Forced vs Intrinsic Variability of the Kuroshio Extension System on Decadal Timescales

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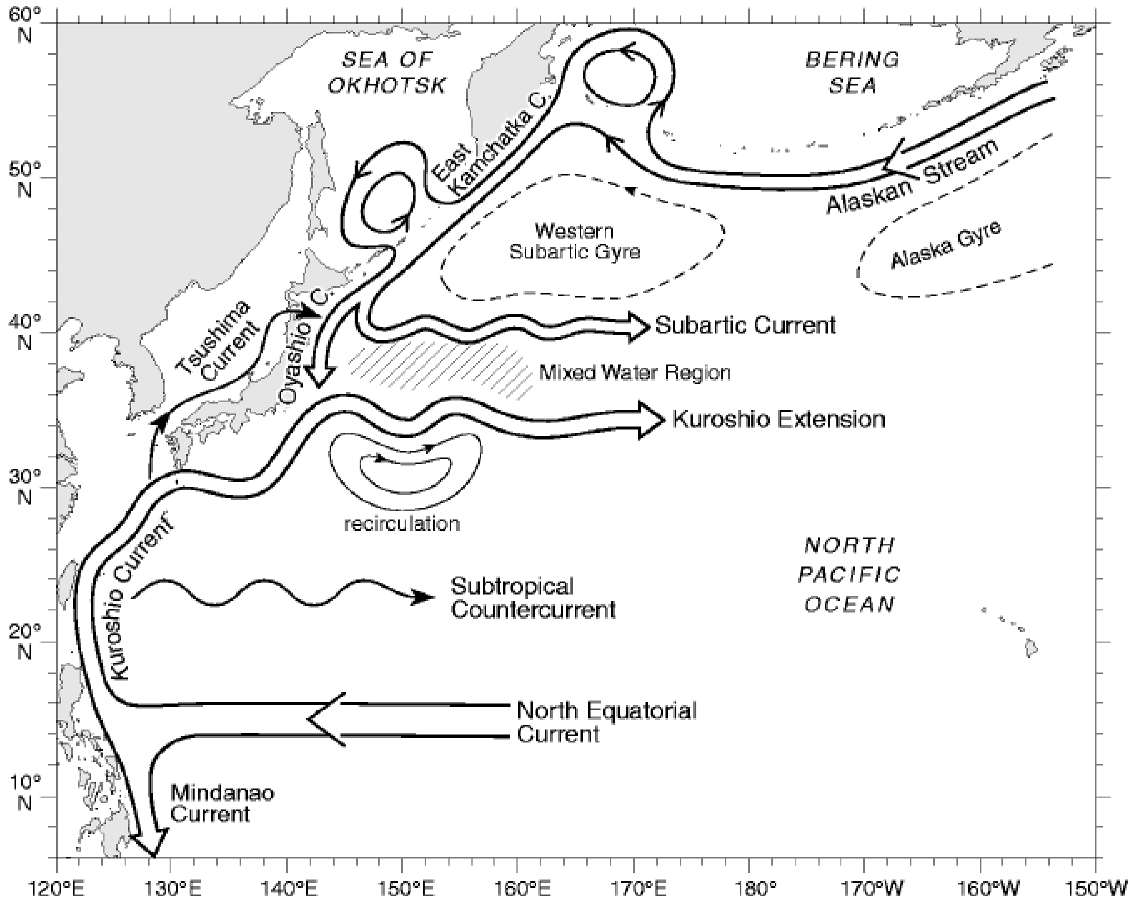
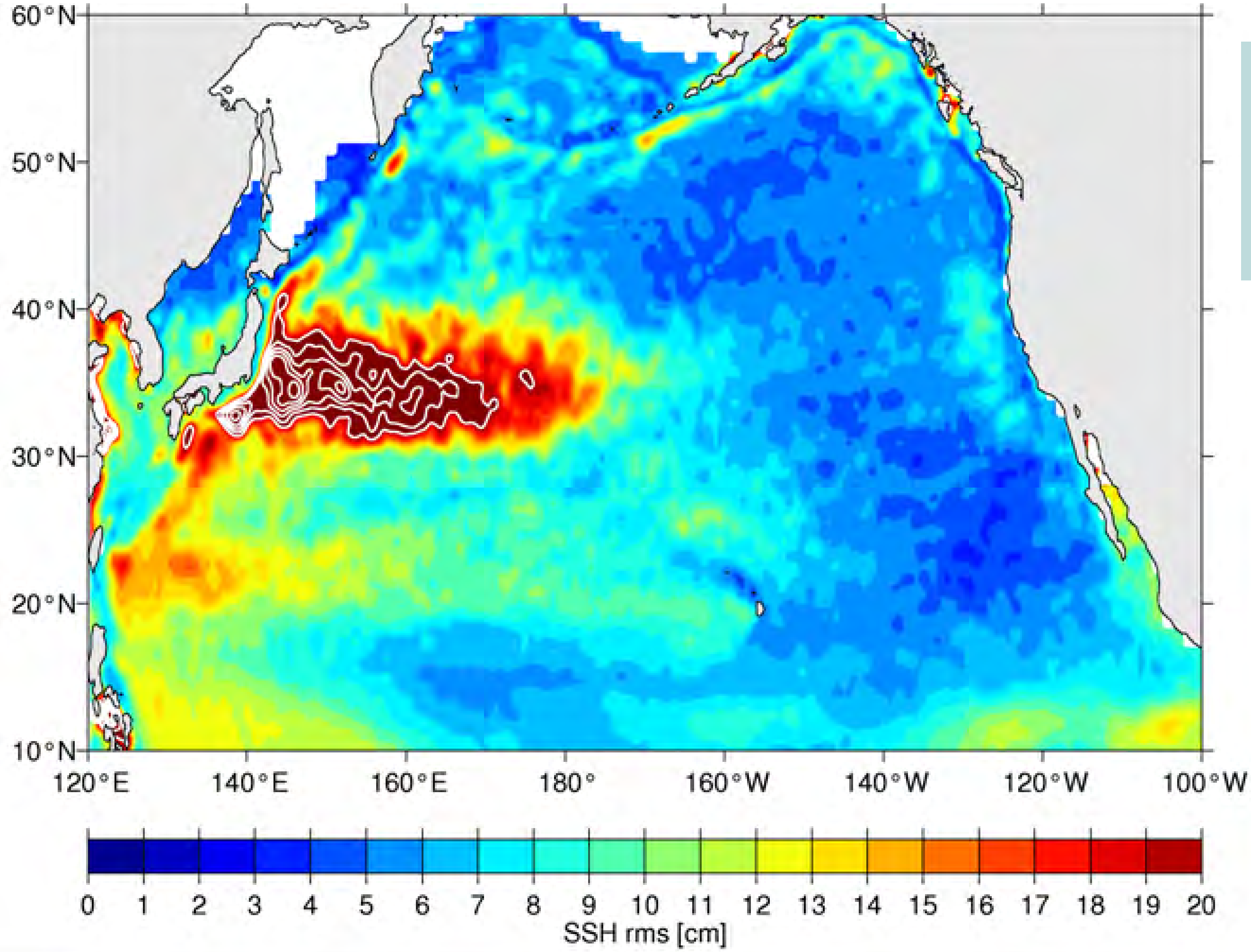


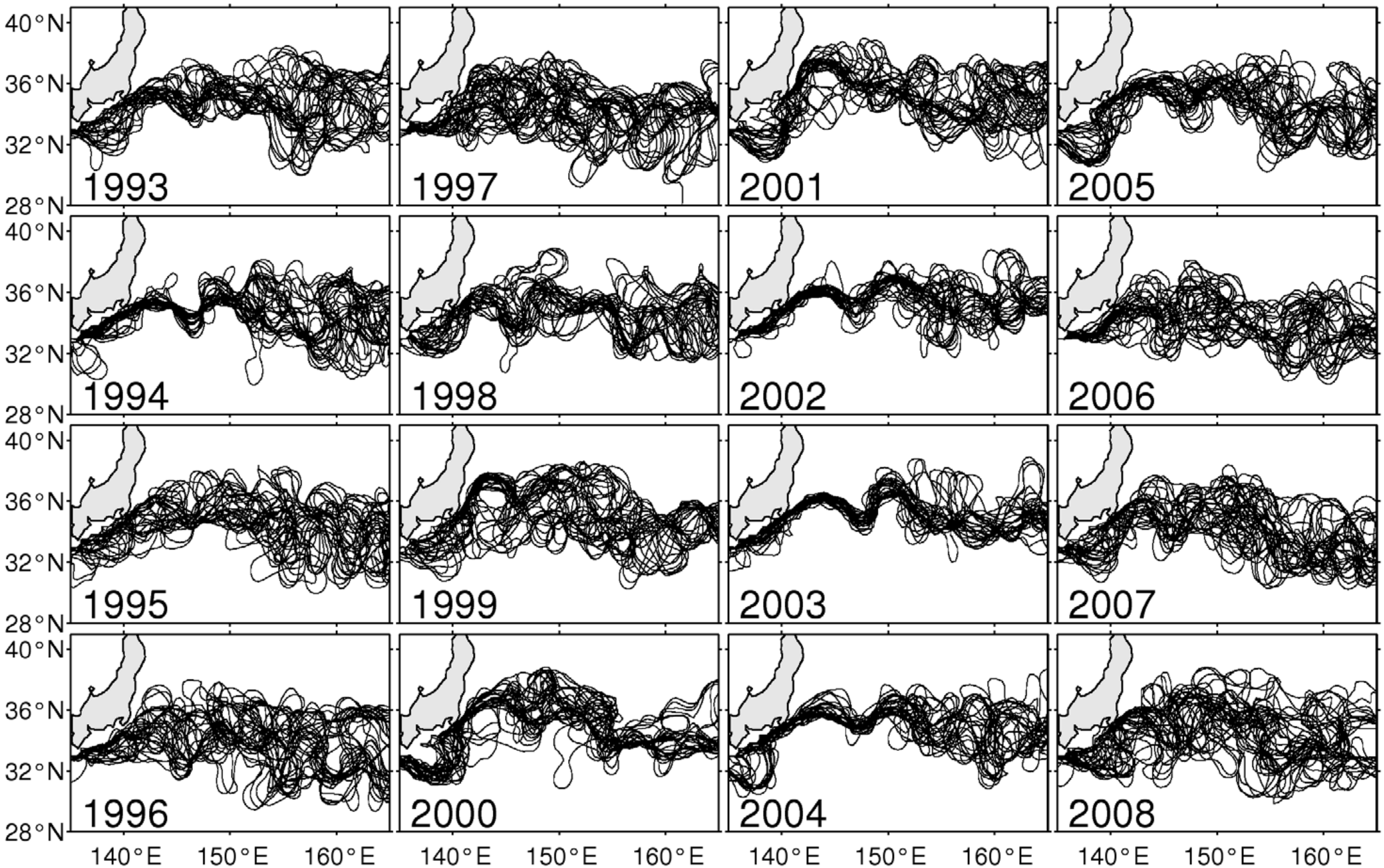


Satellite altimeter-derived rms SSH variability (10/1992-present)

Topics

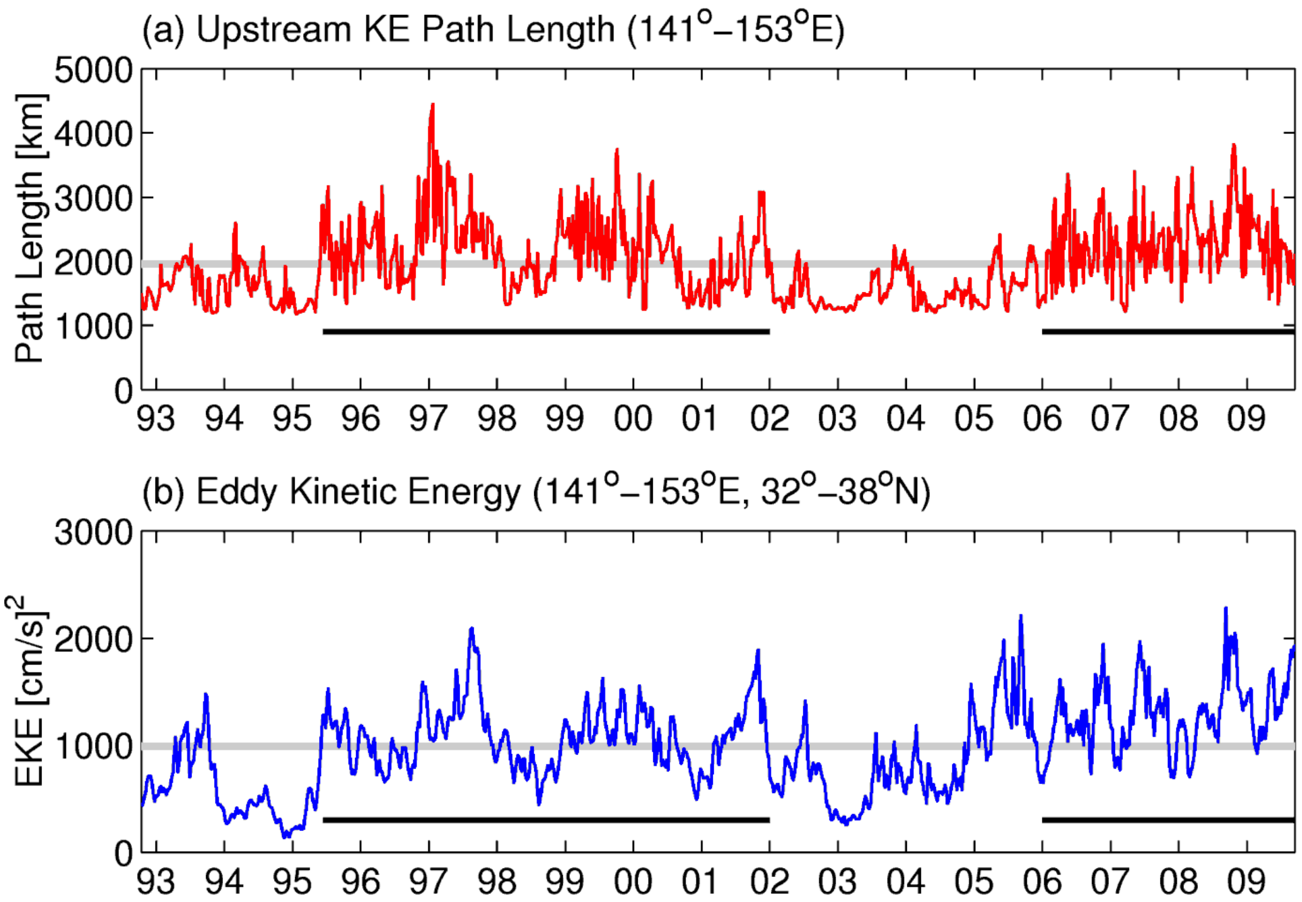
- **Observed decadally-varying KE system**
- **Relative roles of wind forcing vs nonlinear eddy dynamics**
- **Decadal KE variability as a midlatitude coupled mode**

Semi-monthly Kuroshio Extension paths (1.7m SSH contours)



