Eddy-driven air-sea interactions in the California Current System and the western Arabian Sea

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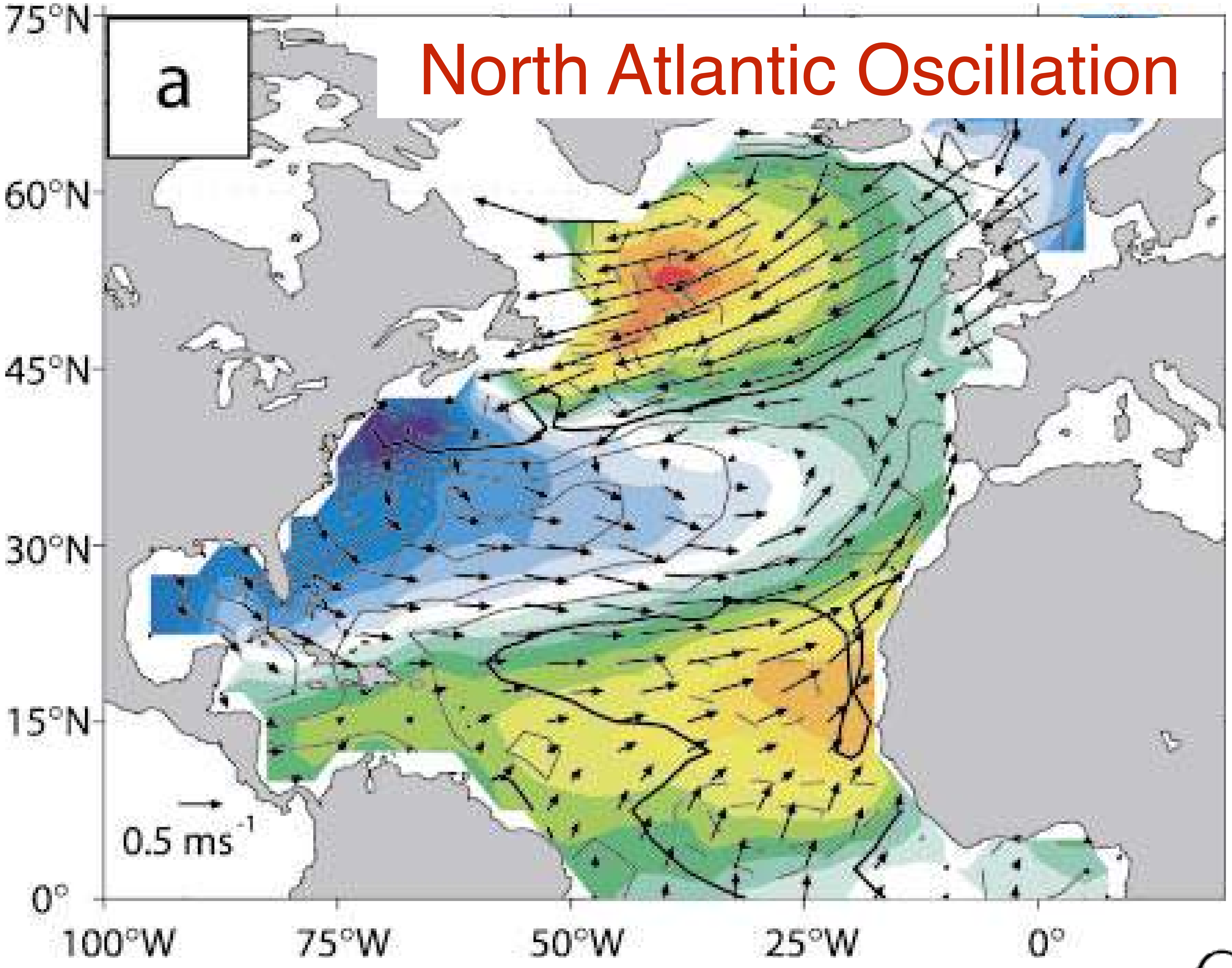
