Hamburg Workshop 2015

On the Wind Power Input and Eddy Residence Time

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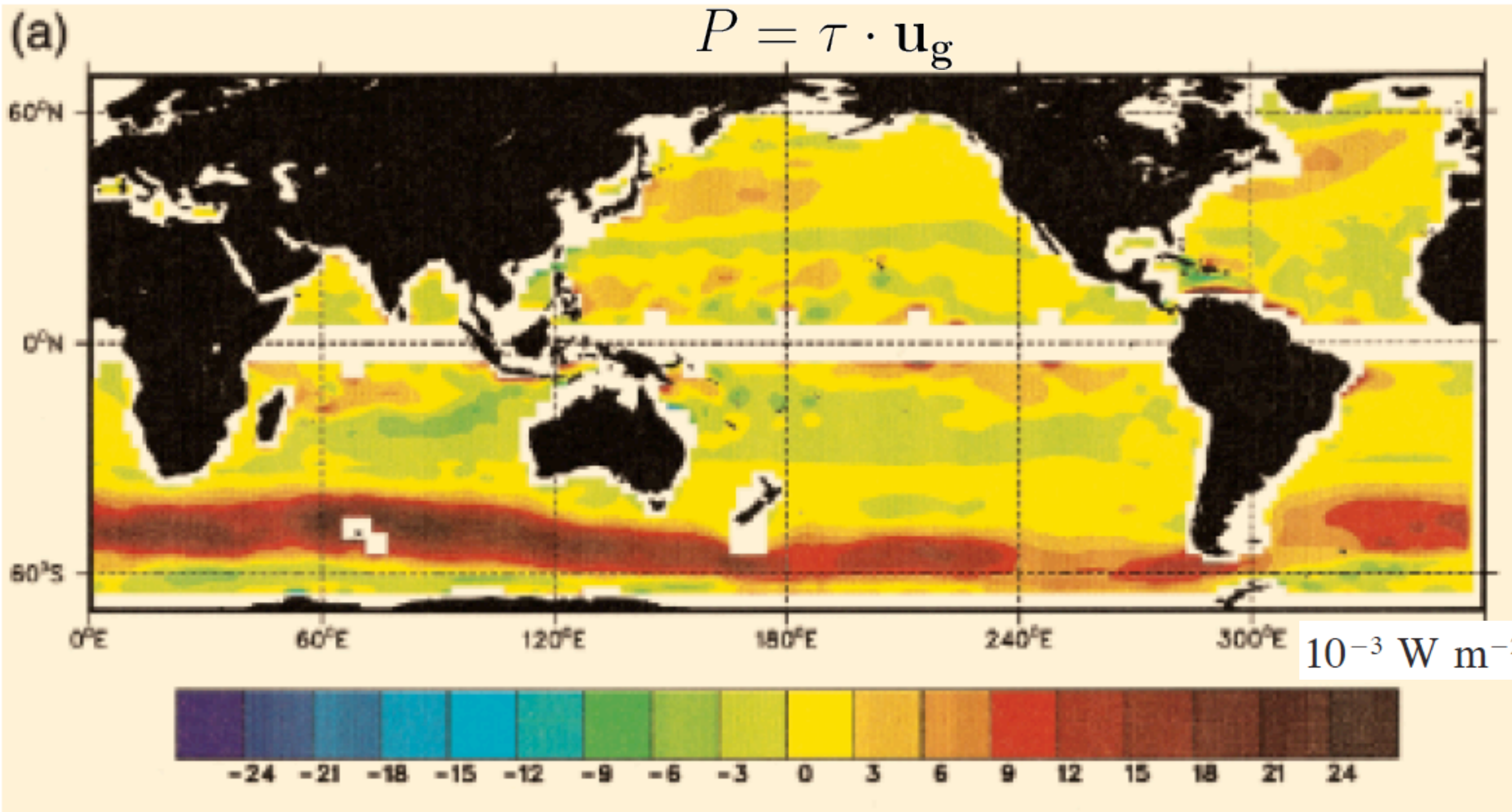
Outline

- Wind power input to ocean general circulation: role of synoptic winds and time-mean winds
- Estimating global eddy energy residence time

Introduction

- Wind power input to the ocean general circulation is a major energy source for driving the large-scale ocean circulation.



Wunsch (1998)

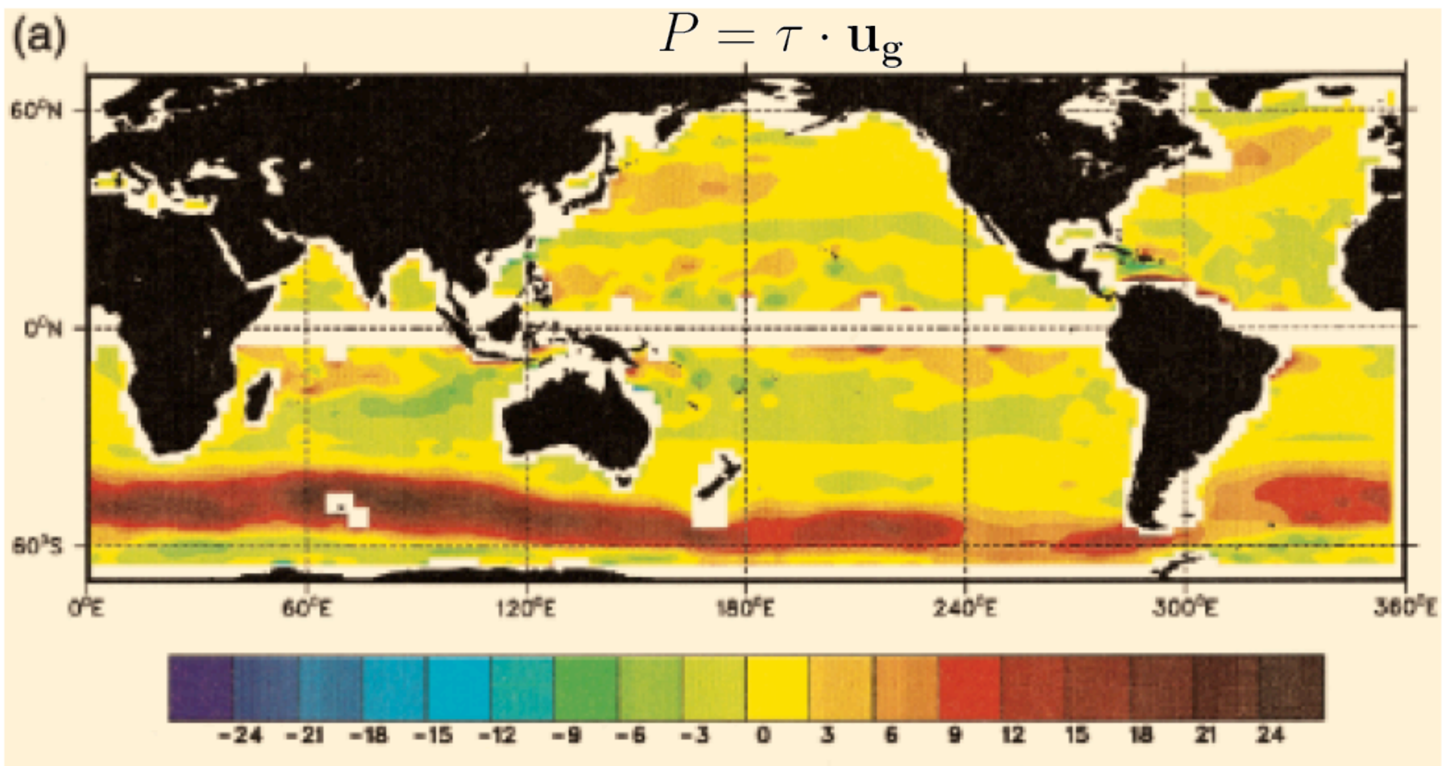
- Is it dominated by the time-averaged wind as sometimes suggested?

Wind stress bulk formula

$$\boldsymbol{\tau} = \rho_a c_d |\mathbf{U}_{10} - \mathbf{u}_o| (\mathbf{U}_{10} - \mathbf{u}_o)$$

- *Quadratic dependence:* the high-frequency wind does not average out but contributes to the time-averaged wind stress *(e.g., Thompson et al. 1983)*.

monthly wind stress ≠ *stress associated with monthly wind*

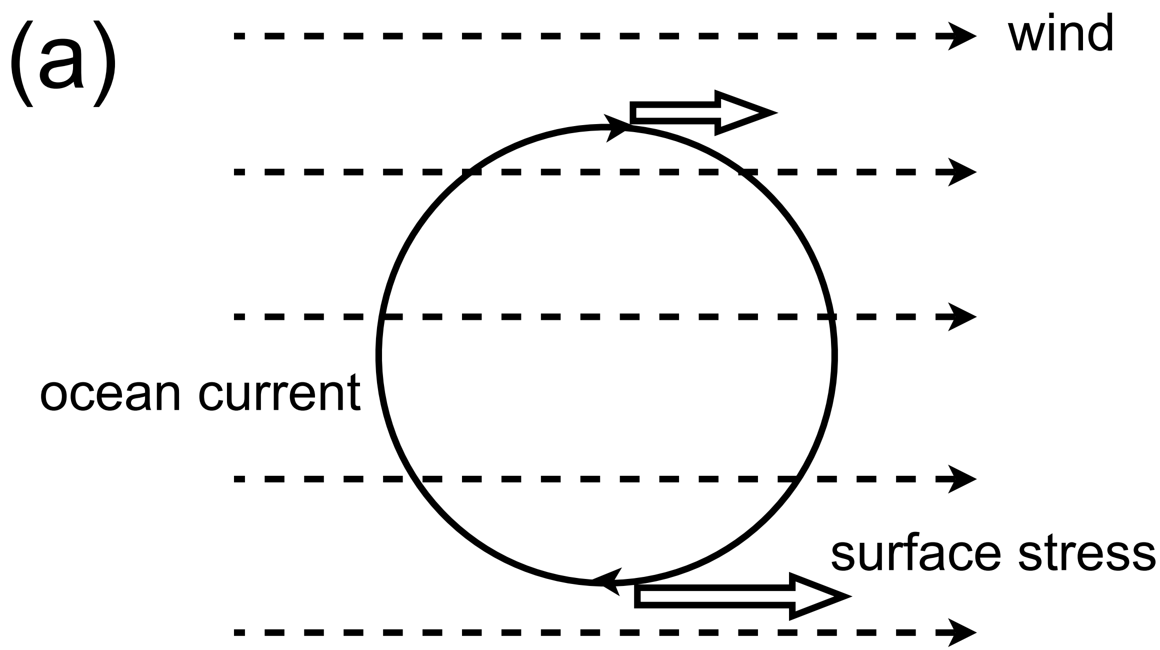


Resting ocean approximation

Surface wind stress: $\tau = \rho_a c_d |\mathbf{U_{10}} - \mathbf{u_o}|(\mathbf{U_{10}} - \mathbf{u_o})$

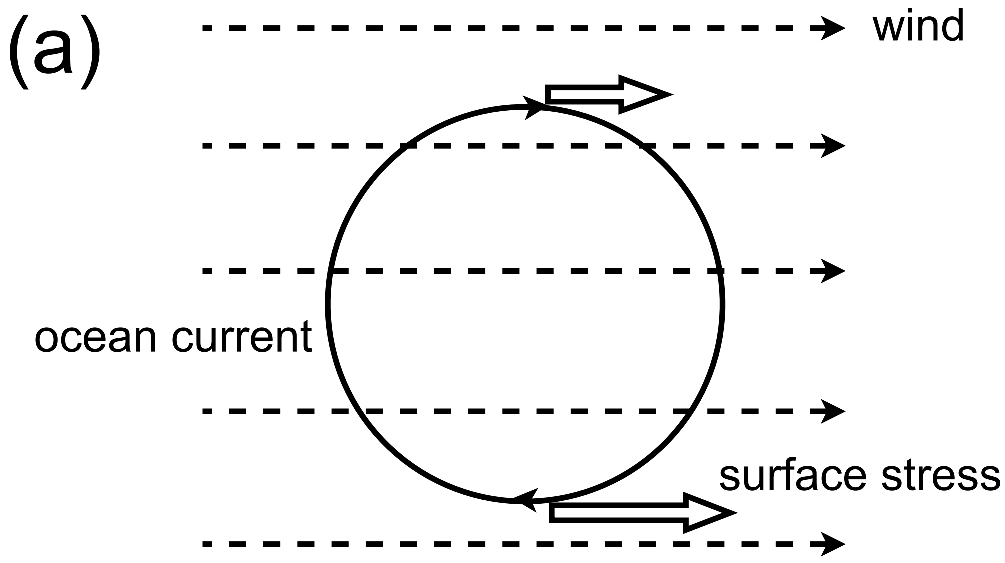
Common practice: $\tau = \rho_a c_d |\mathbf{U_{10}}|\mathbf{U_{10}}$

- Recent studies have found a positive bias in calculations of wind power input (20%-30%) when "resting ocean approximation" is used (*Duhaut and Straub, 2006; Zhai and Greatbatch, 2007; Hughes and Wilson, 2008*).

