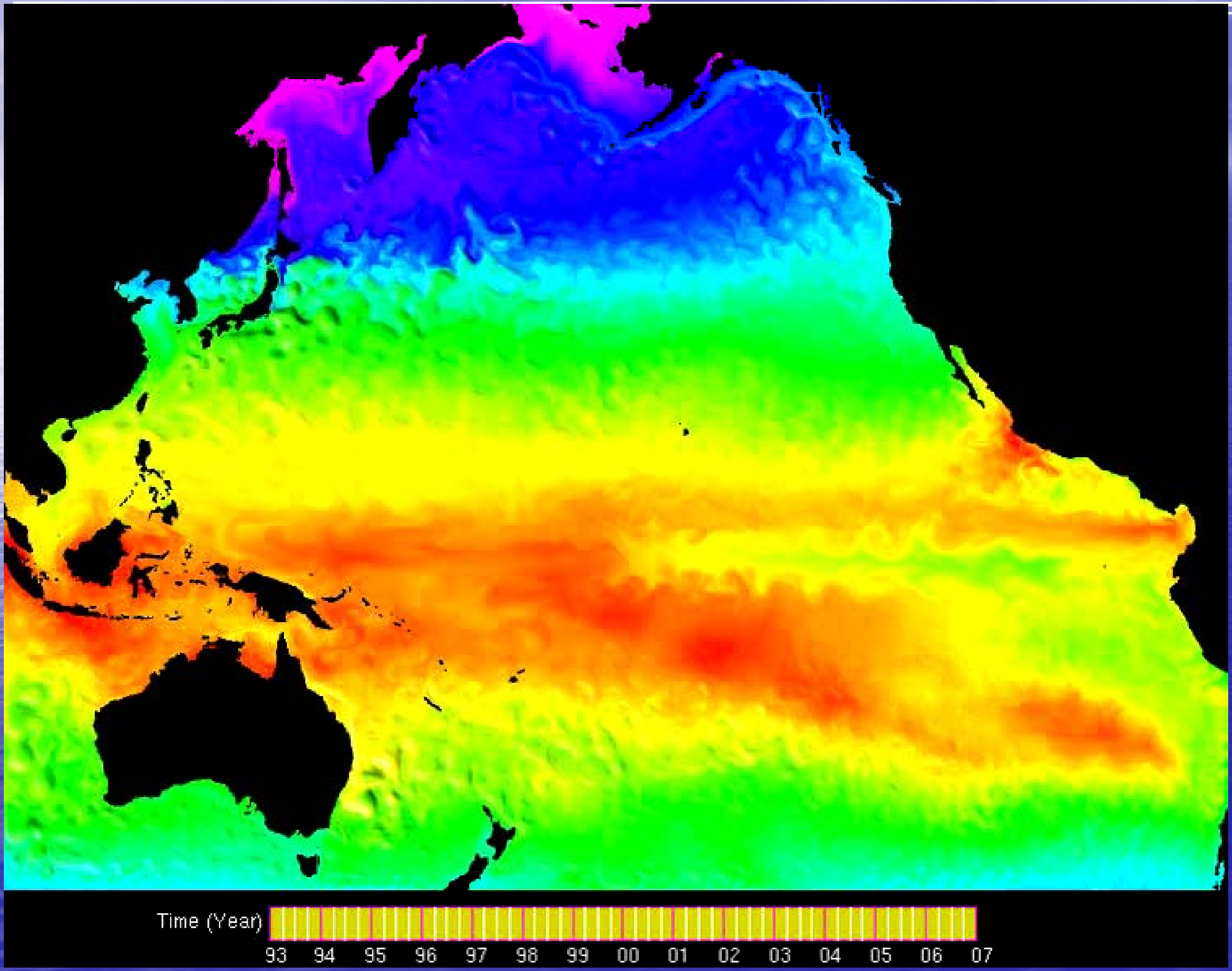


La Vieja

MBARI time series



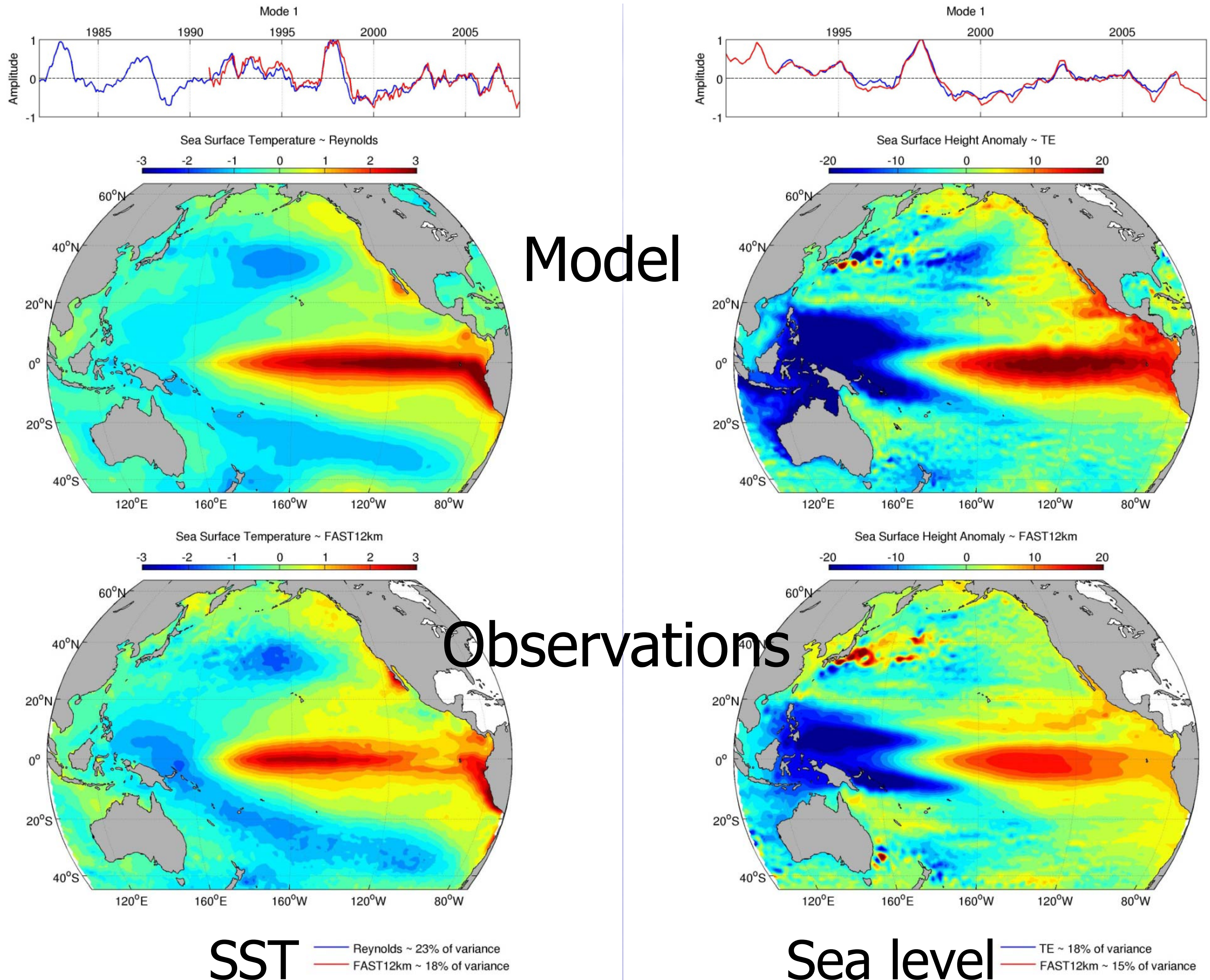
Regional Ocean Model System 12-km with NPZ
(red warm, blue cold, relief sea surface height = eddies)



