# Ocean – Atmosphere Interaction

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# Ocean-Atmosphere Interaction

1. Tropical-Extratropical, Interhemispheric Climate Interaction : Atmospheric Bridge and Oceanic Tunnel
2. Dynamics of Decadal Climate Variability and Tropical Decadal Variability
3. Ocean-Atmosphere Interaction: A Global Scale, Coupled Climate Dynamics and Bjerknes Compensation
4. Timescale and Reversibility of Climate Change

Liu, Z., 2012: Dynamics of interdecadal climate variability: A historical perspective. *J. Climate*, 25, 1963-1995.

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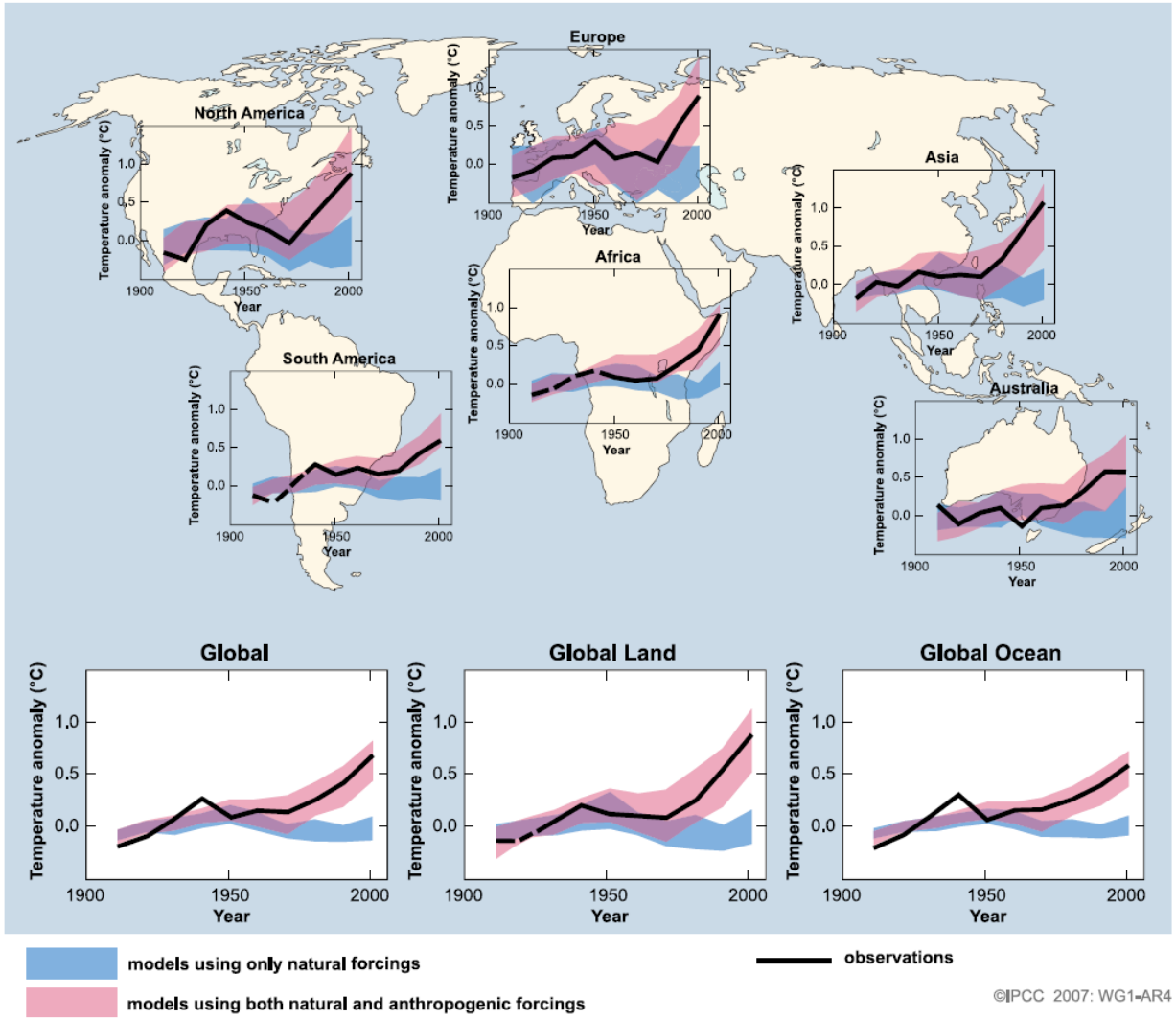
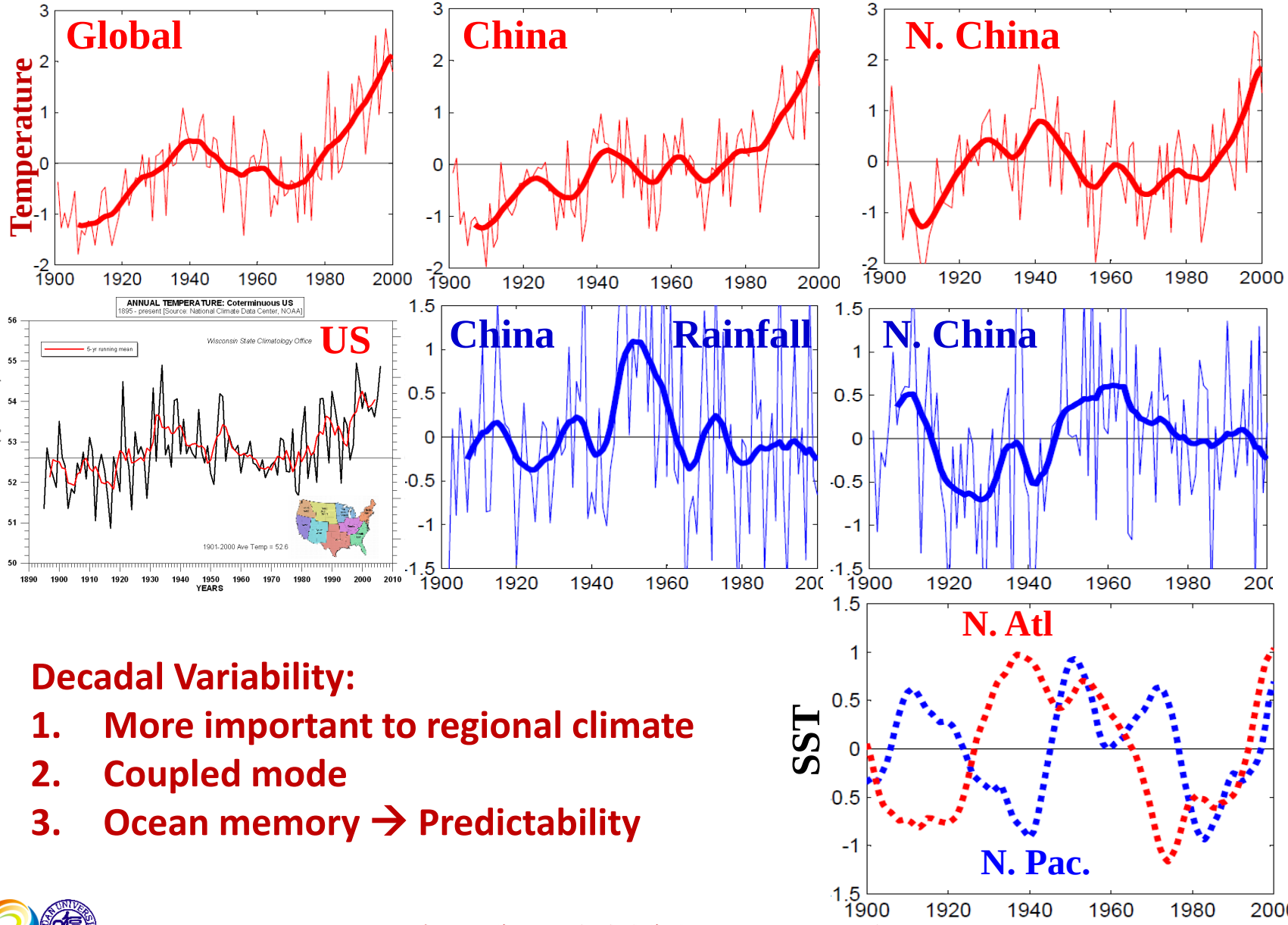
# Climate Change and Climate Variability




IPCC, 2007

# Climate Change: Global to Regional




**Decadal Variability:**

1. **More important to regional climate**
2. **Coupled mode**
3. **Ocean memory → Predictability**

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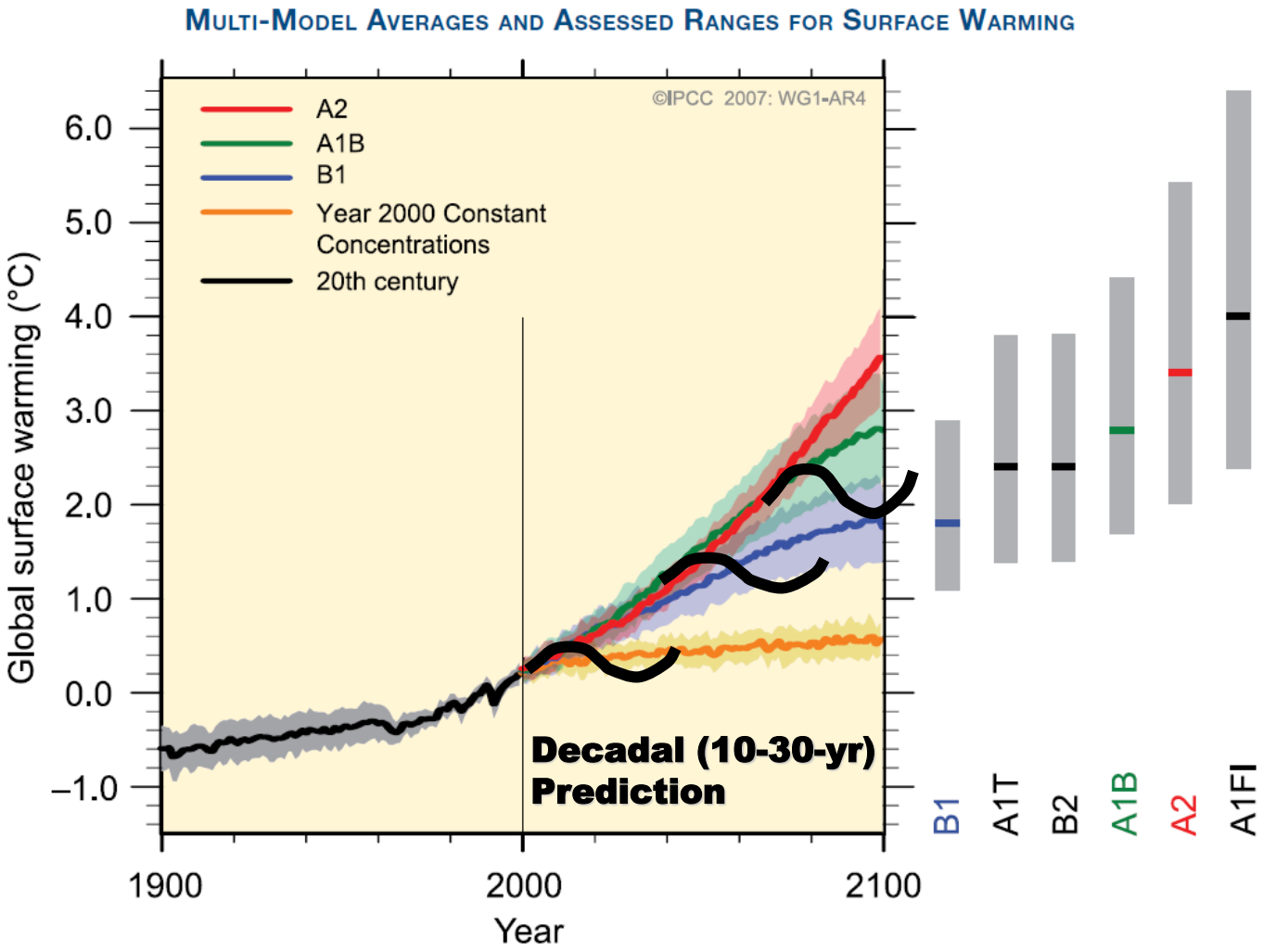
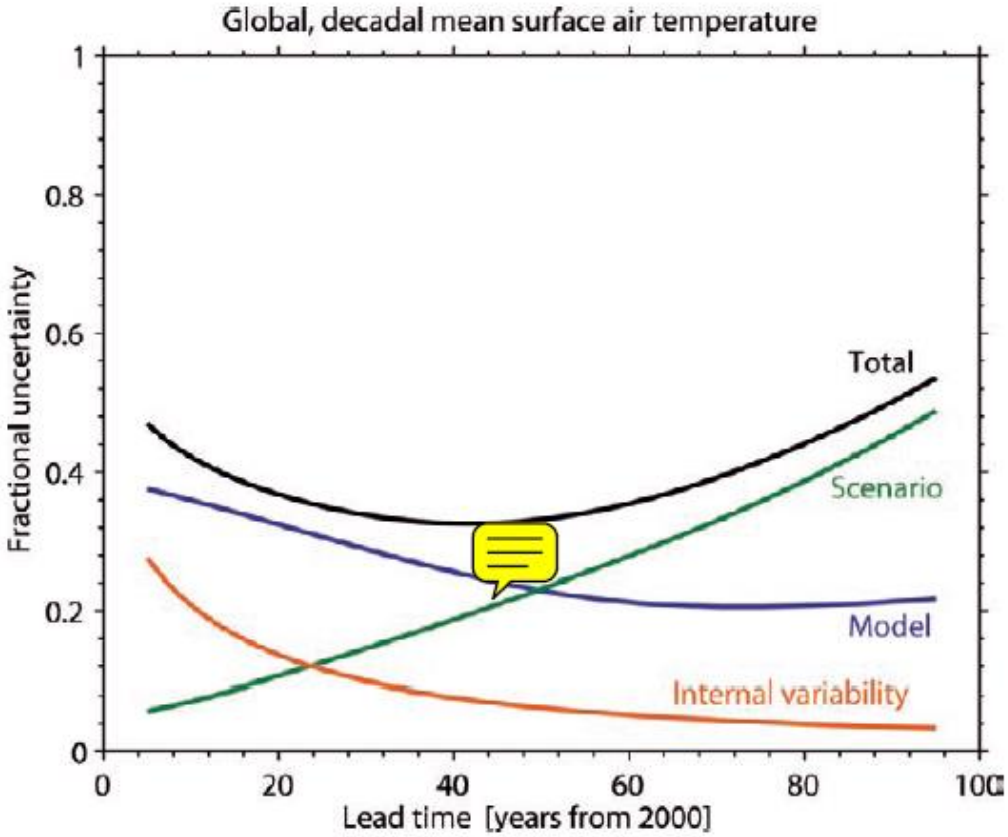
# Climate Projection and Decadal Prediction




IPCC, 2007

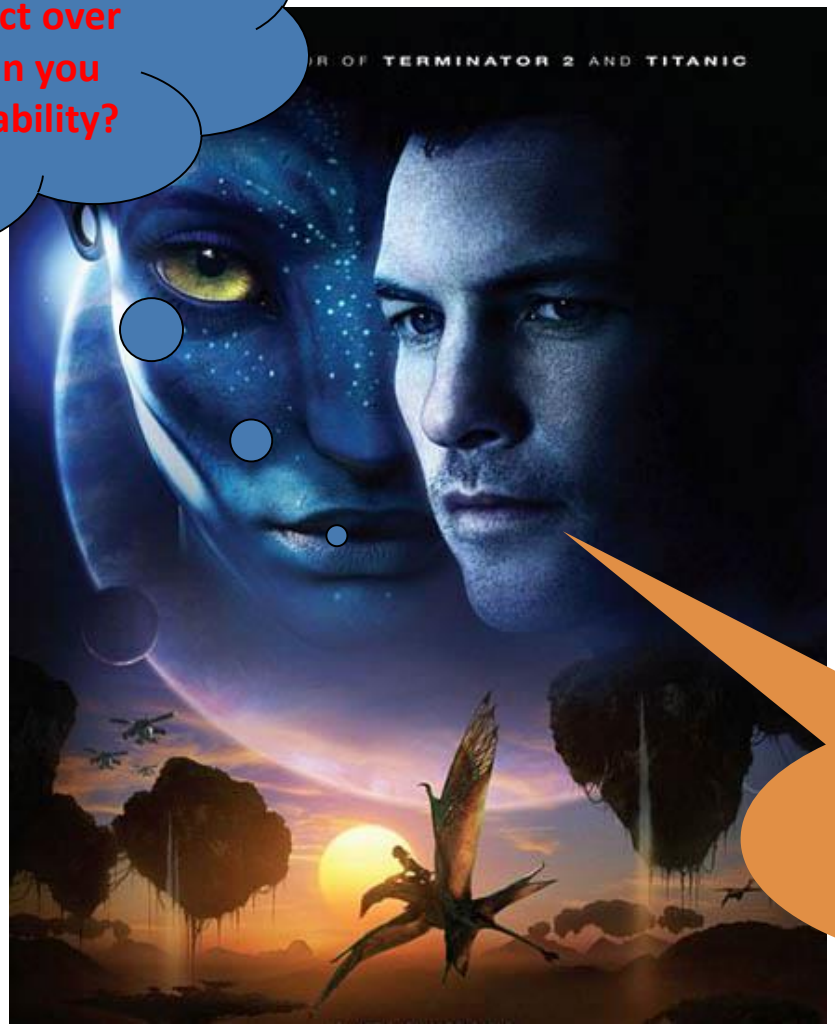
# Attributing Uncertainty of Climate Change




Hawkins and Sutton, 2009, BAMS

# Avatar & Decadal Prediction

You got to be kidding!
You can't even predict over ENSO cycle, how can you predict decadal variability?