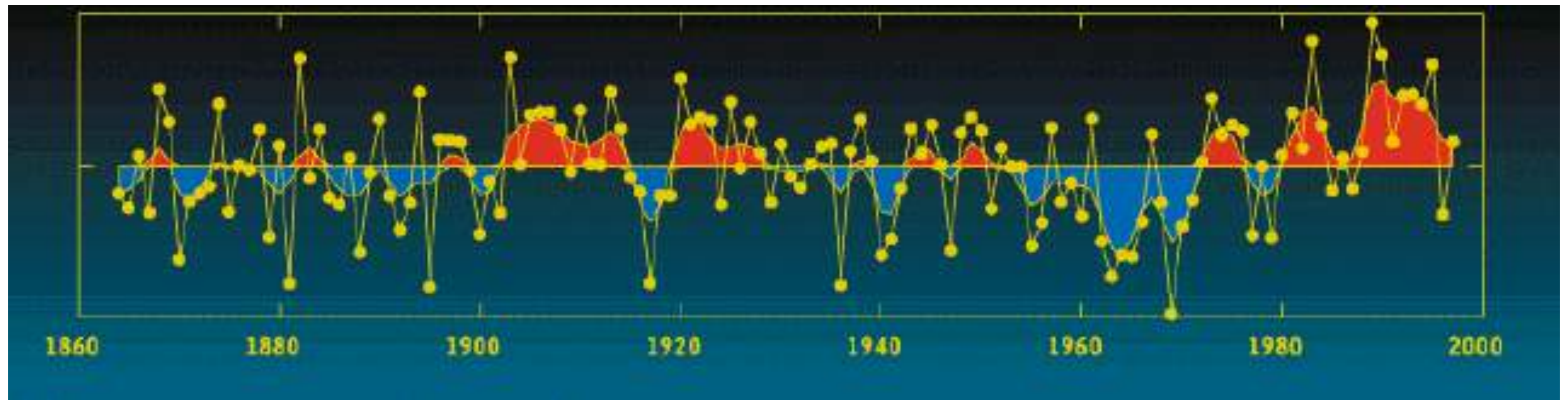
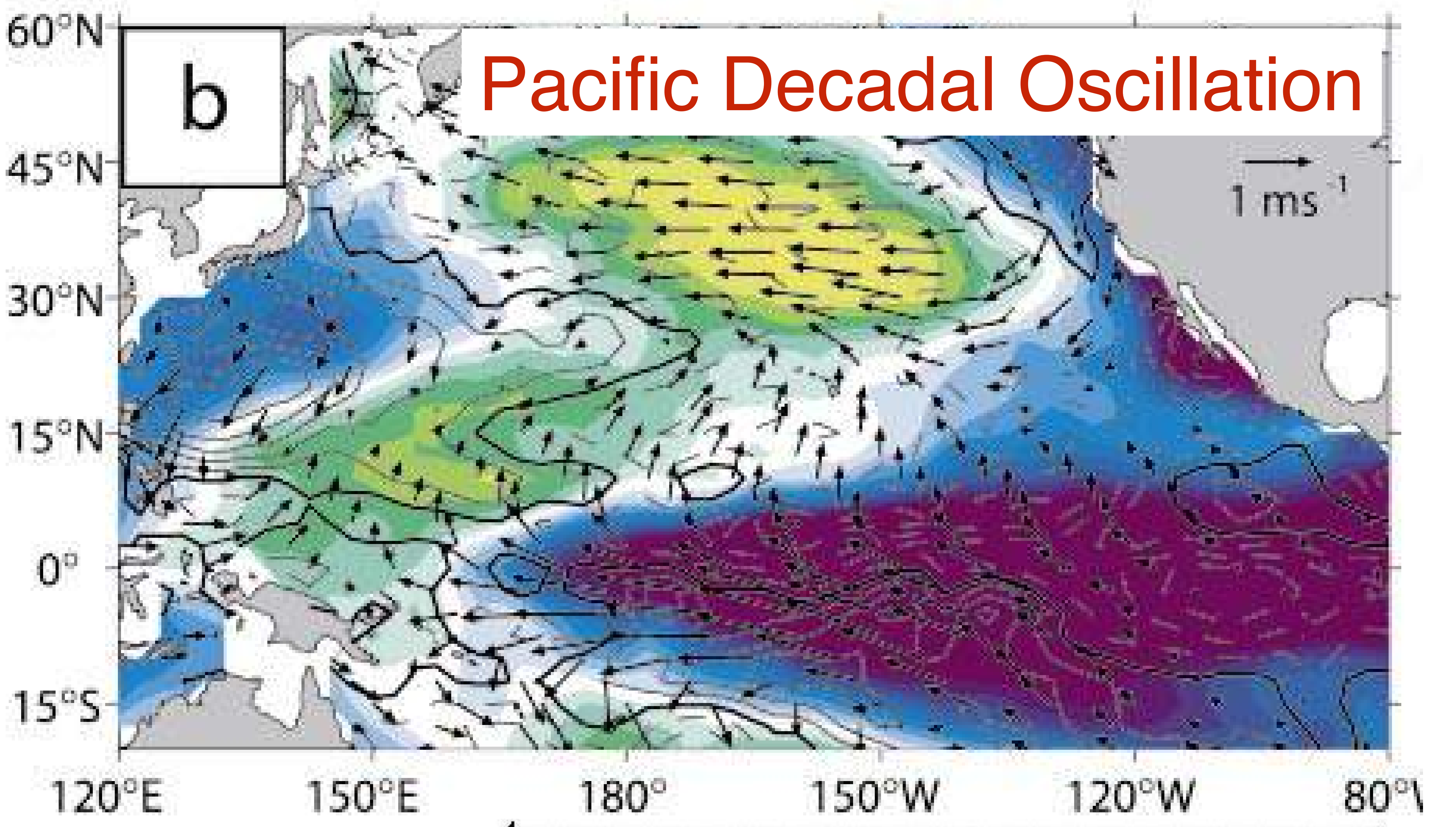
SeaWiFS surface chlorophyll concentration
O(10³km)
O(10km)
Air-sea interaction over different oceanic scales?
http://earthobservatory.nasa.gov