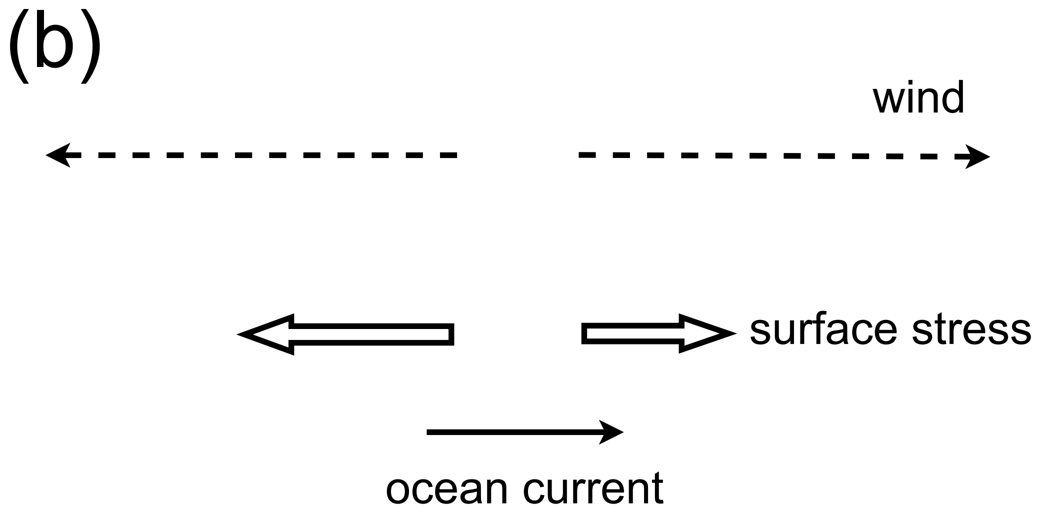


A second look: “*wind mechanical damping effect*”

(i) Ocean: small spatial scale



(ii) Atmosphere: fast time scale



Data and method

- Ocean surface geostrophic velocity:

$$\mathbf{u_g} = \frac{g}{f}\hat{\mathbf{k}} \times \nabla\eta = \frac{g}{f}\hat{\mathbf{k}} \times \nabla\left(\bar{\eta} + \eta'\right)$$

ocean mean dynamic height (*Maximenko and Niiler, 2005*) → $\bar{\eta}$

SSH anomaly from CLS (*Le Traon et al., 1998*) → η'

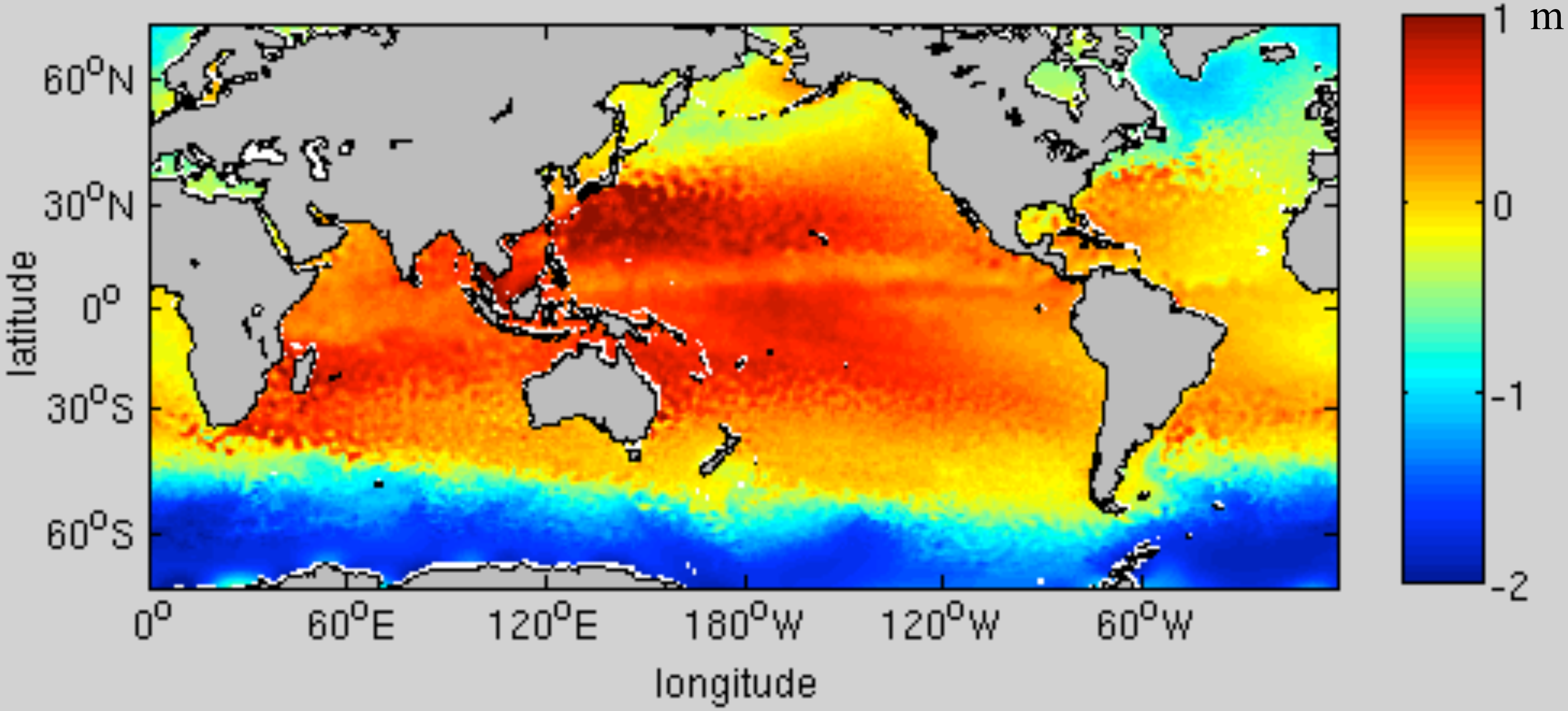
- Wind stress: NCEP reanalysis

6-hourly wind
daily wind
monthly wind

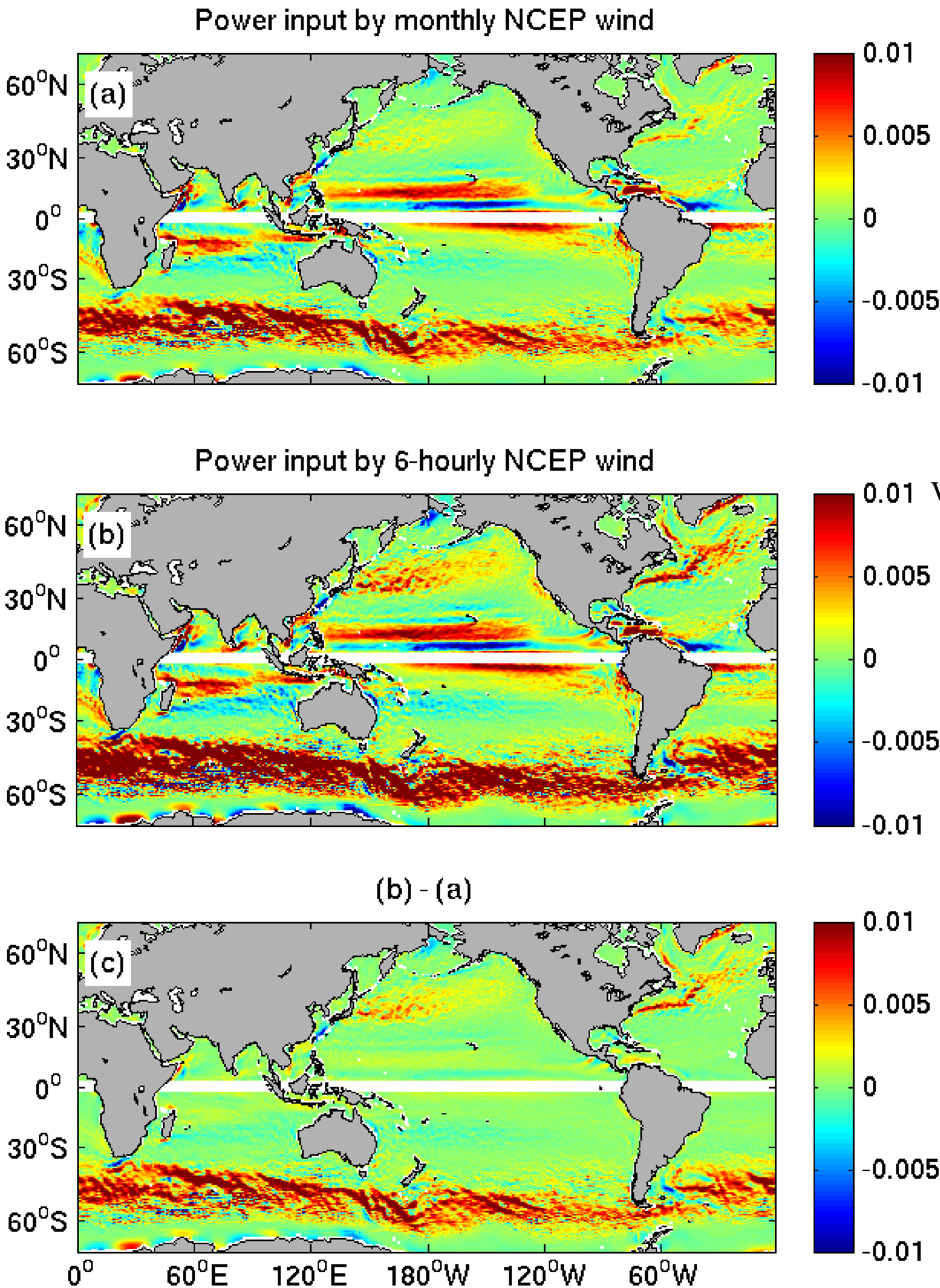
→ *Large et al. (1994)* →

stress associated with 6-hourly wind
stress associated with daily wind
stress associated with monthly wind