Stable yrs: 1993-94, 2002-04

Unstable yrs: 1996-2001, 2006-08



KE path length

Level of EKE

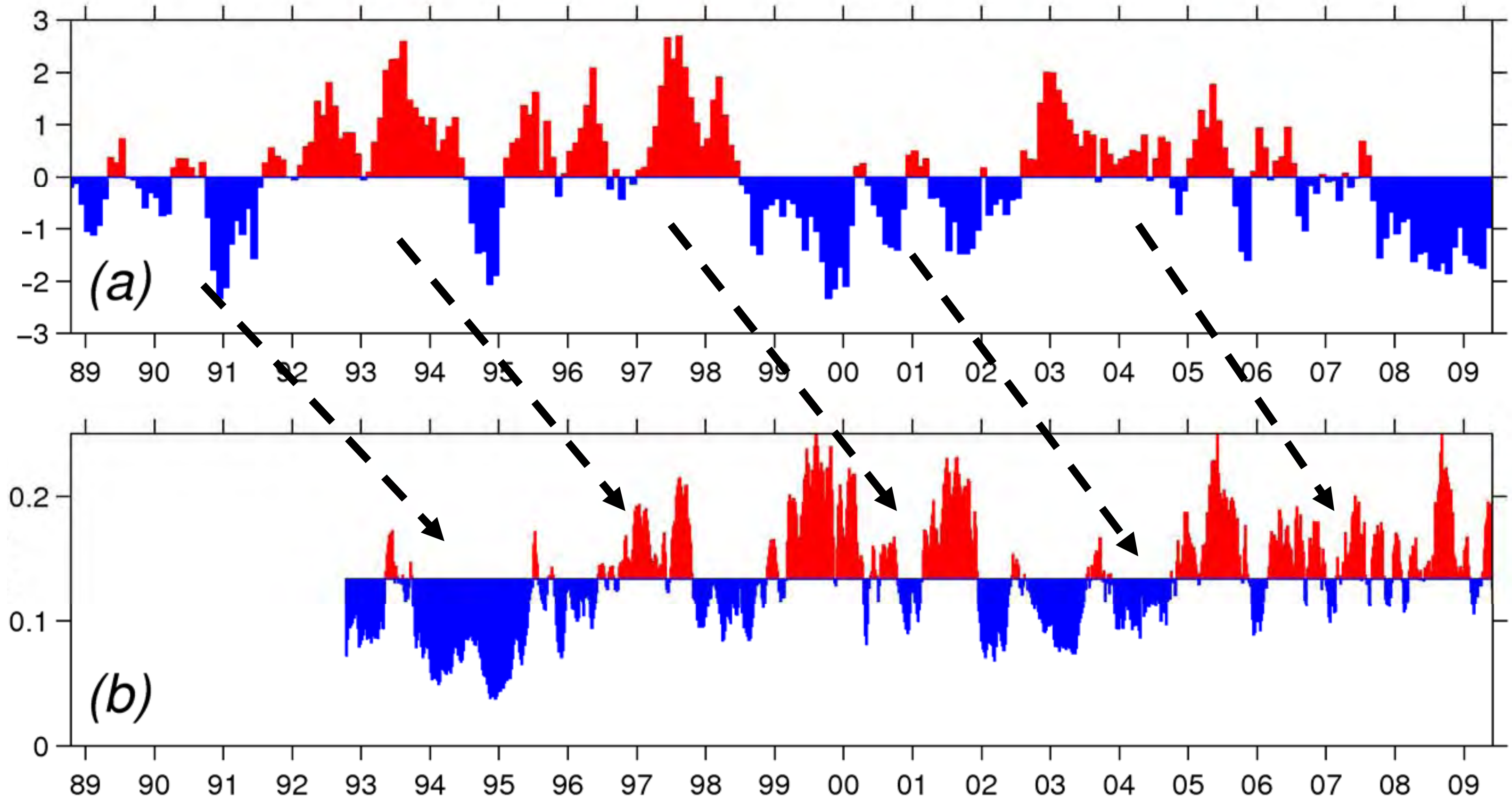
Stable yrs: 1993-94, 2002-04

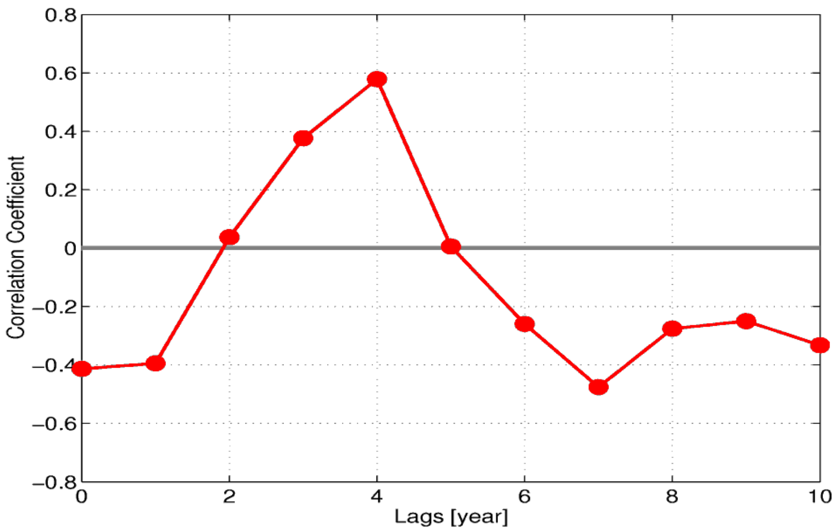
Unstable yrs: 1996-2001, 2006-08

- **Q1: What causes the transitions between the stable and unstable dynamic states of the KE system?**

PDO index

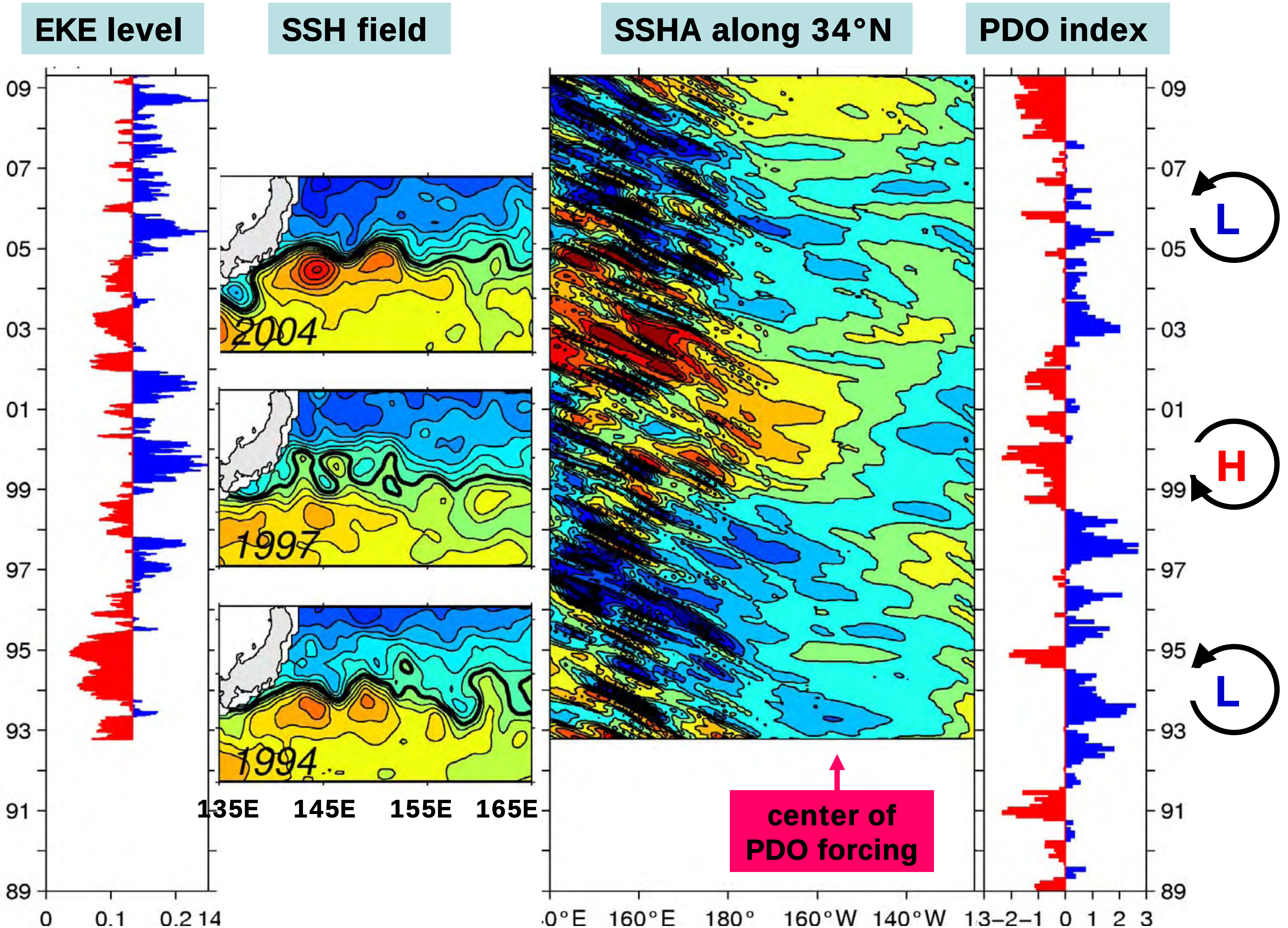
EKE level





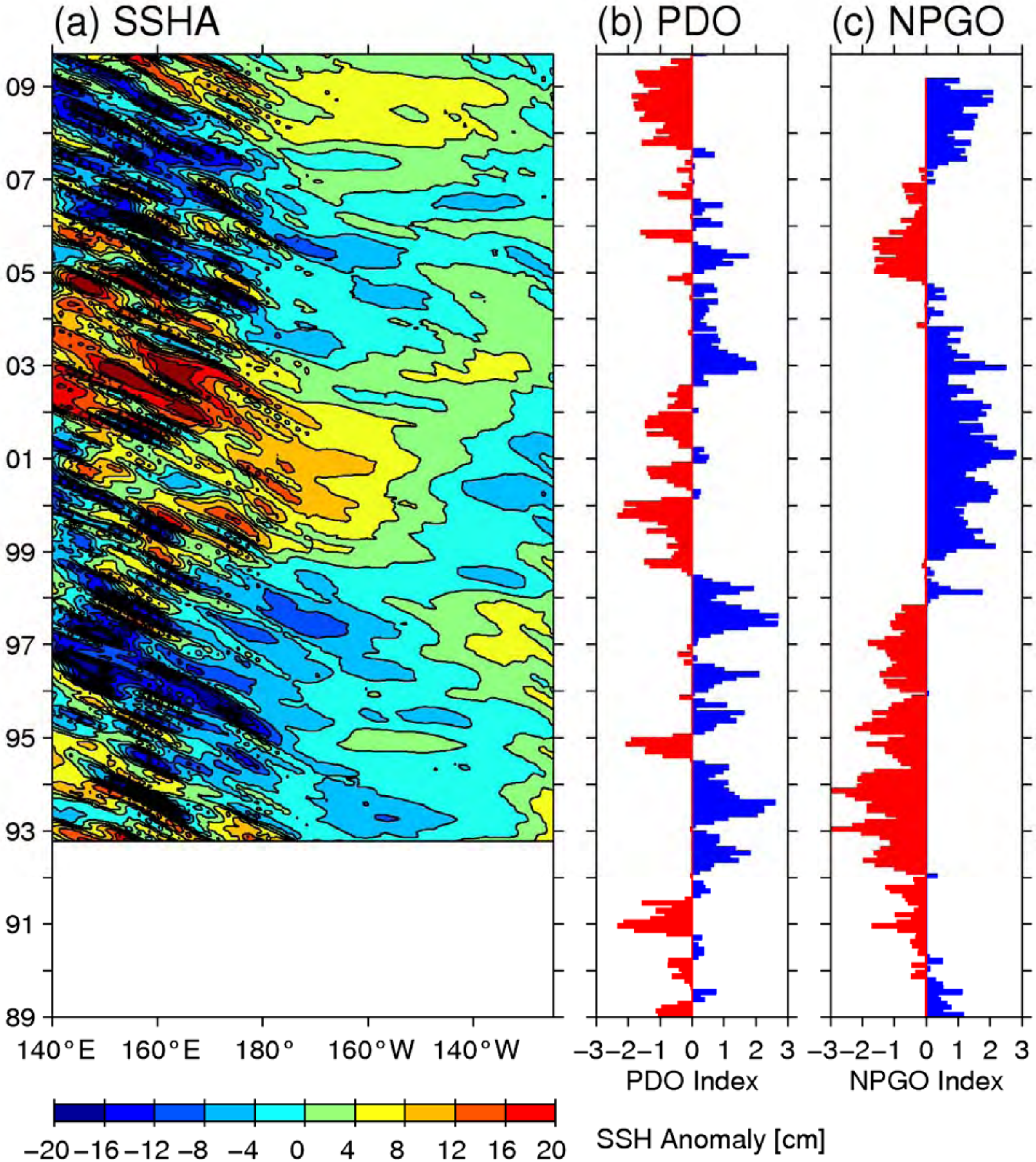
Mesoscale EKE level in the KE region lags the PDO index by ~ 4 yrs

(e.g. Miller et al. 1998; Seager et al. 2001; Schneider et al. 2002; Qiu 2002; Taguchi et al. 2007; Ceballos et al. 2009)



EKE level
SSH field
SSHA along 34°N
PDO index
2004
1997
1994
135E
145E
155E
165E
center of
PDO forcing
L
H
L
09
07
05
03
01
99
97
95
93
91
89
0
0.1
0.2
160°E
180°
160°W
140°W
-2
-1
0
1
2
3

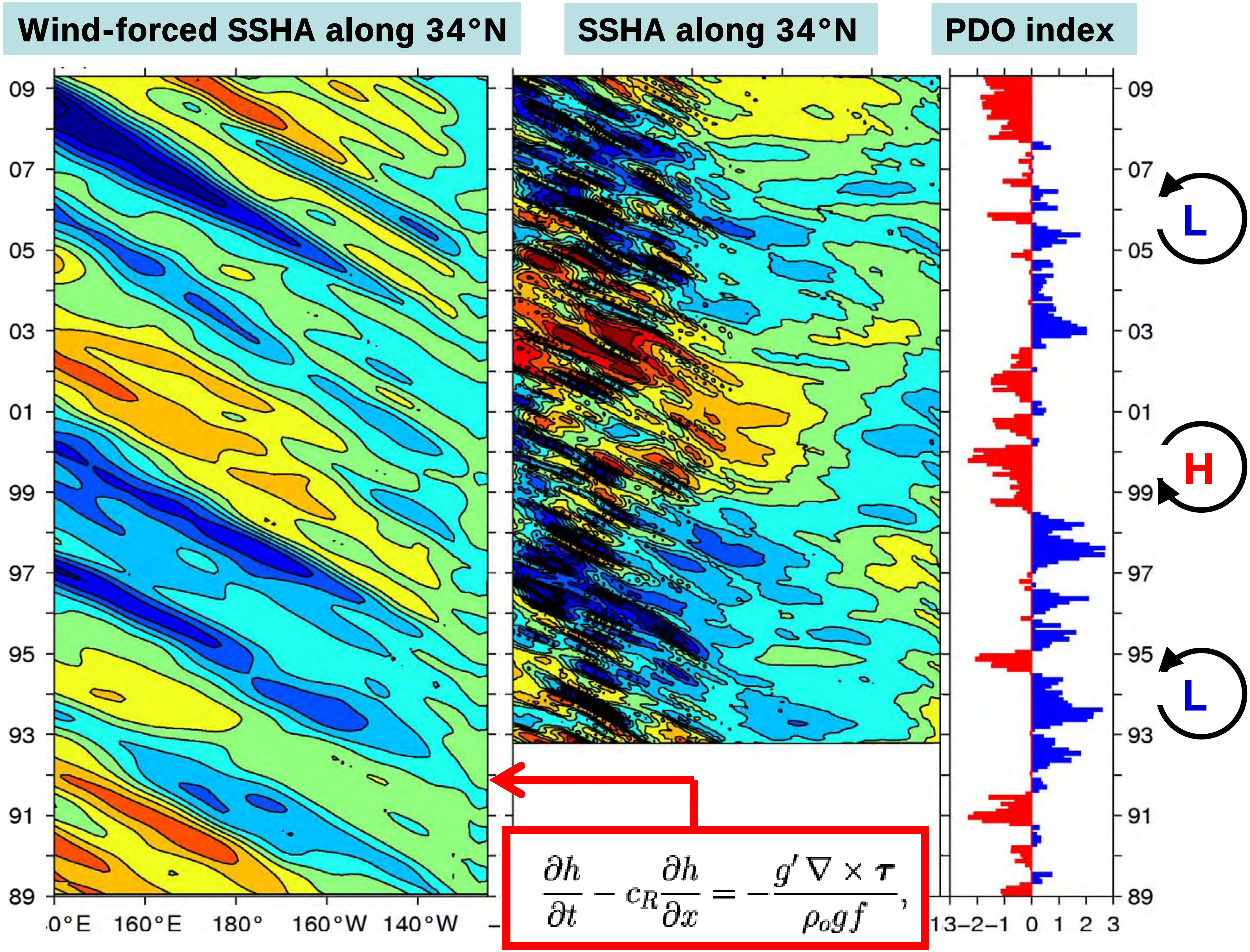
(Di Lorenzo et al. 2008)



PDO-NPGO linear correlation:

-0.38 (monthly)