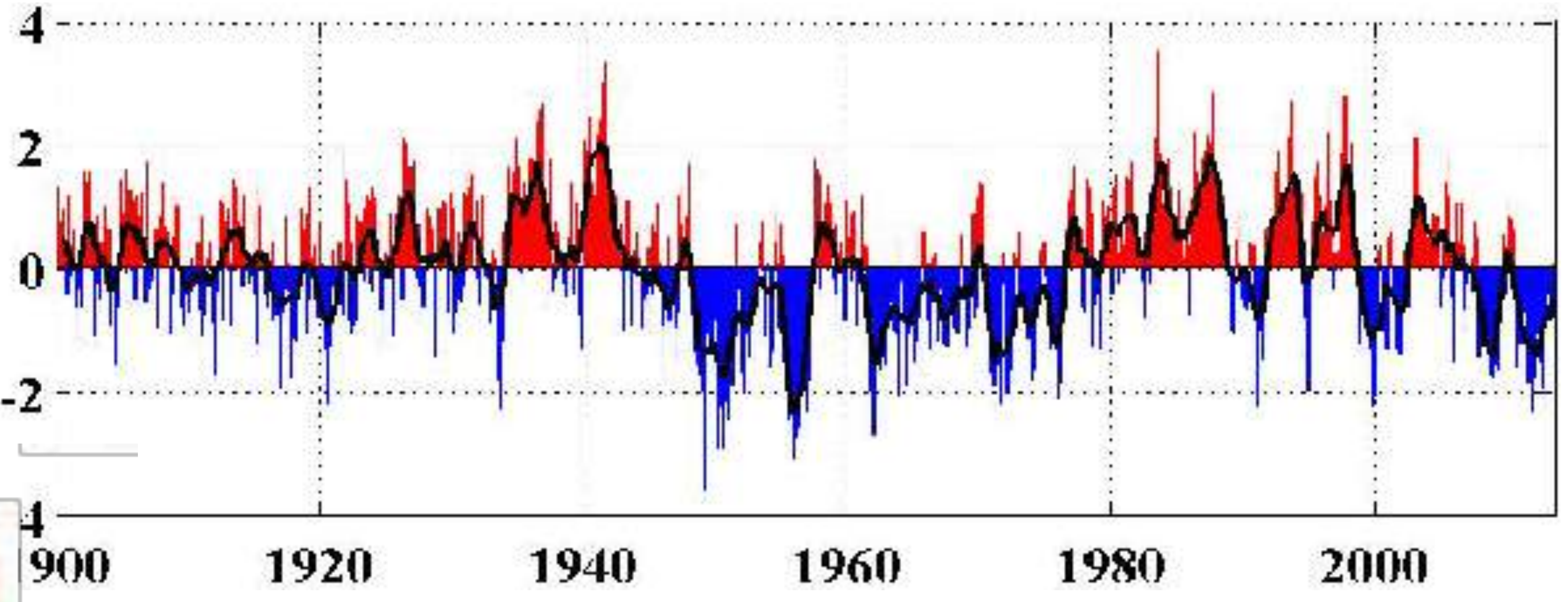
Large-scale air-sea interactions:

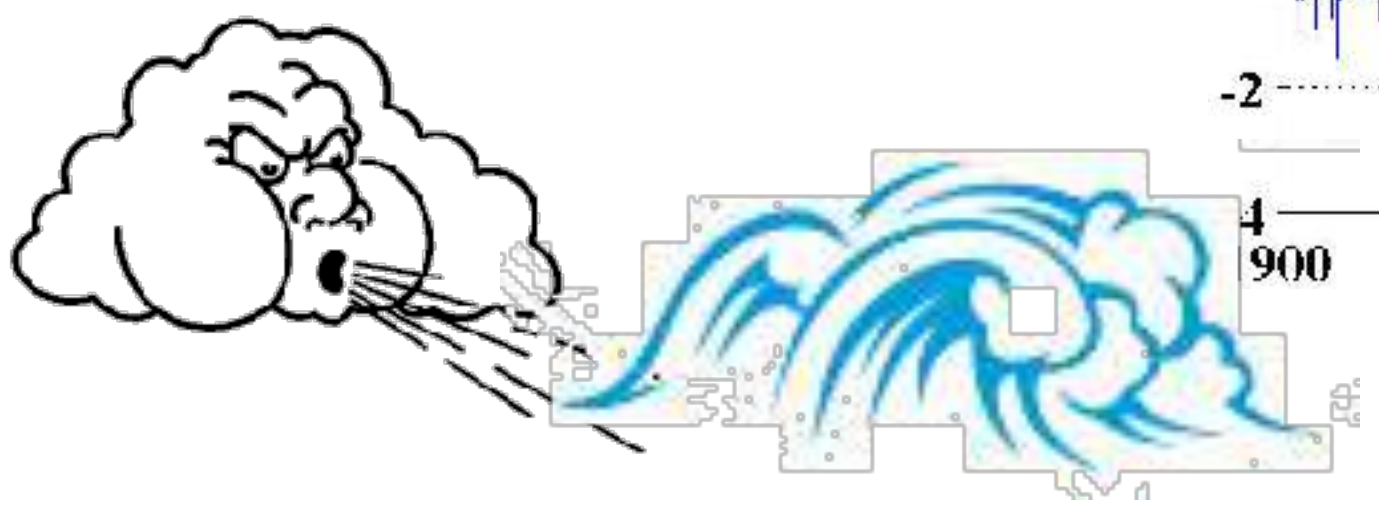
Winds over a slab ocean without dynamic eddies/fronts