**Decadal prediction !**

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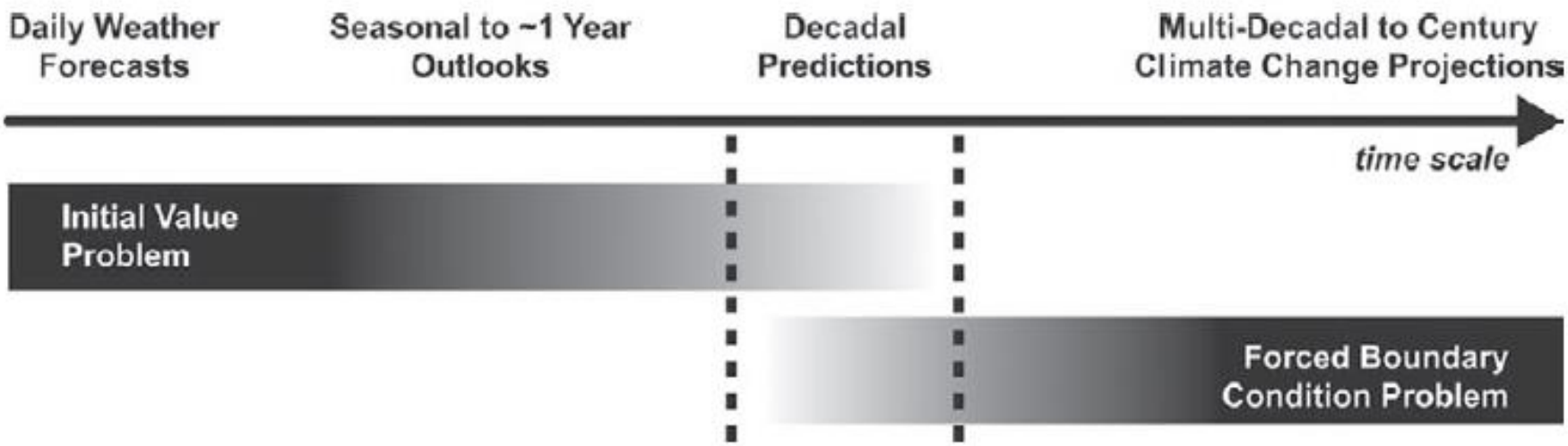
# Initial Value (natural variability)

VS

# Forced Problem (human effect)

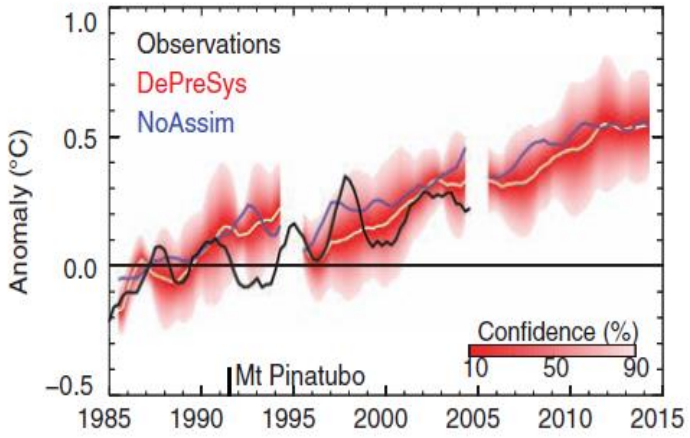



Meehl et al., 2009, BAMS

# First Attempts of Decadal Prediction

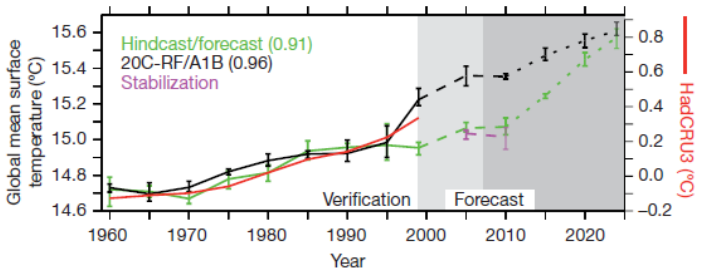
**HadCM3**

## Global Mean Temp



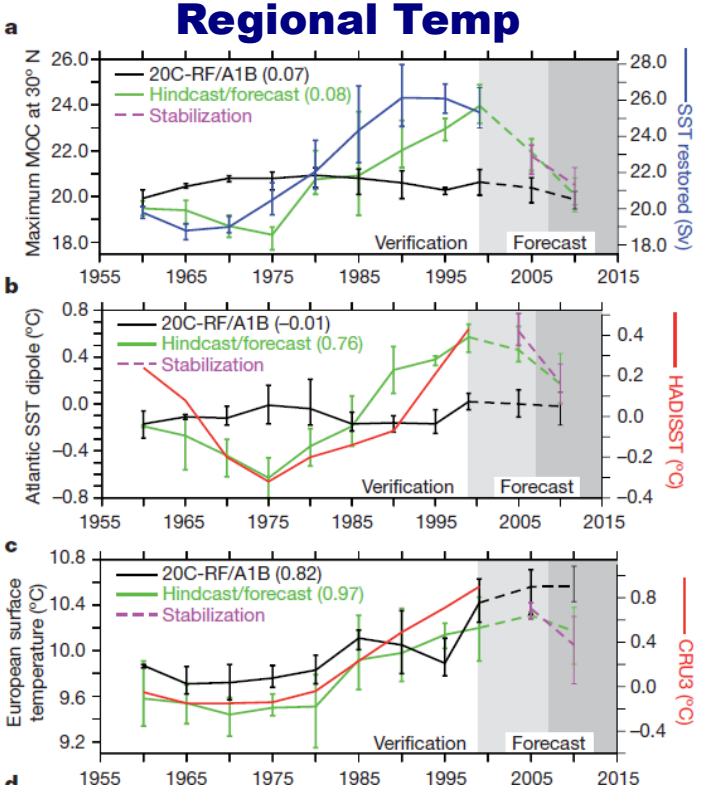

Smith et al., 2007

**ECHAM5/MPI-OM**




Keenlyside et al., 2008

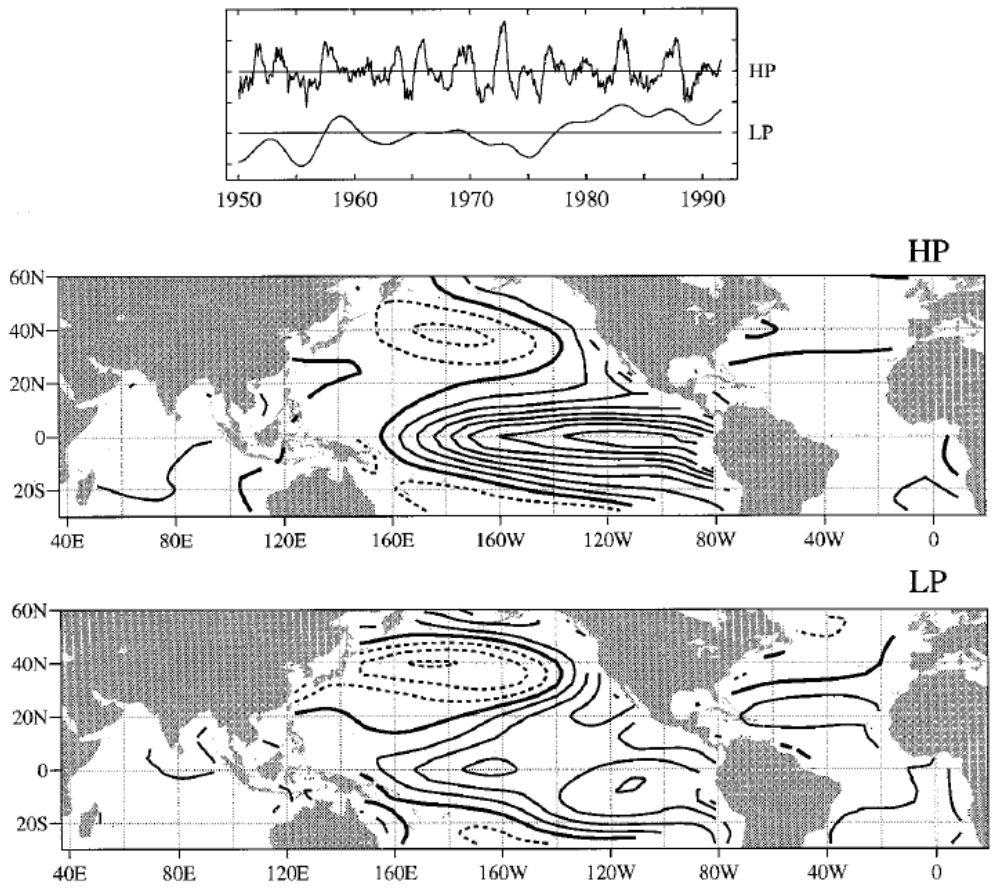
## Regional Temp




Keenlyside et al., 2008

# Observed Decadal Variability I:

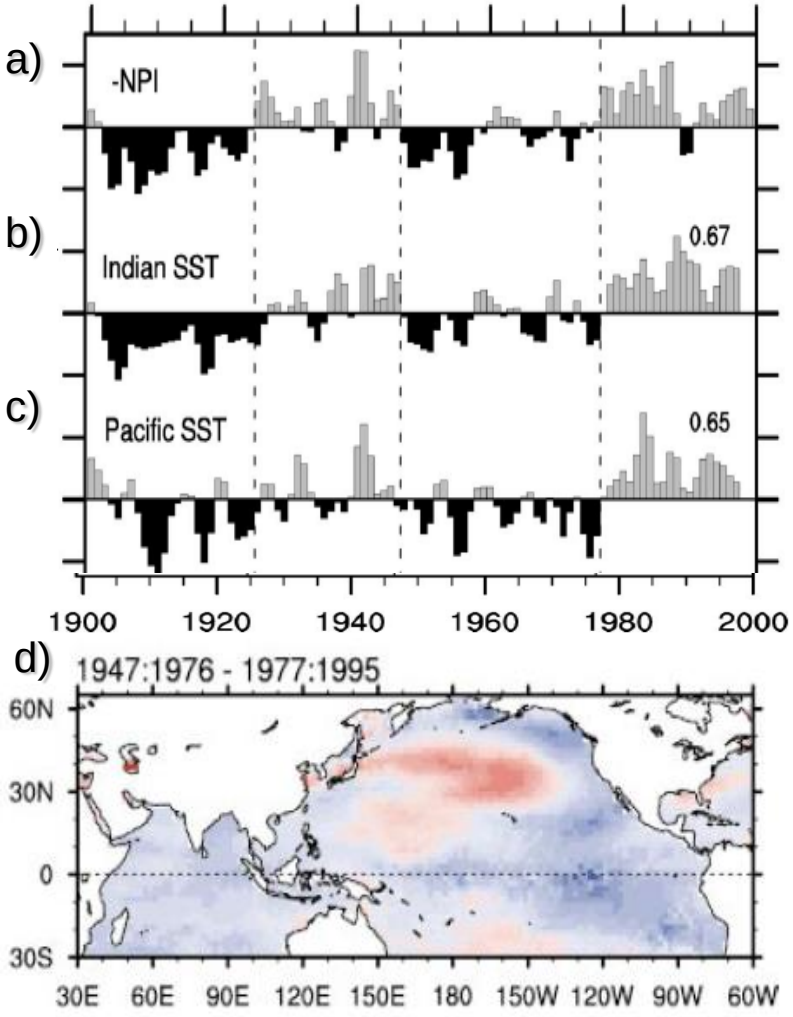
## ENSO-like Pacific Decadal Variability (PDO)




Zhang et al., 1997, JC

# Observed Decadal Variability II:

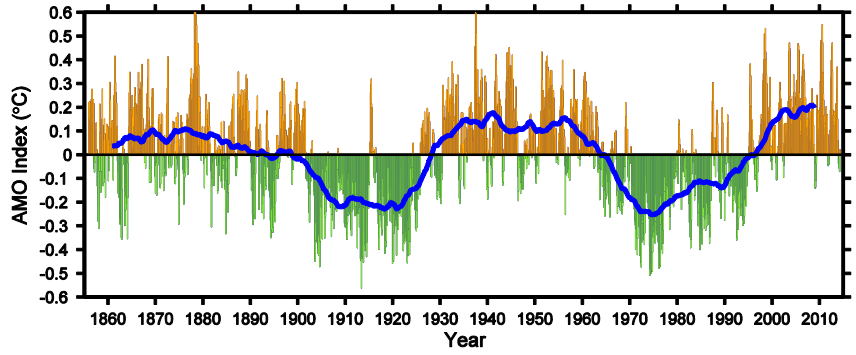
## North Pacific Multi-decadal Variability

