What have we learnt about the ocean and climate using adjoint models that we perhaps did not know before?

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What have we learnt about the ocean and climate using adjoint models that we perhaps did not ***appreciate*** before?

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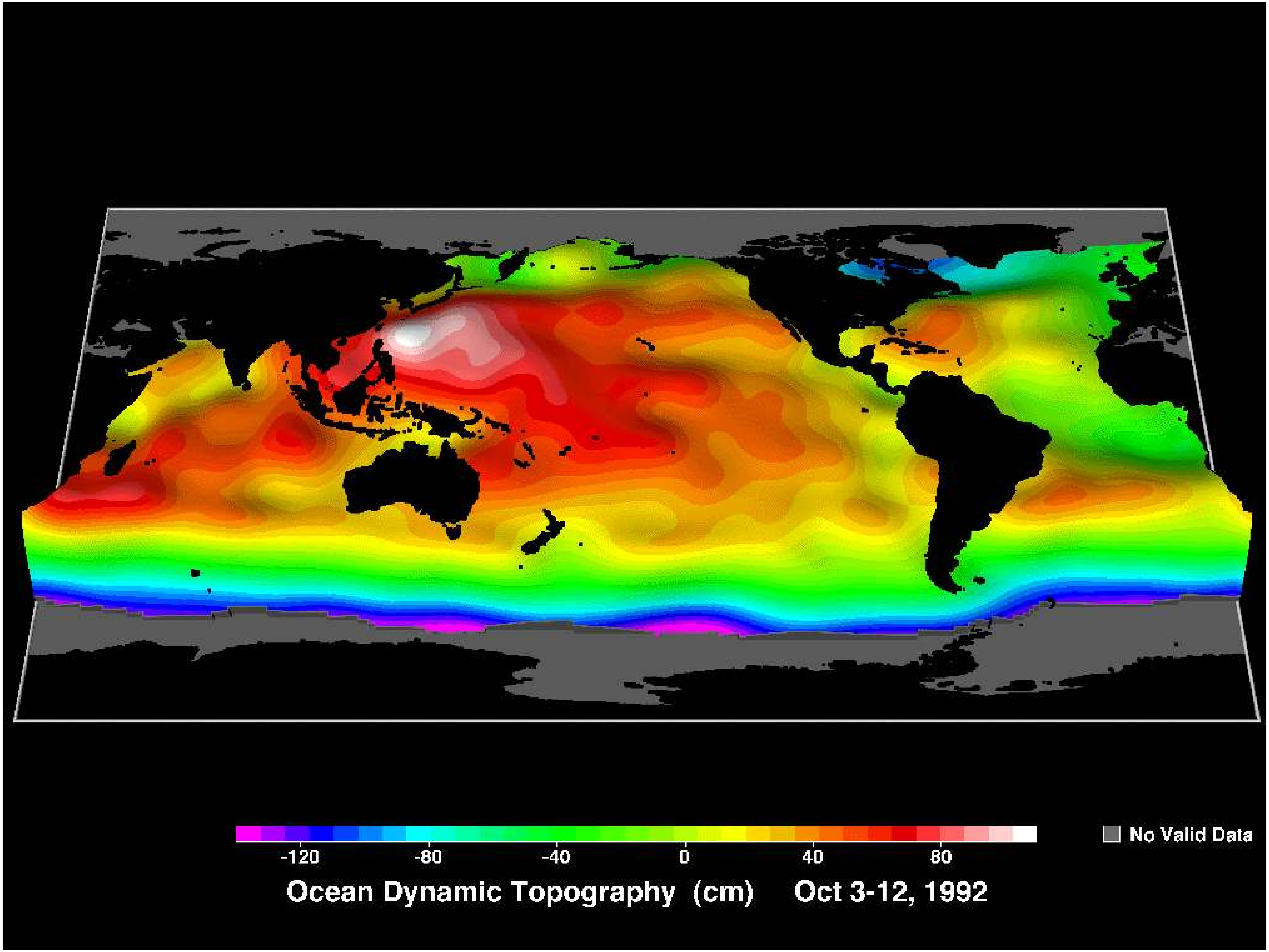
An exercise in hindsight…

Increasing Scales

- Island wakes and passages
- Coastal currents and upwelling
- Linear waves and ocean gyres
- Thermohaline circulation
- Tropical climate variability

Tools of the Trade

- Adjoint sensitivity analysis
- Singular value decomposition
- Data Assimilation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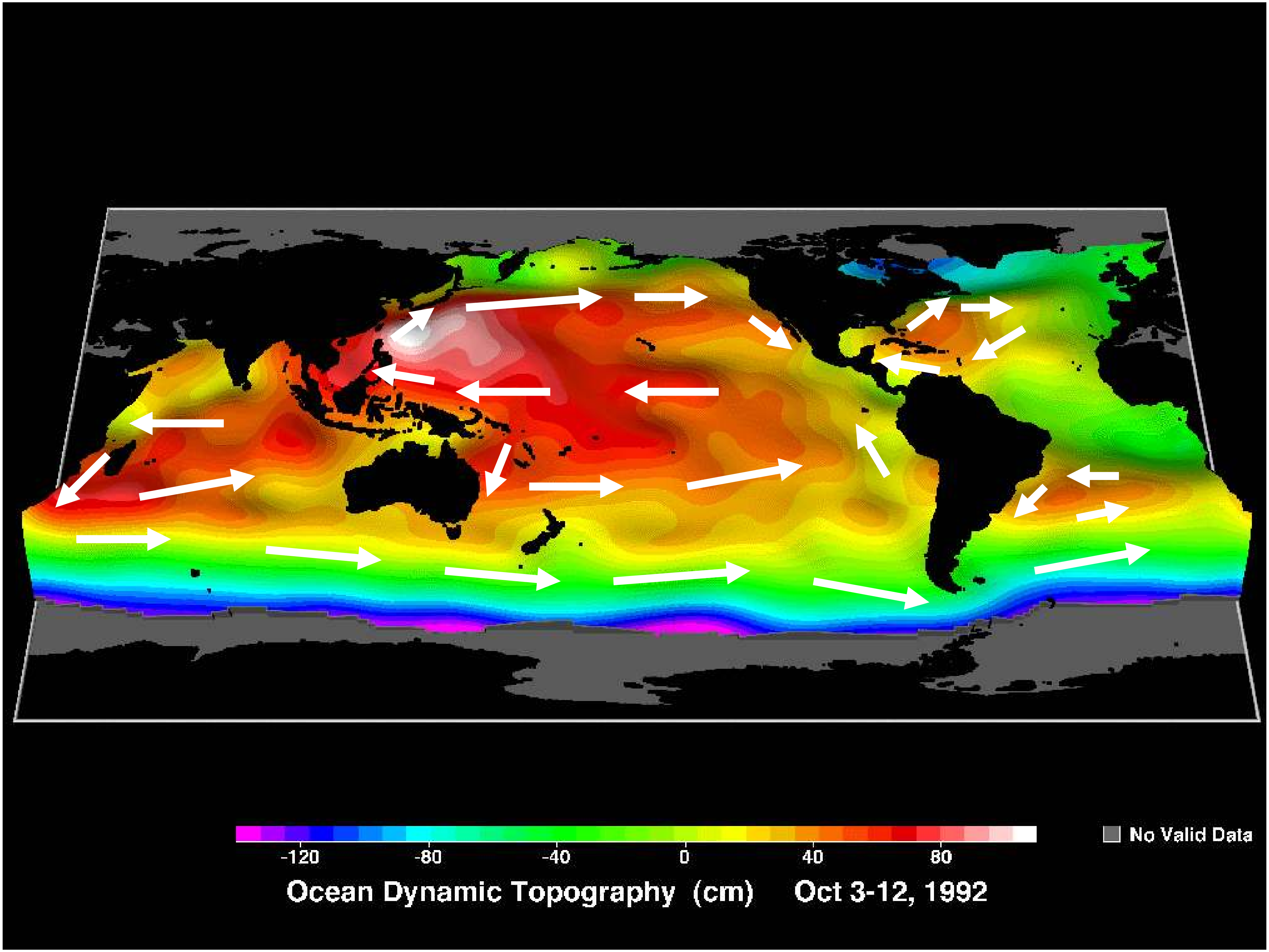
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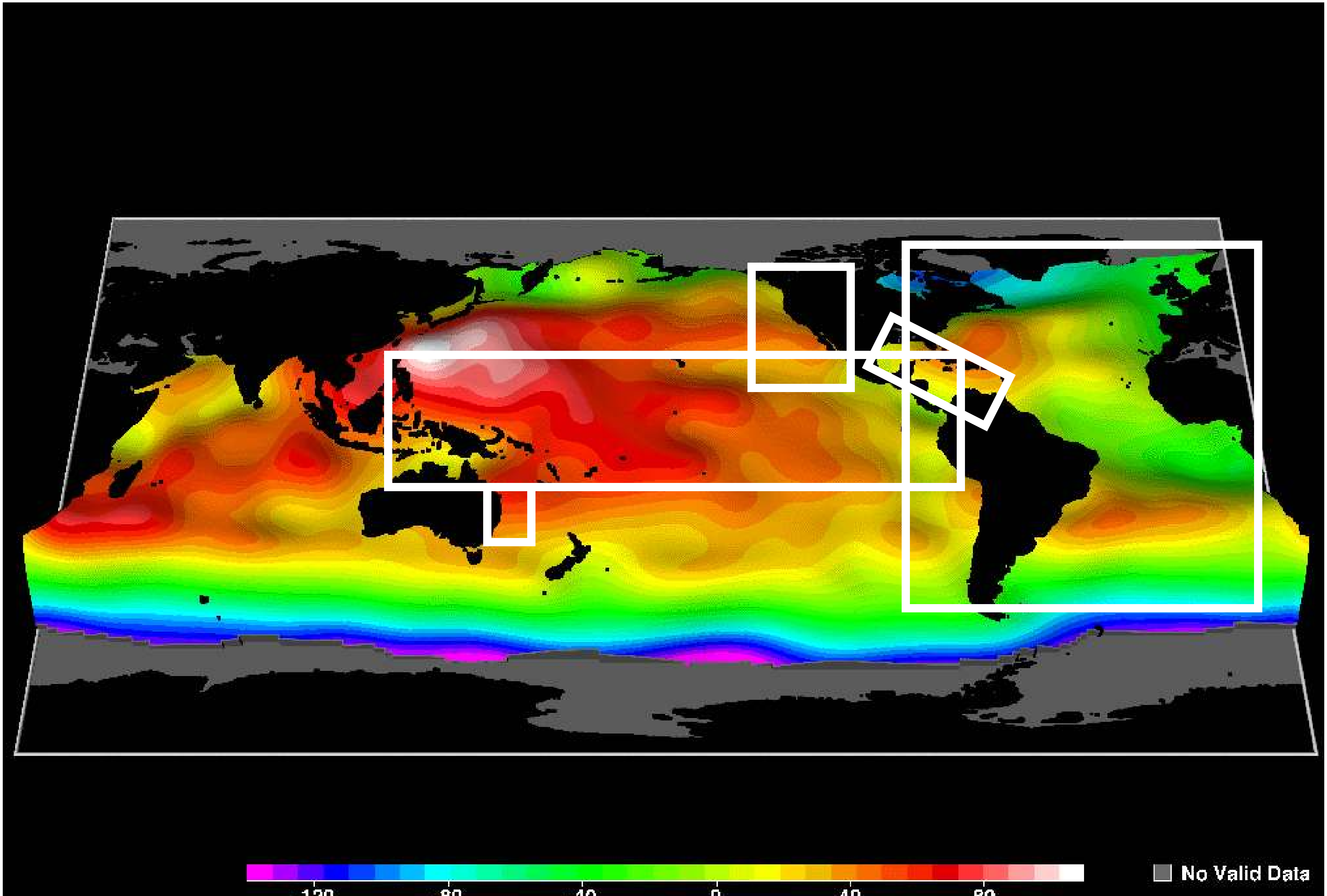

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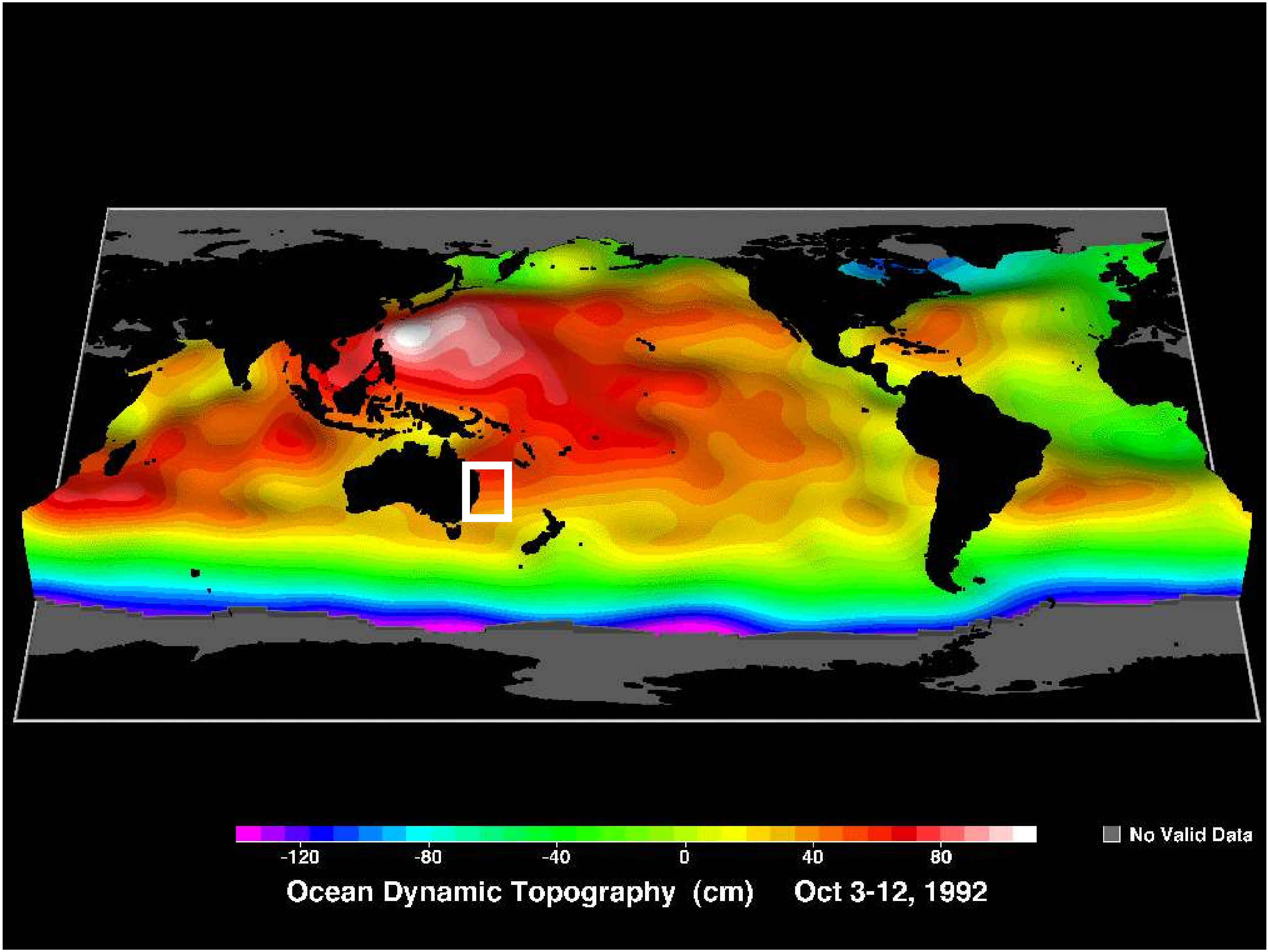