Ecological Forecasting of Central California salmon

Peruvian anchoveta

Fei Chai and Yi Chao

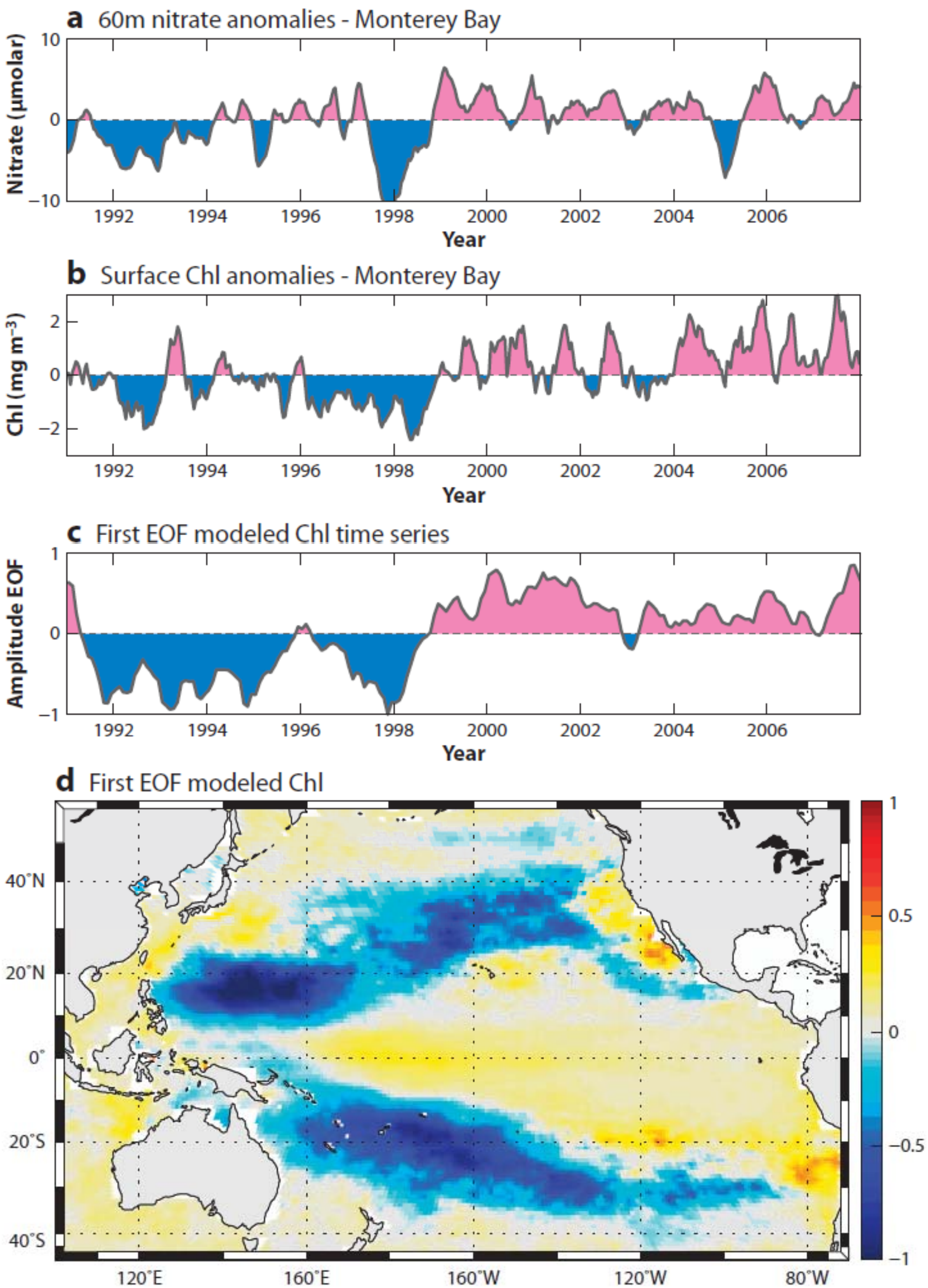


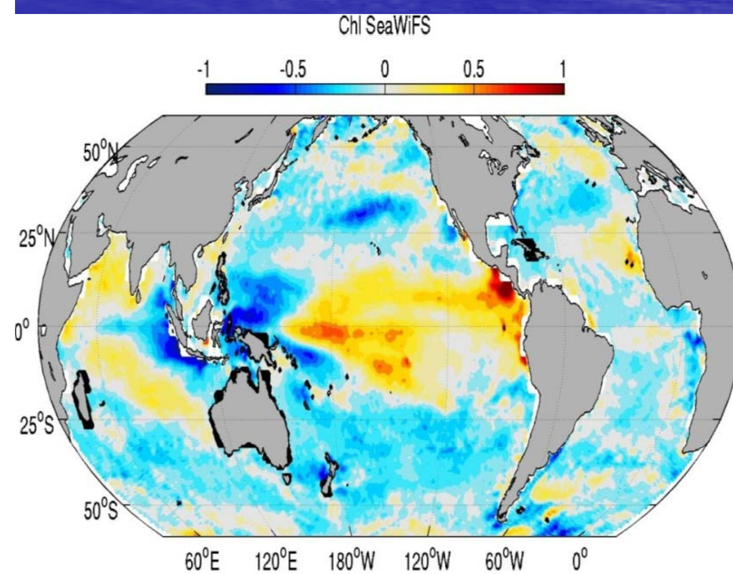
High resolution blended winds

Chlorophyll

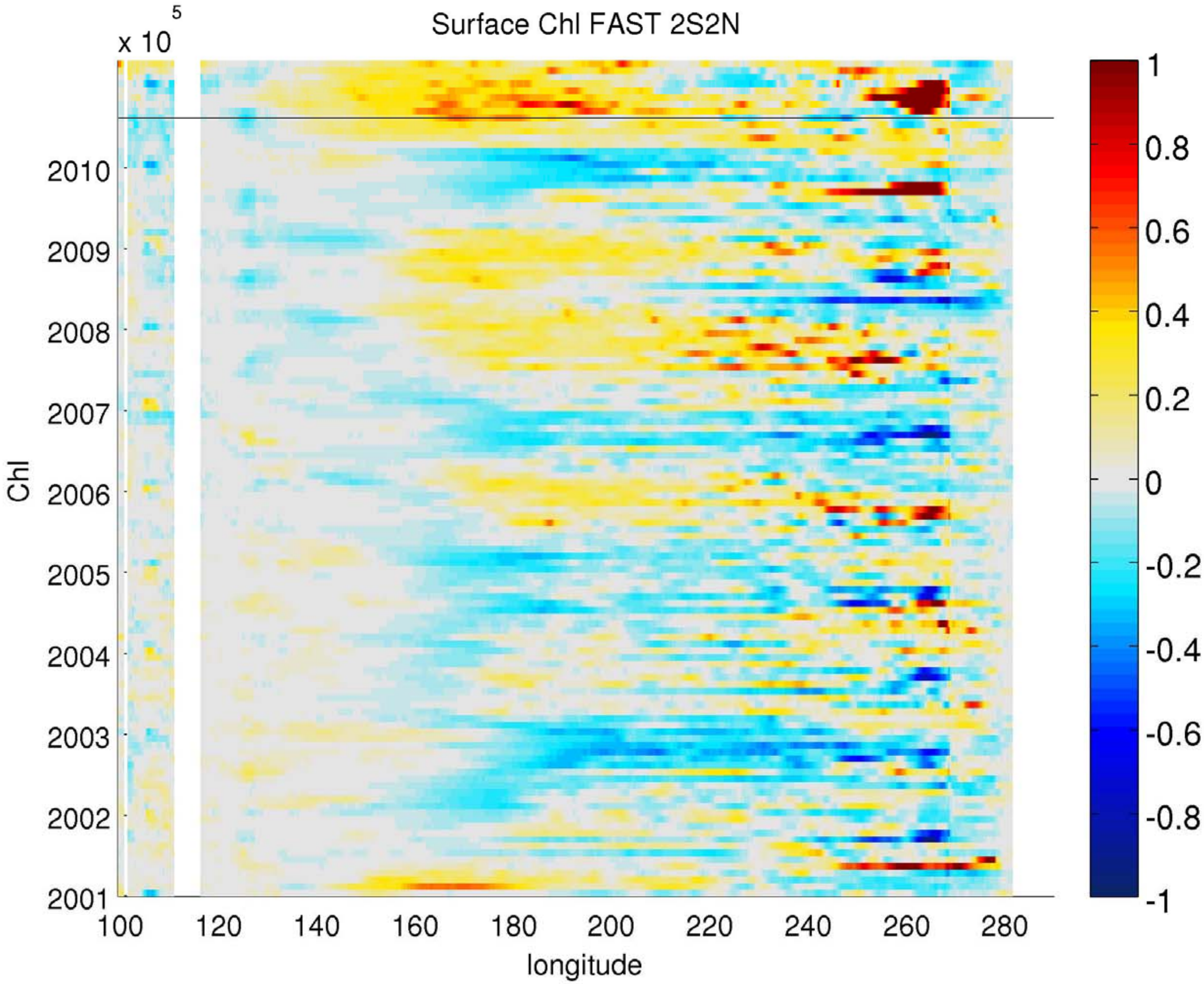
Model

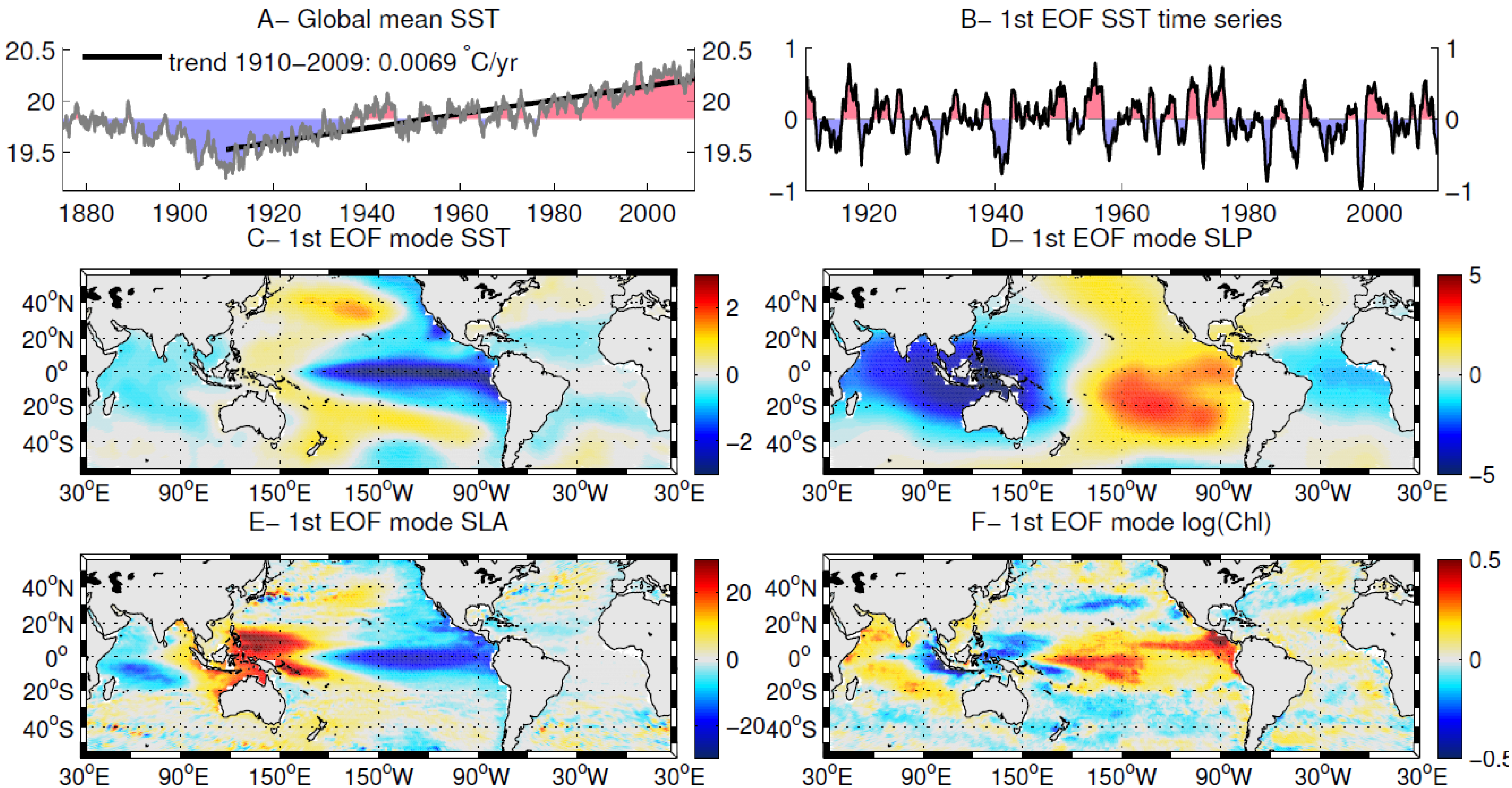
SeaWiFS