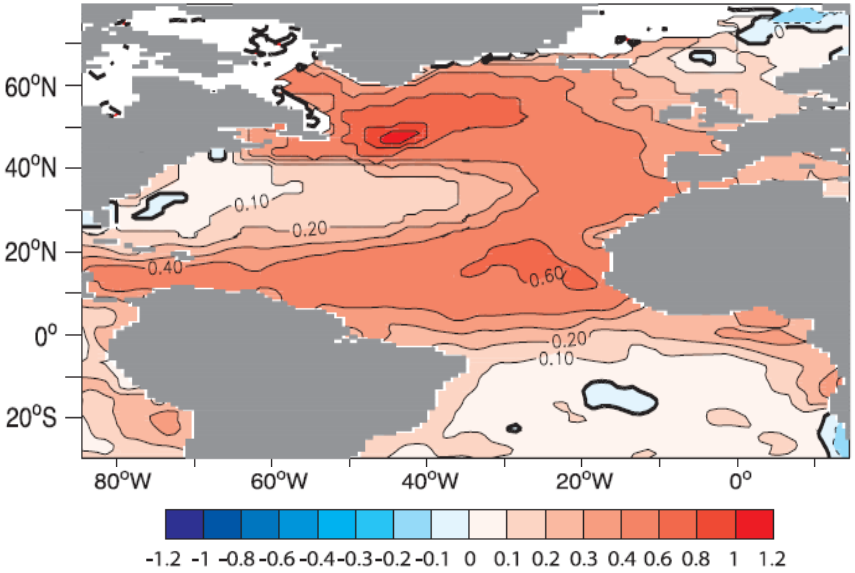



Deser et al., 2004, JC

# Observed Decadal Variability III:

## Atlantic Multi-decadal Oscillation (AMO)

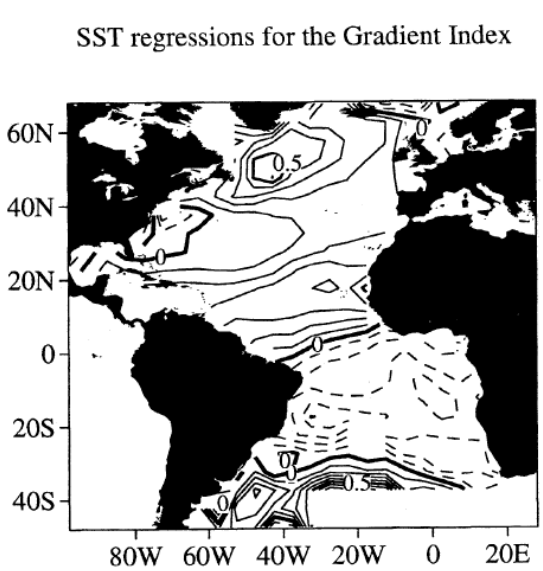


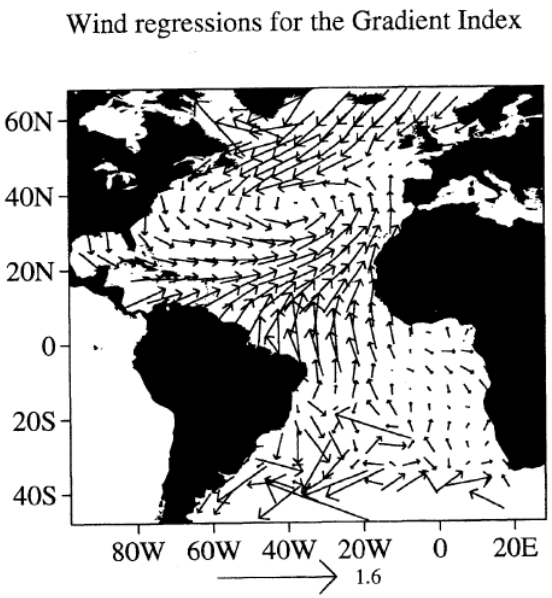



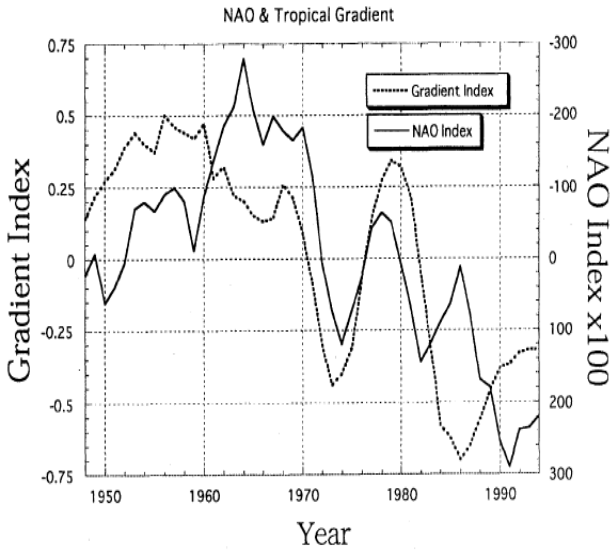

Delworth et al., 2007

# Observed Decadal Variability IV:

## Atlantic Decadal Variability



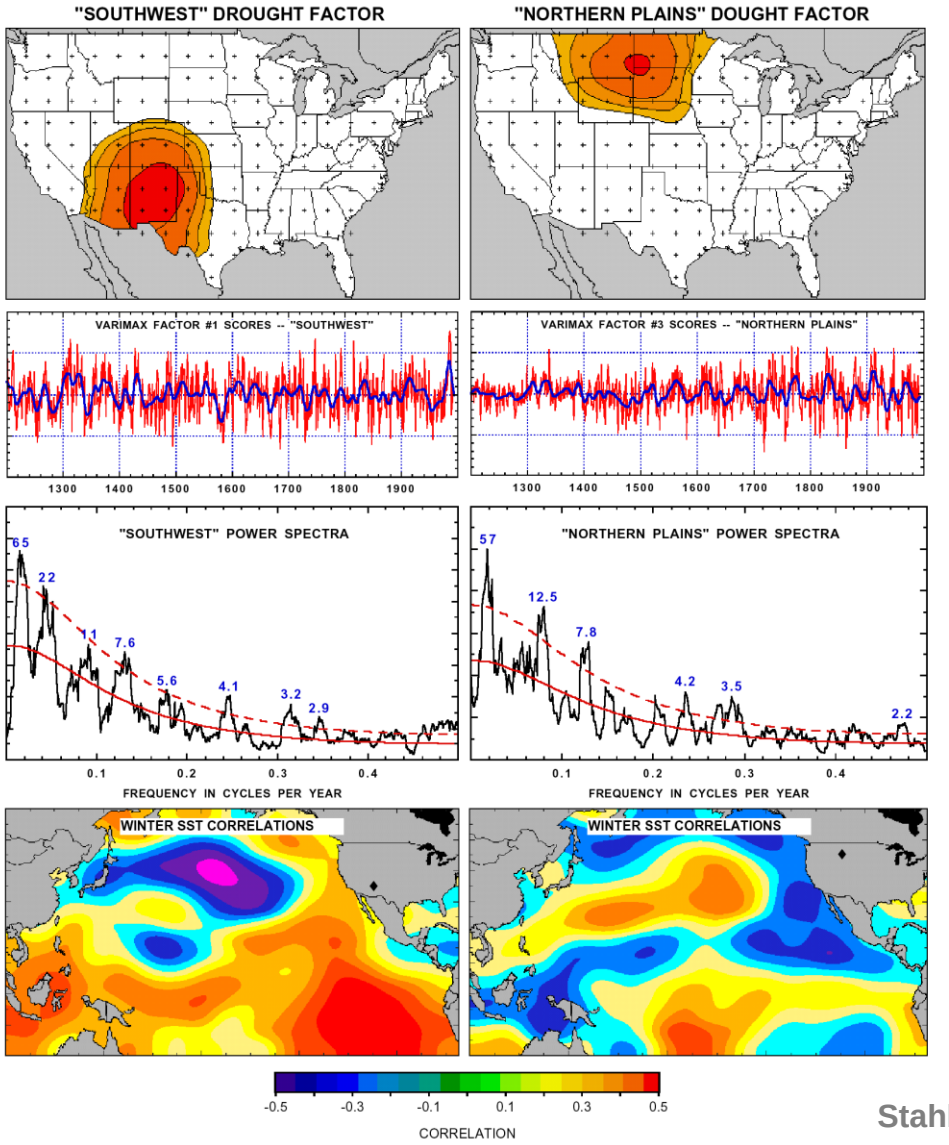




Tanimoto and Xie, 1999.

# A Paleo-Perspective of PDO

## Tree Ring Reconstruction




Stahle and Cook, 2002, BAMS

# Mechanism for Decadal Variability

## Where are we?

General Issues: Stochastic vs. Dynamics

Pacific Issue: Extratropics vs. Tropics

Atlantic Issue: Thermohaline vs. wind-driven

Coupling Issue: Atmospheric response to extratropical SST

## Where do we go?

# Mechanism for Decadal Variability

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## Where do we go?

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# General Mechanisms: Stochastic Climate Models

$$\frac{dT}{dt} = -\lambda T + w(t)$$

$$\frac{\partial T}{\partial t} + C_u \frac{\partial T}{\partial x} = -\lambda T + w(t)$$

$$\frac{\partial T}{\partial t} + C_u \frac{\partial T}{\partial x} = -\lambda T + w(x,t)$$

$$T = T(h)$$
$$\frac{\partial h}{\partial t} + N(h) = -\lambda h + w(t)$$

$$\Psi = \Psi(T)$$
$$T = T(h) + a\Psi$$
$$\frac{\partial h}{\partial t} + N(h) = -\lambda h + b\Psi + w(t)$$

**Local Interaction, Red noise**

Hasselmann, 1976

**Propagation, accumulation of var**

Frankignoul et al., 1997; Jin, 1997

**Propagation+Spatial Forcing**

**Spatial Resonance (time scale selection)**

Saravanna and McWilliam, 1997

**Ocean Dynamics**

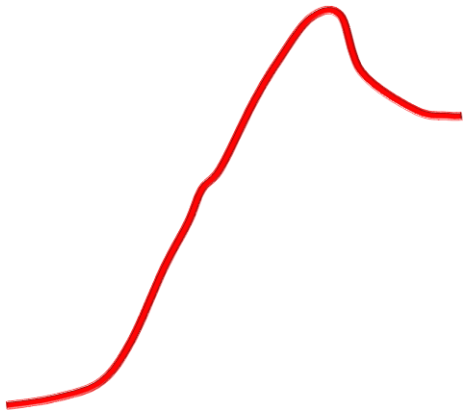
**Ocean Mode Resonance**

……

**Coupled Mode**

**Coupled Mode Resonance**

……



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# Ocean Dynamics and Time Scale Selection

$$\frac{\partial h}{\partial t} + C\frac{\partial h}{\partial x} = -\lambda h + w(t)$$

$+$ B.C. $\quad U_B=0$

High modes, advection

$+$ Shear $\quad U(y)$

$$\frac{\partial T}{\partial t} + \vec{U}\bullet\nabla T = -\lambda(T_{z=0} - T_a) + w(t)$$

$$\frac{\partial S}{\partial t} + \vec{U}\bullet\nabla S = H_{z=0} + w(t)$$

$+$ coupling (positive feedback)

**Planetary wave (1st mode)**

Latif and Barnett, 1994; Jin, 1997; Qiu, 2003

**Planetary wave basin mode**

Cessi and Louazel, 2001; Liu, 2003

**Ventilation**

Gu and Philander, 1997; Wu et al., 2003

**Unstable planetary waves** (flux b.c.)

Colin de Verdiere, 1986; Zhang and Greatbatch, 1995;

Note: nonlinear synoptic modes provide noise forcing, instead of time scale selection

**Thermohaline mode** (mixed b.c.)

Welander, 1986; Weaver and Sarachik, 1991;

**Coupled Mode**

Latif and Barnett, 1994; Gu and Philander, 1997; Chang et al., 1997

Example: local positive feedback + planetary wave ➔ Delayed Oscillator

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## Where do we go?

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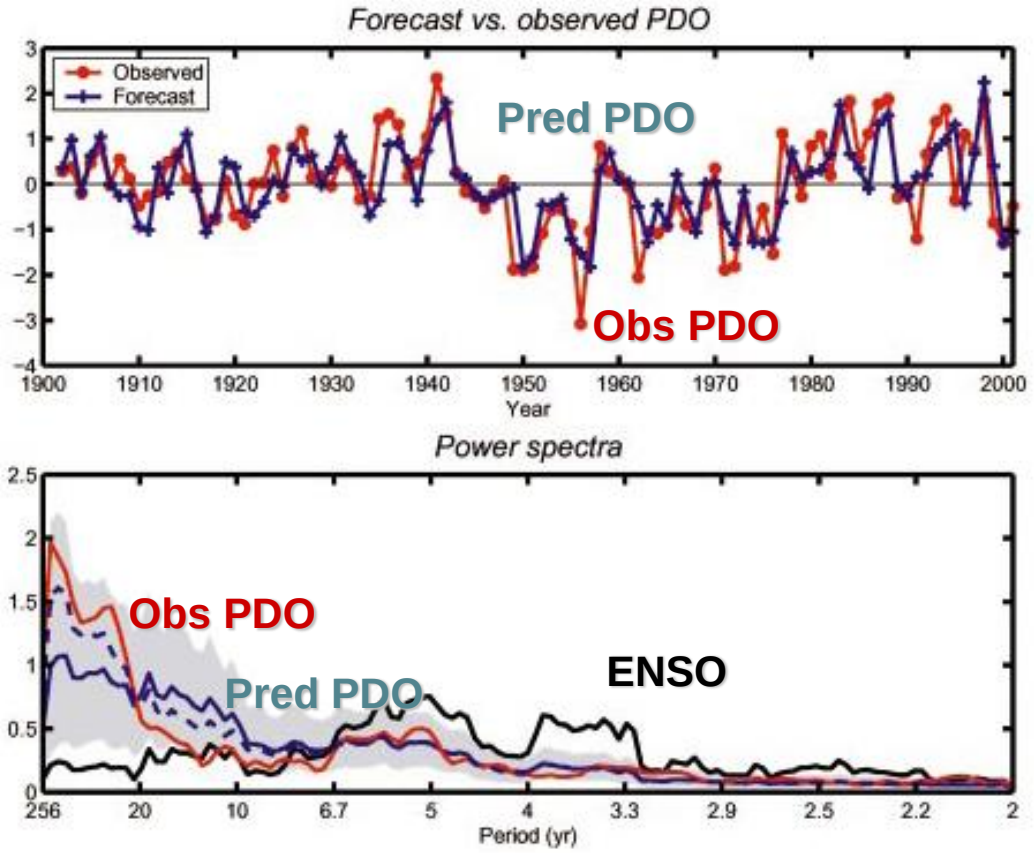
# Role of Tropics



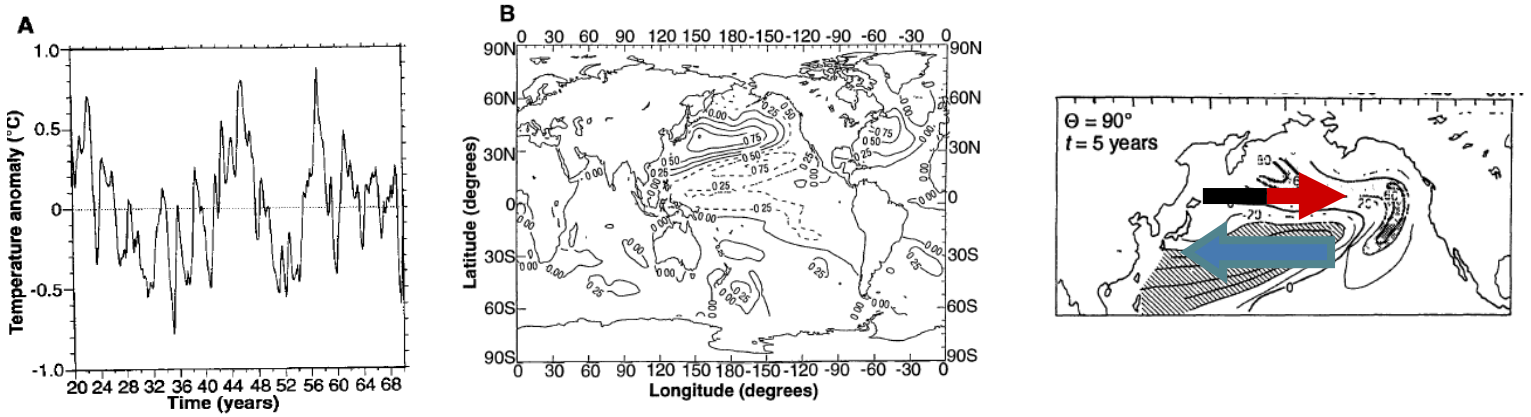

$$P(n) = P(n-1) + ENSO + N$$

What determines the low frequency tail of ENSO (beyond noise tail)?

Newman et al., 2003, JC

# Pacific Decadal Variability

## Latif-Barnett mode




warm NP ← ? reduce heat loss

warm KOE → reduce Aleutian Low → gyre spin-down via subtropical wave

reduce Aleutian Low → reduce westerly

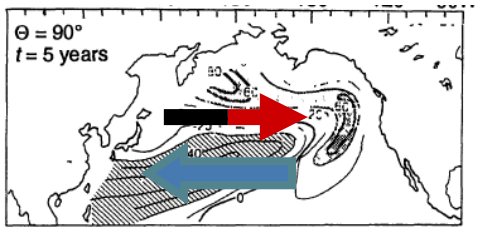
cool KOE ← weaken Kuroshio

gyre spin-down via subtropical wave → weaken Kuroshio

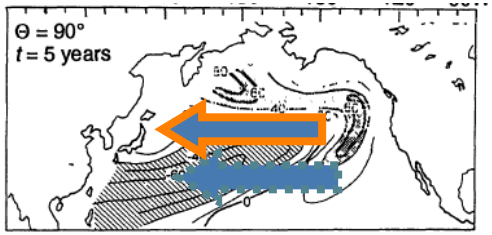
Latif and Barnett, 1994, Science

# Pacific Decadal Variability

Latif-Barnett mode




Schneider et al., 2002




warm NP ← ? reduce heat loss

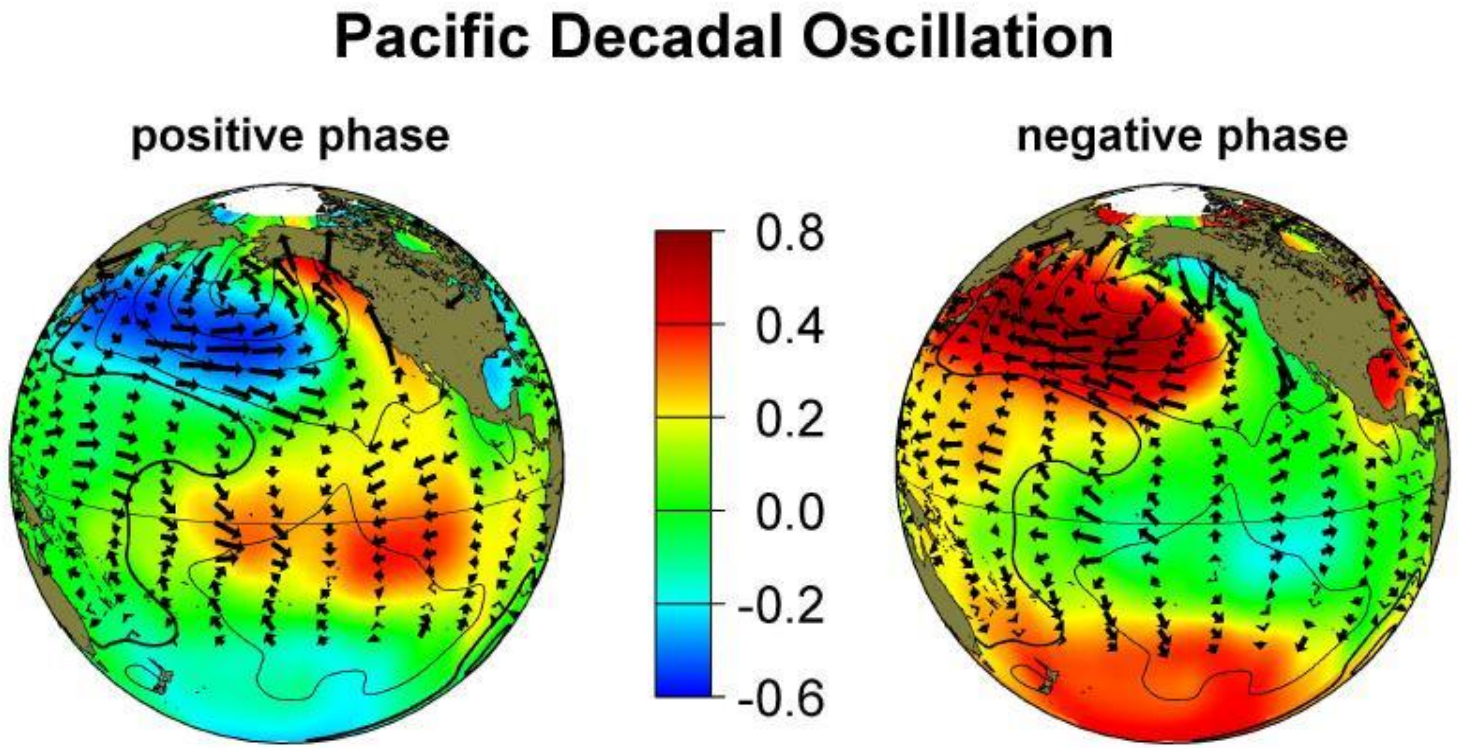
warm KOE → ? reduce Aleutian Low → gyre spin-down via subtropical wave

reduce Aleutian Low → reduce westerly Shift gyre north → deepen thermocline Via mid-lat wave

deepen thermocline Via mid-lat wave → weaken Kuroshio → cool KOE → warm KOE

# North Pacific Multi-decadal Variability (NPM)

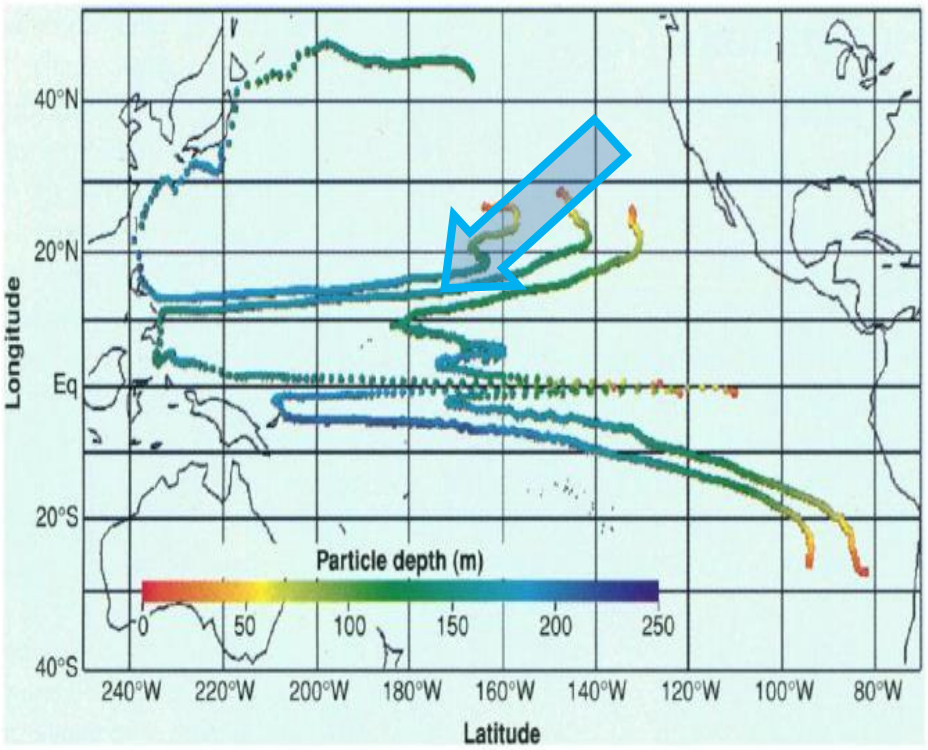
## The Role of Tropics?



