Challenges and Advances of Regional Ocean Data Assimilation

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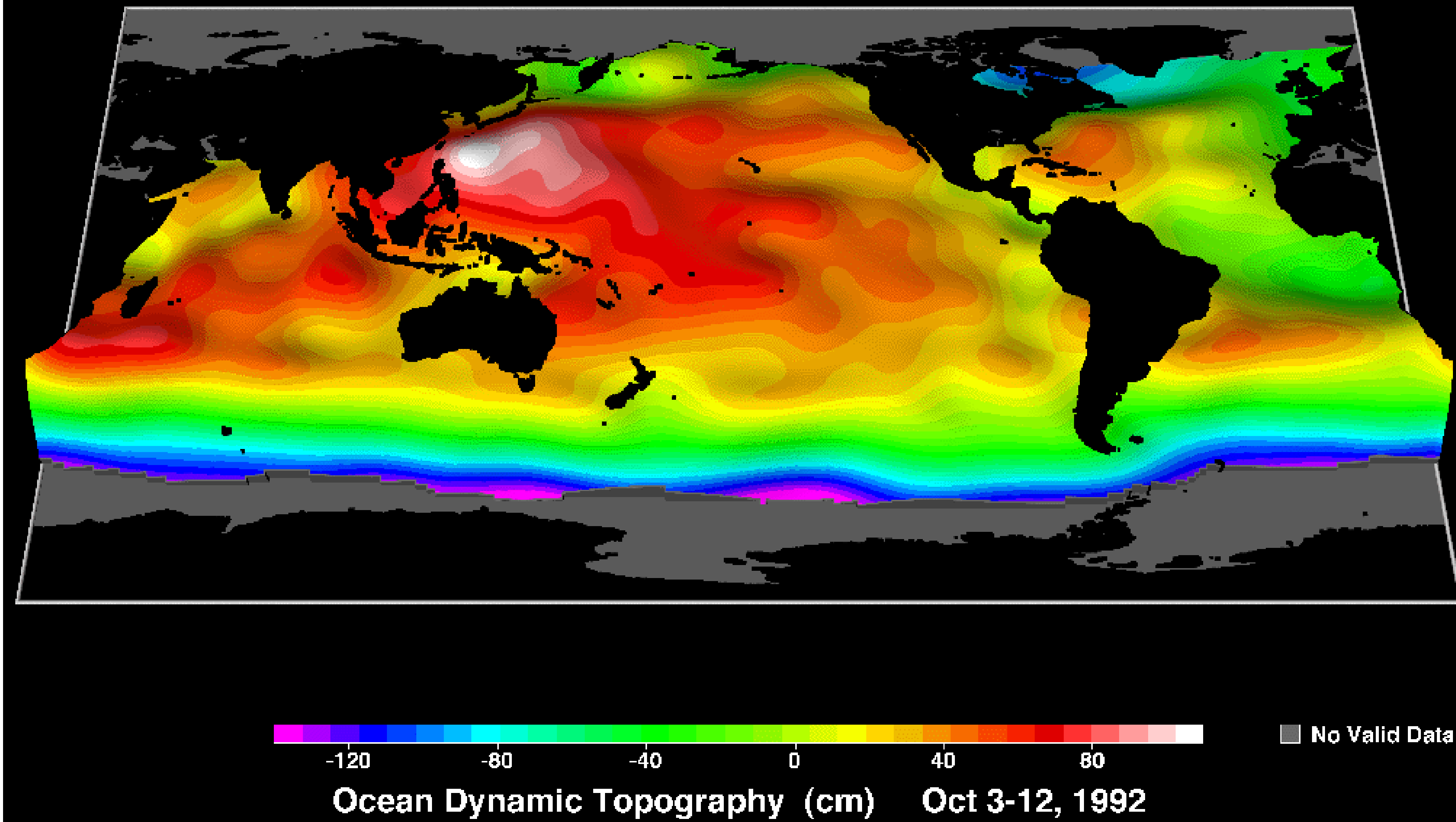
The Large Scale Ocean Circulation



Diverse Approach

Global versus Regional

Global –

- ECMWF
- MERCATOR
- ECCO(2)
- NASA/GMAO
- NCOM
- HYCOM
- FOAM
- BLUElink
- SODA
- GLORYS
- Others…

Regional & Nested –

- MFS
- HOPS
- NCOM
- MODAS
- FOAM
- ROMS

Methods

- 3D-Var
- En-3D-Var
- 4D-Var
- Nudging
- EnKF
- SEEK
- MVOI

Mature Applications

Scientific

- Ocean analyses
- Climate variability
- Climate change
- ENSO, MOC
- Eddy variability
- Coastal upwelling

Practical

- Oil spill (eg. DWH)
- Search and rescue
- Contaminant dispersal (eg. Fukoshima)
- Forecasting (eg.IOOS)
- Fisheries management

Overview

Part I – Challenges

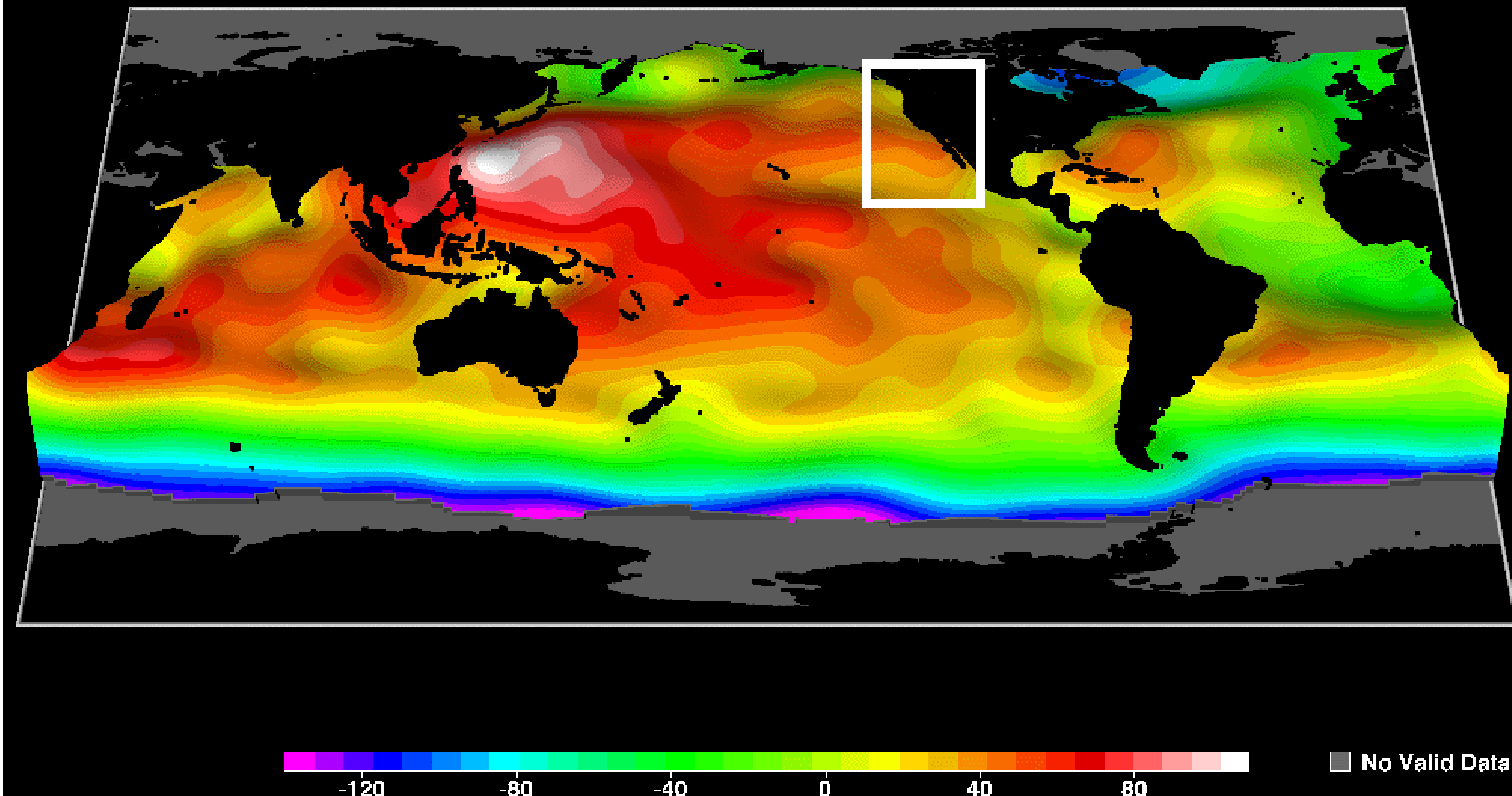
Part II – Recent Advances

Part I - Challenges

- Space- and time-scales
- Observations
- Control vector
- Correlation functions
- Tracers in the ocean
- Initialization shocks

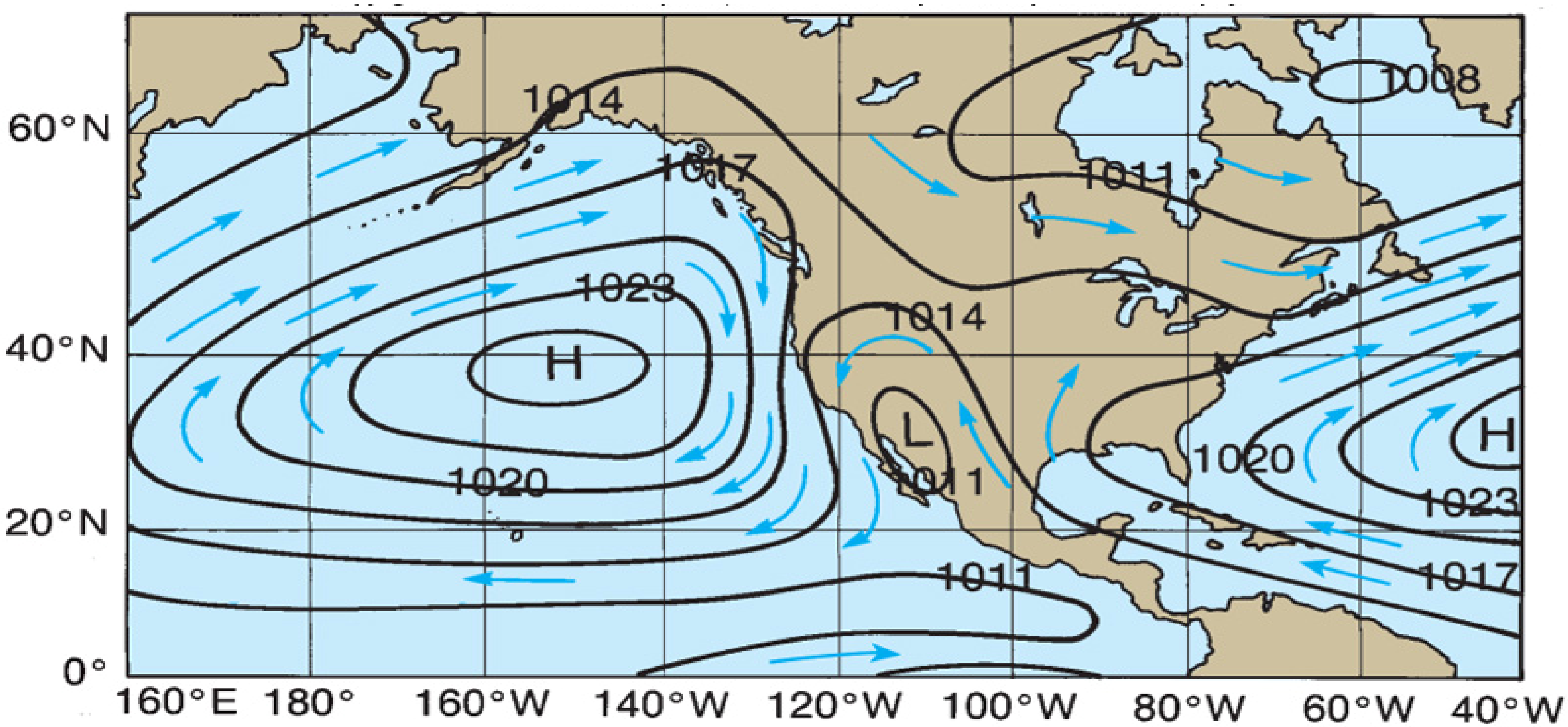
The California Current Large Marine Ecosystem