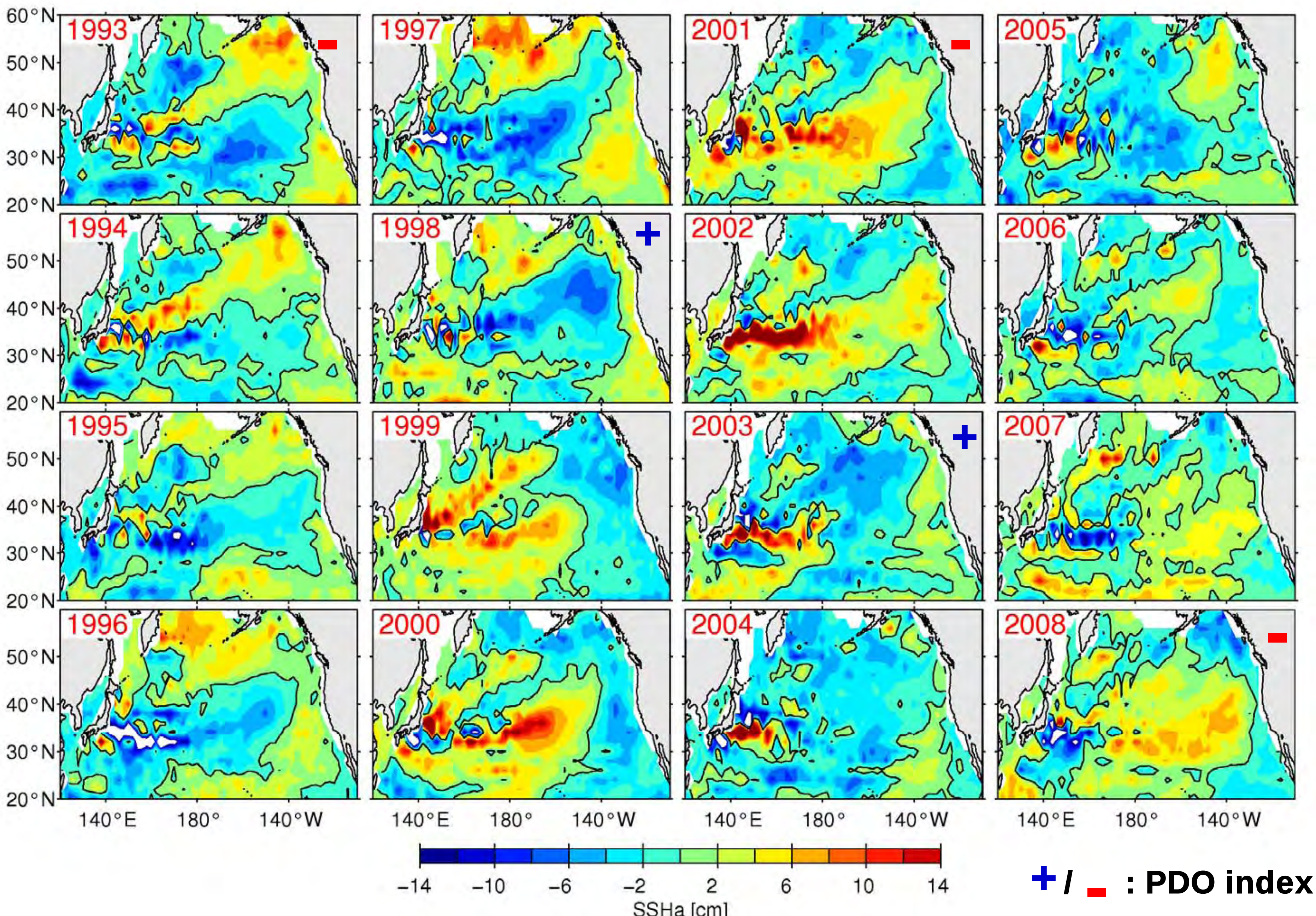
-0.62 (interannual)


Wind-forced SSHA along 34°N
SSHA along 34°N
PDO index
09
07
05
03
01
99
97
95
93
91
89
0°E
160°E
180°
160°W
140°W
3 −2 −1 0 1 2 3
L
H
L
$$\frac{\partial h}{\partial t} - c_R \frac{\partial h}{\partial x} = -\frac{g' \nabla \times \boldsymbol{\tau}}{\rho_o g f},$$

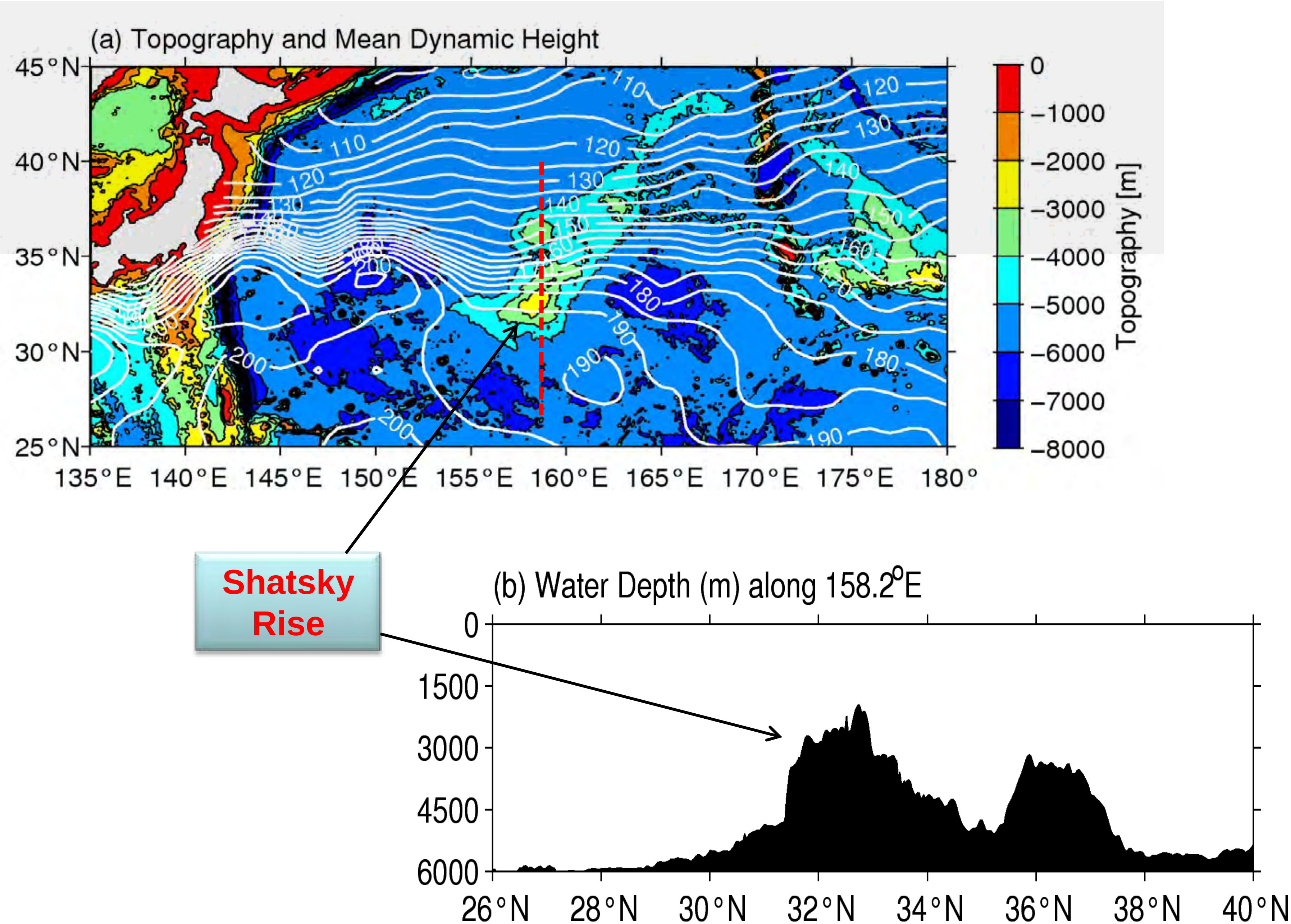
- **Q1: What causes the transitions between the stable and unstable dynamic states of the KE system?**

- **Q2: What roles does the nonlinear ocean dynamics play?**

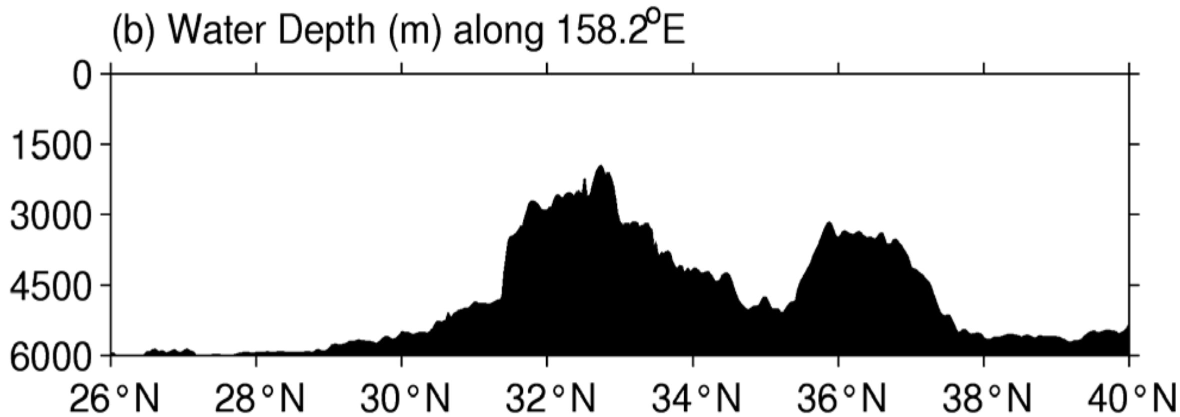
Yearly SSH anomaly field in the North Pacific Ocean

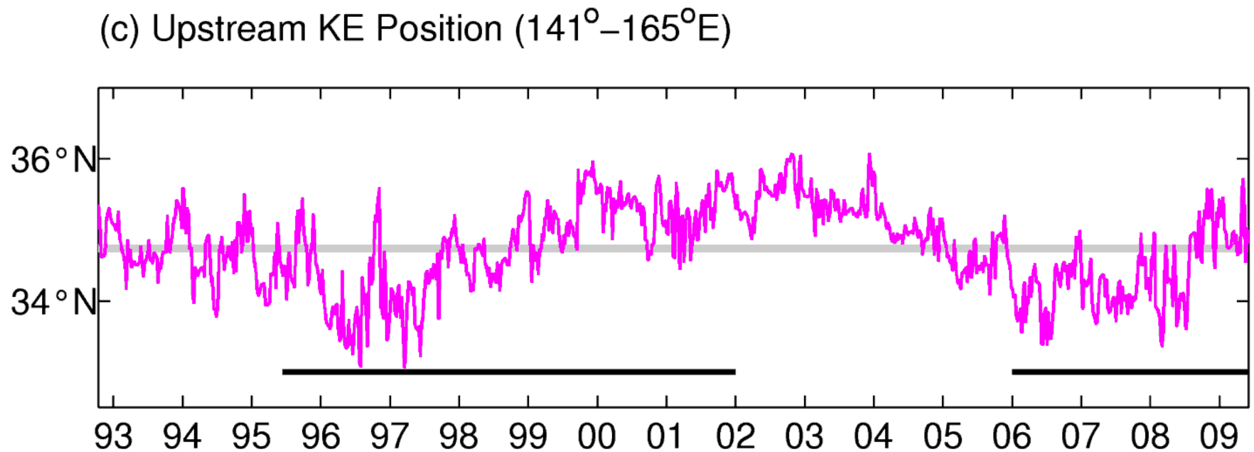


+ / − : PDO index

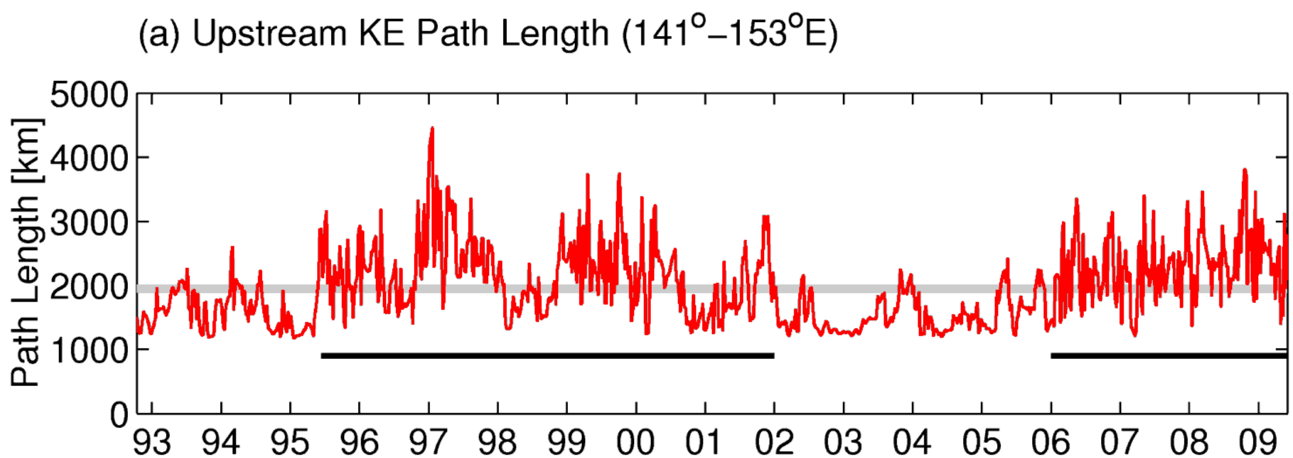


(a) Topography and Mean Dynamic Height
45°N
40°N
35°N
30°N
25°N
135°E 140°E 145°E 150°E 155°E 160°E 165°E 170°E 175°E 180°
0
−1000
−2000
−3000
−4000
−5000
−6000
−7000
−8000
Topography [m]
Shatsky Rise
(b) Water Depth (m) along 158.2°E
0
1500
3000
4500
6000
26°N 28°N 30°N 32°N 34°N 36°N 38°N 40°N





KE y-position



KE path length

Feedback of eddies to the modulating time-mean flow:

- **Surface ocean vorticity equation:**

$$\frac{g}{f}\frac{\partial(\nabla^2\overline{h})}{\partial t} + \frac{g}{f}J(\overline{f+\zeta}, \overline{h}) = -\nabla\cdot(\overline{\mathbf{u}'\zeta'})$$