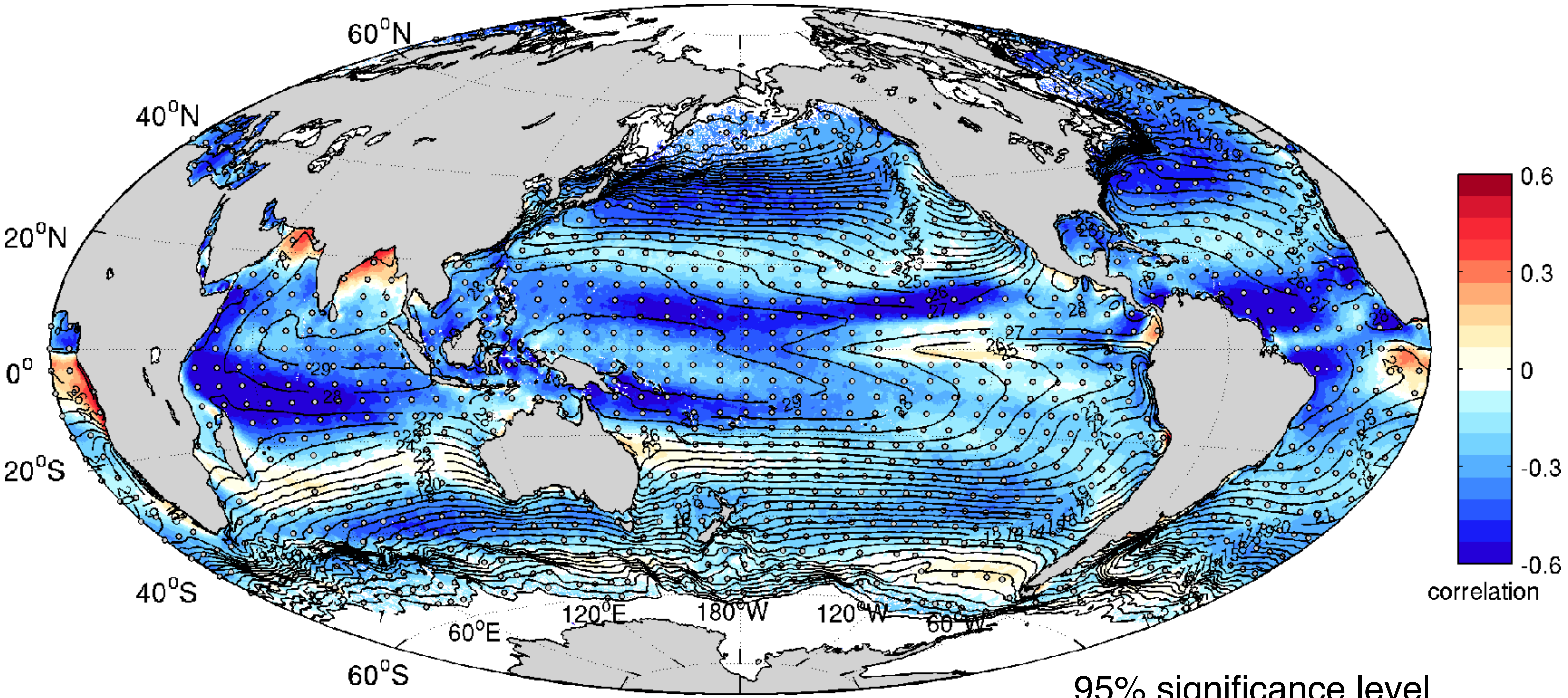






Kushnir et al. 2002

Air-sea interaction with no dynamic role of oceans
— Correlation between wind speed and SST



95% significance level

2000-2009 daily
QuikSCAT WS
NOAA-OI SST

Higher (lower) wind speed ➔ colder (warmer) SST
Negative correlation: Oceanic response to the atmosphere

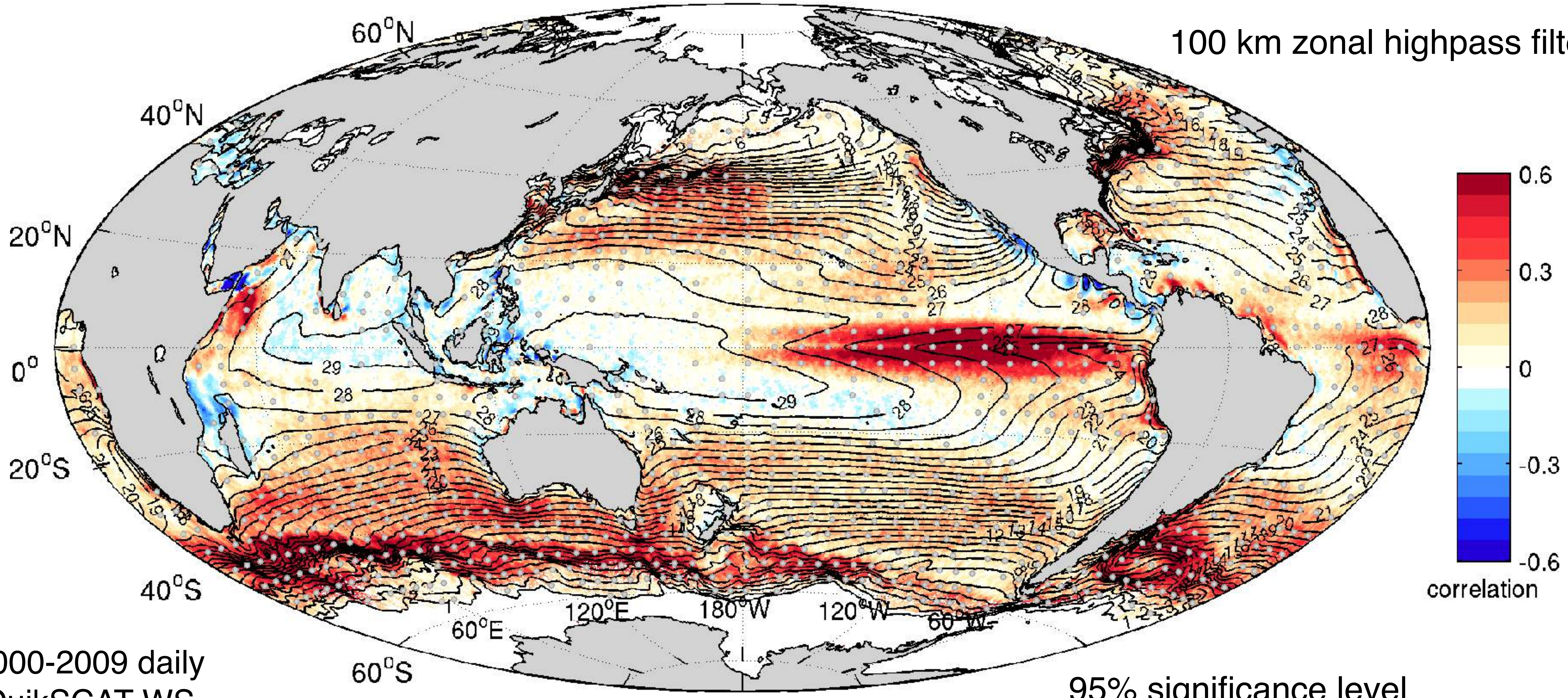
However, the oceans are filled with energetic eddies and fronts

