Re-Envisioning the Ocean: The View from Space

Mark R. Abbott
College of Oceanic and Atmospheric Sciences
Oregon State University

Introduction

- It was once said that the "G" in JGOFS would not be achieved until an ocean color sensor was launched
- But the first research-quality sensor was not launched until 1996!
- However, many other sensors were available during JGOFS for ocean research
- These came about from a confluence of proposed satellite missions and global ocean research in the early 1980's

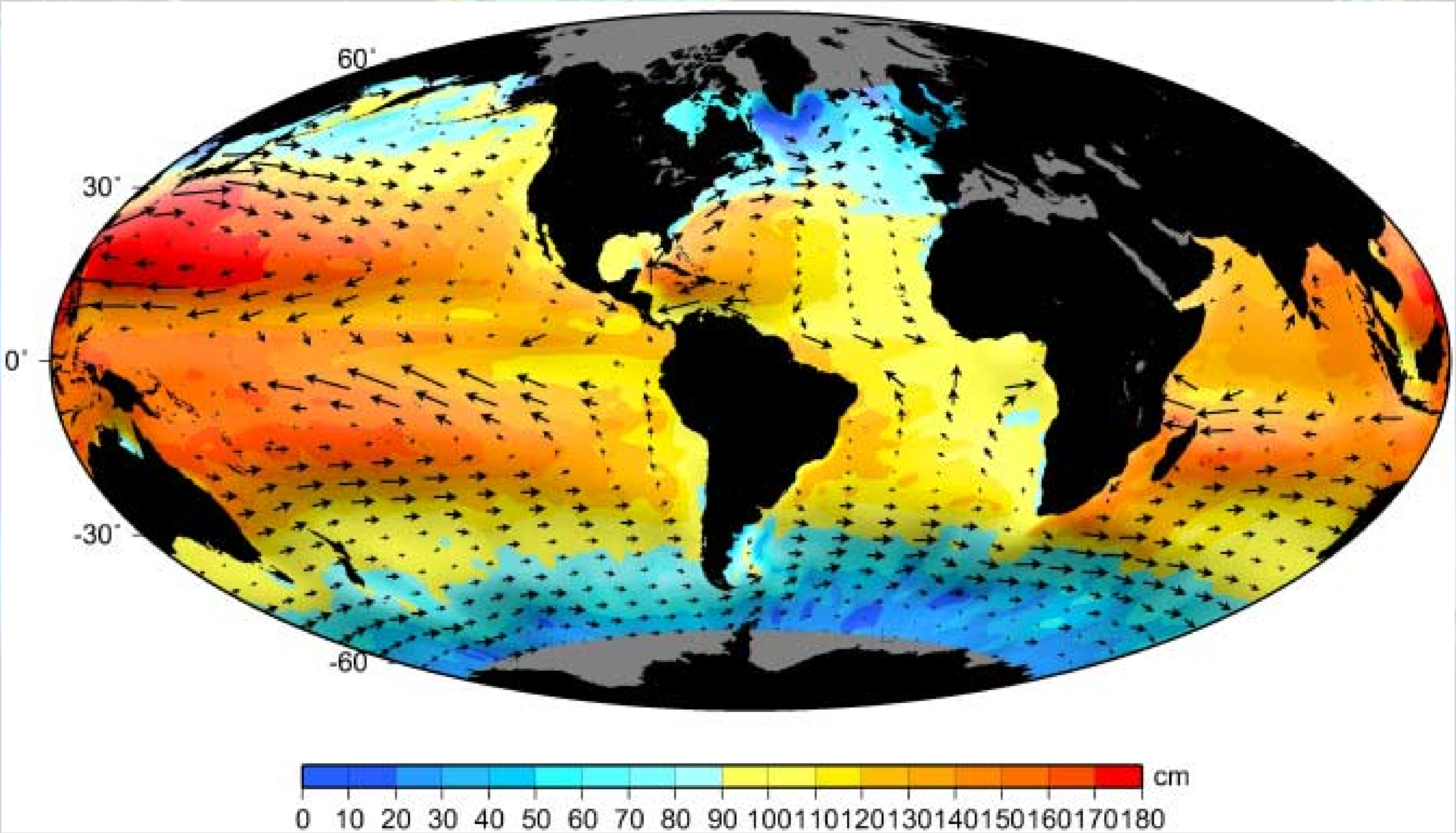
The Keystone Year - 1978

- Seasat - the “100-day” mission
  - Radar altimeter
  - Scatterometer
  - SAR
  - Passive microwave radiometer
- TIROS-N
  - Advanced Very High Resolution Radiometer
- Nimbus-7
  - Coastal Zone Color Scanner
  - Passive microwave radiometer

Preparing for the Next Missions

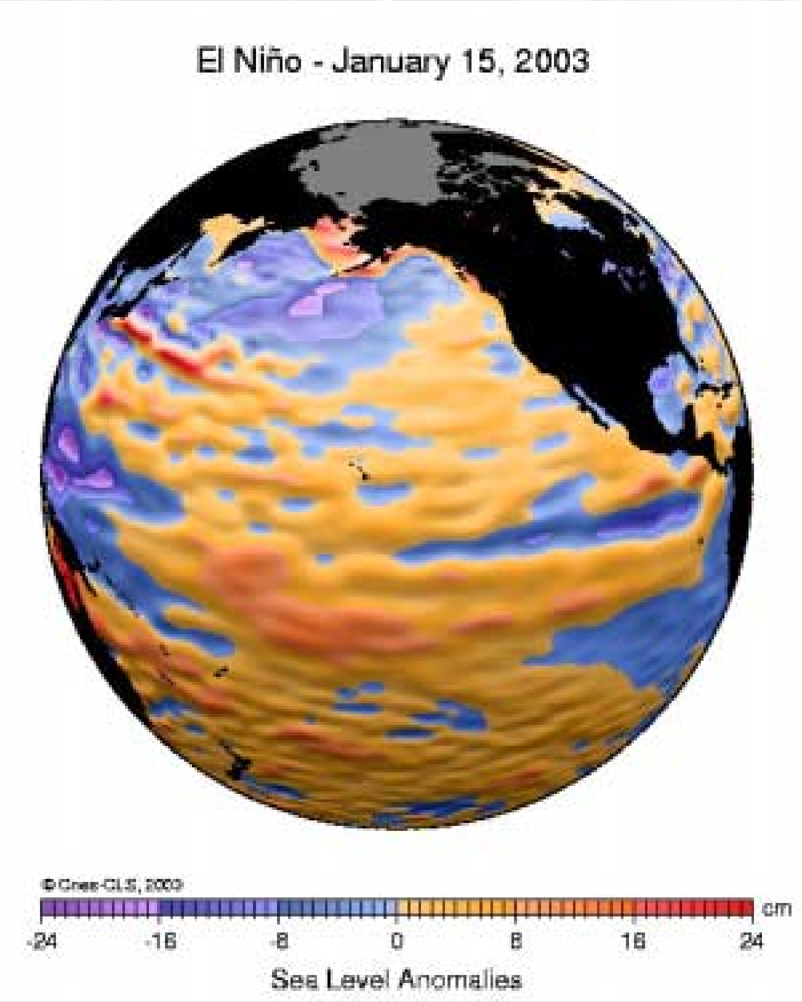
- 1978 missions showed great promise for ocean research
- Standard practice to begin building support for new missions right away
- WOCE and beyond
  - Dynamic topography, mesoscale variability
    - TOPEX/POSEIDON, ERS-1, ERS-2, Jason-1
  - Wind stress
    - ERS-1, ERS-2, ADEOS-1 (NSCAT), QuikSCAT, Envisat, ADEOS-2 (SeaWinds)

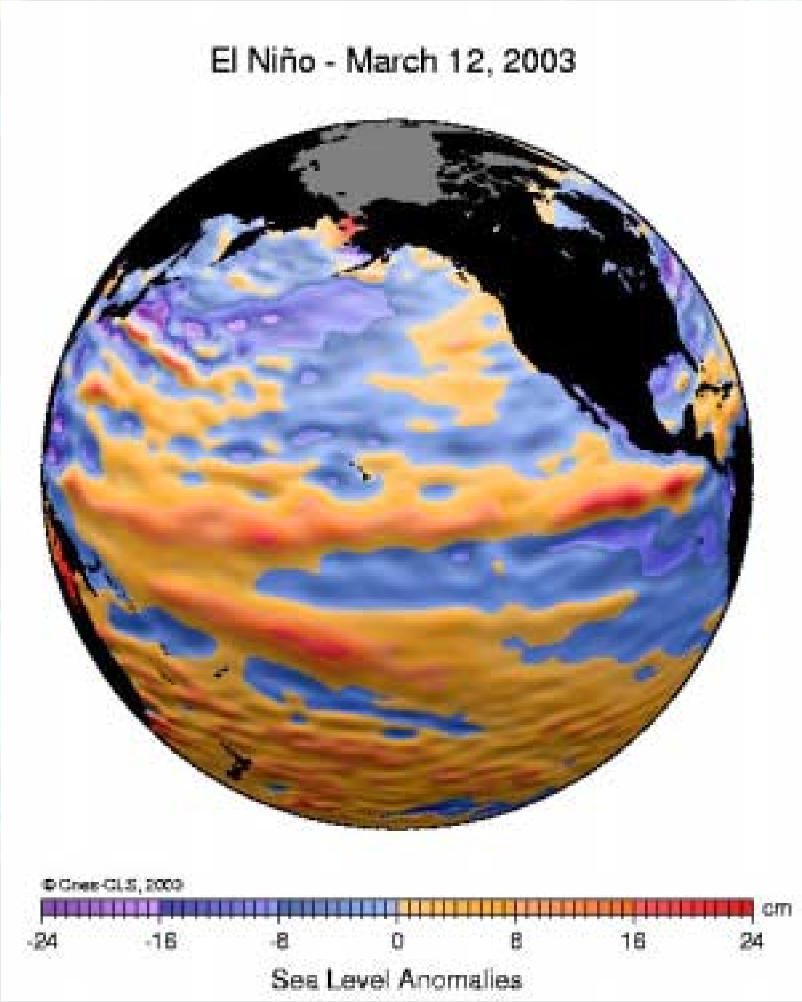
Ocean Currents from TOPEX/Poseidon



AVISO/CNES

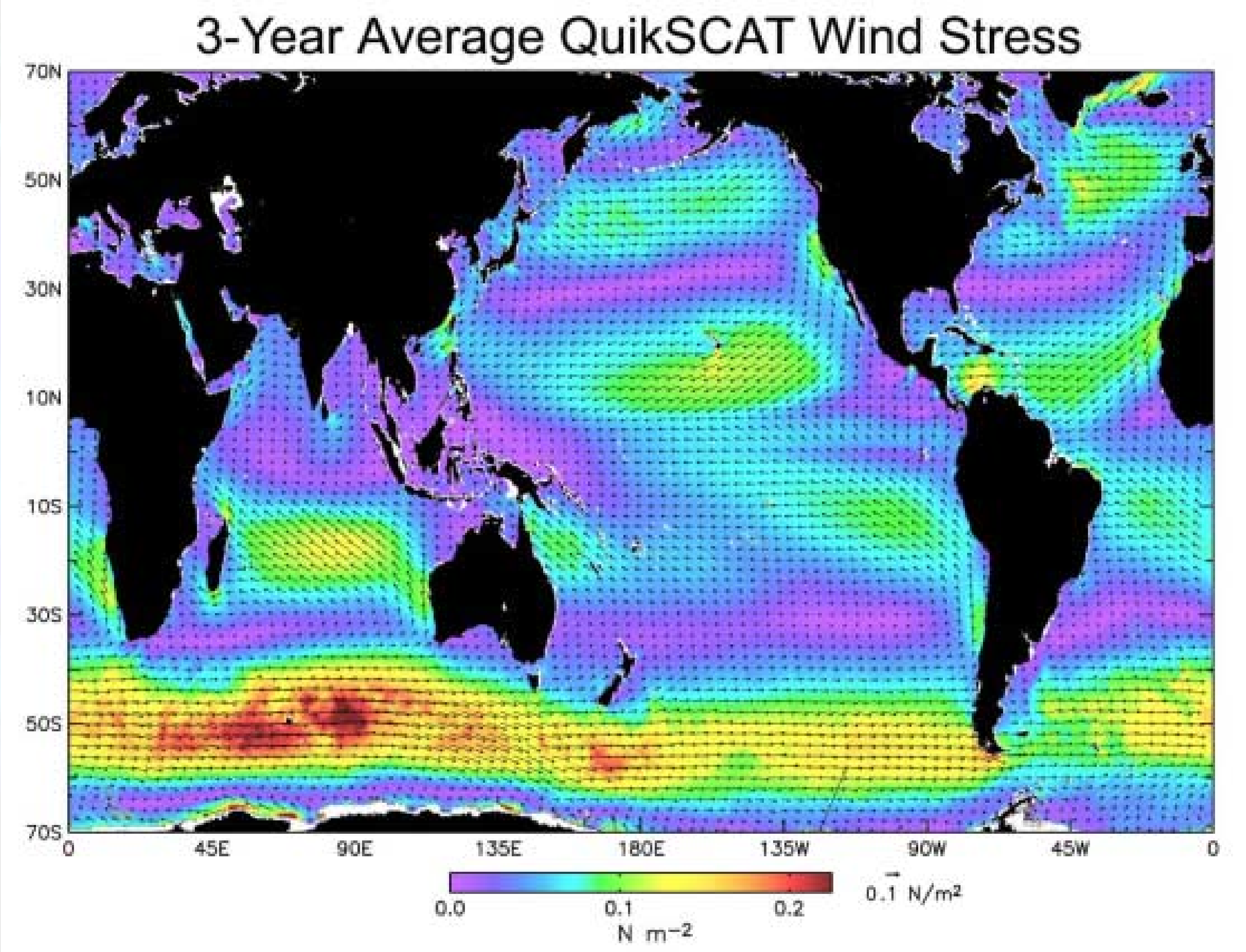
Decline of the 2002/03 El Niño





AVISO/CNES

Global Wind Field



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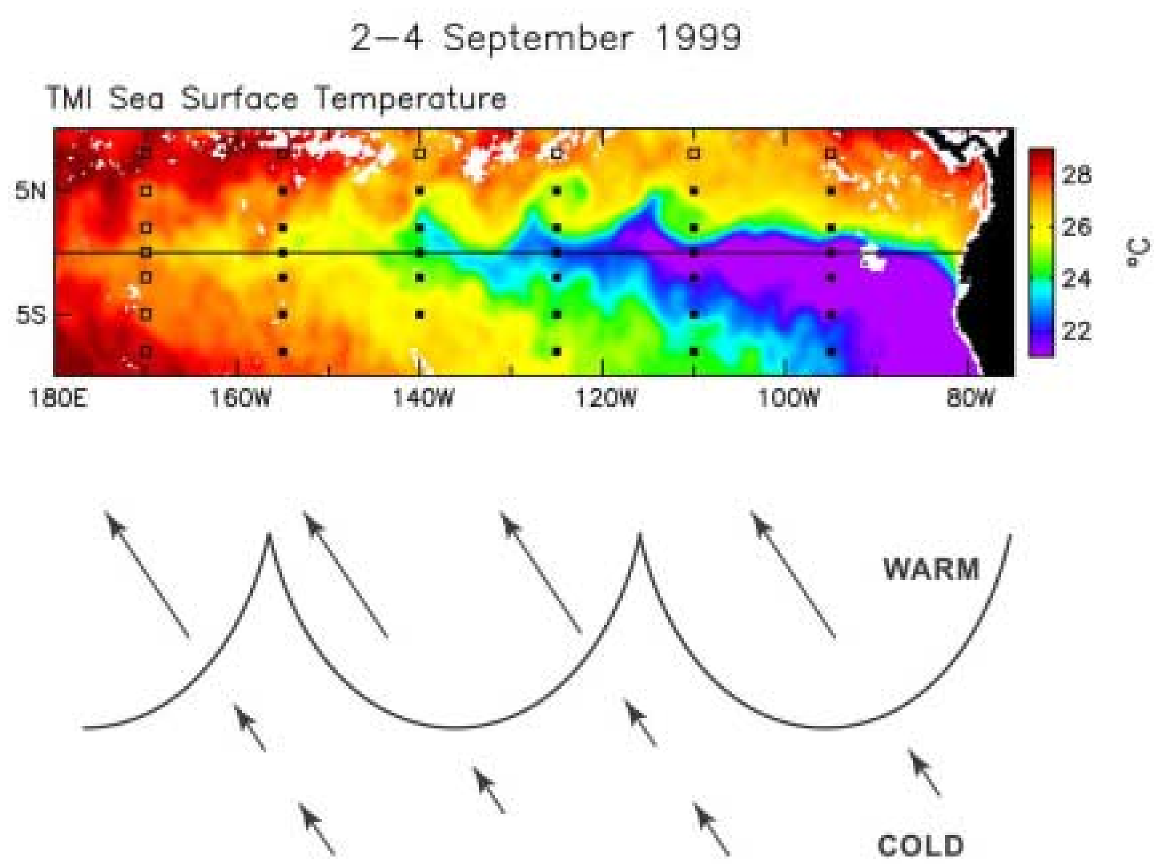
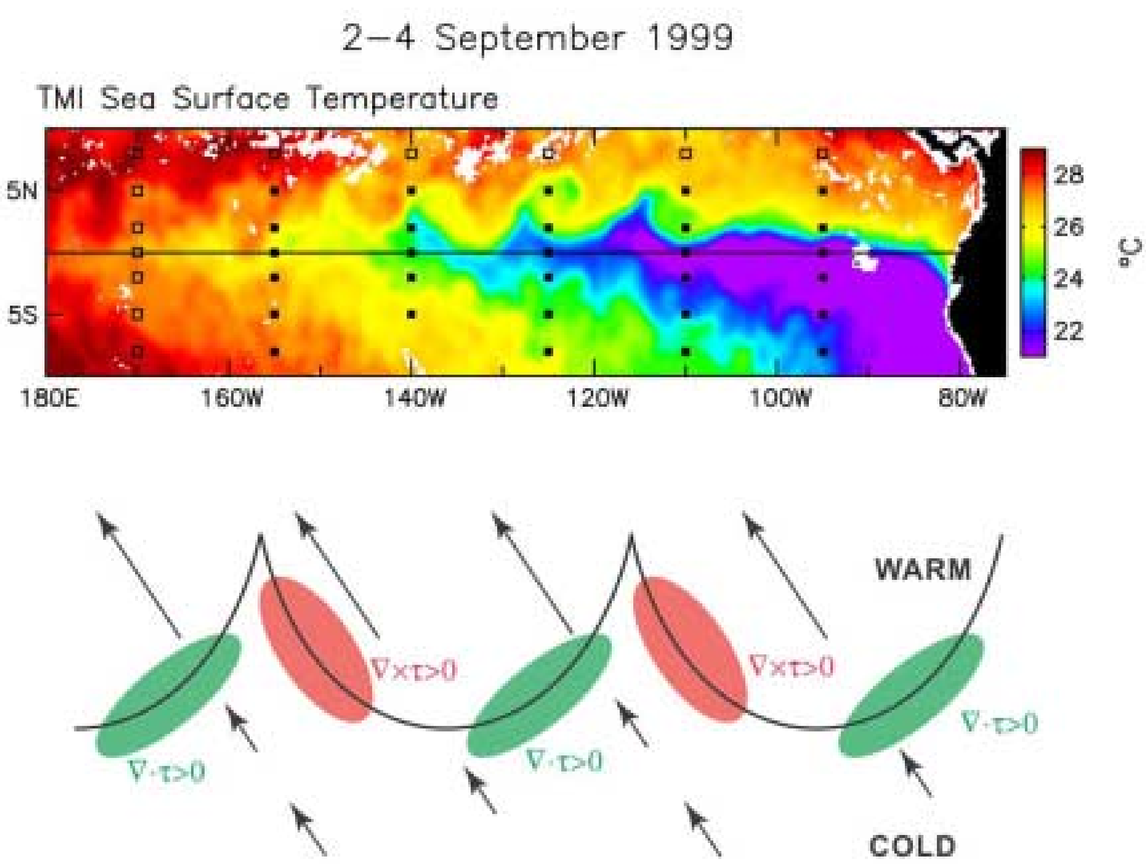
Ocean/Atmosphere Interactions