instantaneous SSH



With resting ocean approximation



w/m²

a) monthly NCEP wind

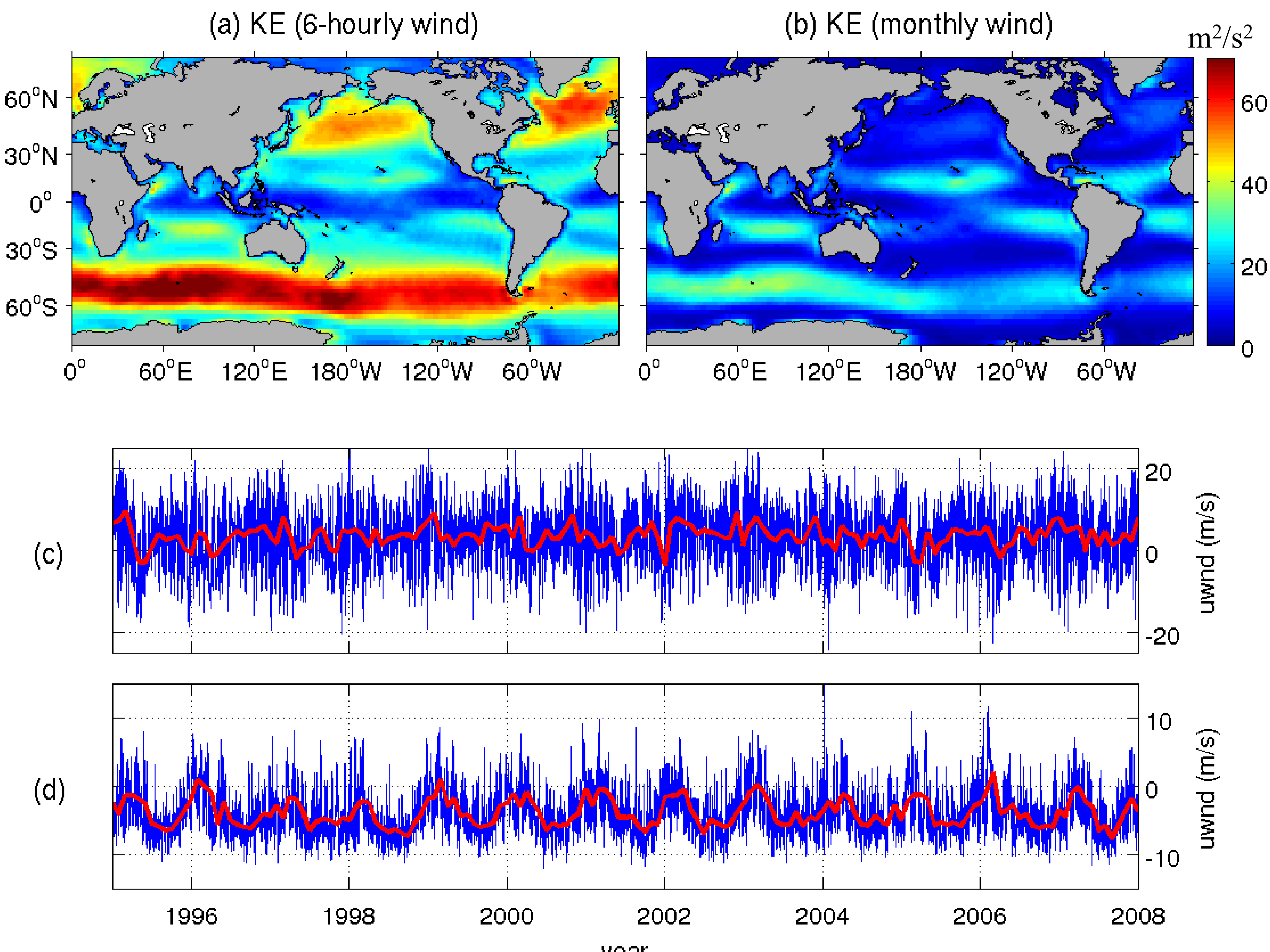
0.42 TW

b) 6-hourly NCEP wind

0.72 TW

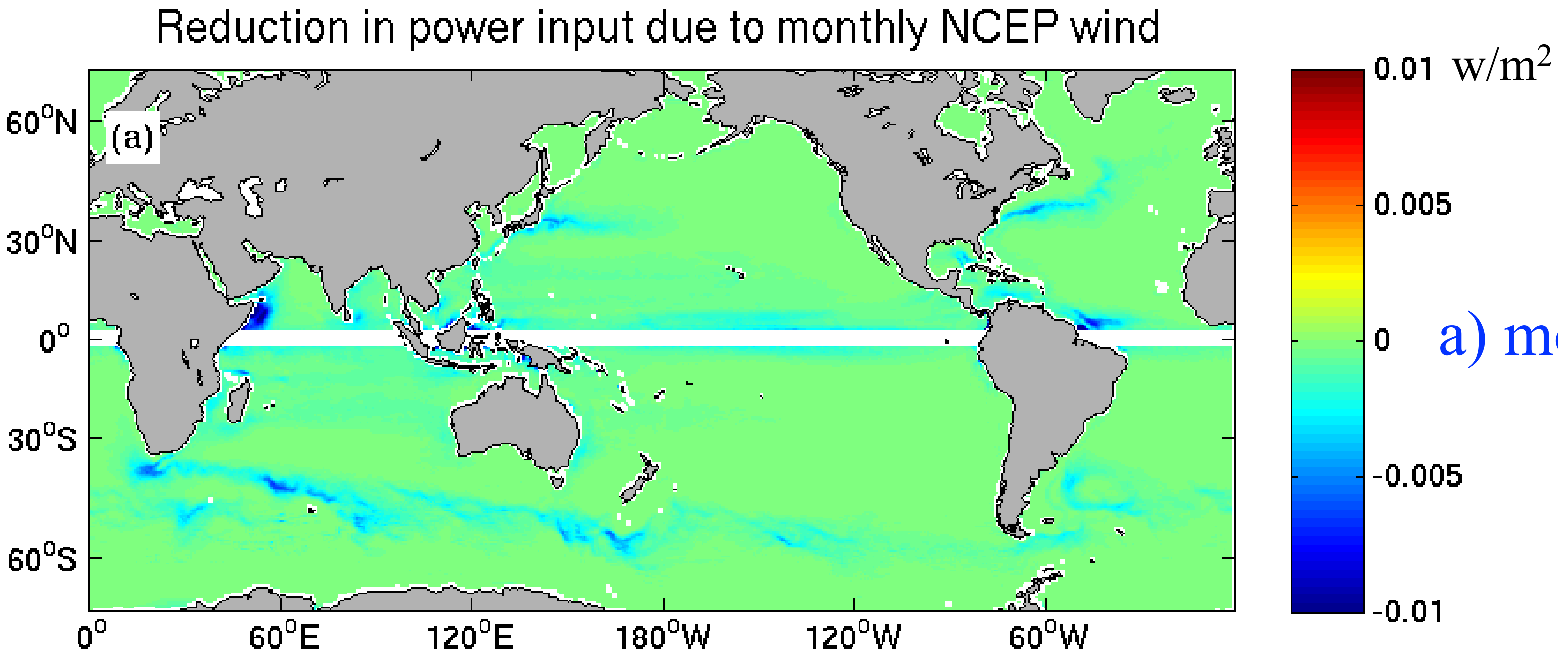
b) - a)

Zhai et al. (2012)



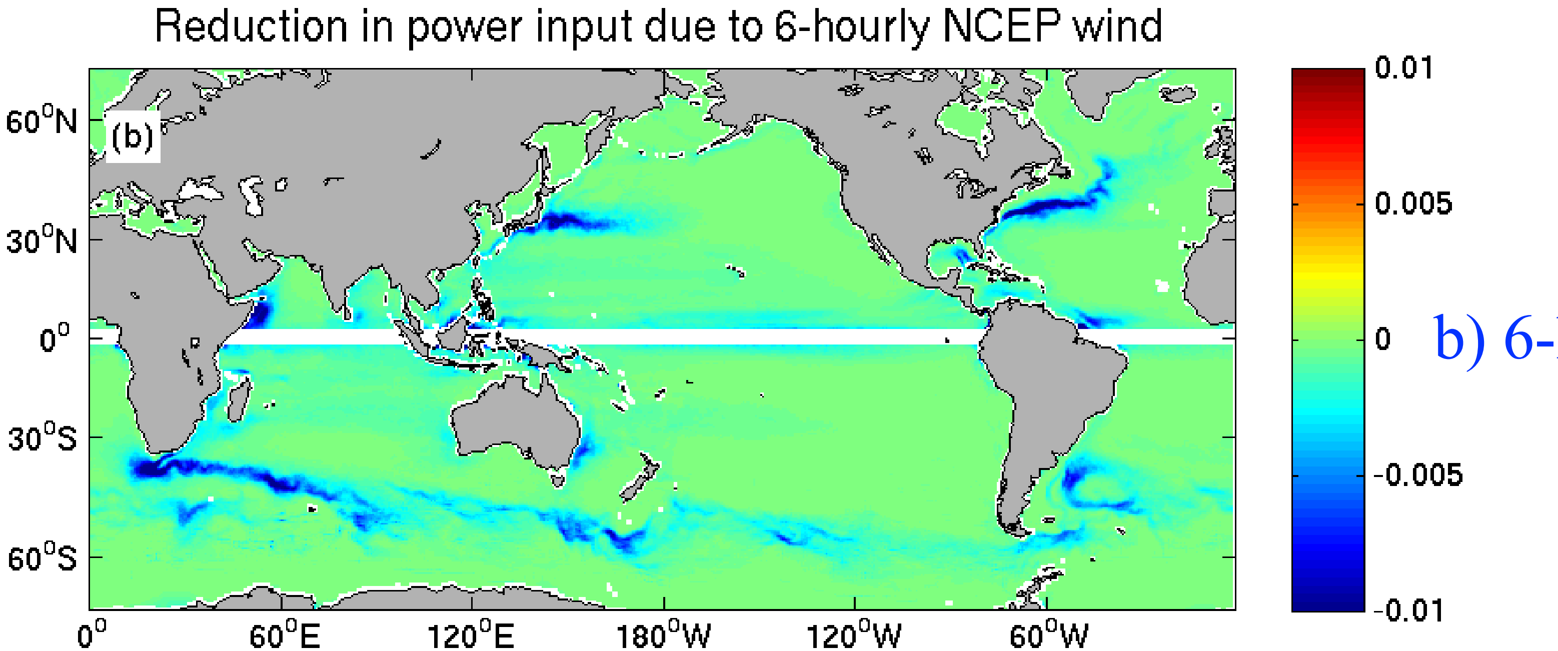
(a) KE (6-hourly wind)
(b) KE (monthly wind)
m2/s2
60°N
30°N
0°
30°S
60°S
0°
60°E
120°E
180°W
120°W
60°W
60
40
20
0
(c)
(d)
20
0
-20
10
-10
uwnd (m/s)
1996
1998
2000
2002
2004
2006
2008
year