ECCO2 ocean state estimation based on MITgcm
http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3820

Eddy-mediated air-sea interaction

—Correlation between high-pass filtered wind speed and SST

100 km zonal highpass filter

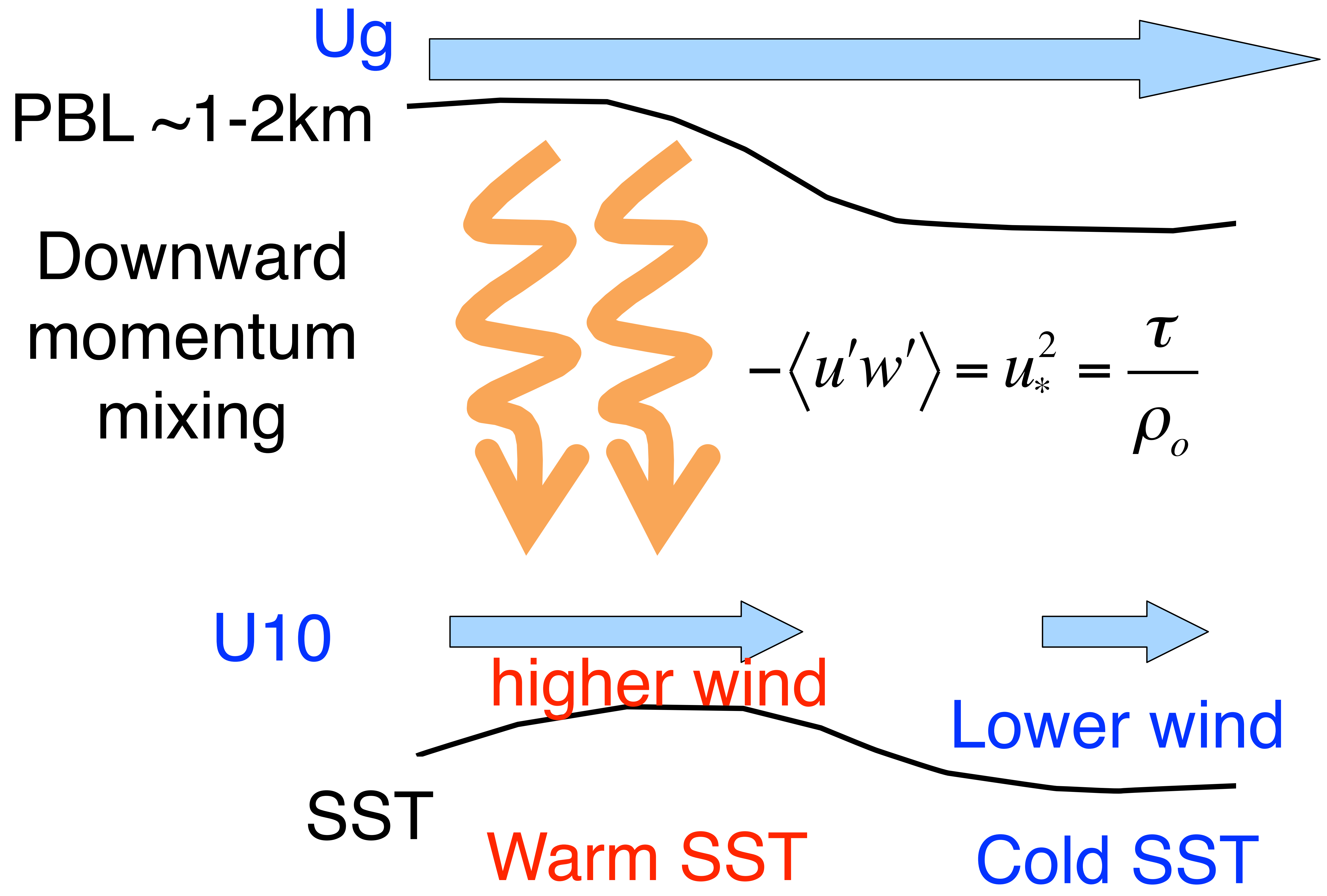


2000-2009 daily
QuikSCAT WS
NOAA-OI SST

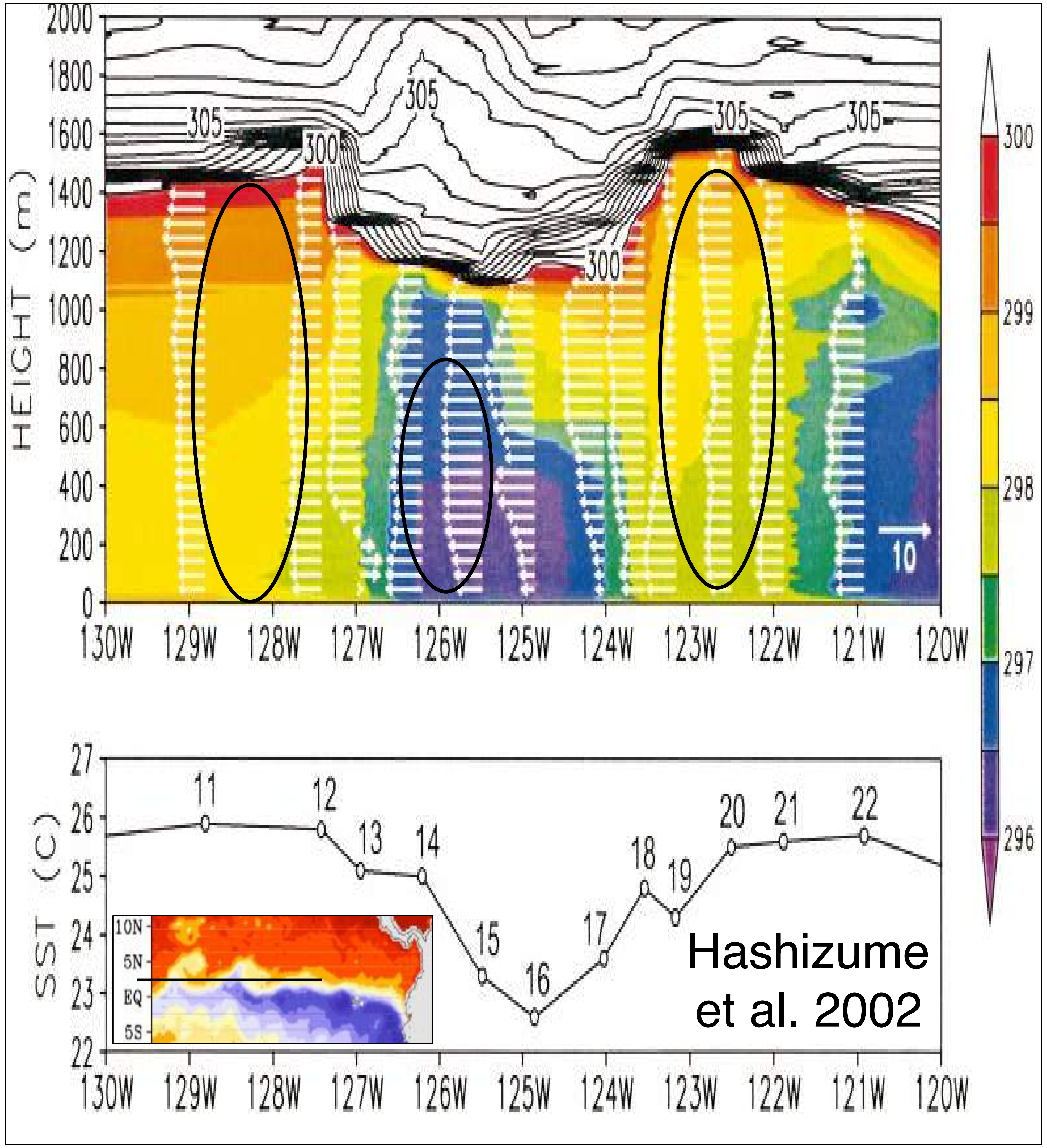
95% significance level

Oceanic forcing of the atmosphere on frontal and mesoscales. Seo 2017 JCLI

Mesoscale SST alters the vertical mixing in the ABL



$$-\langle u'w' \rangle = u_*^2 = \frac{\tau}{\rho_o}$$



- 1-D turbulent boundary layer process
- A shallow and rapid adjustment (~hrs)

Limited to the MABL, the atmospheric response to mesoscale SST may not affect the deep troposphere.