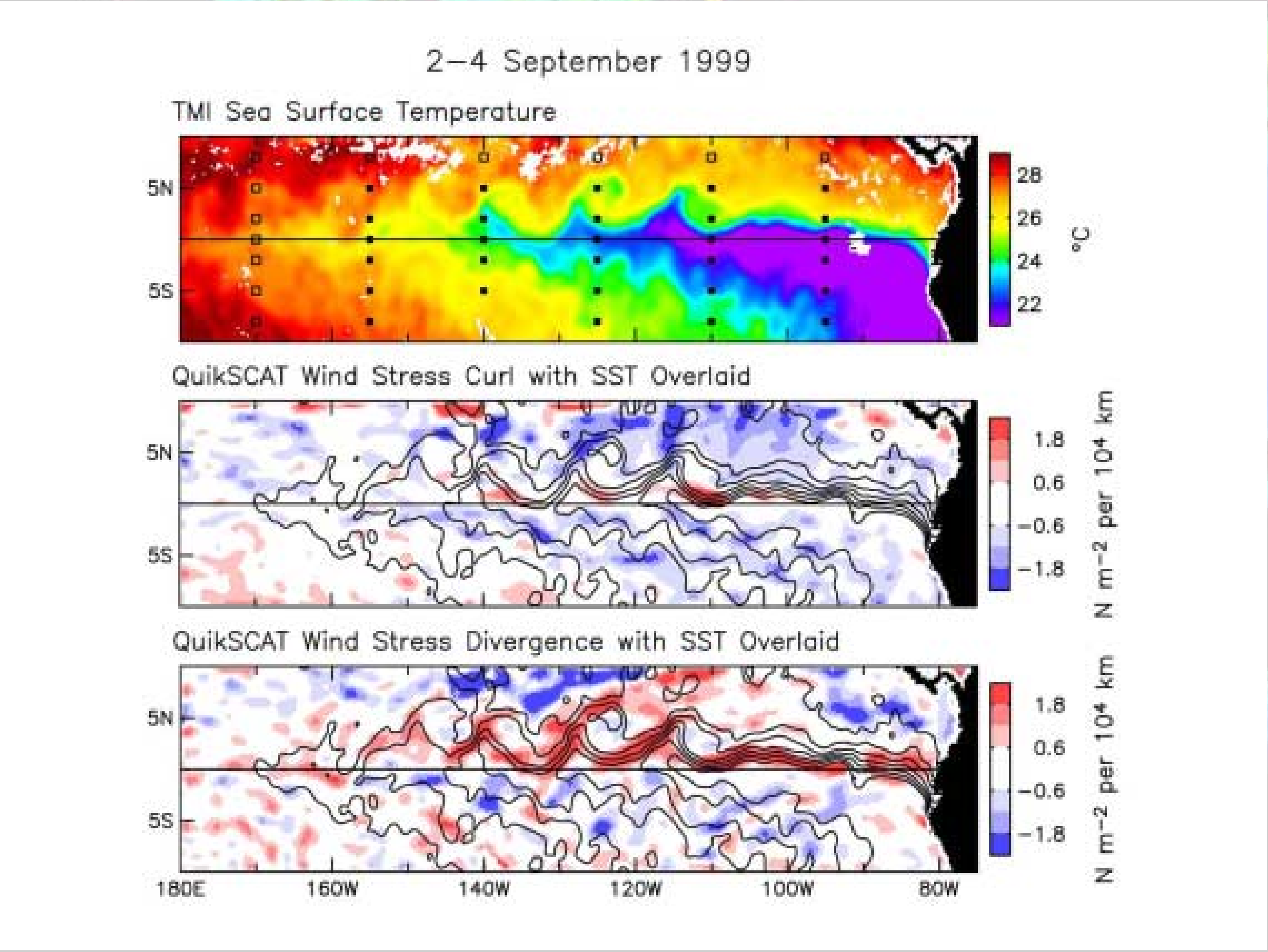
Chelton et al., J. Climate (2001)

How Vector Winds Respond



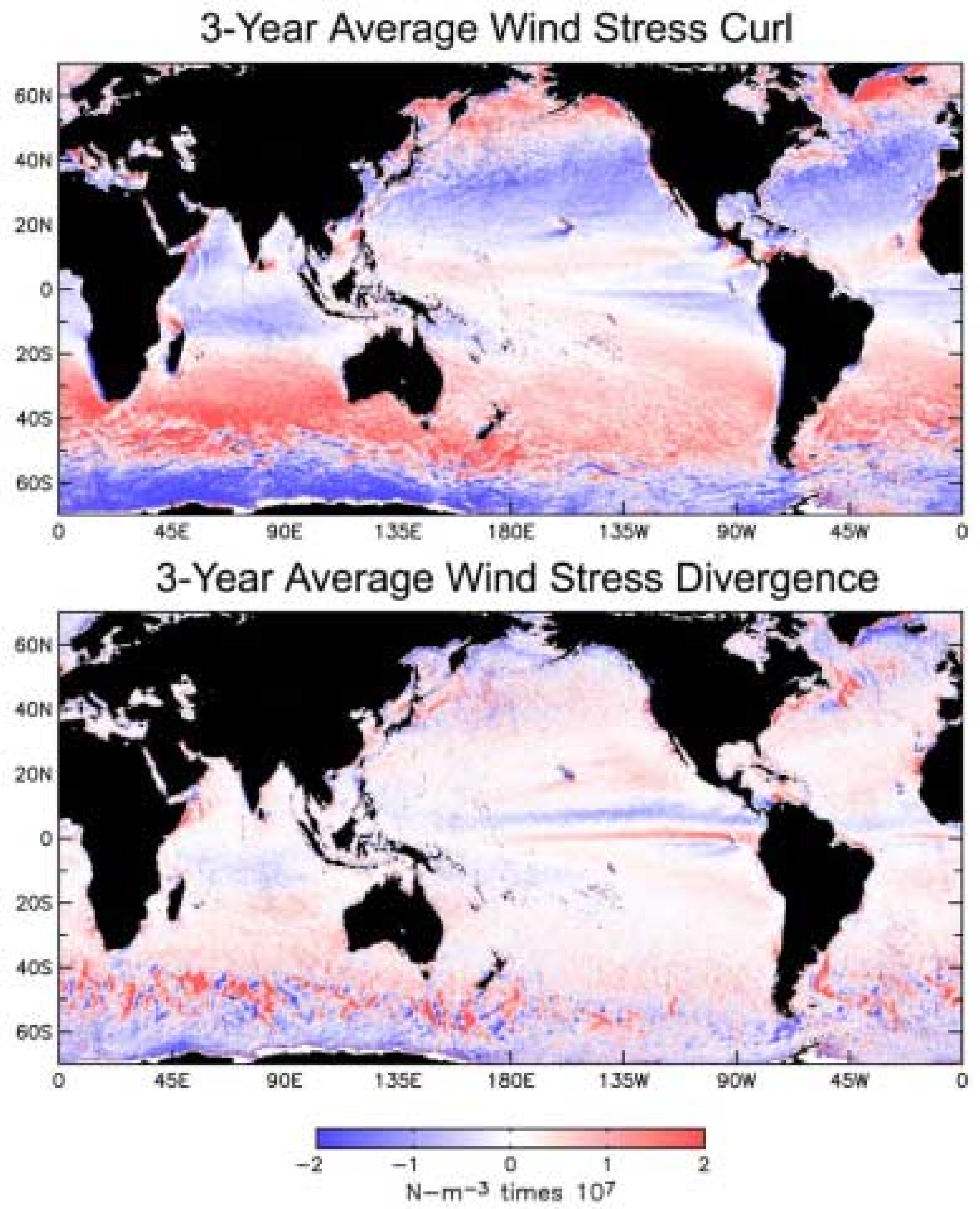
Chelton et al., J. Climate (2001)

An Animation of Vector Winds and SST



Chelton et al., J. Climate (2001)

Curl and Divergence



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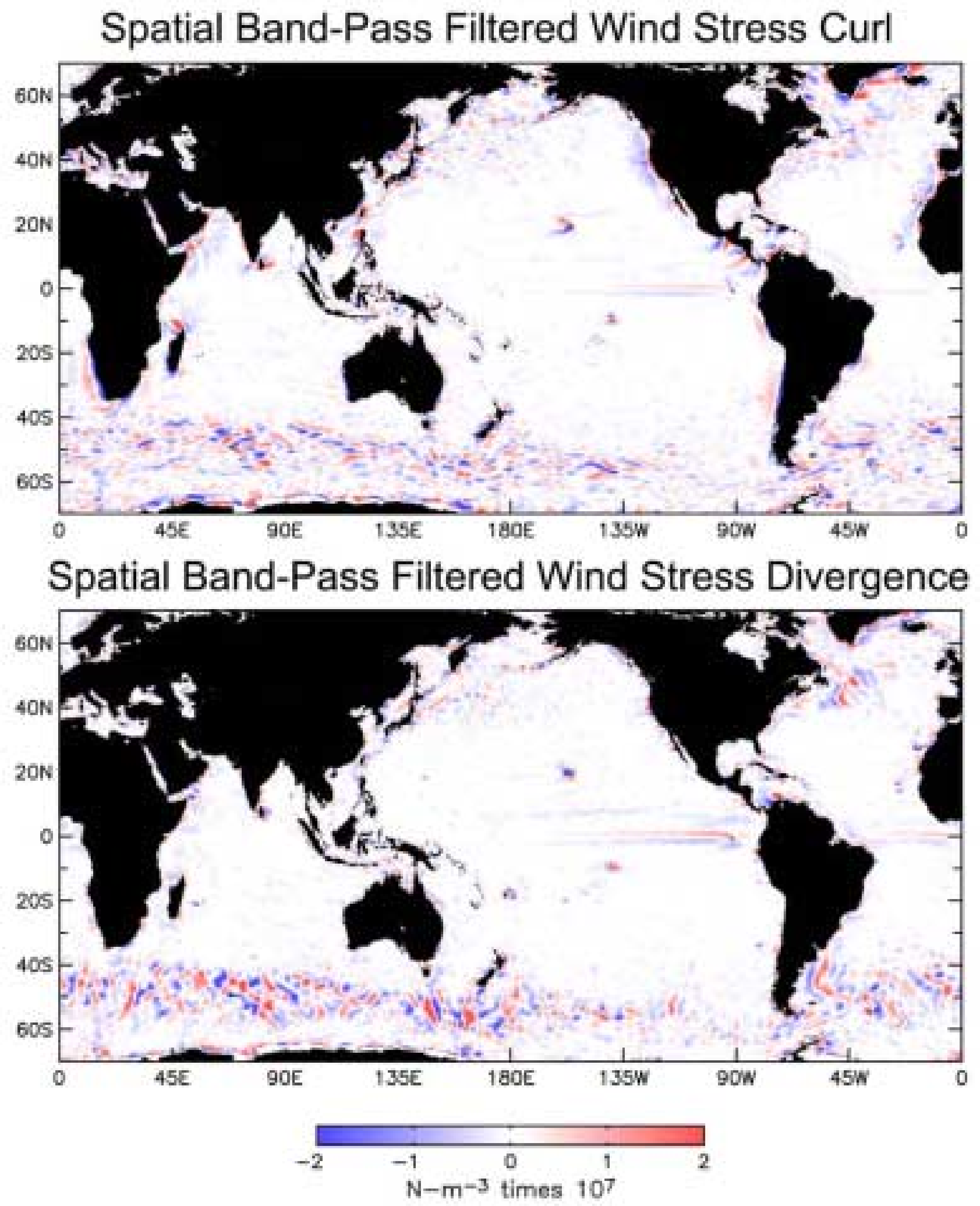
Filtered Curl and Divergence Fields



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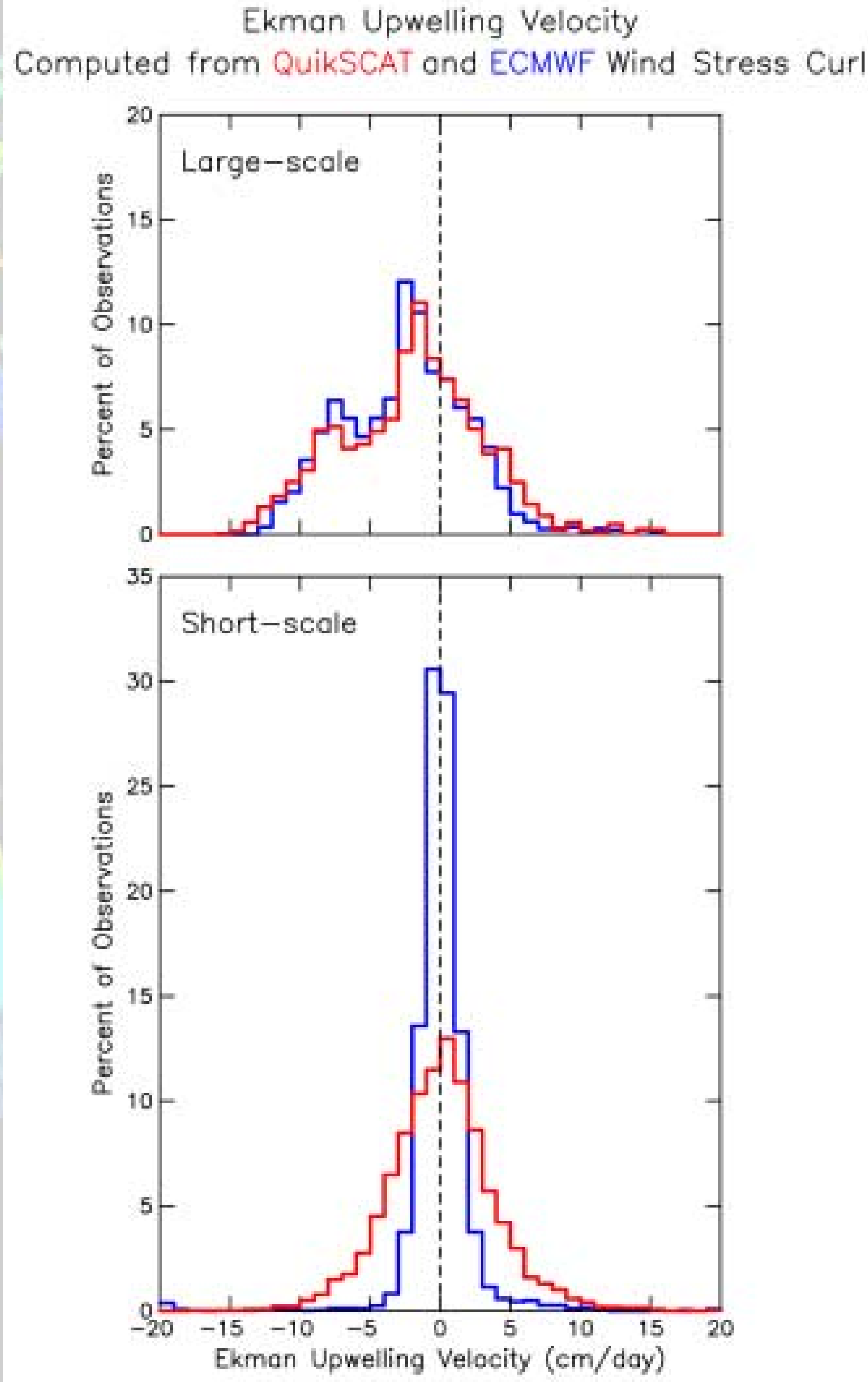
Ekman Upwelling Velocity Estimates