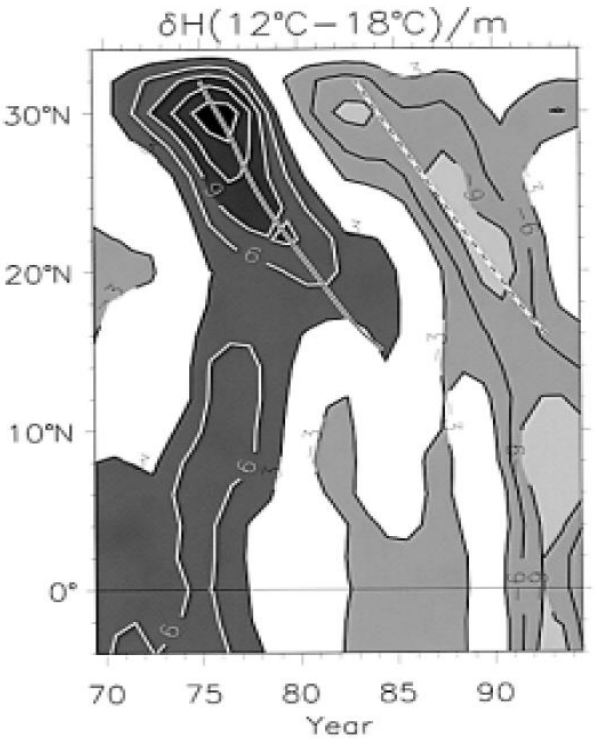

Deser et al., 2004, JC

# NPM: The Role of Tropics

Gu and Philander mode (1997, Nature)



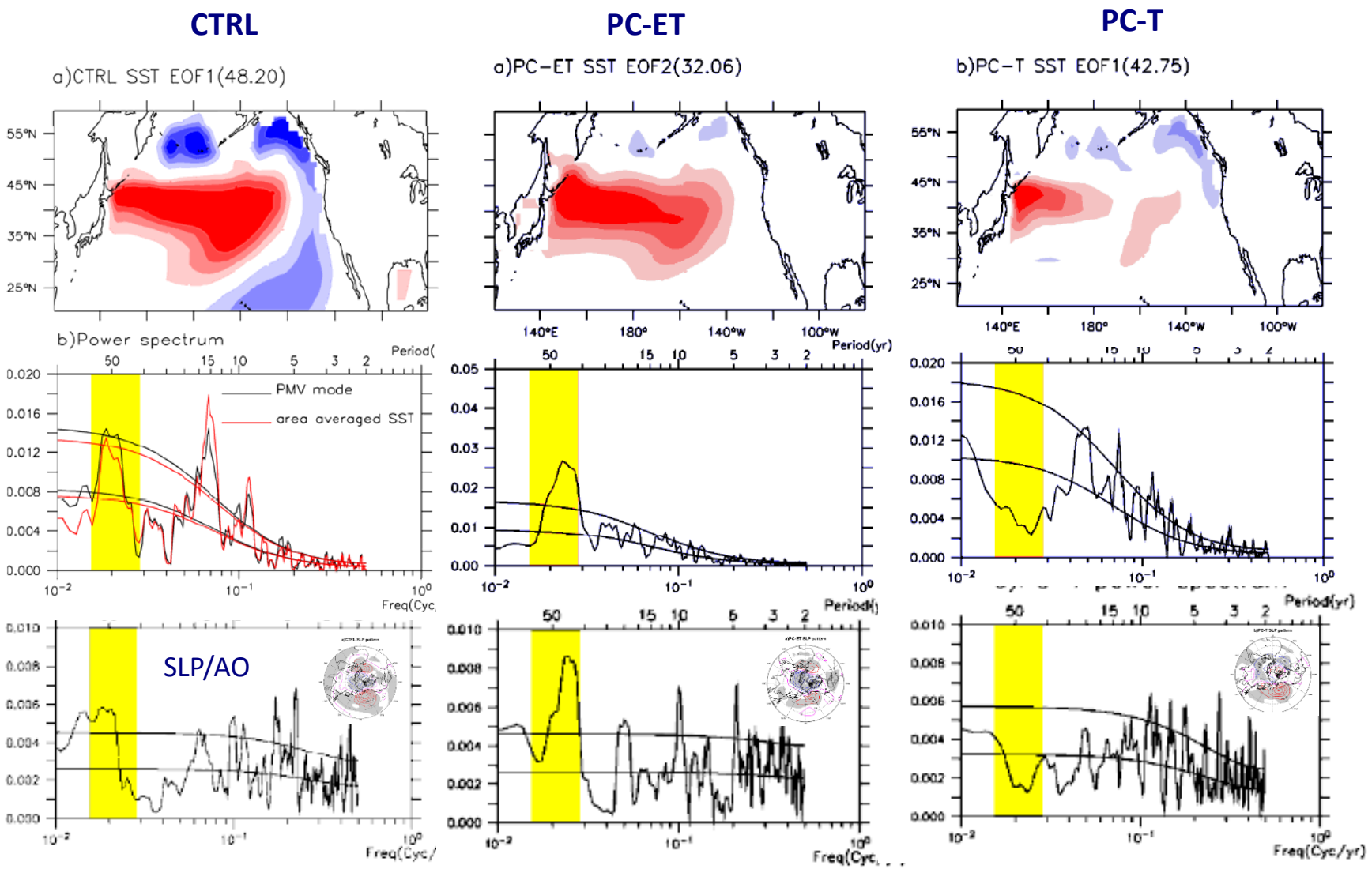

Schneider et al. (1999, JPO)




Subduction from the South Pacific? Wang and Liu, 2000, CSB; Luo et al., 2001, JGR

Spiceness mode? Schneider et al., 2000

# NPM: Ocean-Atmos. Interaction




Zhong et al., 2008, JC

# Mechanism for Decadal Variability

## Where are we?

General Issues: Stochastic vs. Dynamics

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**Coupling Issue: Atmospheric response to extratropical SST**

## Where do we go?

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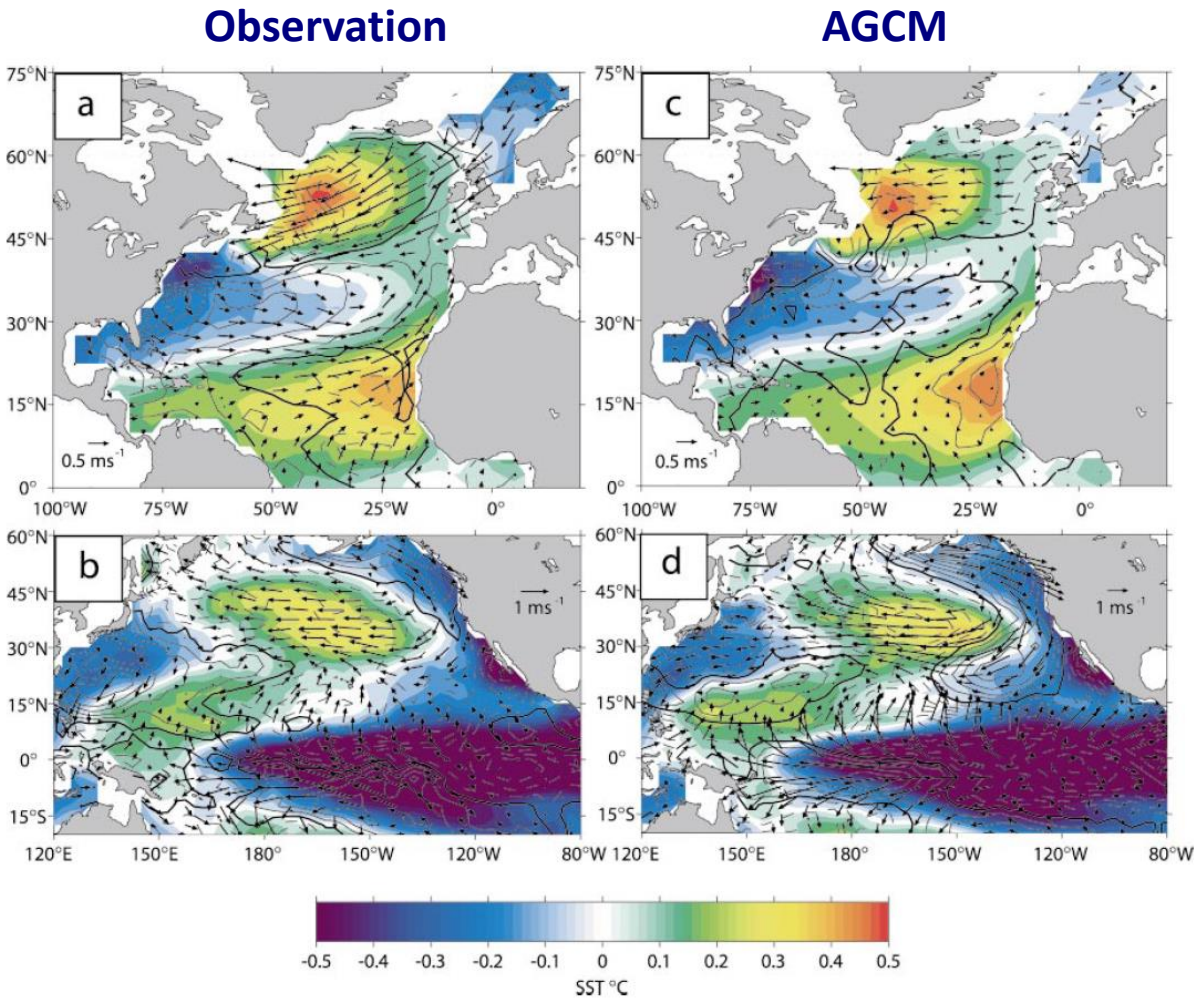
# Atmospheric Response to SST



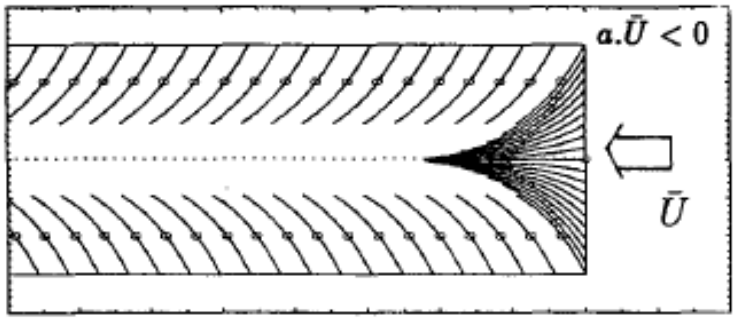

**Obs, mixes cause/effect, Model: diverse with different models and methods**

Kushnir et al., 02, JC

# Extratropical Impact on Tropics

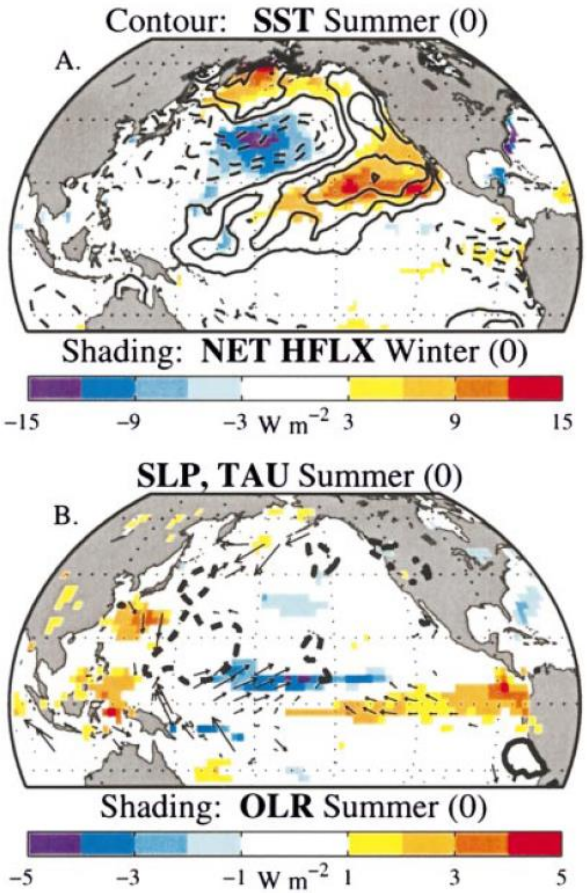
## Coupled WES Teleconnection

WES, coupled teleconnection




Liu and Xie, 94, JAS

Seasonal Footprint




Vimont et al., 03, JC

i) Atmospheric dynamics (days)

ii) WES coupled ocean-atmosphere teleconnection (months)

iii) Ventilation/ocean waves (years)

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## Where do we go?

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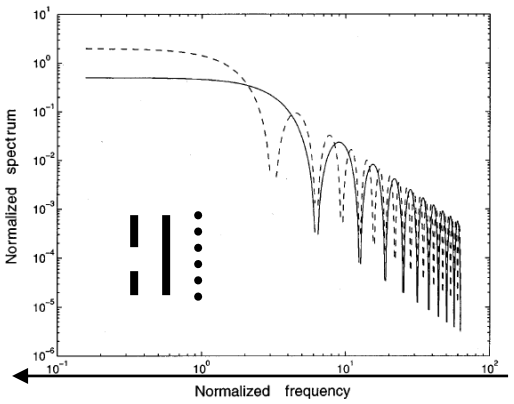
# North Atlantic Decadal Variability