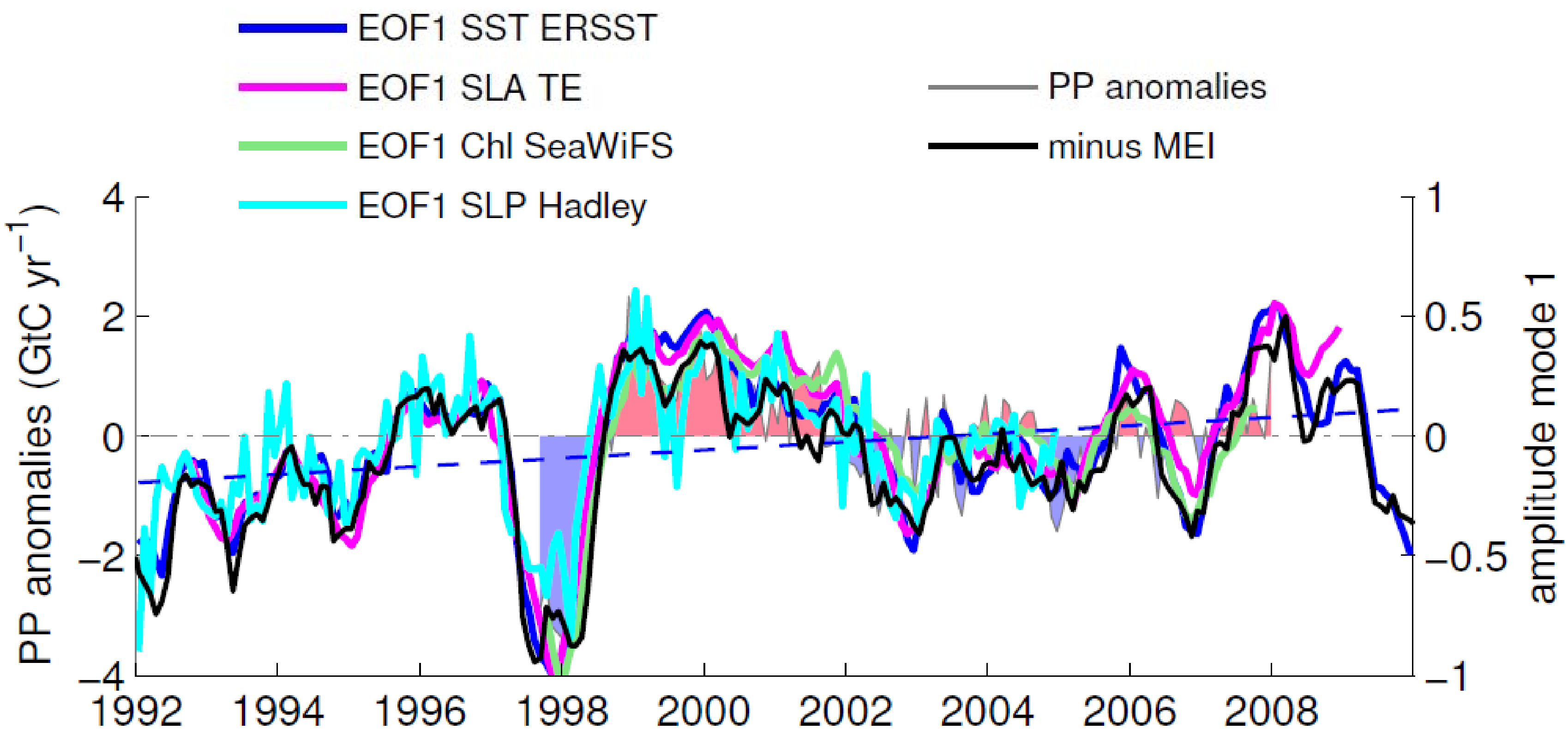




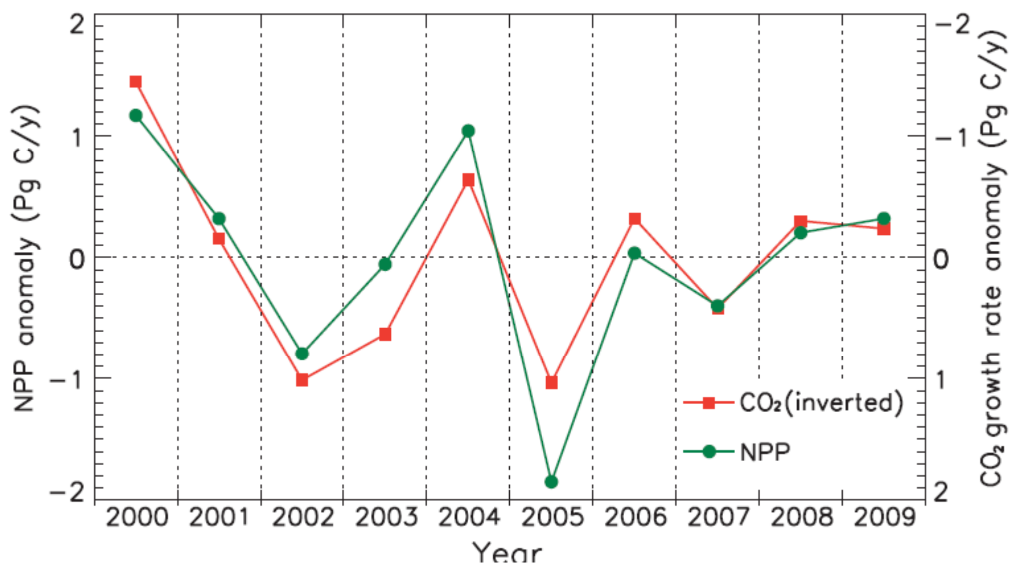
Equatorial Pacific Chlorophyll Forecast

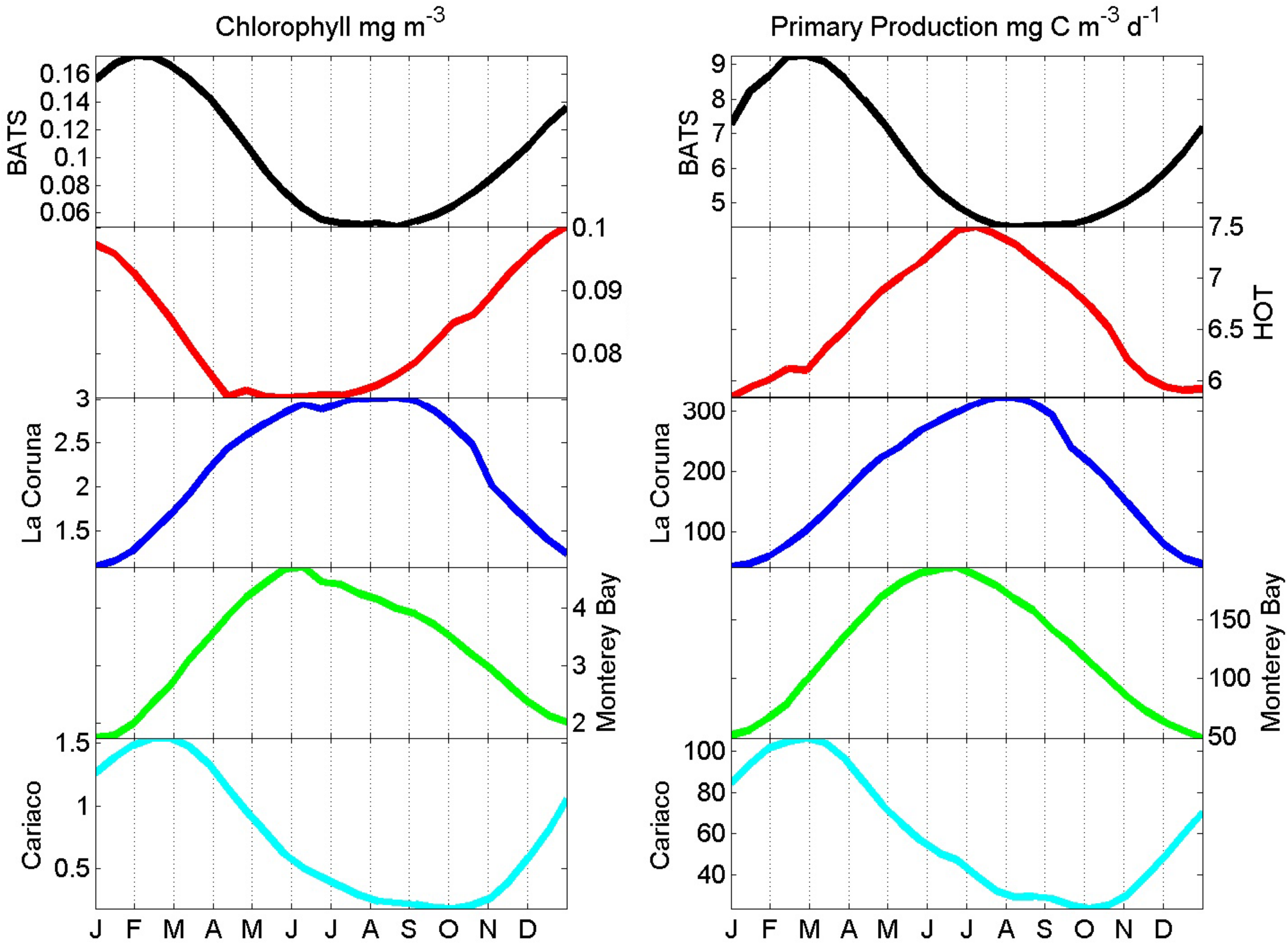



A– Global mean SST
trend 1910–2009: 0.0069 °C/yr
B– 1st EOF SST time series
C– 1st EOF mode SST
D– 1st EOF mode SLP
E– 1st EOF mode SLA
F– 1st EOF mode log(Chl)