Without resting ocean approximation



0.14 TW

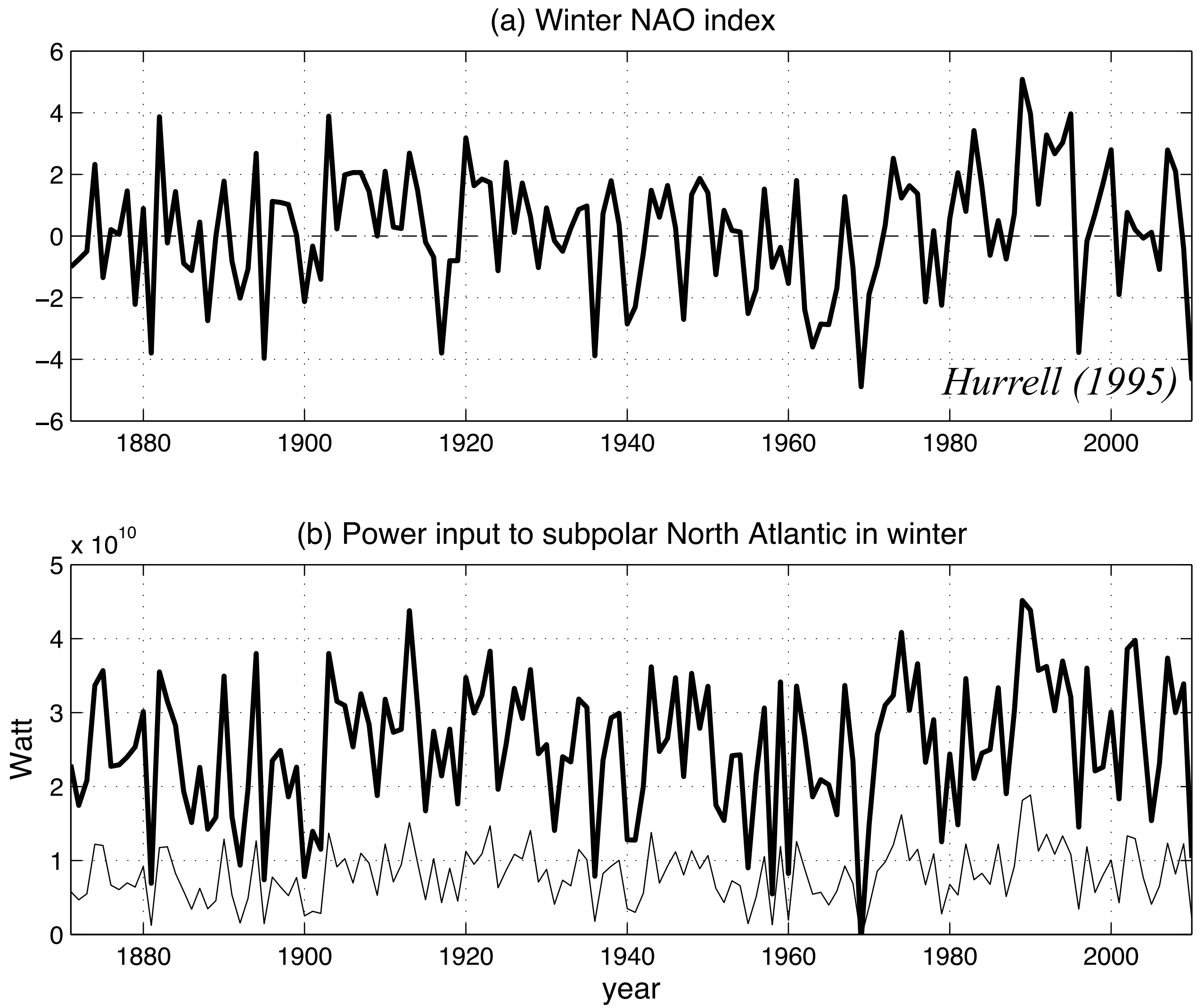
a) monthly NCEP wind



0.25 TW

b) 6-hourly NCEP wind

Variability of wind power input



Power input varies significantly on interannual time scales.

Winter NAO index and P highly correlated at all frequencies at zero phase lag.

Atmospheric winds inject more energy during NAO+ years.

Enhanced storm activities account for greater power input during NAO+ years.

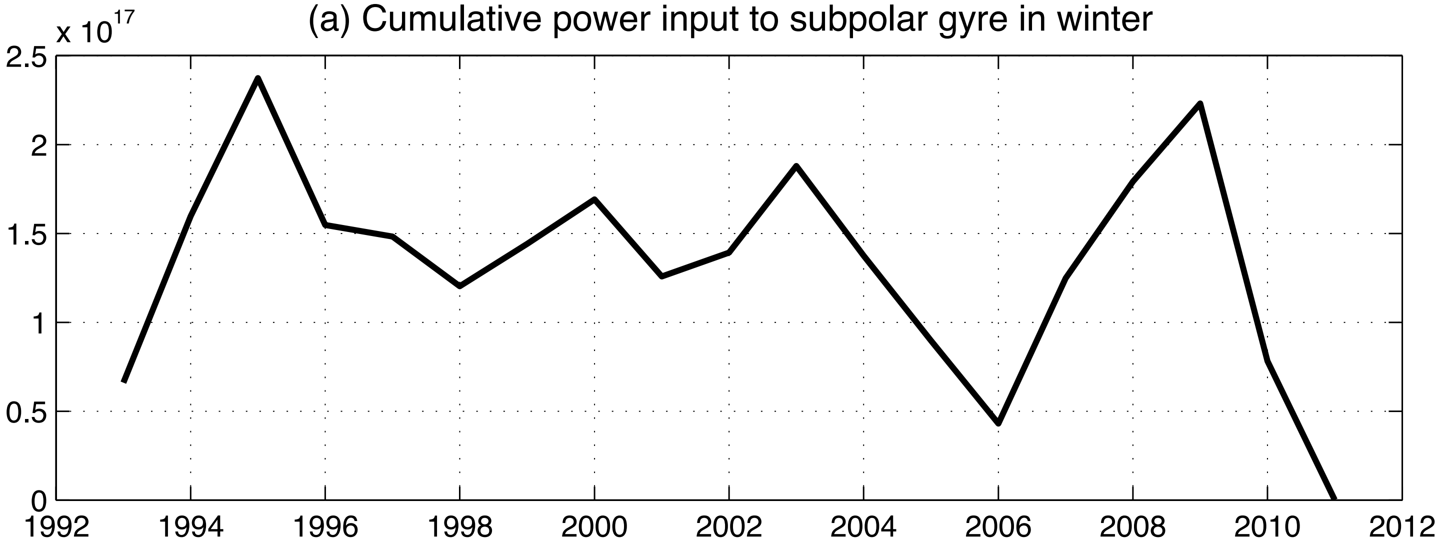
P estimated using monthly stress from 20CR.

P_m owing to stresses calculated from monthly winds.

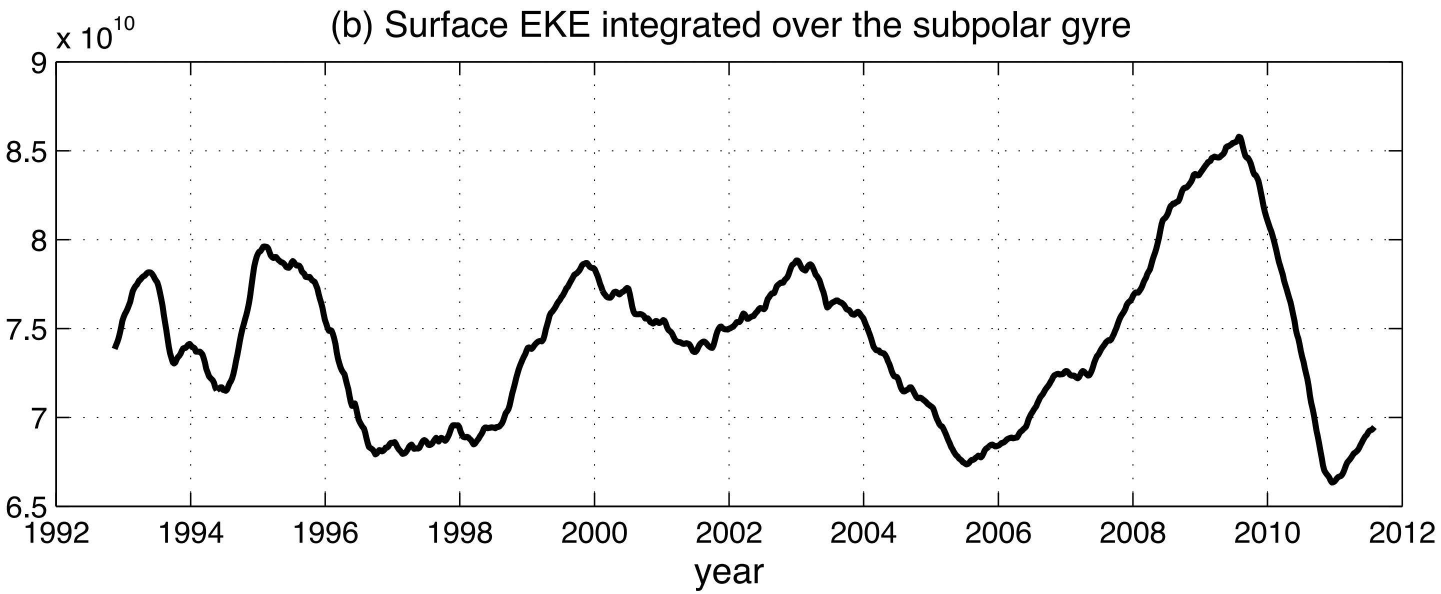
Surface flow estimated using time-averaged ECCO SSH.

Zhai and Wunsch (2013)