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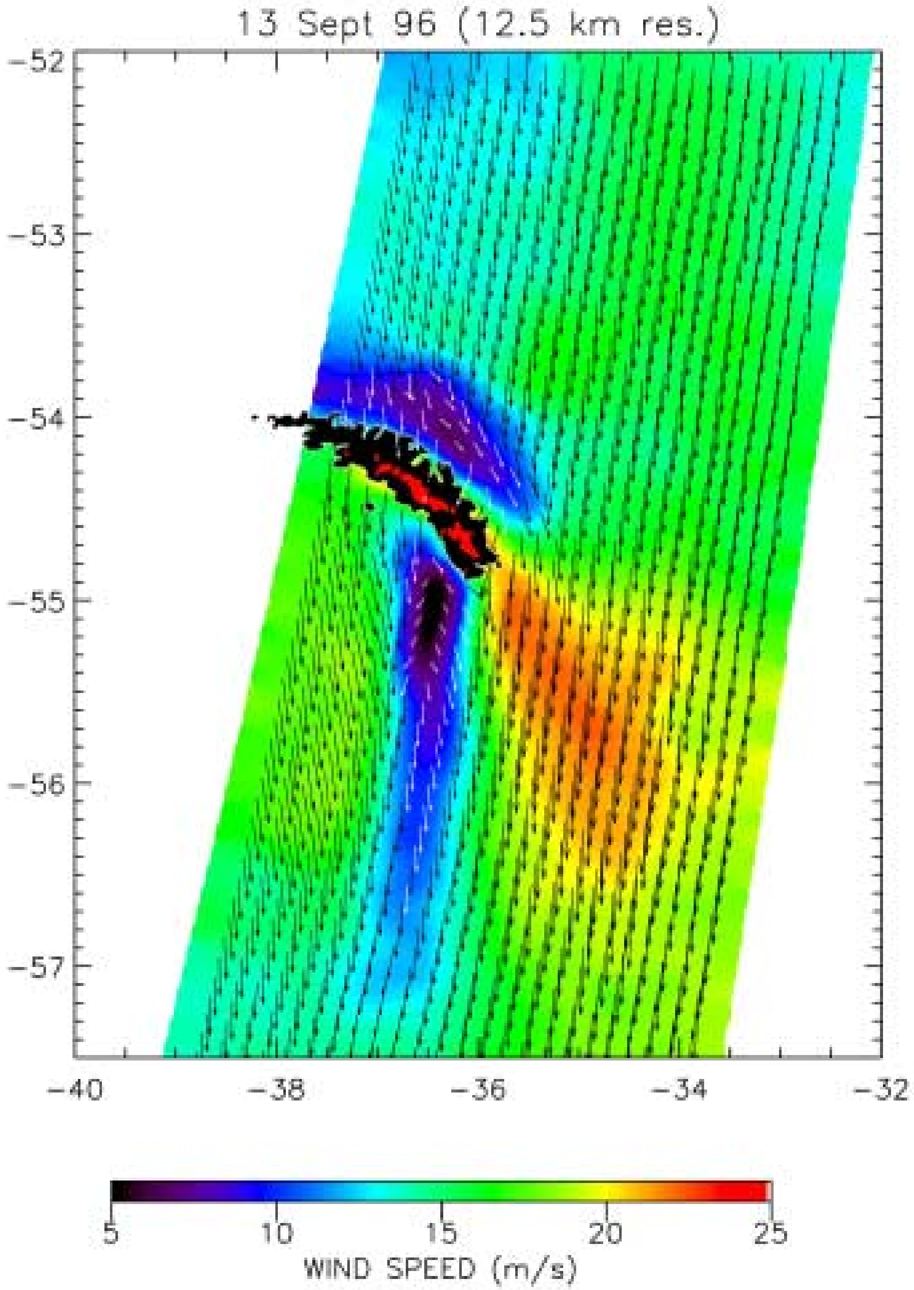
Mesoscale Variability

Wind shadow adjacent to South Georgia Island



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"Operational" Sensors for Ocean Research

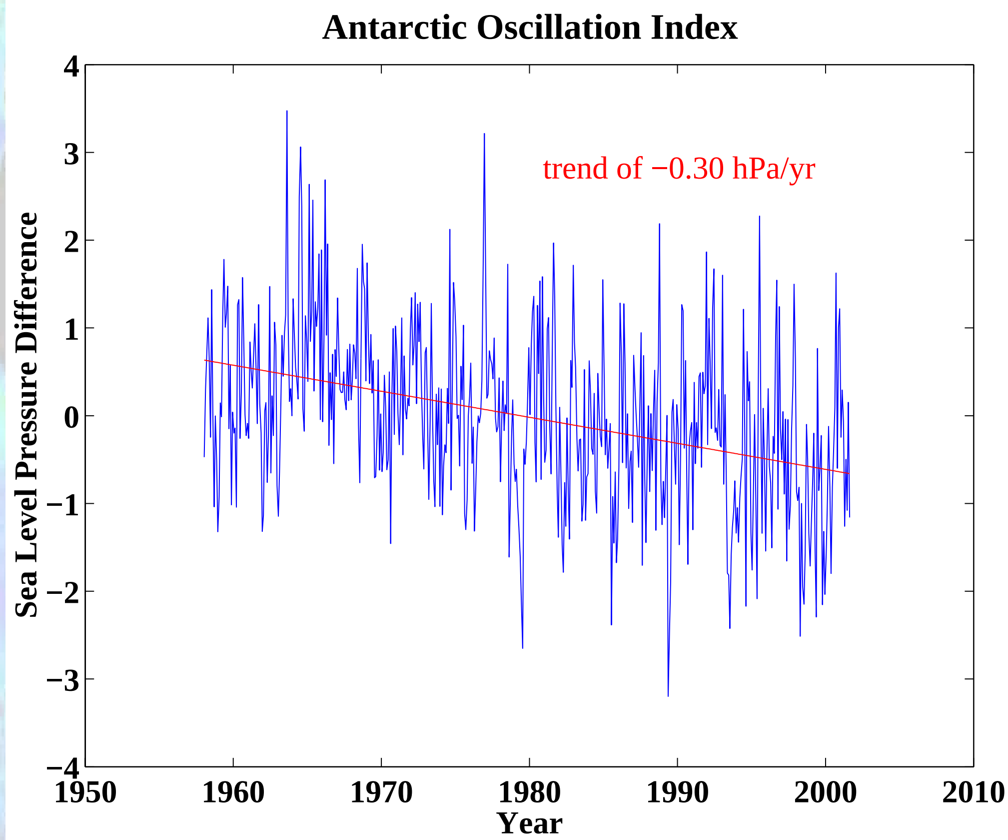
- Infrared – AVHRR
  - Series begun in 1978
  - JPL/NASA/NOAA global reprocessing for period 1987-1999
- Passive microwave – SSM/I
  - Series begun in 1987
  - Sea ice, wind speed, atmospheric properties
  - Lower frequencies on Tropical Rainfall Measuring Mission (TRMM) to measure SST

Can We Use Satellites to Study Long Time Scale Processes?

- “Operational” satellites (those designed primarily for short-term forecasting needs and other mission-critical functions)
  - Polar-orbiters such as those operated by NOAA (POES) and US Dept. of Defense (DMSP)
  - Time series of SST and water vapor (Frank Wentz, Remote Sensing Systems
- Some research satellites have now generated long time series
- An example from the Southern Ocean

Antarctic Oscillation Index

- Antarctic Oscillation Index (AOI) is a proxy for the variability of the winds over the Southern Ocean
- AOI= P*40°S - P*65°S where P*40°S and P*65°S are the zonally averaged sea level pressure (SLP) at 40°S and 65°S respectively



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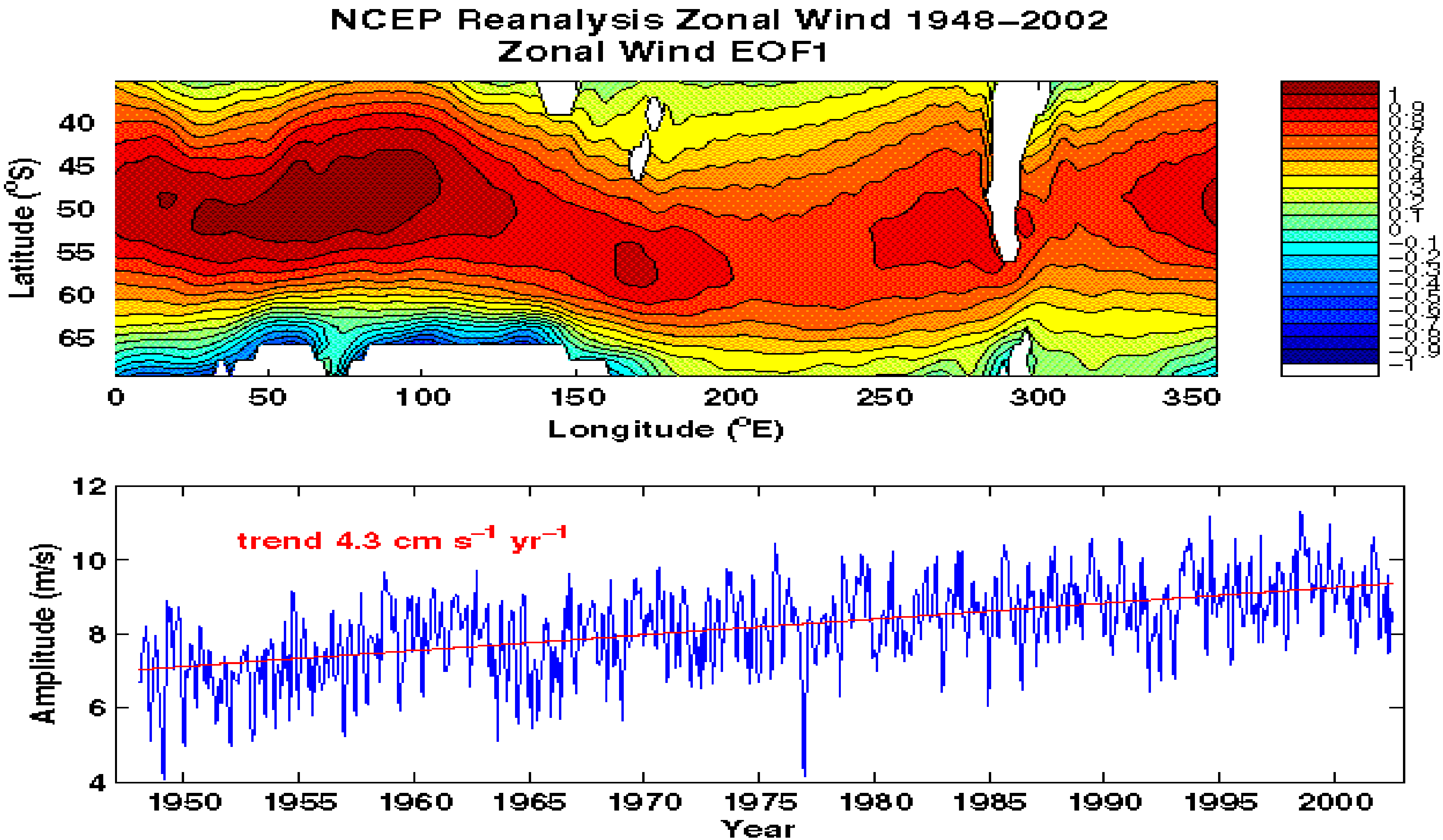
Zonal Winds in the NCAR/NCEP Reanalysis



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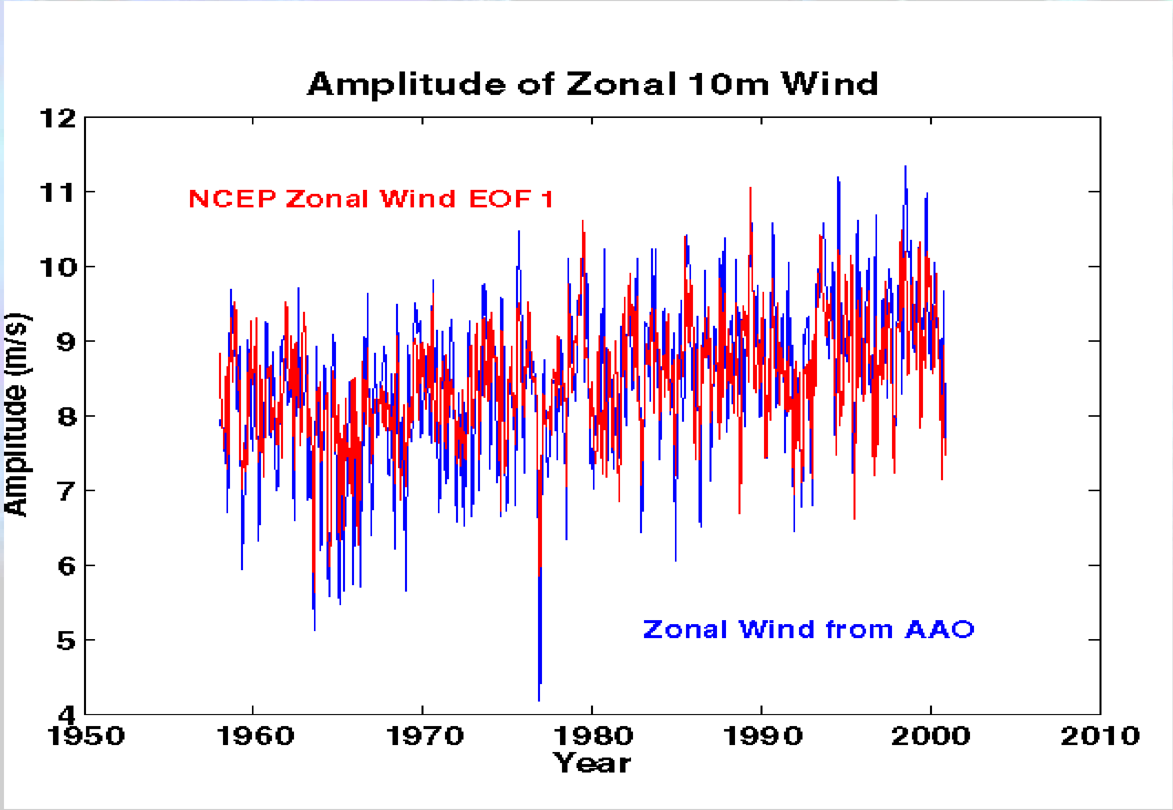
Comparison of the Zonal Wind EOF and the Antarctic Oscillation Index

- The geostrophic wind can be calculated from the Antarctic Oscillation Index
- AOI geostrophic wind is highly correlated with the amplitude of the 10 m zonal wind EOF amplitude (r=0.79)



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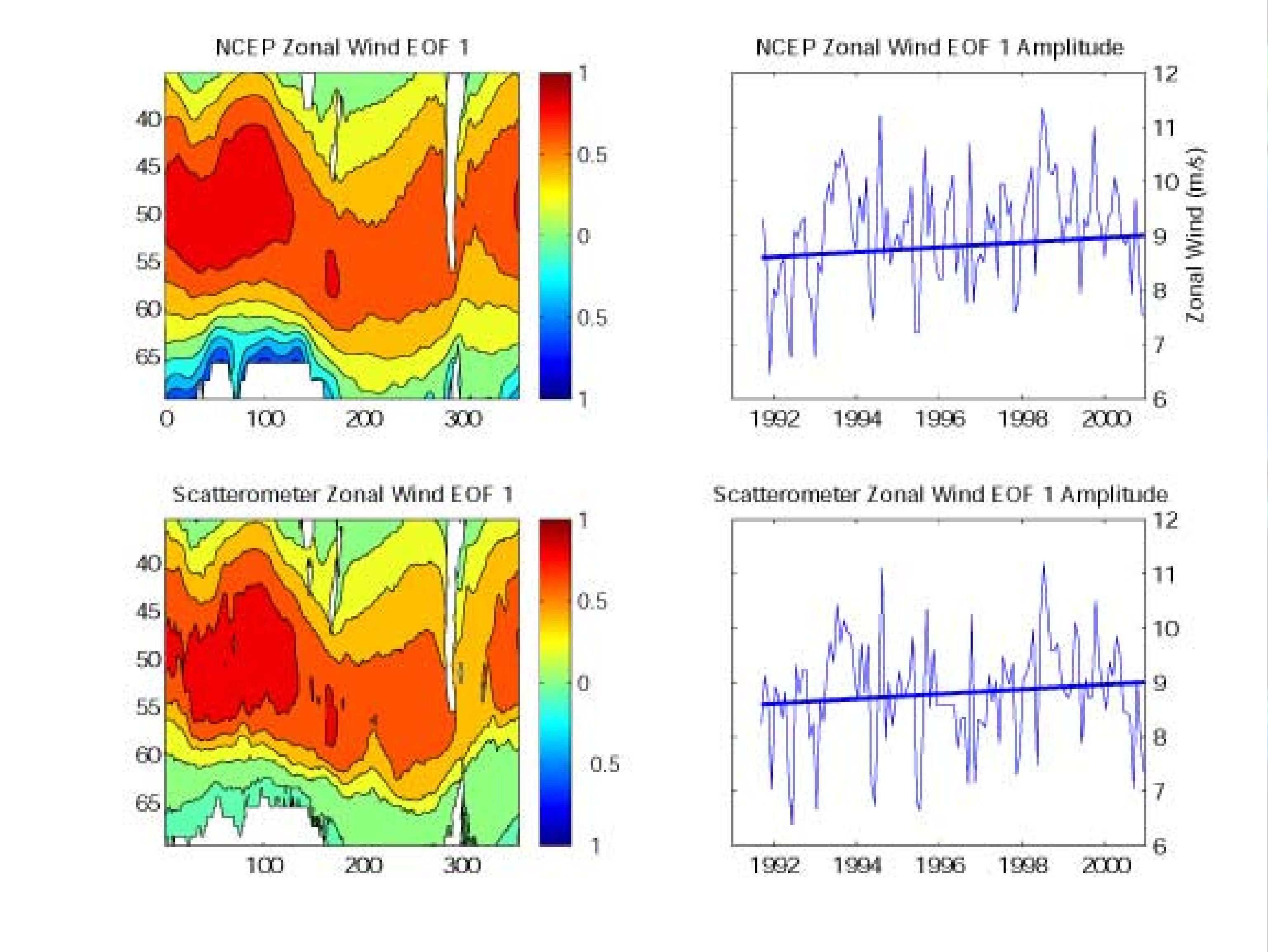
Interannual Changes in Wind Forcing