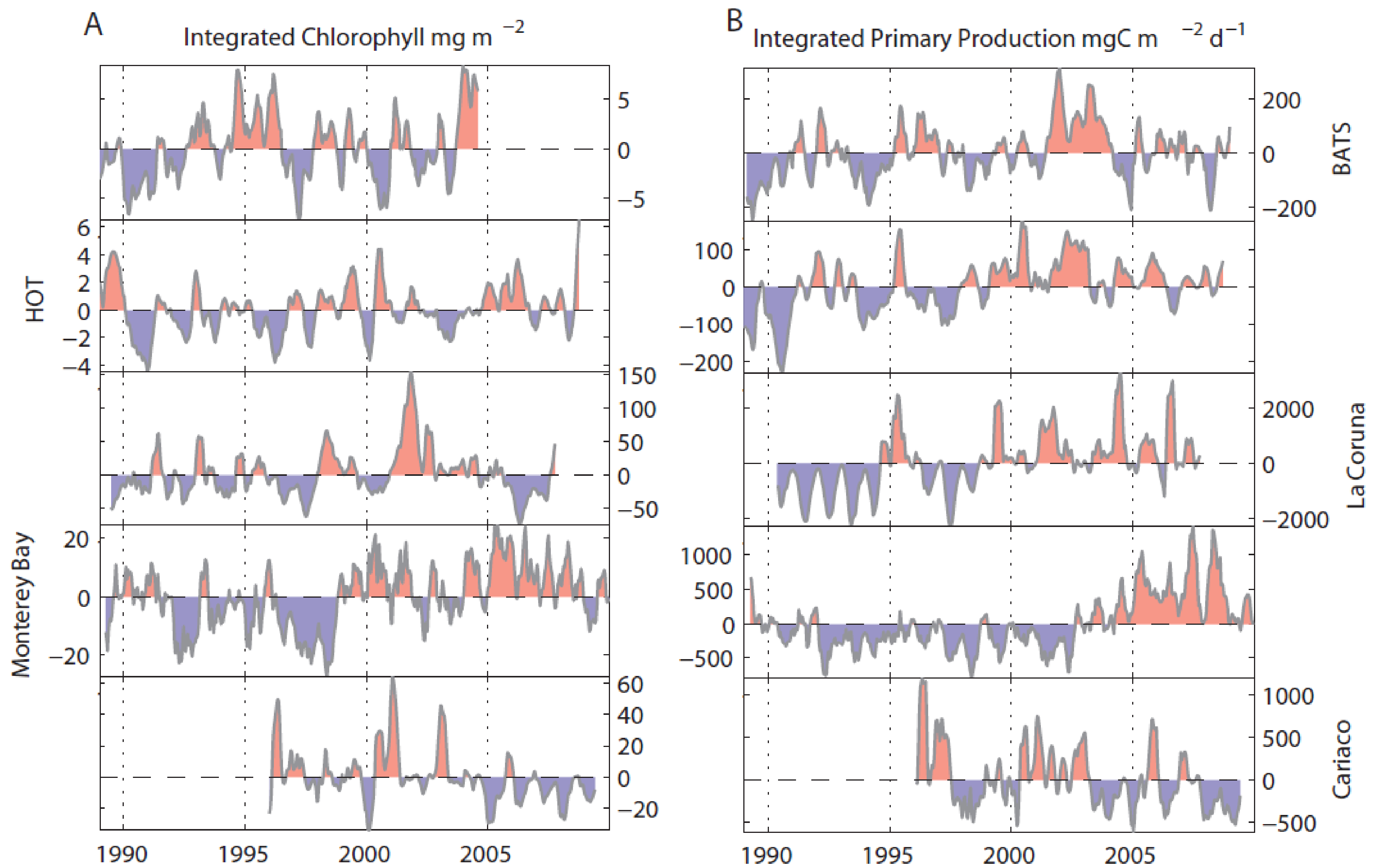


Terrestrial NPP



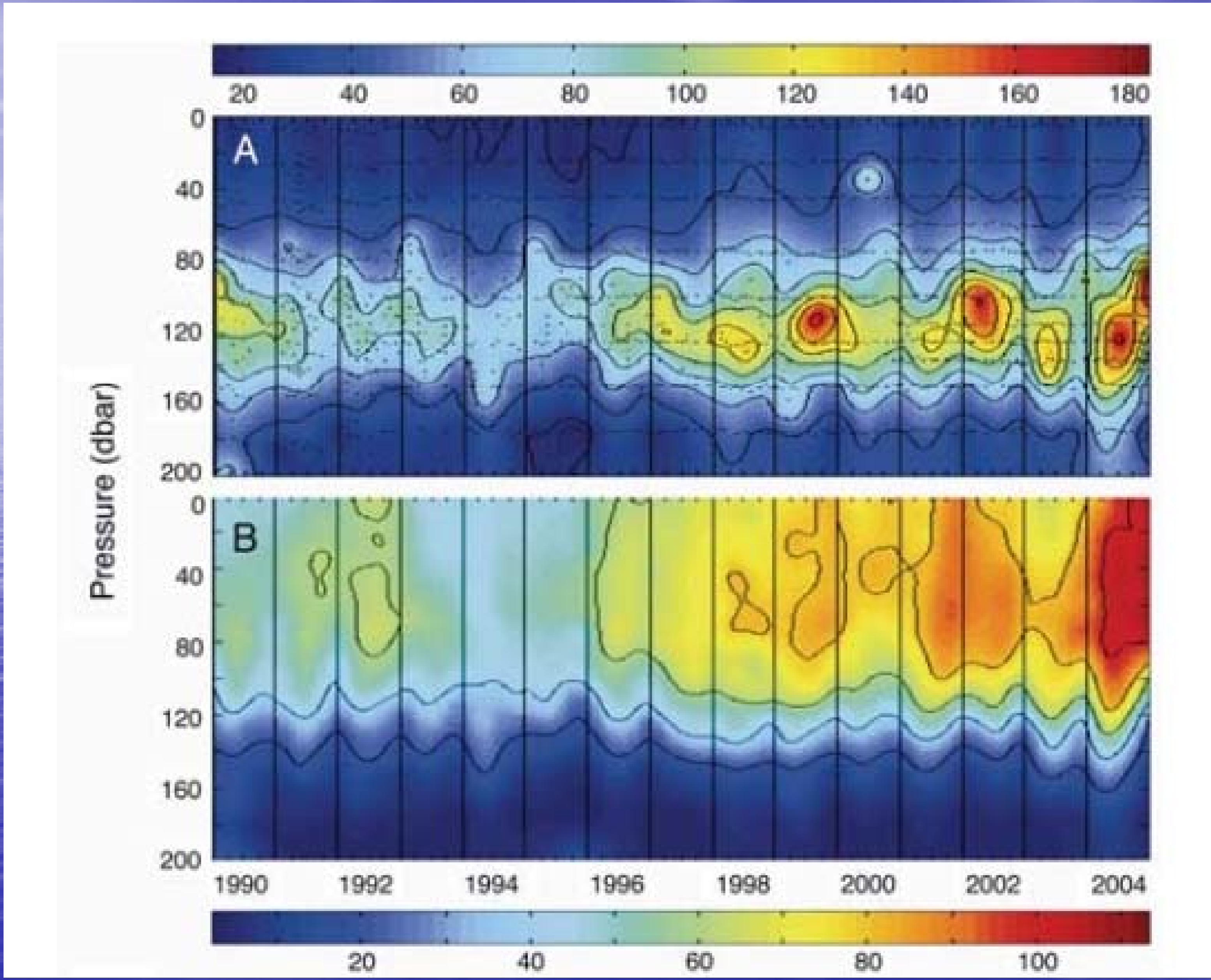


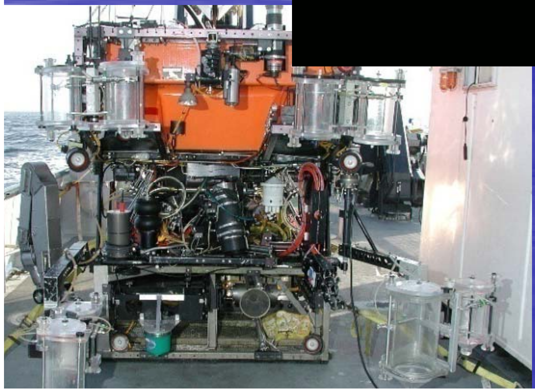
Chlorophyll mg m-3
Primary Production mg C m-3 d-1
BATS
HOT
La Coruna
Monterey Bay
Cariaco
0.16
0.14
0.12
0.1
0.08
0.06
0.1
0.09
0.08
3
2.5
2
1.5
4
3
2
1.5
1
0.5
9
8
7
6
5
7.5
7
6.5
6
300
200
100
150
100
50
100
80
60
40
J F M A M J J A S O N D