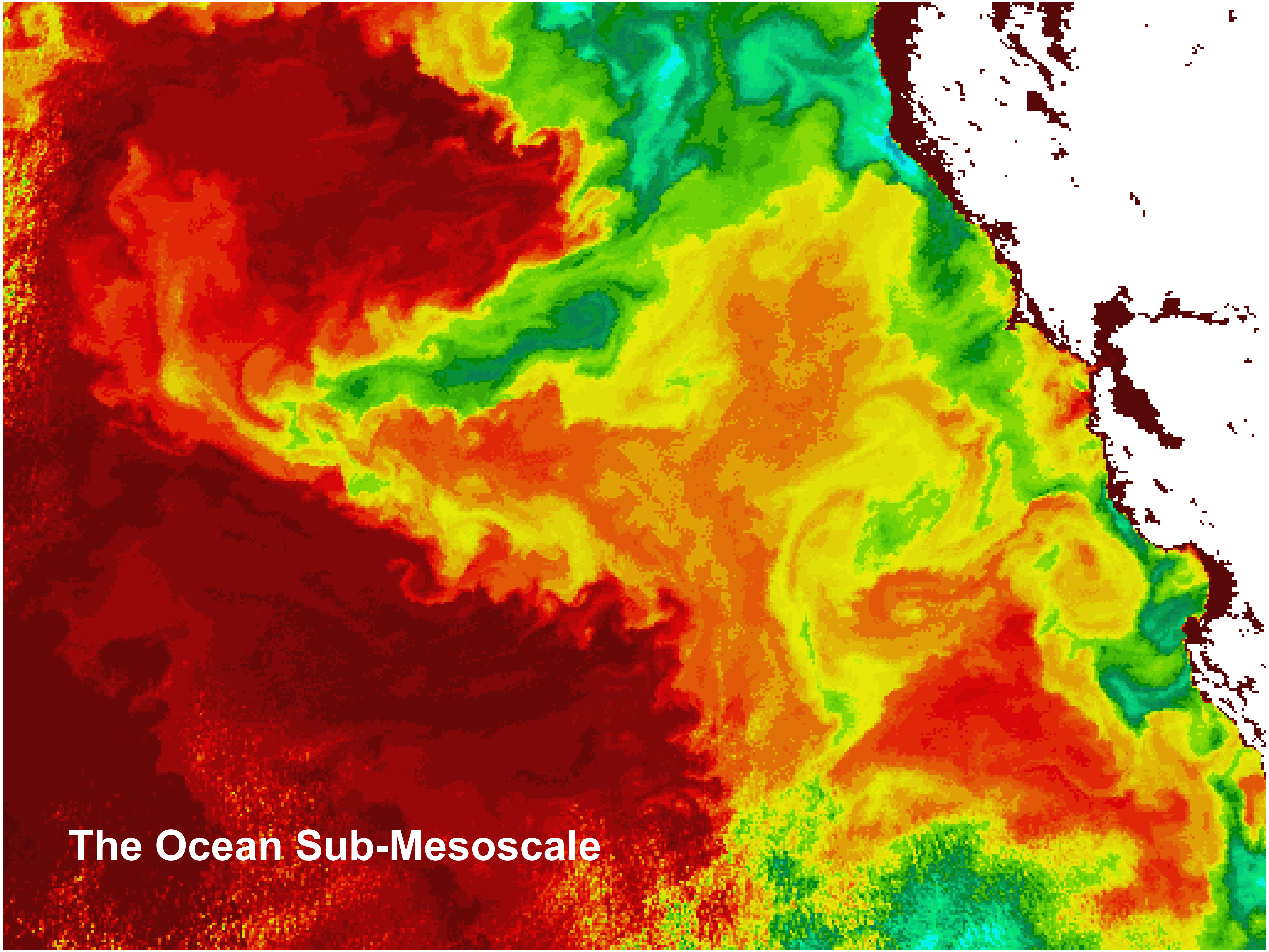
Ocean Space- and Time-Scales



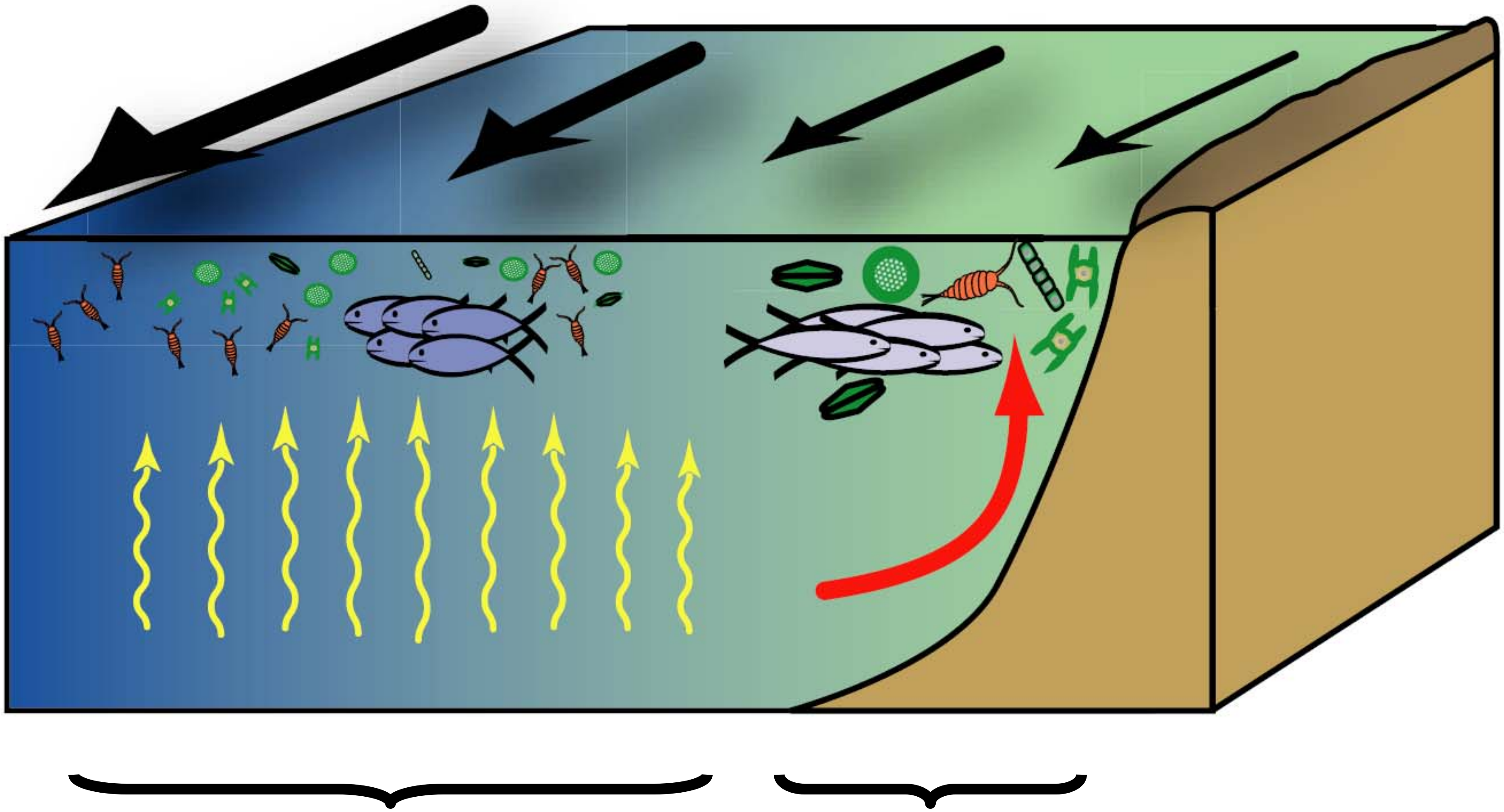
Ocean Dynamic Topography (cm) Oct 3-12, 1992

The California Current




The Ocean Sub-Mesoscale

Coastal Upwelling & CCLME



Upwelling due
to wind stress
curl

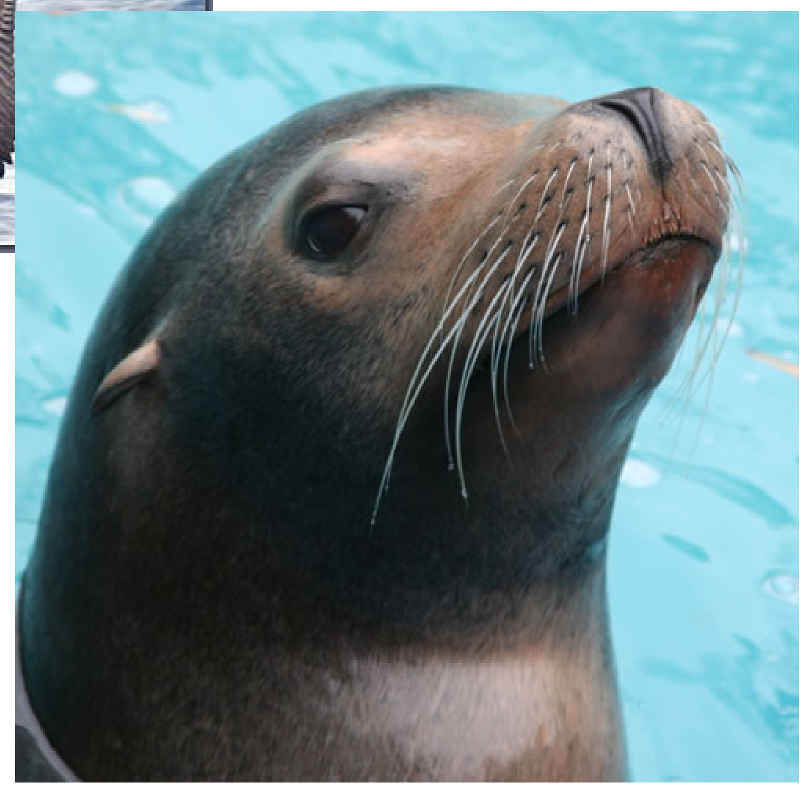
Sardines

Upwelling due
to divergence

Anchovies

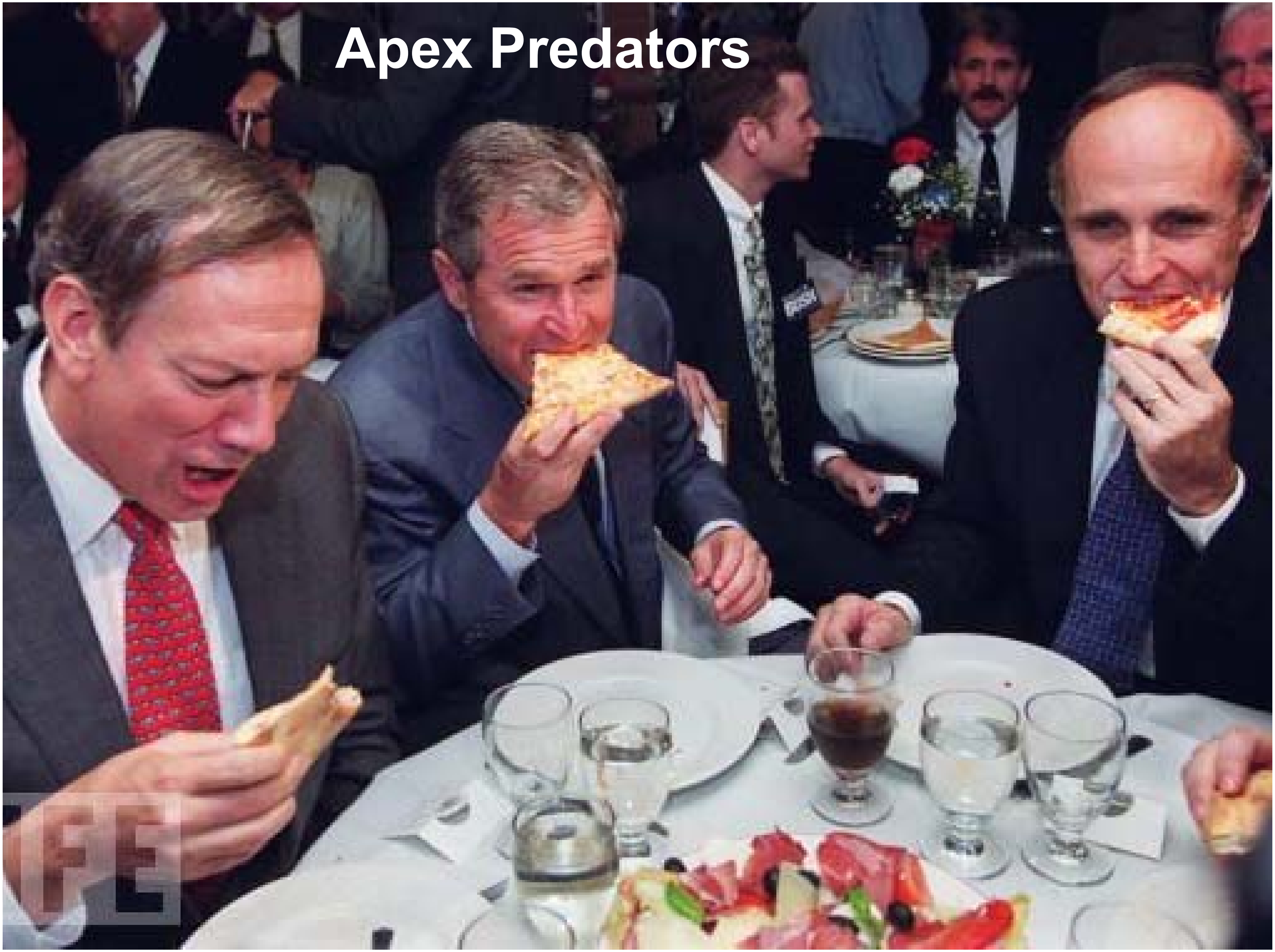
Rykaczewski &
Checkley (2007)