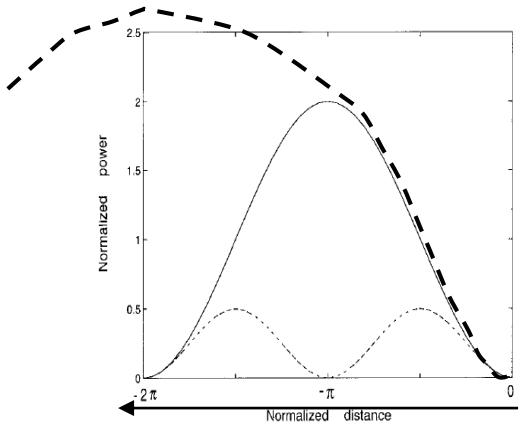
## Wind-Driven

Power Spectrum

Power Distribution

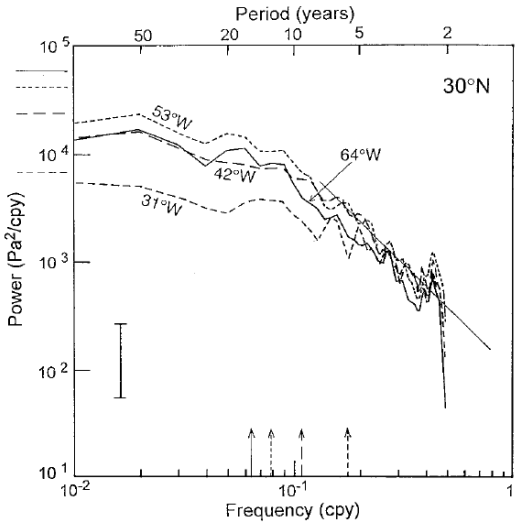
**Theory**

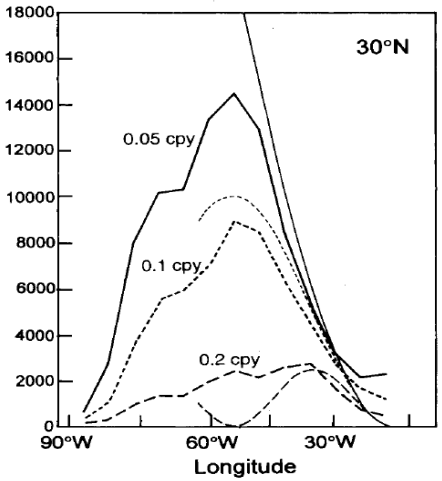



**Xe**

**ECHAM1/LSG**



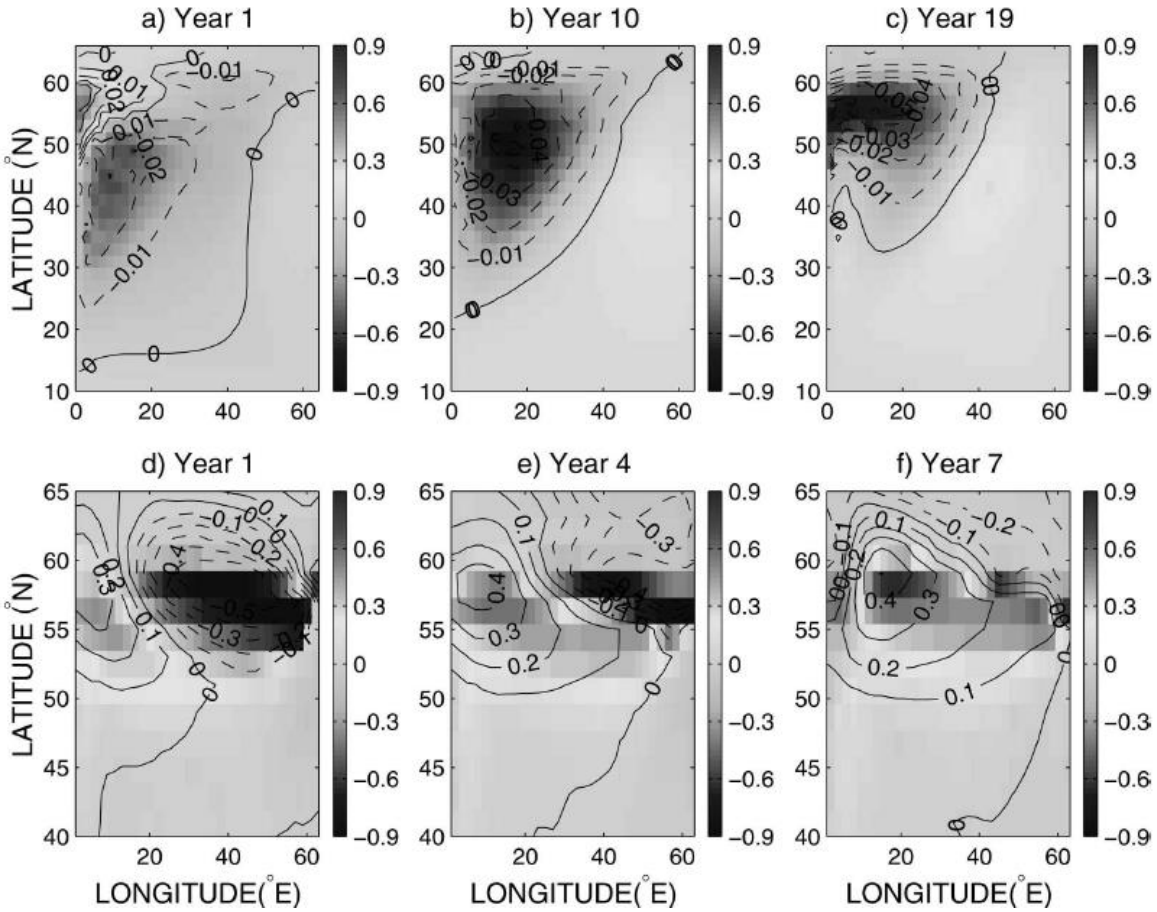




Frankignoul et al., 1997

# OGCM Simulation of THC Decadal Variability

Heat flux forcing

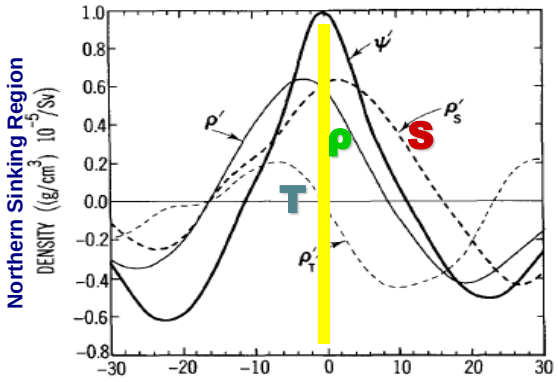
Mixed B.C.

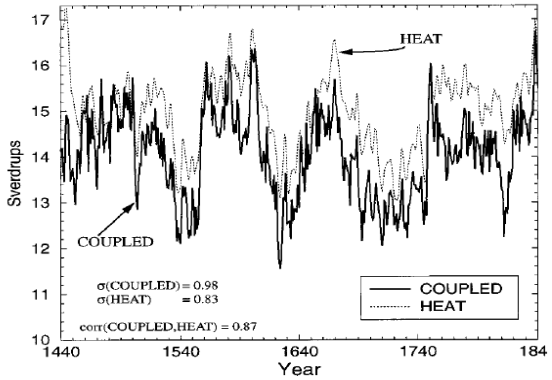



Arzel et al., 2006

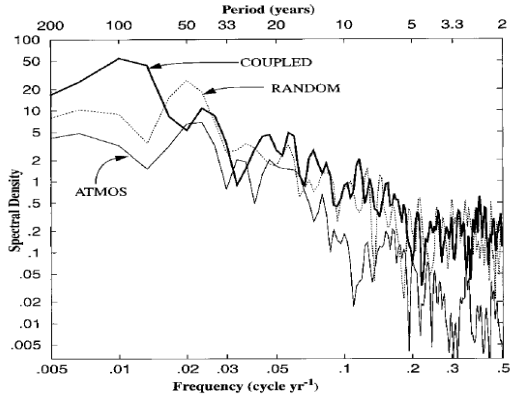
# CGCM Simulation of North Atlantic Multidecadal Variability

Delworth et al., 1993, JC, GFDL/R15,30

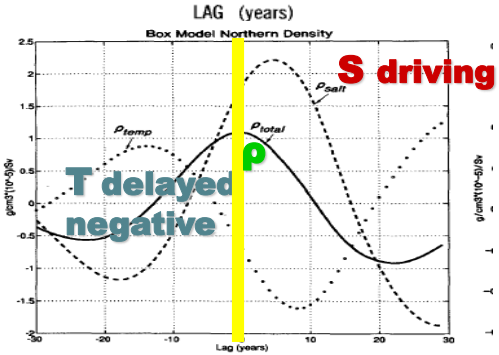


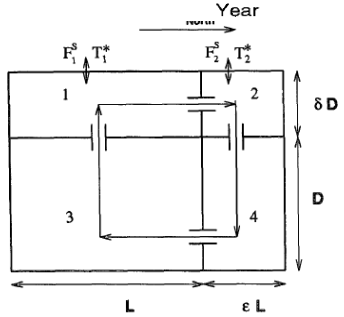




Heat flux driven mode



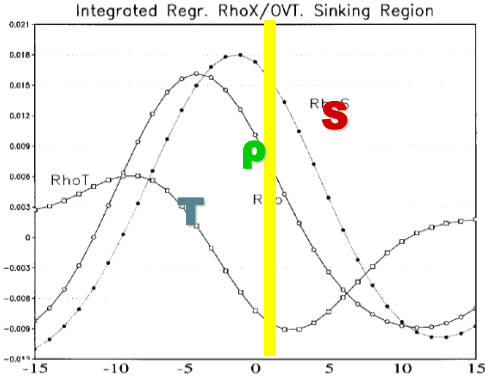

Delworth and Greatbatch, 00, JC

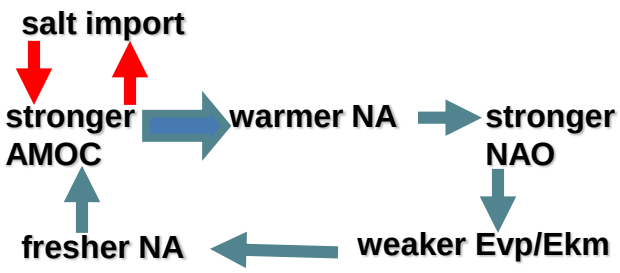


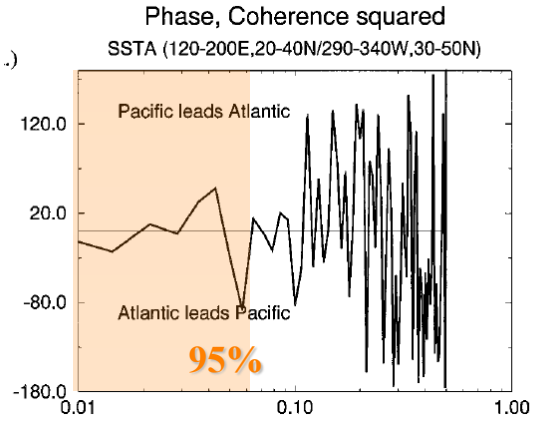

Griffies and Tziperman., 1995, JPO

Timmermann et al., 1998, JC, ECHAM1/LSG




Atmos response and (Implied) coupled mode

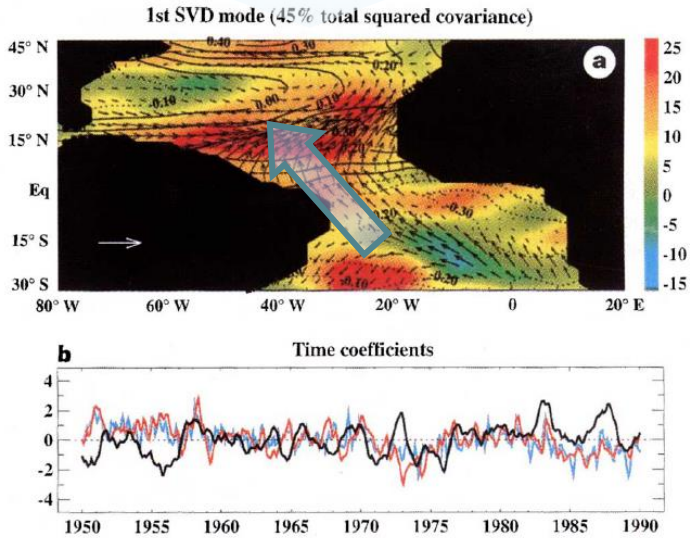


# Atlantic Decadal Variability

NAO impact: Visbeck et al., 98, GRL; Tanimoto and Xie, 99, GRL; Czaja et al, 02, JC

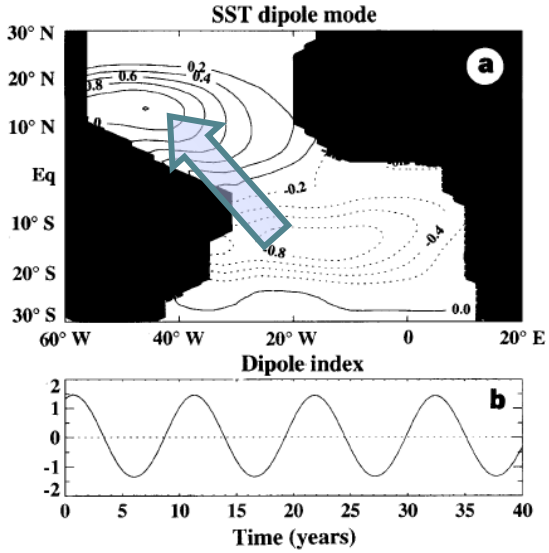
## NAO

Observation




## Why decadal? Wind or THC?

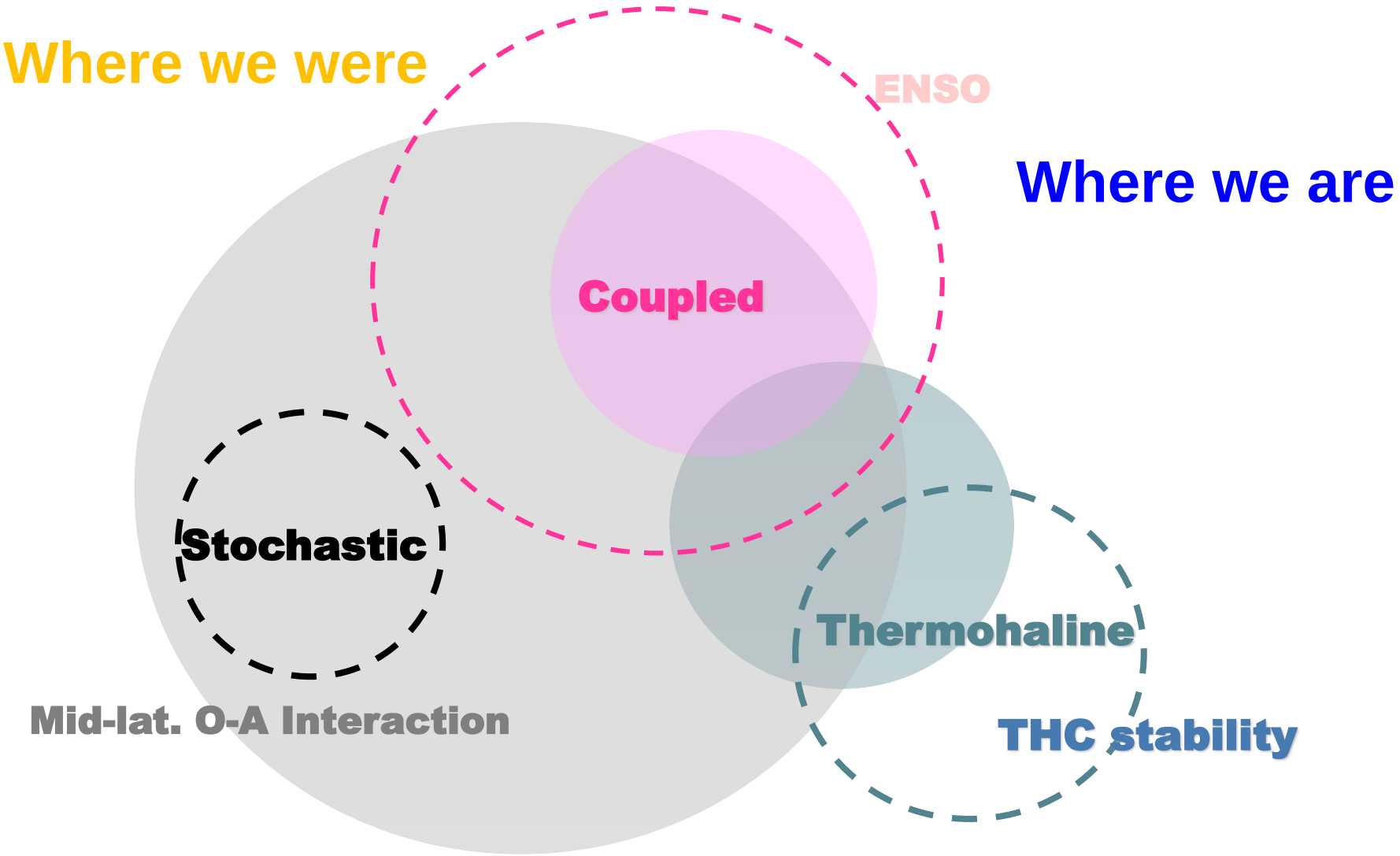
Theory





Chang et al., 97, Nature

# Decadal and Multidecadal Variability



# Decadal and Multidecadal Variability

| | What we know? | What we don't know? |
|---|---|---|
| Overall | Noise important for driving<br>Ocean dynamics important<br>Tropical atmosphere important for global response<br>Extratropical atmospheric response modest | Preferred time scale in the real world?<br>Role of extratropical ocean-atmosphere feedback?<br>Role of tropics? |
| Pacific Decadal Variability | Subtropical-mid latitude Rossby wave for time scale selection | Role of tropical ocean? |
| Pacific Multidecadal Variability | Subpolar Rossby wave for time scale selection | Role of salinity and temperature variability? |
| Atlantic Decadal Variability | Tropical WES feedback important<br>NA/THC variability may be important driving | What determines the time scale? |
| Atlantic Multidecadal Variability | THC important for time scale | Role of subpolar gyre? |

# Role of Ocean Dynamics?

- **Oceanic internal variability:**
  eddies and nonlinear interactions (needs high resolution models for ocean, and coupled model)

- **Planetary wave dynamics:**
  instability, interaction with eddies, 3-D basin modes, forced basin mode response

- **Subpolar dynamics:**
  T vs S, wind-driven vs. THC, deep mixed layer, weak stratification, sea ice

- **Coupled stochastic dynamics**

# Extratropical-Tropical Decadal Variability

## A Basin Mode View

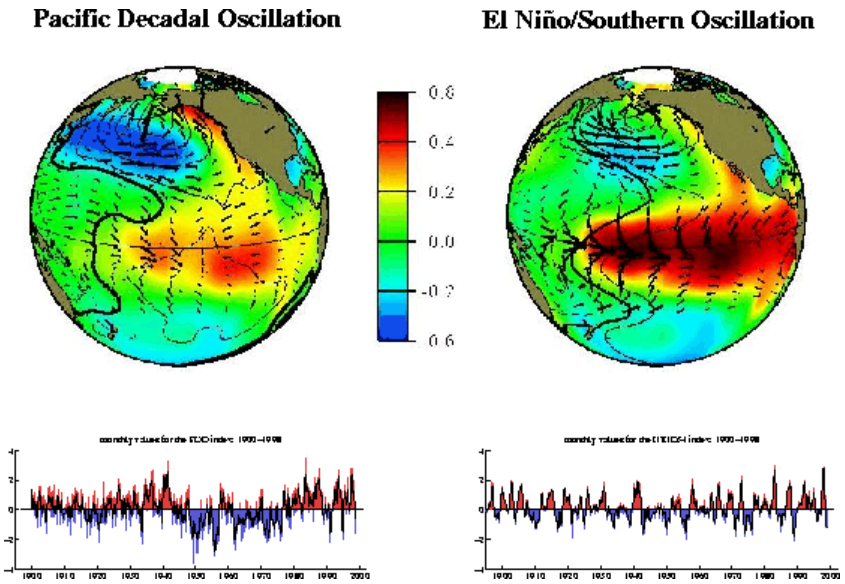

Yang, H. and Z. Liu, 2003: Basin modes in a tropical-extratropical basin. *J. Phys. Oceanogr.*, 33(12), 2751-2763.