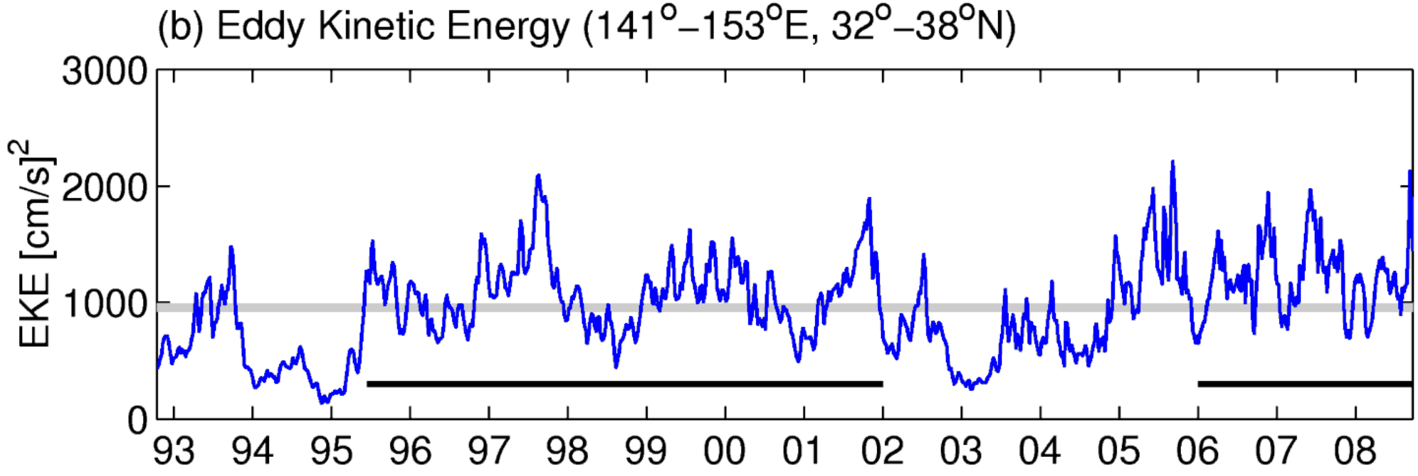
eddy-driven mean flow modulation

- **Evaluate:**

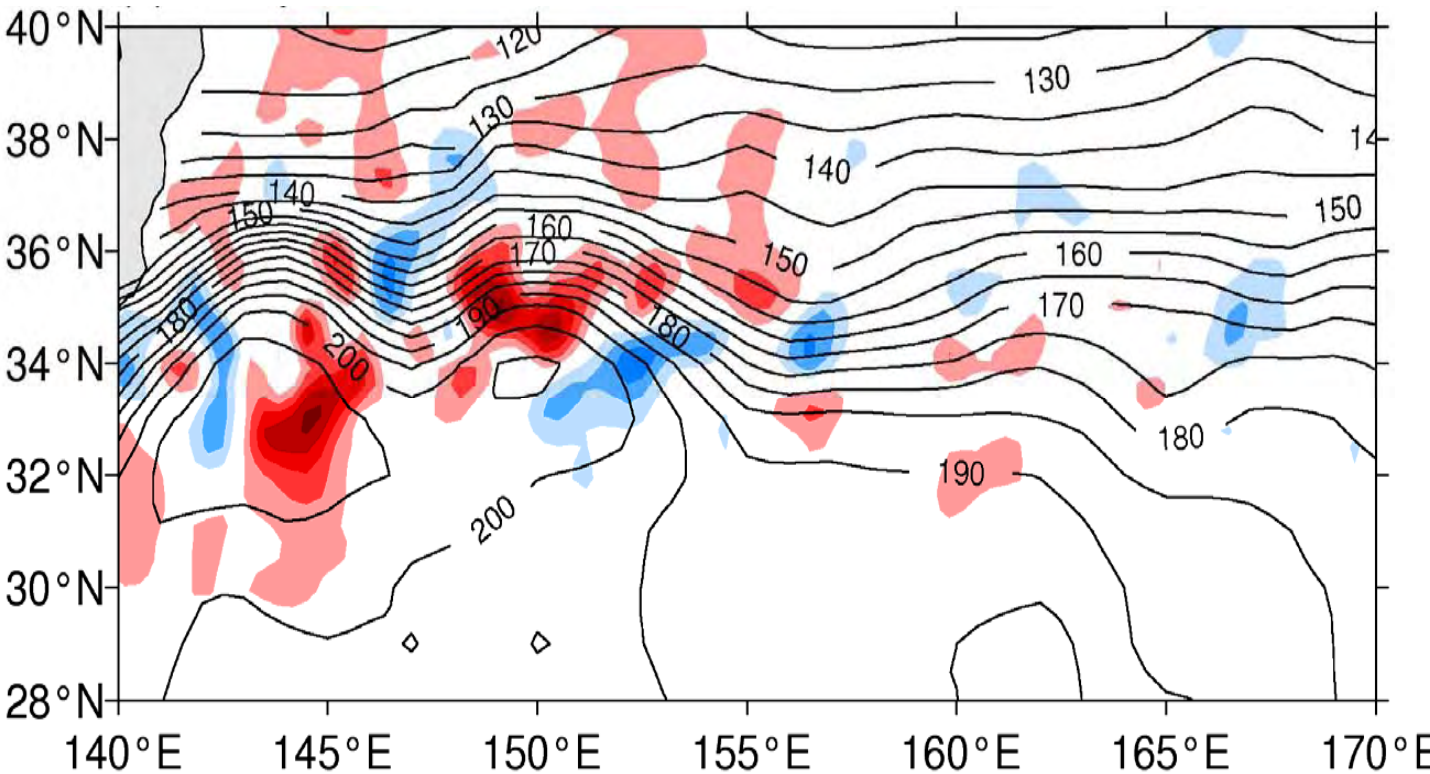
$$S(x,y,T) \equiv \frac{g}{f}\overline{h} = \nabla^{-2}\left[-\nabla\cdot(\overline{\mathbf{u}'\zeta'})\right]$$

mechanical feedback of eddies onto the time-varying SSH field (e.g. Hoskins et al. 1983, JAS)

- **Regress S(x,y,T) field to the observed EKE time series:**

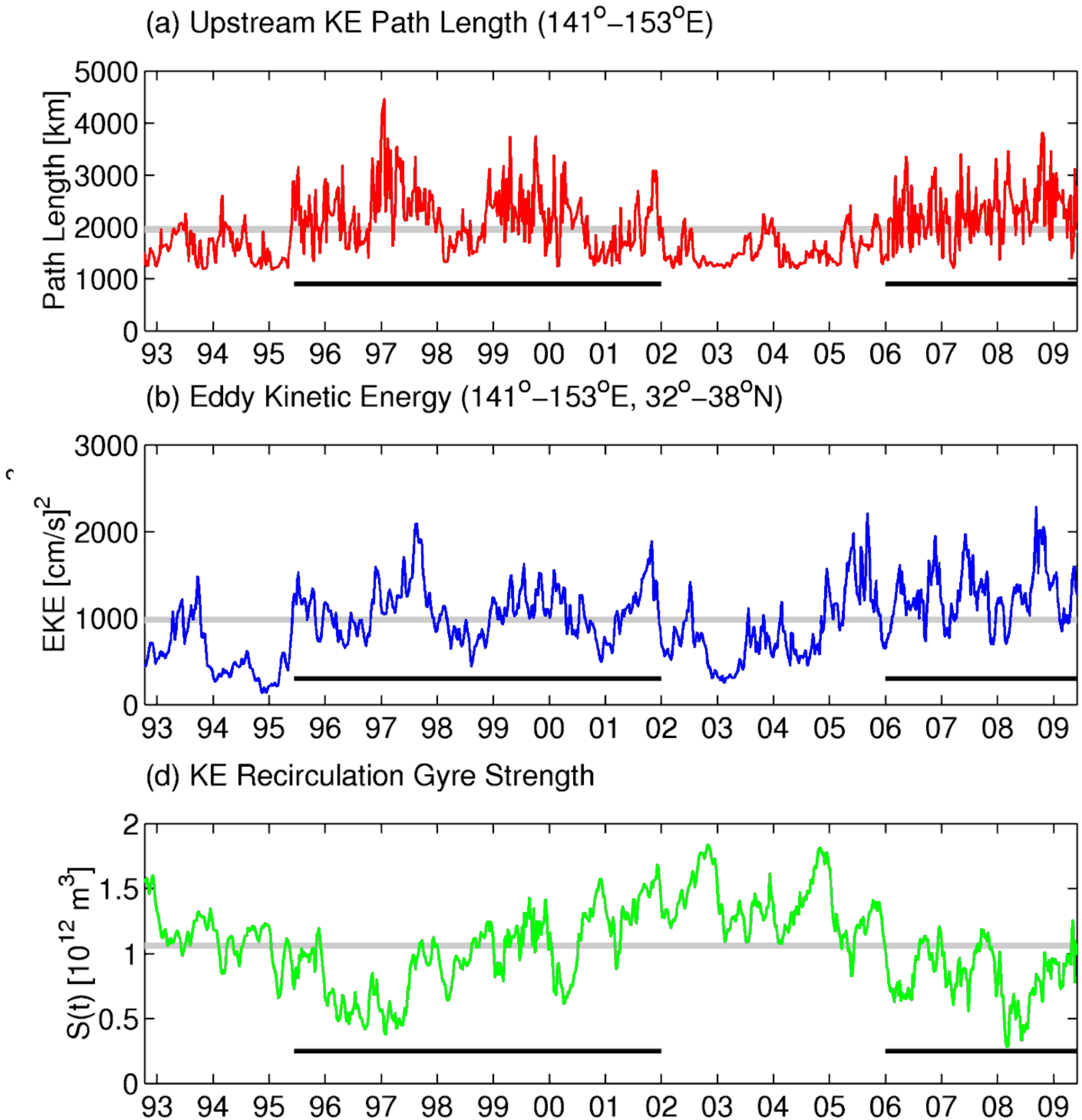


Eddy-forced S(x,y,T) field regressed to the EKE time series



contours: mean SSH field

- **+: anticyclonic forcing vs . –: cyclonic forcing**
- **In the upstream KE region, enhanced eddy variability works to increase the intensity of the southern RG.**
- **Enhanced eddy variability strengthens the two quasi-stationary meanders (cf. Rossby lee-wave dynamics)**



KE path length

Level of EKE

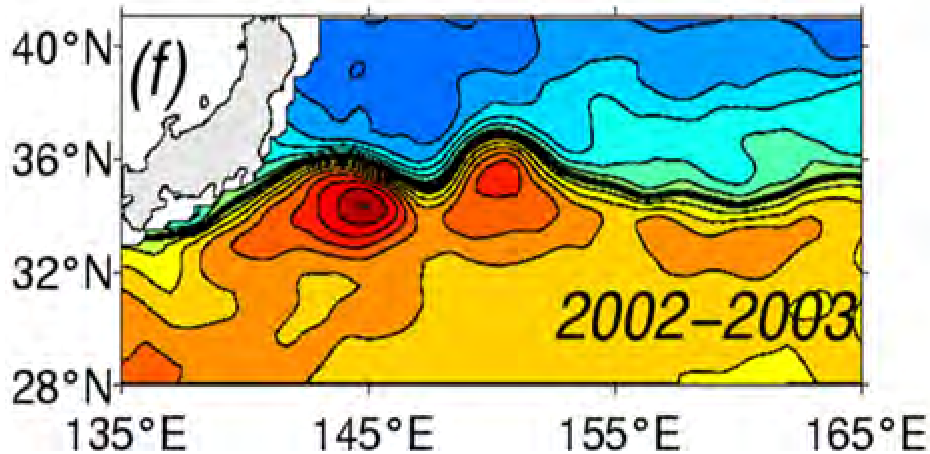
RG strength

Stable yrs: 1993-94, 2002-04

Unstable yrs: 1996-2001, 2006-08

Strong Jet / RG-Low EKE State

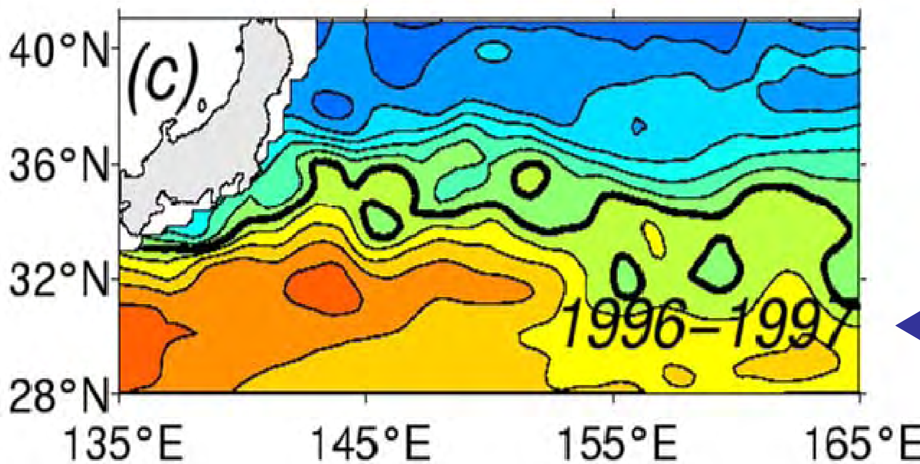
- Bypassing S.R. and reduced EKE level
- Strengthening RG and northerly KE jet
- Incoming positive SSHA
- Ekman conver-gence in the east



+ PDO

- Ekman diverg-ence in the east
- Incoming negative SSHA
- Weakening RG and southerly KE jet
- Overriding S.R. and enhancing local EKE level

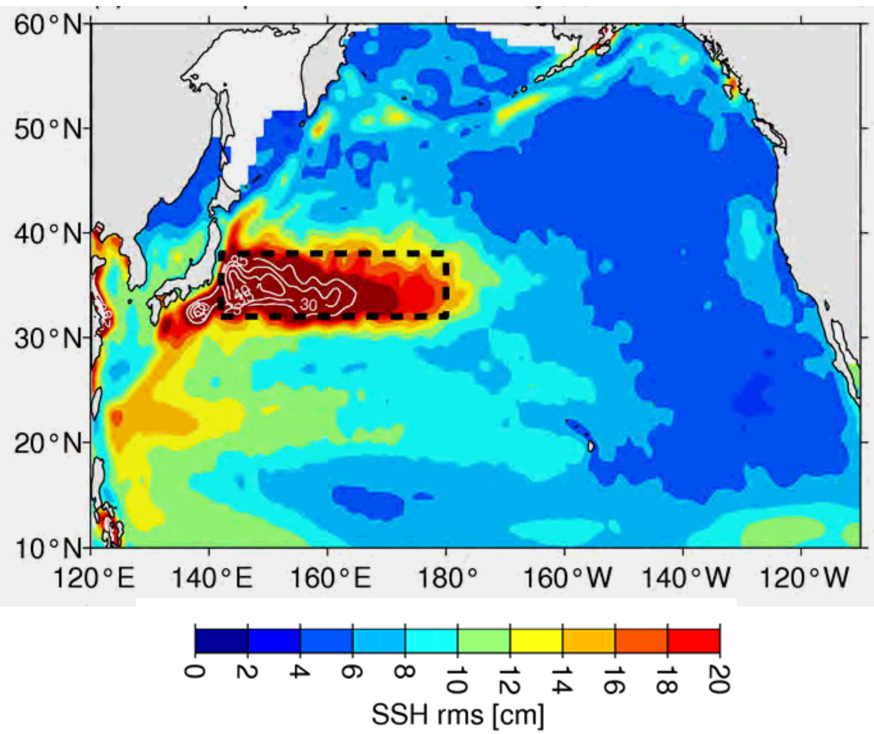
Weak Jet / RG-High EKE State



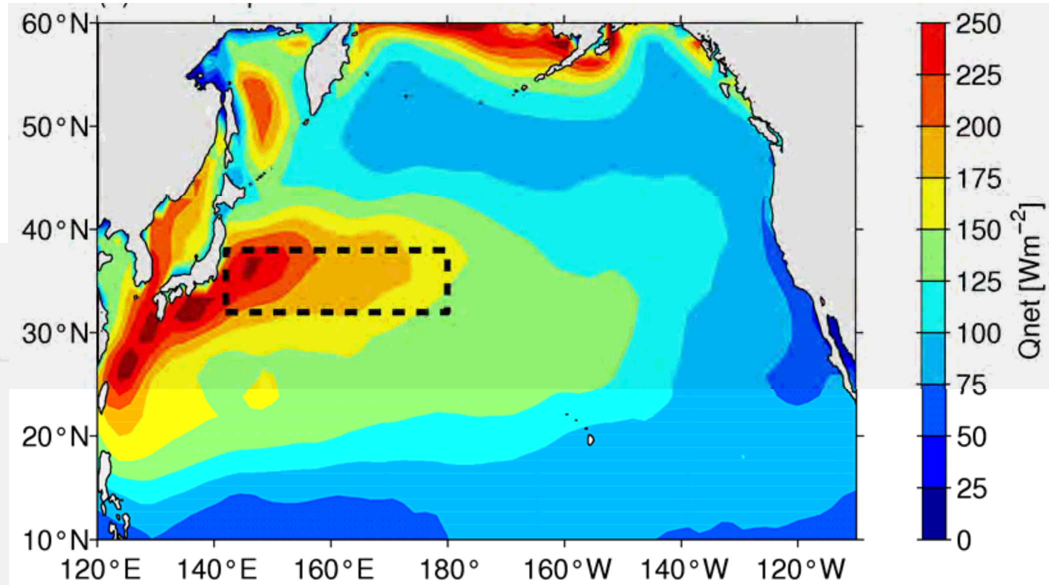
– PDO

- **Q1: What causes the transitions between the stable and unstable dynamic states of the KE system?**
- **Q2: What roles does the nonlinear ocean dynamics play?**
- **Q3: What determines the observed, preferred decadal timescale?**

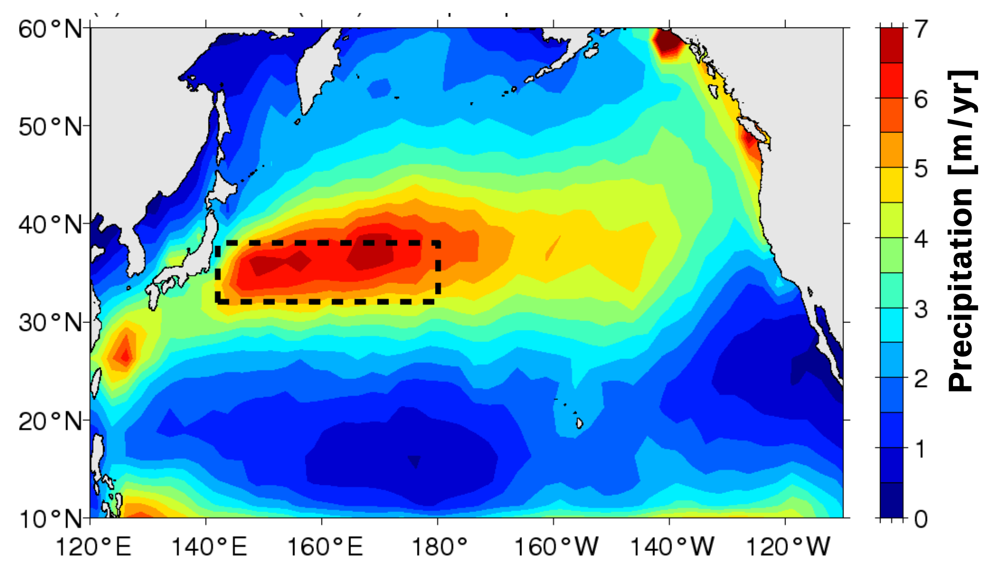
RMS SSH variability (AVISO data)