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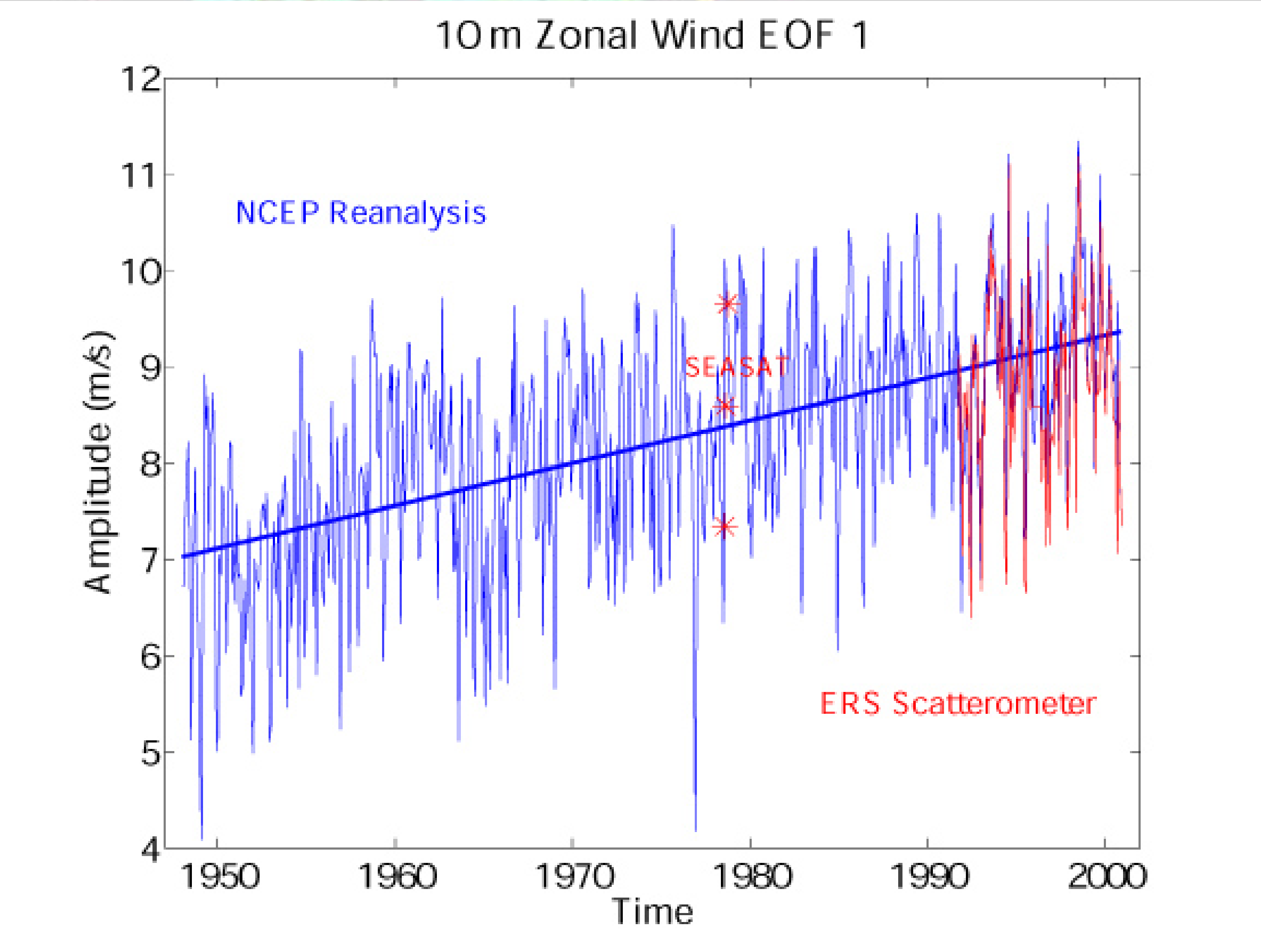
Multiple Scatterometers



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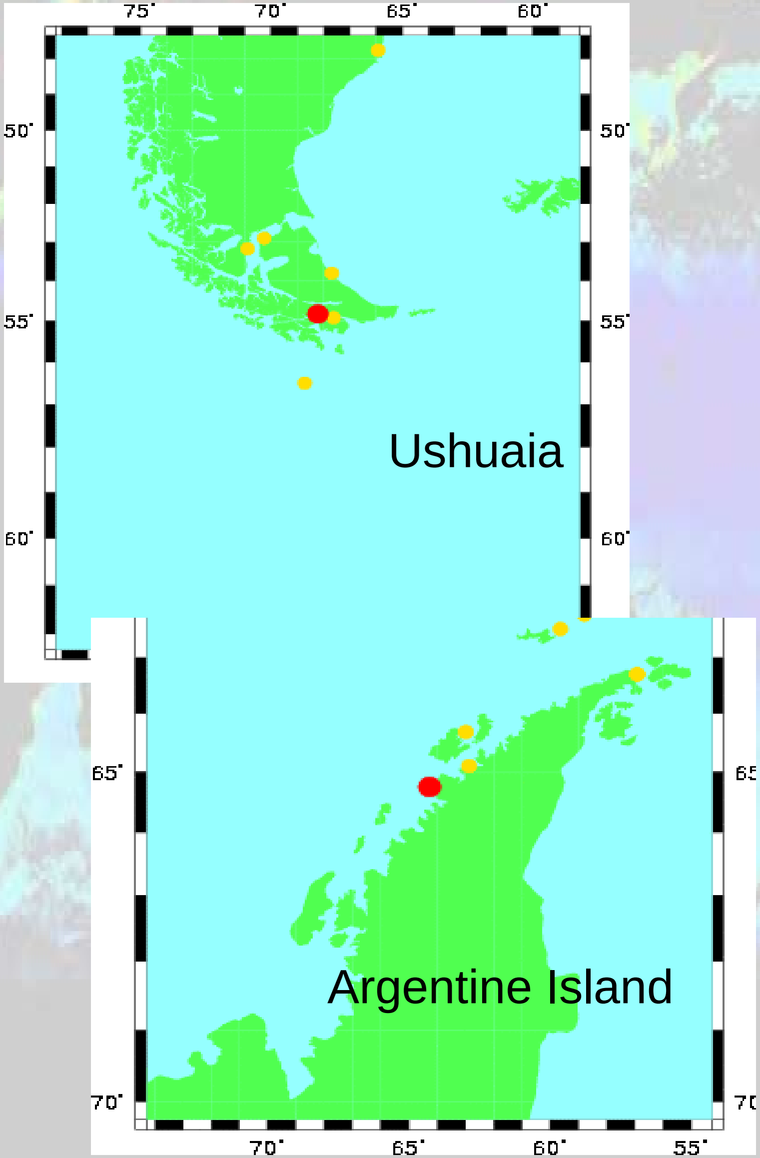
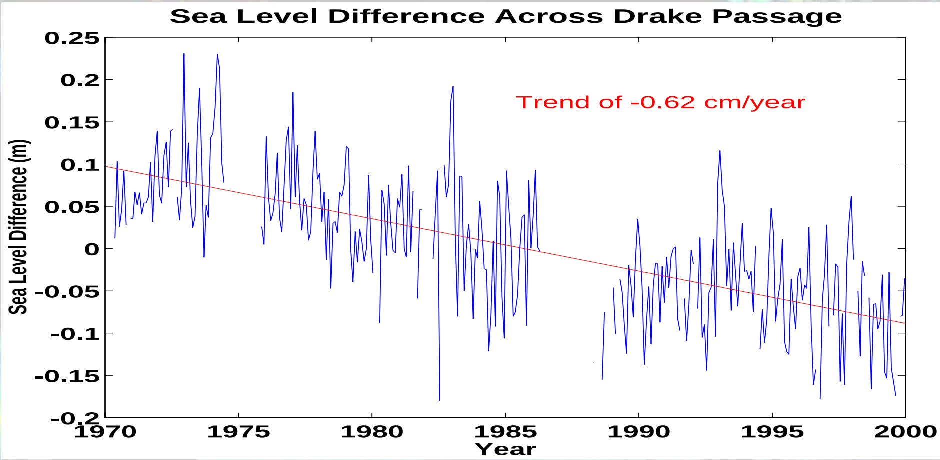
Sea Level across Drake Passage

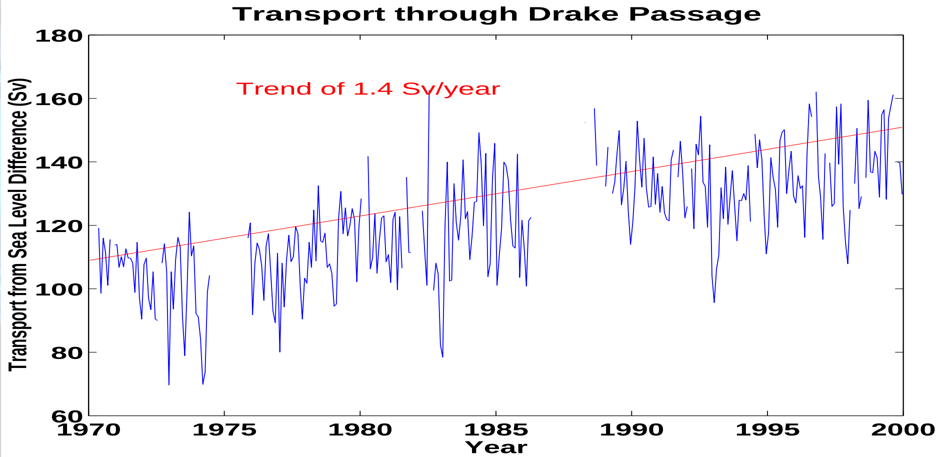
- Transport through Drake Passage was monitored during ISOS
  - Most of the transport was baroclinic and fluctuations were barotropic
- To look at the trends in transport, two long term sea level stations will be used
- Ushuaia is located on the north side of the Passage
- Argentine Island is located on the south side of the Passage



Transport and Sea Level Difference across Drake Passage

- The sea level difference across the Passage shows a trend of -0.62 cm/year
- Assuming that the transport fluctuations are barotropic with a 2.25 Sv/cm and transport of 123 Sv in 1980, the modeled transport has a trend of 1.4 Sv/year increasing from 110 Sv in 1970 to 150 Sv at present





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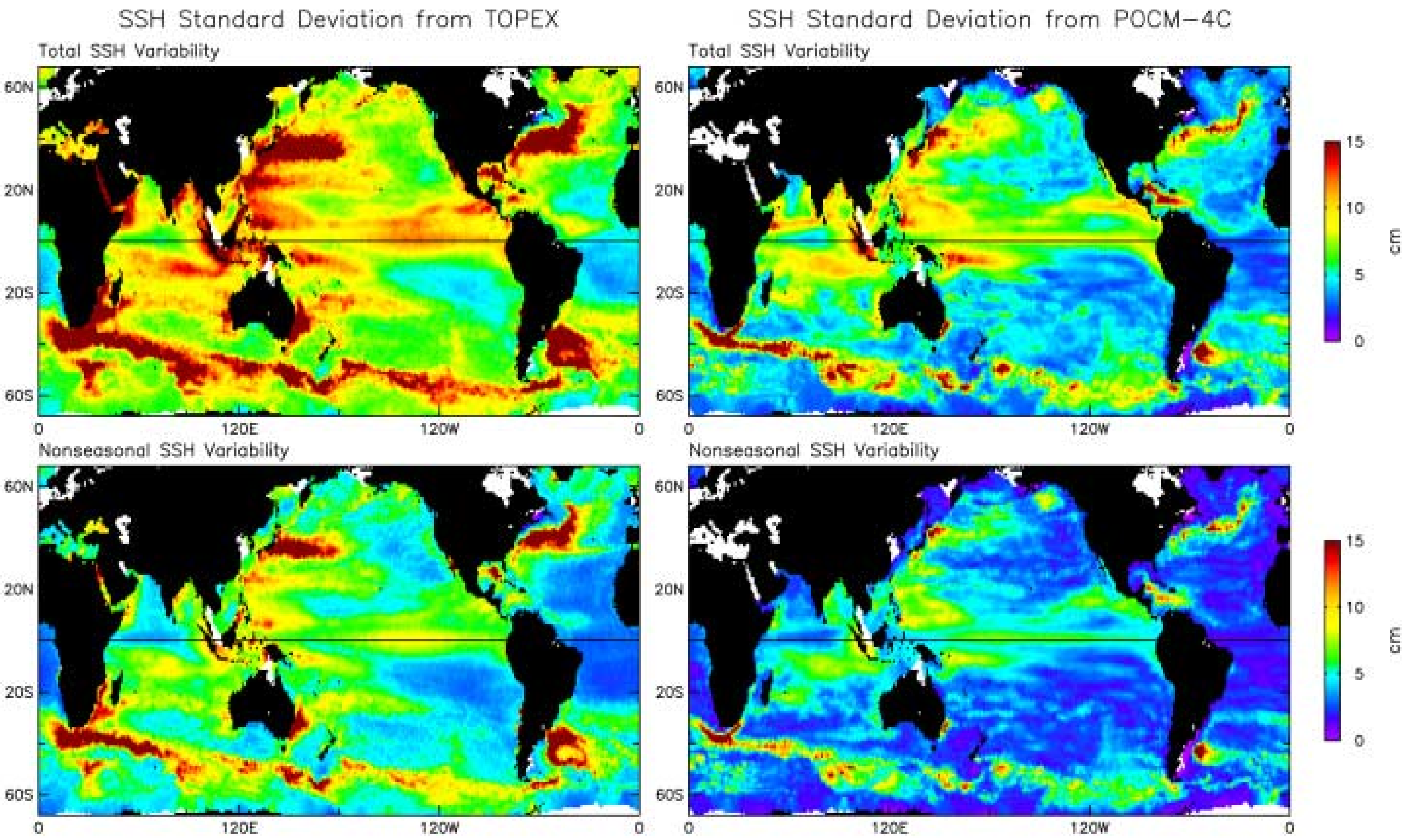
Summary of Long-Term Changes in the Southern Ocean

- Winds over the Southern Ocean from the NCAR/NCEP Reanalysis show a trend of 4.4 cm/s/yr increasing from a mean of 7 m/s to 9.2 m/s over 53 years,
  - This represents a 50% increase in the wind stress
- Satellite scatterometers show a similar trend of 3.9 cm/s/yr in the 1990s and the 3 months of SEASAT in 1979 are consistent with the long term trend
- Drake Passage transport shows an increase of 1.4 Sv/yr corresponding to an increase from 123 Sv in 1980 to 150 Sv in 2000

Impacts

- Increasing winds will increase transport
- But observed transport does not increase sufficiently to account for increased wind-driven transport
- Increased vertical transport of momentum via eddies is one possibility
- How well do models capture eddy processes?

Models Underestimate Sea Level Variability



Ocean Color Satellites

- Strong connections with JGOFS, building on success of CZCS
- Recent missions
  - OCTS – on ADEOS-1 (1996-1997)
  - SeaWiFS – on ORBIMAGE (1997 – present)
  - MODIS – on EOS-Terra (1999 – present) and EOS-Aqua (2002 – present)
  - MERIS – on Envisat (2002 – present)
  - GLI – on ADEOS-2 (2002 – present)
- Research missions
  - High quality sensors, algorithms
  - Strong science involvement

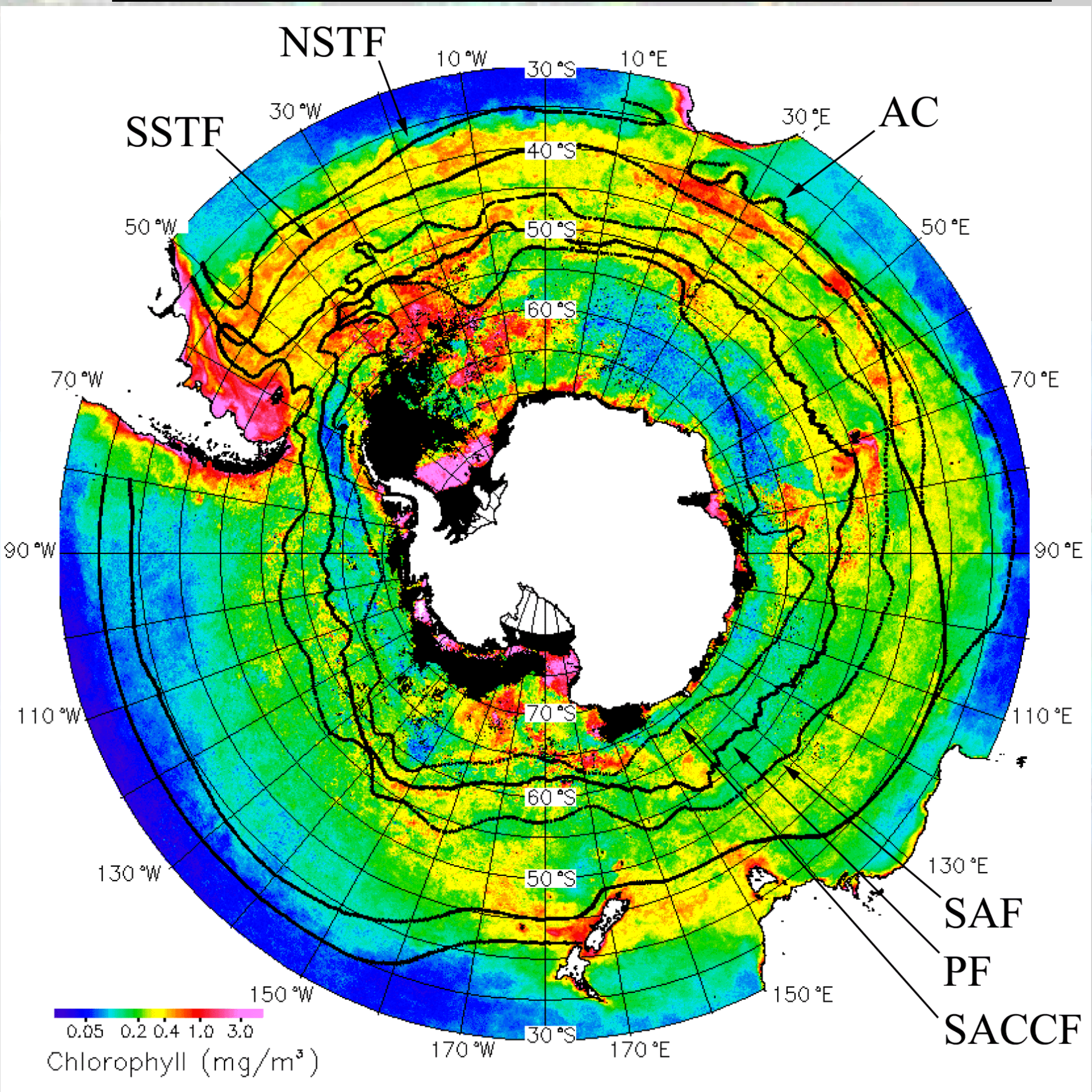
Where Did We Start?