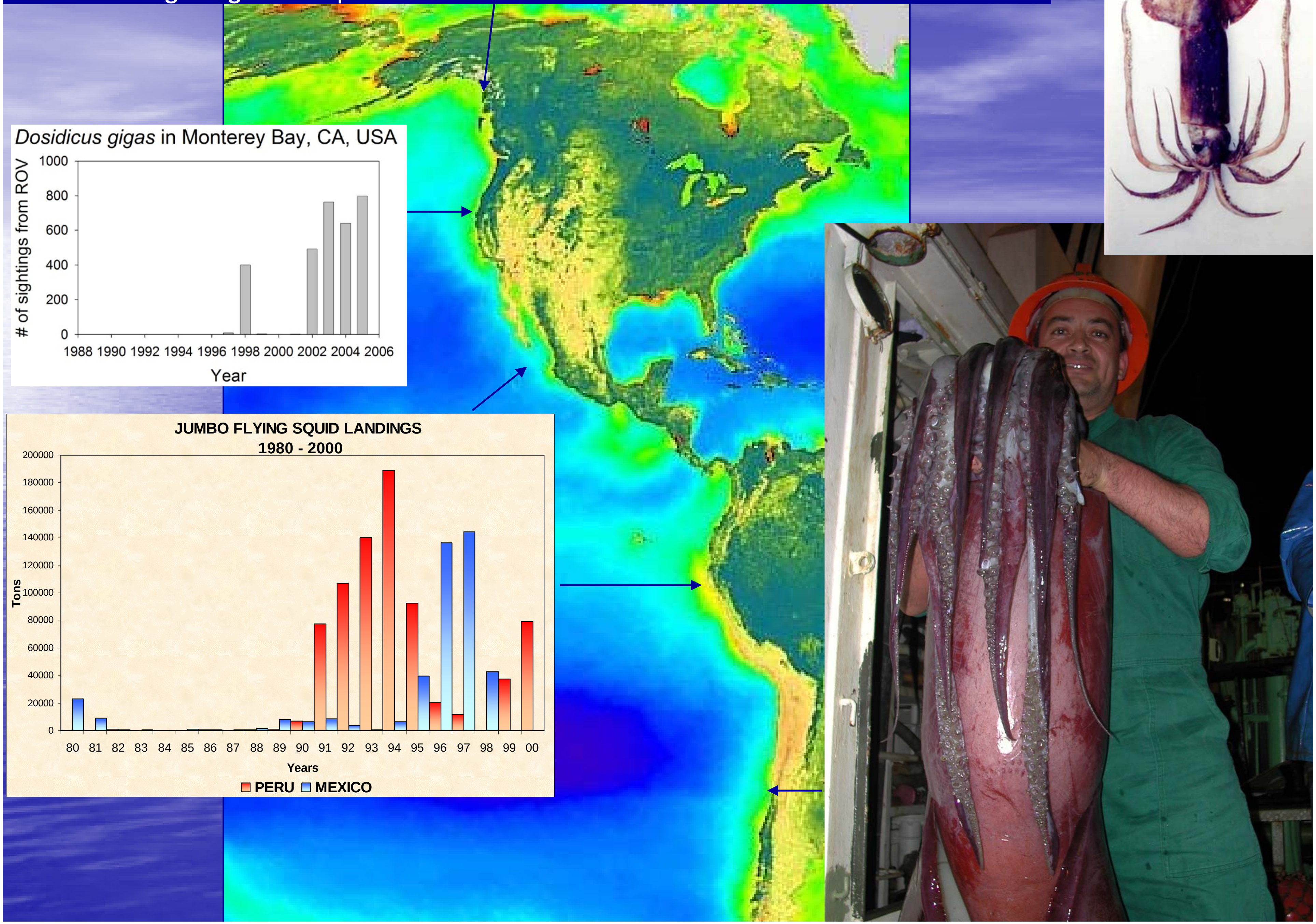
A
Integrated Chlorophyll mg m −2
B
Integrated Primary Production mgC m −2 d −1
HOT
Monterey Bay
BATS
La Coruna
Cariaco
1990
1995
2000
2005

Bidigare et al. (2009) The 1997-98 regime shift at HOT

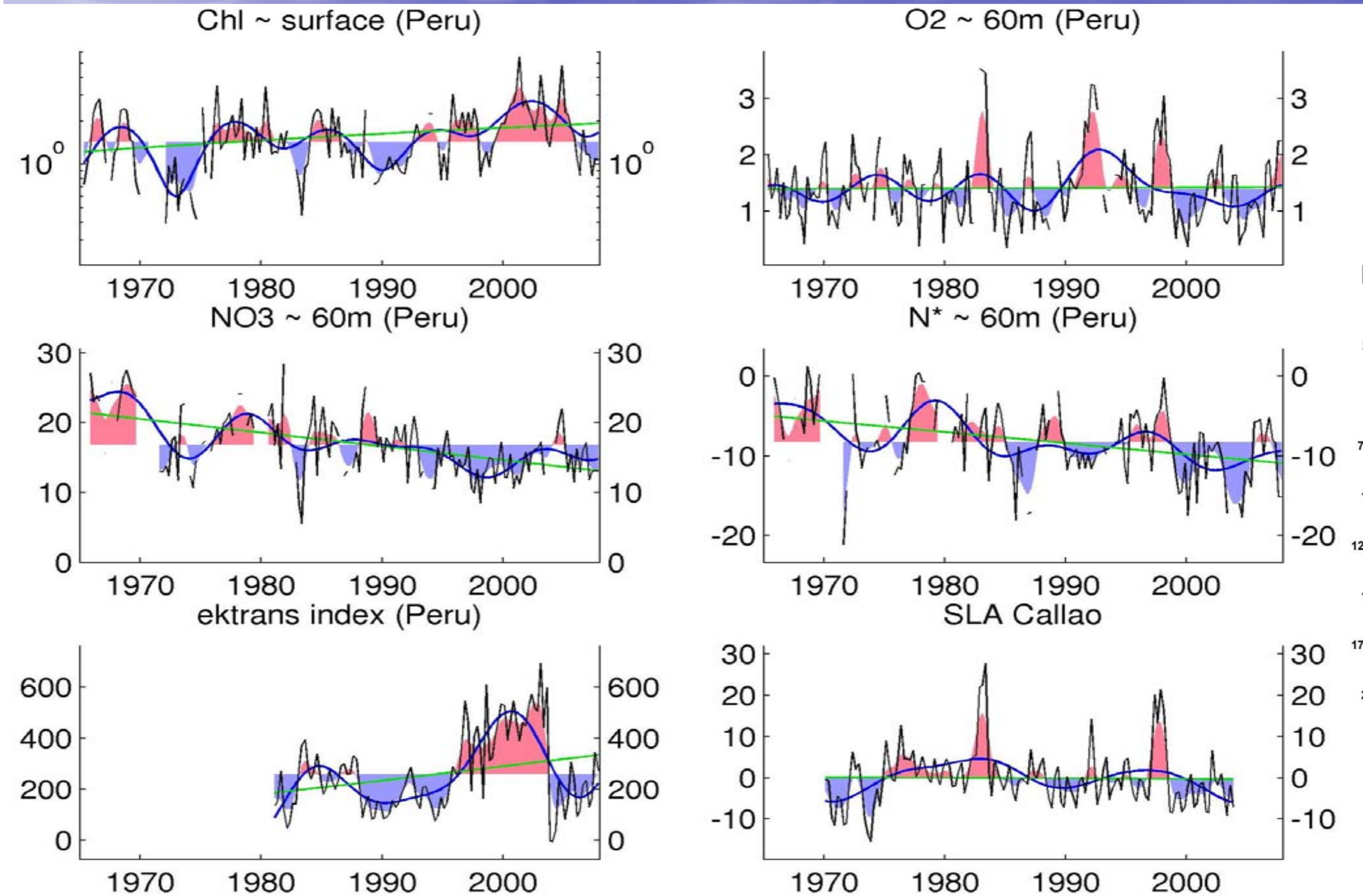


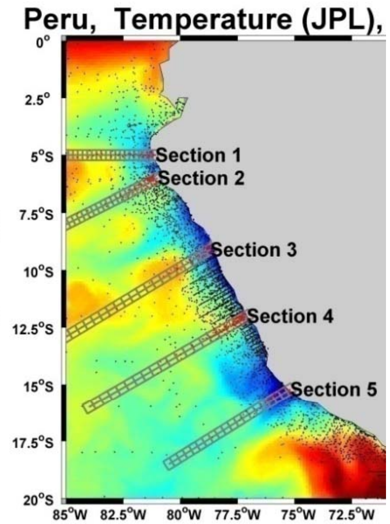


A large Humboldt squid caught offshore from Sitka in October 2004 is among numerous sightings of a species seen for the first time in waters of the Far North