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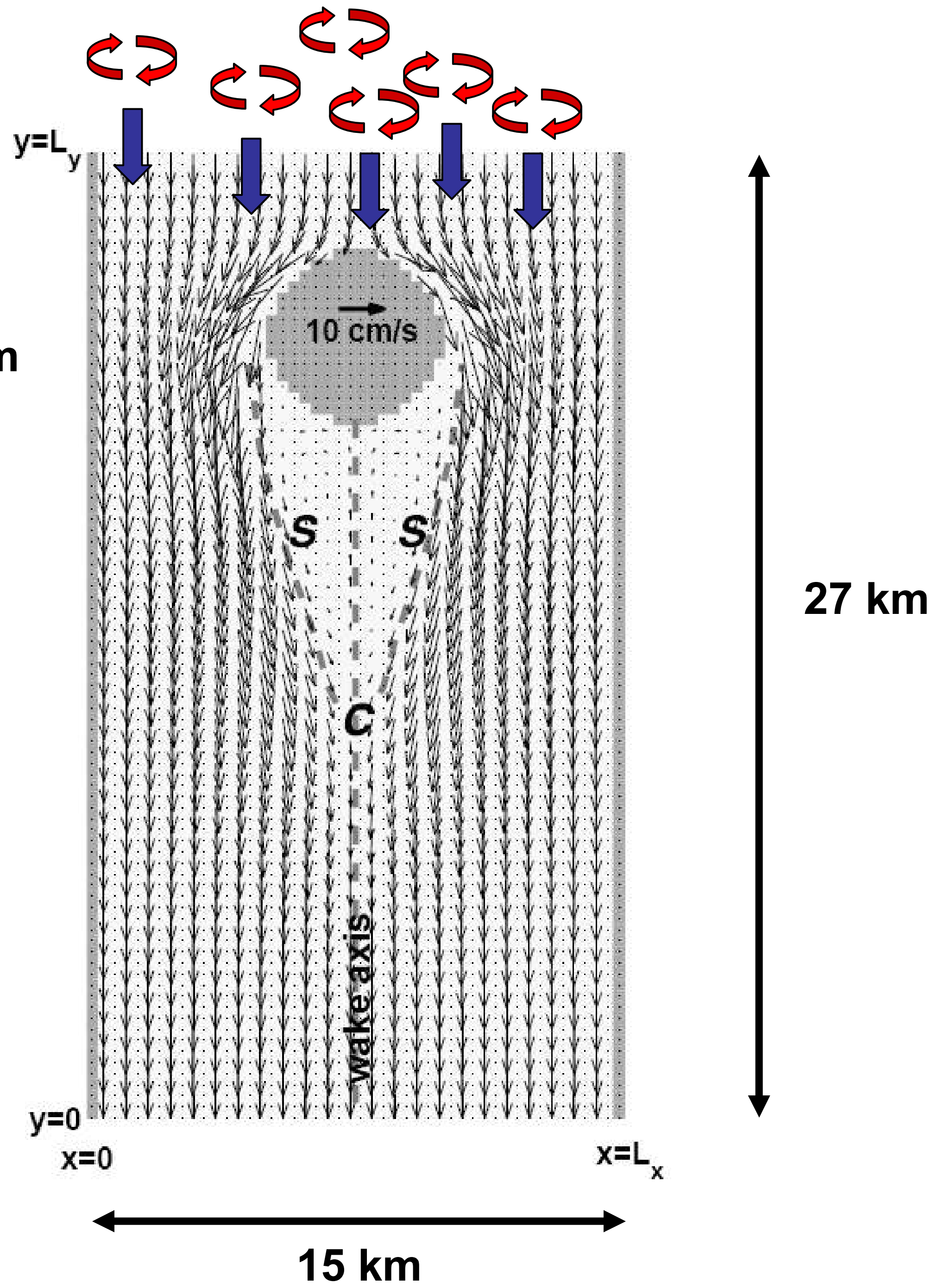
Ocean Dynamic Topography (cm) Oct 3-12, 1992

Island radius= 5 km
Channel depth = 10 m

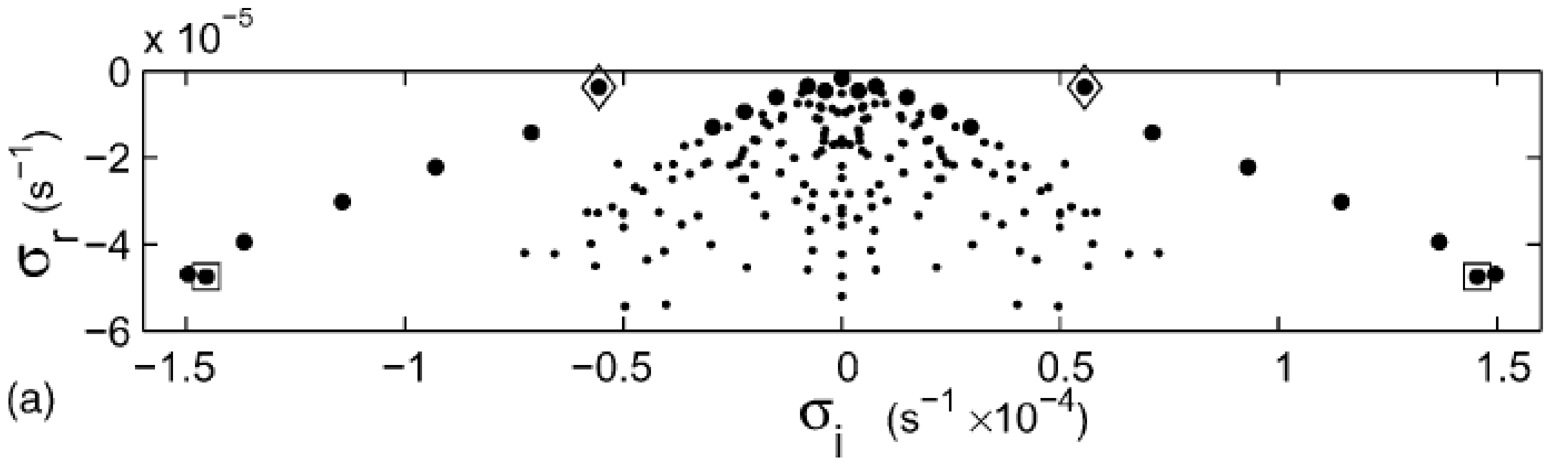


Aiken et al (2003)

Tools Used & Relevant Ideas

- Singular value decomposition of stochastically-forced circulation variance
- “Stochastic optimals”
- Pseudospectra
- Nonnormal dynamics: linear eigenmode interference
- Model: barotropic, shallow water.