Liu, Z., 2003: Tropical ocean decadal variability and the resonance of planetary wave basin modes: I: Theory. J. Clim., 16, 1539-1550.

Yang, H., Z. Liu and Q. Zhang, 2004: Tropical ocean decadal variability and resonance of planetary wave basin modes: II. Numerical study. *J. Climate*, 17, 1711-1721.

# PDO versus ENSO

**PDO is a long lived ENSO-like pattern of Pacific climate variability.**




## Similarity:

- Spatial pattern
- Warm phase – El Nino
  - E. Tropical Pacific: + ΔSST
  - W. North Pacific: – Δ SST
- Cool Phase – La Nina
  - E. Tropical Pacific: – Δ SST
  - W. North Pacific: + ΔSST

## Difference:

- Time scale
  - PDO: 20-30 years; ENSO: 6-60 months
- Signal center
  - PDO: Most visible in North Pacific, secondary in Tropics
  - ENSO: Most visible in Tropics; Minor signature in North Pacific

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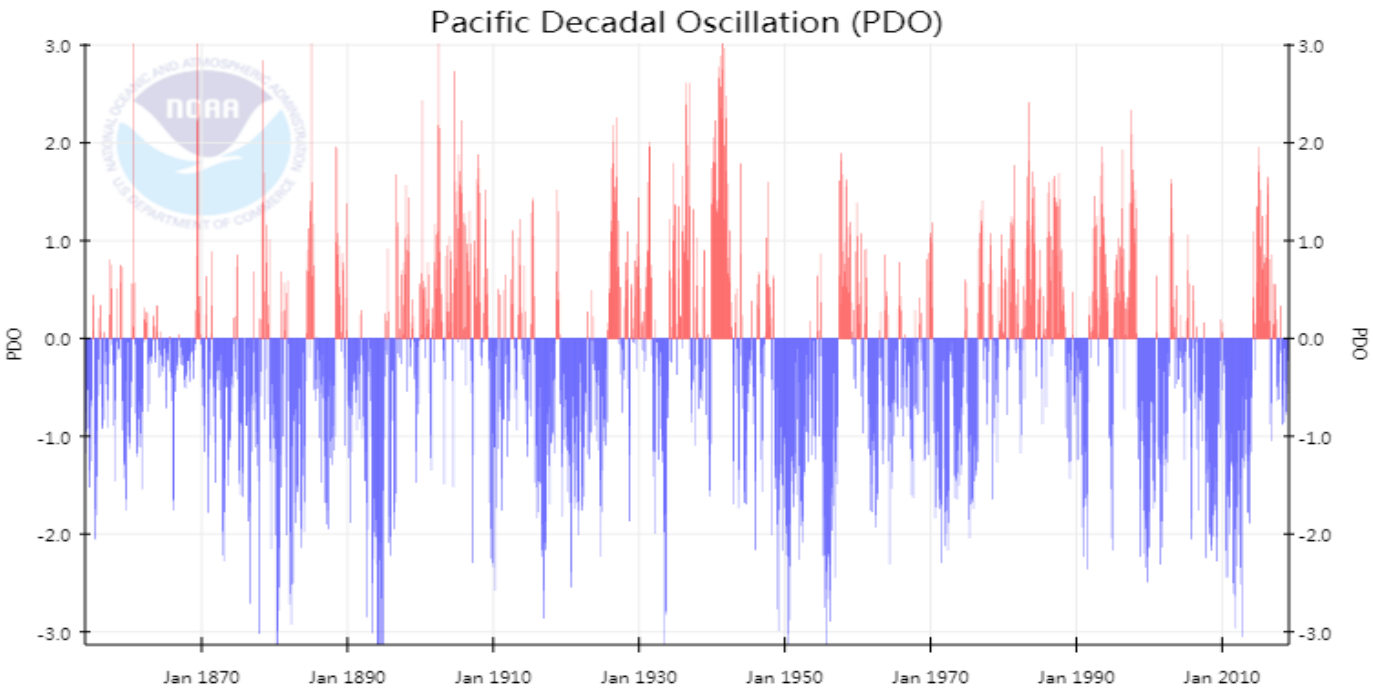
# What is PDO index?

- PDO SST index: Defined as the leading PC (EOF) of North Pacific monthly SST anomaly (poleward of 20°N)




- PDO SLP index: Defined as an area-averaged North Pacific monthly SLP anomaly (poleward of 20°N)

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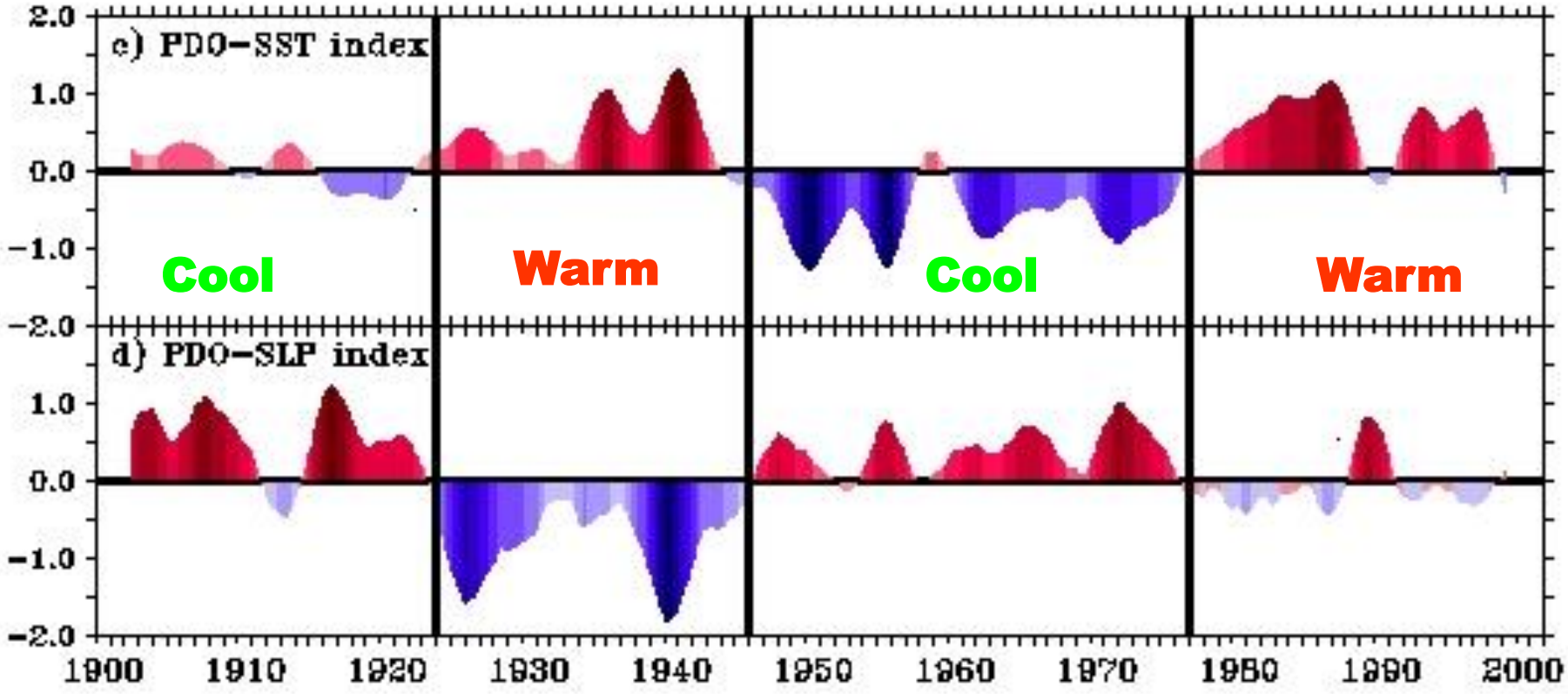
# Historical PDO Records




20th Century PDO Regime shifts: 1924/25, 1946/47, 1976/77

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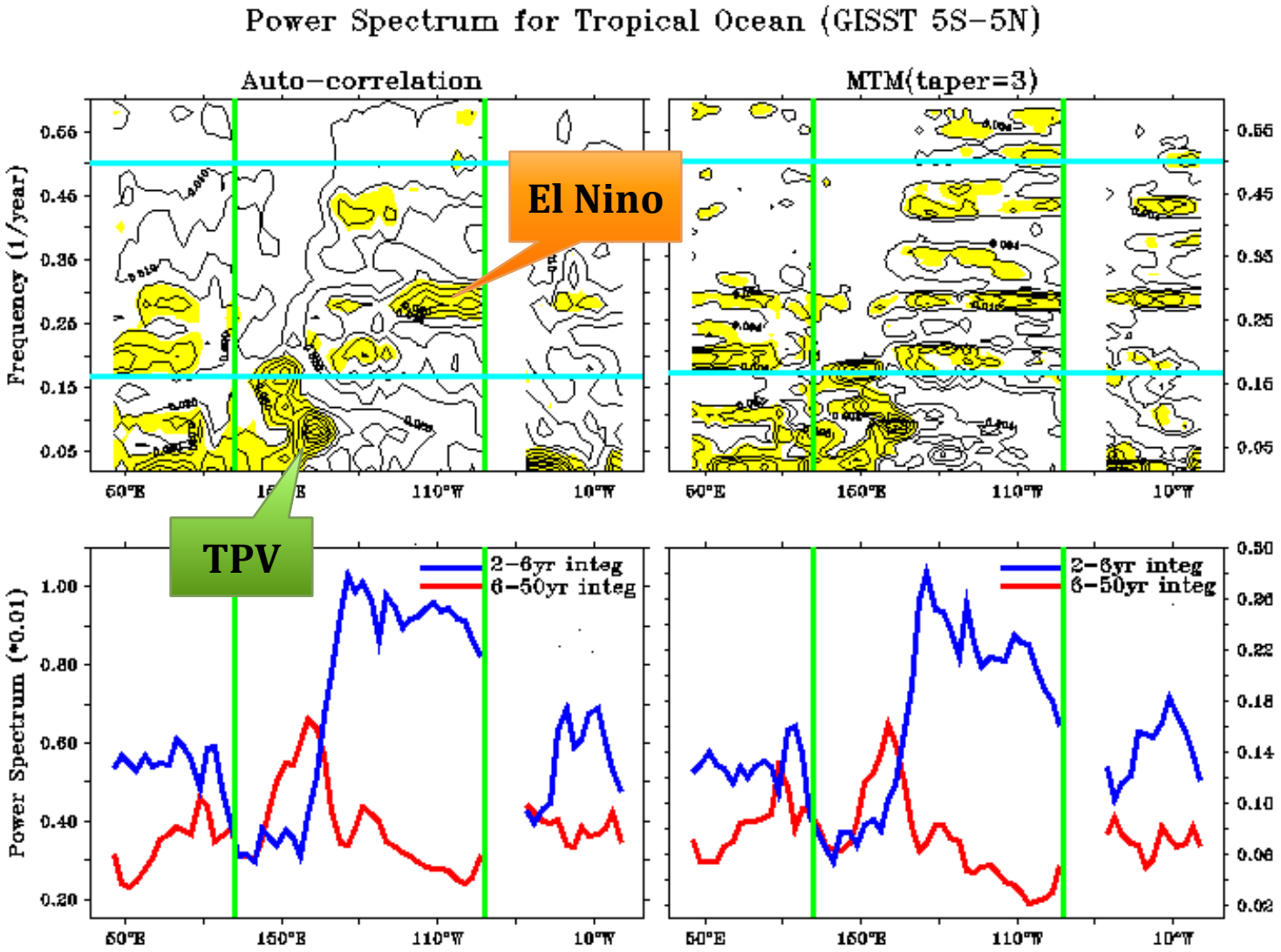
# What is Tropical Decadal Variability?



# TDV: what we know, and don't know

- **Signal(✓)**

  Subtle, need more evidence

- **Mechanisms(?)**

  Single or Multiple ? need Quantification

- **Origin(?)**

  Extratropics (50%?)

  Tropics: Equatorial and Off-equatorial (50%?)

# Where does the TDV memory come from?

- Local

  Equatorial Basin mode (Jin, 2001)

  **Infinite** ☒ for infinite Beta-plane

- Remote

  Extratropical planetary wave basin mode (Liu, 2002)

  **Finite** ☑ for finite Beta-plane

# Shallow Water Model

$$\partial_t u - yv = -\partial_x h, \quad \partial_t u + yu = -\partial_y h, \quad \partial_t h + \partial_x u + \partial_y v = 0.$$

- **Planetary Wave** (Cessi and Louazel, 2001)
- **Equatorial Wave** (Jin, 2001)

| | | |
|---|---|---|
| $-yv = -\partial_x h, \quad yu = -\partial_y h,$ $\partial_t h + \partial_x u + \partial_y v = 0.$ | Equation | $\partial_t u - yv = -\partial_x h, \quad yu = -\partial_y h,$ $\partial_t h + \partial_x u + \partial_y v = 0.$ |
| $h\|_{x=1} = h_e(t), \quad \int_0^{Y_N} dy \int_0^1 h dx = 0$ | B.C | $u\|_{x=1} = 0, \quad \int_0^{Y_N} u_{\|x=0} dy = 0$ |
| $H = \exp[\sigma_P (x-1) y^2]$ | Solution | $q = \sum_{n=0}^{N} q_{2n}(x)\psi_{2n}(y), \quad p = \sum_{n=0}^{N-1} p_{2n}(x)\psi_{2n}(y)$ |
| $\int_{Ys}^{Y_N} [1 - \exp(-\sigma_P y^2)] / y^2 dy = 0$ | Eigenvalue | $1 - \sum_{n=1}^{N} \frac{(2n-3)!!}{(2n)!!} \exp(-4n\sigma_s) = 0$ |

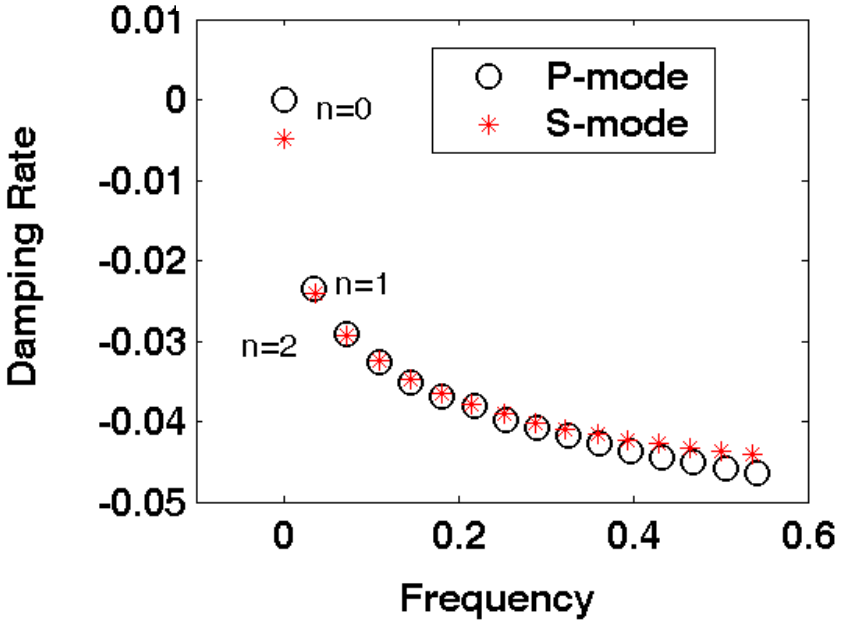
$\omega_{P1} = 2\pi / Y_N^2$ $\quad N = Y_N^2/4 \quad$ $\omega_{S1} = \pi / 2N$