Apex Predators

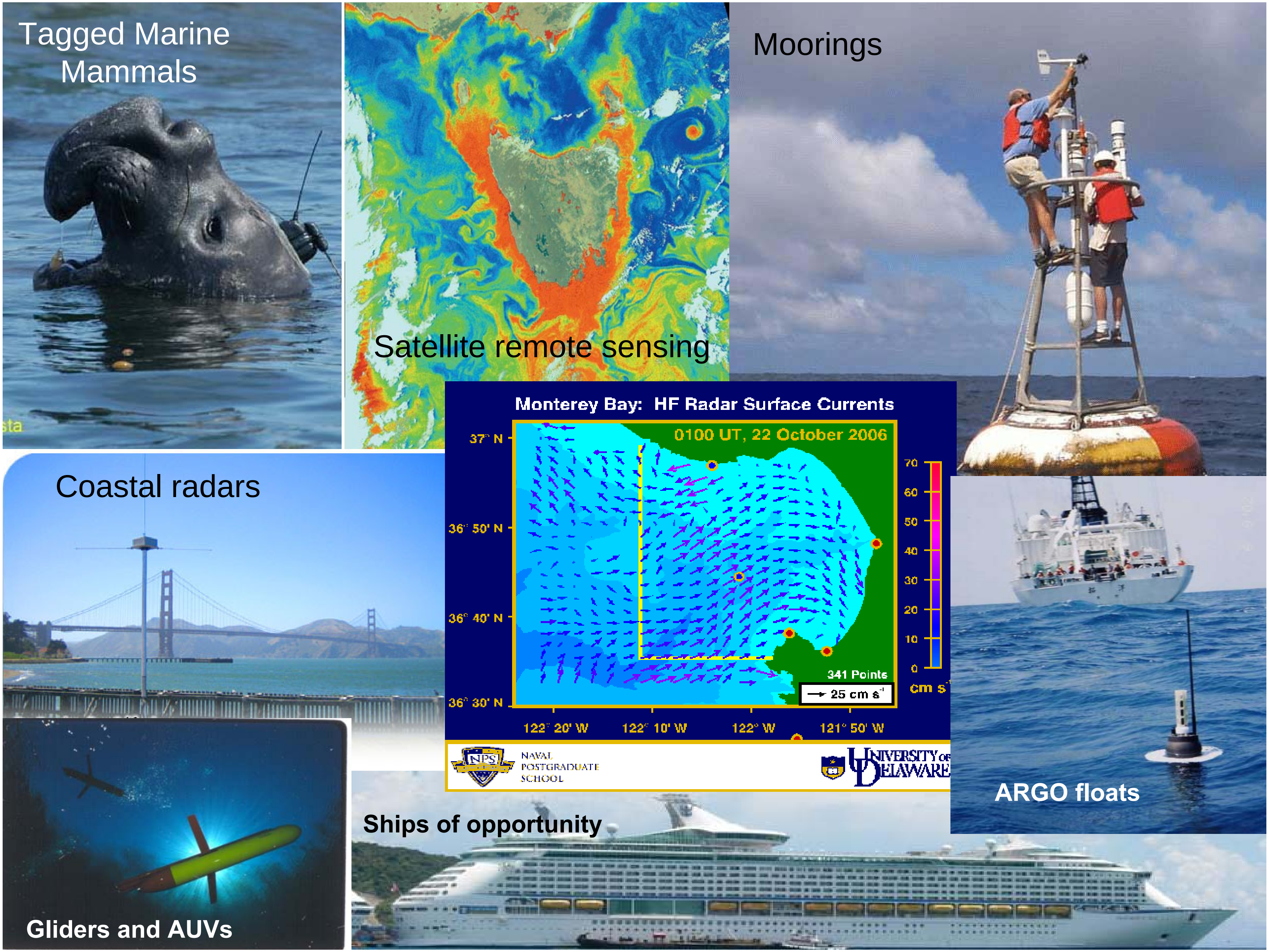


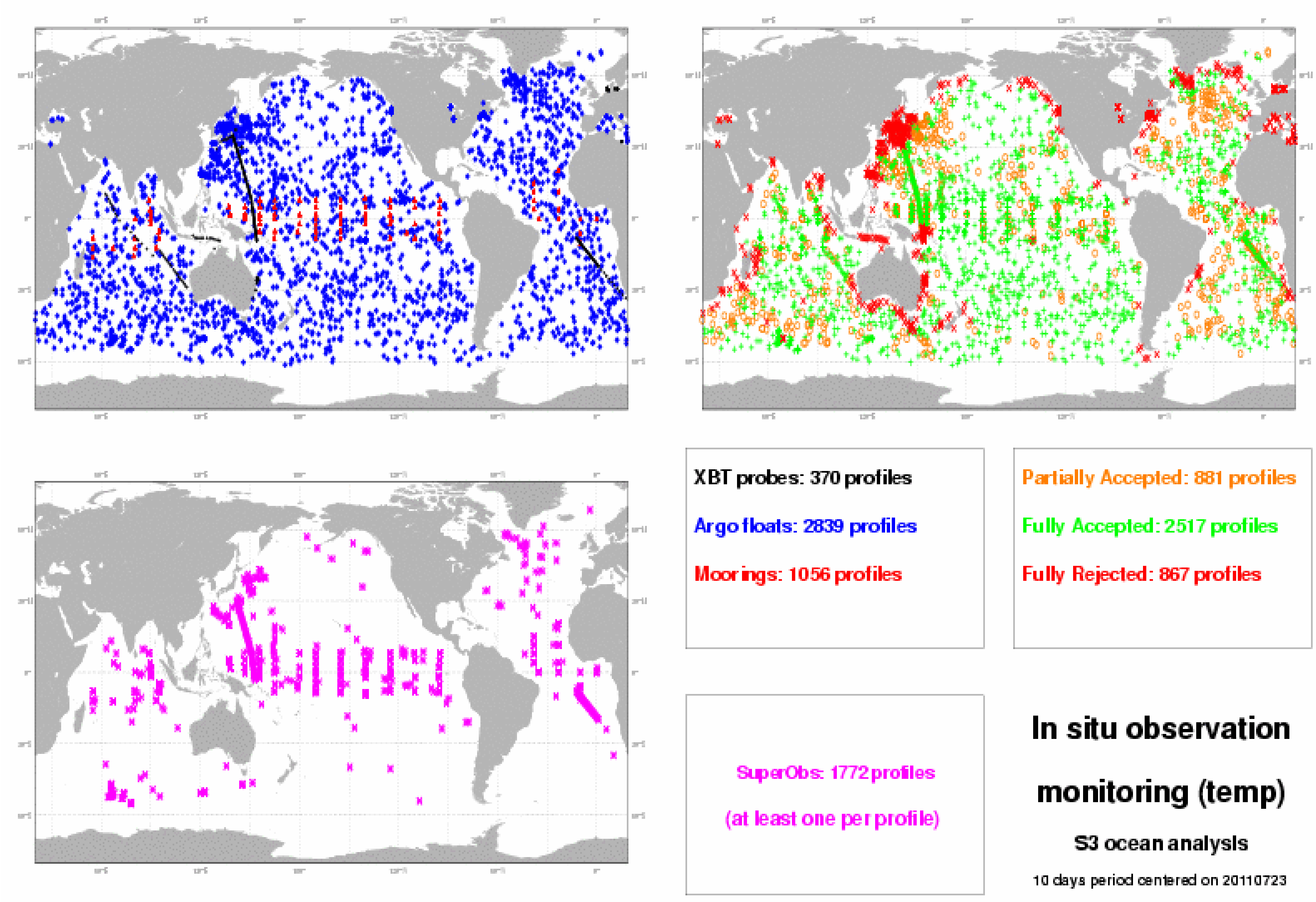
Other Food Webs

Apex Predators



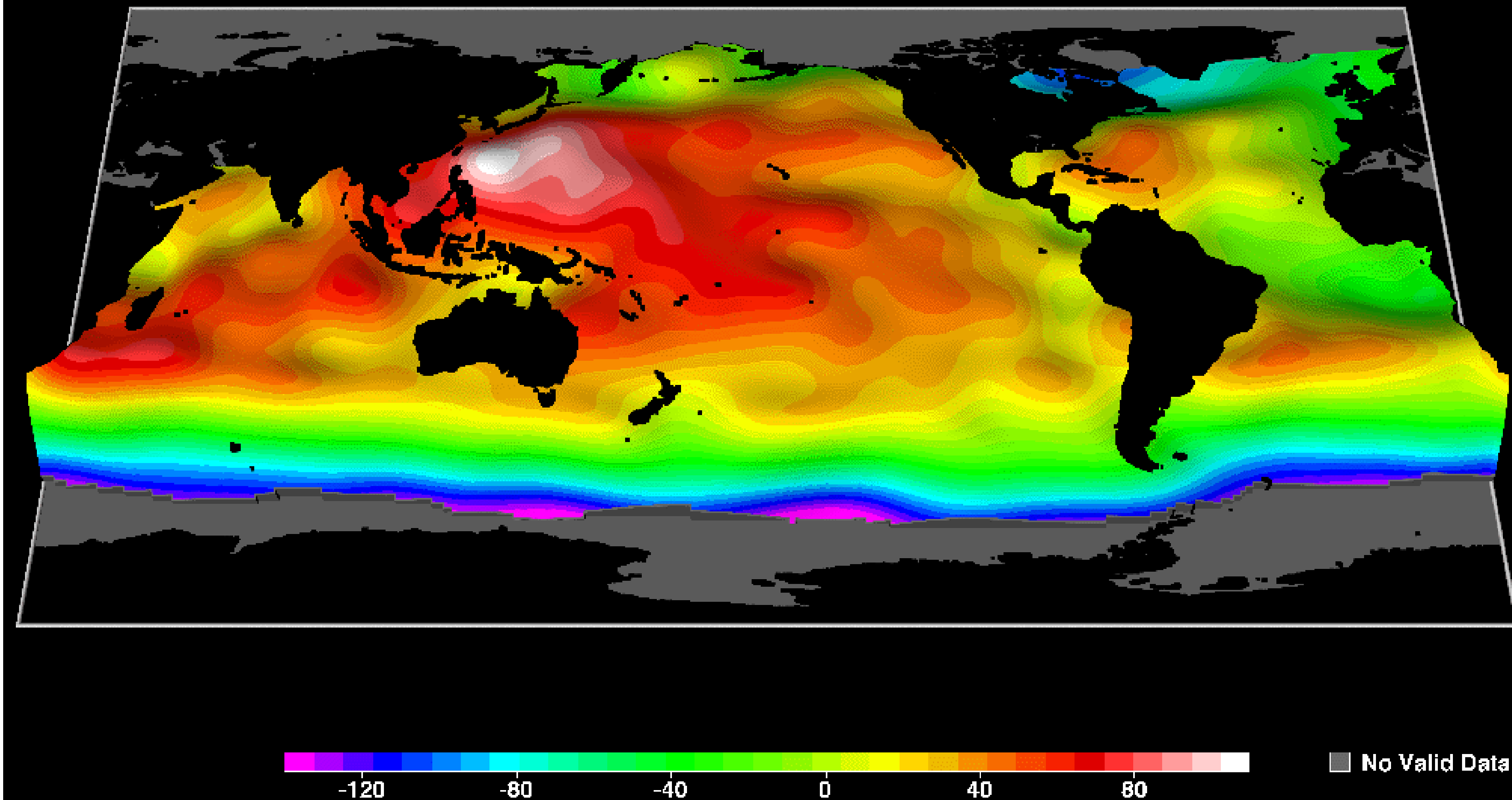
Ocean Observations


Tagged Marine Mammals
Satellite remote sensing
Moorings
Coastal radars
Monterey Bay: HF Radar Surface Currents
0100 UT, 22 October 2006
37° N
36° 50' N
36° 40' N
36° 30' N
122° 20' W
122° 10' W
122° W
121° 50' W
70
60
50
40
30
20
10
0
cm s⁻¹
341 Points
25 cm s⁻¹
NAVAL POSTGRADUATE SCHOOL
UNIVERSITY OF DELAWARE
ARGO floats
Ships of opportunity
Gliders and AUVs



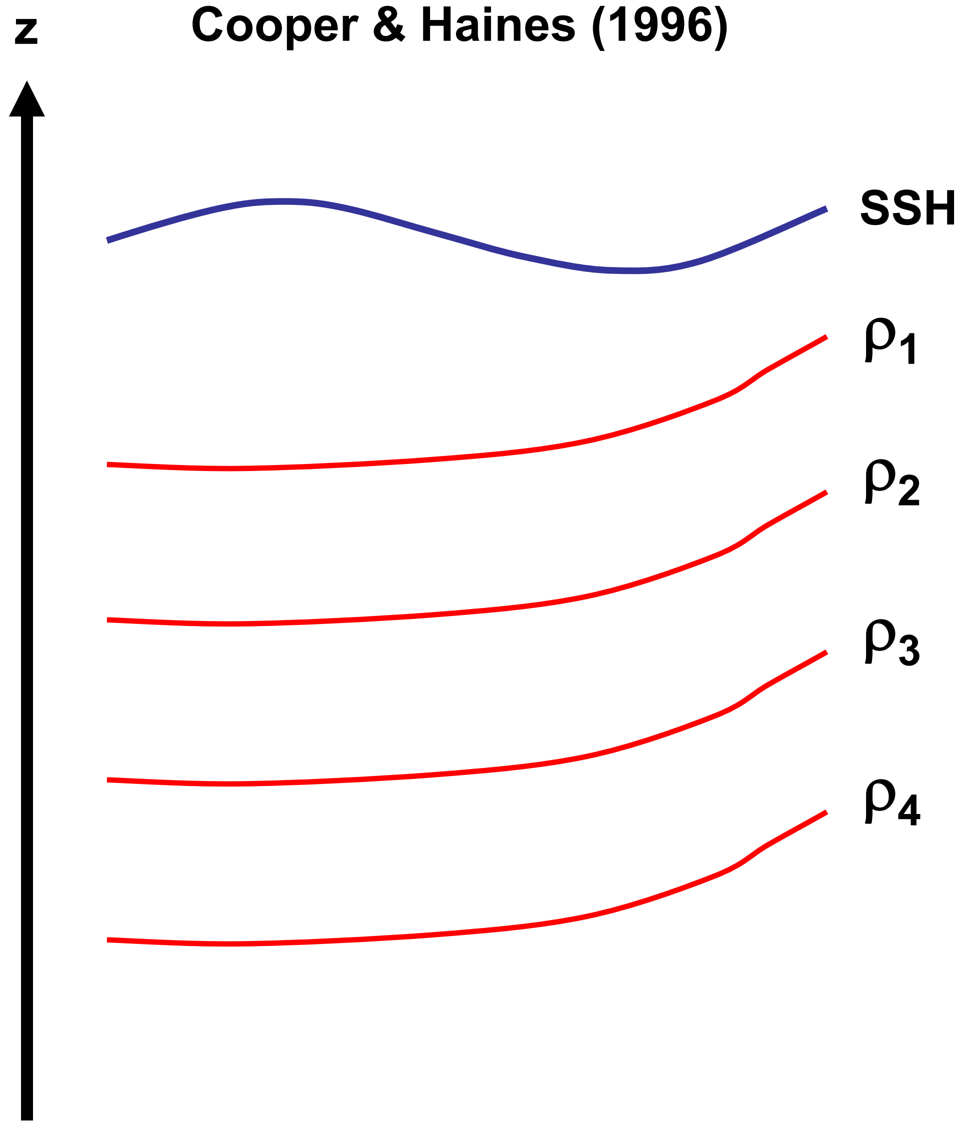
Typical 10 day sample of hydrographic obs for ECMWF global ocean analysis