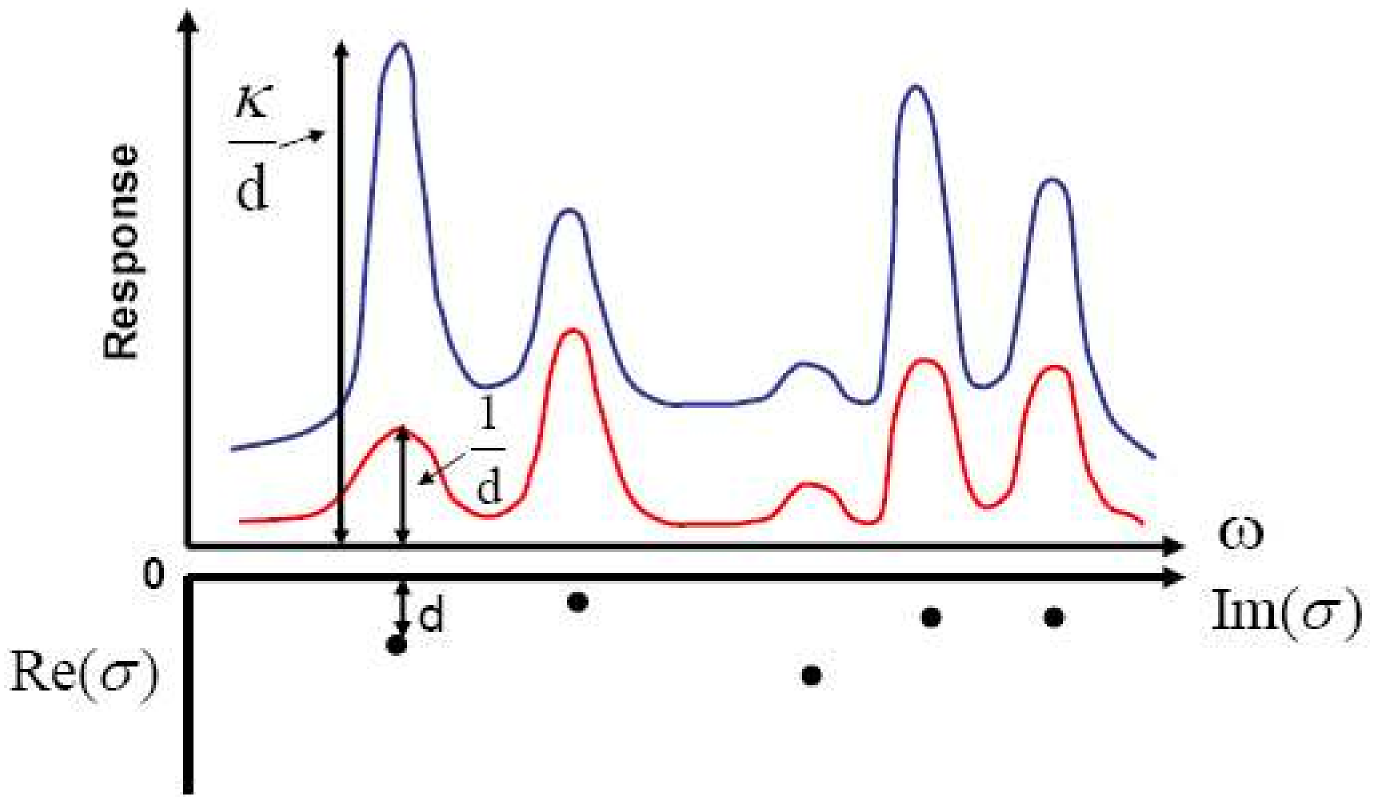
Eigenspectrum



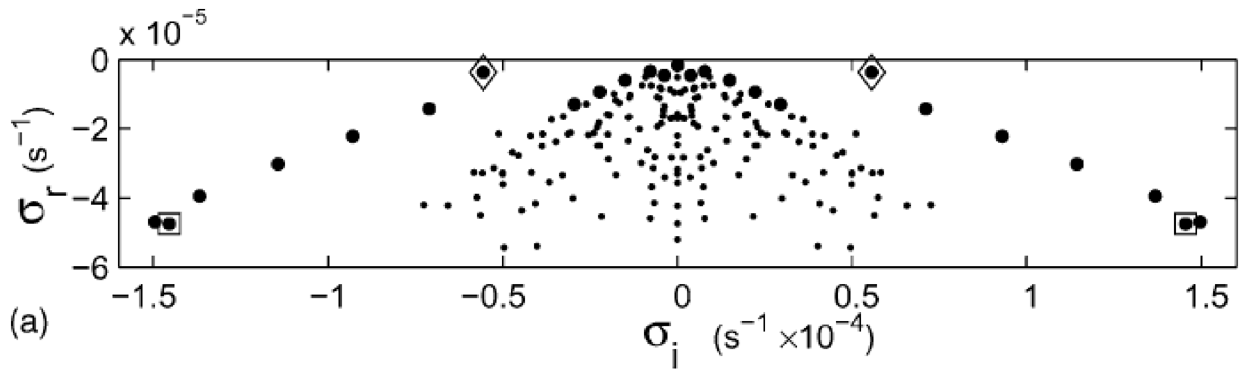
12hr 17hr 35hr 35hr 17hr 12hr

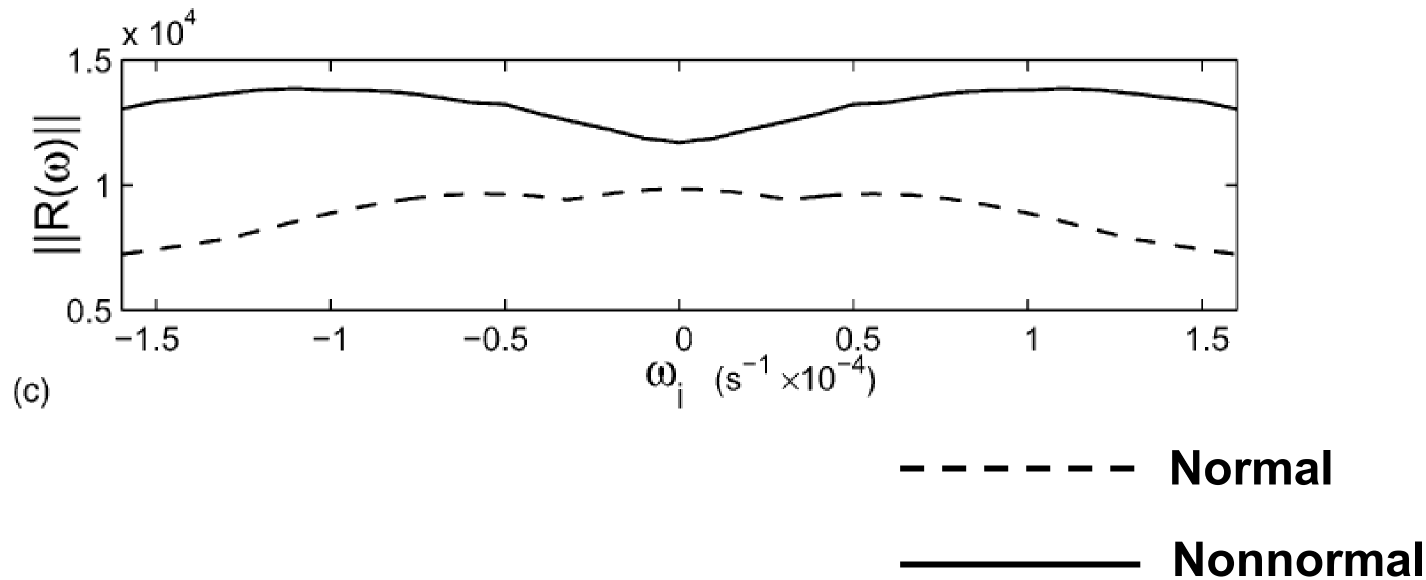
Subcritical Reynolds number

Resonance vs Pseudoresonance



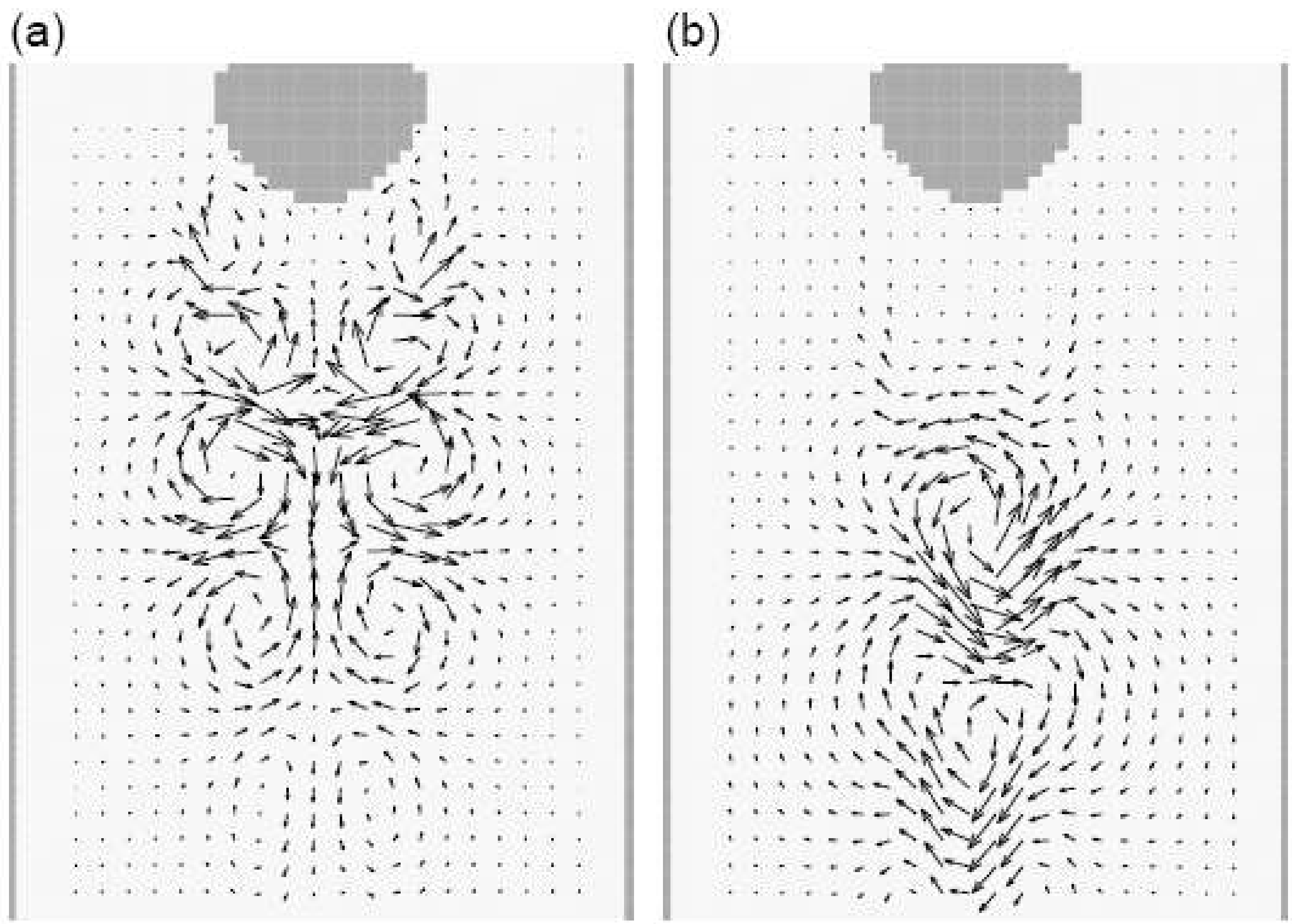
Pseudoresonance





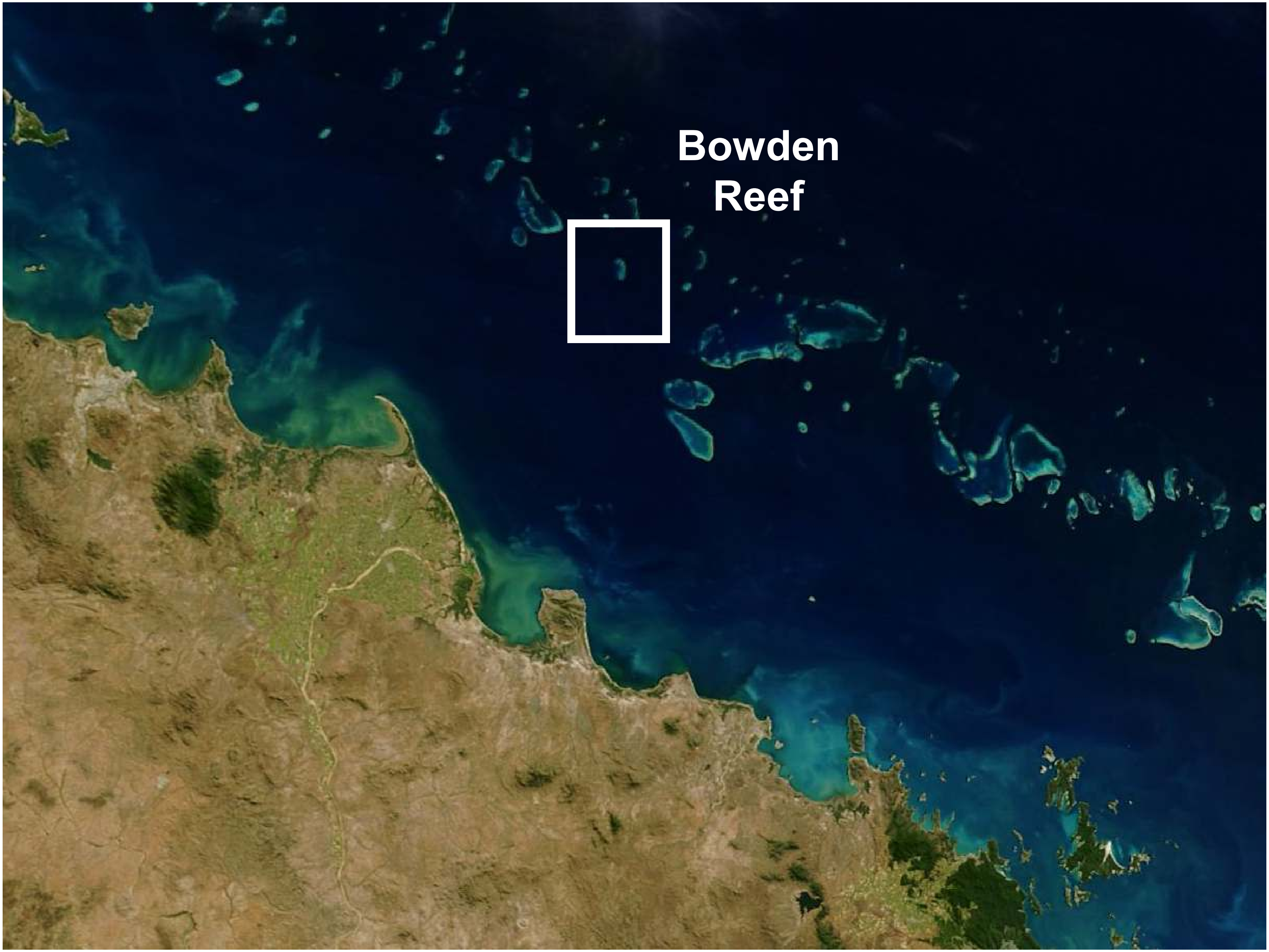
Pseudoresonance

Leading EOF in presence of stochastic forcing

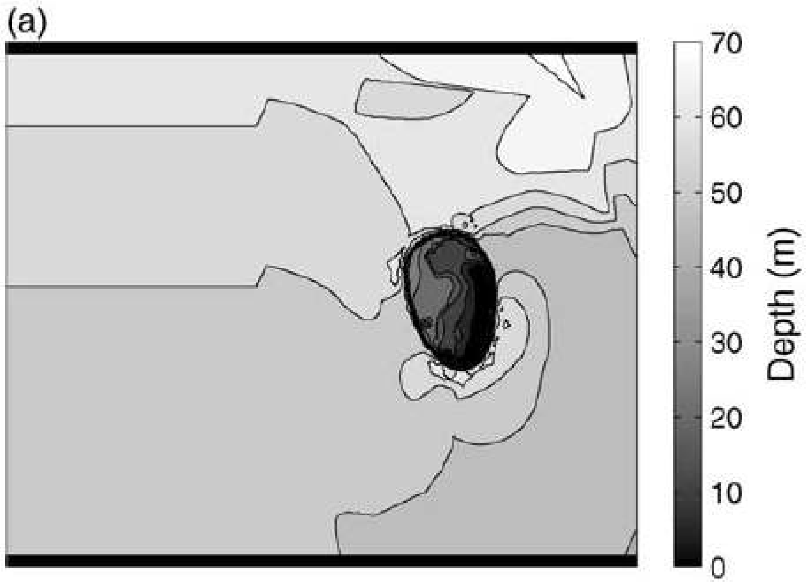


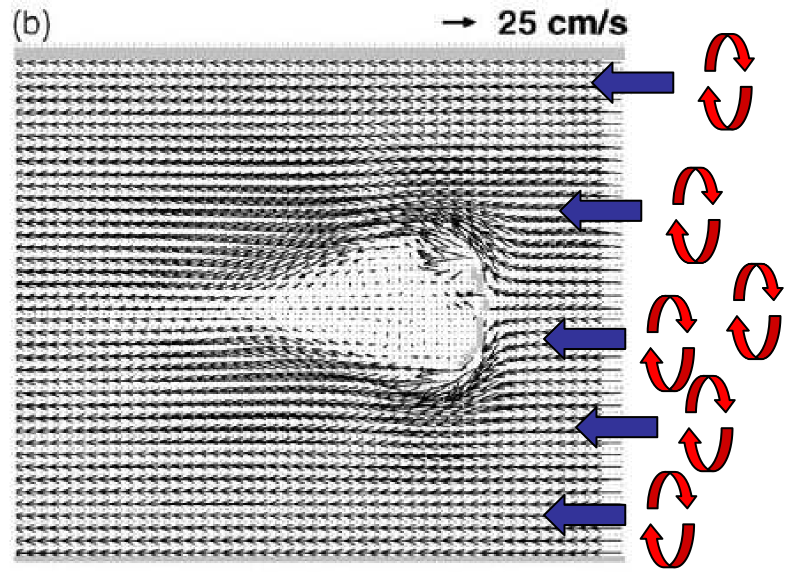
Symmetric forcing

Asymmetric forcing

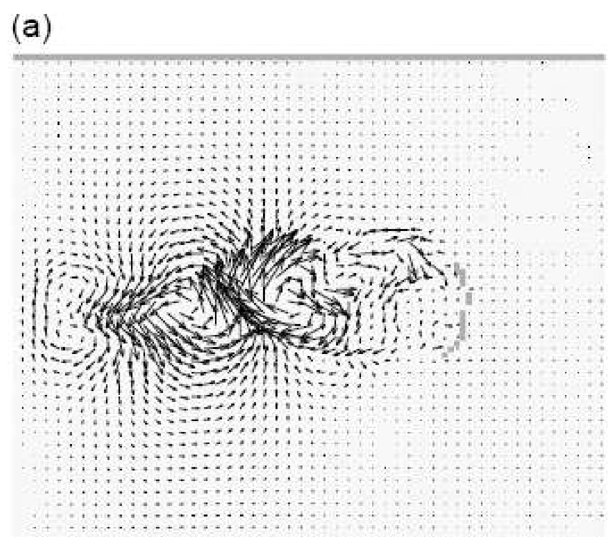

Bowden
Reef

Steady incident flow

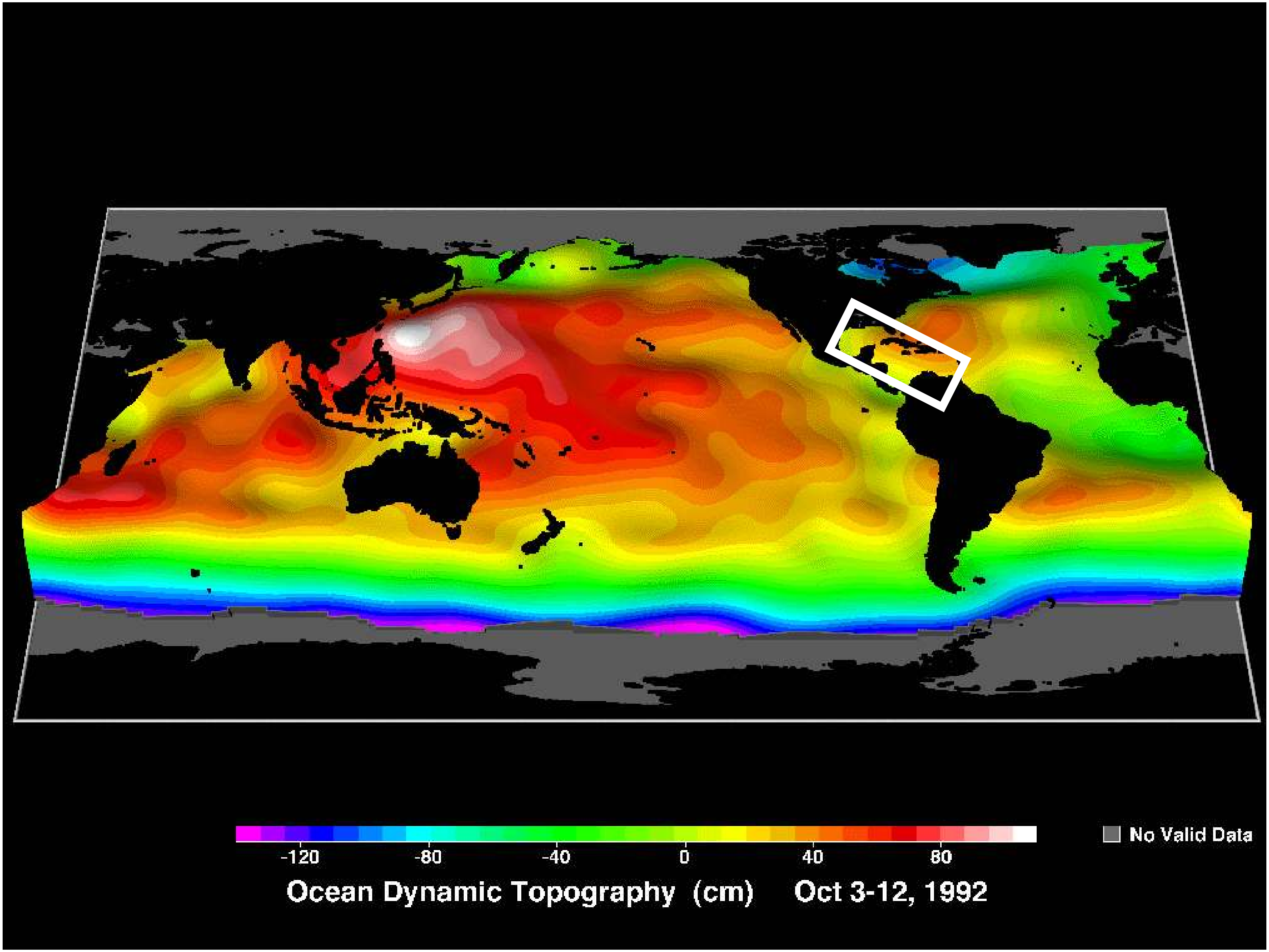




Bowden Reef



Leading EOF with stochastic forcing



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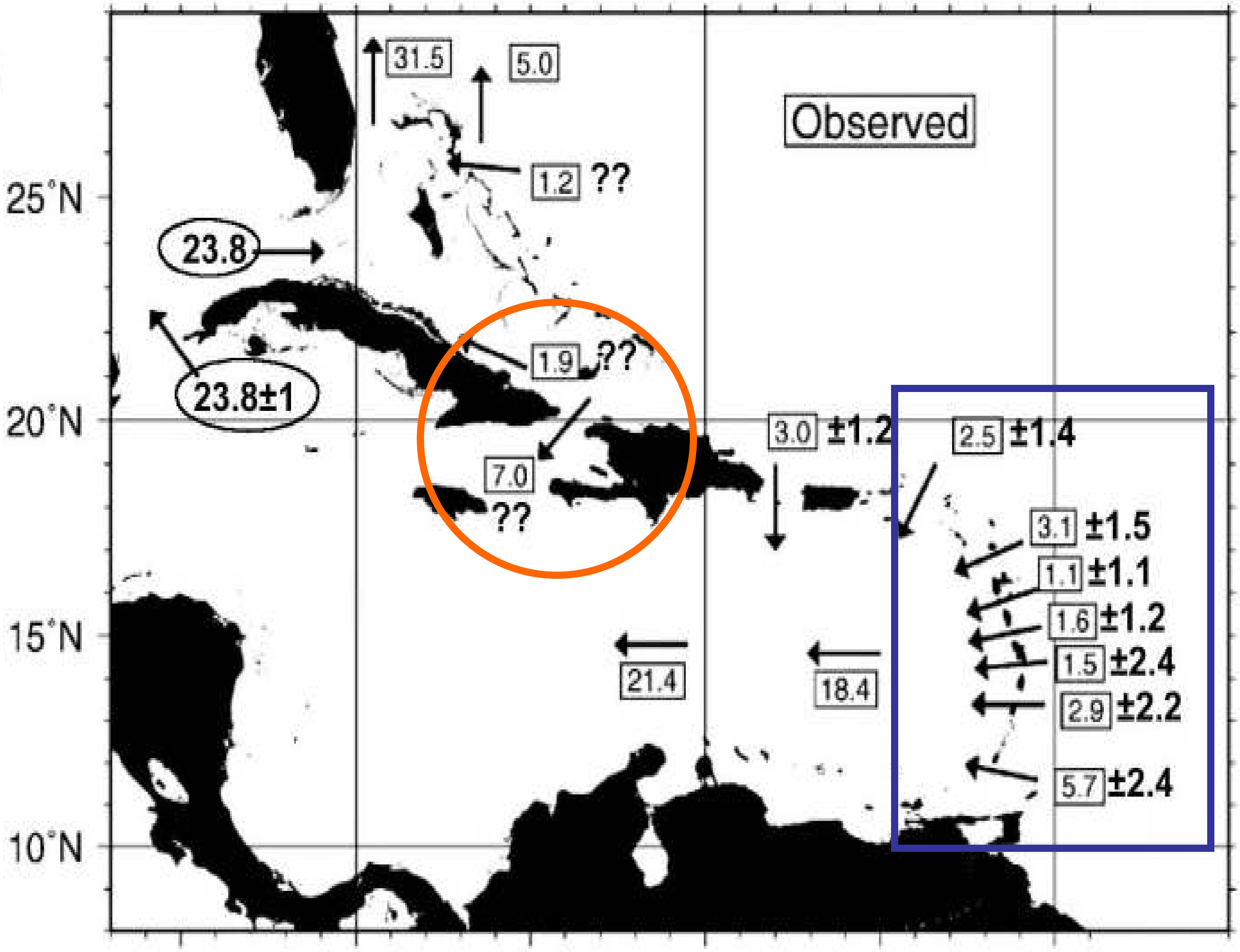
Ocean Dynamic Topography (cm)
Oct 3-12, 1992

Island Passage Transport Variability

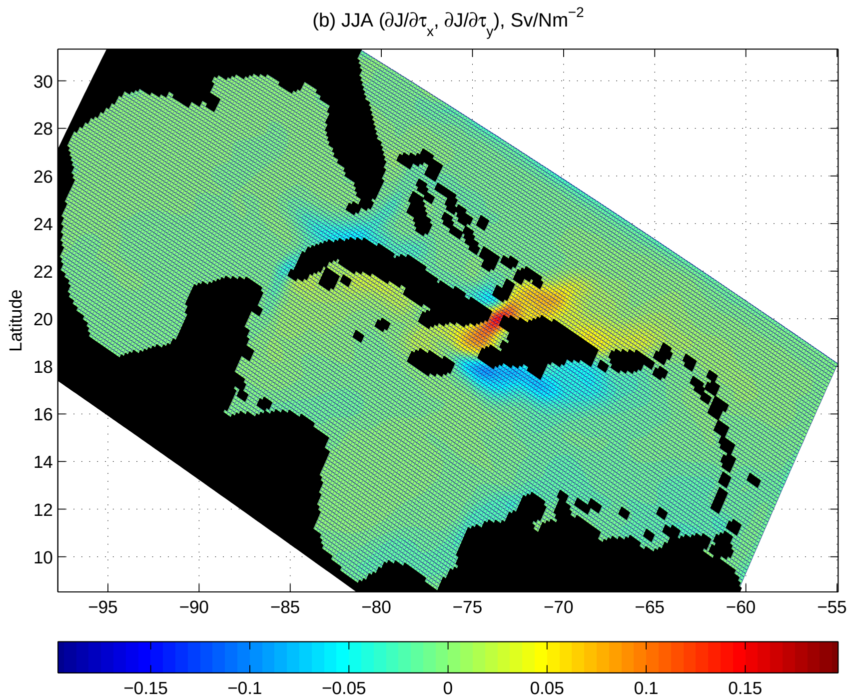


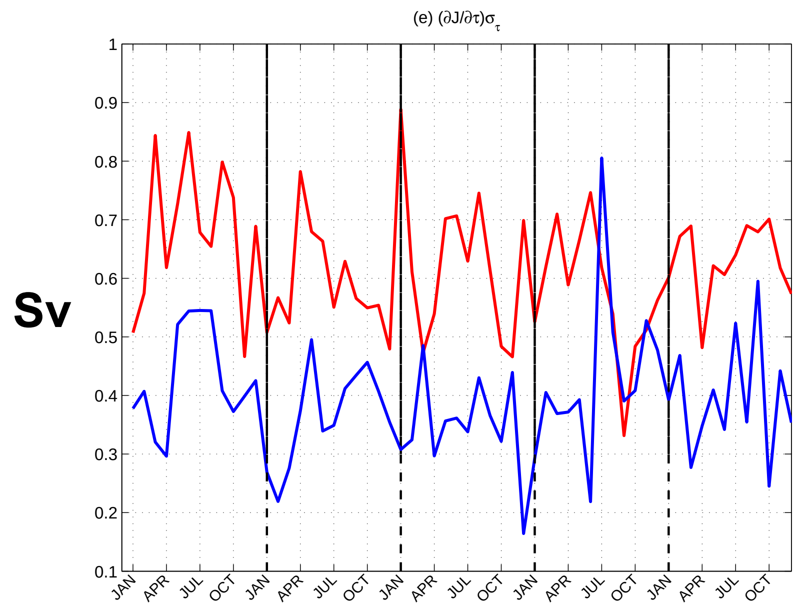
Wilson and Johns (1996)