**P-Mode** **Equivalence Condition** **S-Mode**

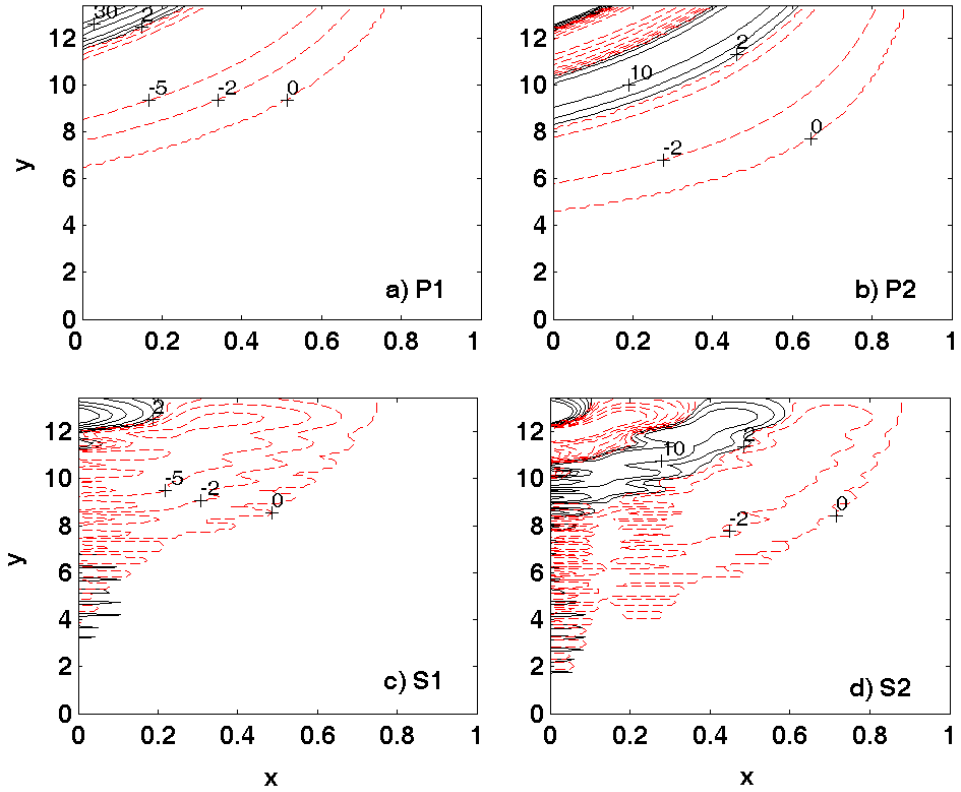
# Theoretical Solution

$N=Y_N^2/4$ ➔ S-mode = P-mode

## Eigenvalues

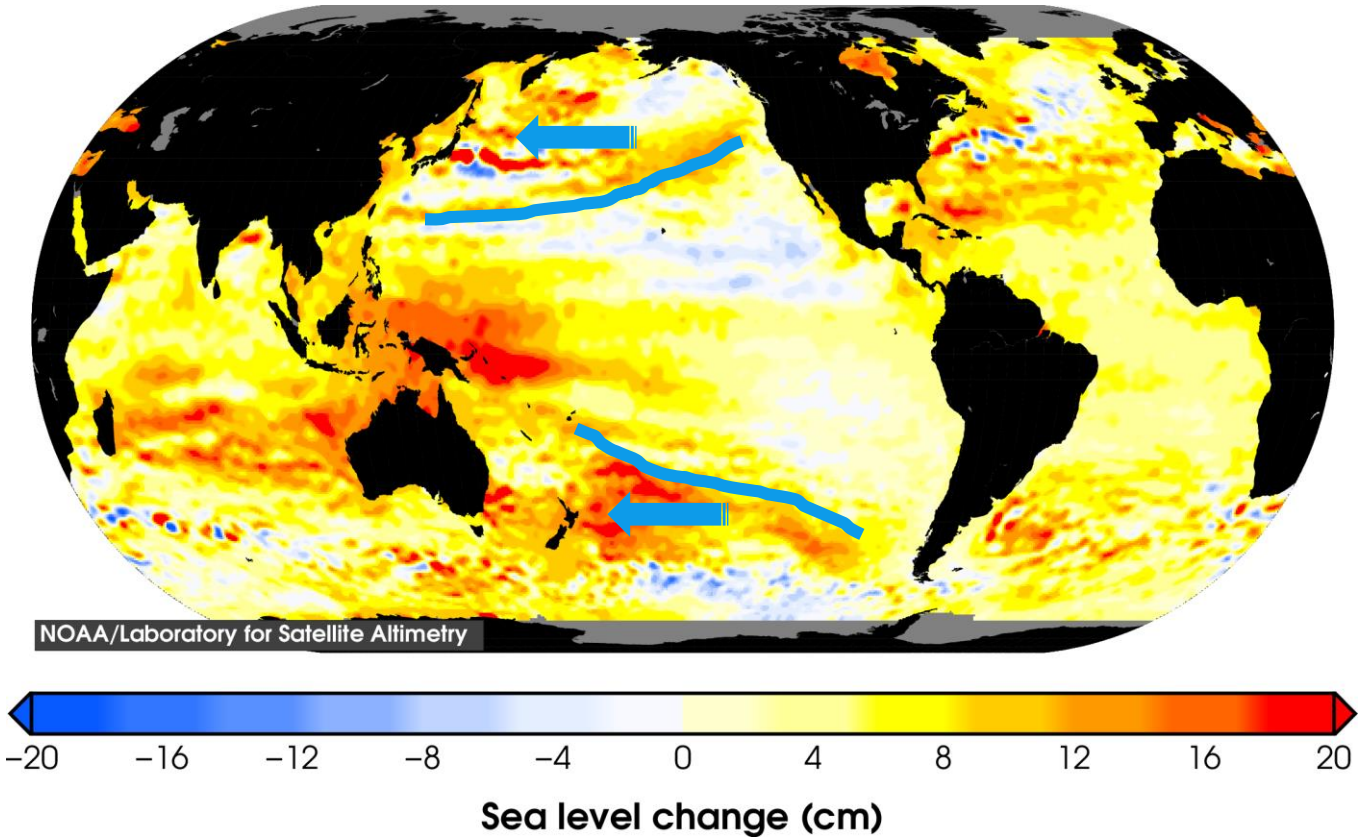



## Eigenfunctions



# Rossby Wave Dynamics

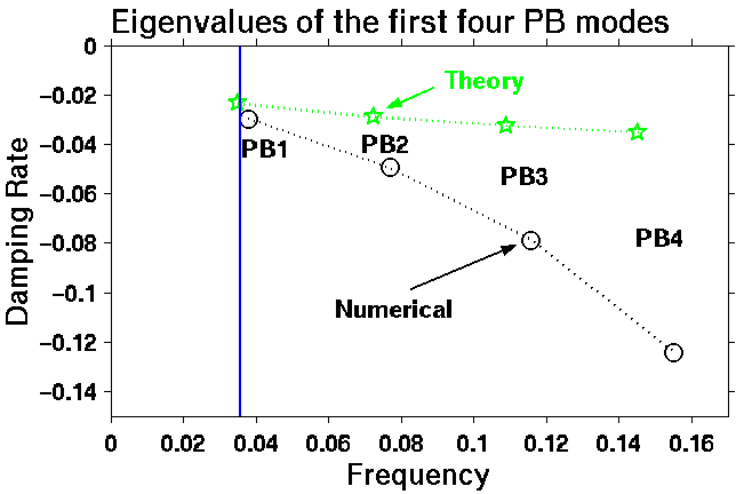
Topex/Poseidon SSHA: Large-scale ocean wave (1993-2014)



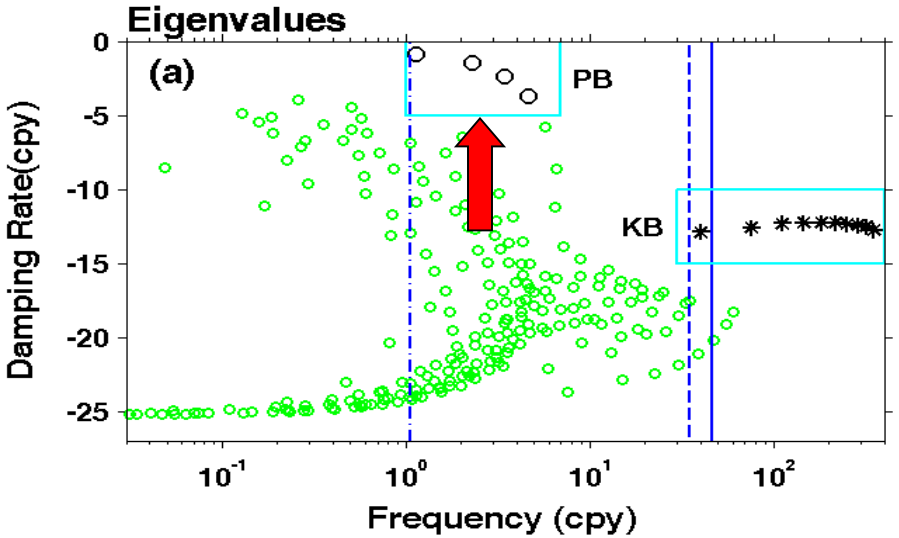
# Numerical Solution

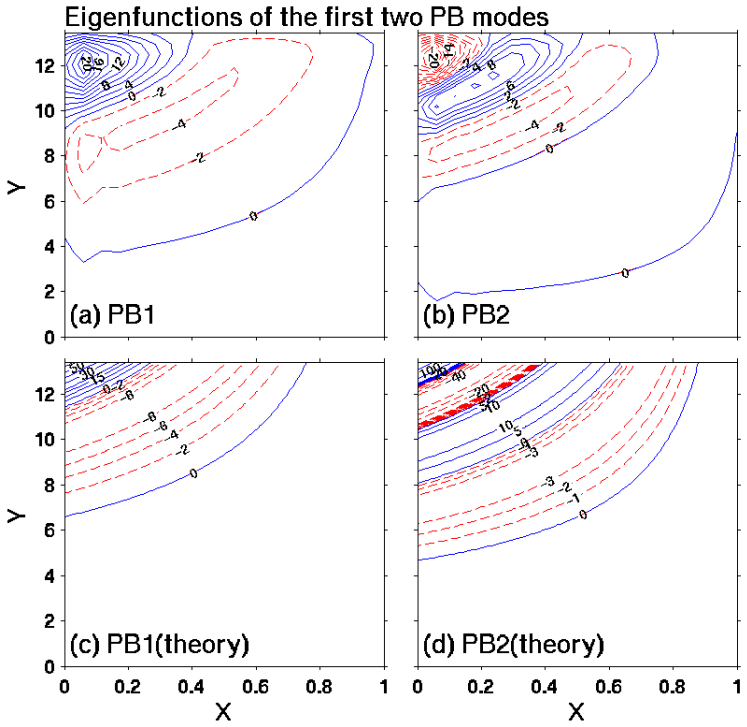
$$\begin{cases} u_t - yv + h_x + ru = 0 \\ v_t + yu + h_y + rv = 0 \\ h_t + u_x + v_y = 0 \end{cases} \Rightarrow \begin{pmatrix} u \\ v \\ h \end{pmatrix} = e^{-i\sigma t} \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix} (x, y)$$

$$\Rightarrow i\sigma \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix} = \begin{pmatrix} r & -y & \partial_x \\ y & r & \partial_y \\ \partial_x & \partial_y & 0 \end{pmatrix} \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix} = L \begin{pmatrix} \hat{u} \\ \hat{v} \\ \hat{h} \end{pmatrix}$$




P-mode -- the least damping mode

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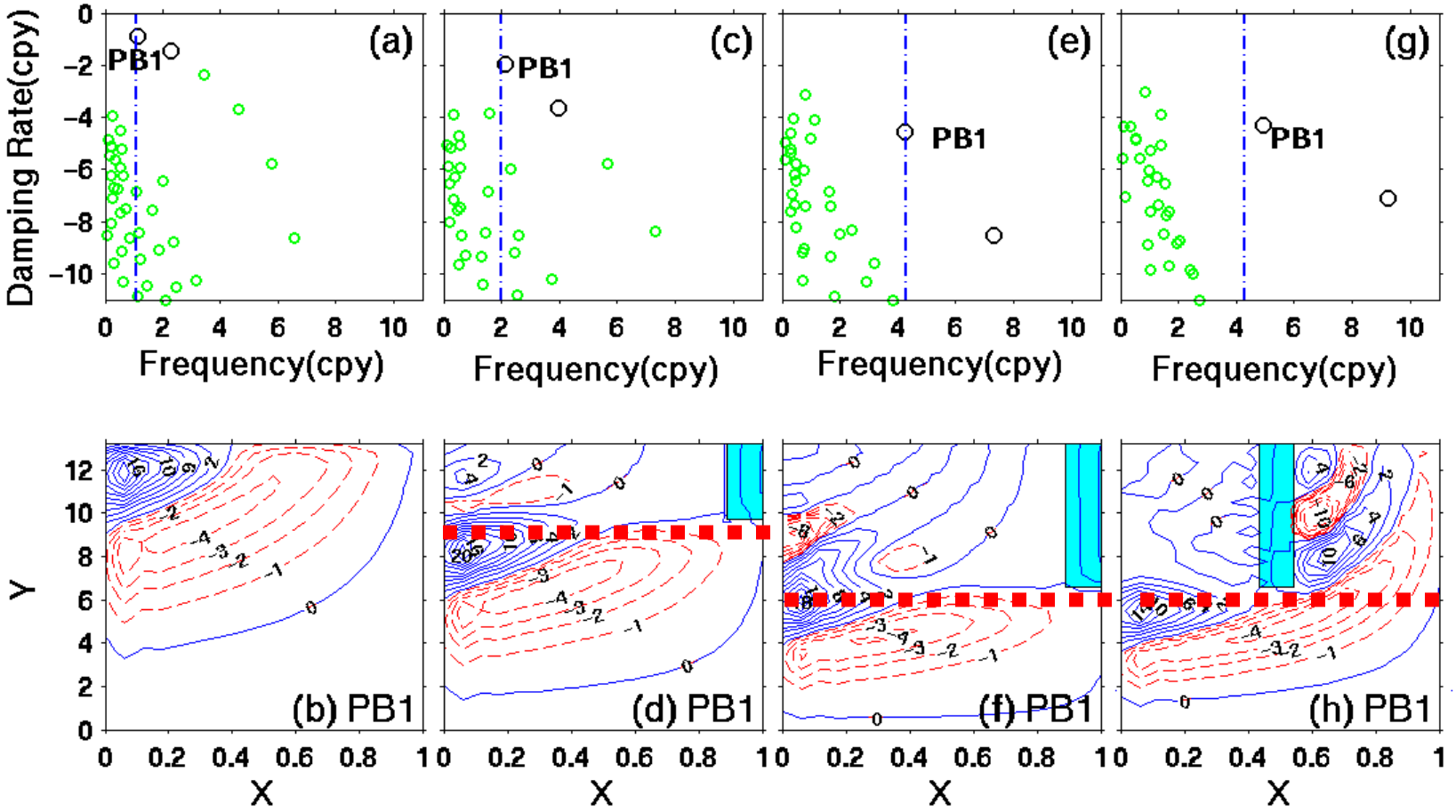
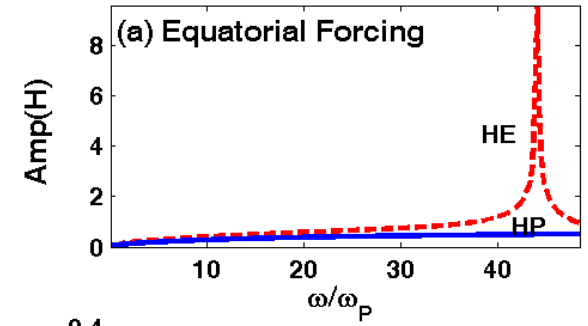
# Physically Meaningful Modes

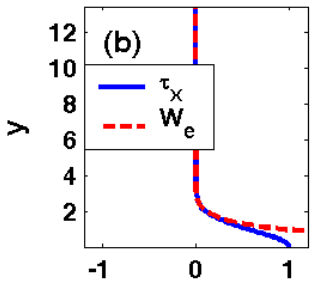
# What Determines the P-mode?