Sea Surface Topography

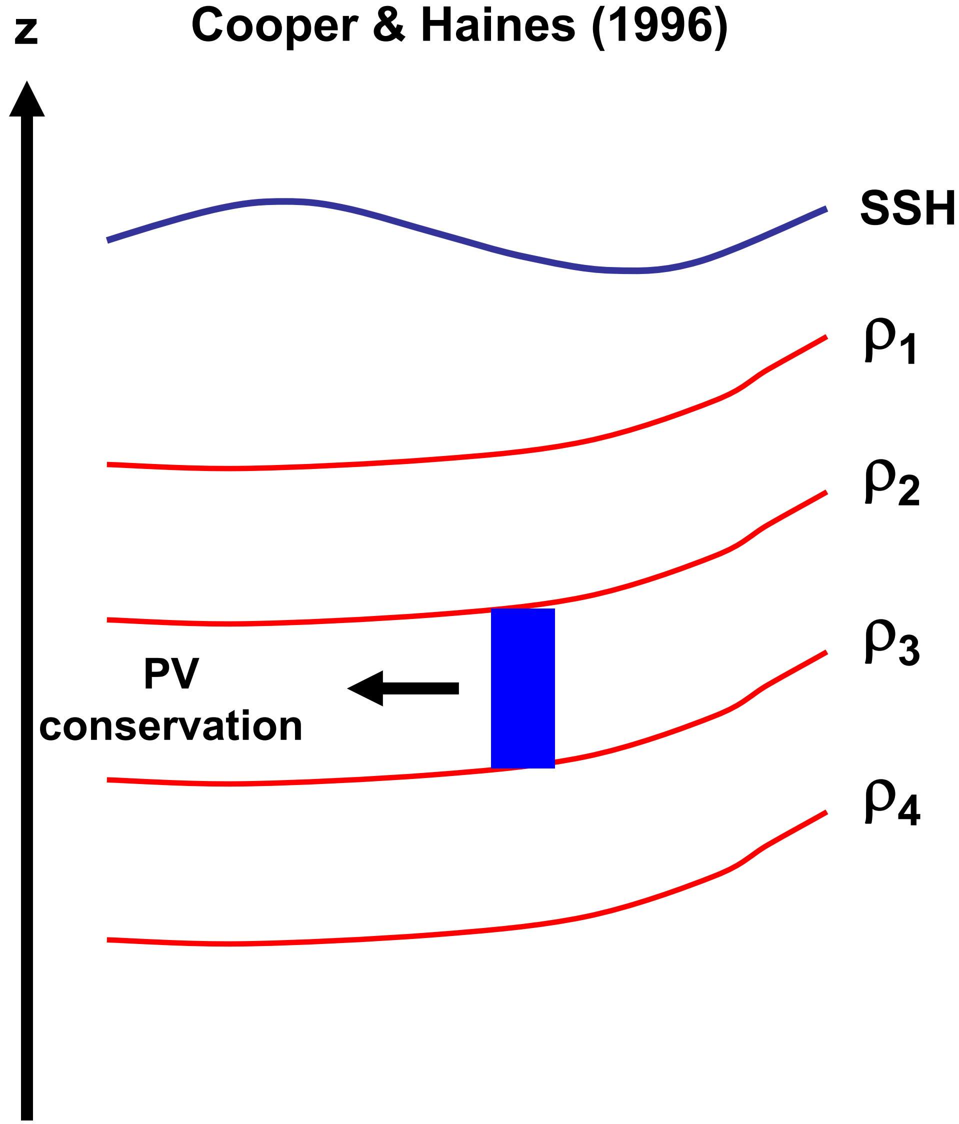


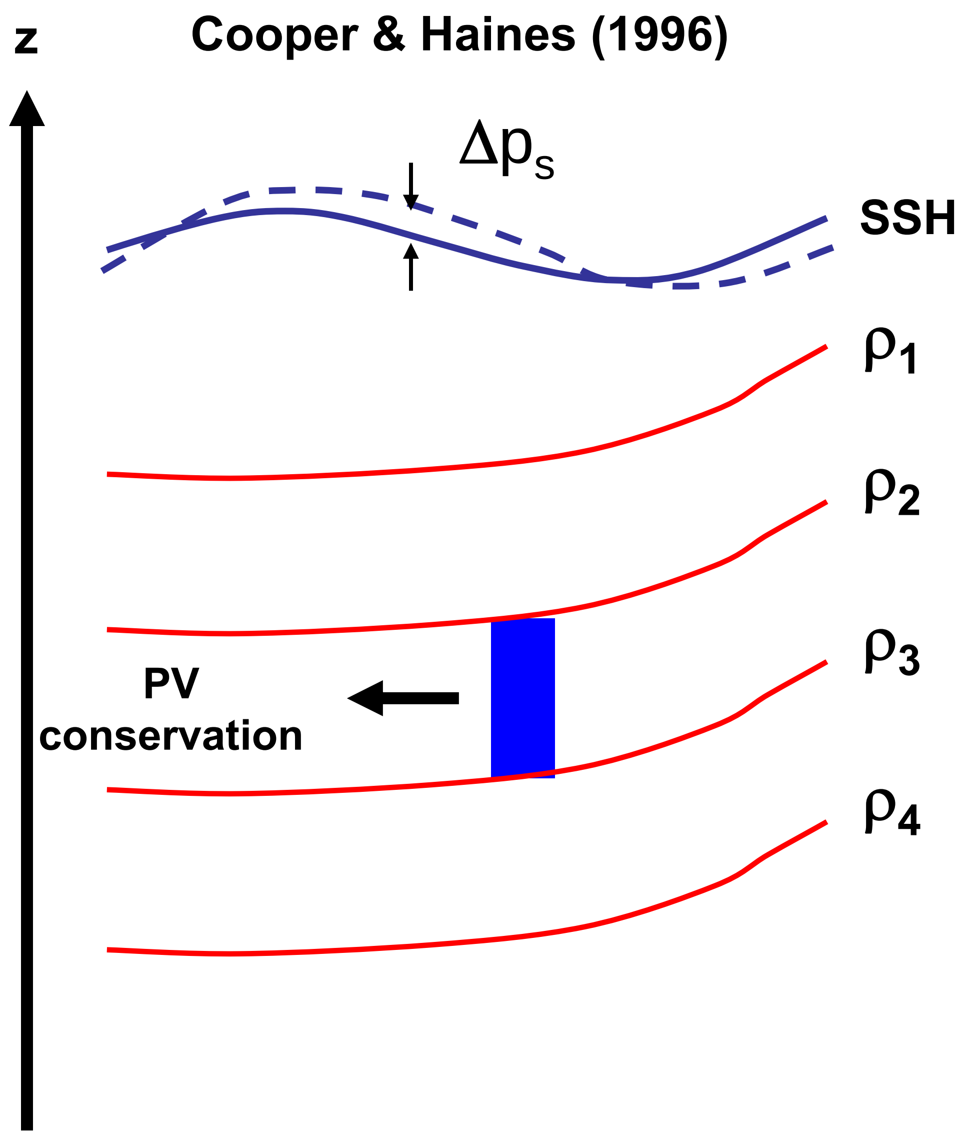
Ocean Dynamic Topography (cm)   Oct 3-12, 1992

Cooper & Haines (1996)



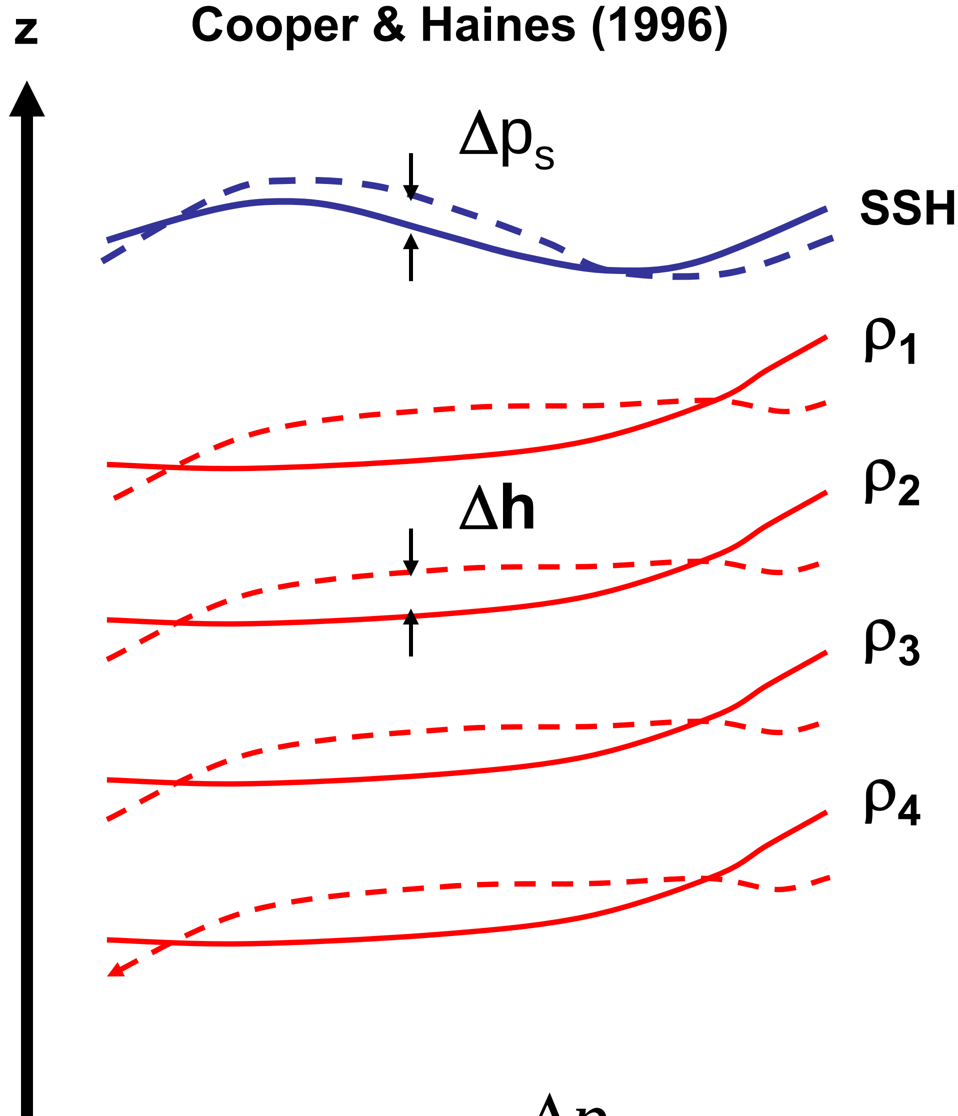
Cooper & Haines (1996)





z
Cooper & Haines (1996)
Δp_s
SSH
ρ_1
ρ_2
ρ_3
ρ_4
PV
conservation

Cooper & Haines (1996)

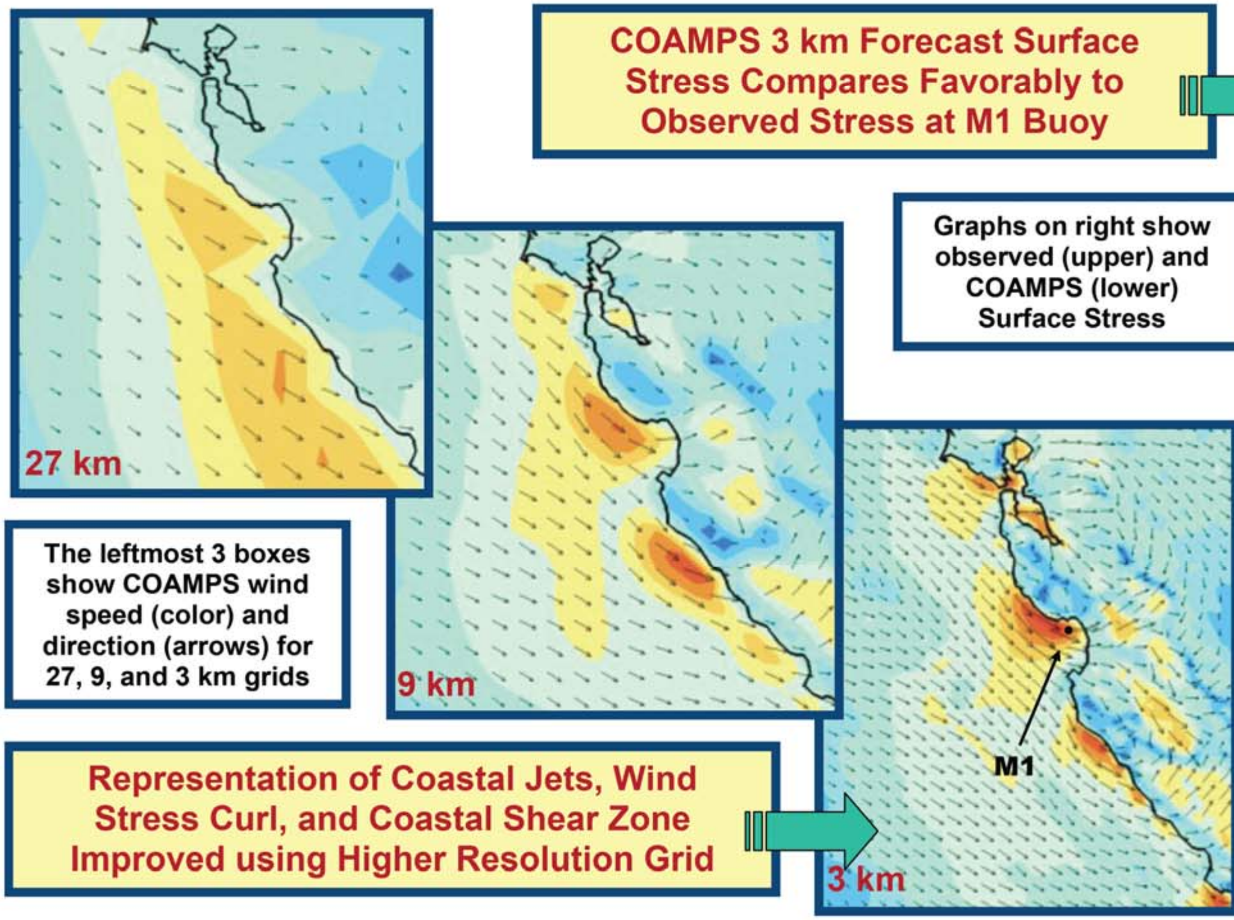


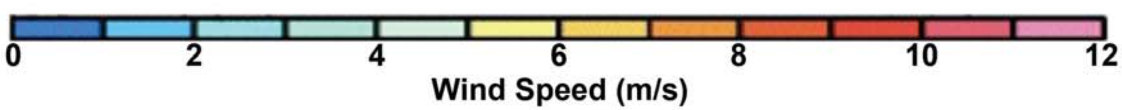
$$\Delta h = \frac{\Delta p_s}{g\left(\rho(0) - \rho(-H)\right)}$$

The Ocean Control Vector

COAMPS Real-Time Forecasts

Products for Atmospheric/Oceanic Forecasting



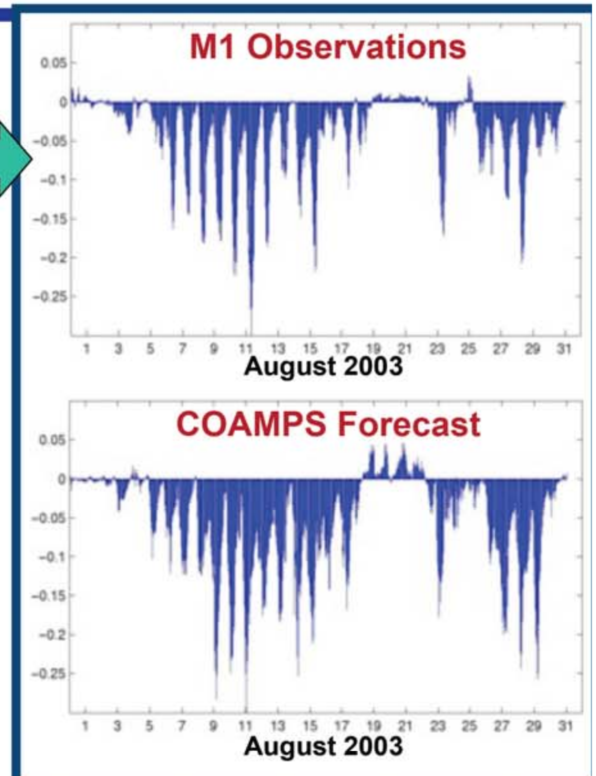


COAMPS 3 km Forecast Surface Stress Compares Favorably to Observed Stress at M1 Buoy

Graphs on right show observed (upper) and COAMPS (lower) Surface Stress

The leftmost 3 boxes show COAMPS wind speed (color) and direction (arrows) for 27, 9, and 3 km grids

Representation of Coastal Jets, Wind Stress Curl, and Coastal Shear Zone Improved using Higher Resolution Grid

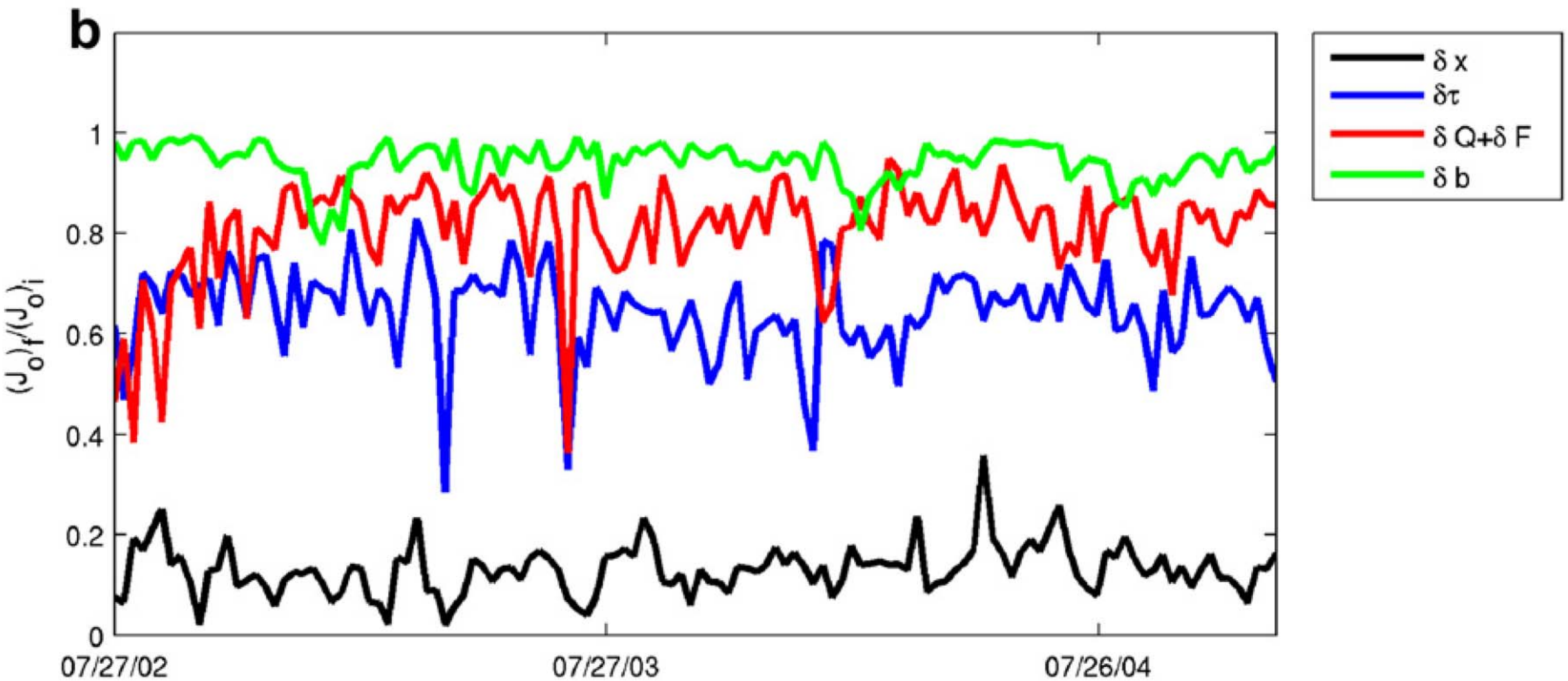


Improved representation of the wind stress curl using the 3 km grid at the coast should drive improved representation of wind-driven processes (e.g., upwelling)