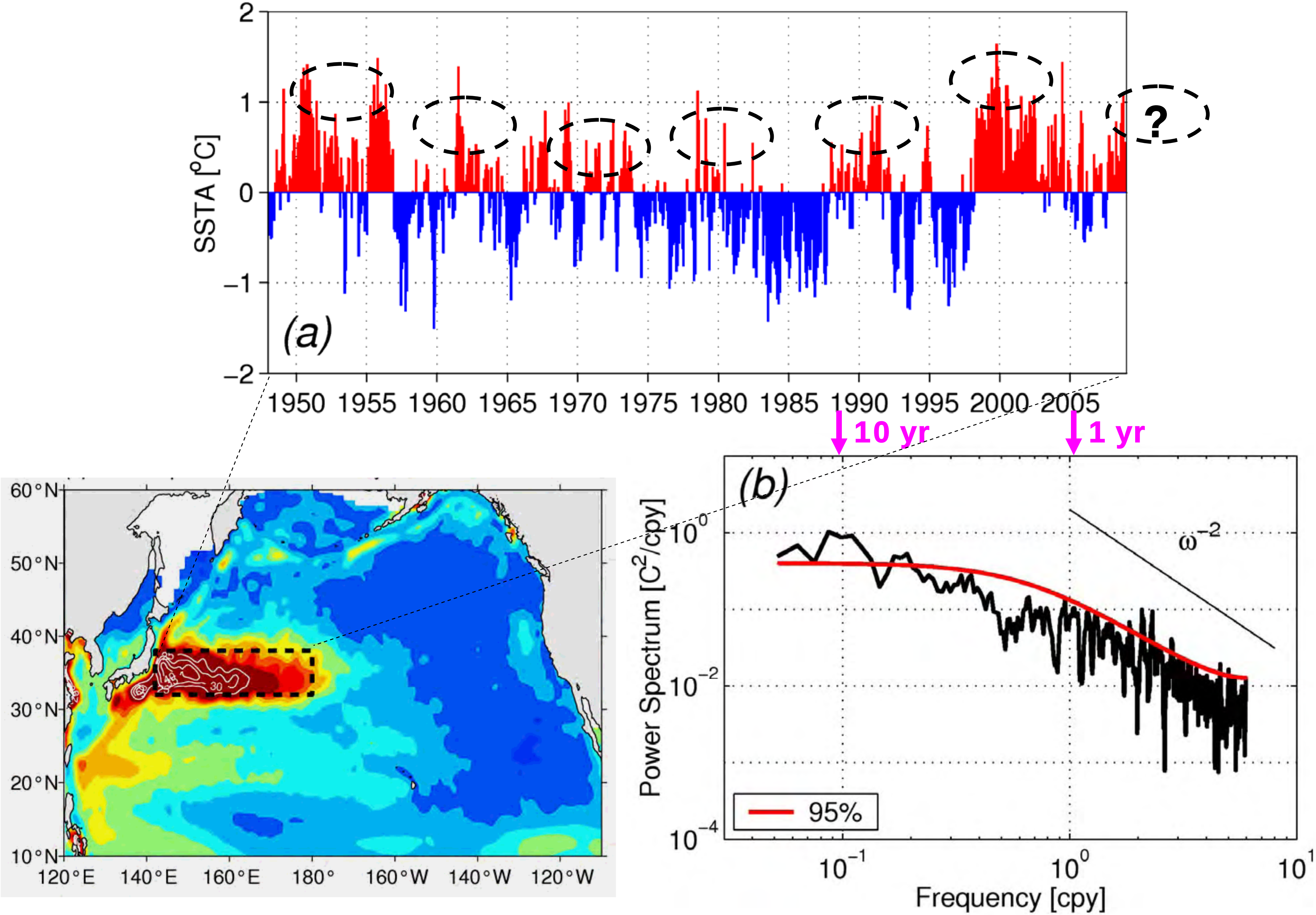
JFM rms net surface heat flux variability (NCEP reanalysis)



JFM precipitation (proxy for winter stormtracks)



SST anomaly time series in the KE region



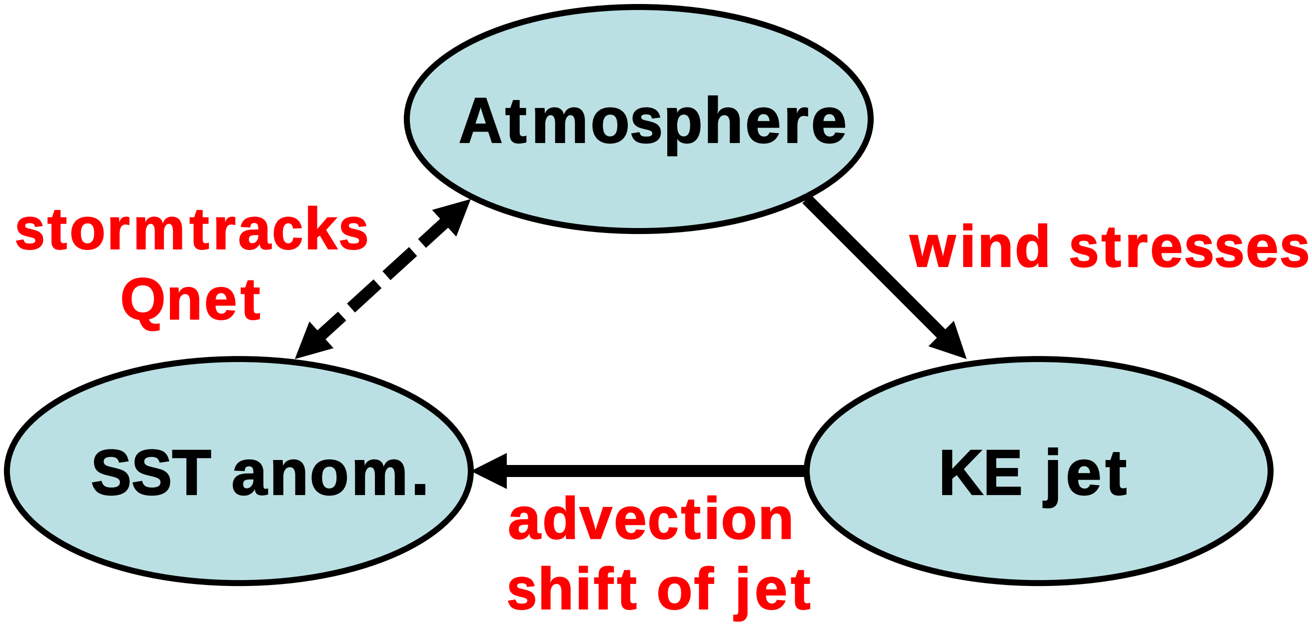
An idealized air-sea coupled system:

$$\frac{\partial h(x,t)}{\partial t} - c_R \frac{\partial h(x,t)}{\partial x} = -\frac{g' \,\mathrm{curl}\boldsymbol{\tau}}{\rho_o g f} \qquad (1)$$

$$\frac{\partial T(t)}{\partial t} = a\,\overline{h(t)} - \lambda T(t) + q(t) \qquad (2)$$

$$-\frac{g' \,\mathrm{curl}\boldsymbol{\tau}}{\rho_o g f} = \sum_{n=1}^{2} \sin\left(\frac{n\pi x}{W}\right) w_n(t) + b \sin\left(\frac{2\pi x}{W}\right) T(t) \qquad (3)$$

intrinsic **feedback**



SST's impact from the lagged correlation approach

(Czaja and Frankignoul 1999, 2002)

Let an atmospheric variable C(t) be:

$$C(t) = f(t) + F(T)$$

$$\sim f(t) + b\,T(t)$$

where f represents intrinsic atmospheric processes, b, the dynamic feedback coefficient, and T, SST anomalies.

Taking lagged correlation with T(t-m) and ensemble average:

0

$$\{T(t-m)C(t)\} = \{T(t-m)f(t)\} + b\{T(t-m)T(t)\}$$

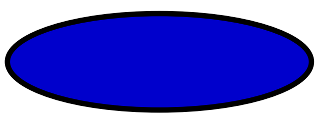
if m > a few weeks

The covariance between SST and C(t) when SST leads is proportional to the strength of the feedback.

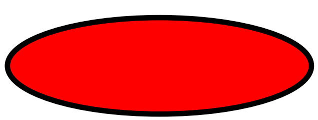
(cf. Liu and Wu 2004; Frankignoul and Sennechael 2007)

Lagged regression between KE SSTA and NP curl-tau field

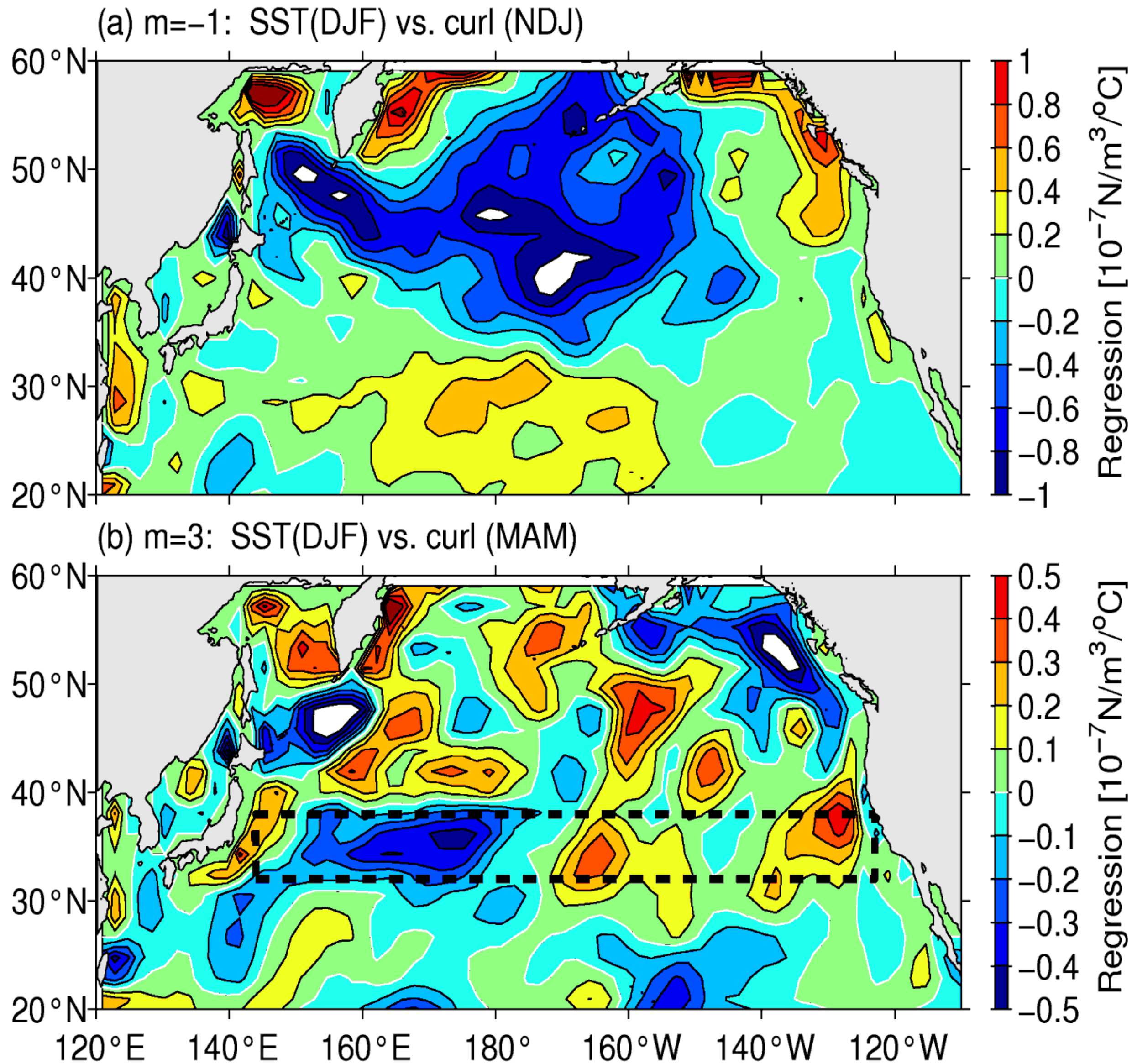
- **NCEP reanalysis data (1950-2008)**
- **ENSO signals (Nino 3.4) regressed out**
- **Different curl patterns with + / - lag**



p’ > 0; curl-tau < 0



p’ < 0; curl-tau > 0

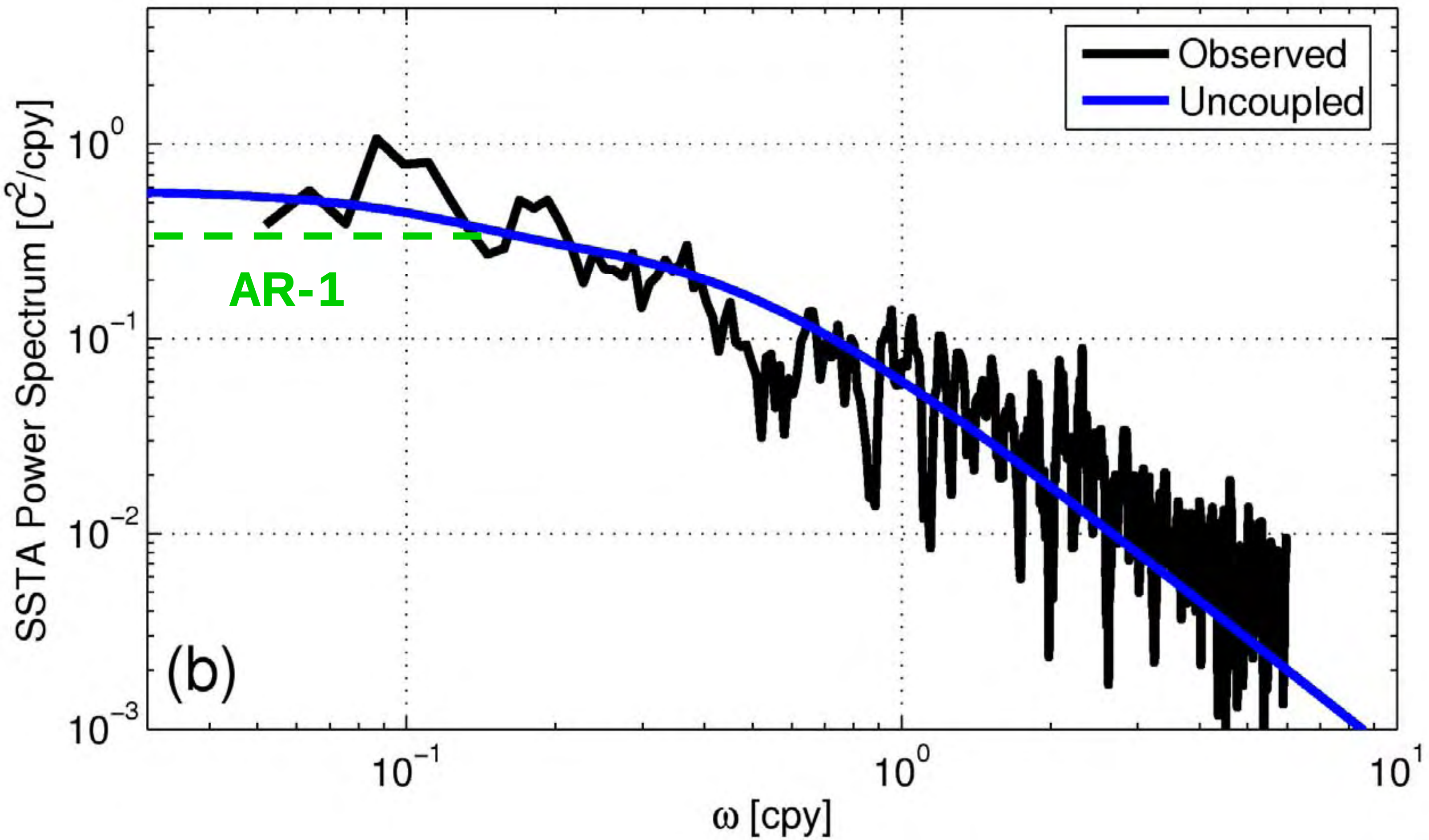


Parameter values appropriate for N. Pacific:

$y = 35°\text{N}, \quad c_R = 0.033\ \text{m/s}$	**band of action**
$W = 95°\text{lon.}, \quad L = 40°\text{lon.}$	**band configuration**
→ $a = 2.73{\times}10^{-7}\ \text{K/m/s}$	**advection parameter (likely underestimated!)**
$\lambda = 1/129.2\ \text{days}$	**oceanic damping timescale**
$\lvert\widehat{w_1}(\omega)\rvert^2 = 1.127{\times}10^{-18}\ \text{m}^2/\text{s}^2/\text{cpy}$	**power of stochastic wind stress forcing (n=1)**
$\lvert\widehat{w_2}(\omega)\rvert^2 = 0.643{\times}10^{-18}\ \text{m}^2/\text{s}^2/\text{cpy}$	**power of stochastic wind stress forcing (n=2)**
$\lvert\hat{q}(\omega)\rvert^2 = 2.89{\times}10^{-15}\ \text{K}^2/\text{s}^2/\text{cpy}$	**power of stochastic heat flux forcing**
→ $b = 6.64{\times}10^{-10}\ \text{m/s/K}$	**air-sea coupling parameter**