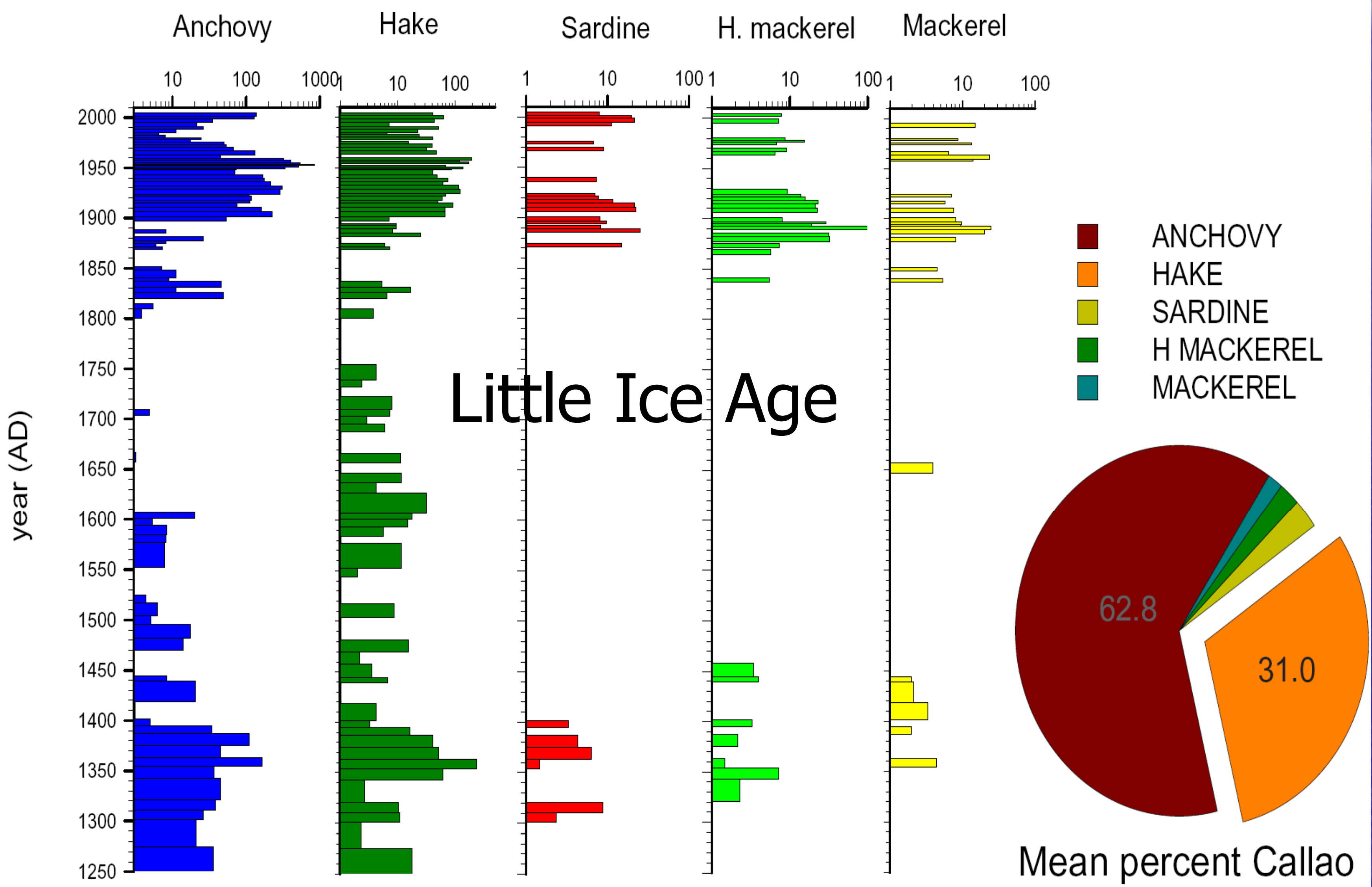


In situ oceanographic data off Peru shows that ocean losing nitrate (oxygen is zero so nitrate electron donor) and increasing productivity





Fish Scale Record from a core off Peru



Gutierrez et al. (2009) Biogeosciences

Cores off Callao (and Pisco), Peru show dramatic changes in oxygen and ocean productivity from the LIA (higher oxygen, lower productivity) to the present (lower oxygen, higher productivity). Is this trend continuing and being exaggerated by global warming? How long can it continue?