- Global Ocean Flux study (1984)
  - Satellite/Surface Productivity group
    - McCarthy, Abbott, O. Brown, Eppley, Flierl, Gagosian, Minster, Morel, Pollard, R. Smith, Walsh, and Yentsch
- Recommendations included:
  - Routine measurements of ocean color, SST
  - Development of optical buoys (about 70)
  - Relate surface and subsurface properties
  - Design of optimal sampling strategies
  - Coordination with field programs
  - Development of coupled global models
  - Development of scientific infrastructure

And What Did We Hope to Achieve?

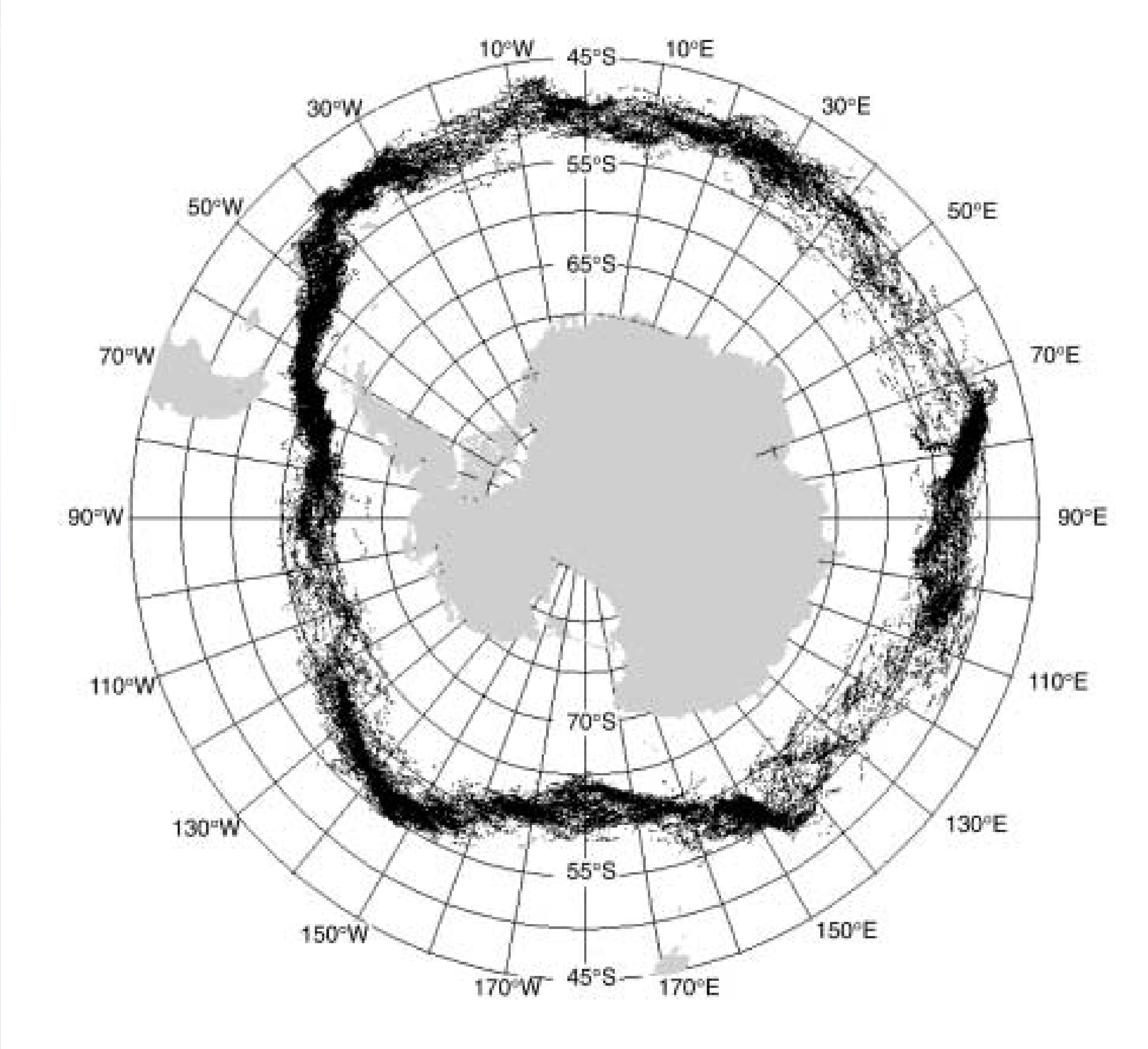
"Prognostic models...must have adequate parameterization of small-scale processes. Such models should be able to predict the biological response to physical forcing. Moreover, the statistical properties of these models must be correct. That is, they should be able to predict the spatial and temporal variability of processes such as carbon flux in response to variable physical processes, both oceanic and atmospheric. Such modeling efforts will require sophisticated computational techniques to incorporate global pigment and SST data as well as wind and altimetric data." (NRC 1984)

Annual Mean Chlorophyll



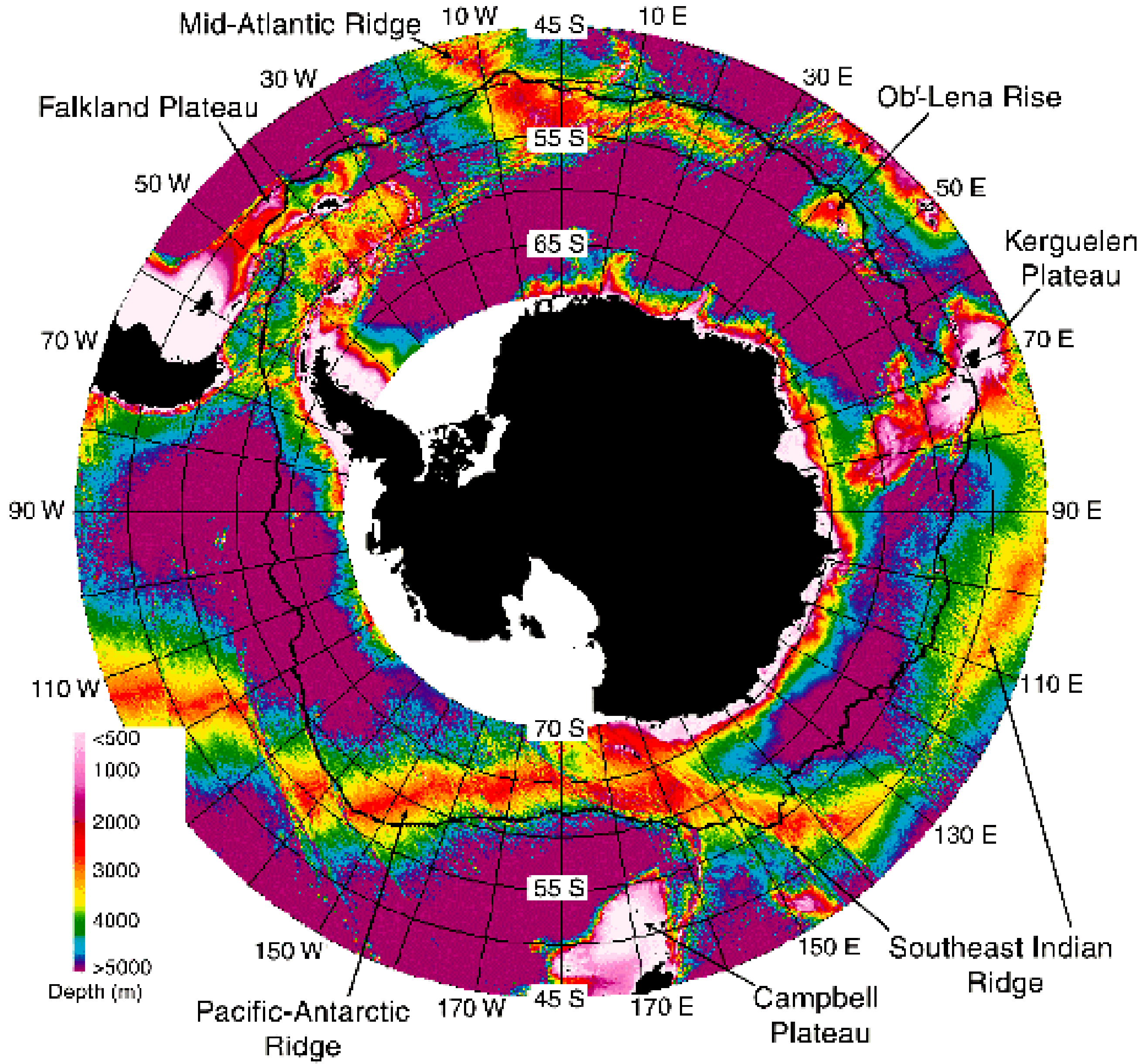
Moore and Abbott, JGR (2000)

Variations in the Position of the Polar Front, 1987-1998



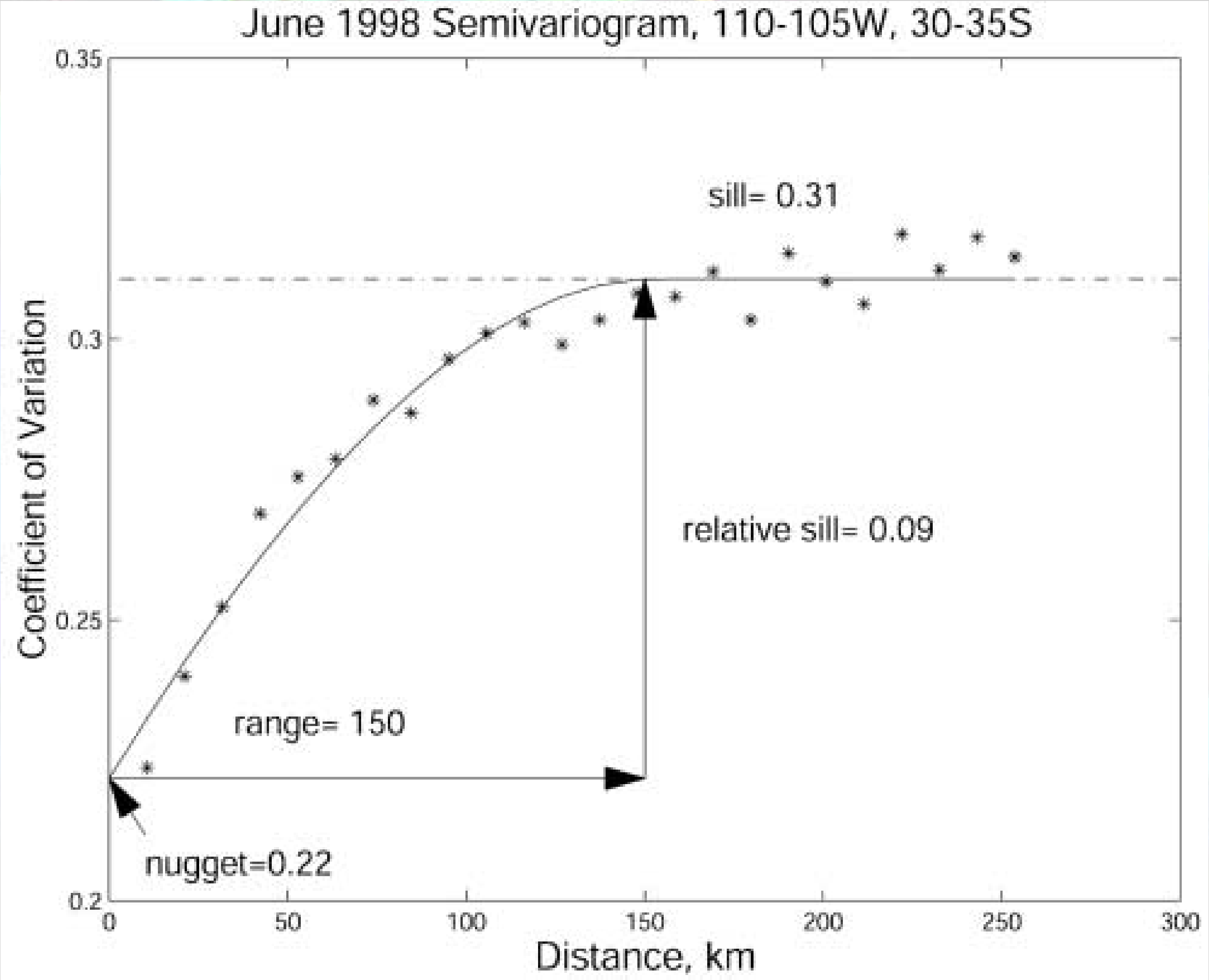
Moore et al., JGR (1999)

- Steering of Polar Front by bottom topography
- Meanders more common where topography is flat



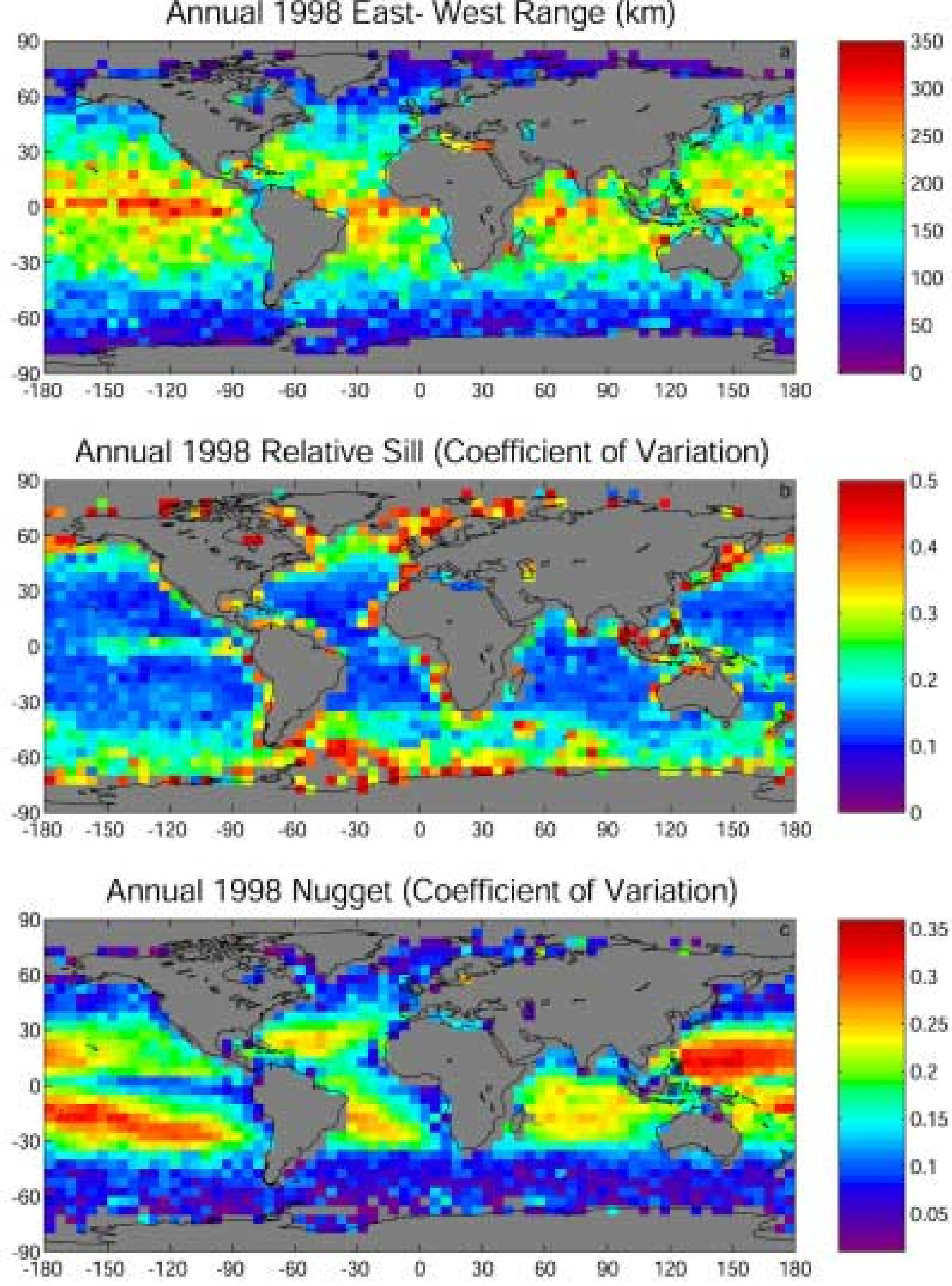
Moore et al., JGR (1999)