Variability of wind power input

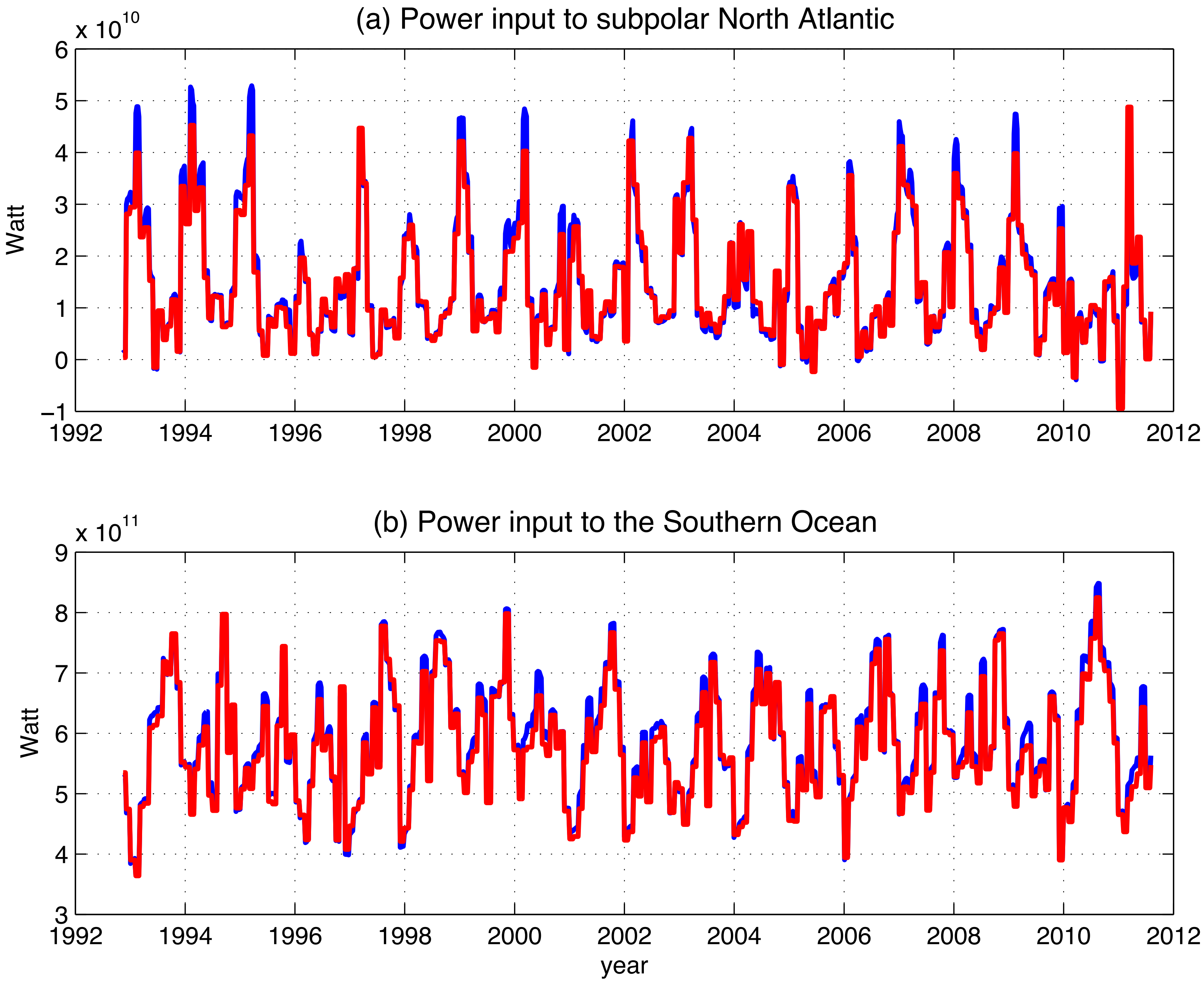


Cumulative P



EKE

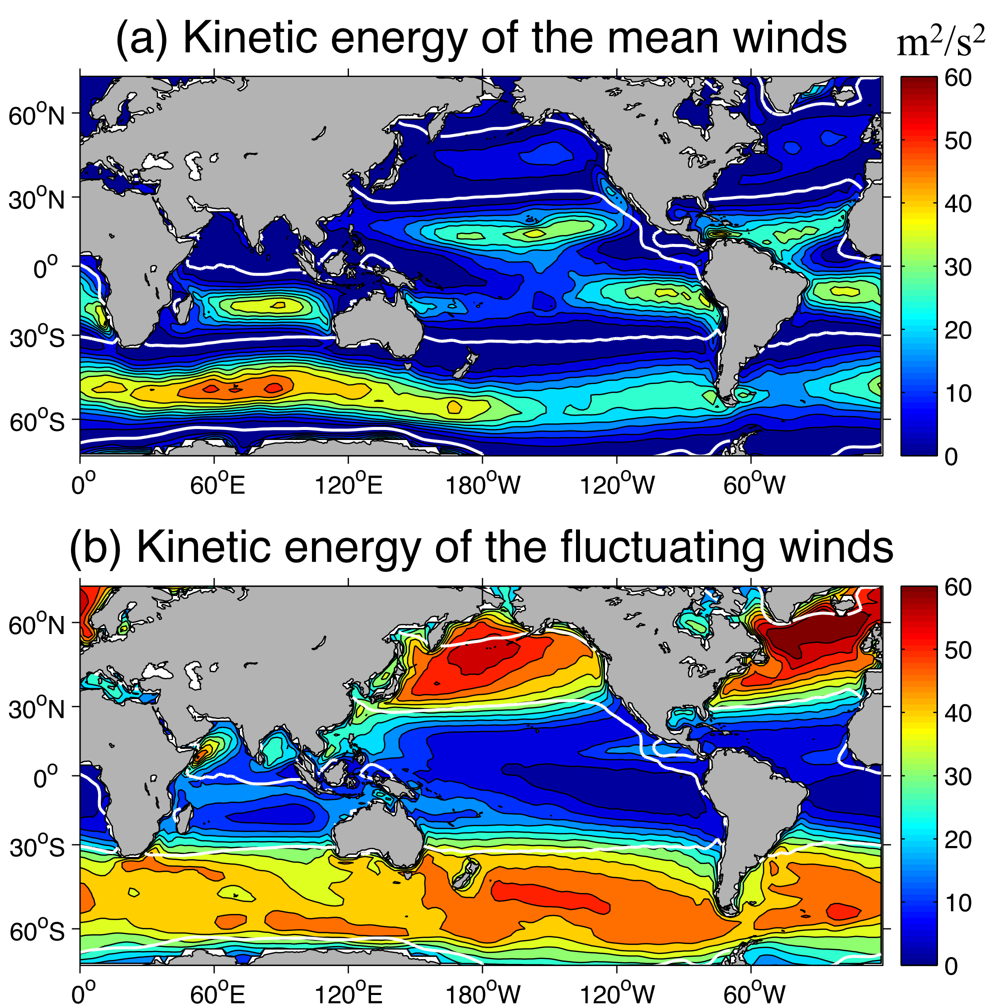
Steady ocean circulation approximation



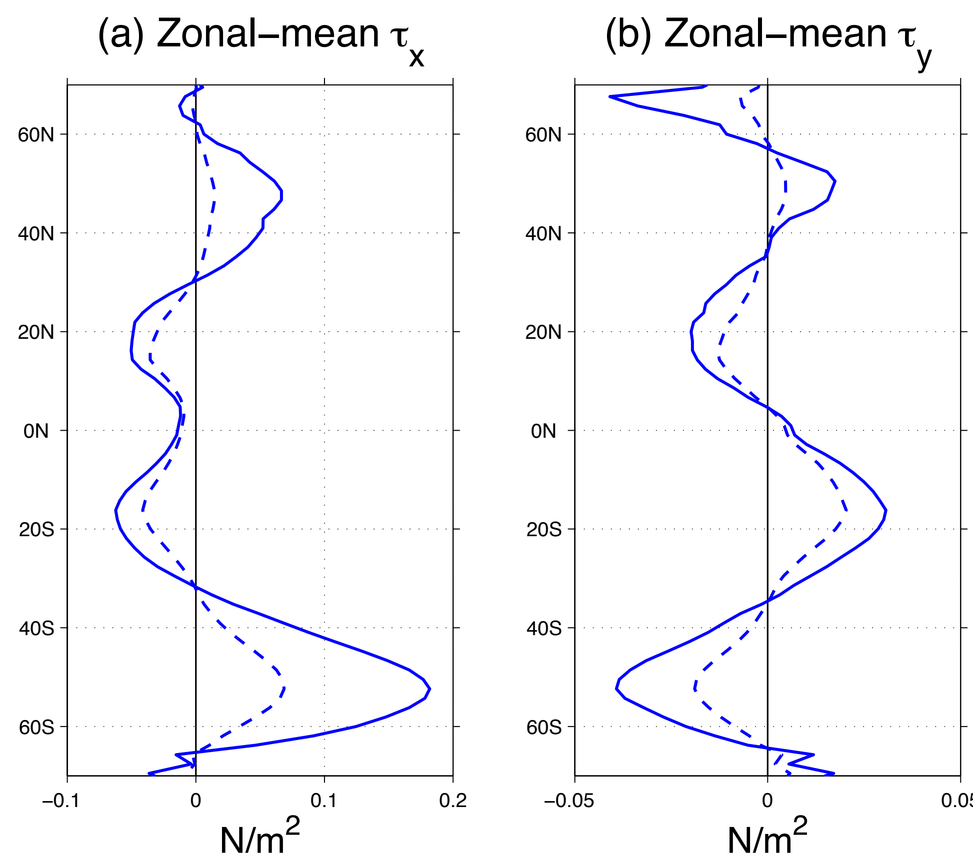
Blue: without

Red: with

- P is often regarded as a transfer of atmospheric KE into the ocean, including KE associated with both time-mean and time-varying winds.
- Are wind momentum and power input high wherever surface atmospheric *total* kinetic energy is high?



White contours: zero time-mean zonal wind stress

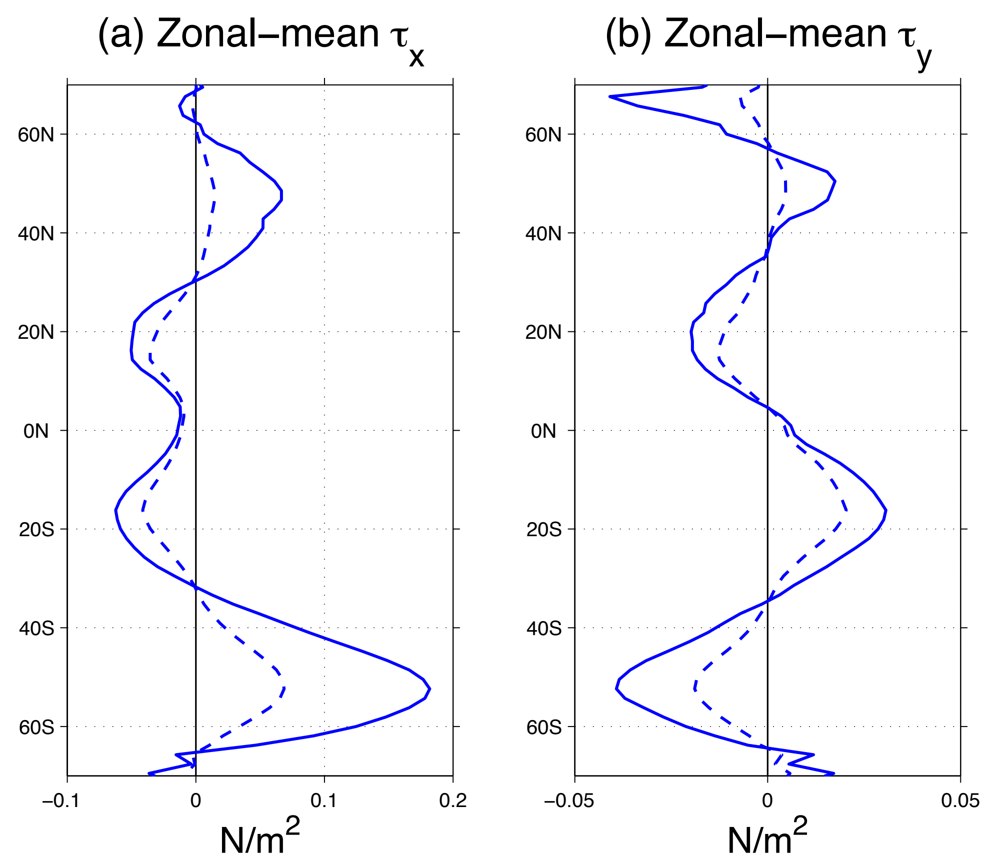


Solid lines: time-mean wind stresses
Dashed lines: stresses calculated from mean winds alone

Zhai (2013)

- P is often regarded as a transfer of atmospheric KE into the ocean, including KE associated with both time-mean and time-varying winds.
- Are wind momentum and power input high wherever surface atmospheric *total* kinetic energy is high?

  - Fluctuating winds enhance stresses calculated from the mean winds alone, regardless of their directions.
  - Wind stresses vanishes in regions where there are no mean winds, irrespective of the amount of wind fluctuations in those regions.



Solid lines: time-mean wind stresses
Dashed lines: stresses calculated from mean winds alone

Zhai (2013)

Wind stress bulk formula

$$\tau = \rho_a c_d |U_{10}| U_{10}$$

Decompose 10 m winds into time mean and fluctuating components, the time-mean wind stress is:

$$\bar{\tau} = \rho_a c_d \overline{|\bar{U}_{10} + U'_{10}|(\bar{U}_{10} + U'_{10})}$$

The stress calculated from mean winds alone is:

$$\bar{\tau}_m = \rho_a c_d |\bar{U}_{10}| \bar{U}_{10}$$

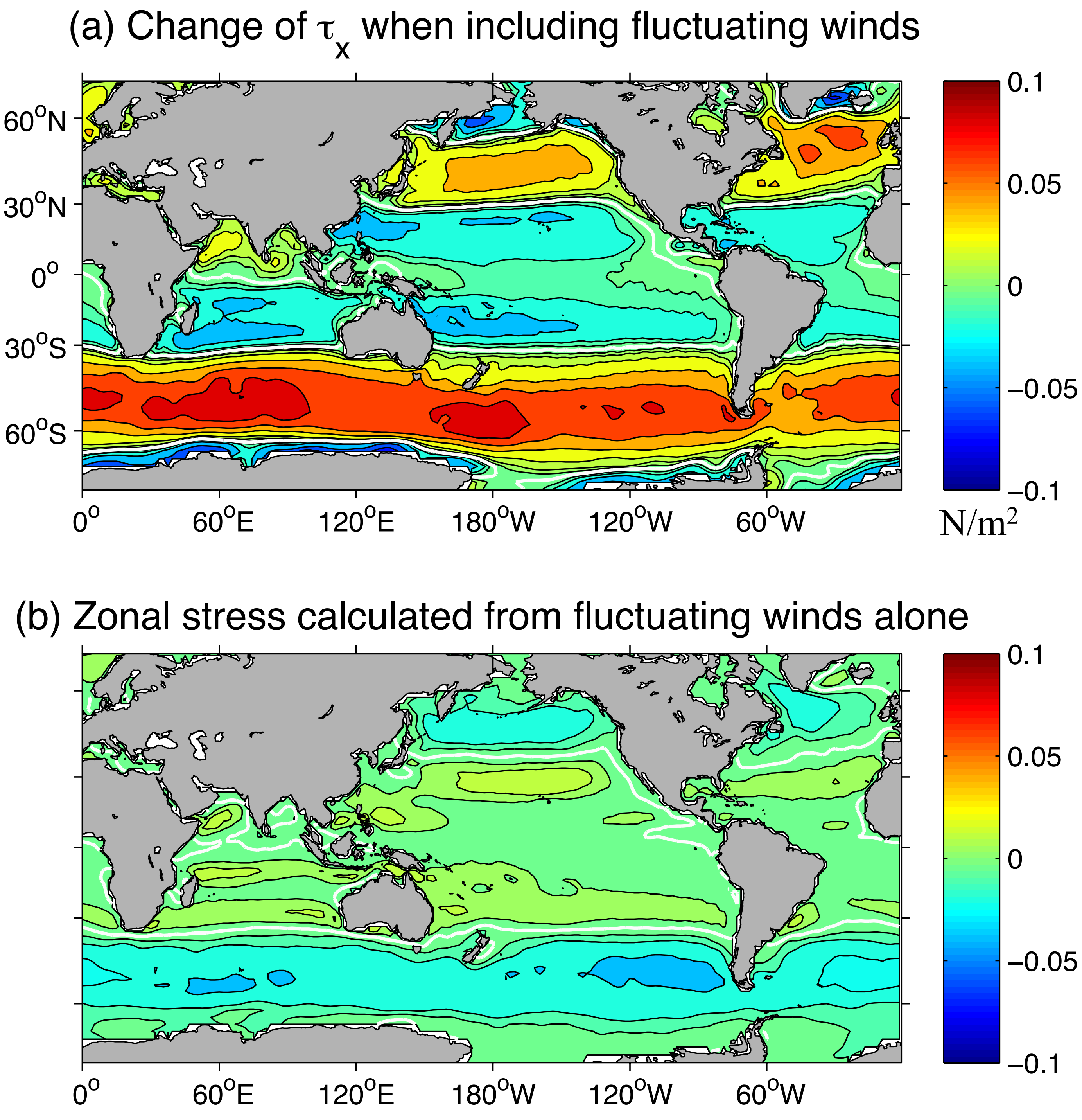
The effect of including fluctuating winds is diagnosed as the residue:

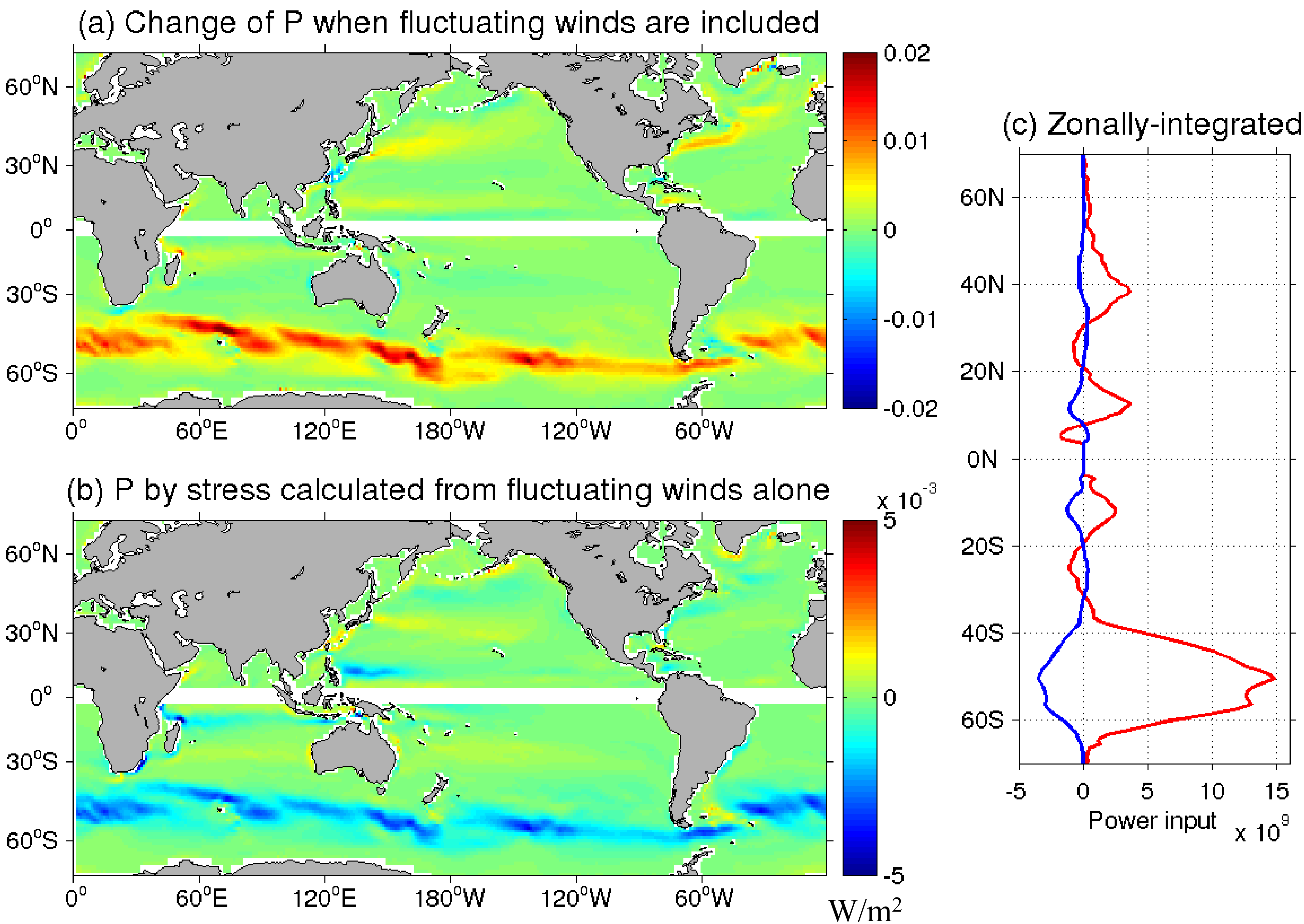
$$\bar{\tau} - \bar{\tau}_m = \rho_a c_d \left[\left(\overline{|U_{10}|} - |\bar{U}_{10}| \right) \bar{U}_{10} + \overline{|U_{10}| U'_{10}} \right]$$

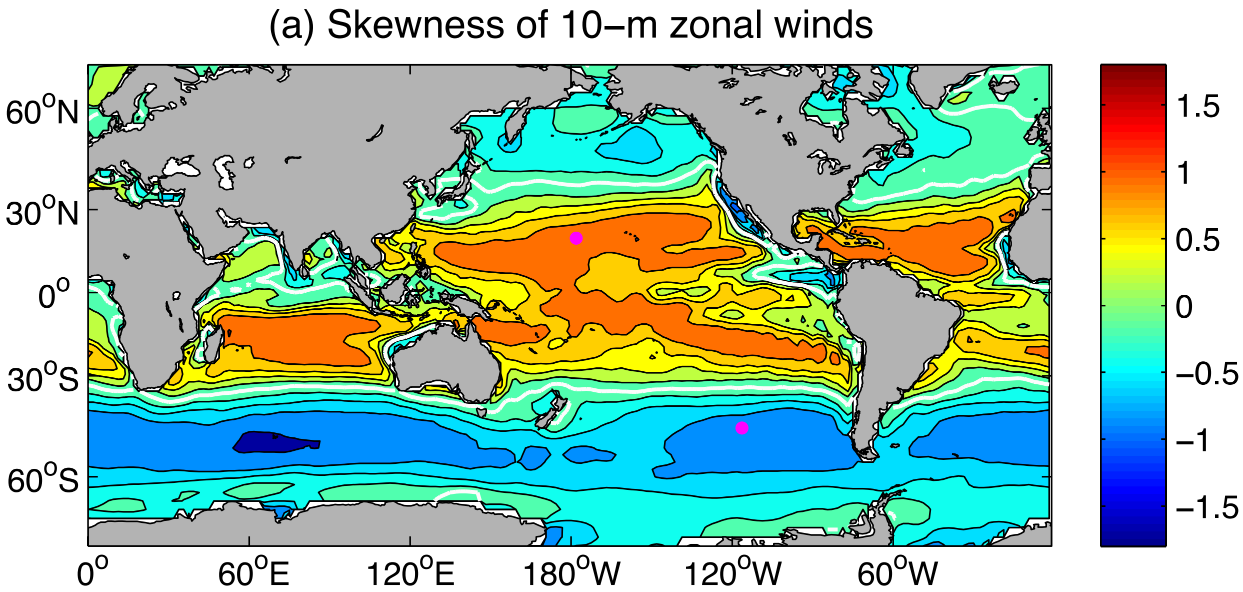
If mean winds ignored, the mean stress is determined solely by fluctuating winds:

$$\bar{\tau}_f = \rho_a c_d \overline{|U'_{10}| U'_{10}} \begin{cases} >0 & \text{for } S > 0, \\ =0 & \text{for Gaussian-distributed } U_{10} \\ <0 & \text{for } S < 0, \end{cases}$$

where S is skewness.

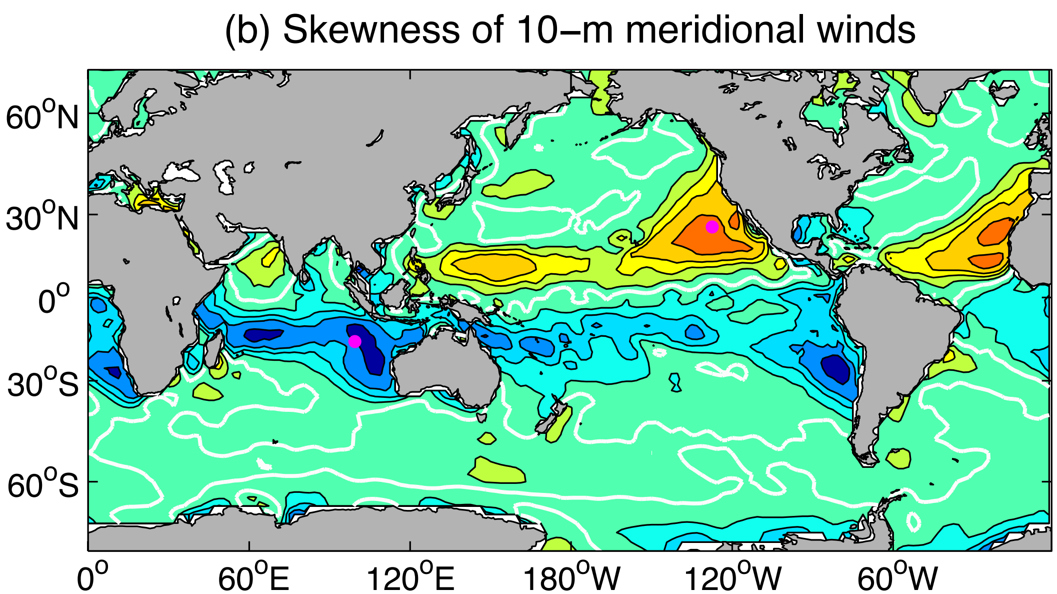

(a) Change of τx when including fluctuating winds
60°N
30°N
0°
30°S
60°S
0°
60°E
120°E
180°W
120°W
60°W
0.1
0.05
0
−0.05
−0.1
N/m²
(b) Zonal stress calculated from fluctuating winds alone
0°
60°E
120°E
180°W
120°W
60°W
0.1
0.05
0
−0.05
−0.1