*Effective* northern basin boundary

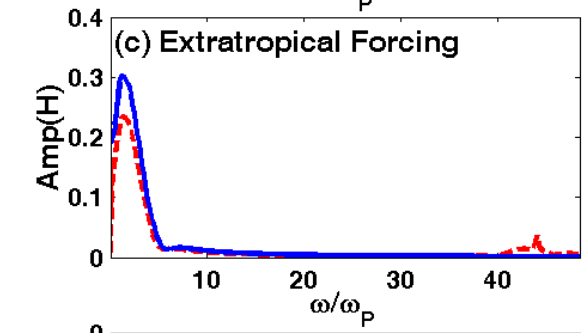


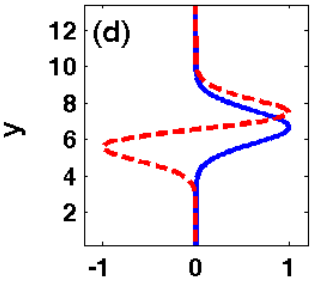
# Forced Response: Theoretical Solution



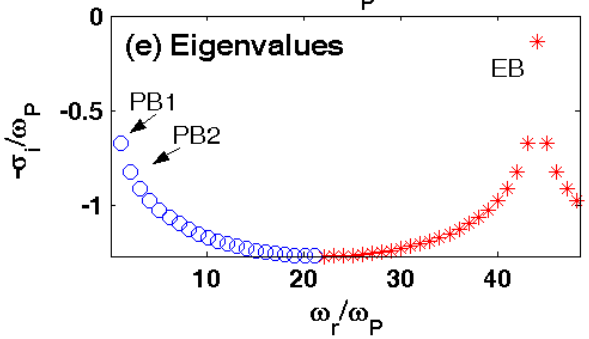




Equatorial Wind



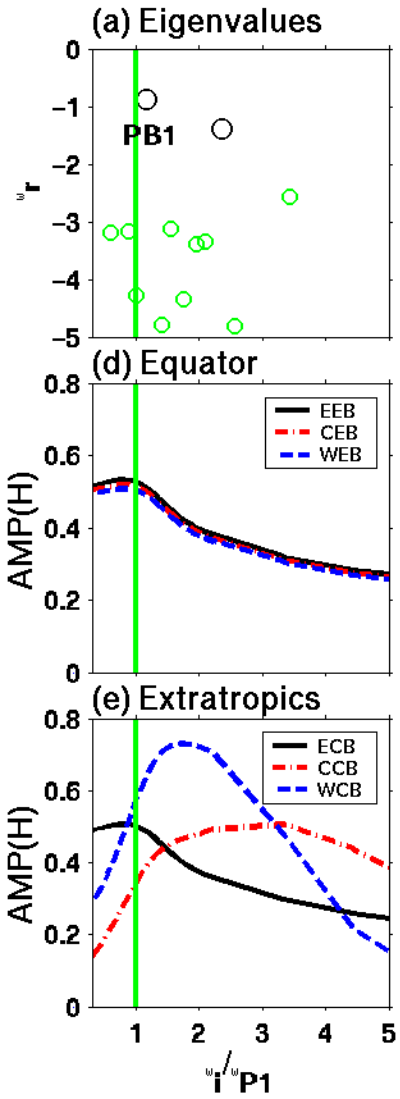



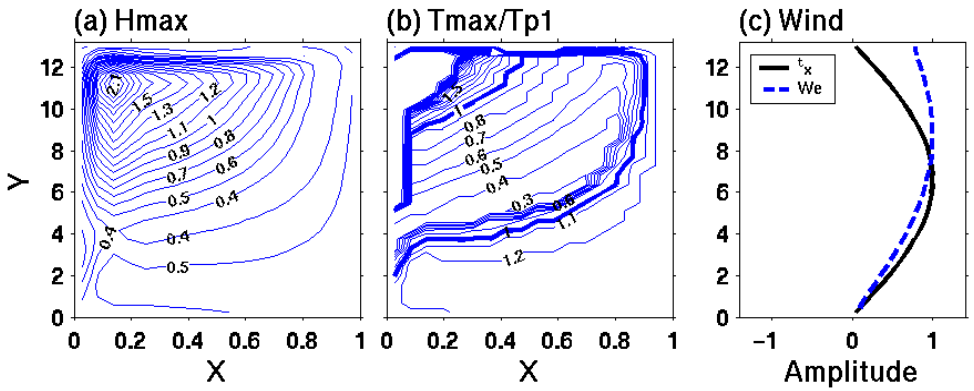

Extratropical Wind




Mechanism:
Resonance of P-mode

# Forced Response: Numerical Solution

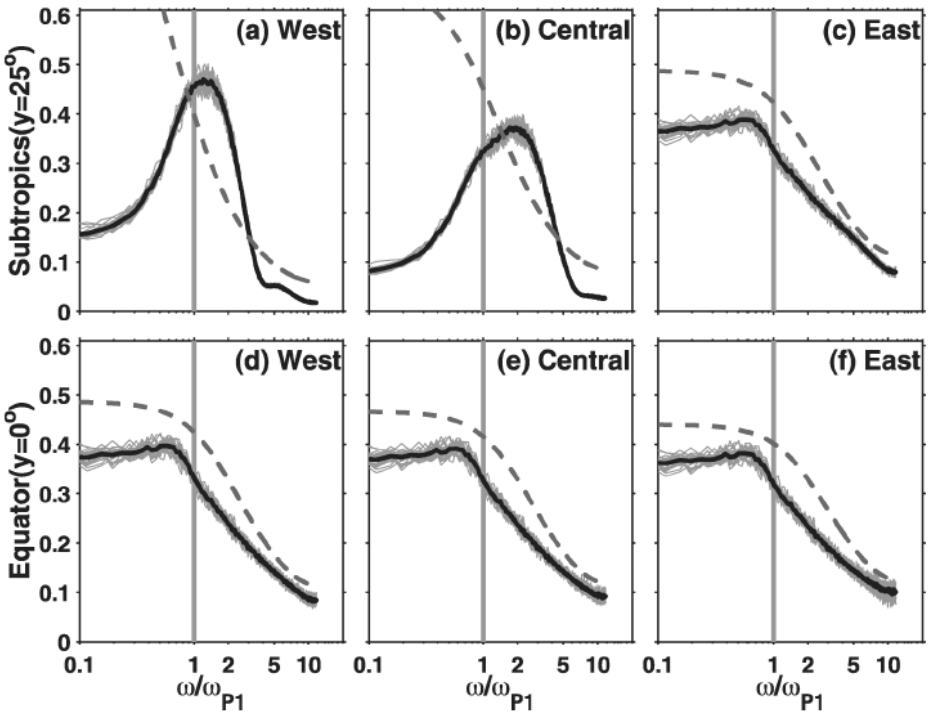



Equatorial response forced by Extratropical wind

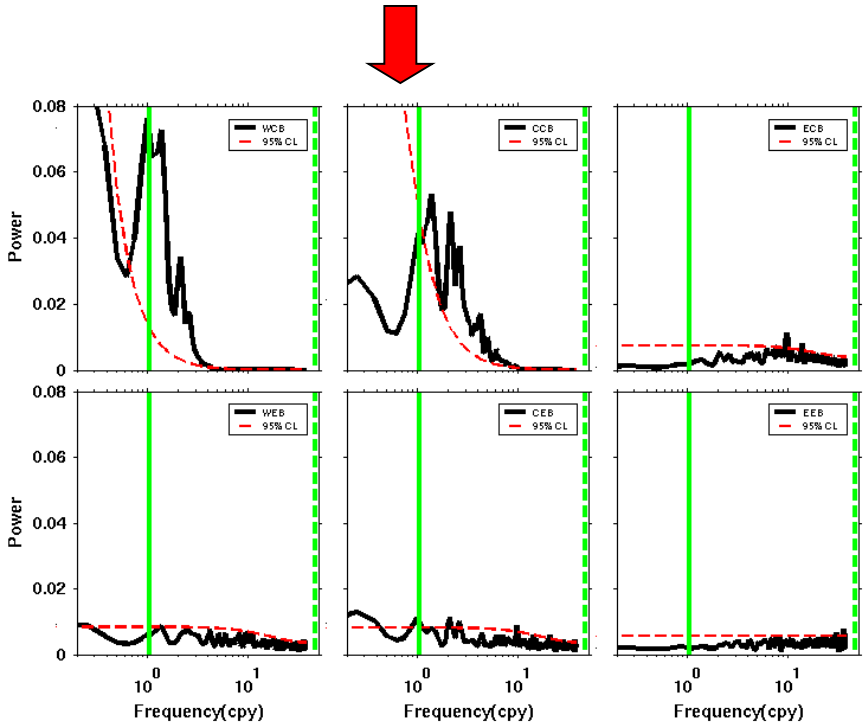
Extratropical response

# SW Model Forced by Stochastic Wind



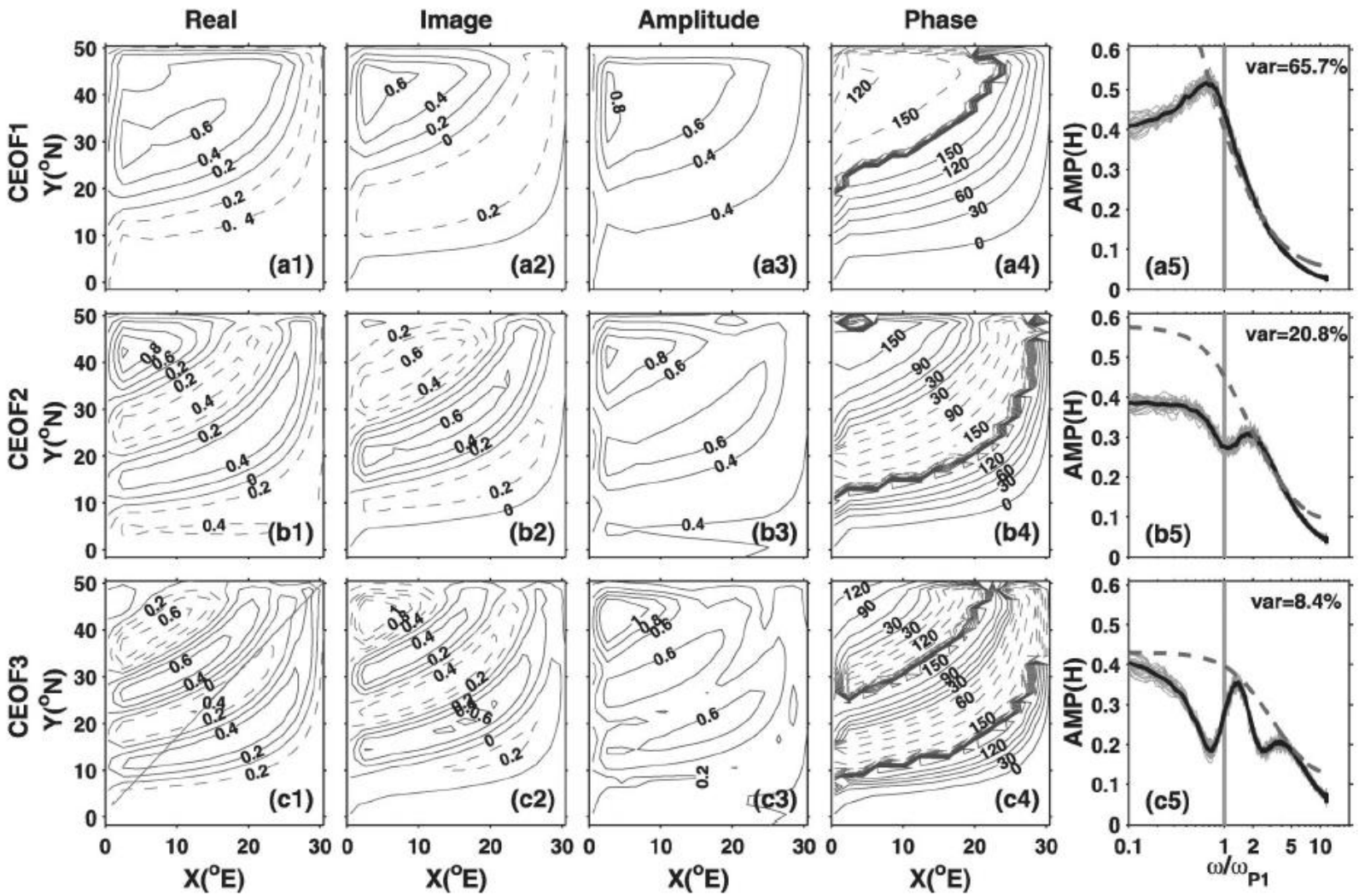

Extratropical Forcing

Equatorial Forcing

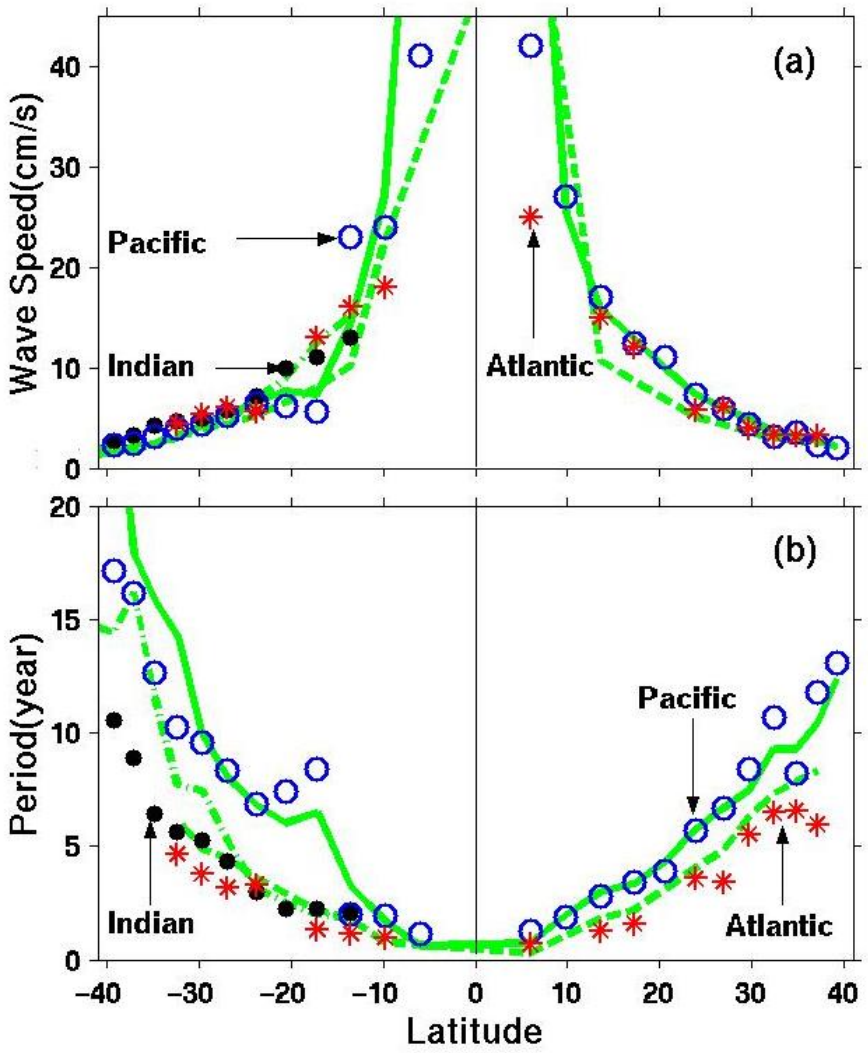



Only extratropical forcing ➔ decadal response in Tropics

# SW Model Forced by Stochastic Wind



# Wave Speed and Cross Basin Time




Wave Speed

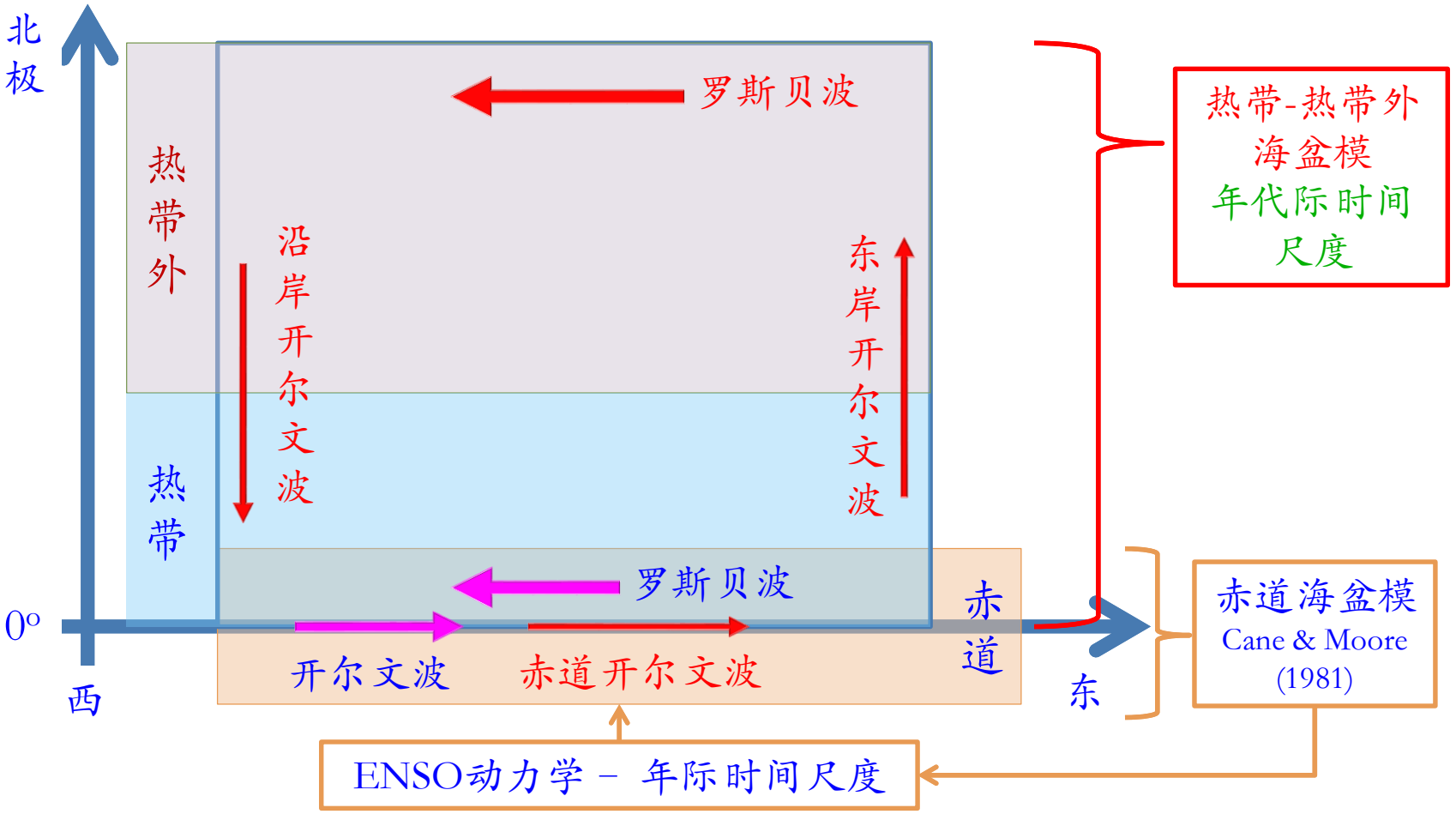
*D. Chelton*

Cross-Basin Time

*Yang and Liu, 2003*

# Planetary Wave Basin Mode

基于观测的热带-热带外海盆模型



# Tropical Decadal Memory

Origin:

From extratropics

Time scale:

Determined by the PW cross-basin time along the effective northern basin boundary

Mechanism:

Resonance of P-mode

# Discussion

How to further understand decadal climate variability in the coupled model ?

- Diagnostics
- Dynamic sensitivity experiments, modeling surgery in the coupler (PC, ensemble coupling), ocean, atmosphere …

LaCOAS

北京大学气候与海-气实验室

Thanks

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