Uncoupled case (b=0)

$$|\widehat{T}(\omega)|^2_{\text{uncoupled}} = \frac{1}{\lambda^2+\omega^2}\left[a^2 \sum_{n=1}^{2} |P_n(\omega)|^2 |\widehat{w}_n(\omega)|^2 + |\hat{q}(\omega)|^2\right]$$



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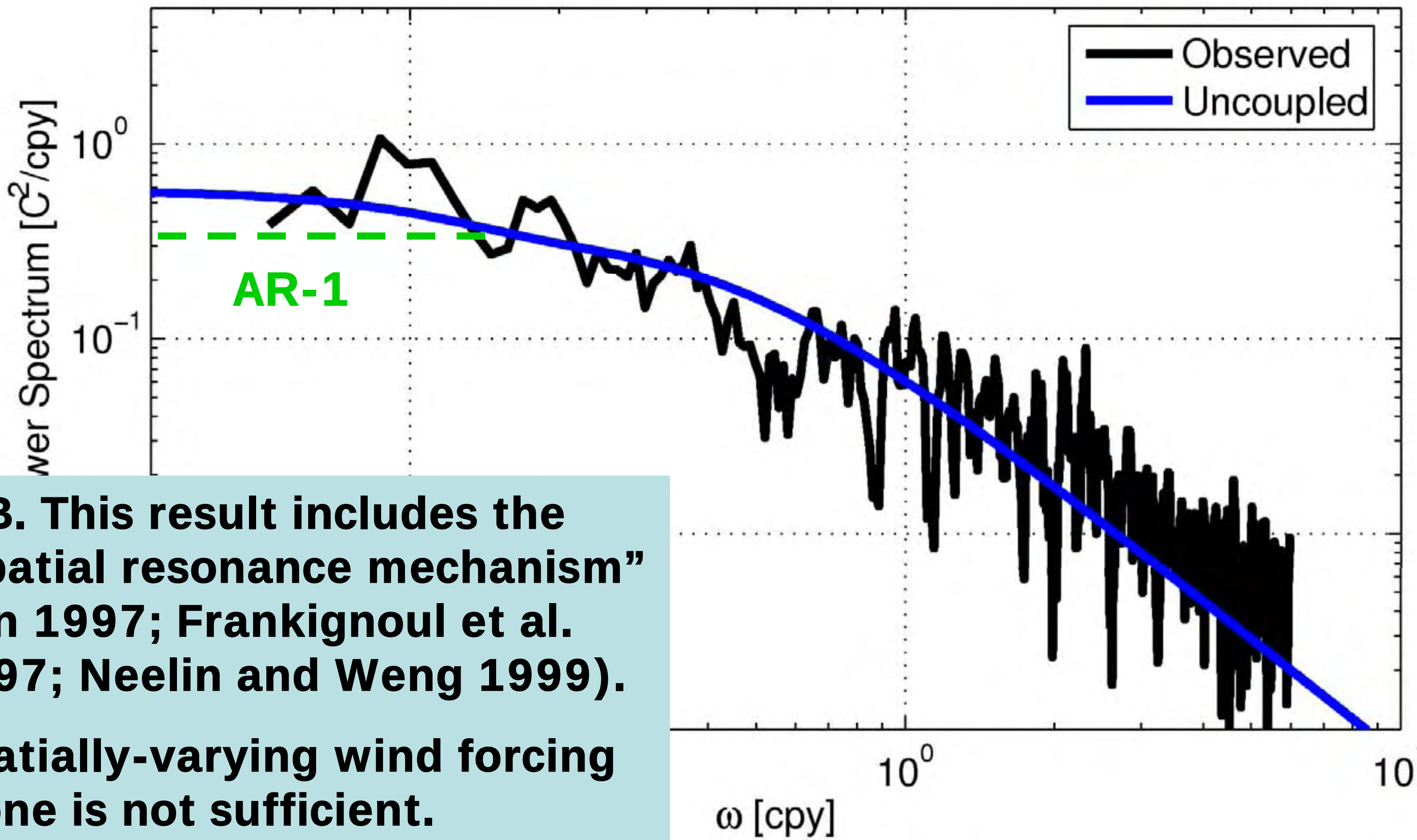
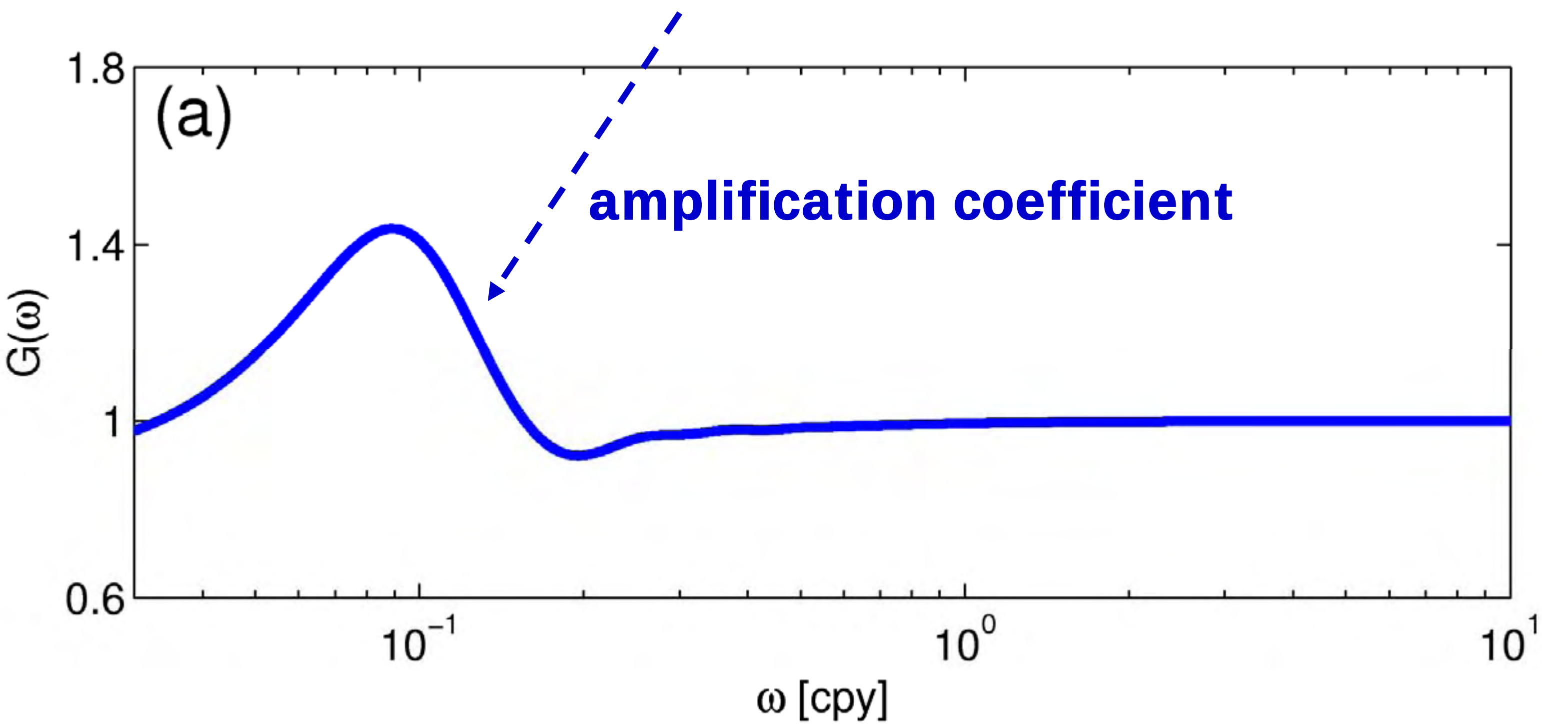


N.B. This result includes the "spatial resonance mechanism" (Jin 1997; Frankignoul et al. 1997; Neelin and Weng 1999).

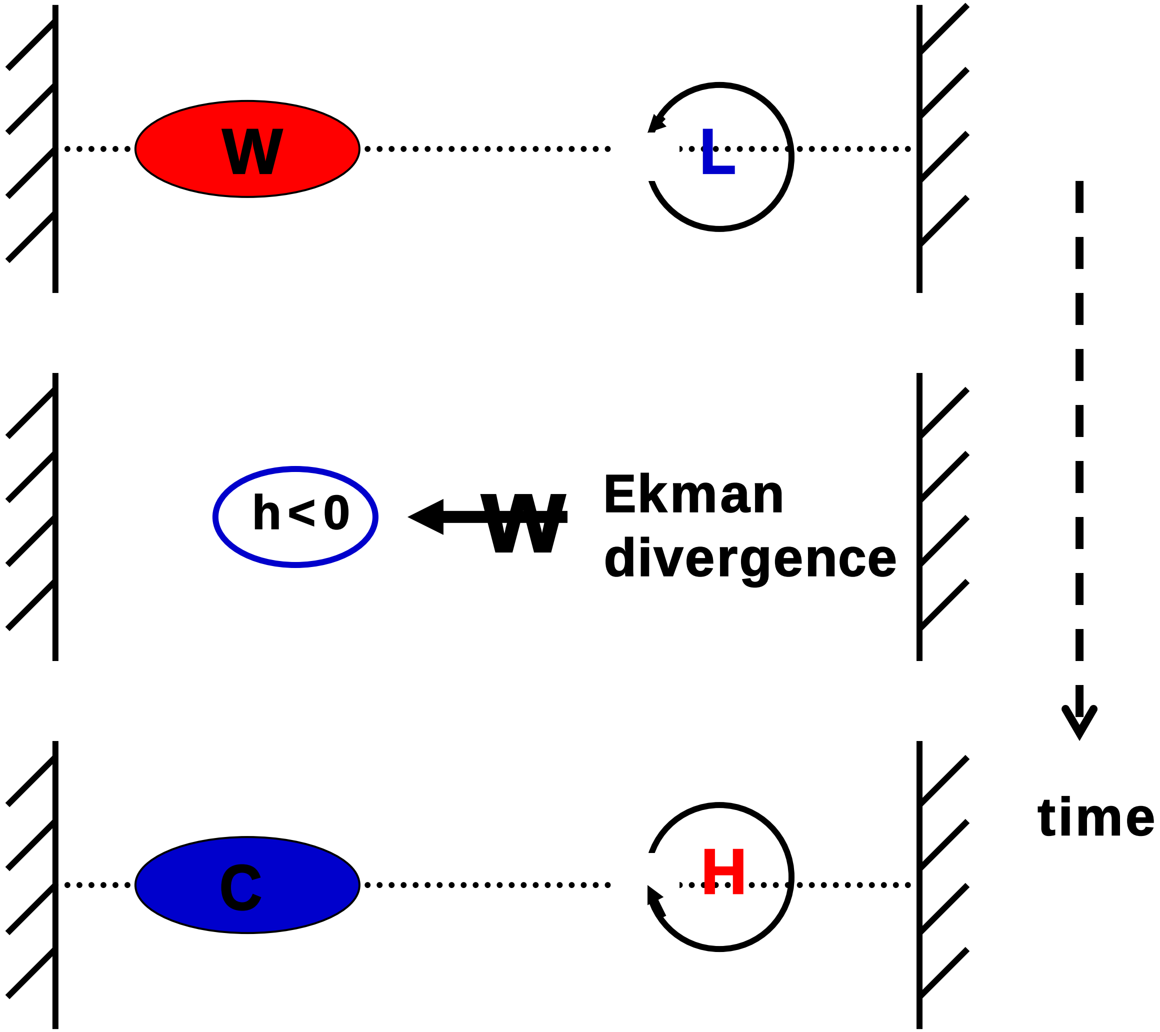
Spatially-varying wind forcing alone is not sufficient.

Coupled case (b ≠ 0)

$$|\widehat{T}(\omega)|^2_{\text{coupled}} = \left|\frac{\lambda + i\omega}{\lambda + i\omega - abP_2(\omega)}\right|^2 |\widehat{T}(\omega)|^2_{\text{uncoupled}}$$



Schematic for the coupled oscillation



half of the optimal period ~ (W / 2) / c_R

Coupled case (b≠0)

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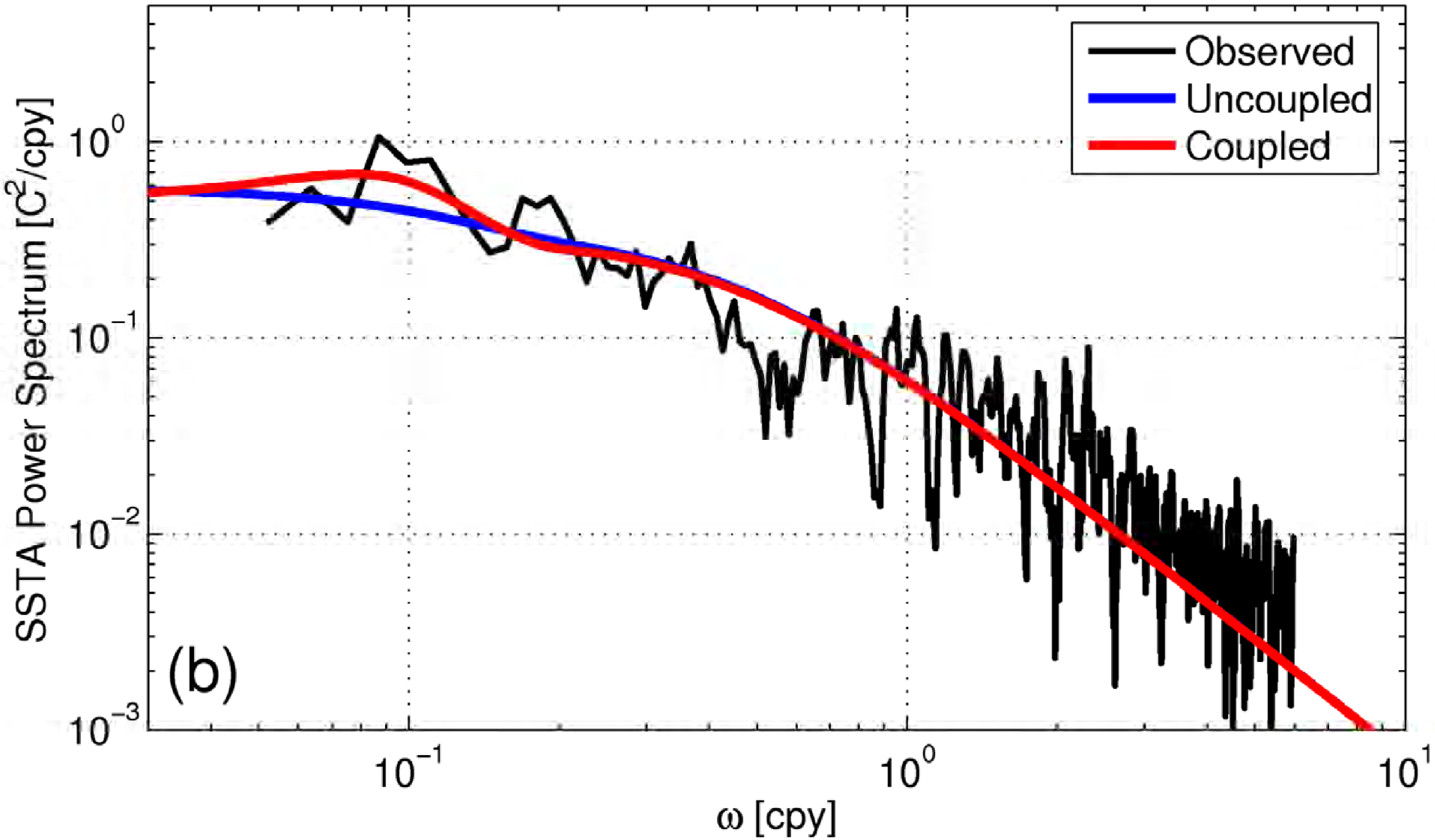