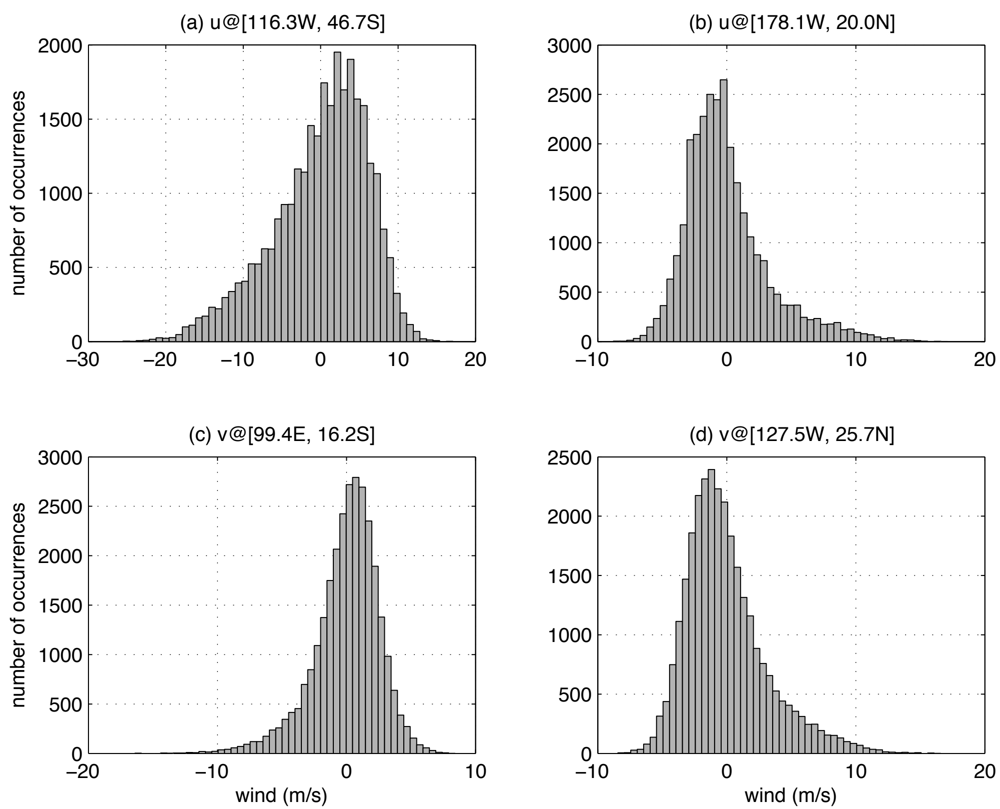

(a) Change of P when fluctuating winds are included
60°N
30°N
0°
30°S
60°S
0°
60°E
120°E
180°W
120°W
60°W
0.02
0.01
0
-0.01
-0.02
(b) P by stress calculated from fluctuating winds alone
x 10^-3
5
0
-5
W/m²
(c) Zonally-integrated
60N
40N
20N
0N
20S
40S
60S
-5
0
5
10
15
Power input
x 10^9



The skewness and mean of 10 m winds are negatively correlated as a consequence of quadratic stress law *(Monahan, 2004)*.

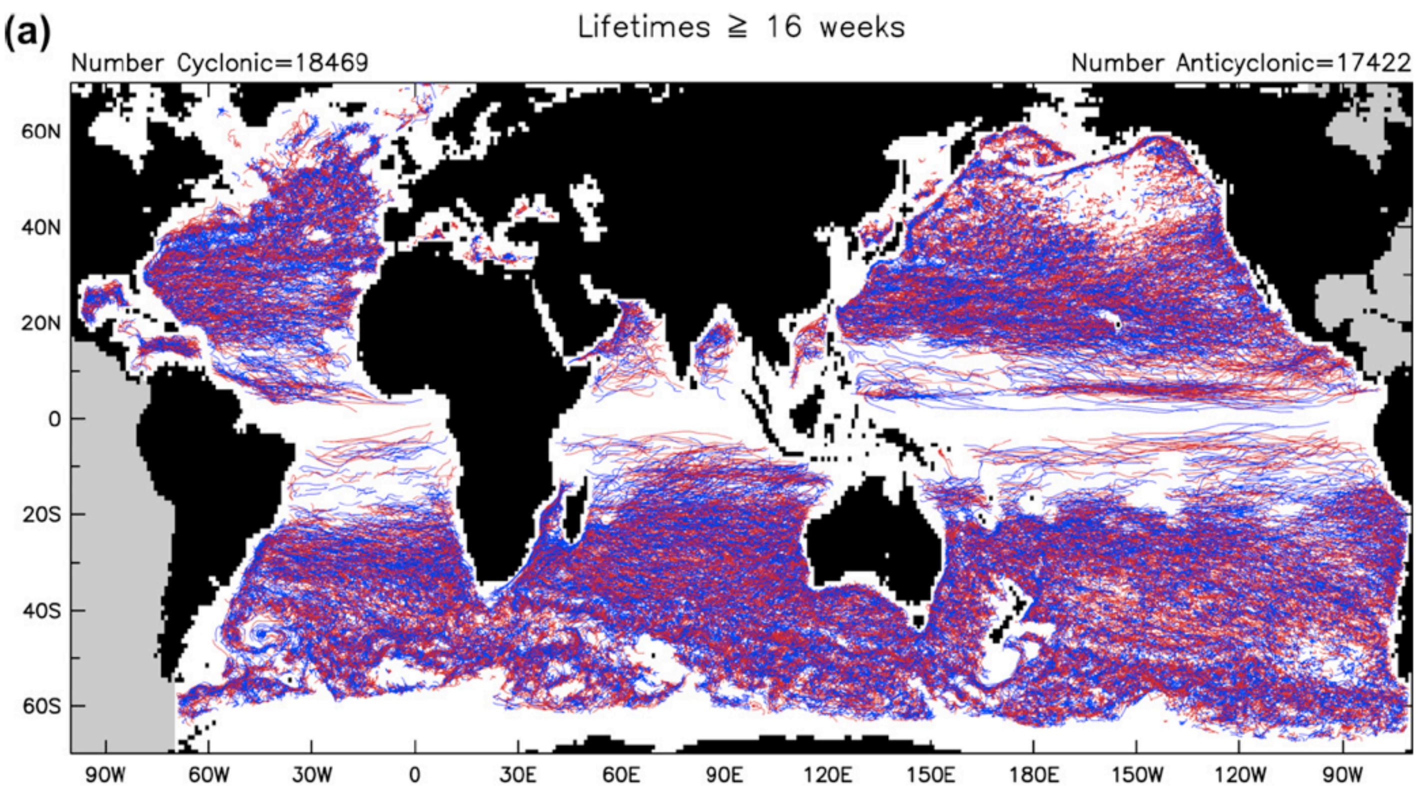
Wind perturbations in the same direction as mean winds are subject to a larger surface drag and are preferentially damped.





Estimating global eddy energy residence time

- How long eddies live influences the role they play, particularly in tracer transport. (Meddies...)
- Limited knowledge of eddy lifetime.
- *Chelton et al*. (2011) recently estimated that long-lived eddies have an average lifetime of 32 weeks based on an automated eddy tracking procedure.



- Consider eddy energy integrated in a closed basin:

$$P = \frac{E}{\lambda}$$

where P is net rate of eddy energy supply, E is volume-integrated eddy energy, and λ is the *average* eddy energy residence time.

- If a village has a steady population of 800 people, and the birth rate is 10 people per year, then

$$10 \text{ people/yr} = \frac{800 \text{ people}}{80 \text{ yrs}}$$

Estimating P

- Wind power input to ocean general circulation is the primary energy source of generating eddies through instability of the mean flow *(e.g., Gill et al., 1974; Wunsch, 1998; Zhai and Marshall, 2013)*.

$$P = \int \overline{\tau \cdot \mathbf{u_g}} dS$$

Estimating E

- Make use of two findings from previous surveys of global current meter records *(e.g., Wunsch, 1997; Ferreri and Wunsch, 2010):*

  1) The horizontal KE away from the Tropics is dominated by, and approximately equally-partitioned between, the batrotropic and first baroclinic modes.

  2) The altimetry data reflect mostly the first baroclinic mode in open ocean.

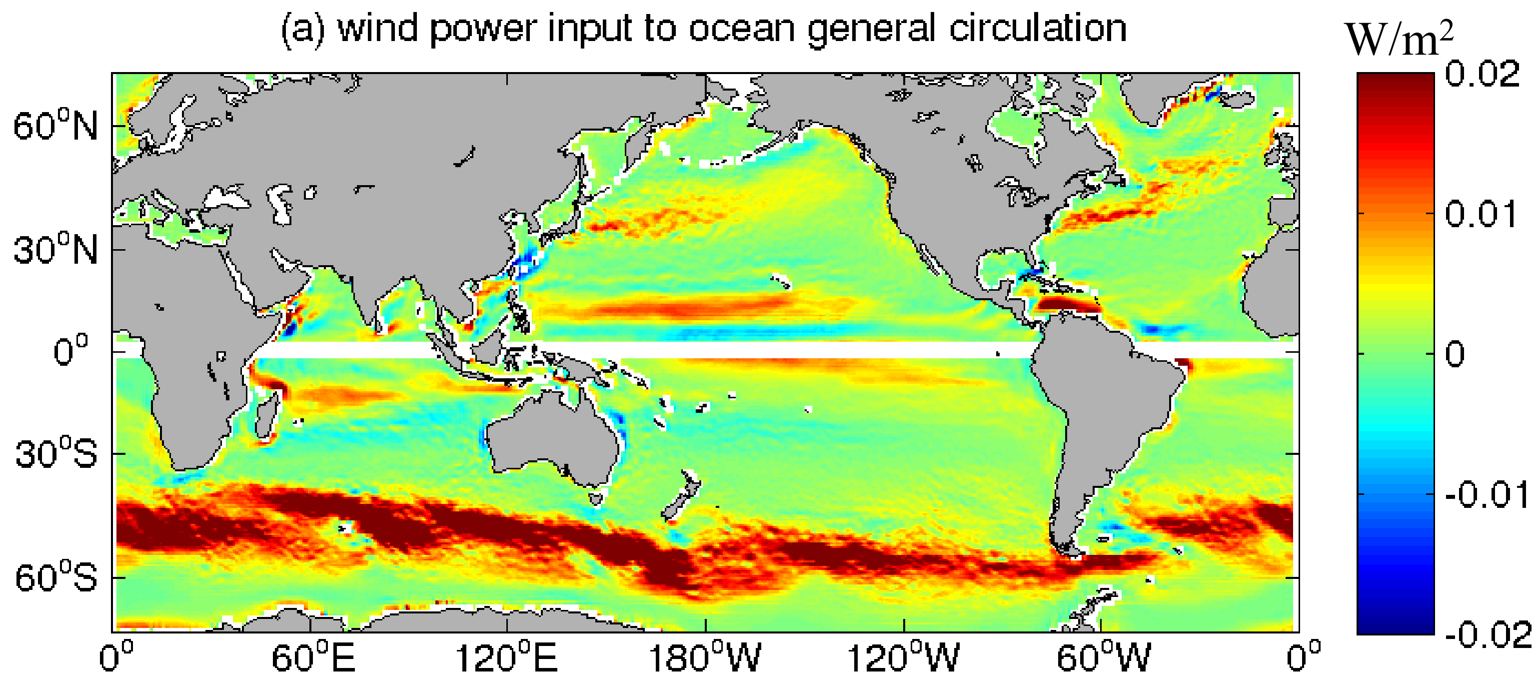
- EKE in the first baroclinic mode:

$$EKE_{bc} = \int_{-H}^{0} \frac{1}{2}\rho_0 \overline{|\mathbf{u}_1'(z)|^2} dz = \frac{\rho_0 g^2 \overline{|\nabla\eta'|^2}}{2f^2} \int_{-H}^{0} \frac{F_1(z)^2}{F_1(0)^2} dz$$