1 Sv = 10^6 m^3 s^{-1}

Tools Used

- Adjoint sensitivity analysis
- Model: Regional Ocean Modeling System (ROMS)





Windward Passage Transport

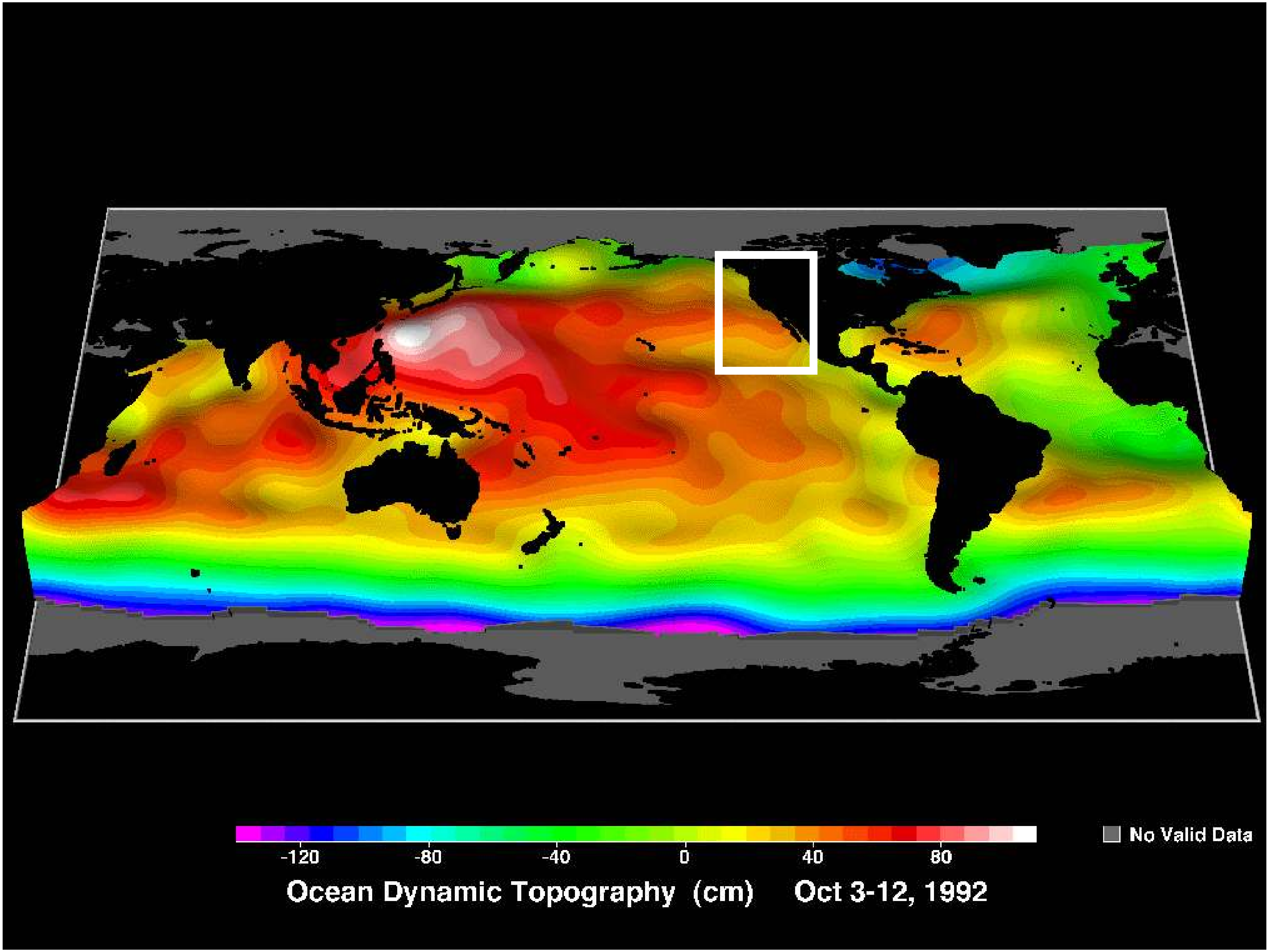
(Chhak, 2006)

Transport driven by wind variability and via coastally trapped waves

Zonal wind

Meridional wind

1 Sv = 10^6 m^3 s^{-1}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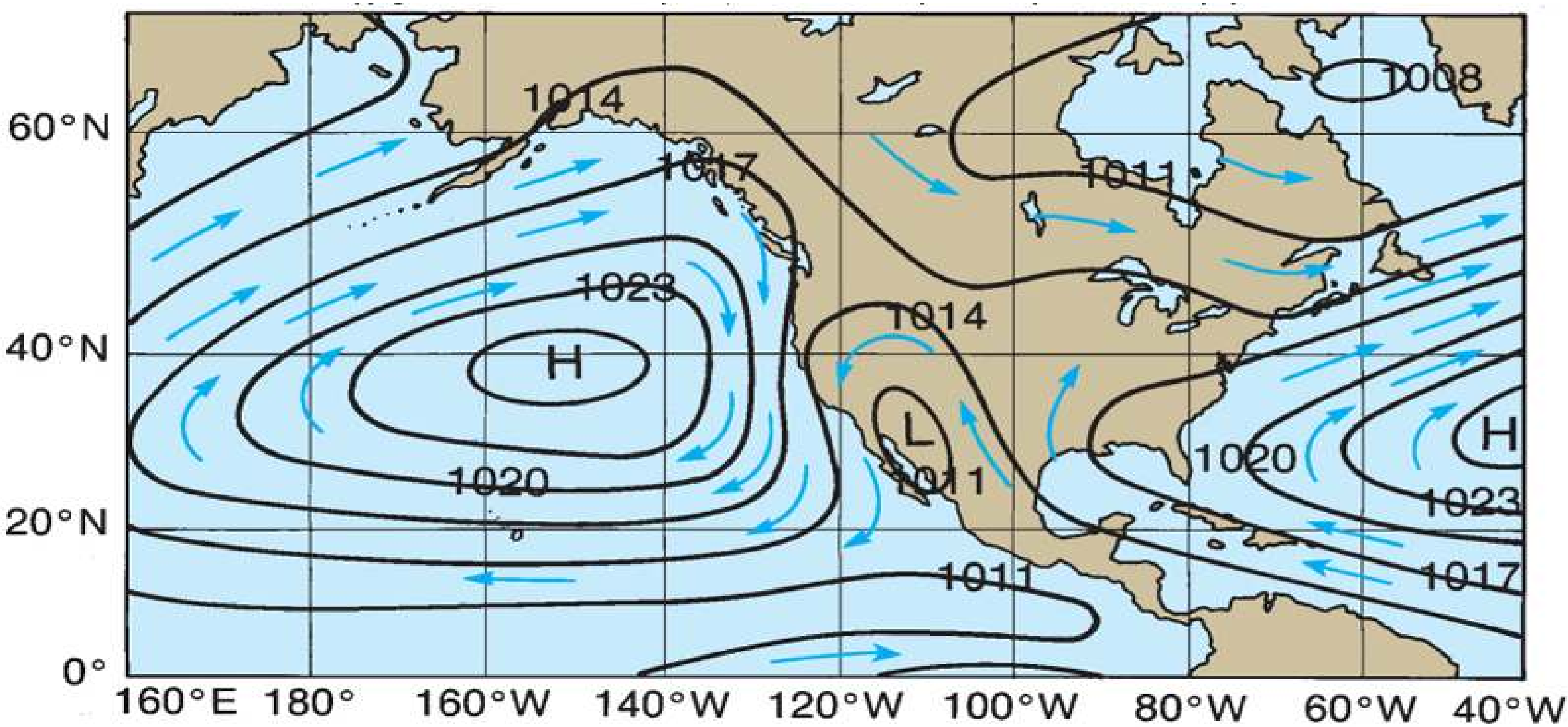
The California Current (CCS)

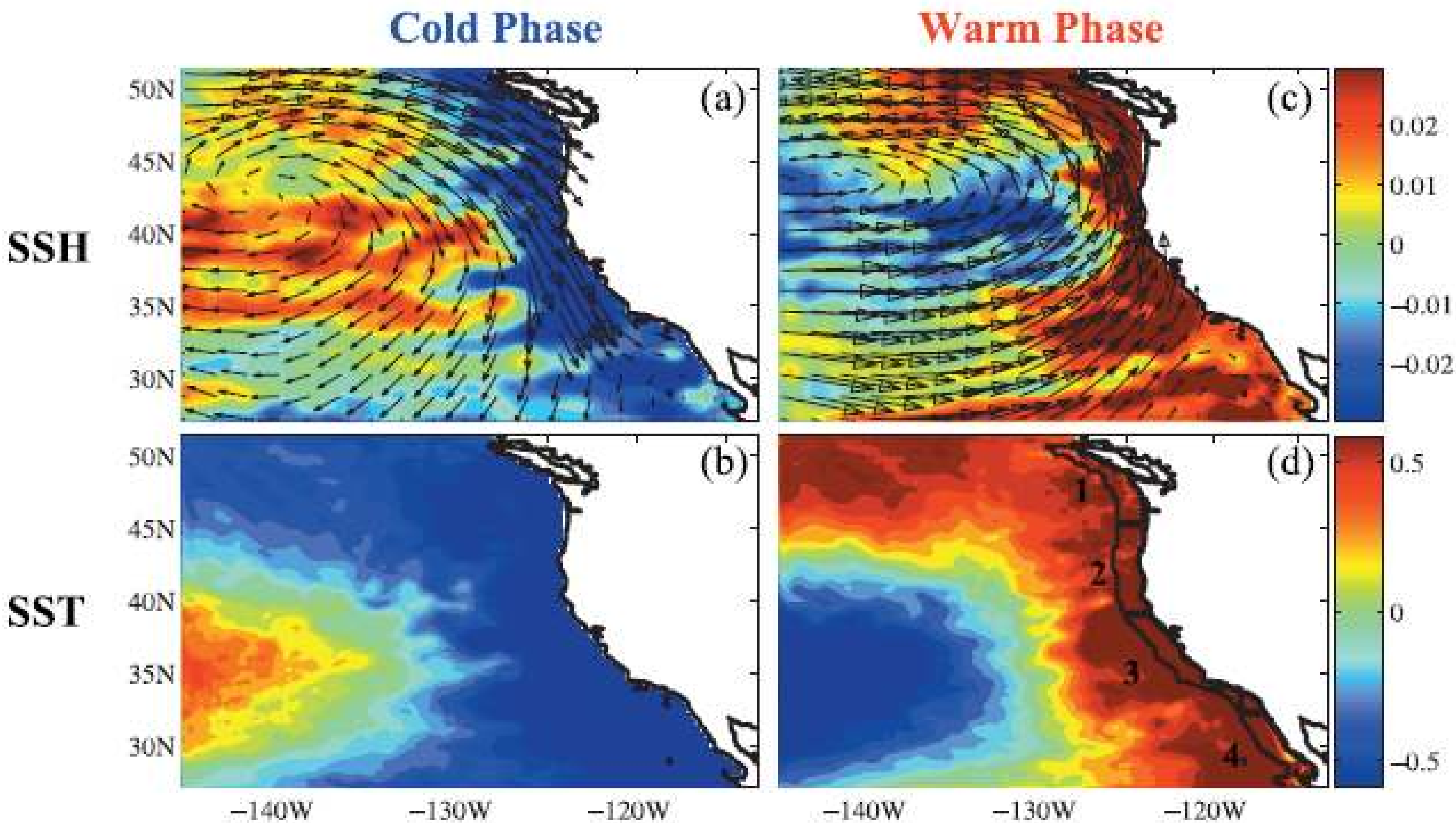


Decadal variations in California Current Upwelling Cells (Chhak & Di Lorenzo, 2007)

Tools used :

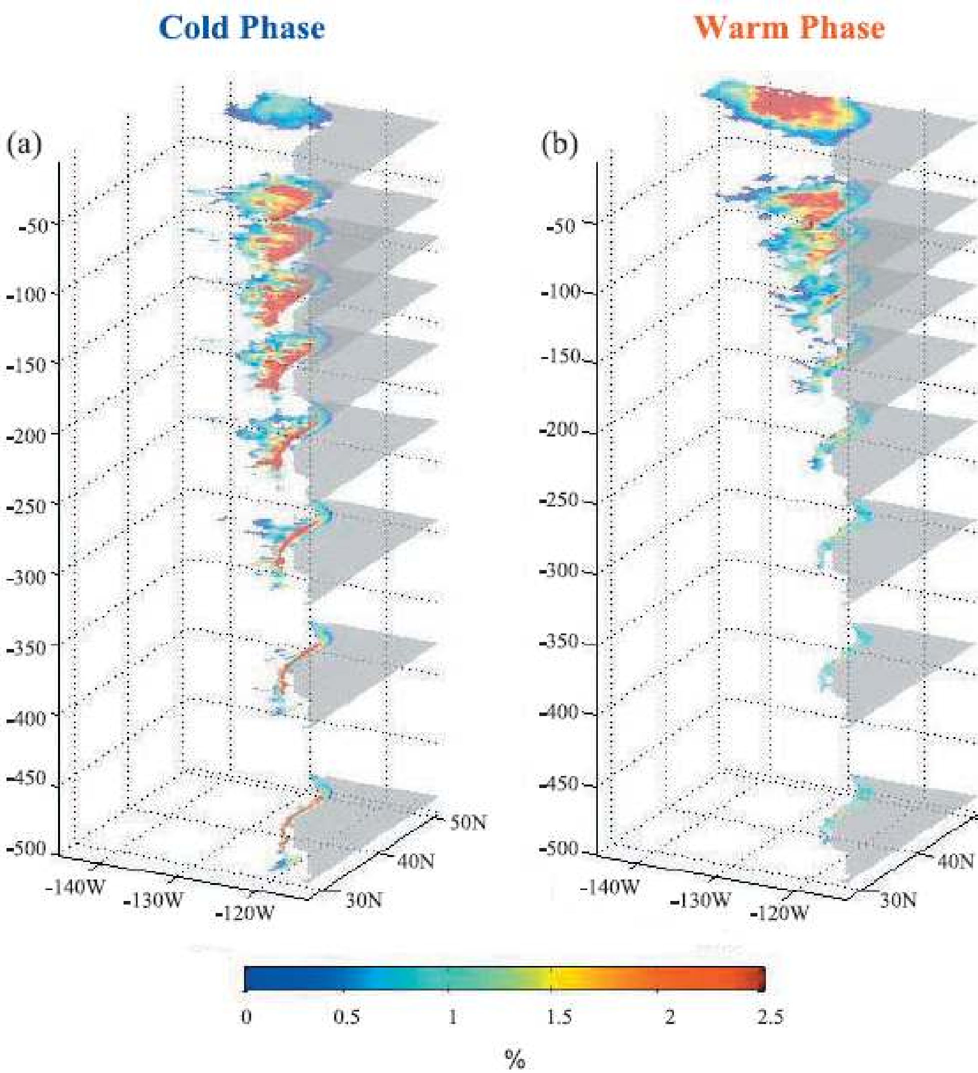
- Adjoint sensitivity analysis
- Model: Regional Ocean Modeling System (ROMS)

Decadal variations in California Current Upwelling Cells
(Chhak & Di Lorenzo, 2007)



Pacific Decadal Oscillation (PDO)