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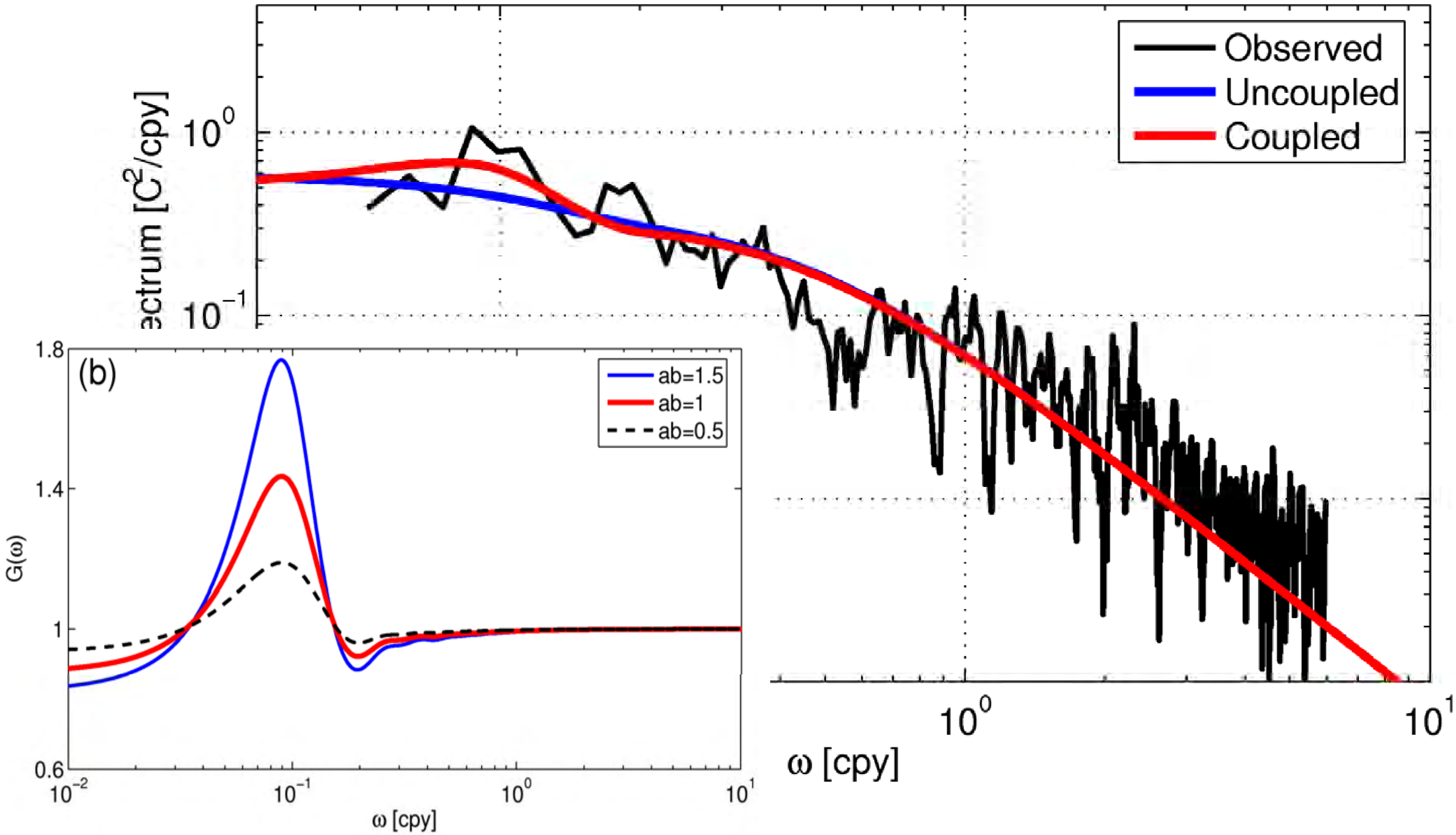
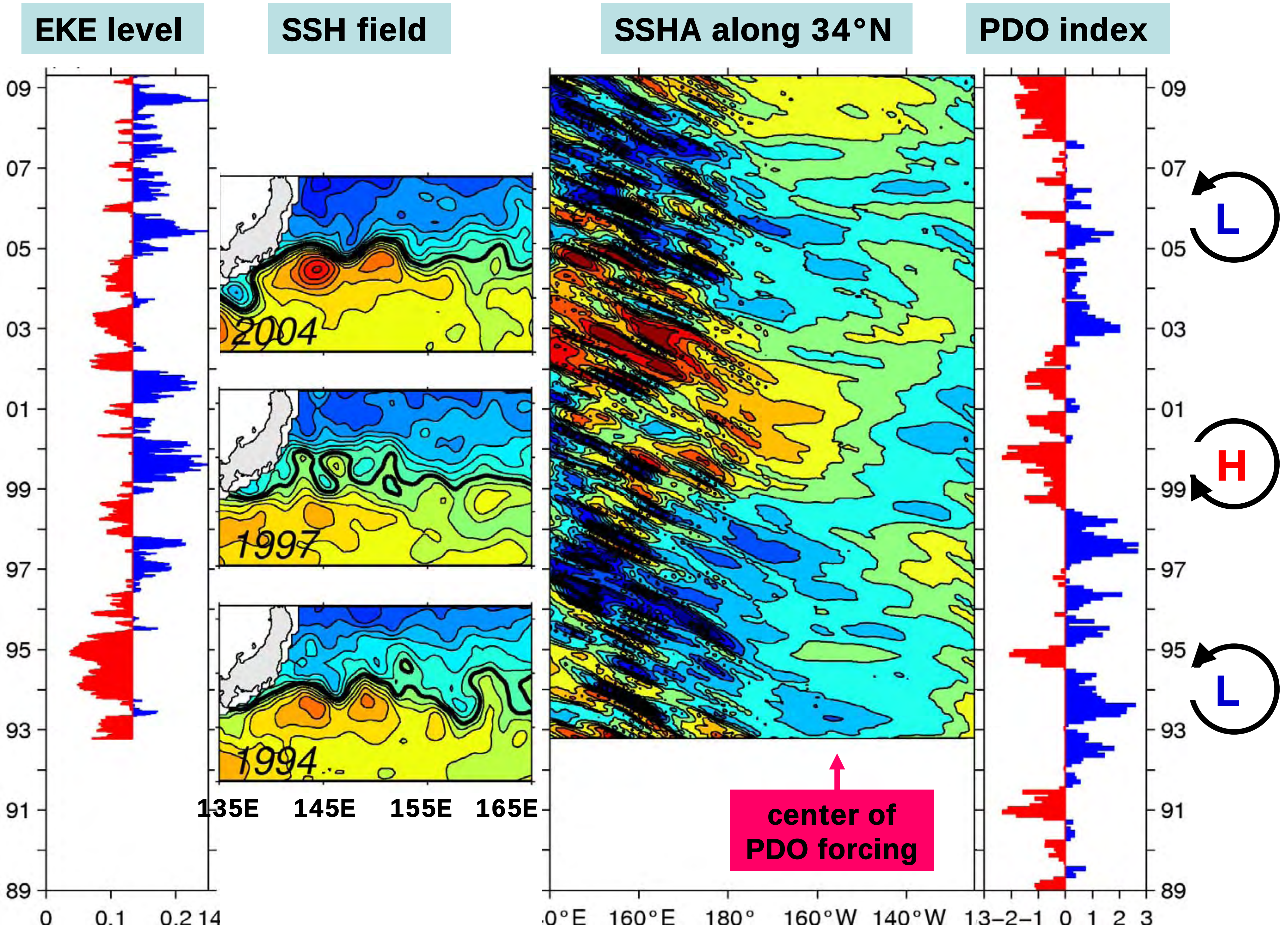


Summary

- Decadal variability dominates SSH, SST and other oceanic variables in the KE region. With the observed wind stress data, this variability can be predicted with a 3~4 yr lead.
- Ocean dynamics alone "reddens" the SST spectrum, but generates no decadal spectral peak as observed.
- Wintertime KE SST anomalies induce overlying-high and downstream-low pressure anomalies. This feedback favors a coupled mode with a ~10 yr timescale.
- Nonlinear eddy-mean flow interaction can increase the amplitude of this coupled mode by enhancing regional SST anomalies (via parameter a).
- While the variance explained by this coupled mode is small for atmosphere (~15%), it is the driving force for decadal changes in oceanic variables: KE's path, SST, eddy level, and RG intensity.



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160°E
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160°W
140°W
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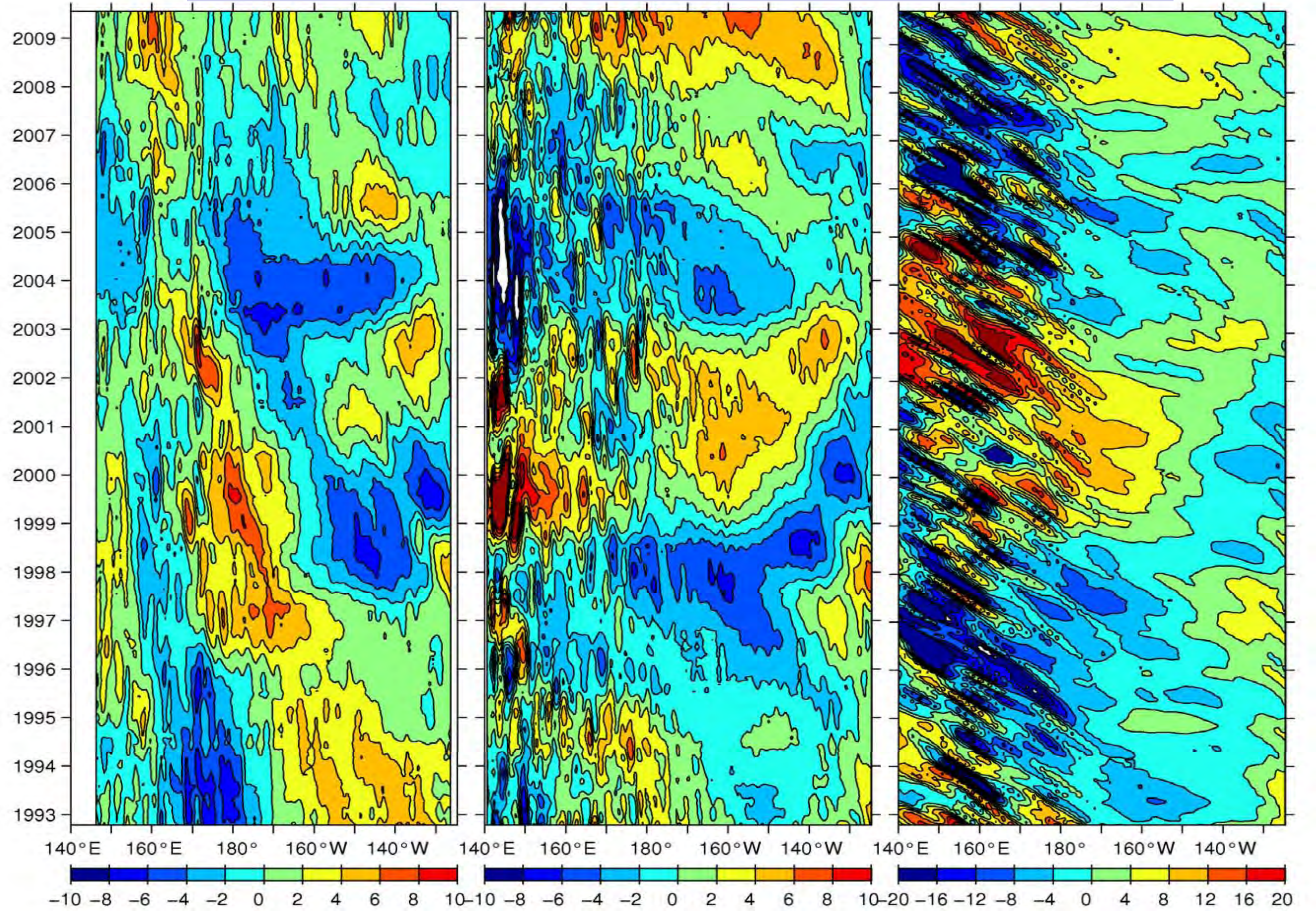
0
1
2
3

Contrast 3 latitude bands: 45-50N, 37-42N, 32-34N



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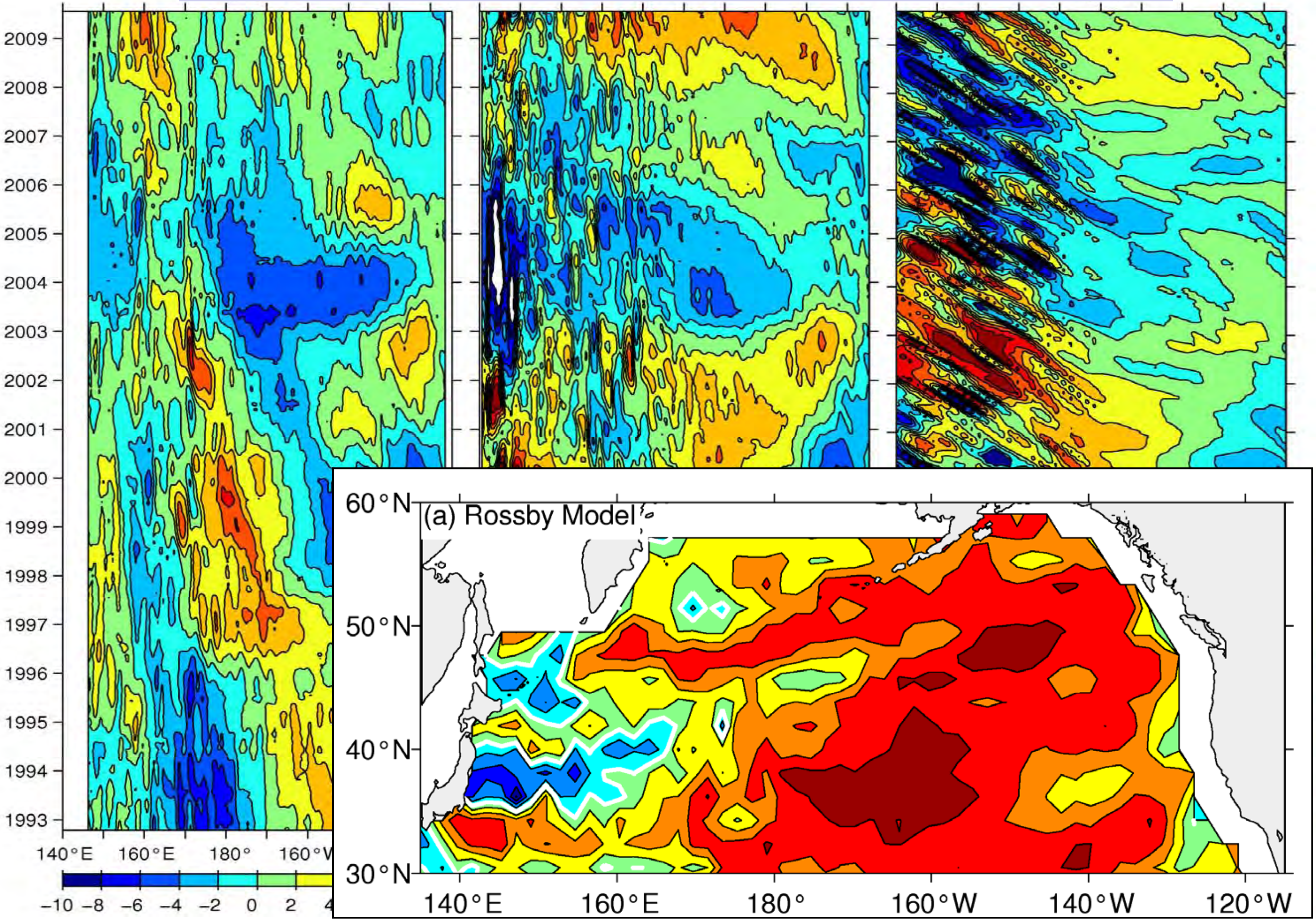
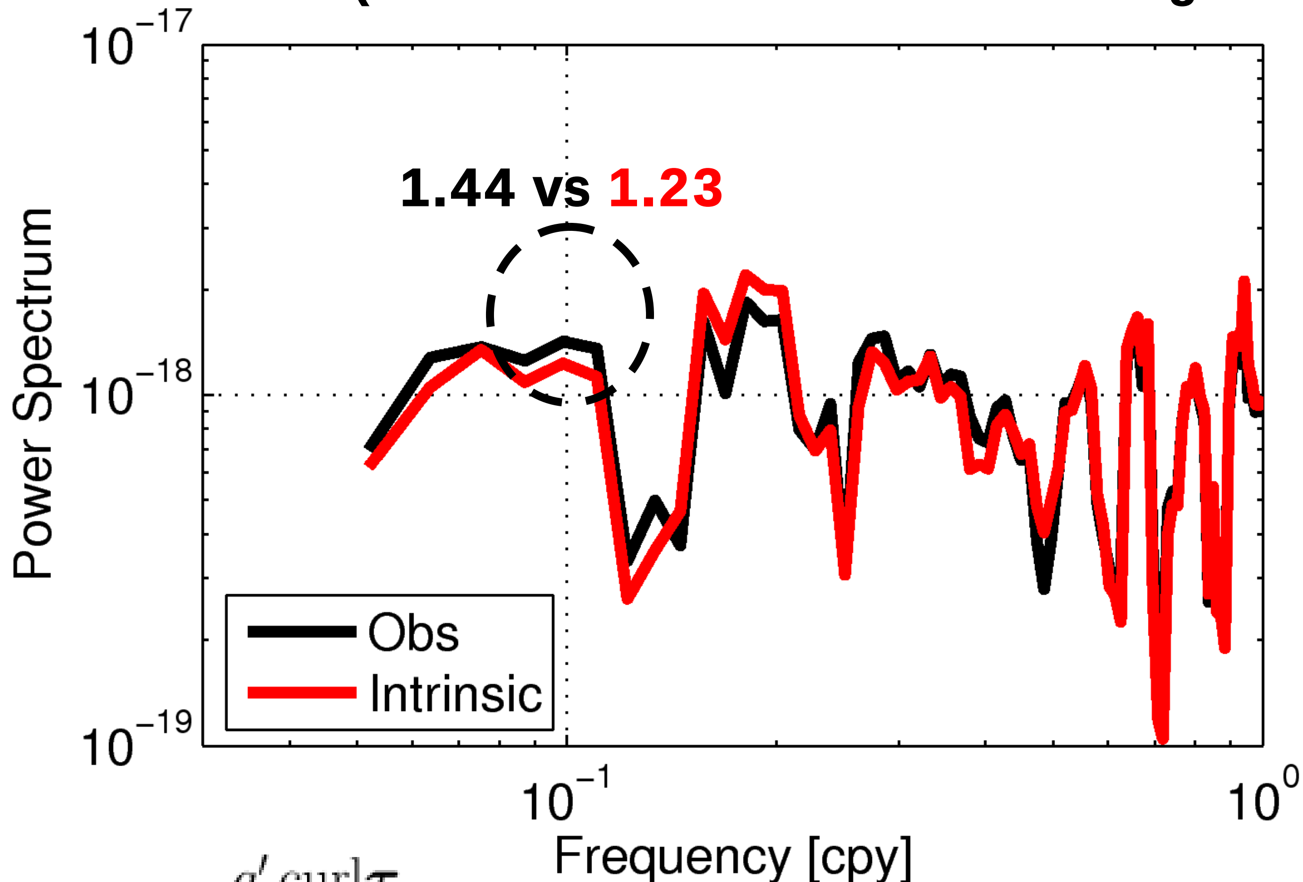