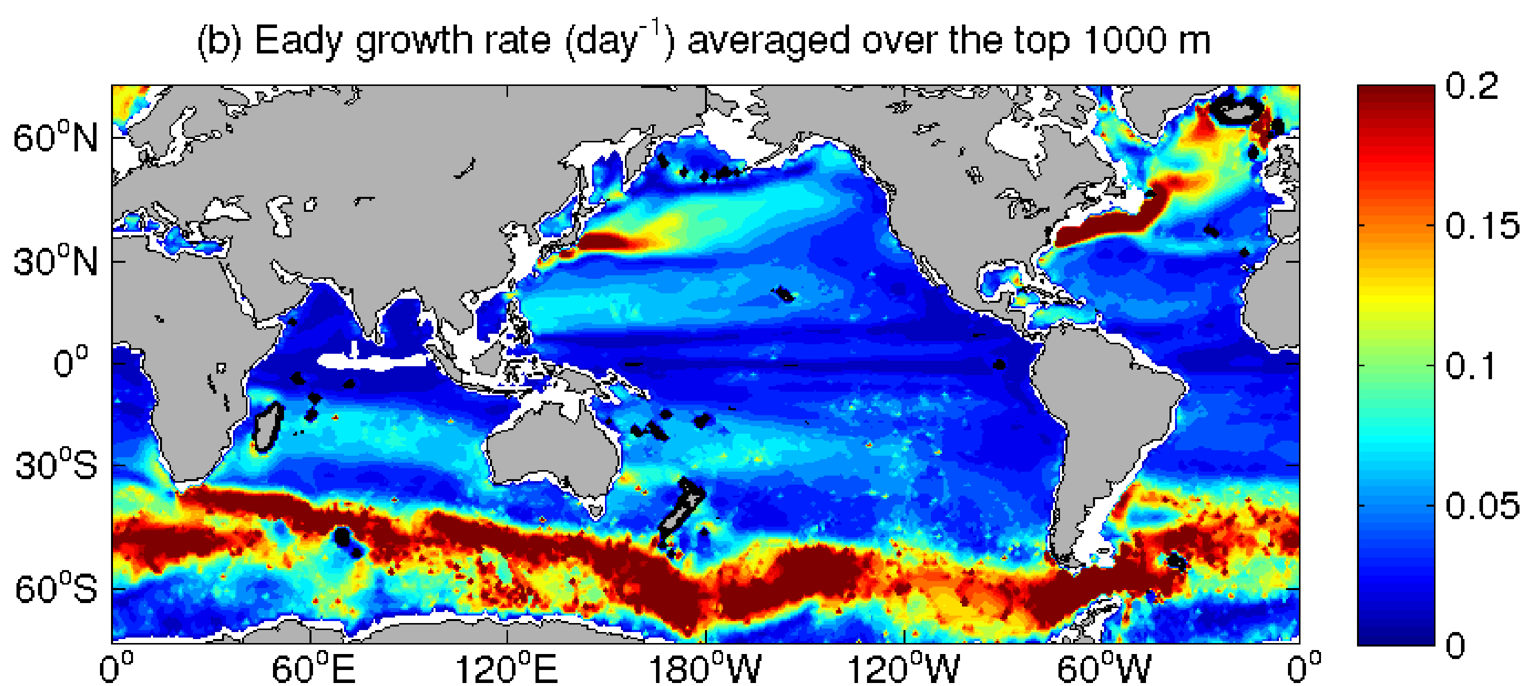
- EPE in the first baroclinic mode: $EPE_{bc} \approx \frac{\rho_0 g^2}{2g'} \overline{\eta'^2}$

- Total eddy energy in the barotropic and 1st baroclinic modes:

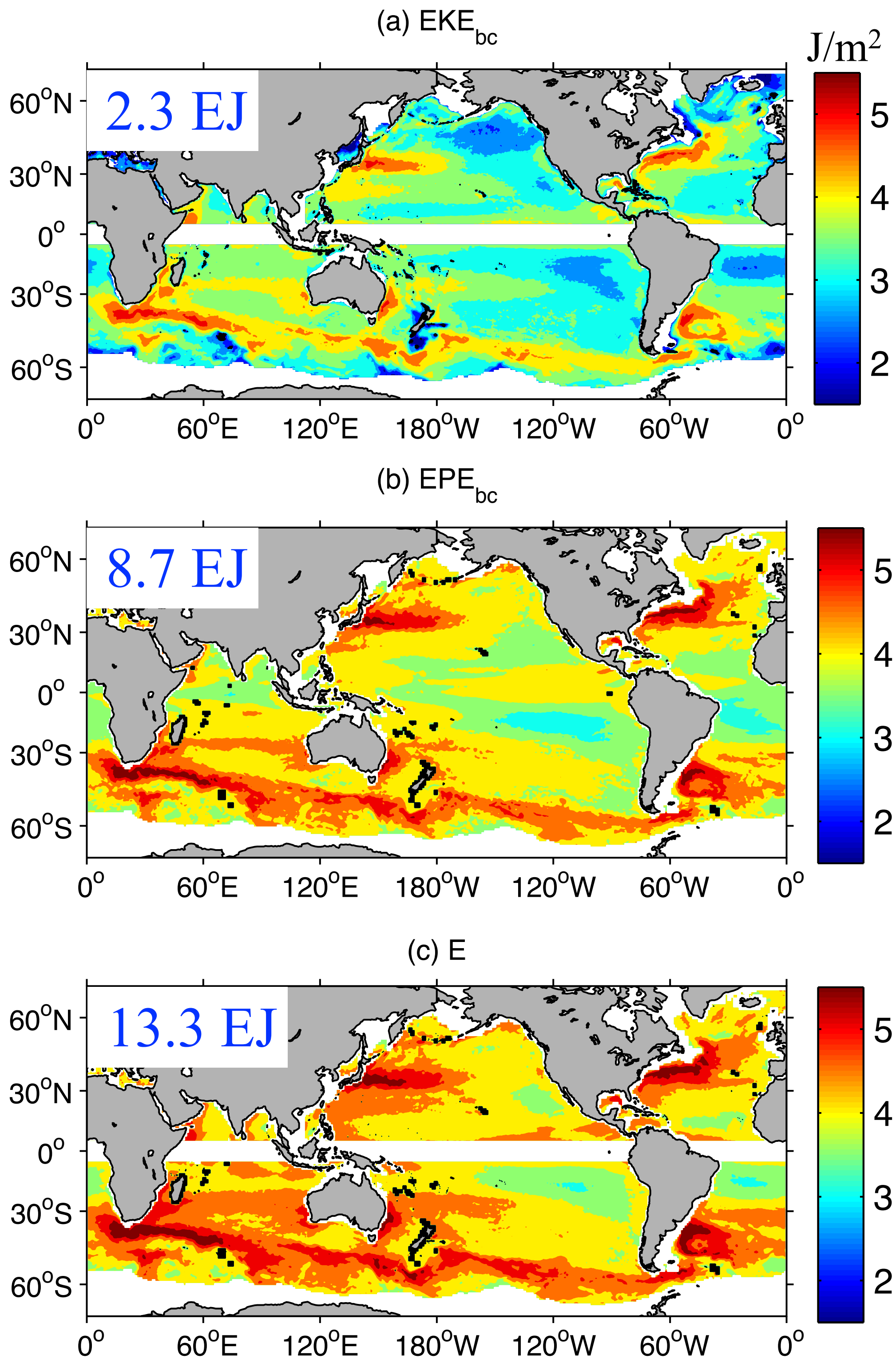
$$E \approx \int \left(\frac{\rho_0 g^2 \overline{|\nabla\eta'|^2}}{f^2} \int_{-H}^{0} \frac{F_1(z)^2}{F_1(0)^2} dz + \frac{\rho_0 g^2}{2g'} \overline{\eta'^2} \right) dS$$



0.88 TW
(80% in SH)



c.f. Stammer (1998),
Smith (2007)



- Zang and Wunsch (2010) estimated global eddy energy to be about 10 EJ based on spectra of observed ocean variability.

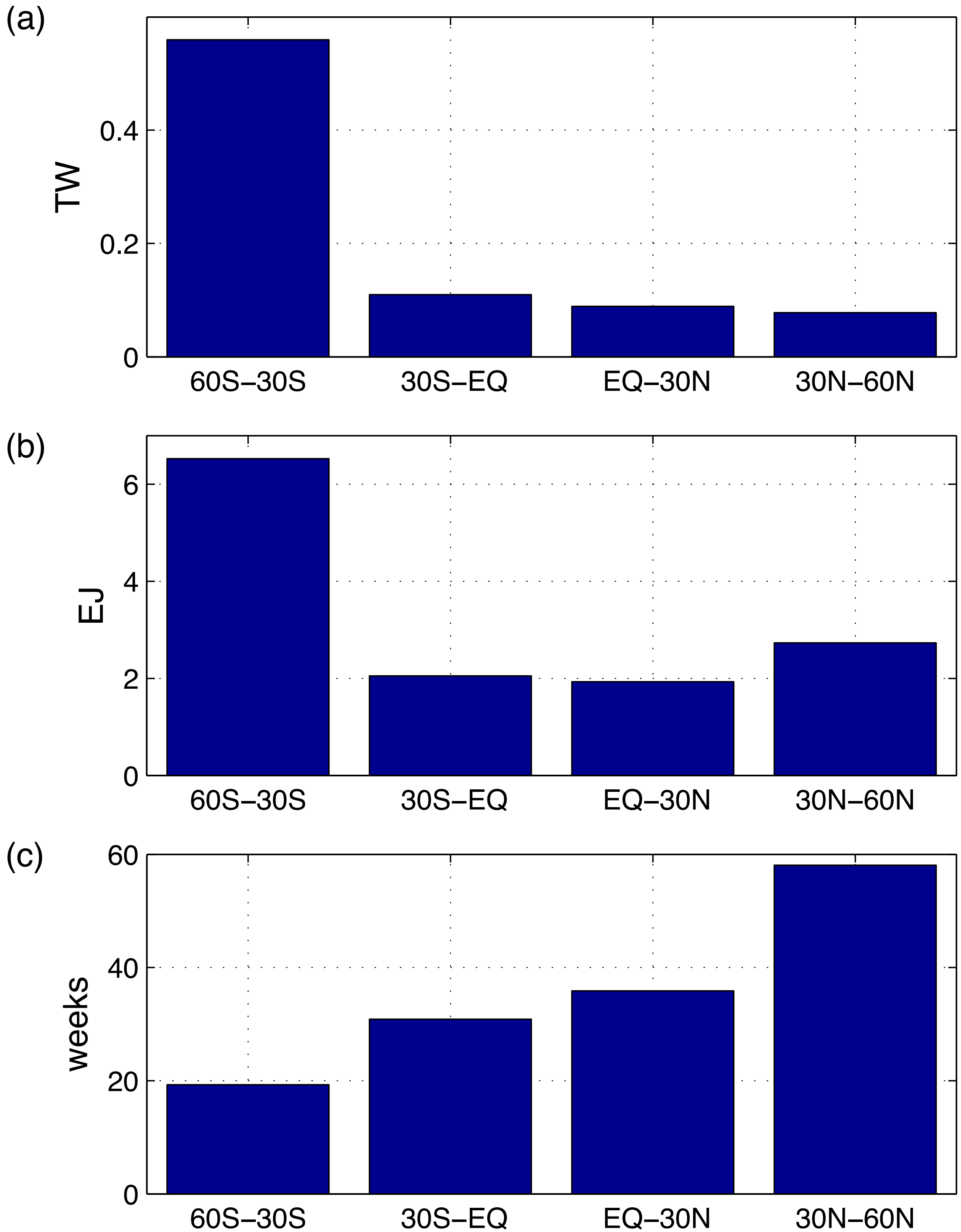
- Global eddy energy residence time:

$$\lambda = \frac{E}{P} \approx 25 \text{ weeks}$$

- Assuming small inter-hemispheric energy exchange:

$$\lambda_{NH} \approx 46 \text{ weeks}$$

$$\lambda_{SH} \approx 20 \text{ weeks}$$



- Eddy energy residence time is shortest in the Southern Ocean (~18 weeks).

- Possibly due to frequent eddy interaction with rough topography *(e.g., Nikurashin et al., 2012)*.

- Eddy energy residence time is a bulk or integrative parameter.

Conclusions

- Synoptic winds are important in supplying energy to ocean general circulation and also in taking energy out of the ocean when the ocean surface velocity is taken into account in the wind stress calculation.

- The impact of wind variability on wind momentum and energy input to the ocean depends strongly on the presence of the mean winds.

- The global average eddy energy residence time is estimated to be about half a year. The eddy energy residence time is found to be shortest in the Southern Ocean (~18 weeks).