Passive tracer introduced mid-April each year (55 yrs); adjoint run for 1 yr



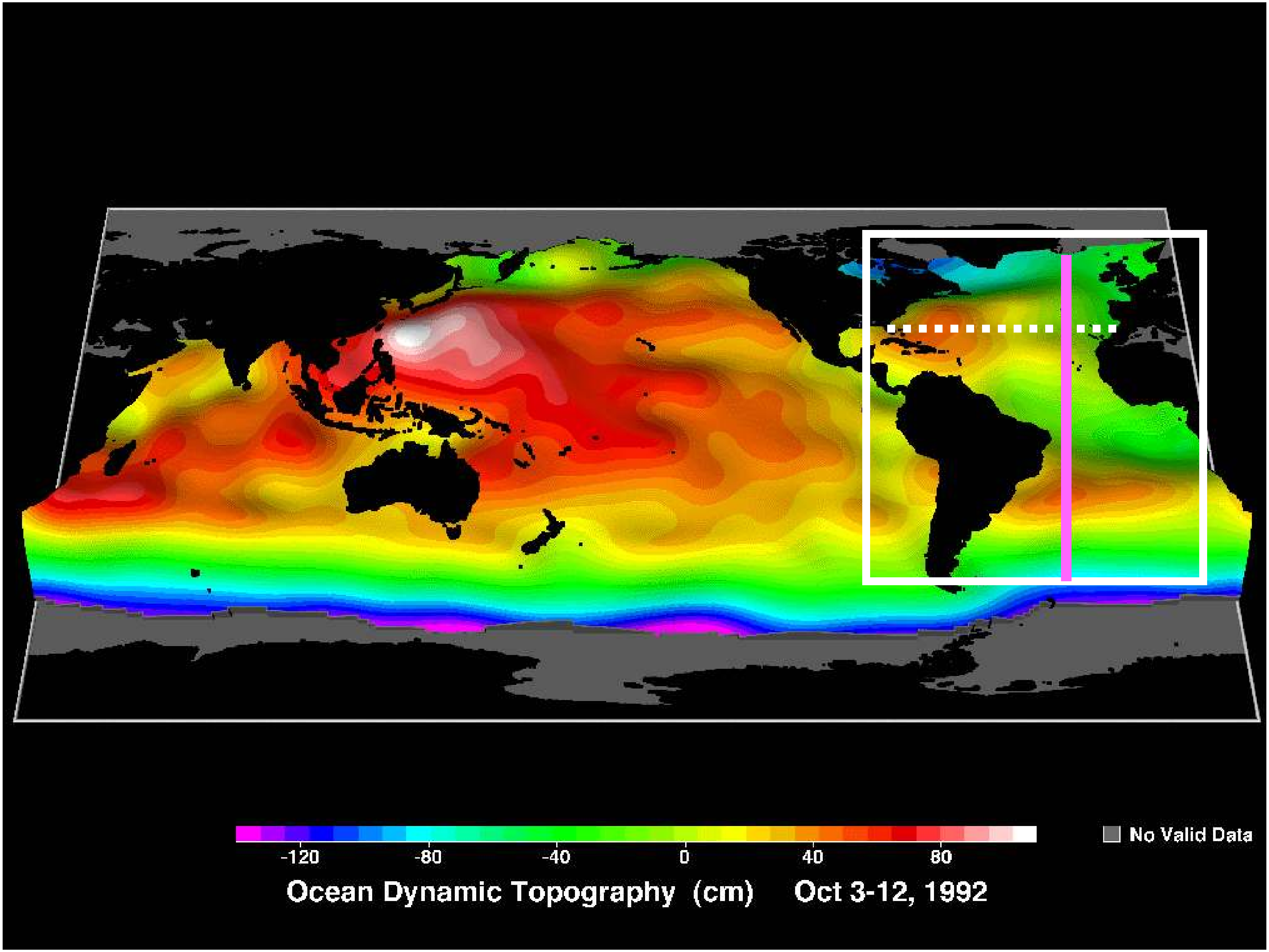
Cold phase: deeper source of upwelled, nutrient rich water.

↓

Supported by observations of phytoplankton & zooplankton

Origin of upwelling waters 1 yr prior to following year upwelling max.

Chhak & Di Lorenzo (2007)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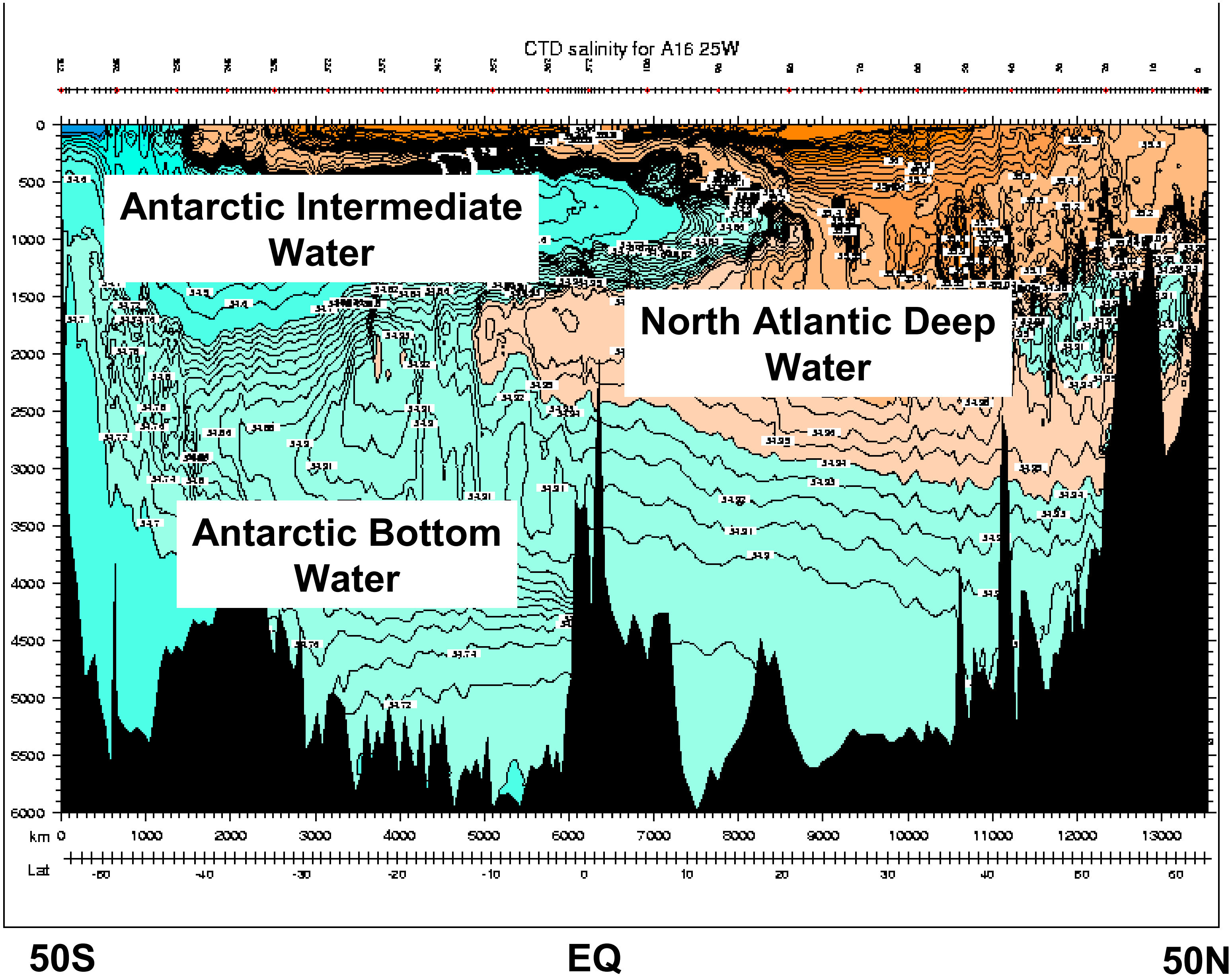
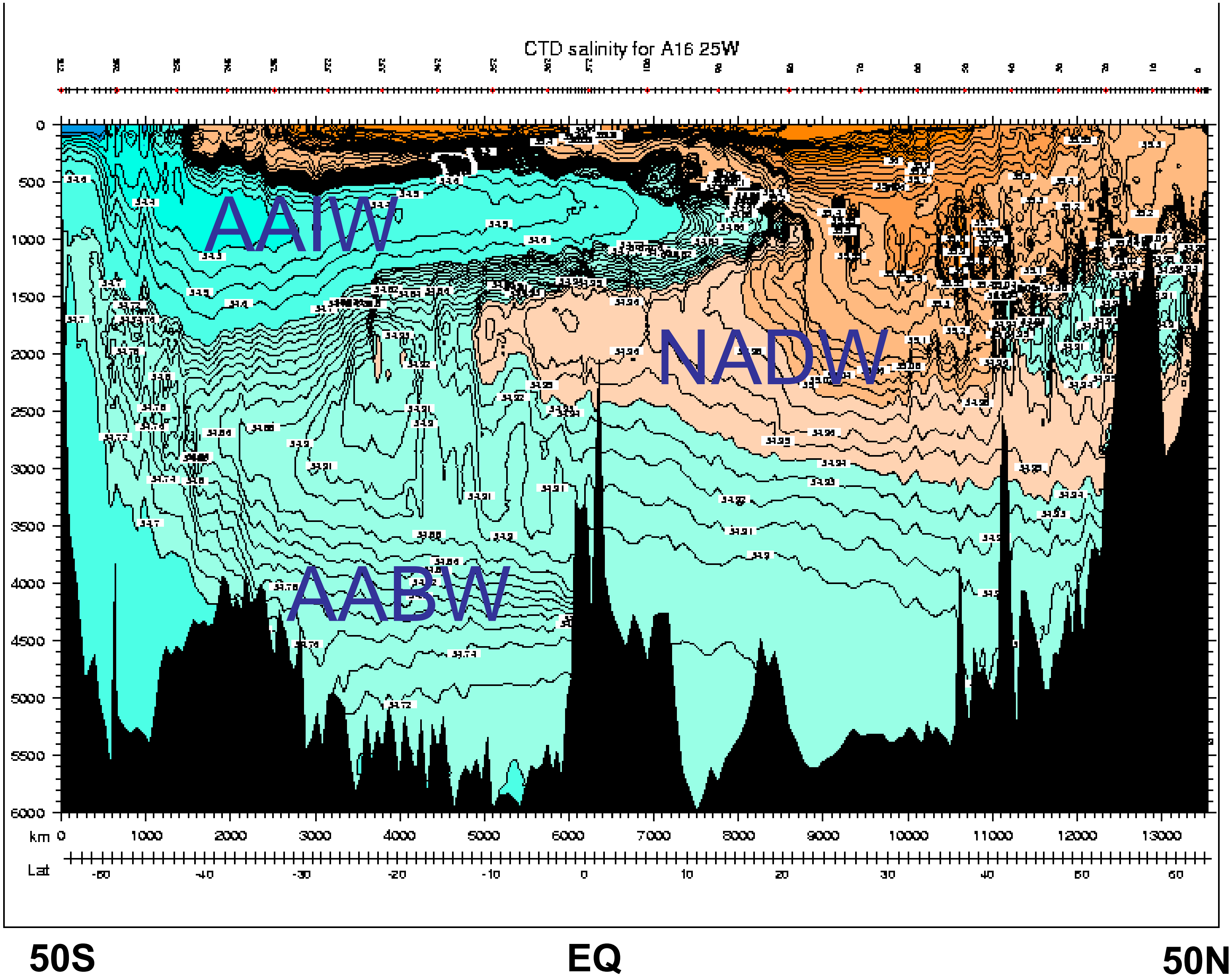
Ocean Dynamic Topography (cm) Oct 3-12, 1992

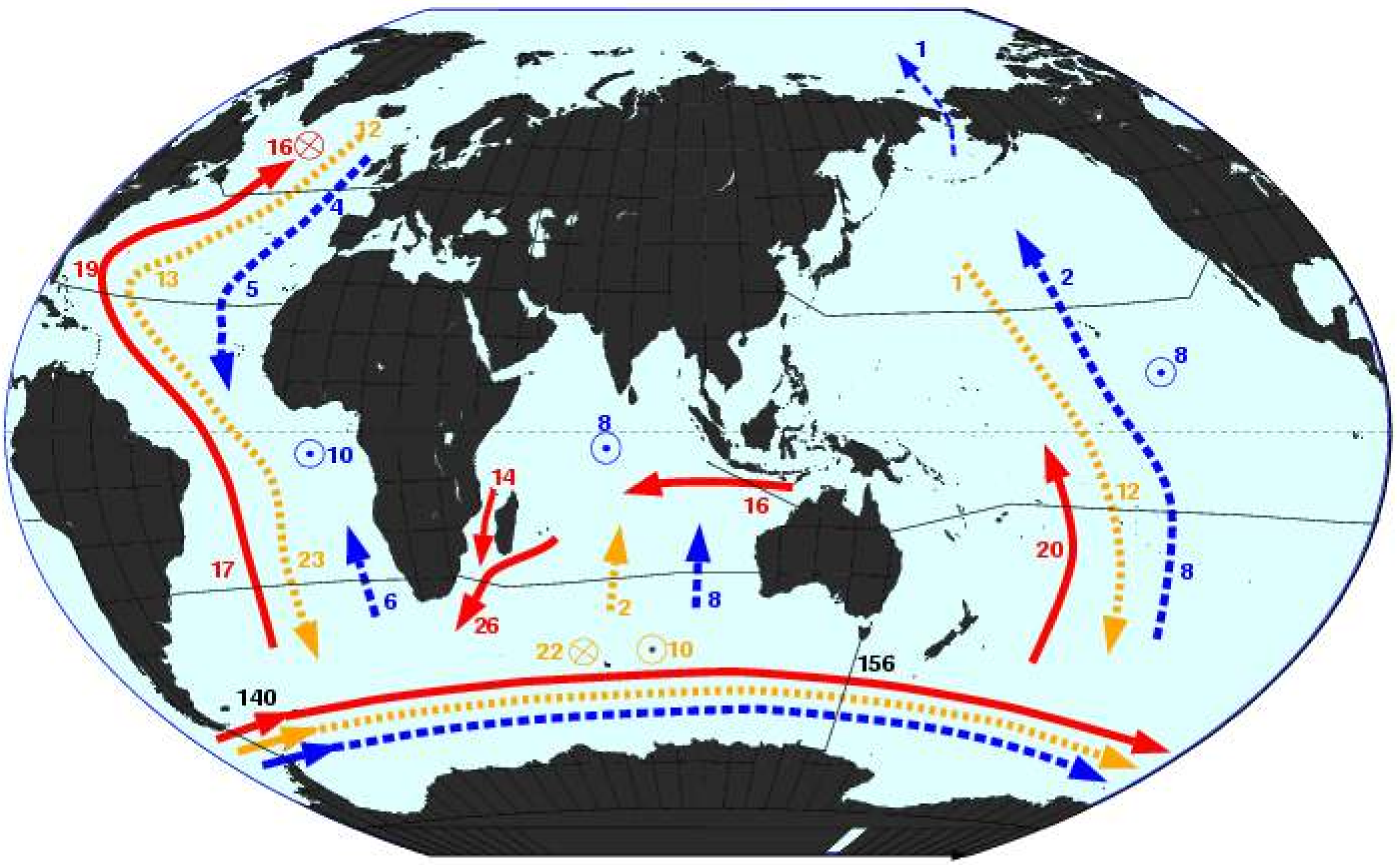
Observed Salinity Section Along 25W showing NADW, AAIW and AABW



Observed Salinity Section Along 25W showing
NADW, AAIW and AABW



Meridional Mass Transport Inferred from WOCE lines



shallow; intermediate; deep

WOCE line

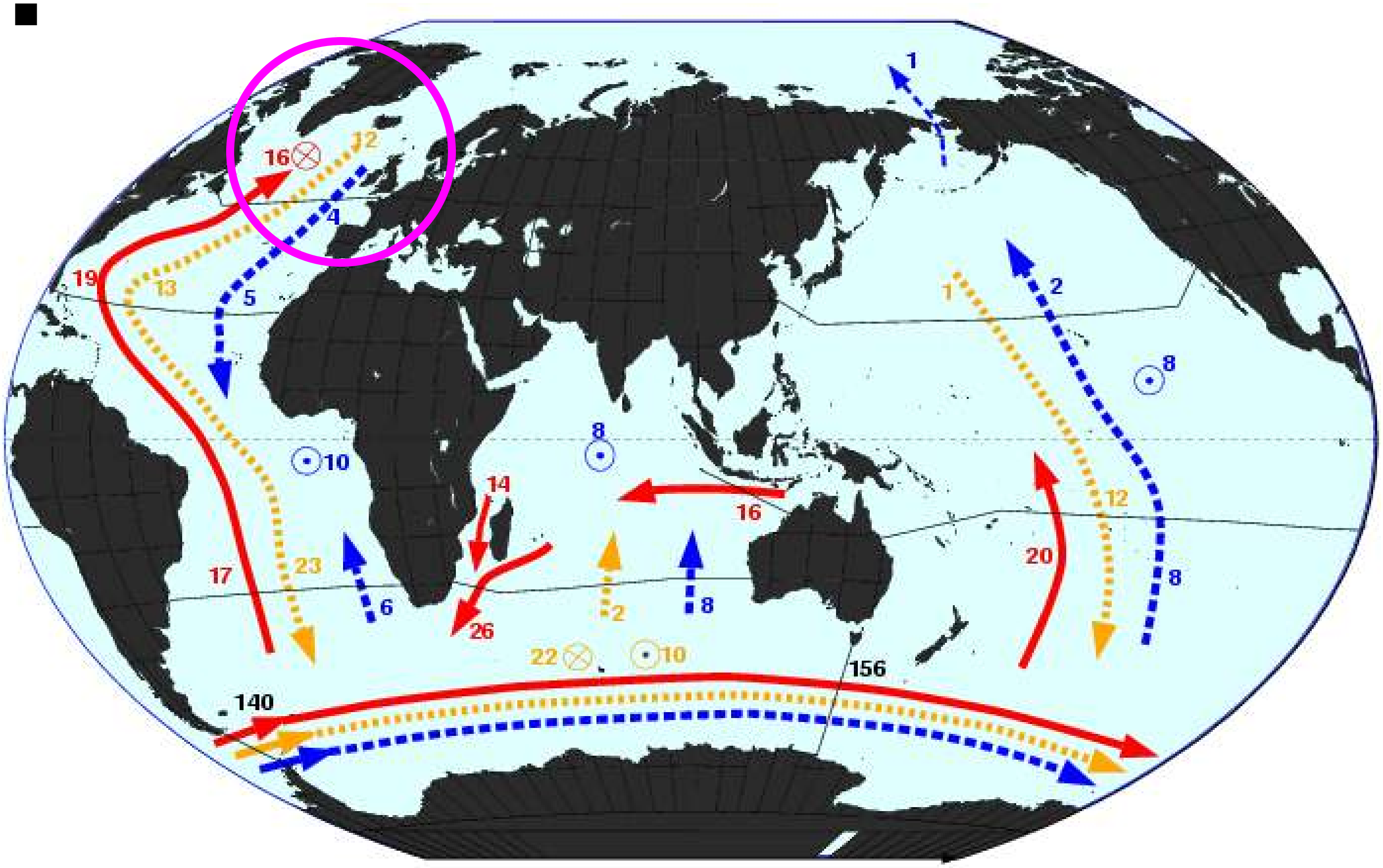
(Talley)