J. Doyle (NRL)

The Ocean Control Vector

4D-Var Cost function: $J = J_b + J_o$



$$\left(J_o\right)_{\text{final}} / \left(J_o\right)_{\text{initial}} \text{ vs time}$$

ROMS, California Current System, 4D-Var, 7 day cycles

Prior Error Covariance Modeling

Zonal Average Ocean Density

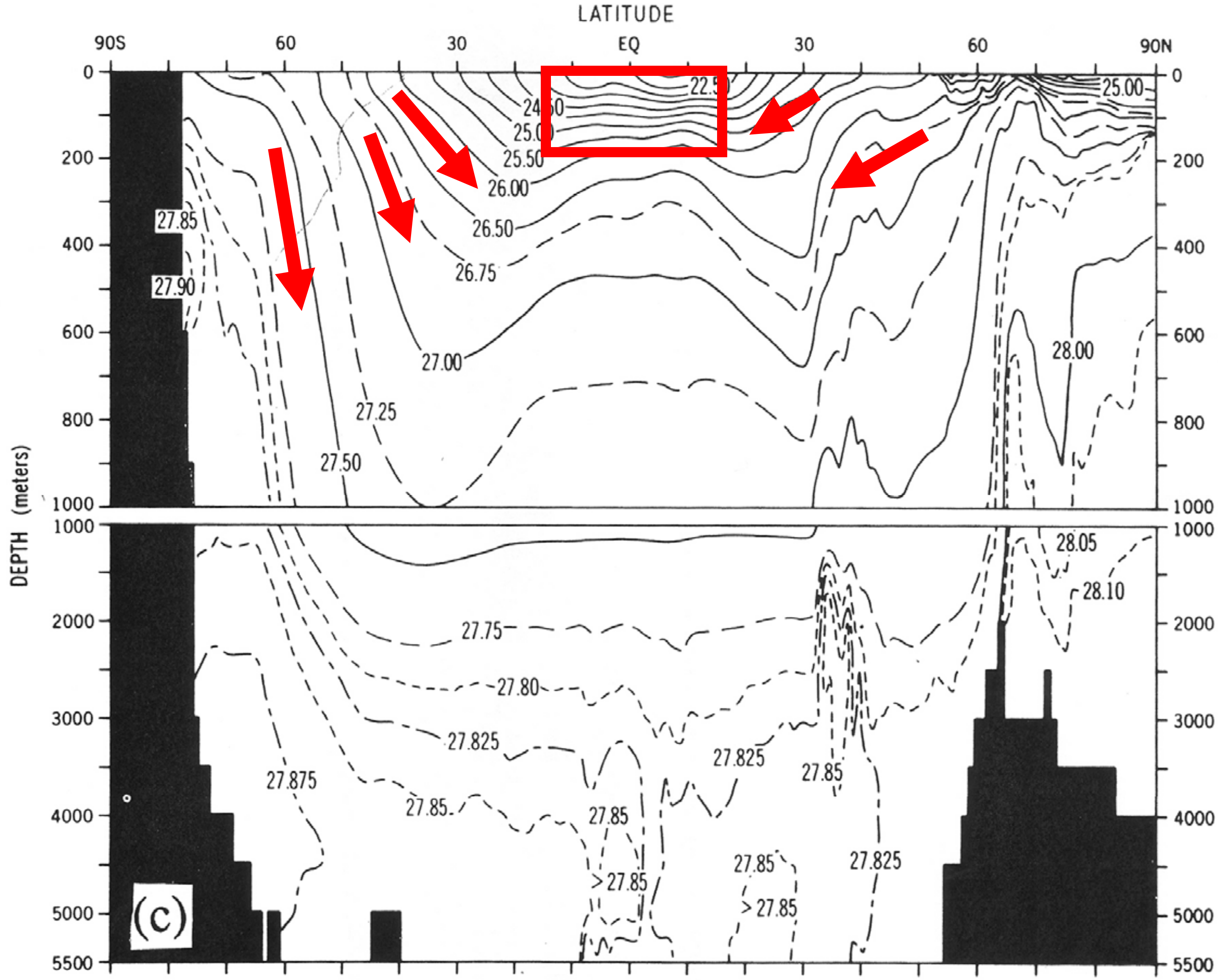
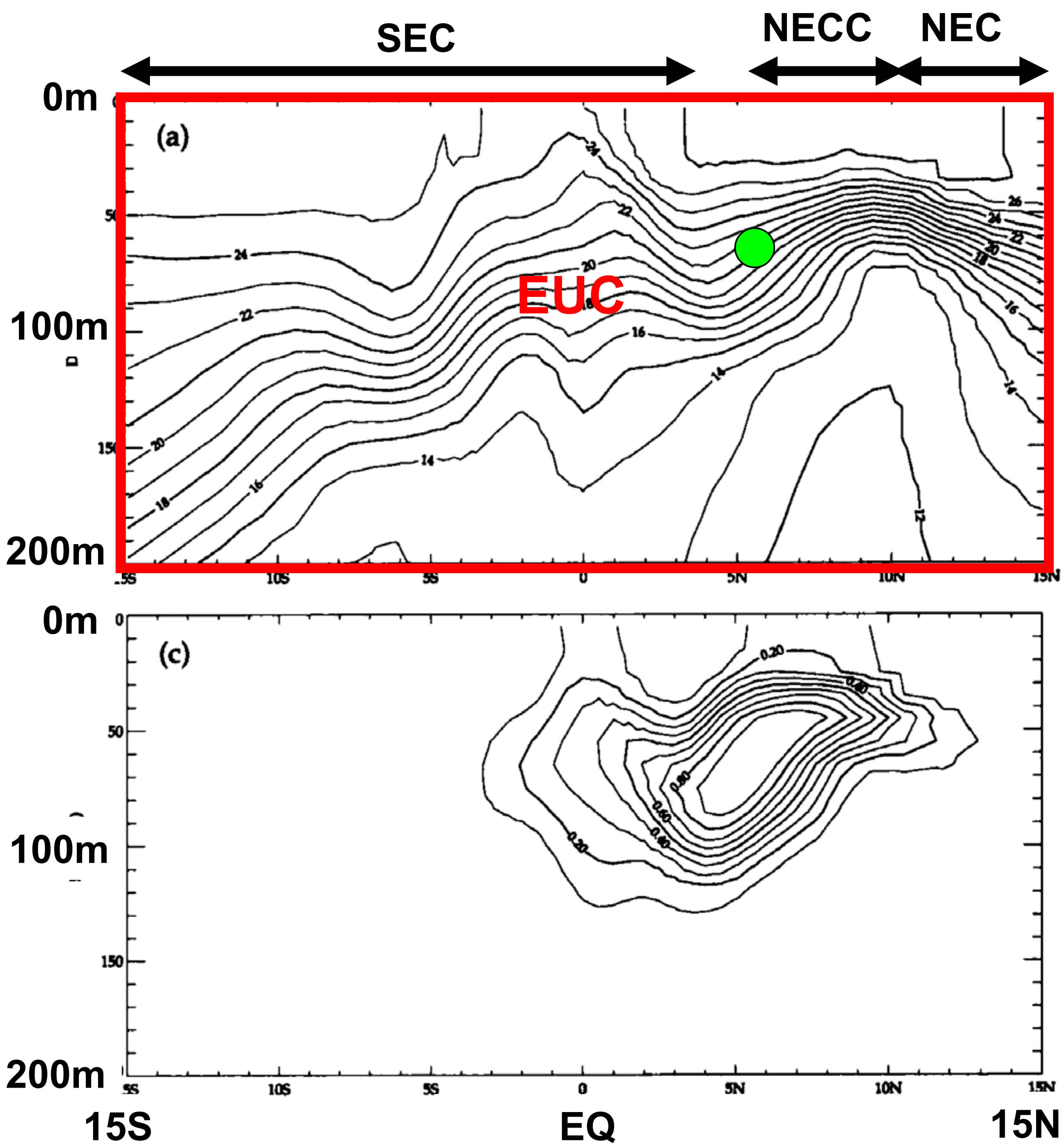


Fig. 7.1—*Continued*

Levitus (1982)

Equatorial Pacific Temperature

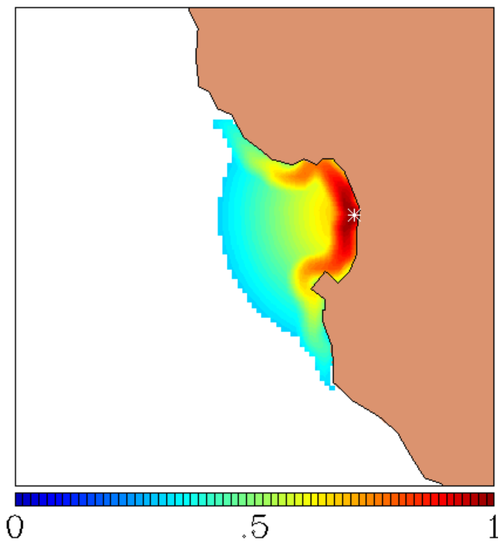


NEC=N. Eq. Curr.
SEC=S. Eq. Curr
NECC=N. Eq. Counter Curr.
EUC=Eq. Under Curr.

Observation

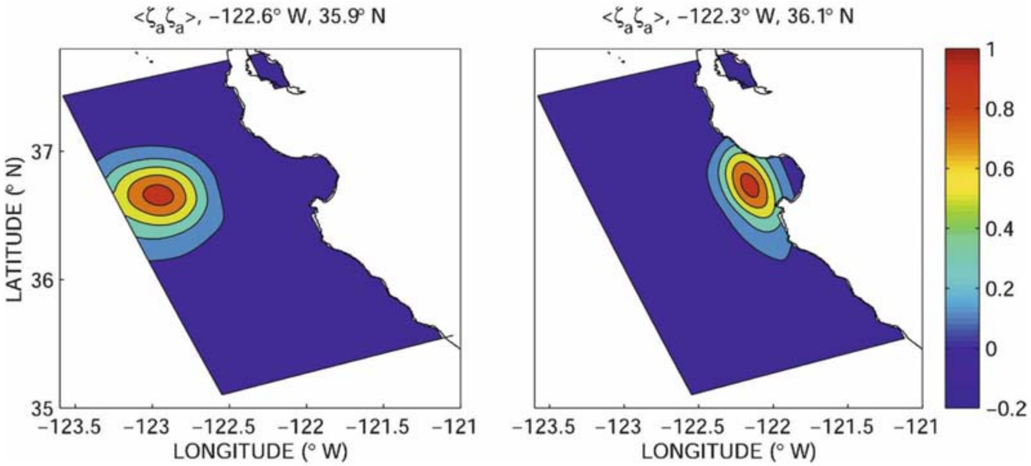
Diffusion eqn with a diffusion tensor.

Weaver and Courtier (2001)
(3D-Var & 4D-Var)

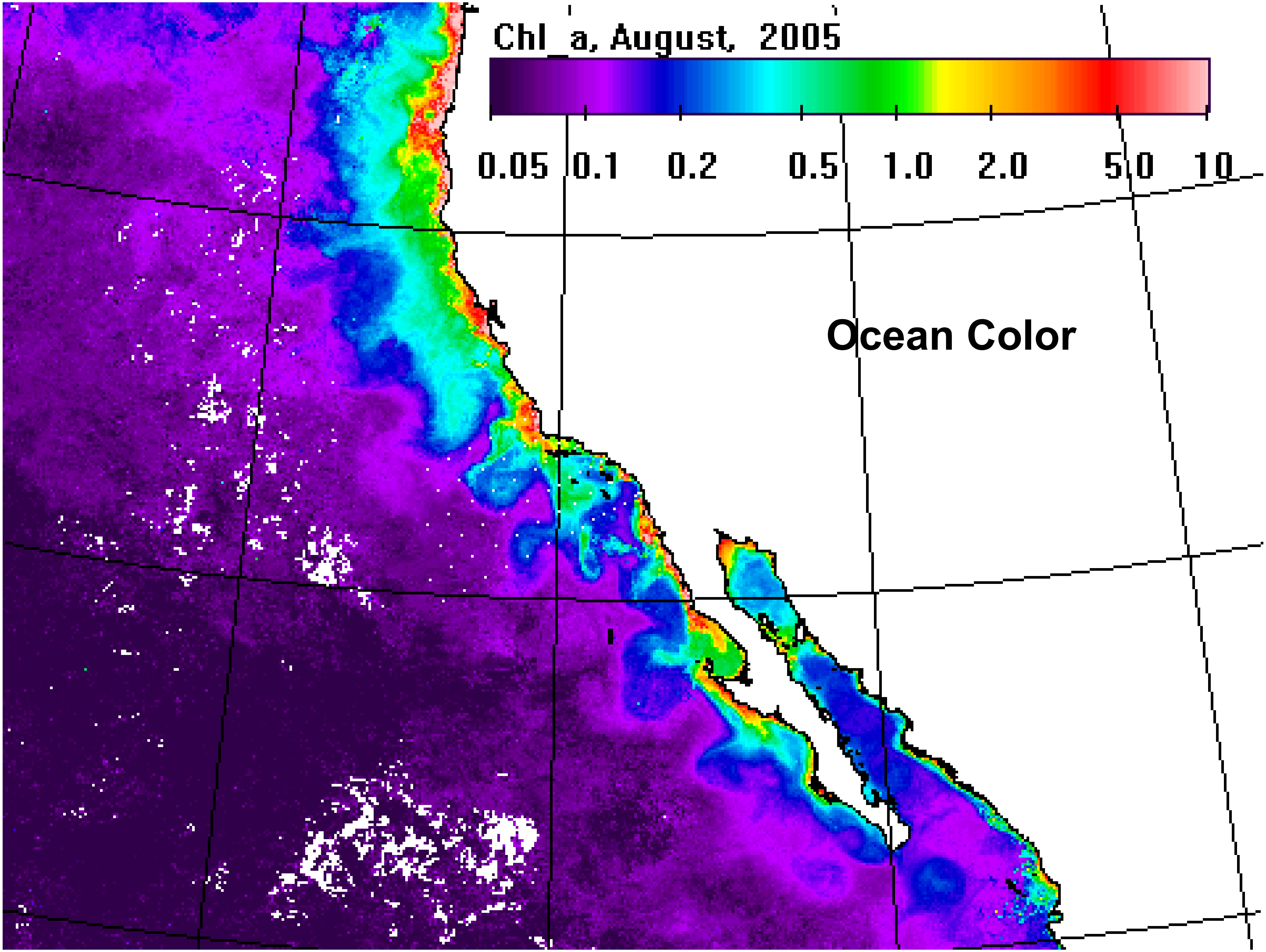


Complex Boundaries and Bathymetry

Courtesy of Jim Cummings
NRL, Monterey (3D-Var)