Spatial Statistics from Ocean Color



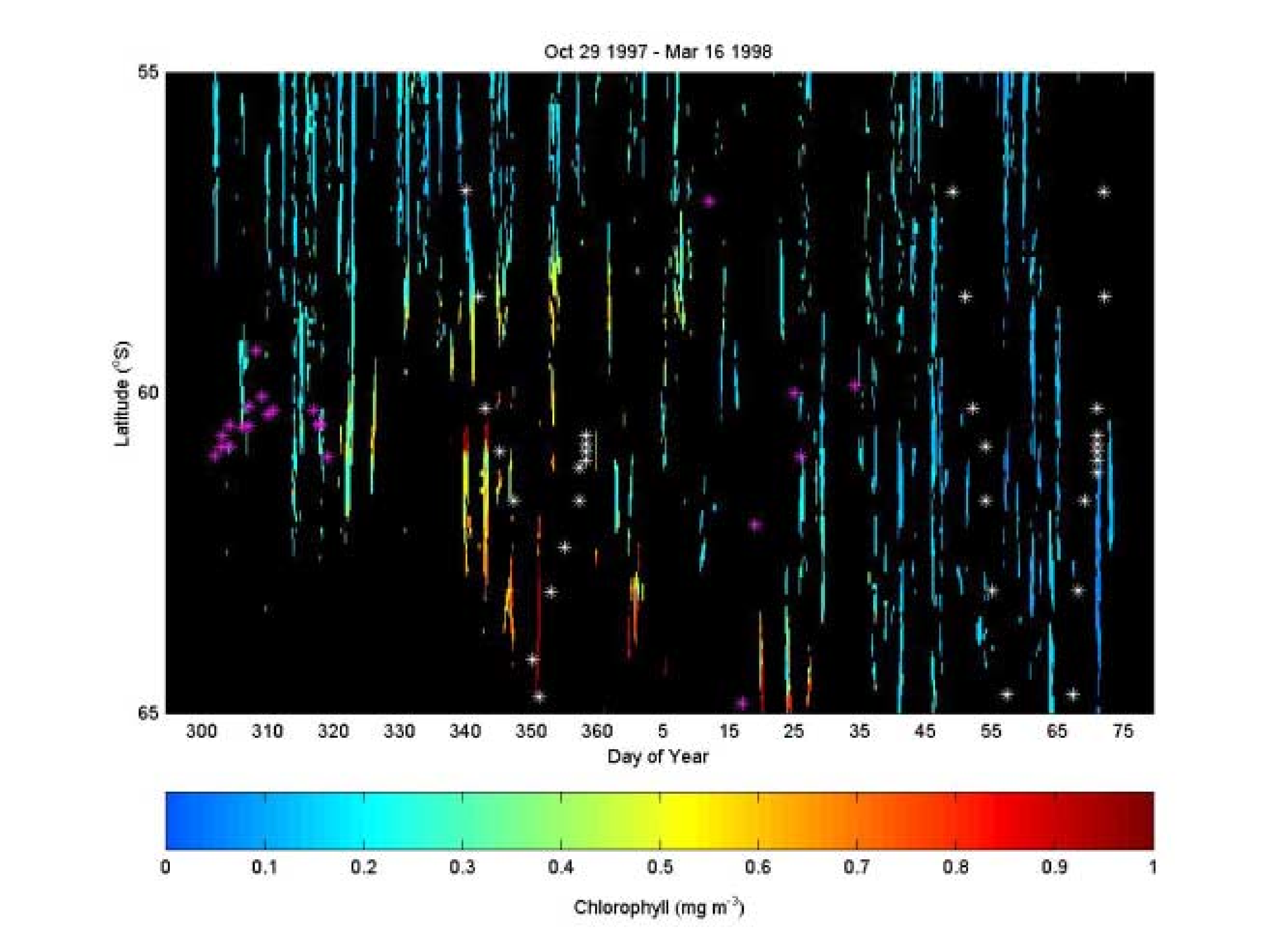
Doney et al., JGR (2003)

Maps of Spatial Statistics

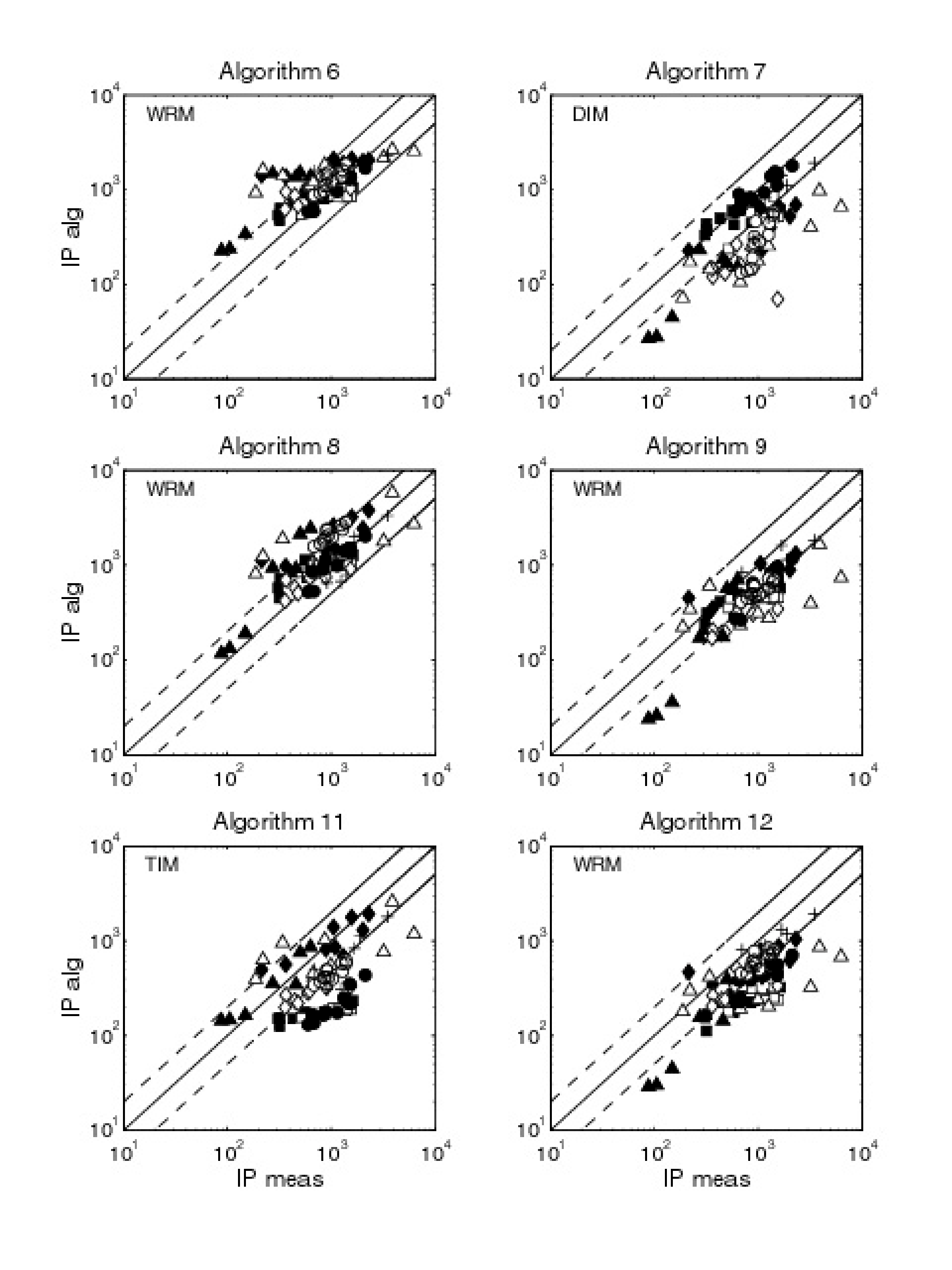


Doney et al., JGR (2003)

SeaWiFS Sampling at the Polar Front



Primary Productivity Round Robin



Campbell et al., GBC (2002)

Estimates of Primary Productivity

Study	Global
Longhurst et al. (1995)	45-50 Pg C/yr
Behrenfeld and Falkowski (1997)	48.5
Martin et al. (1987)	51
Berger (1989)	27.0
Walsh (1988)	29.7

Most of the variability in estimates is due to the uncertainty in the physiological parameters in the models

Fluorescence and Productivity

- $F = [chl] \times (PAR \times a^*) \times \phi_F$

  where F = fluorescence

  [chl] = chlorophyll concentration

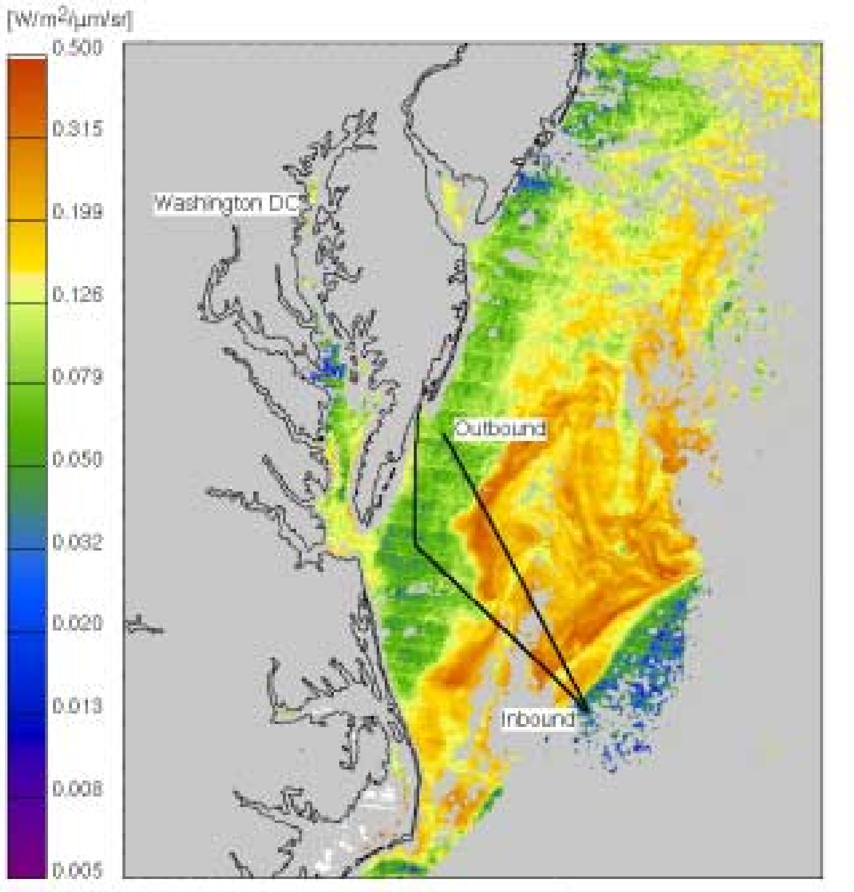
  PAR = photosynthetically available radiation

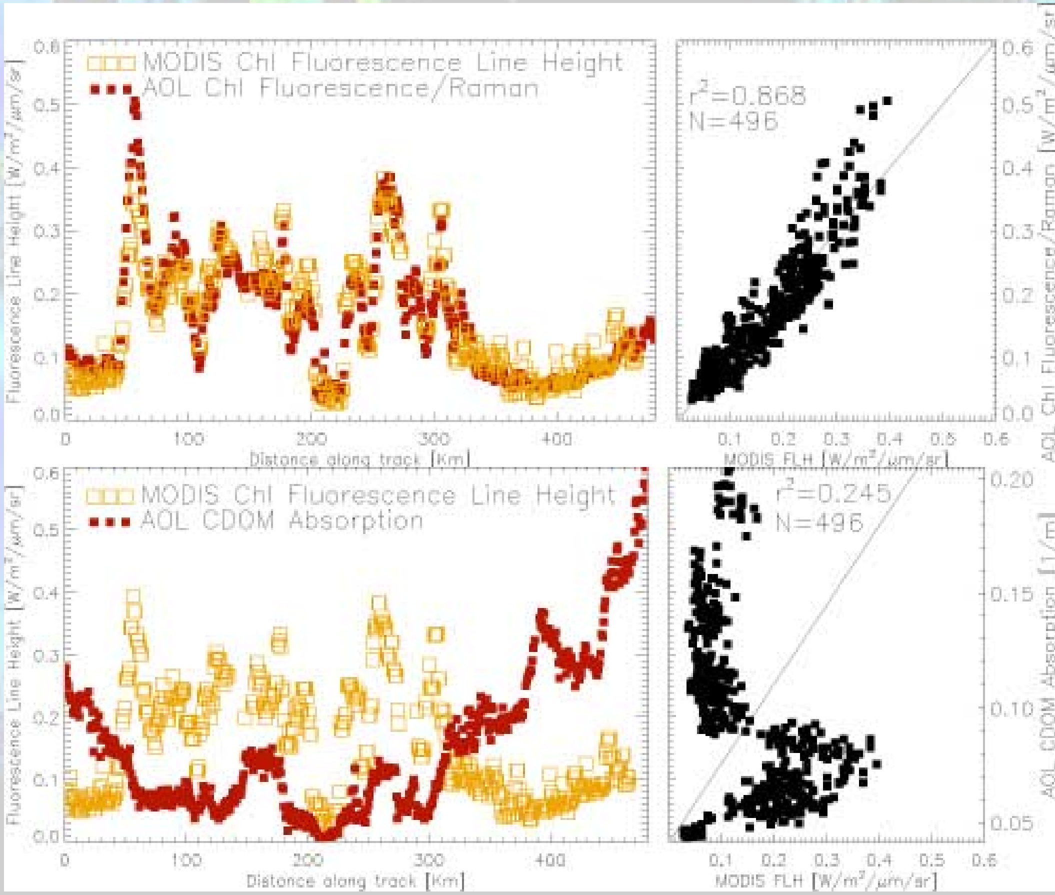
  a^* = chlorophyll specific absorption

  ϕ_F = fluorescence quantum yield

- Absorbed Radiation by Phytoplankton
  - $ARP = a^* \times PAR \times [chl]$
  - ARP calculated independently from [chl]
- F/ARP = Chlor. Fluor. Efficiency (CFE) proportional to ϕ_F

Aircraft Measurements of FLH Compared with MODIS over the Gulf Stream



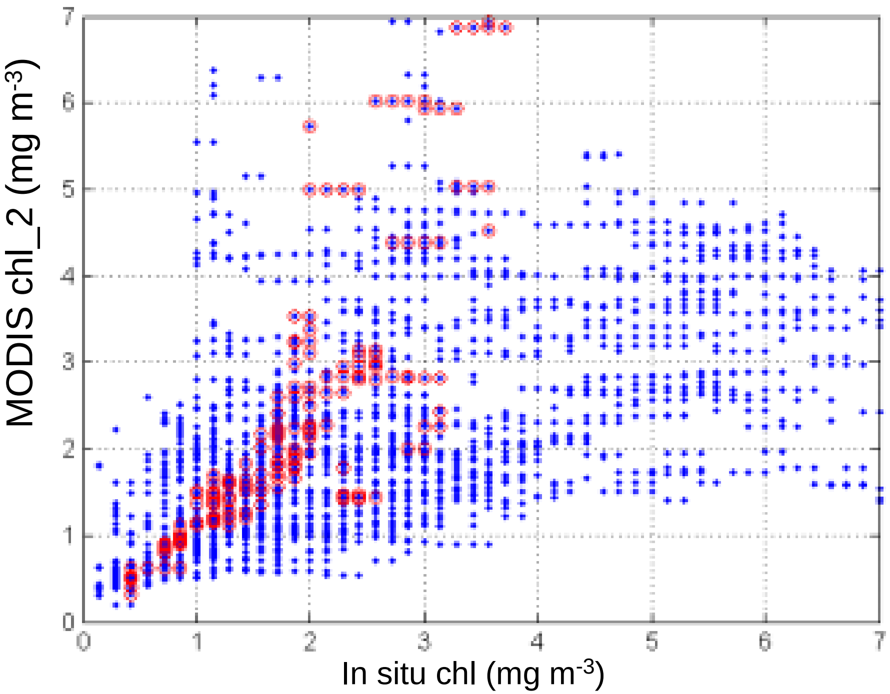


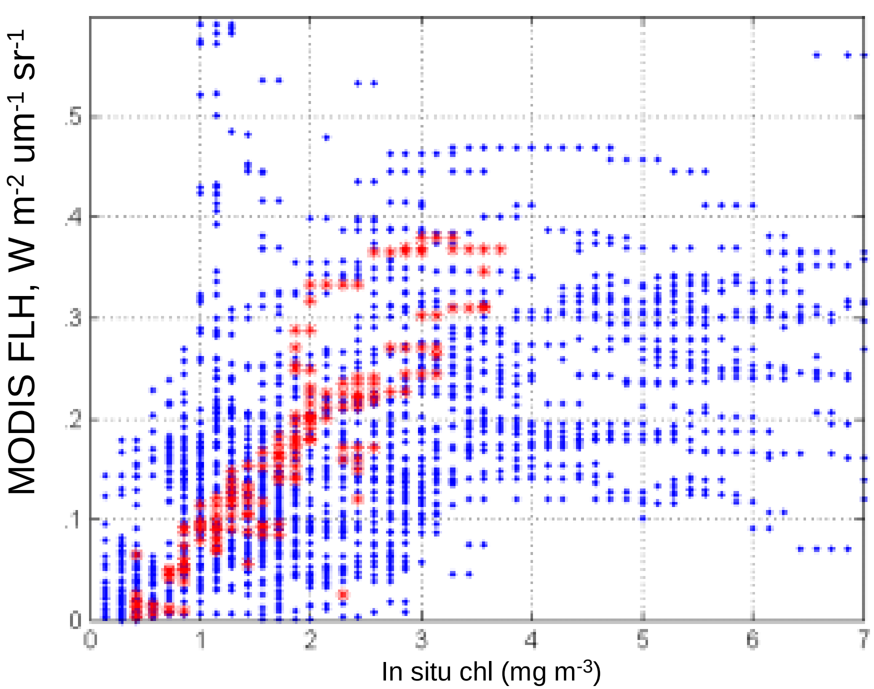
Hoge et al., Appl. Opt. (2003)