Little Ice Age

Present

Oxygen proxy

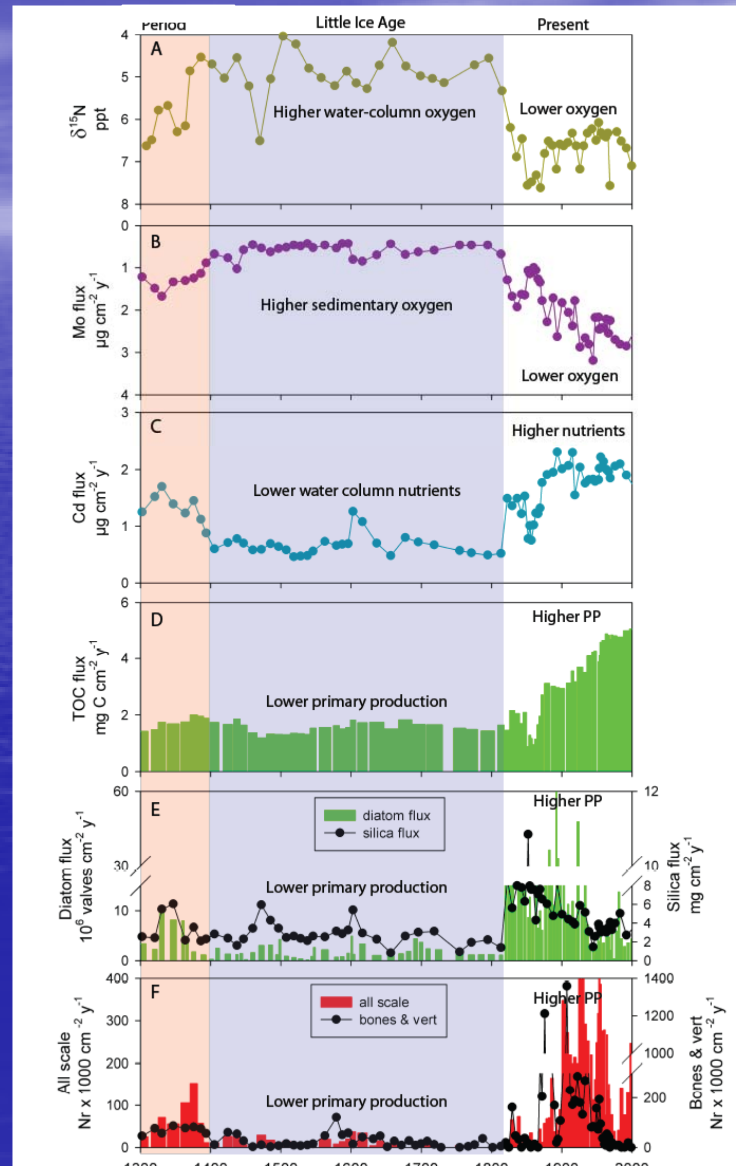
Oxygen proxy

Nutrient proxy

Carbon flux

Diatoms

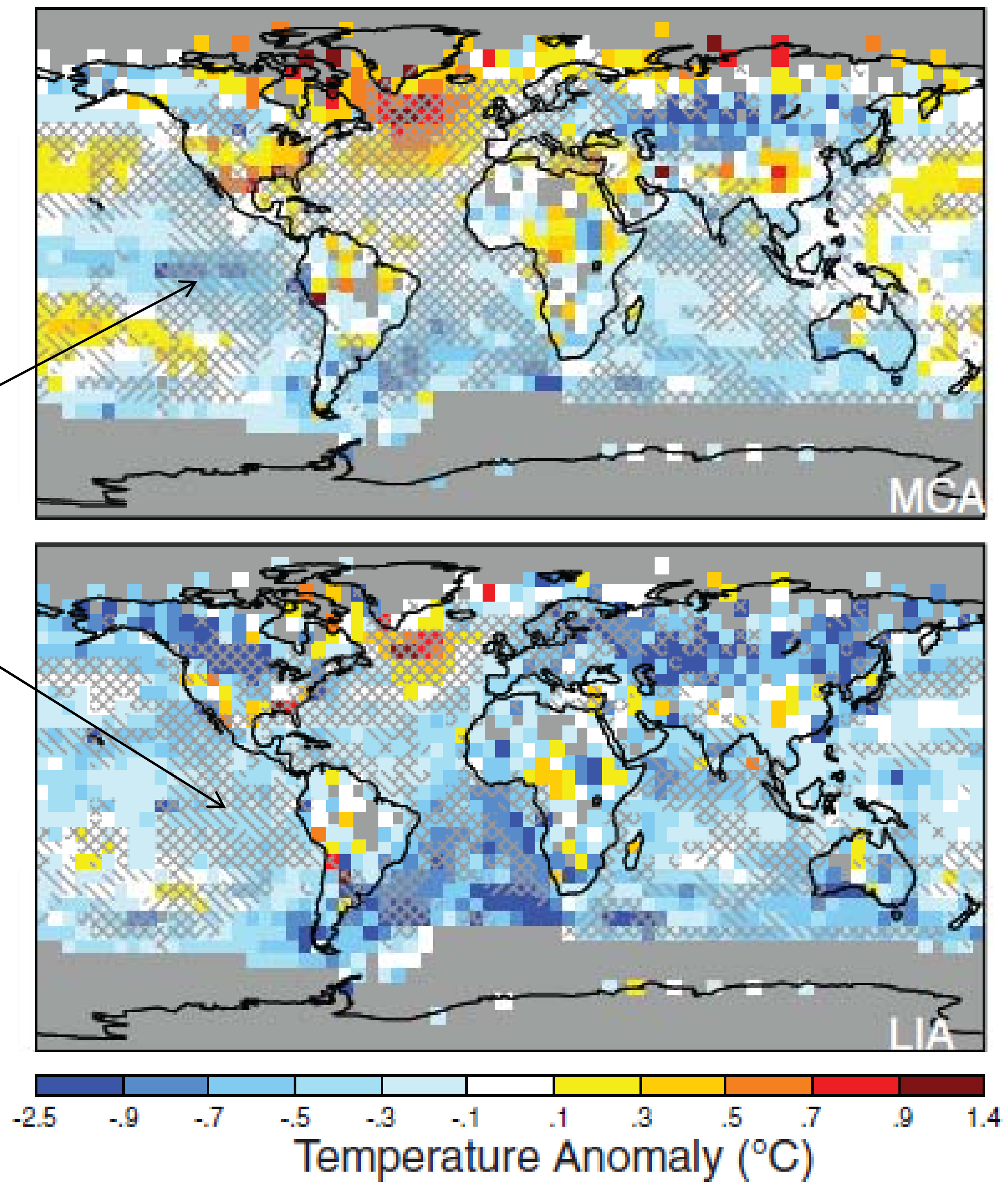
Fish remains



1300

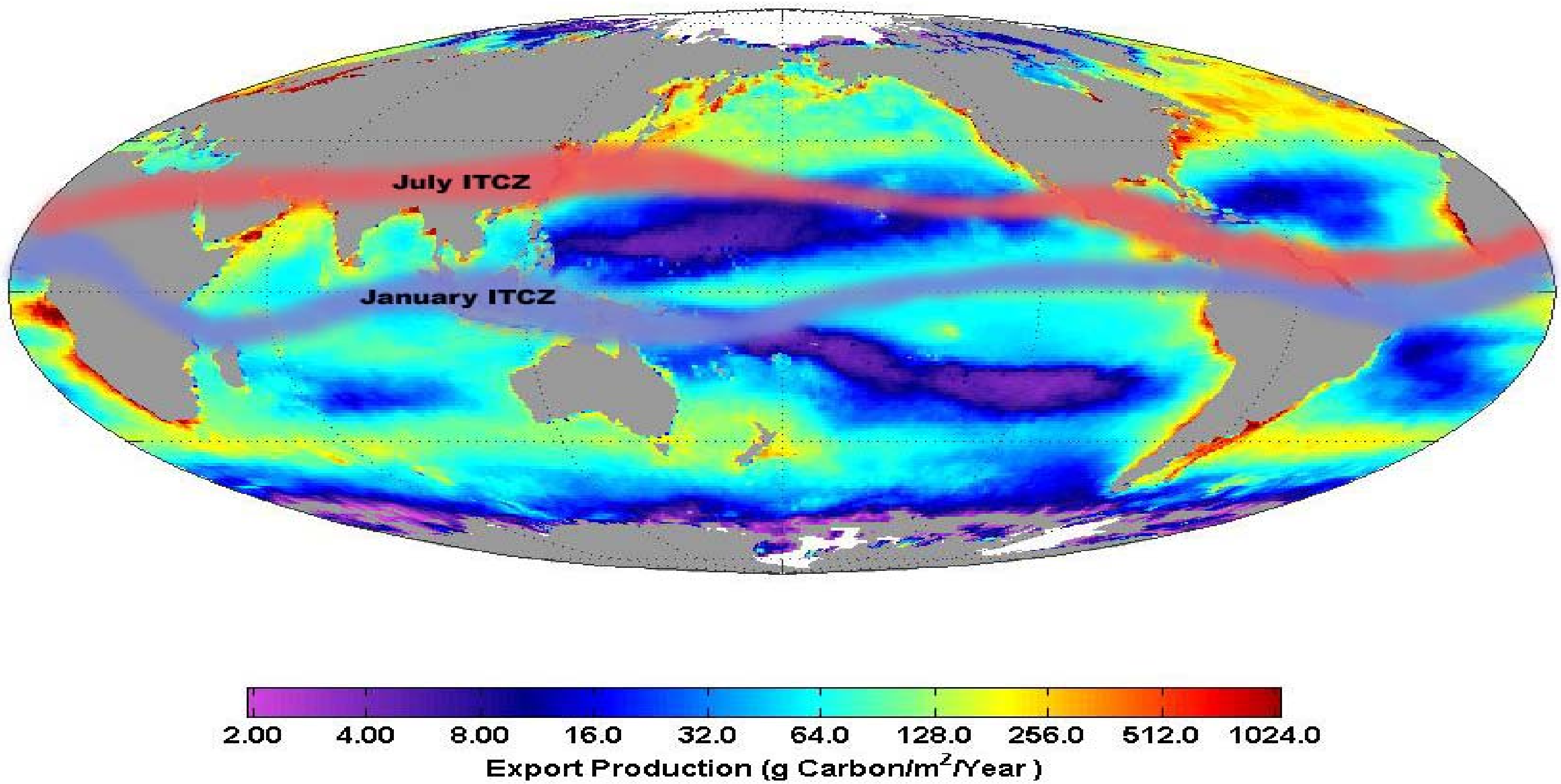
2000

Medieval warm period has the same pattern as present but Little Ice Age does not



Mann et al. 2009, Science

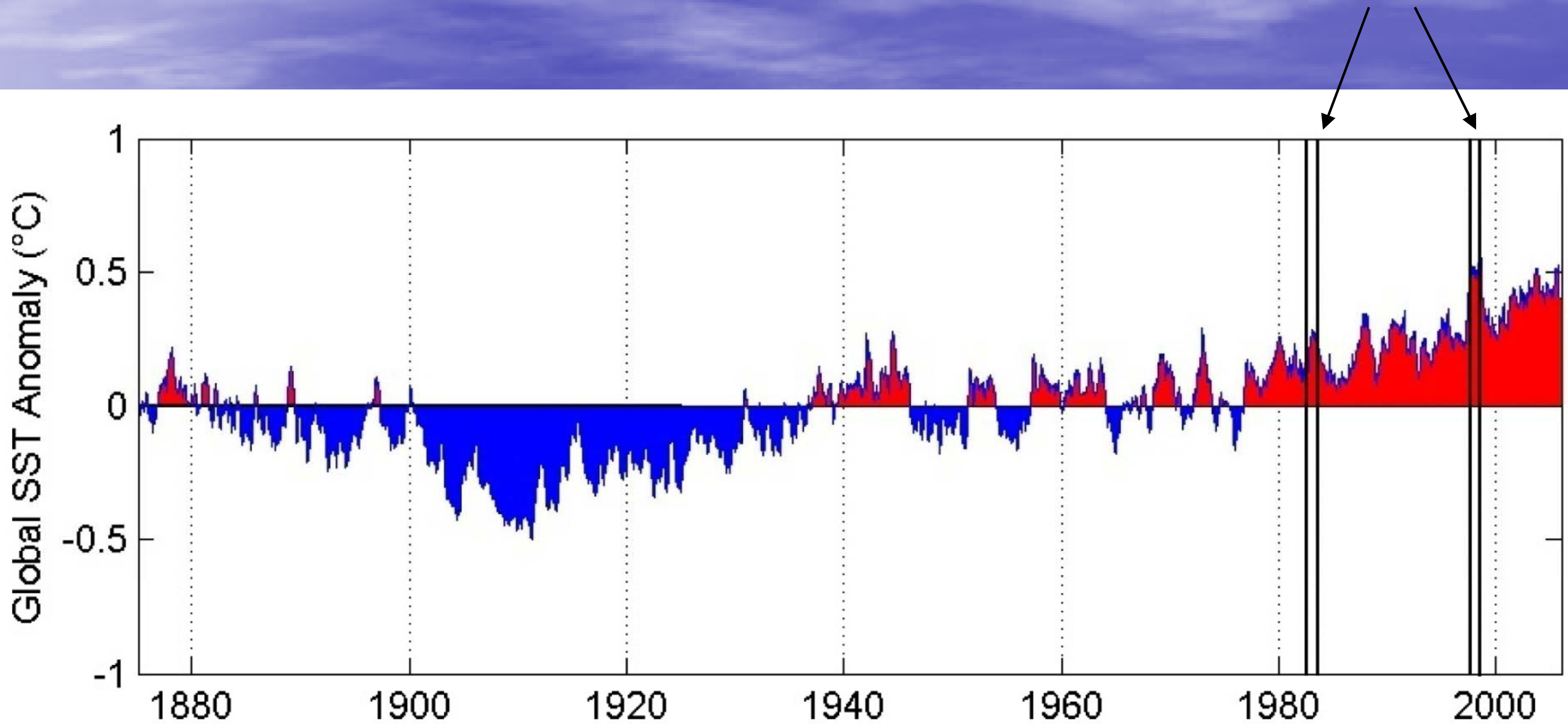
Driven by a southward migration of the Intertropical Convergence zone (ITCZ) during the Little Ice Age



Opposite happening today as the world warms

Ocean warmer during El Niño and El Viejo

El Niños of 82-83, 97-98



Same thing during El Viejo

i.e. warmer coastal upwelling and warmer world

A developing Paradox?

- Observations from the modern record show that the entire globe warms during El Niño and El Viejo and in coastal upwelling systems temperature goes up and biological productivity goes down. The opposite seems to happen during the Little Ice Age when the coastal upwelling system off Peru warmed, ventilated and became less productive. We must be looking at very different mechanisms ….

Conclusions

- Climate variability has strong and measurable impact on global ocean ecosystems
- Ocean ecosystems adapt to large natural climate changes – what are their limits?
- Anthropogenic global change (i.e. ocean acidification, fishing) exists without a doubt but climate change harder to pinpoint
- There will be ”two faces to global warming-driven climate change” just like there are “two faces to climate variations like El Niño (and El Viejo)”
- There will be many surprises. Change may not follow current patterns of climate variability
- Our science (observing/modeling) and management needs to be adaptive; management needs to include variability and change

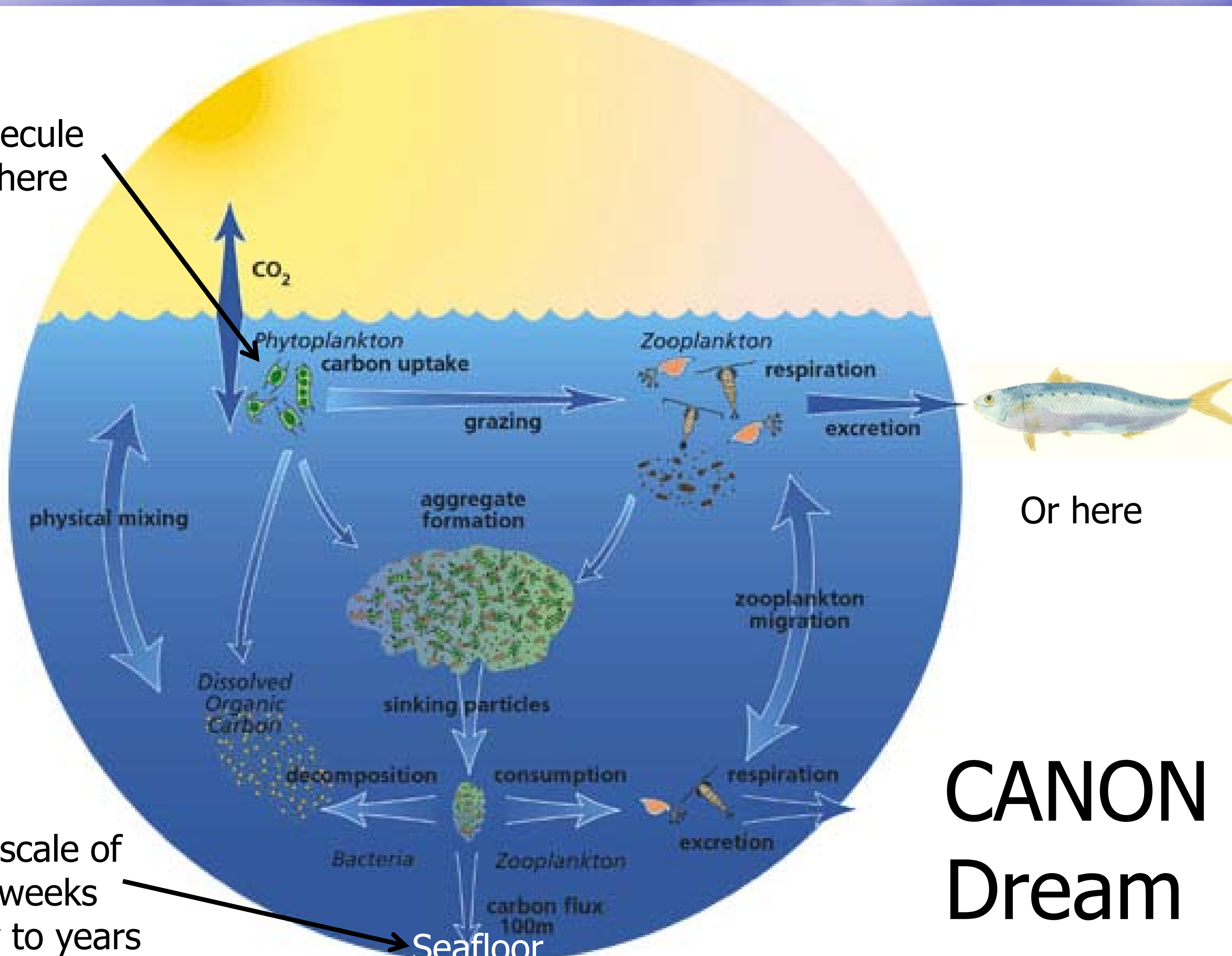
The future

My future that is = retirement

Controlled, Agile and Novel Observing Network (CANON)