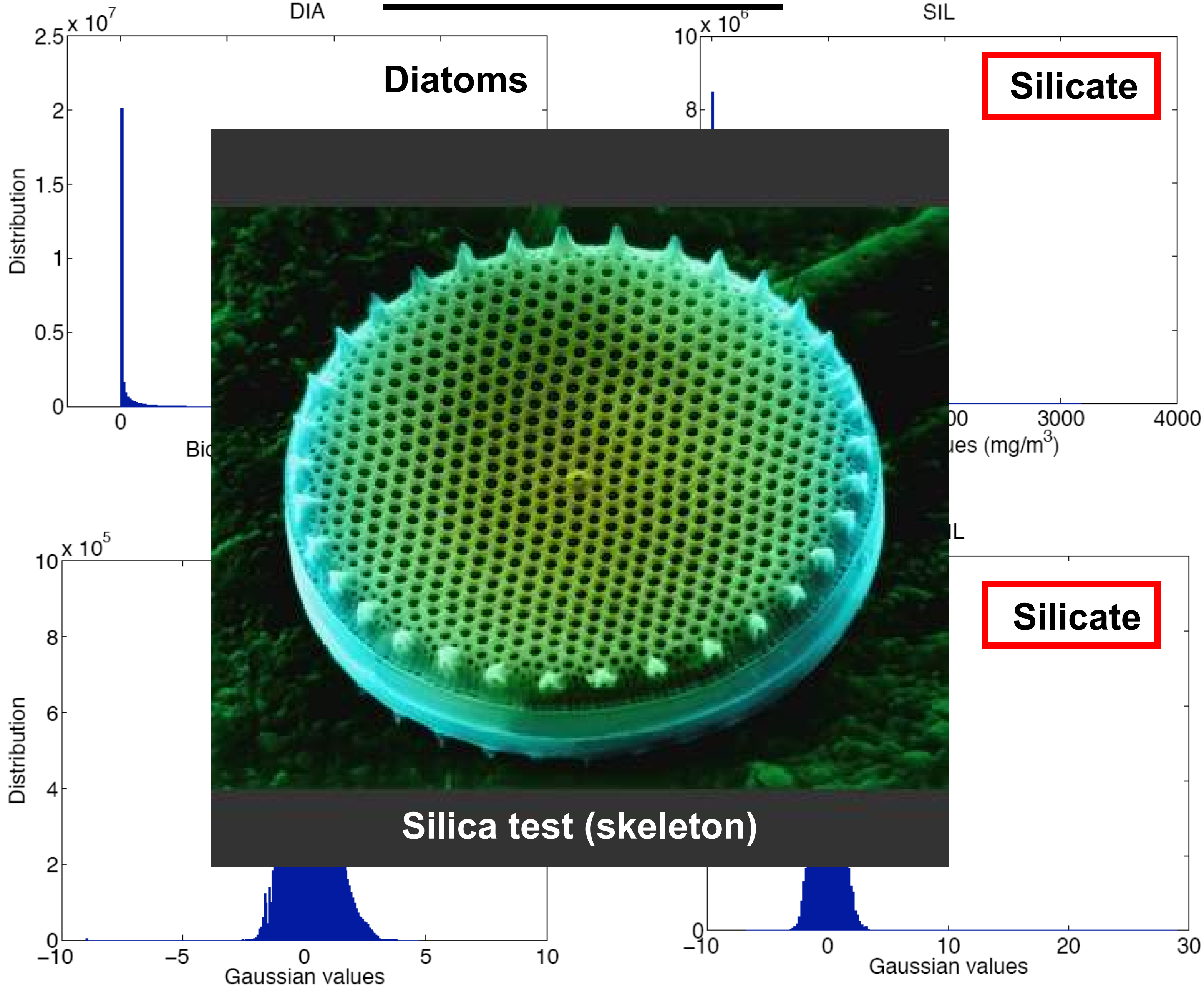


Li et al (2008) (3D-Var)



Chl_a, August, 2005
0.05 0.1 0.2 0.5 1.0 2.0 5.0 10
Ocean Color

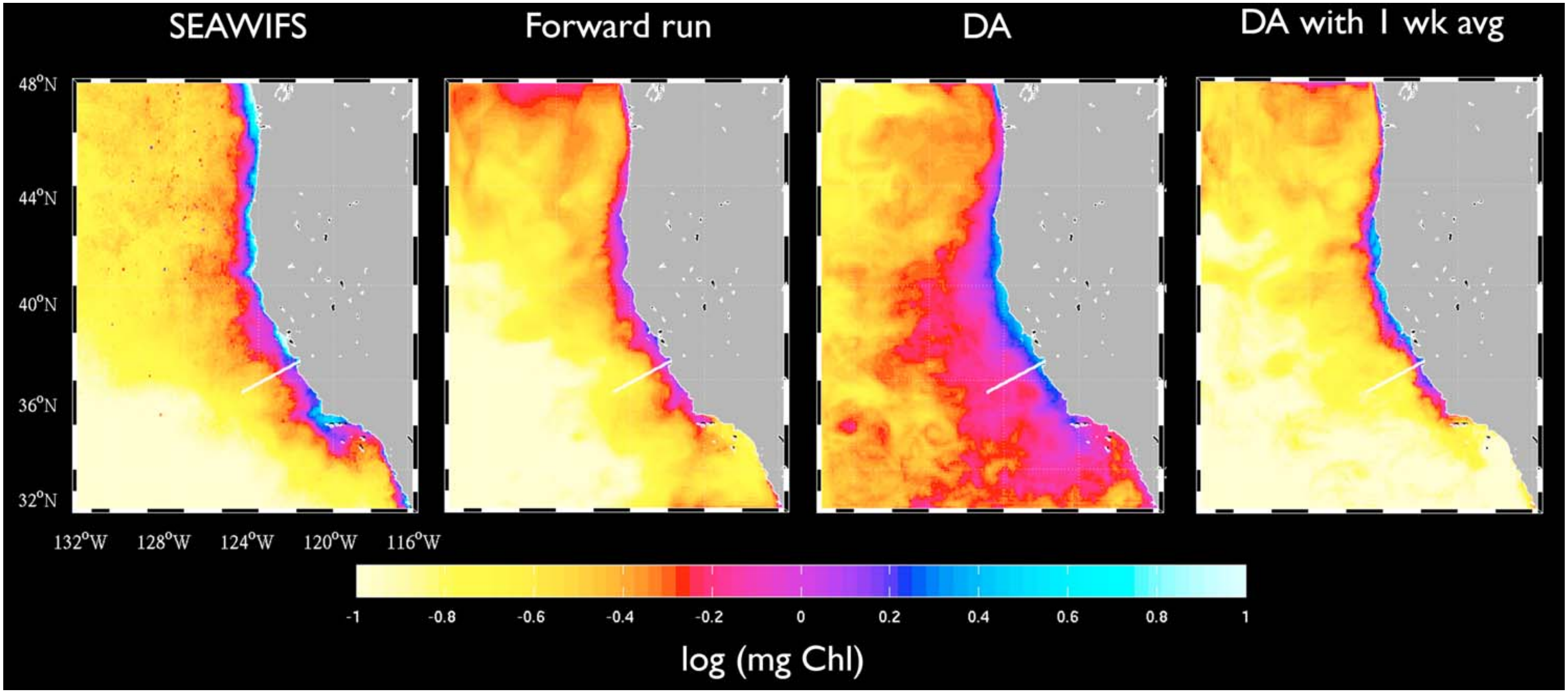
Ocean Tracers



Simon and Bertino (2009) – Interpolated Anamorphosis Functions

Initialization Shock

Initialization Shock



ROMS + DARWIN, California Current

Courtesy of Kaustubha Raghukumar (UCSC)

NMI/DFI and coastally trapped waves?

Part II – Some Recent Advances

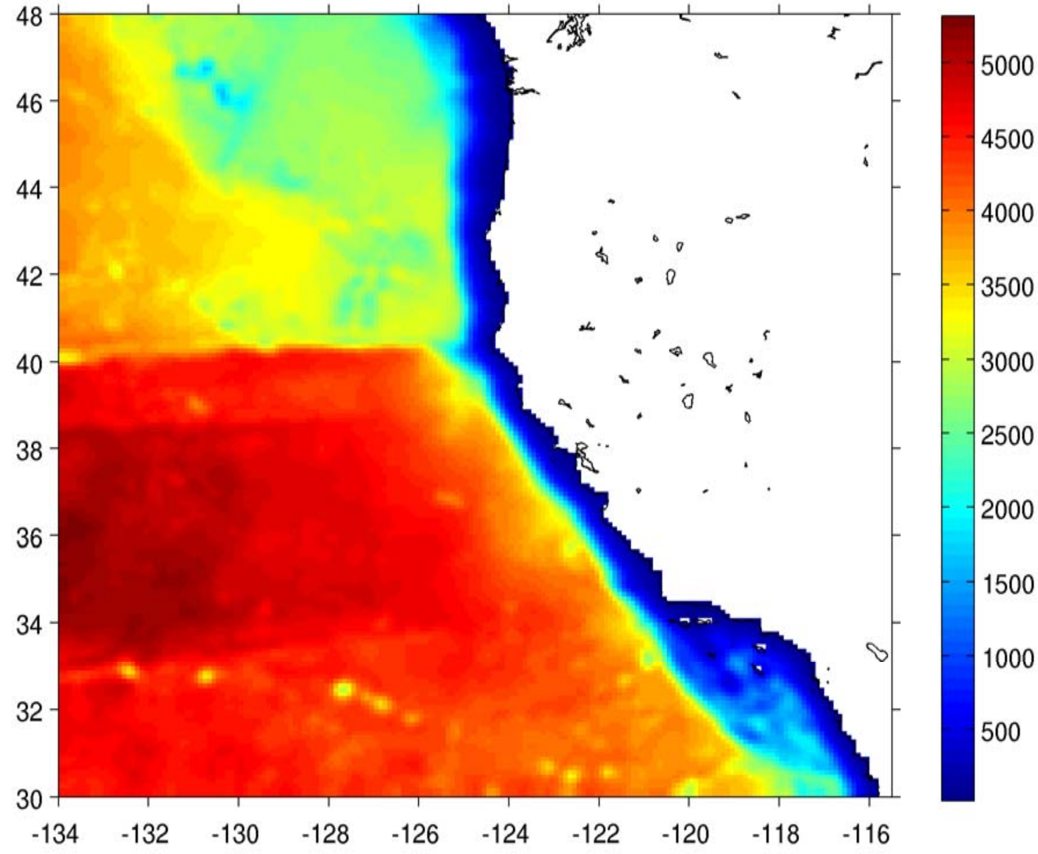
The Regional Ocean Modeling System (ROMS)

- **Diagnostic calculations**
  - Obs impact
  - $(4D\text{-}Var)^T$
    - obs sensitivity
    - expected errors of functions
    - towards adaptive sampling

ROMS: California Current System (CCS)

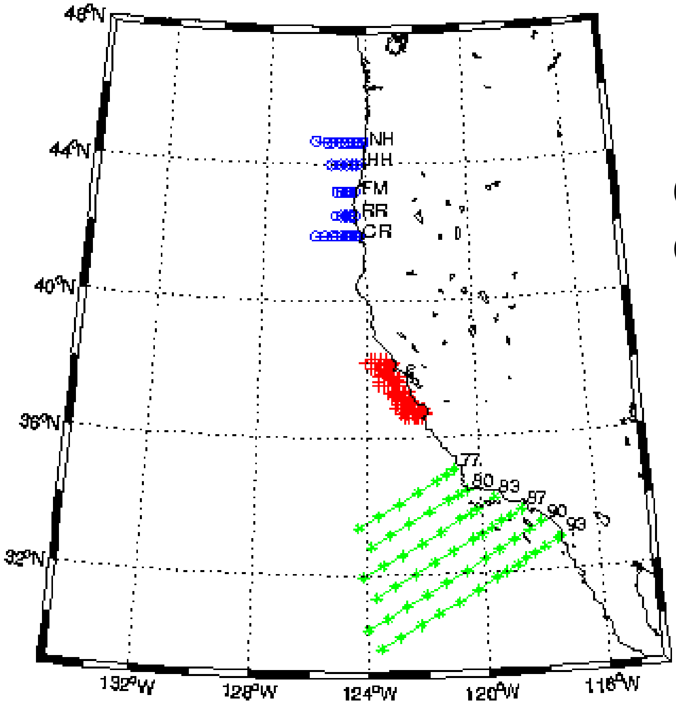
4D-Var applied sequentially every 7 days: Jul 2002-Dec 2004.