Field Measurements of Chlorophyll and MODIS

Chlorophyll

FLH





-Blue = all mesoscale survey data

-Red = Within 0.5 days of the MODIS Image Time stamp

Can we use MODIS CFE to improve the Primary Productivity algorithm?

$$PP = [chl] \times (PAR \times a^*) \times \Phi_p \qquad (1)$$

If $\Phi_p + \Phi_f + \Phi_h = 1$ & $\Phi_h = \text{constant}$

then $\Phi_p = \text{constant} - \Phi_f \qquad (2)$

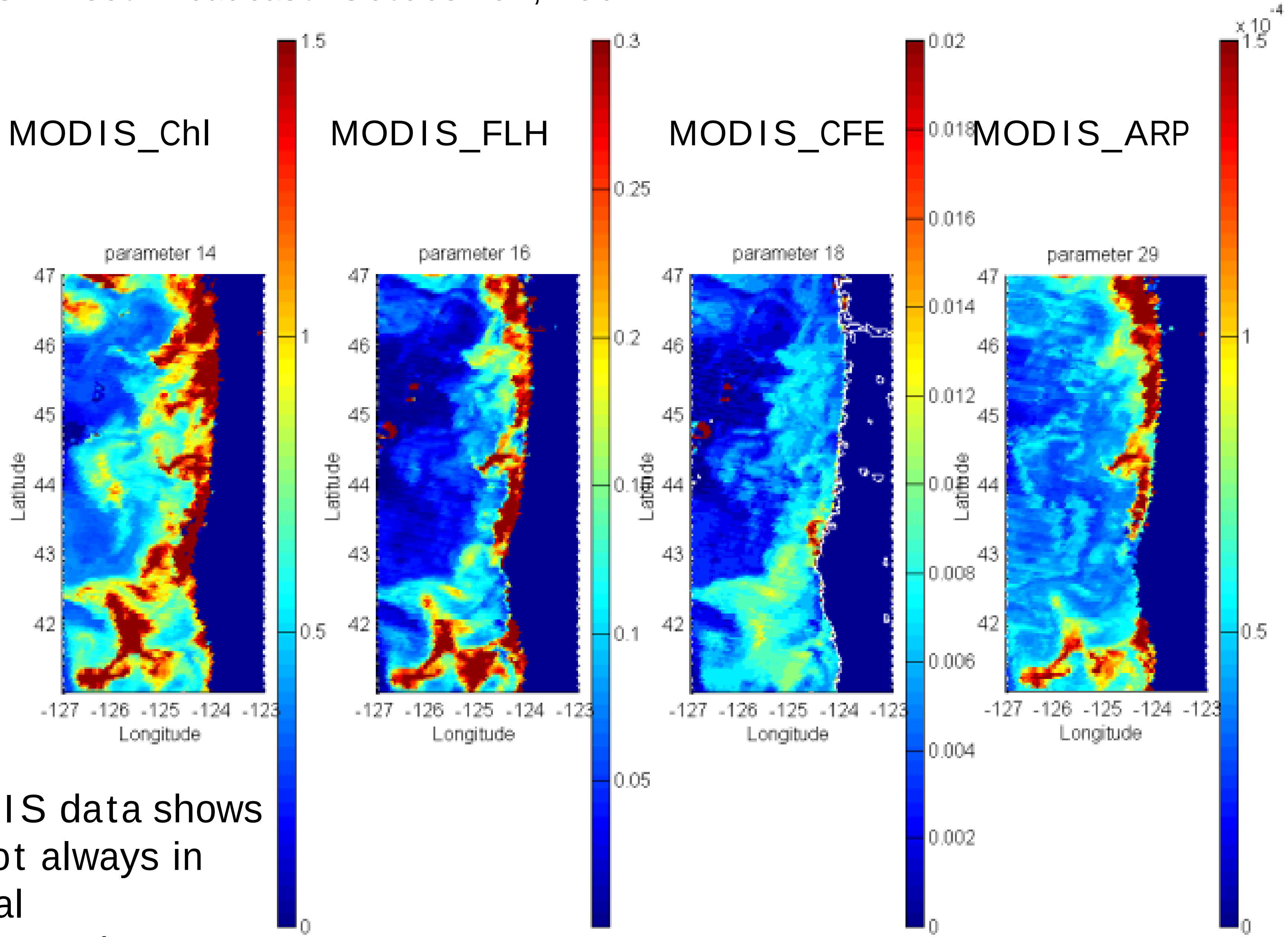
Replacing Φ_p with (2) in (1)

$$PP = \underbrace{[chl] \times (PAR \times a^*)} \times (\text{constant} - \Phi_f)$$

or $PP \;\alpha\; ARP \times (\text{constant} - FLH/ARP)$

$\alpha\; (\text{constant}/ARP) - FLH$

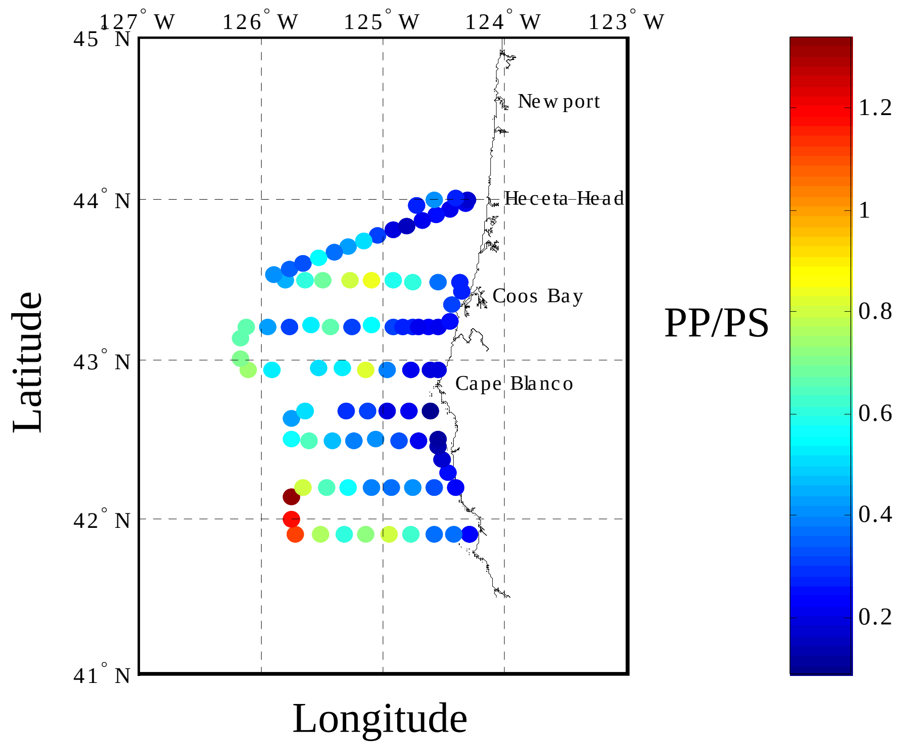
OSU Direct Broadcast October 04, 2001

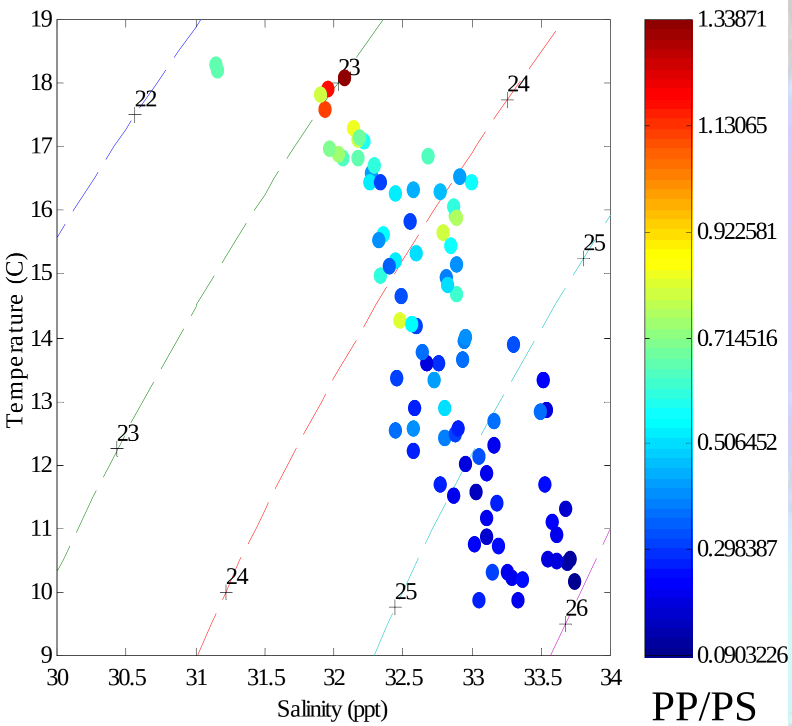


MODIS data shows chl not always in spatial correspondence with fluorescence

Physiological parameters also vary spatially

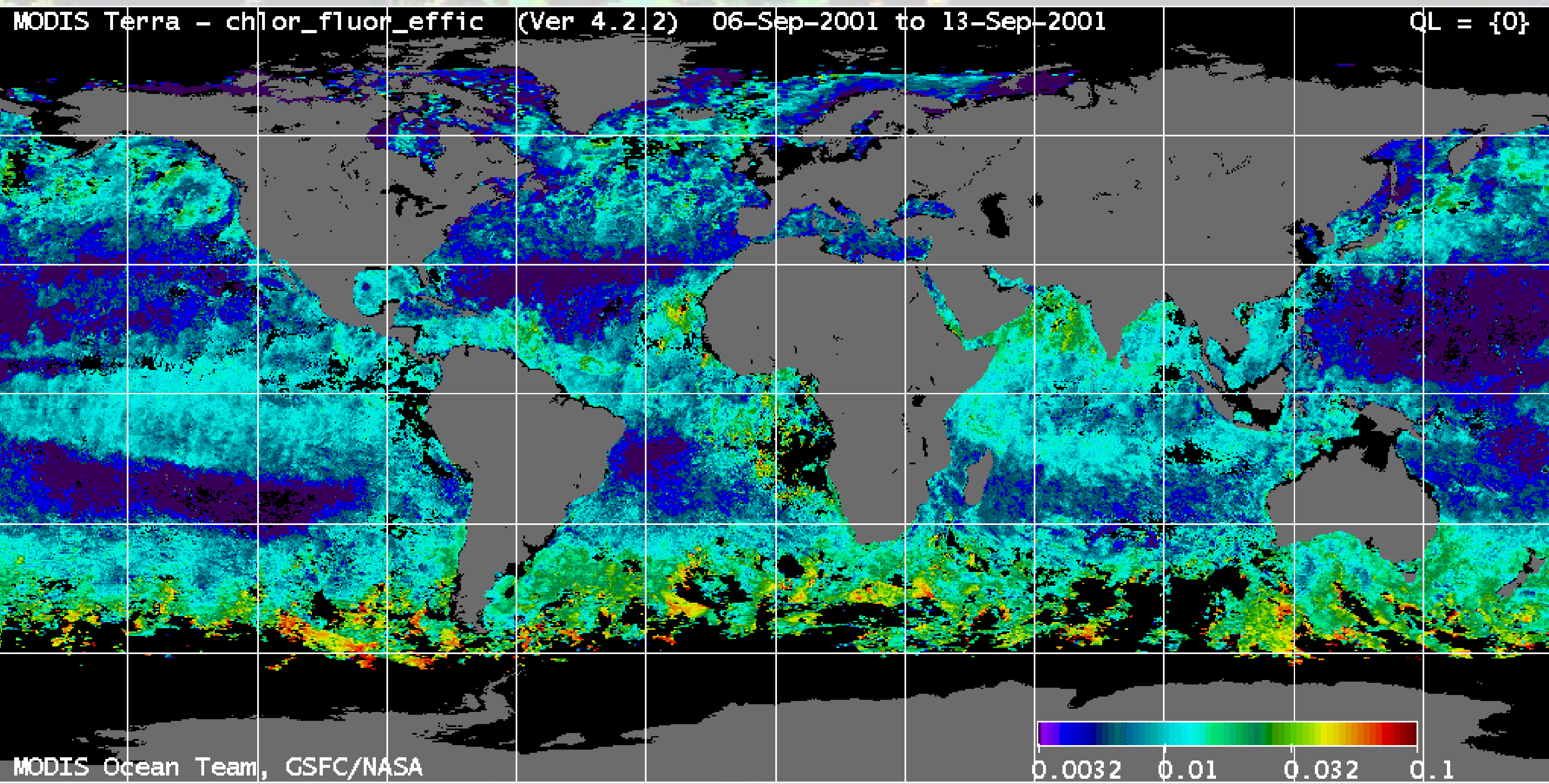
Photoprotective:Photosynthetic pigment ratio





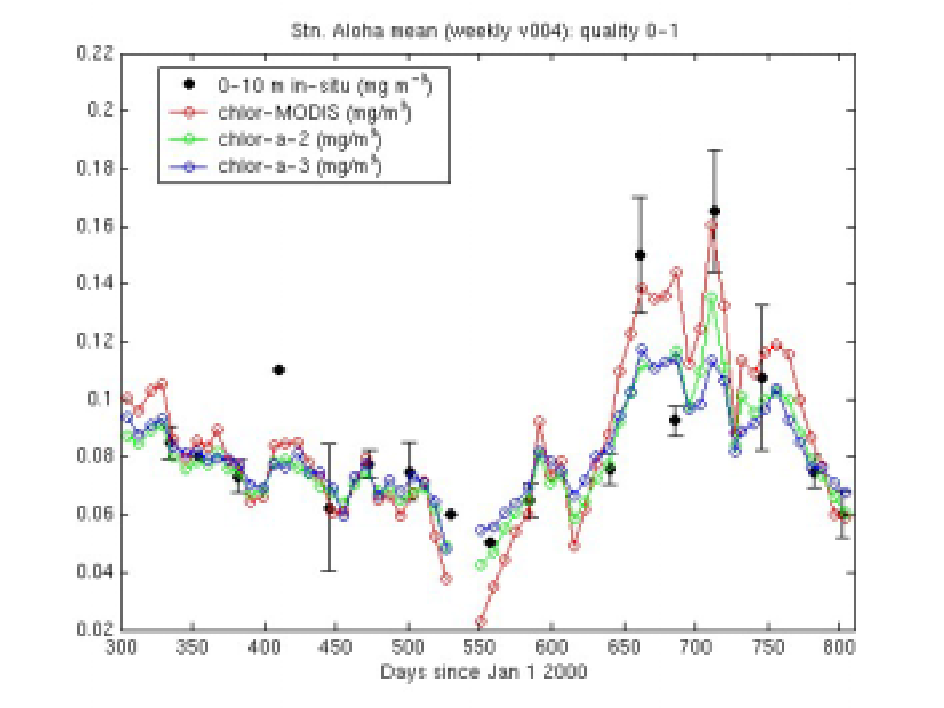
Other alternatives :

- Changes in ARP
- Have not accounted for heat dissipation processes

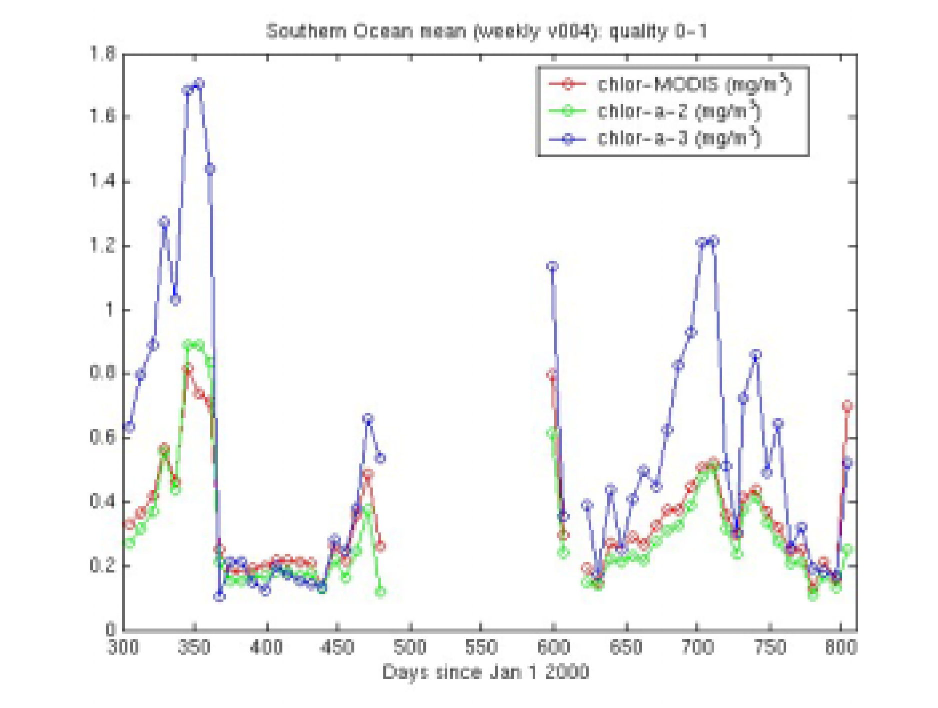

MODIS Terra - chlor_fluor_effic (Ver 4.2.2) 06-Sep-2001 to 13-Sep-2001
QL = {0}
MODIS Ocean Team, GSFC/NASA
0.0032
0.01
0.032
0.1