The biological pump: a complex process in an ever-changing and moving ocean

Follow a molecule of CO_2 from here



Or here

To here on a scale of of hours to weeks and eventually to years

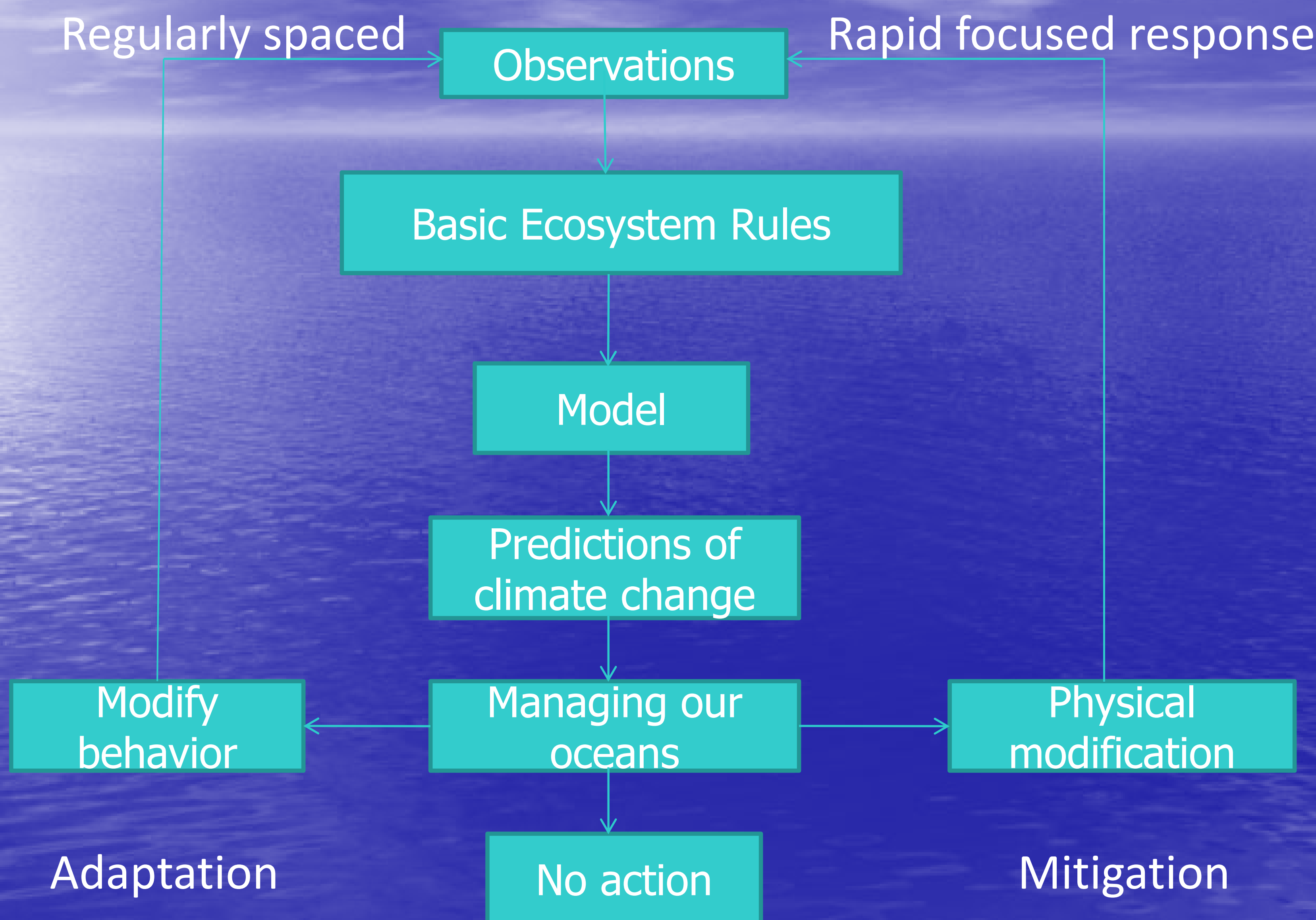
CANON Dream

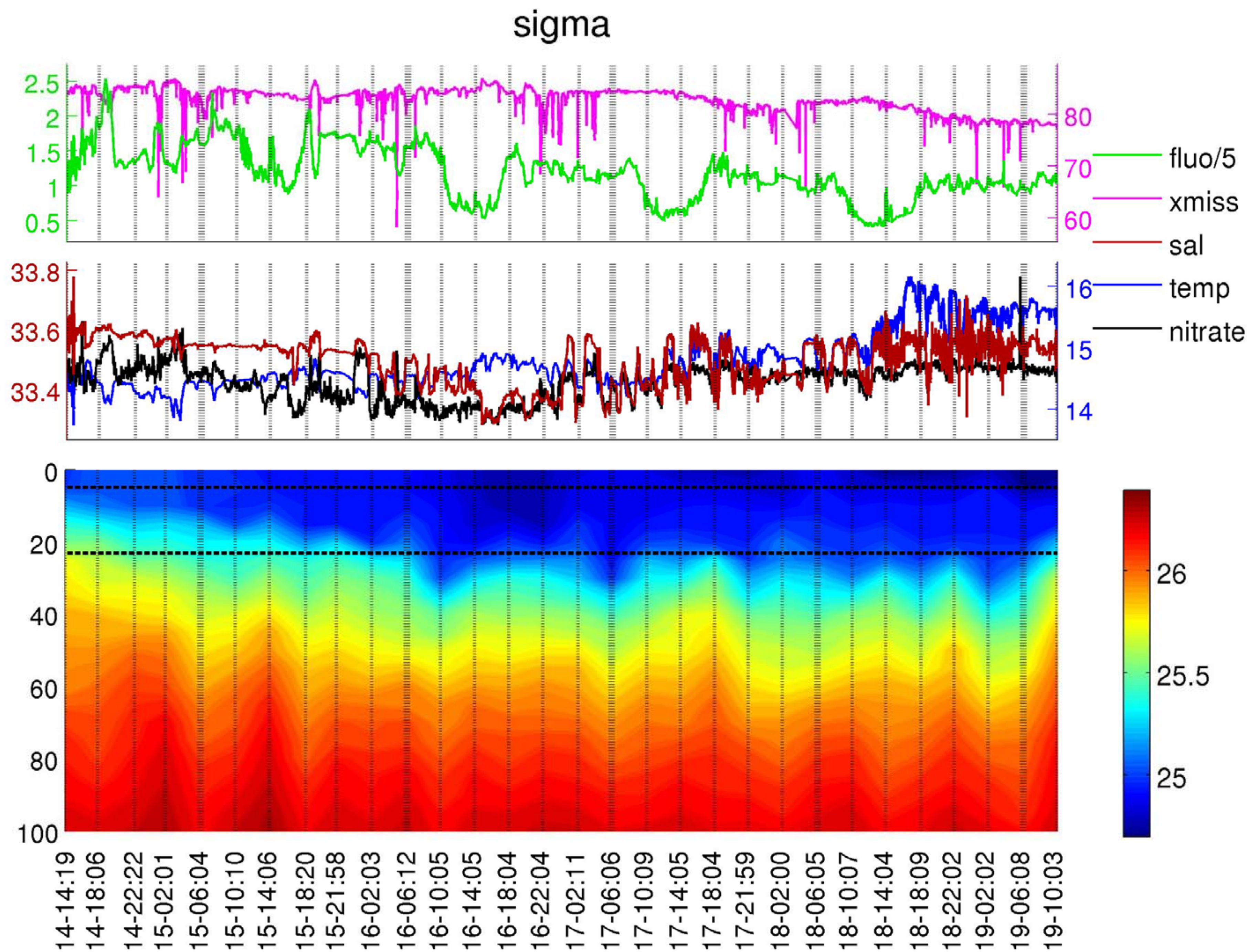
A dream that today has very much a semblance of reality

2010+ development of a system that can follow a process in 4-D

- Start with HABs using toxin as tracer
- Mobile and fixed platforms
- Instrumentation and "samplers" for water, particles, rates
- Novel analytical methods
- Software to intelligently sample and control *in situ* assets
- Decision Support System (DSS) to integrate information, planning and analysis tools

How does CANON fit into the big picture?




sigma
fluo/5
xmiss
sal
temp
nitrate
2.5
2
1.5
1
0.5
80
70
60
33.8
33.6
33.4
16
15
14
0
20
40
60
80
100
26
25.5
25
14-14:19
14-18:06
14-22:22
15-02:01
15-06:04
15-10:10
15-14:06
15-18:20
15-21:58
16-02:03
16-06:12
16-10:05
16-14:05
16-18:04
16-22:04
17-02:11
17-06:06
17-10:09
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19-02:02
19-06:08
19-10:03