0 %

Loading

Dansgaard-Oeschger events
(MOC shutdowns)

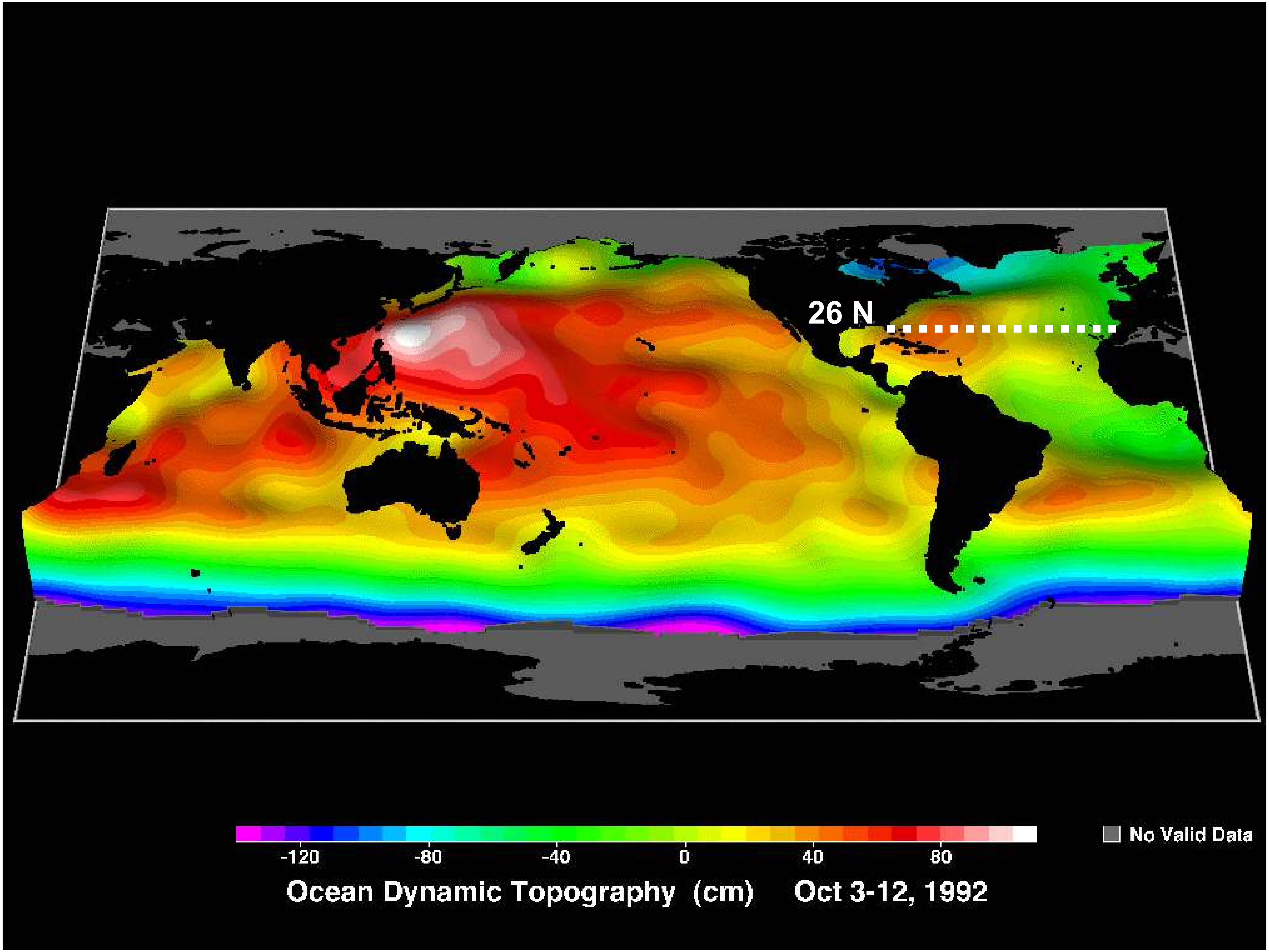
?



Estimated Decadal Changes in the North Atlantic Meridional Overturning Circulation and Heat Flux 1993-2004 (Wunsch & Heimbach, 2006)

Tools used :

- 4D-Var data assimilation
- Estimating the Circulation and Climate of the Ocean (ECCO)
- Model: MITgcm – global, 1 degree



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Estimated Decadal Changes in the North Atlantic Meridional Overturning Circulation and Heat Flux 1993-2004 (Wunsch & Heimbach, 2006)

11 yr assimilation, using all data, free run with adjusted surface fluxes

1 Sv = 10^6 m^3 s^{-1}

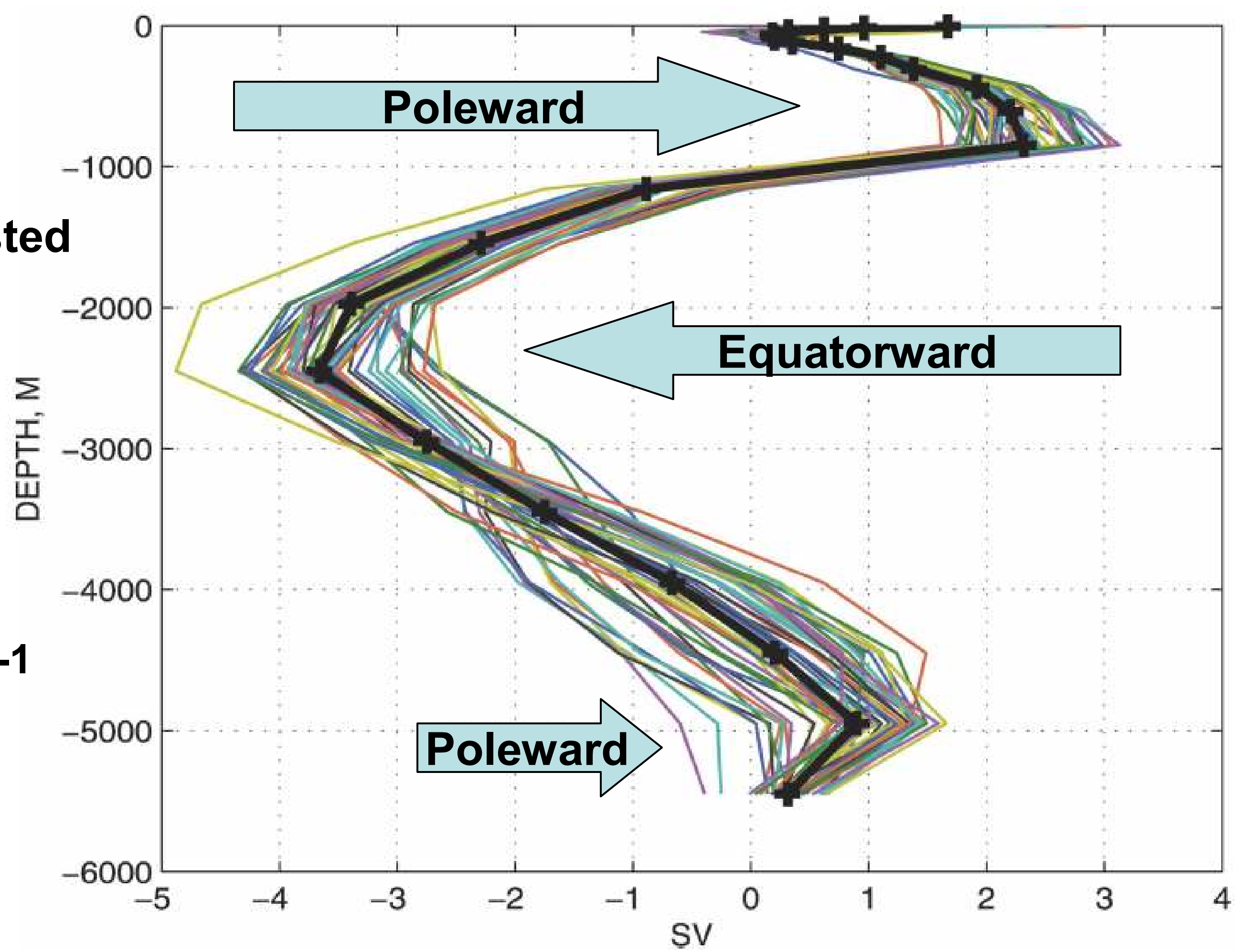


FIG. 3. Zonal integrals (Sv) of the North Atlantic seasonally averaged (3-month mean) velocity fields multiplied by the appropriate layer thickness as a function of depth. There is a near-zero value close to 1165-m depth. Plus signs and heavy line denote the time-mean values.

Estimated Decadal Changes in the North Atlantic Meridional Overturning Circulation and Heat Flux 1993-2004 (Wunsch & Heimbach, 2006)

-0.19 ± 0.05 Sv yr^{-1}

↓ **12 yrs**

-2.3 ± 0.6 Sv

(consistent with direct obs)

Cause? Unknown

Secular or indefinite?

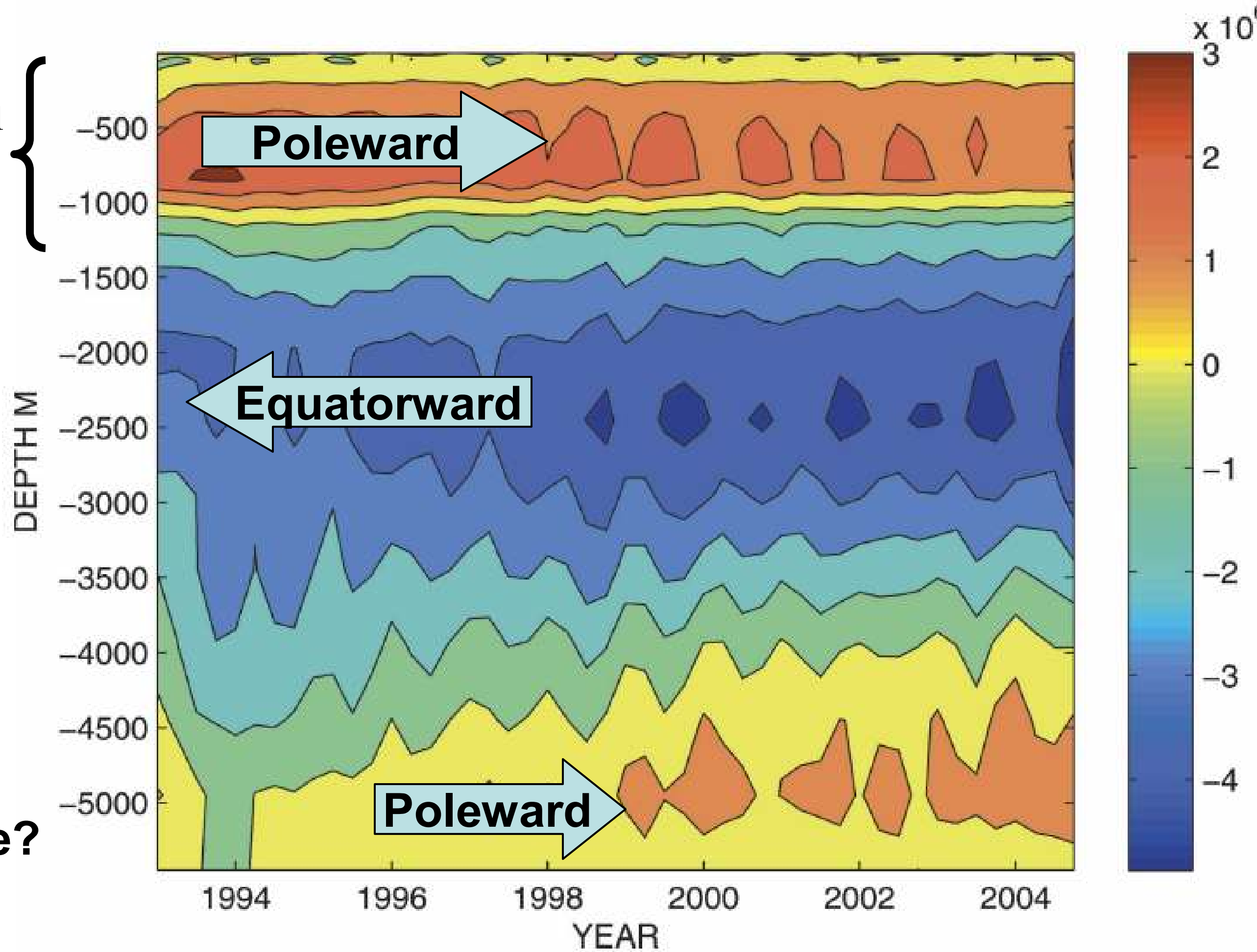


FIG. 9. Seasonal averages (3 months) of volume transport contours ($m^3 s^{-1}$) through time as a function of depth (another rendering of the profiles in Fig. 3).

Sensitivity of MOC to Surface Forcing

- Dansgaard-Oeschger events (MOC slow-downs)
- 0D models: Tziperman & Ioannou (2002)
- 2D models: Alexander & Monahan (2009)
- 3D idealized: Sévellec et al (2009); Zanna et al (2009)

↓

Singular vectors

↓

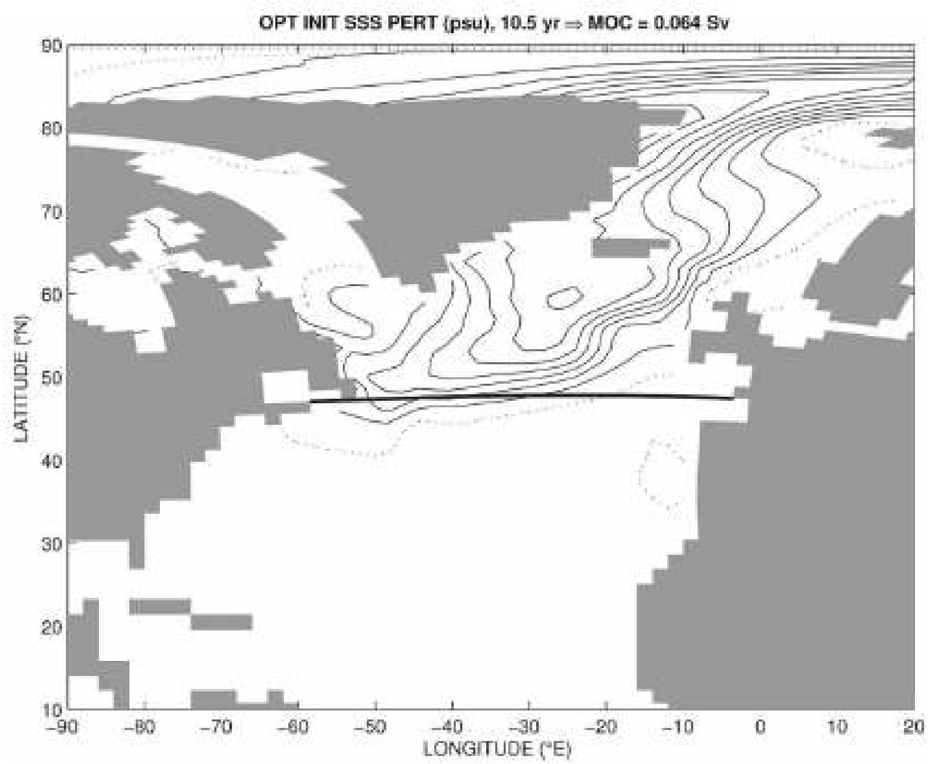
Nonnormal dynamics associated with horizontal and vertical advection