- ROMS: PE, hydro, sigma
- 4D-Var: incremental,
  1 outer, 20-60 inner
- COAMPS forcing
- ECCO open b.c.s
- 10km, 42 levels (obs impact)
- 30 km, 30 levels (obs sensitivity)

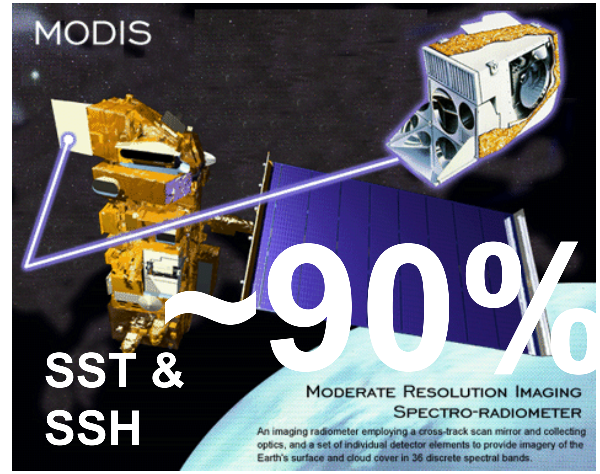


Veneziani et al (2009)
Broquet et al (2009ab, 2011)

Observations (y)

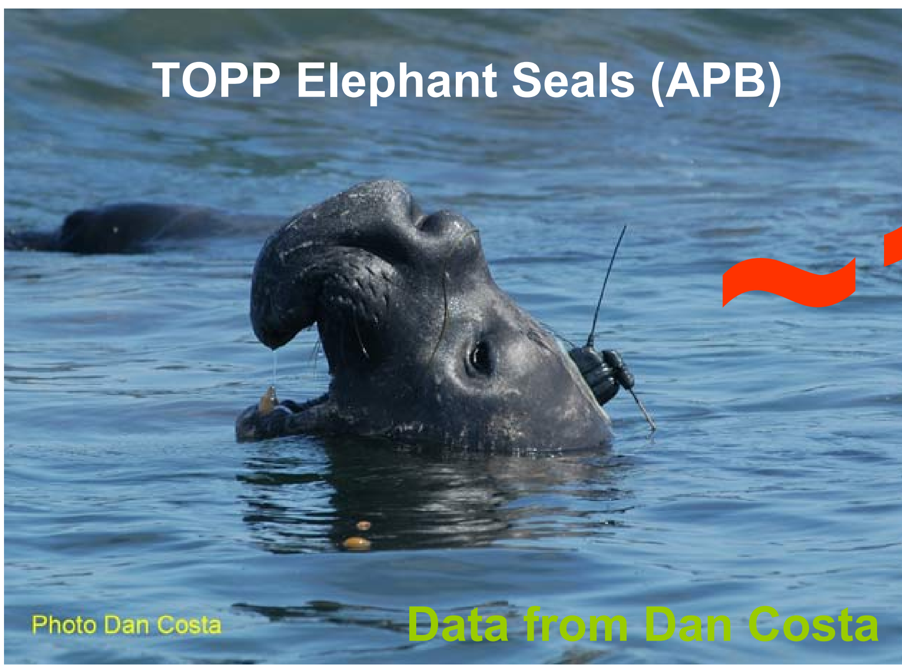


CalCOFI & GLOBEC



EN3

Ingleby and Huddleston (2007)



~10%

Obs Impact vs Obs Sensitivity

Practical Gain matrix

$$\mathbf{x_a} = \mathbf{x_b} + \boxed{\tilde{\mathbf{K}}}\mathbf{d}$$

OR…

$$\mathbf{x_a} = \mathbf{x_b} + \boxed{\mathcal{K}(\mathbf{d}, \underbrace{p_a, p_m}_{\text{parameters}})}$$

4D-Var

Obs impact: $\tilde{\mathbf{K}}^{\mathrm{T}}$

Obs sensitivity: $\left(\partial\mathcal{K}/\partial\mathbf{d}\right)^{\mathrm{T}}$

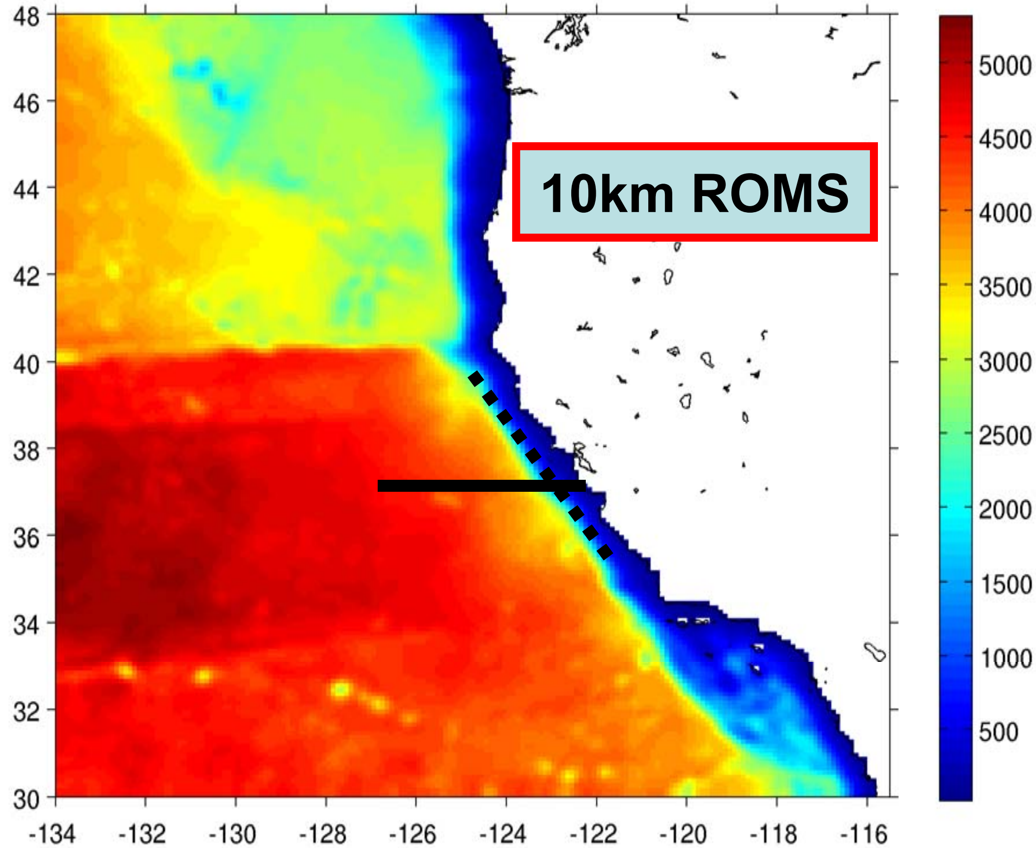
Observation Impacts on Analysis Increments

$\mathcal{J}$ = 7day average transport

$\Delta\mathcal{J}$ = Transport increment

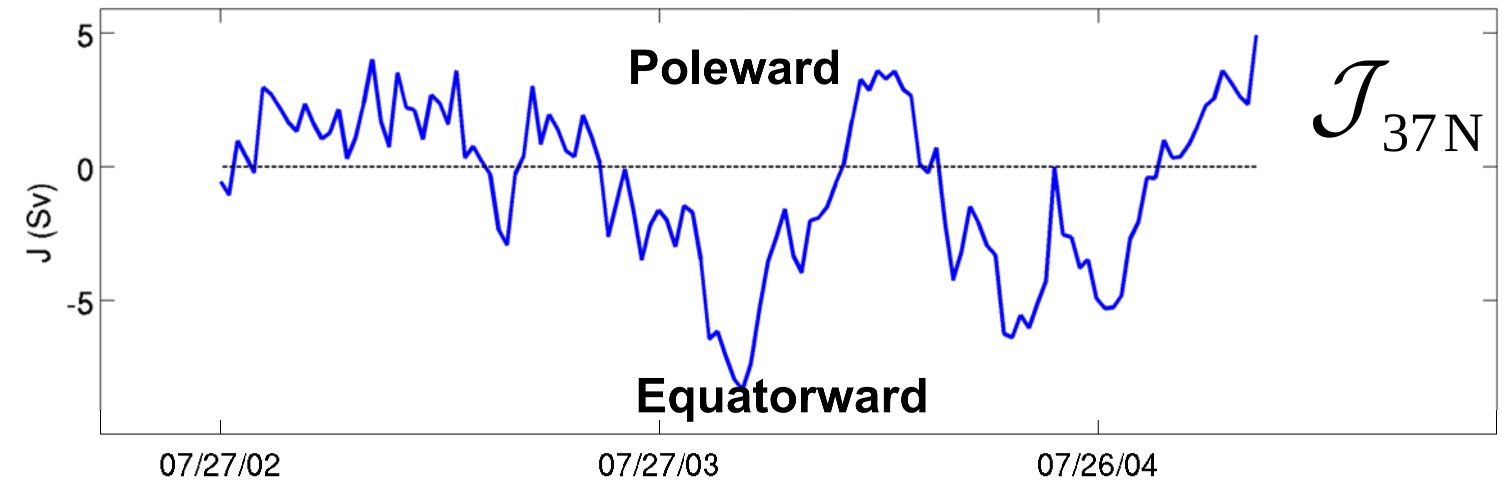
= (Posterior-Prior)

(Langland & Baker, 2004; Gelaro et al., 2007)

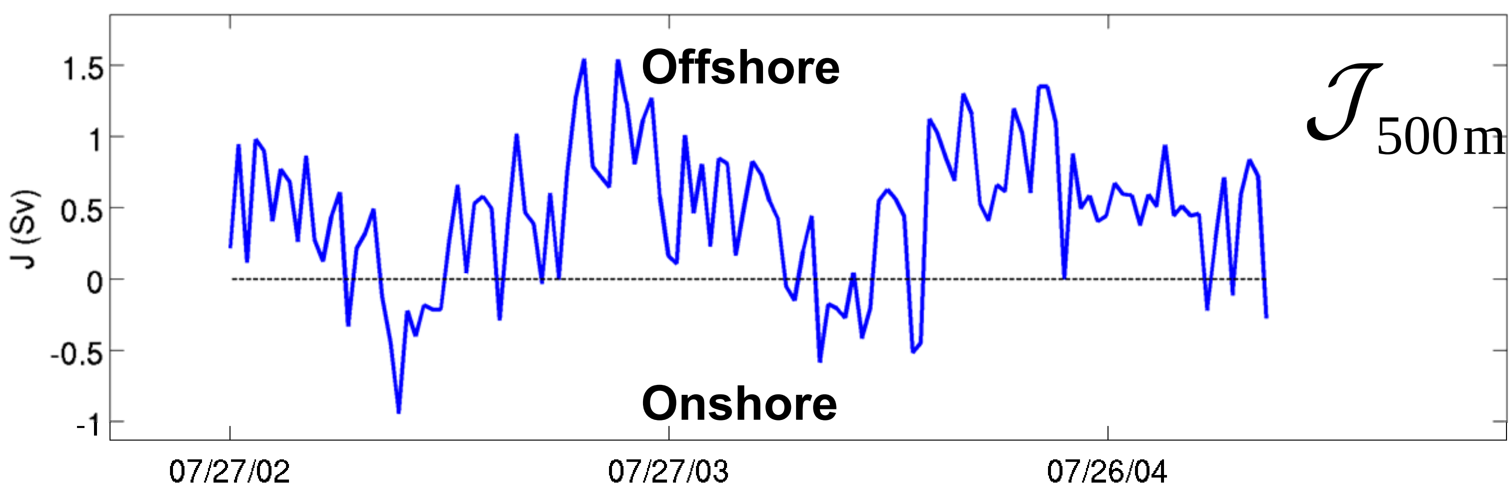


$$\Delta\mathcal{J} \xrightarrow{\tilde{\mathbf{K}}^{\mathrm{T}}} \sum_{p=1}^{platform} \Delta\mathcal{J}_p = \sum_{i=1}^{N_{obs}} \Delta\mathcal{J}_i$$

Prior alongshore transport (CC+CUC+CJ)

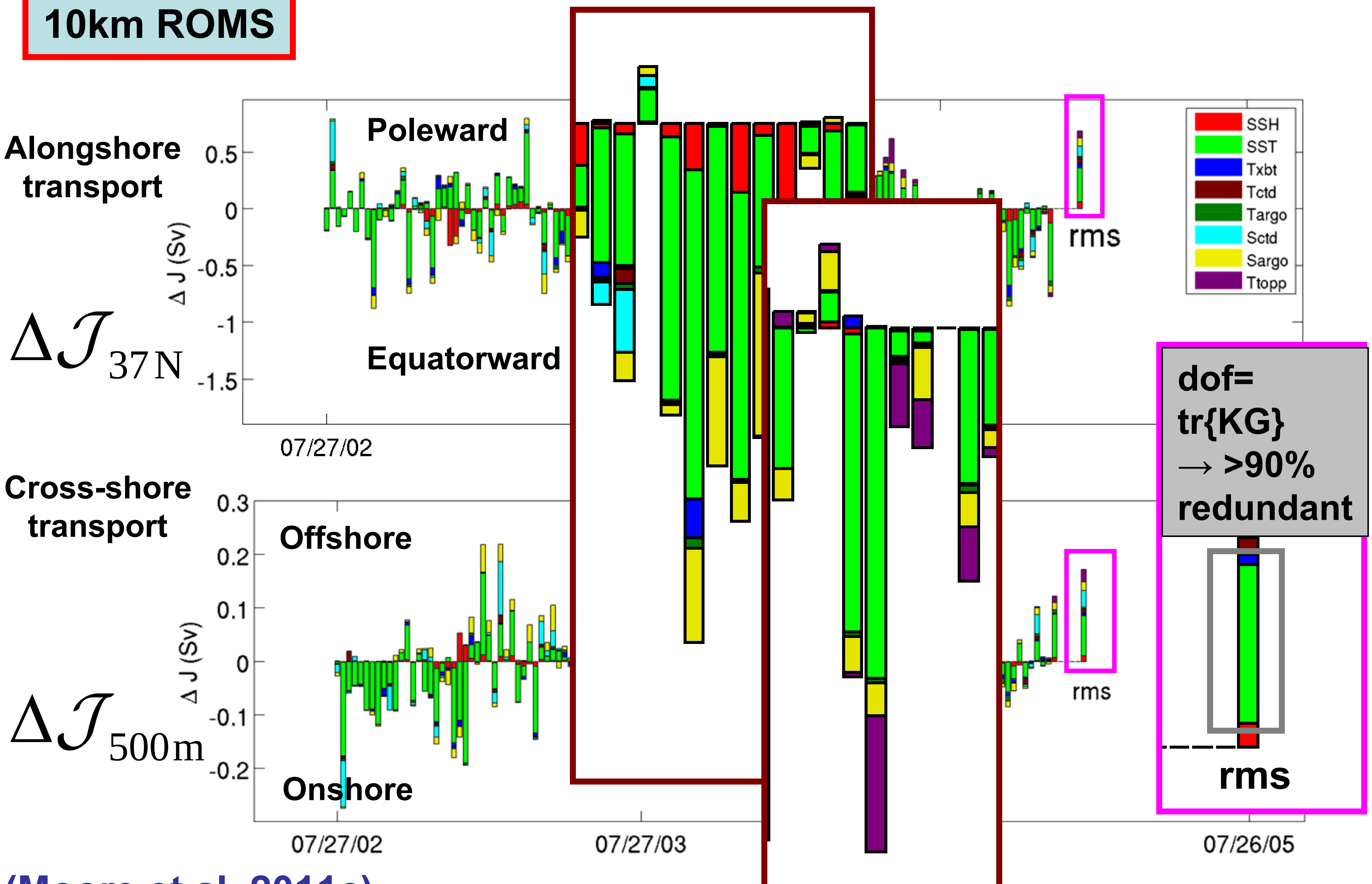


Prior cross-shore transport



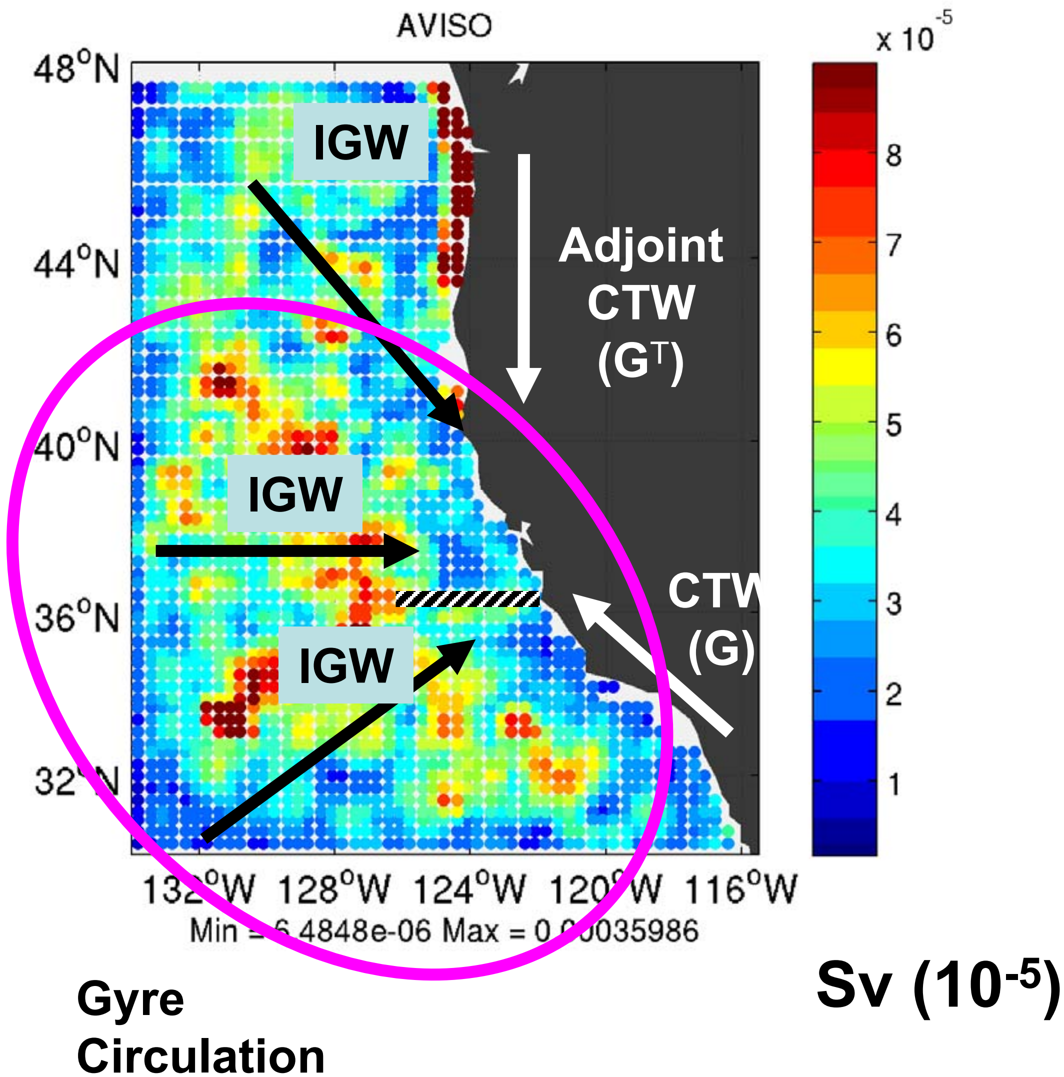
Analysis Cycle – Observation Impacts

10km ROMS



(Moore et al, 2011c)