How large is the SST-induced wind forcing?

(in the eastern half of the NP along the KE band)



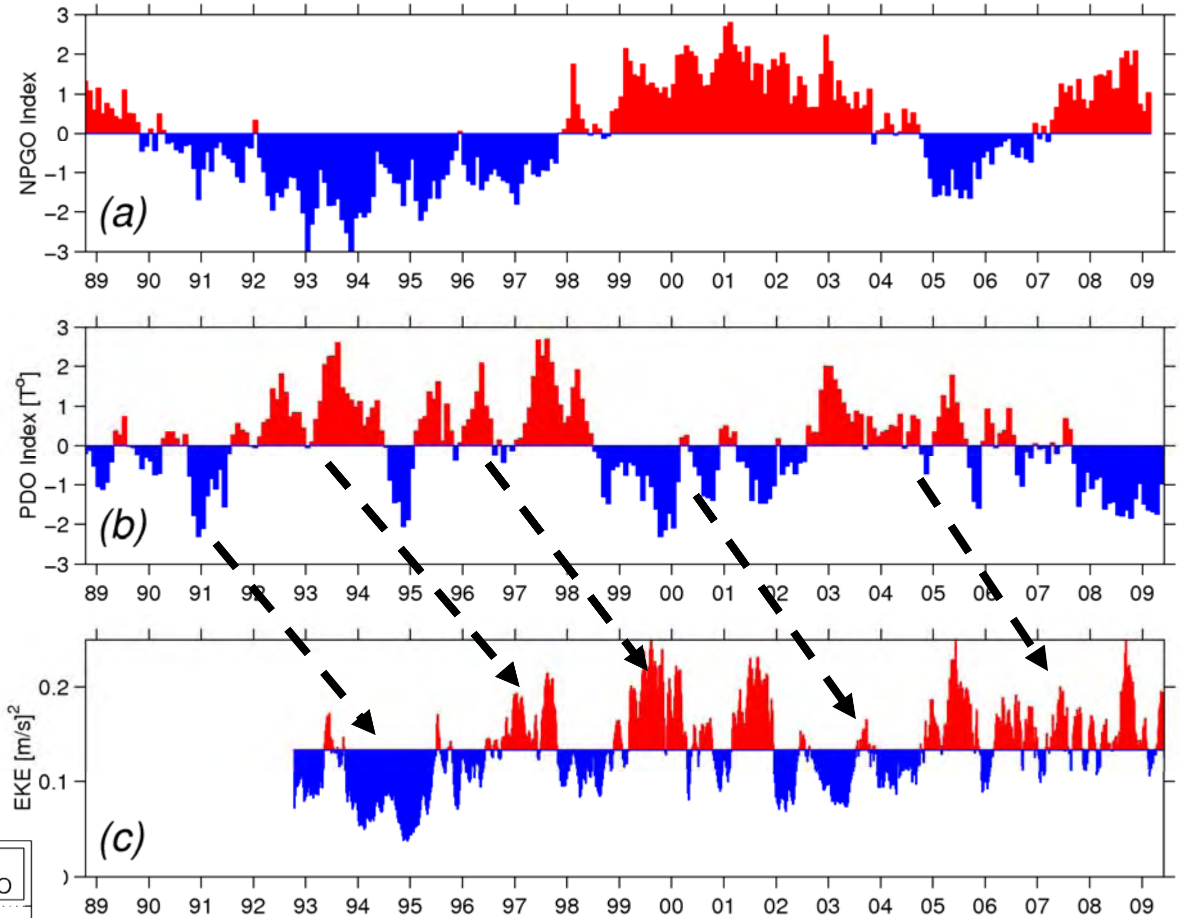
$$-\frac{g' \,\mathrm{curl}\boldsymbol{\tau}}{\rho_o g f}$$

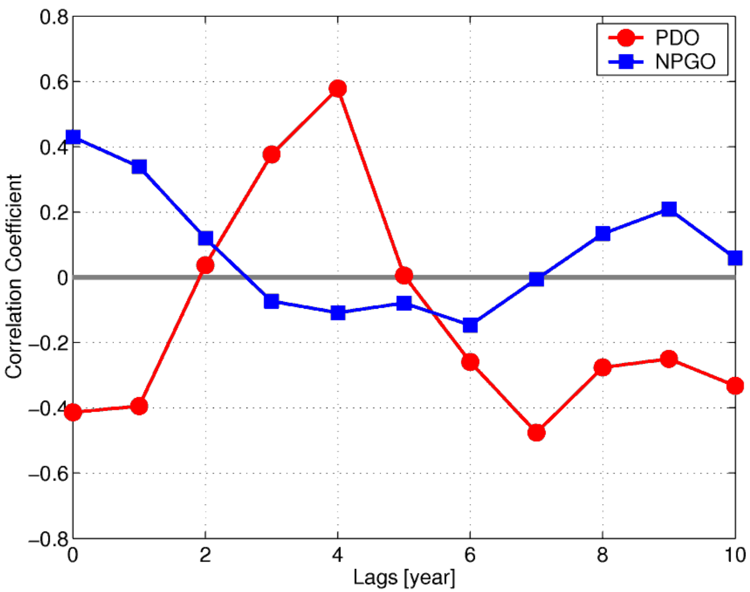
$$-\frac{g' \,\mathrm{curl}\boldsymbol{\tau}}{\rho_o g f} - b \sin\left(\frac{2\pi x}{W}\right) T(t)$$

NPGO index

PDO index

EKE level





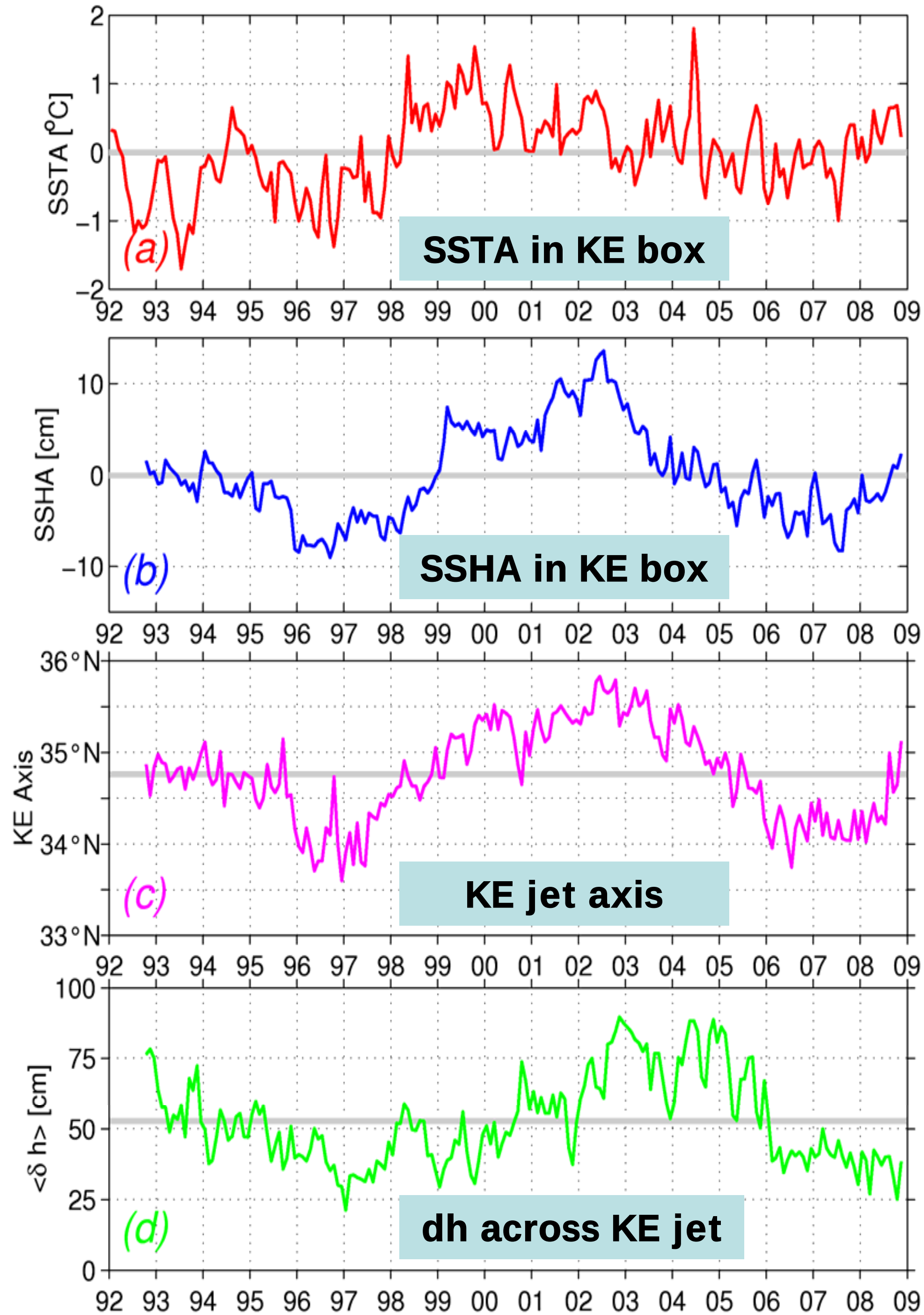
Extended Hasselmann model

$$\frac{\partial T(t)}{\partial t} = a\,\overline{h(t)} - \lambda T(t) + q(t)$$

where

$$\overline{h(t)} \equiv \frac{1}{L}\int_{-W}^{-W+L} h(x,t)\,dx$$

averaged SSHA in the KE box



An idealized air-sea coupled system:

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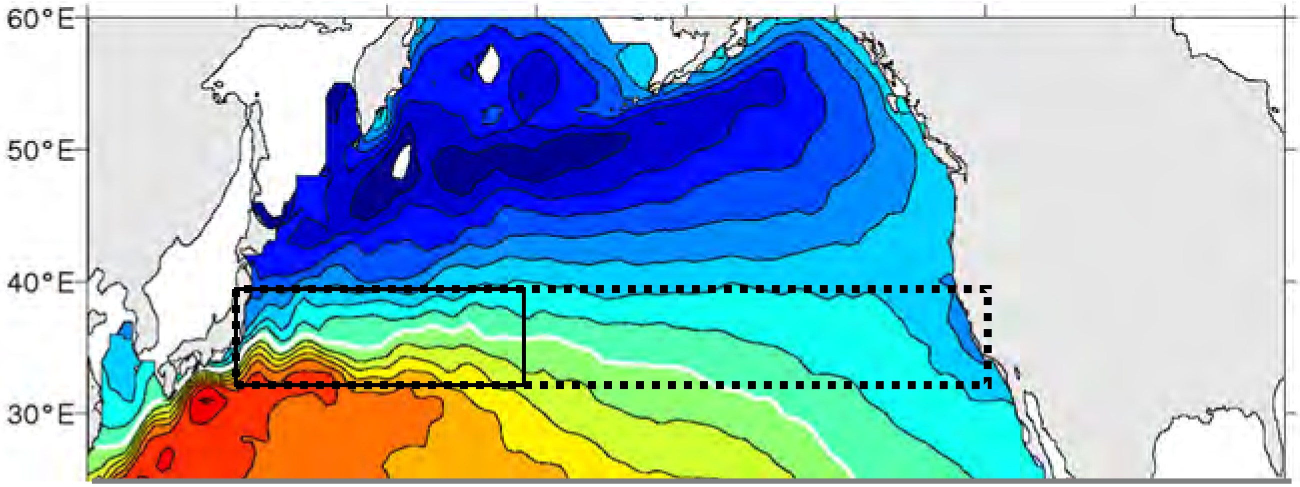
$$-\frac{g' \,\mathrm{curl}\boldsymbol{\tau}}{\rho_o g f} = \sum_{n=1}^{2} \sin\left(\frac{n\pi x}{W}\right) w_n(t) \;+\; b \sin\left(\frac{2\pi x}{W}\right) T(t) \quad (3)$$

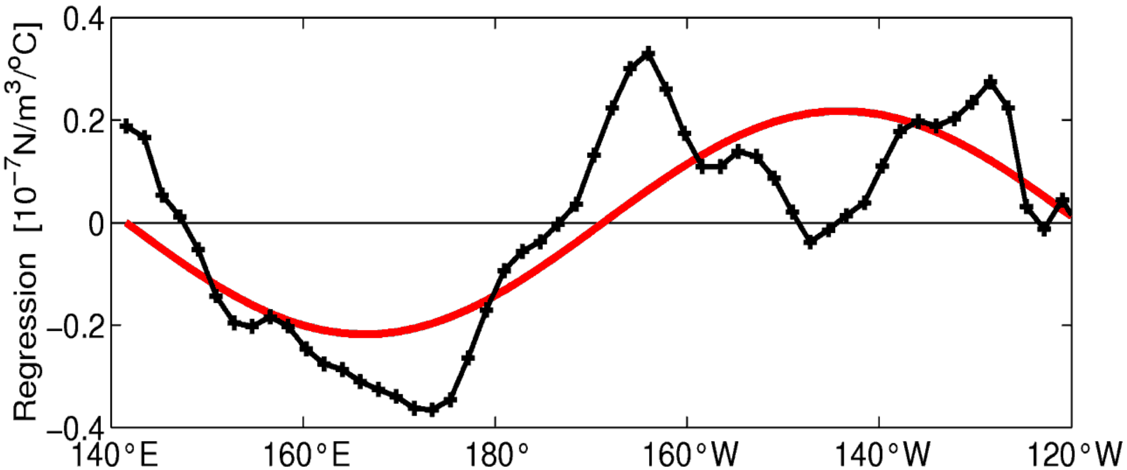
intrinsic feedback

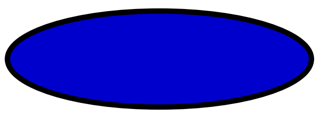


x=-W x=-W+L x=0

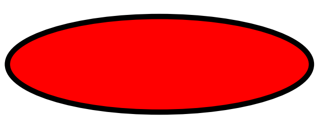
Lagged regression between KE SSTA and NP curl-tau field

- **NCEP reanalysis data (1950-2008)**
- **ENSO signals (Nino 3.4) regressed out**
- **Different curl patterns with + / - lag**





p’ > 0; curl-tau <0



p’ < 0; curl-tau >0