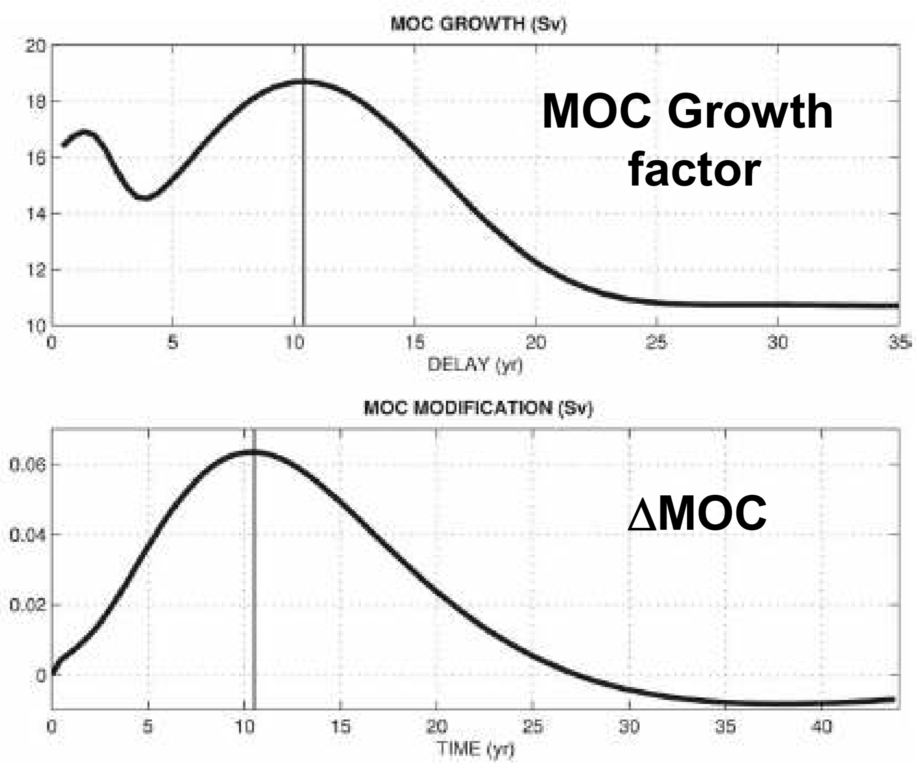
Optimal Surface Salinity Perturbations of the Meridional Overturning and Heat Transport in a Global Ocean General Circulation Model (Sévellec et al, 2008)

Tools used :

- Adjoint sensitivity analysis
- Model: OPA – global 2 degree

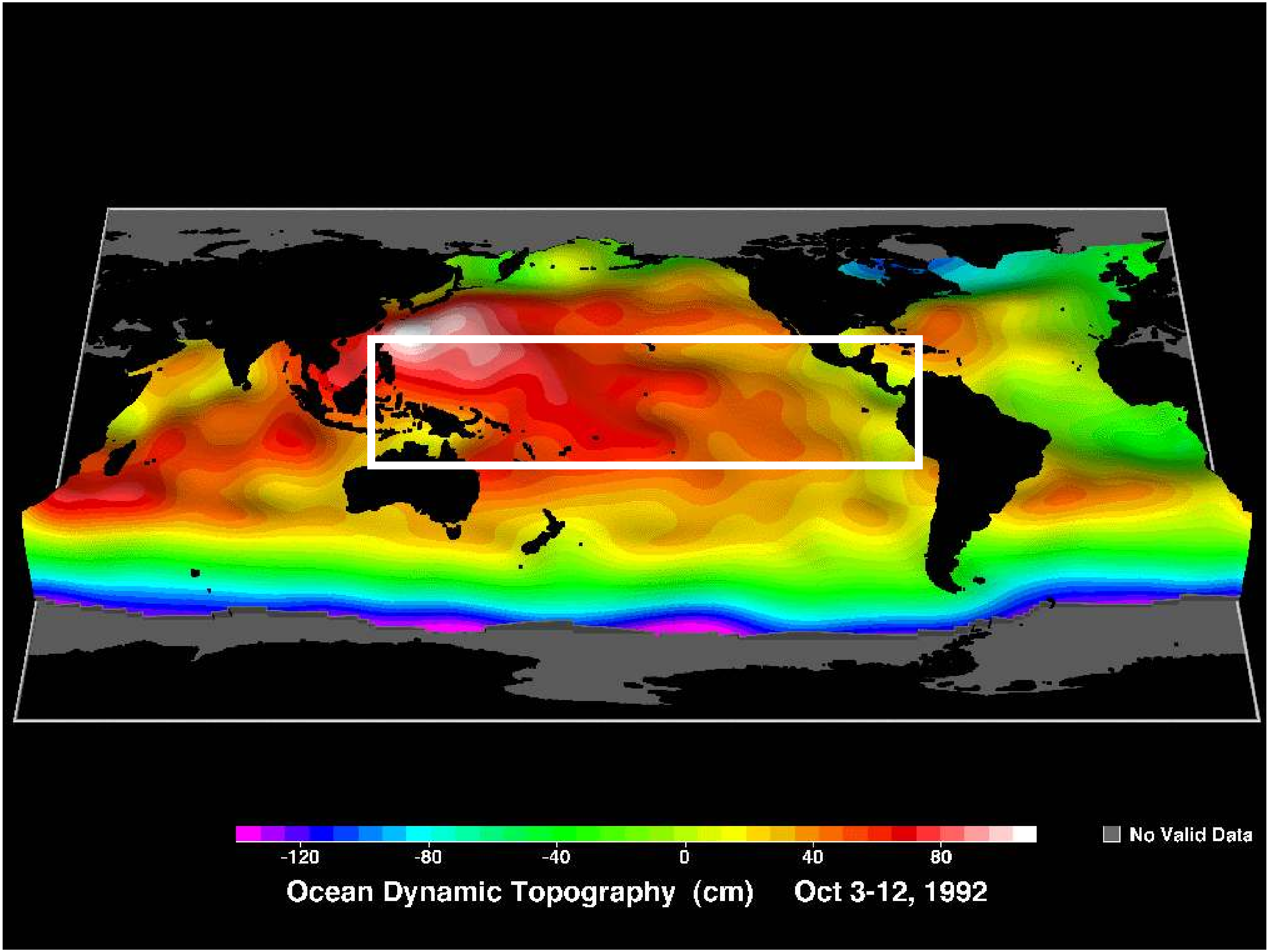
Optimal Surface Salinity Perturbations of the Meridional Overturning and Heat Transport in a Global Ocean General Circulation Model (Sévellec et al, 2008)





Optimal SSS Perturbation
(scaled to 1 psu amp.)

Upper bounds based on GSA:
~0.8 Sv (11% of mean)
~0.03 Pw (5% of mean)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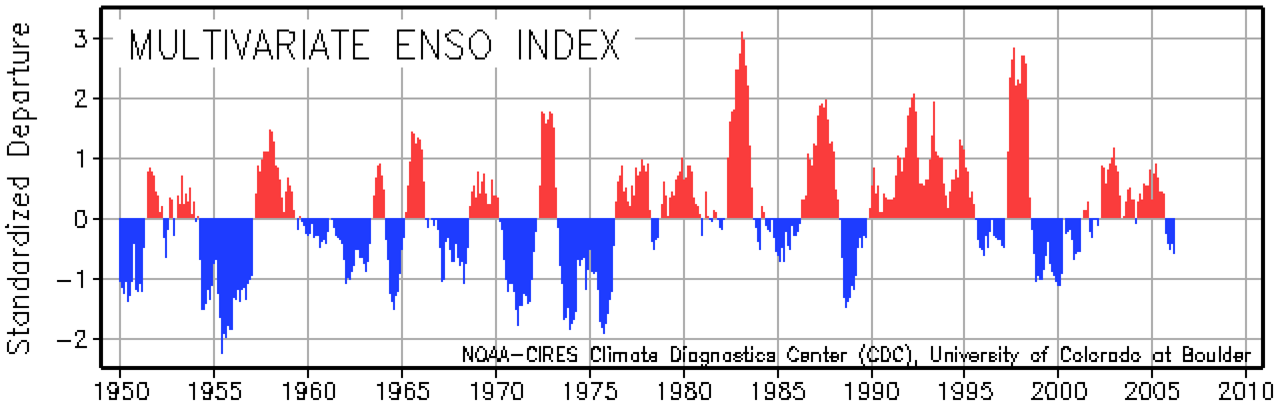
ENSO Irregularity



- The irregular nature of ENSO necessitates arguments related to nonlinearity or stochastic forcing.
- Most current theories of ENSO fall into two categories:

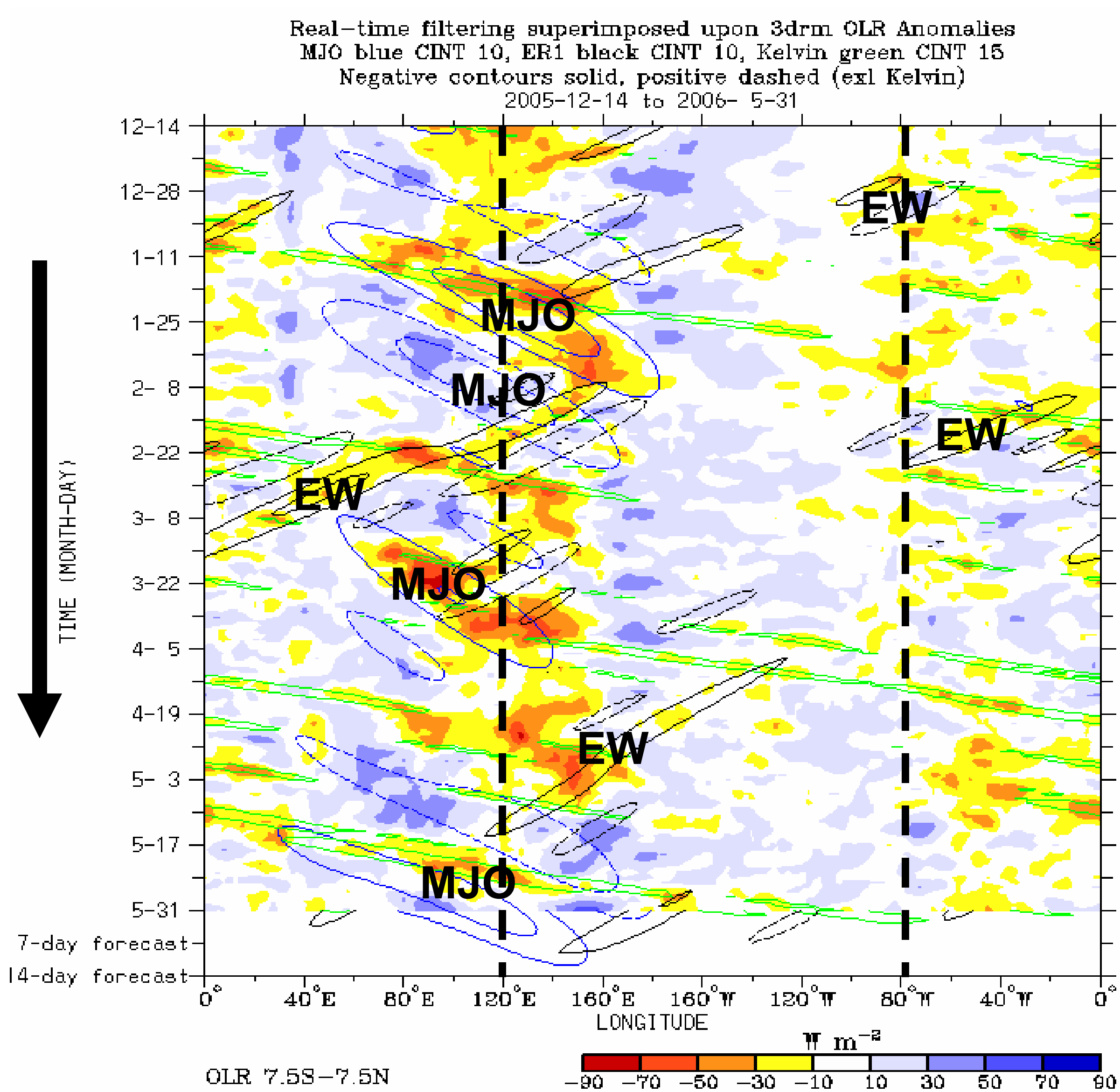
  (1) nonlinear

  (2) linear stochastically forced

Tropical Stochastic Forcing

MJO = Madden-Julian Oscillation

EW=Easterly Wave



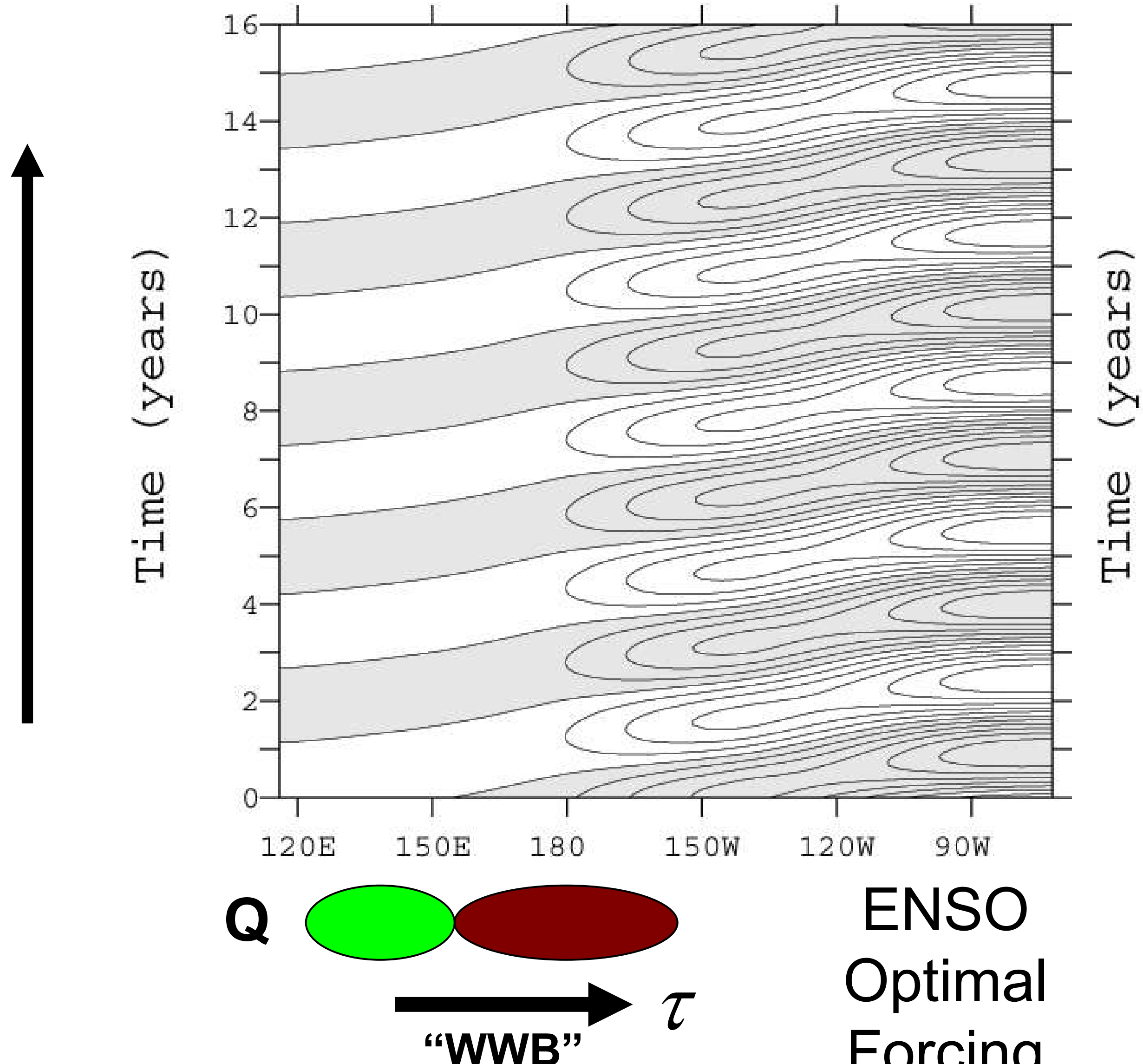
An Important Question

- Are the spatial and temporal characteristics of forcing important, or will any old forcing do the trick?
- In other words, are some forcings more efficient than others for exciting ENSO?
- The answer depends on the *nonnormality* of the dynamics.