Weekly CFE

MODIS Chlorophyll Time Series

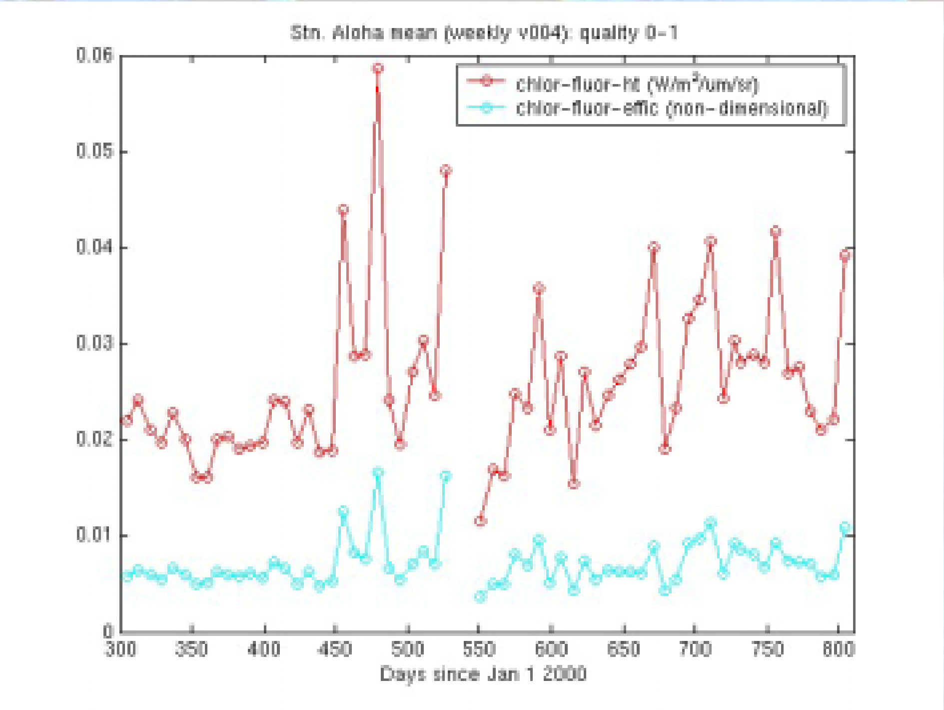


HOT



AESOPS

MODIS FLH and CFE Time Series



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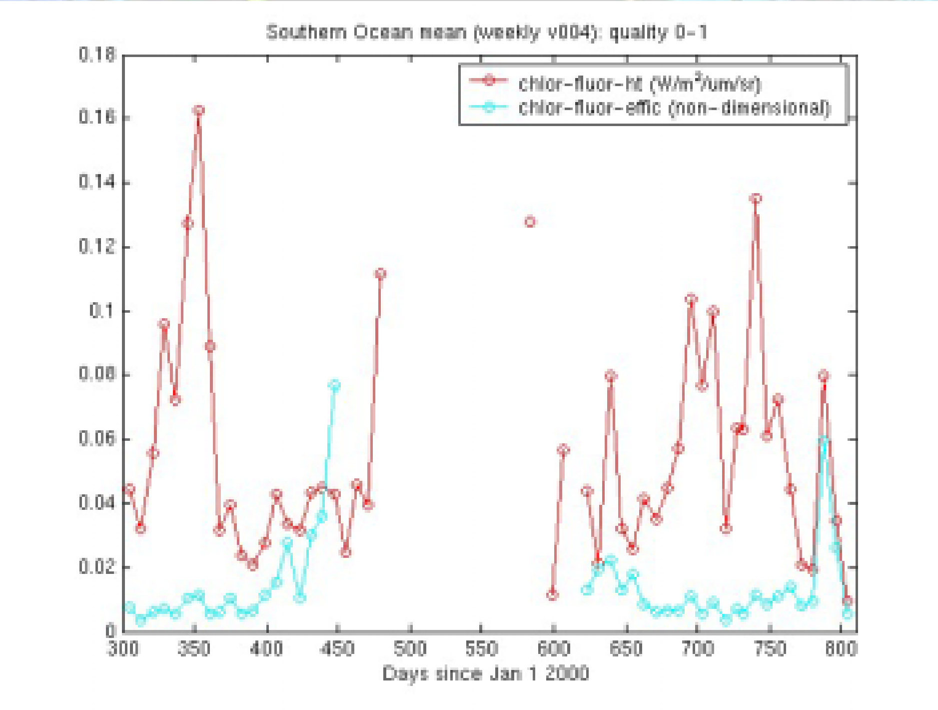
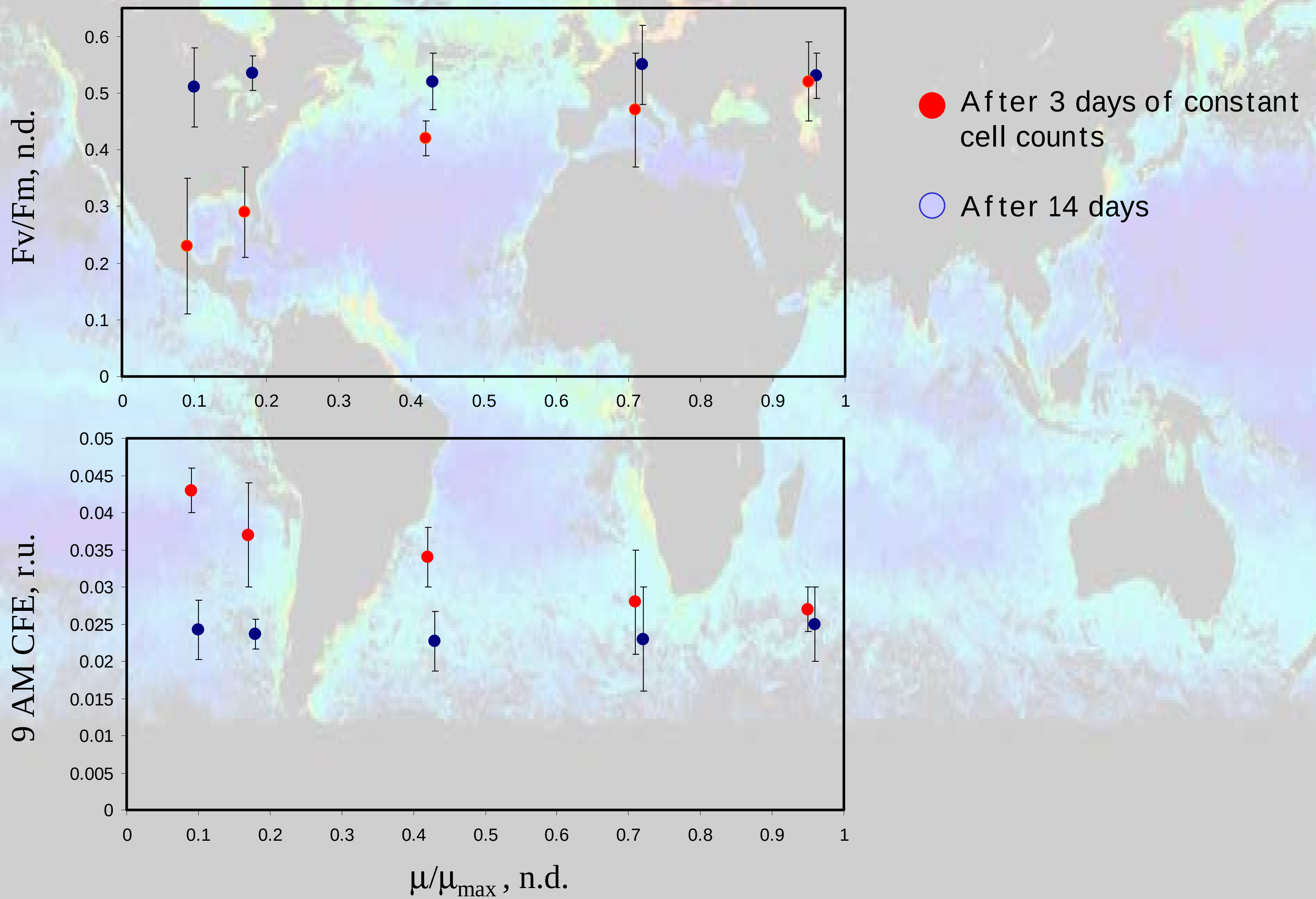


AESOPS

Thalassiosira weissflogii
Chemostat results 2001-2002



Summary of Fluorescence and Productivity

- Fluorescence and chlorophyll
  - Generally a linear relationship between absorption-based estimates and fluorescence-based estimates of chlorophyll
    - Exceptions are apparent, for example near the coast
  - Slope of line relating FLH to chl is related to CFE
- Fluorescence and productivity
  - Challenge is that many processes affect ϕ_F
    - Photoprotective pigments, absorption cross-section
  - Appears, though, that CFE appears to fall into 2 clusters so problem may be tractable
  - High values of CFE appear to be associated with communities far from equilibrium
    - Time history of CFE may be key

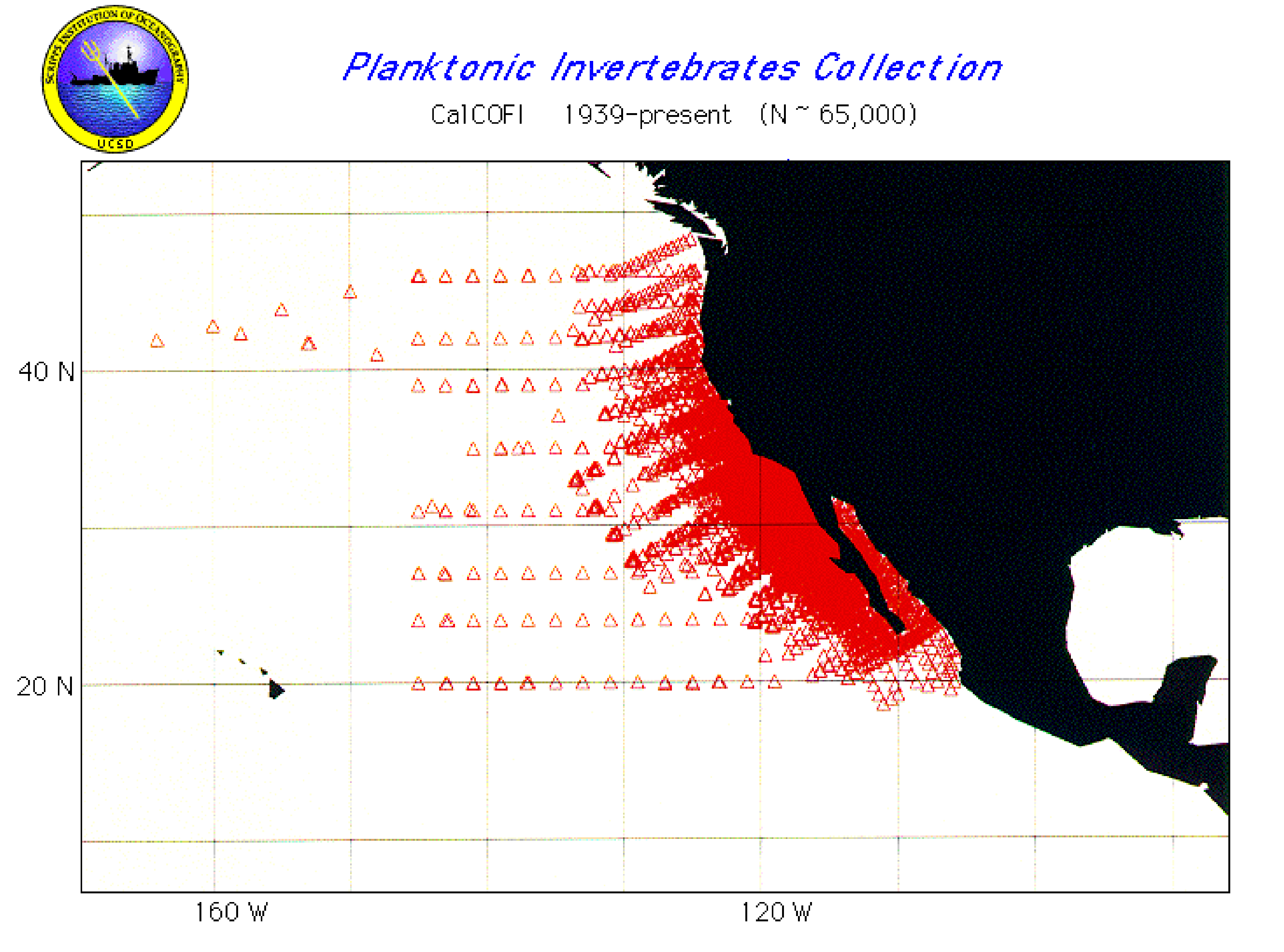
Putting It All Together

- Interactions between wind forcing and mesoscale ocean processes
  - Affects vertical and horizontal fluxes
- Long-term shifts in wind forcing can impact mesoscale processes
- Strong biological/physical coupling at mesoscales
- Satellite measurements of fluorescence may help identify areas where phytoplankton are not in equilibrium with light/nutrient regime
- Good prospects for improving estimates of primary productivity
- Satellites will always “miss” some scales and some processes

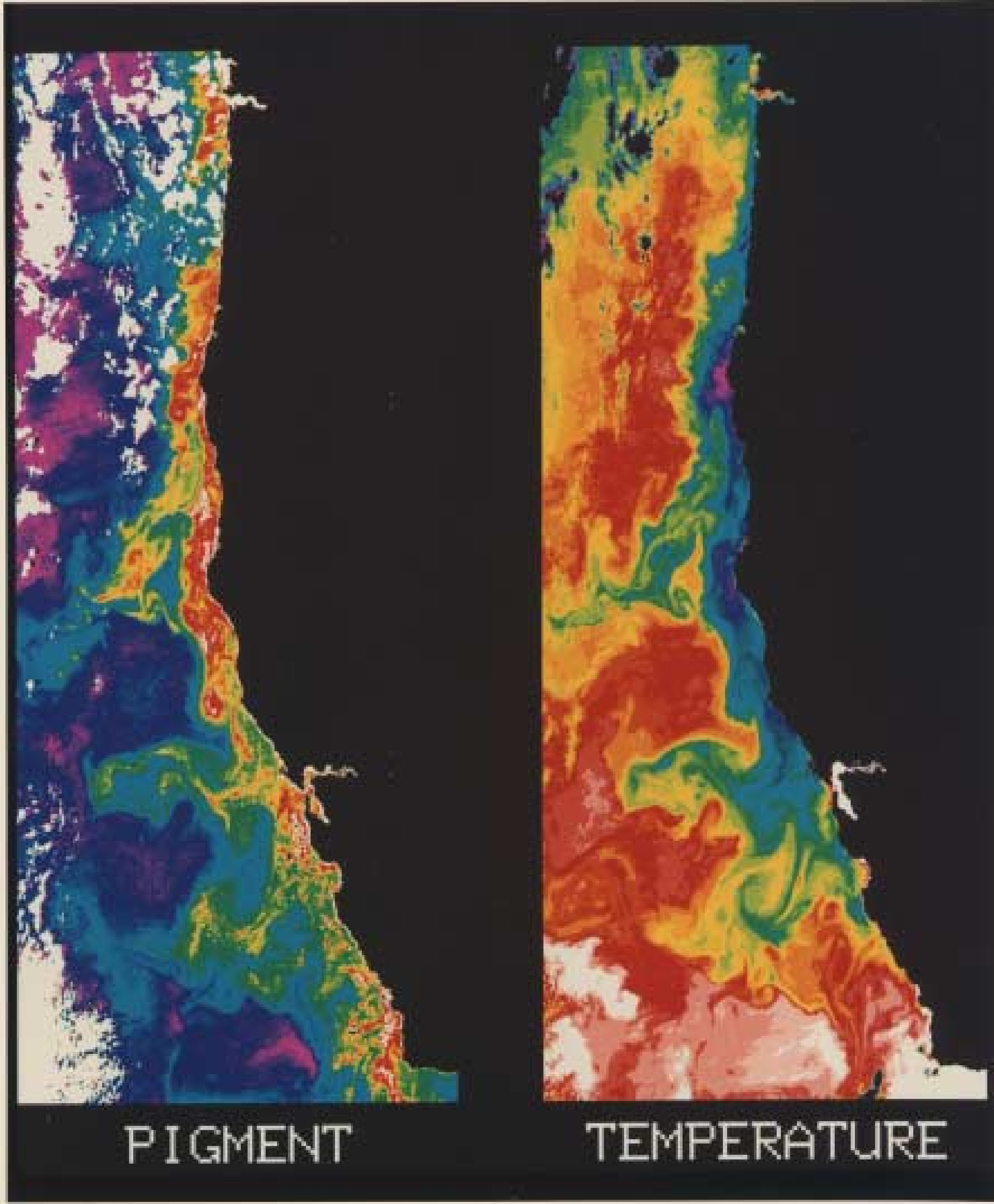
Future Directions

- Programs such as CLIVAR, GODAE, and GOOS emphasize operational observation strategy
- But programs such as JGOFS have shown that much research remains, especially in ecology and physical coupling
  - What processes need to be included?
  - What scales do we need to observe?
  - How do we parameterize for models?
  - Many of these remain as challenges from 1984
- Are ocean sciences ready?
  - We do need long-term, carefully-calibrated series

CalCOFI Sampling Grid



Despite 40 years' of sampling, CalCOFI missed one of the dominant features of the California Current!



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