Alongshore Transport Impacts



SSH

Obs Impact vs Obs Sensitivity

Practical Gain matrix

$$\mathbf{x}_a = \mathbf{x}_b + \boxed{\tilde{\mathbf{K}}}\mathbf{d}$$

OR...

$$\mathbf{x}_a = \mathbf{x}_b + \boxed{\mathcal{K}(\mathbf{d}, \underbrace{p_a, p_m}_{\text{parameters}})}$$

4D-Var

Obs impact: $\tilde{\mathbf{K}}^{\mathrm{T}}$

Obs sensitivity: $\left(\partial\mathcal{K}/\partial\mathbf{d}\right)^{\mathrm{T}}$

Observation Sensitivity and Observing System Experiments (OSEs)

Change in the obs: $\delta\mathbf{y}$

$\boxed{\left(\partial\mathcal{K}/\partial\mathbf{y}\right)^{\mathrm{T}}}$ **yields the change in** $\Delta\mathcal{J}$

(4D-Var)$^{\mathrm{T}}$

For OSE, choose:

$$\delta\mathbf{y} = -\mathbf{W}\mathbf{d} = -\mathbf{W}\left(\mathbf{y} - H\left(\mathbf{x}_{\mathbf{b}}\right)\right)$$

perts to obs

innovation

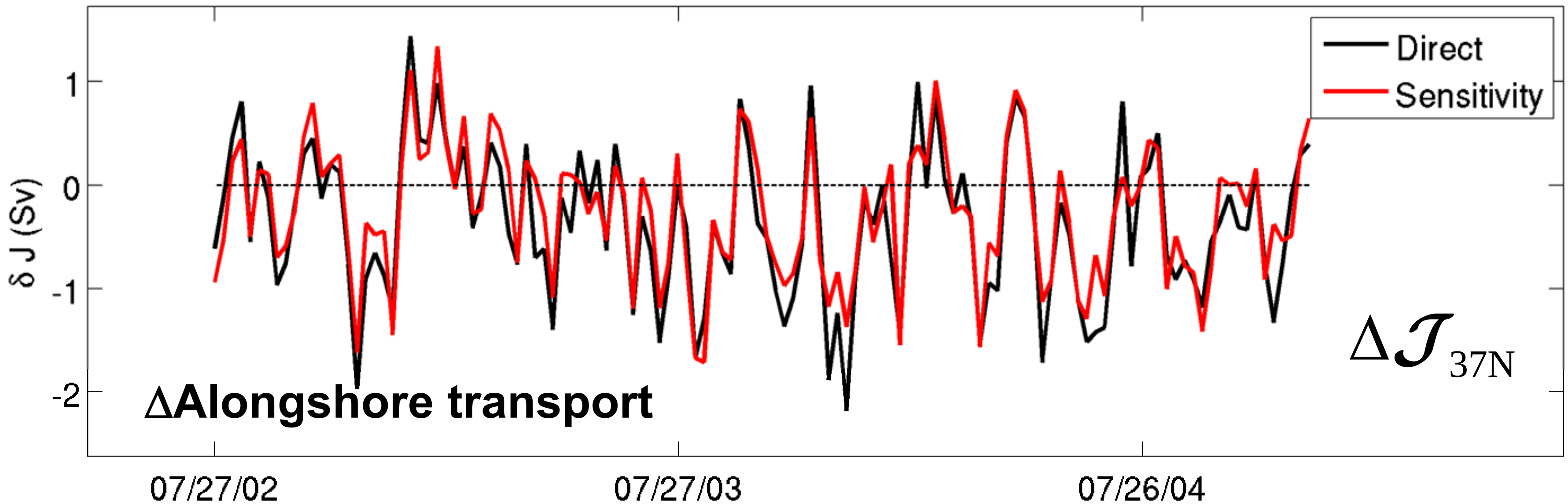
obs

prior

Diagonal matrix that selects obs to be withheld

Observing System Experiments (OSEs)

Altimeter data withheld



Direct computation of 4D-Var

Observation sensitivity using $\left(\partial \mathcal{K} / \partial \mathbf{y}\right)^{T}$

Posterior Errors

Posterior/analysis error covariance:

$$\mathbf{E}^{\mathbf{a}} = \left(\mathbf{I} - \mathbf{KG}\right)\mathbf{B}\left(\mathbf{I} - \mathbf{KG}\right)^{\mathrm{T}} + \mathbf{KRK}^{\mathrm{T}}$$

TL model

Prior error covariance

Obs error covariance

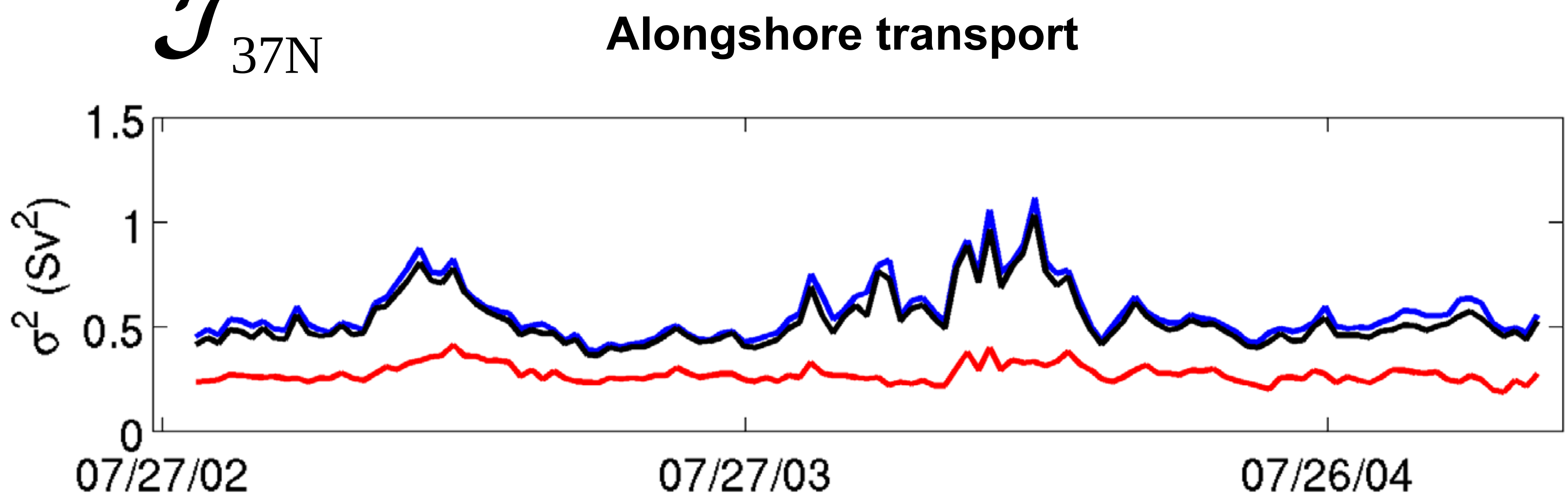
Inspired by ensemble 4D-Var, we can show that:

$$\mathbf{E}^{\mathbf{a}} = \left(\mathbf{I} - \left(\frac{\partial \mathcal{K}}{\partial \mathbf{d}}\right)\mathbf{G}\right)\mathbf{B}\left(\mathbf{I} - \left(\frac{\partial \mathcal{K}}{\partial \mathbf{d}}\right)\mathbf{G}\right)^{\mathrm{T}} + \left(\frac{\partial \mathcal{K}}{\partial \mathbf{d}}\right)\mathbf{R}\boxed{\left(\frac{\partial \mathcal{K}}{\partial \mathbf{d}}\right)^{\mathrm{T}}}$$

(4D-Var)$^{\mathrm{T}}$

Prior and *Posterior* Errors: 37N Transport

$\mathcal{J}_{37\mathrm{N}}$



— $\left(\sigma^b_{\mathcal{J}}\right)^2$ — $\left(\sigma^a_{\mathcal{J}}\right)^2$ — $\left(\tilde{\sigma}^a_{\mathcal{J}}\right)^2$

Using $\tilde{\mathbf{K}}$ instead of $\left(\partial\mathcal{K}/\partial\mathbf{d}\right)^{\mathrm{T}}$

Seldom directly observed!

OSEs and Analysis Errors

Consider the linear function $\mathcal{J}(\mathbf{x}_a)=\mathbf{h}^T\mathbf{x}_a$ (e.g. transport).

The change in the analysis error variance in $\mathcal{J}(\mathbf{x}_a)$ **due to withholding obs**:

$$\left(\tilde{\sigma}^a_{\mathcal{J}}\right)^2=\left(\sigma^a_{\mathcal{J}}\right)^2-2\mathbf{h}^T\mathbf{B}\mathbf{G}^T\mathbf{W}\left(\partial\mathcal{K}/\partial\mathbf{d}\right)^T\mathbf{h}$$
$$+2\mathbf{h}^T\left(\partial\mathcal{K}/\partial\mathbf{d}\right)\left(\mathbf{G}\mathbf{B}\mathbf{G}^T+\mathbf{R}\right)\mathbf{W}\left(\partial\mathcal{K}/\partial\mathbf{d}\right)^T\mathbf{h}$$
$$+\mathbf{h}^T\left(\partial\mathcal{K}/\partial\mathbf{d}\right)\mathbf{W}\left(\mathbf{G}\mathbf{B}\mathbf{G}^T+\mathbf{R}\right)\mathbf{W}\left(\partial\mathcal{K}/\partial\mathbf{d}\right)^T\mathbf{h}$$

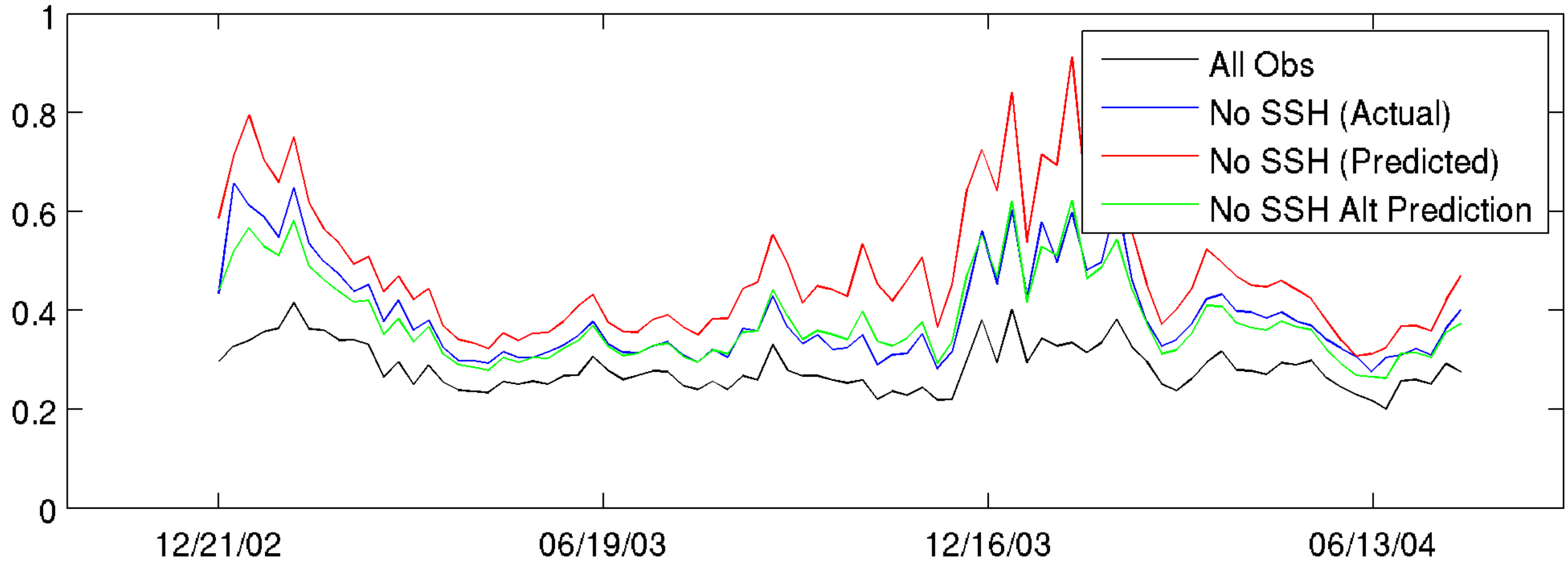
Analysis error with obs withheld

Analysis error assimilating all observations

?

OSEs and Analysis Errors

Analysis error variance of 37N transport:



Apparently there is a missing factor of 2 in $\left(\tilde{\sigma}^{a}_{\mathcal{J}}\right)^{2}-\left(\sigma^{a}_{\mathcal{J}}\right)^{2}$

Summary

- Ocean DA is diverse and mature
- Many basic challenges still exist:
  - expansion of control vector (B?)
  - tracer assimilation
  - initialization shock & filtering
  - vertical projection of satellite obs
  - covariance models
  - biogeochemical data assimilation
  - model error
  - internal tides
  - quality control & bias correction
  - air-sea coupling at all scales
- Sub-mesoscale and deep ocean are poorly observed (and poorly constrained)

Future

- Assessment of existing & new observing systems using OSEs and OSSEs
- High res. regional analyses
- Ensemble DA
- Continued development of ocean forecasting systems

Acknowledgements

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