Tools Used

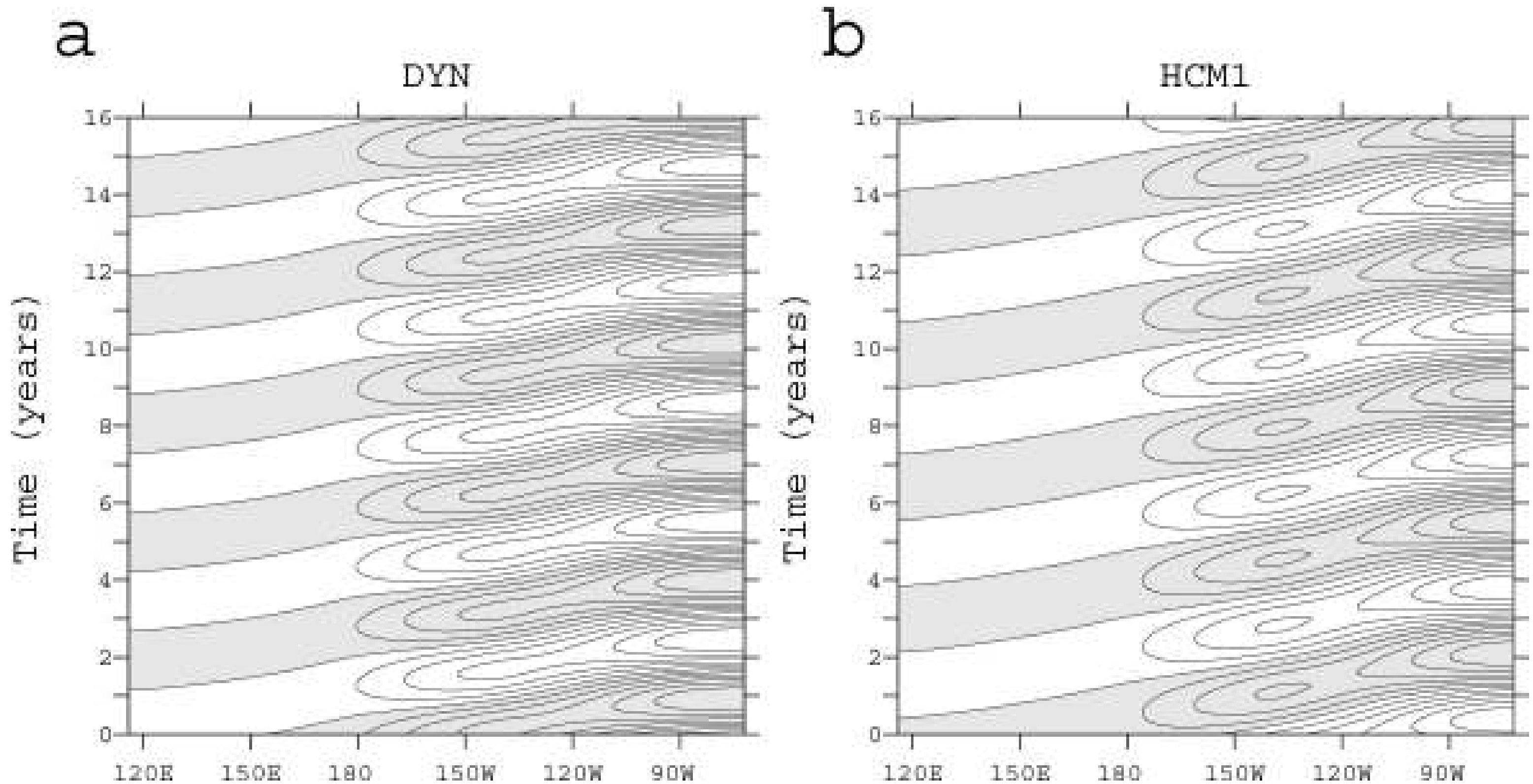
- Singular value decomposition & pseudospectra
- Models: intermediate & hybrid coupled models

Optimal Stochastic Forcing



ENSO
Optimal
Forcing

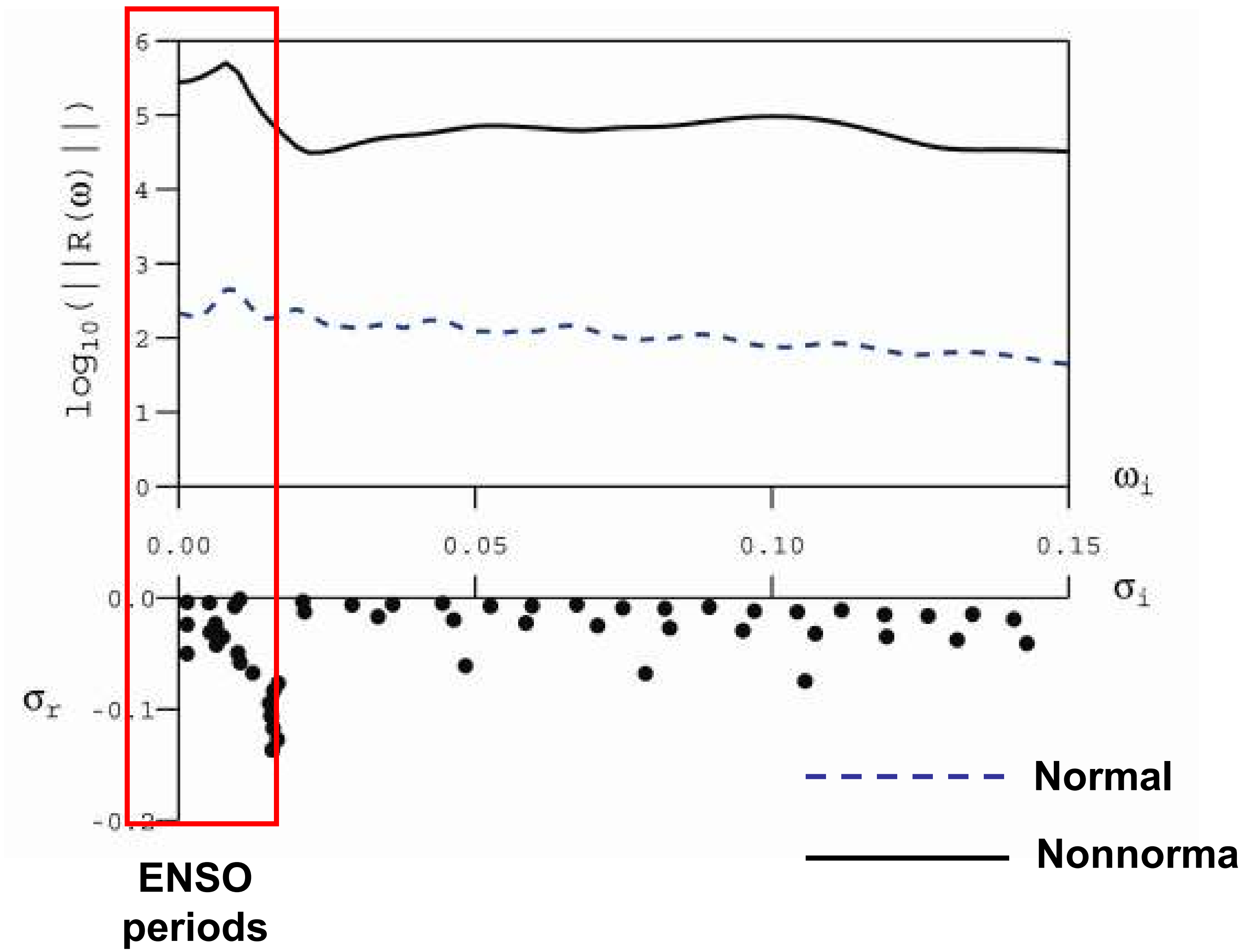
Optimal Stochastic Forcing



"More" Nonnormal

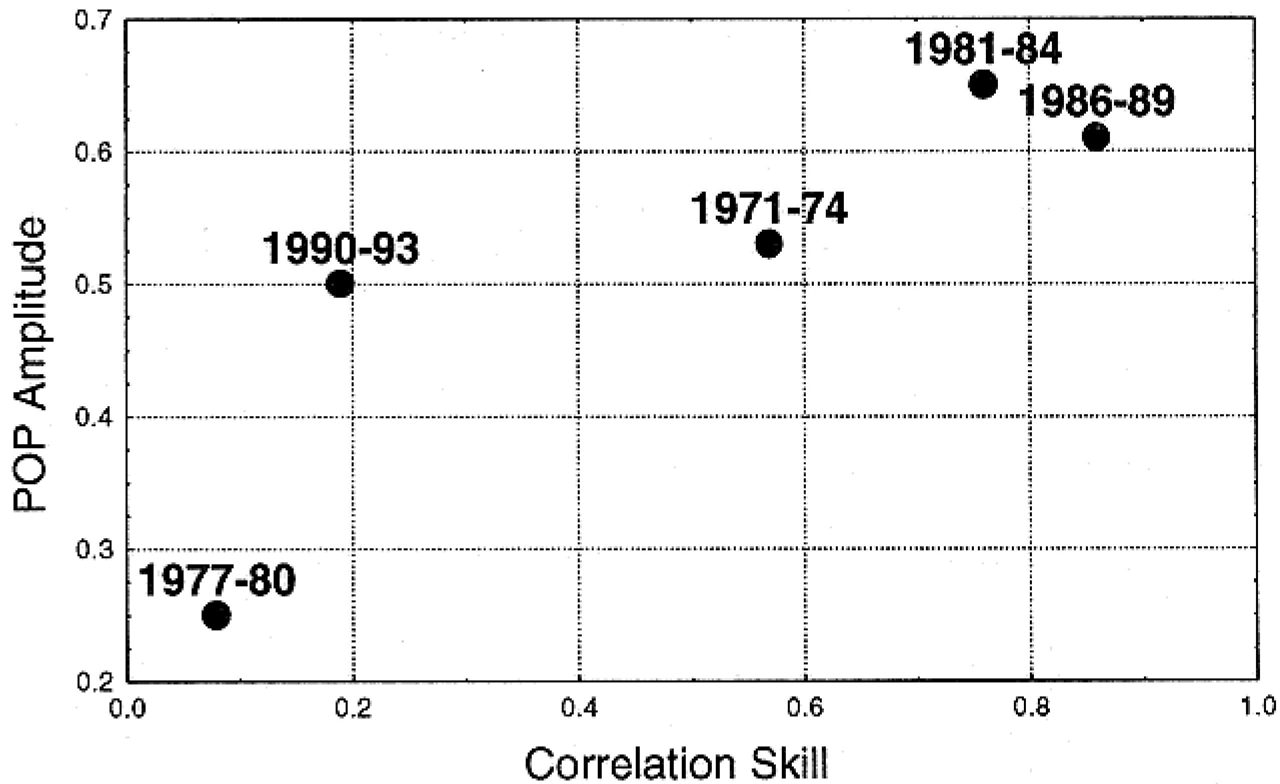
"Less" Nonnormal
("More" Normal)

Pseudoresonance

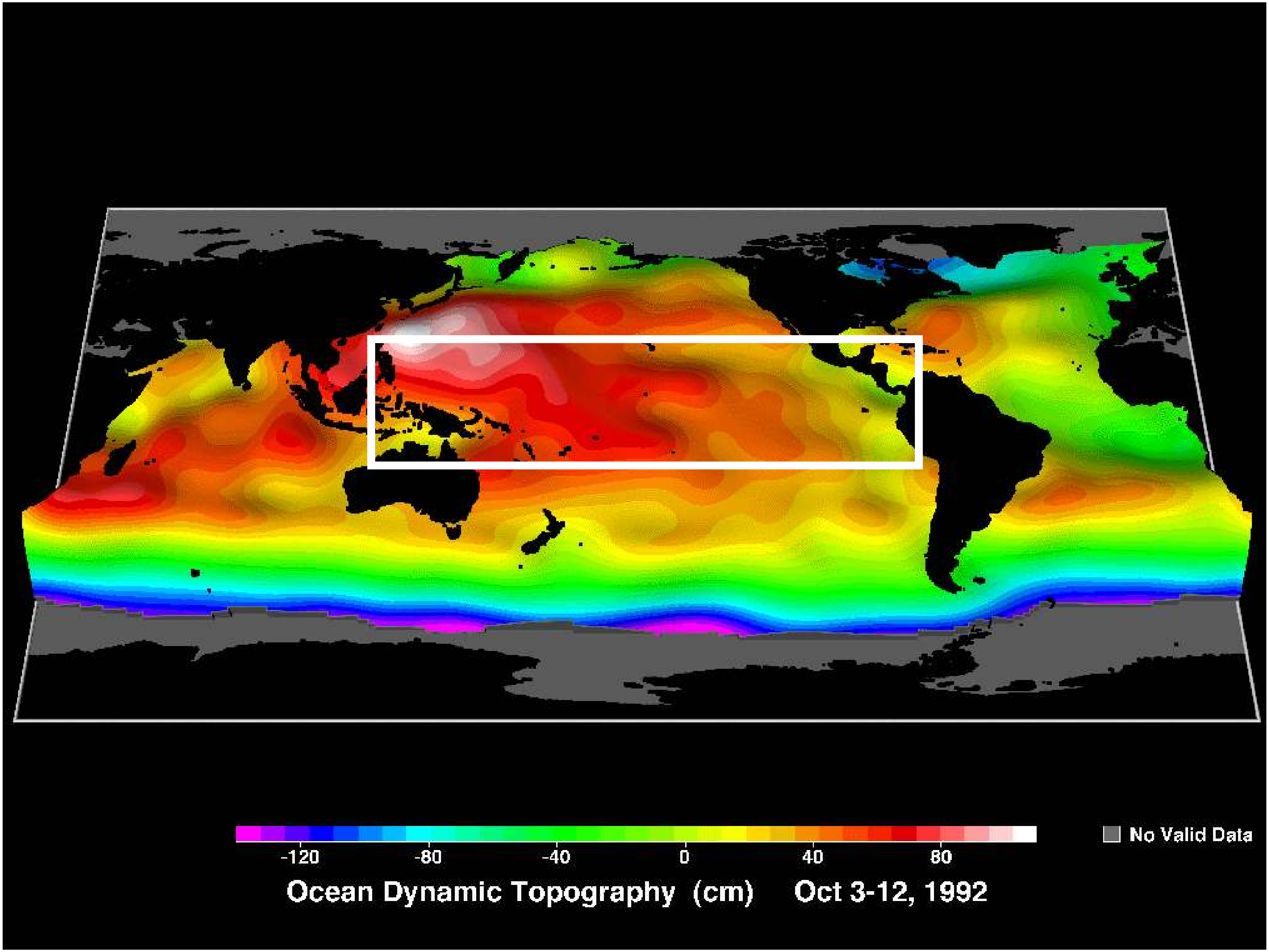


Predictability

Plot of skill versus POP amplitude for various time periods



ENSO hindcast skill is proportional to ENSO amplitude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A Midlatitude-ENSO Teleconnection Mechanism via Baroclinically Unstable Long Rossby Waves (Galanti & Tziperman, 2003)

Tools used :

- Adjoint sensitivity analysis
- Model: MOM, Pacific, 1-3 degrees

A Midlatitude-ENSO Teleconnection Mechanism via Baroclinically Unstable Long Rossby Waves (Galanti & Tziperman, 2003)

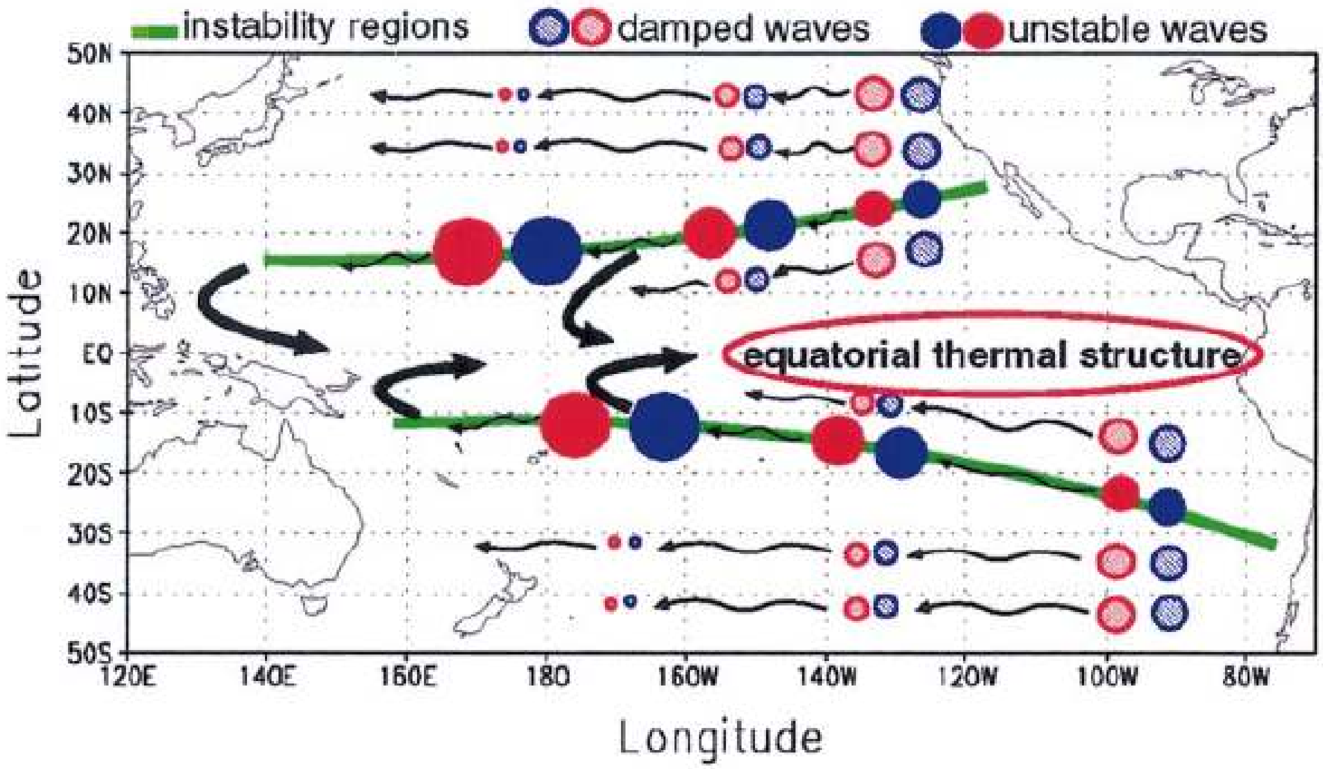

FIG. 1. A schematic figure of the mechanism proposed in this paper for a wave teleconnection from the midlatitude Pacific to the equator. Midlatitude planetary Rossby waves travel westward at all latitudes and are damped. The waves that are amplified in baroclinically unstable regions of the subtropical gyre arrive to the equator with a larger amplitude and therefore dominate the midlatitude signal there.

We really have learned a lot of “cool” things about the ocean using adjoint models!