But it is critically important for ocean circulation through changes in wind stress and wind stress curls.

Let's look at the wind stress

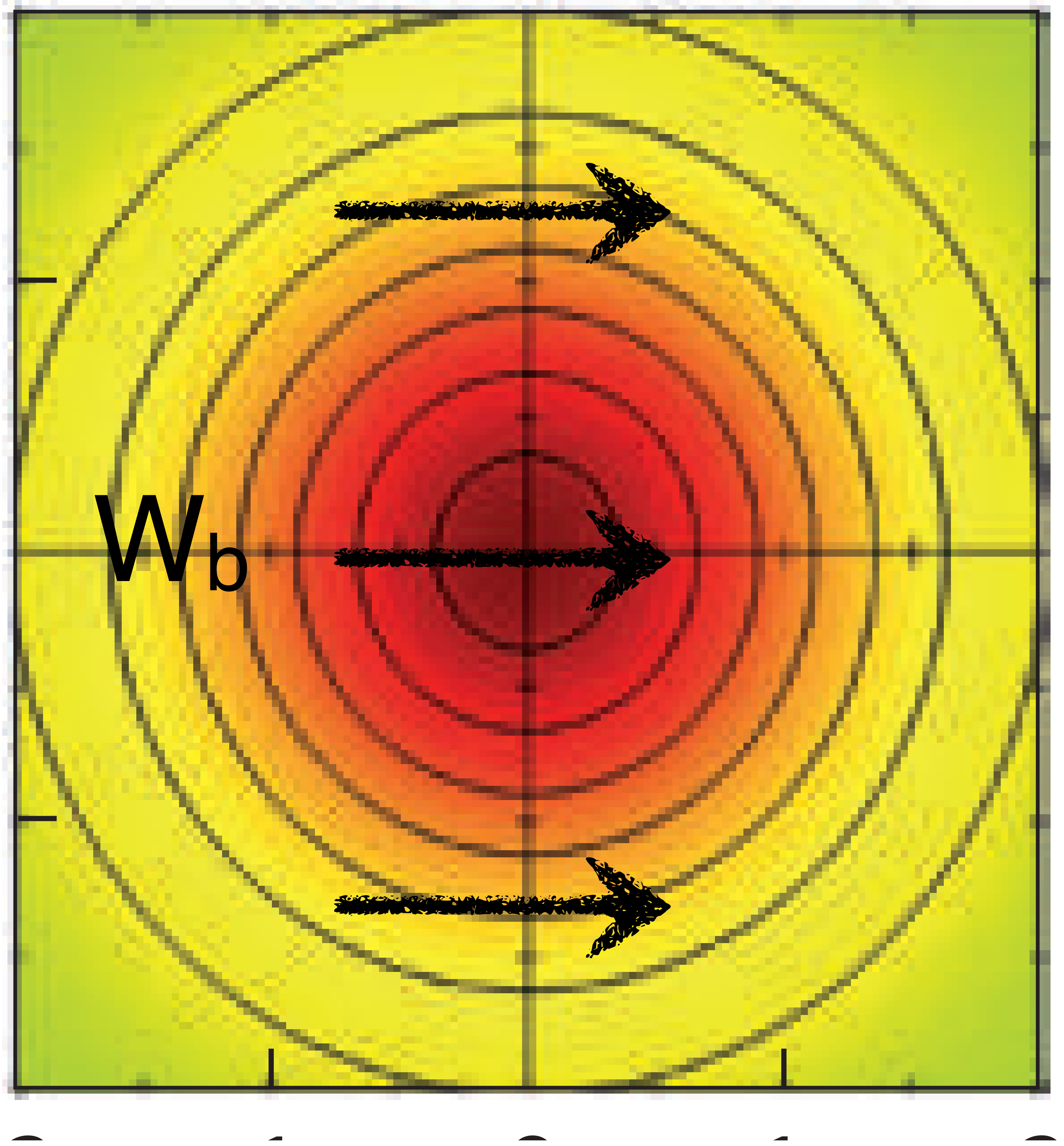
$$\tau = \rho_a C_D (\underline{W} - \underline{U}) |\underline{W} - \underline{U}|$$

$\underline{U}$: surface current vector

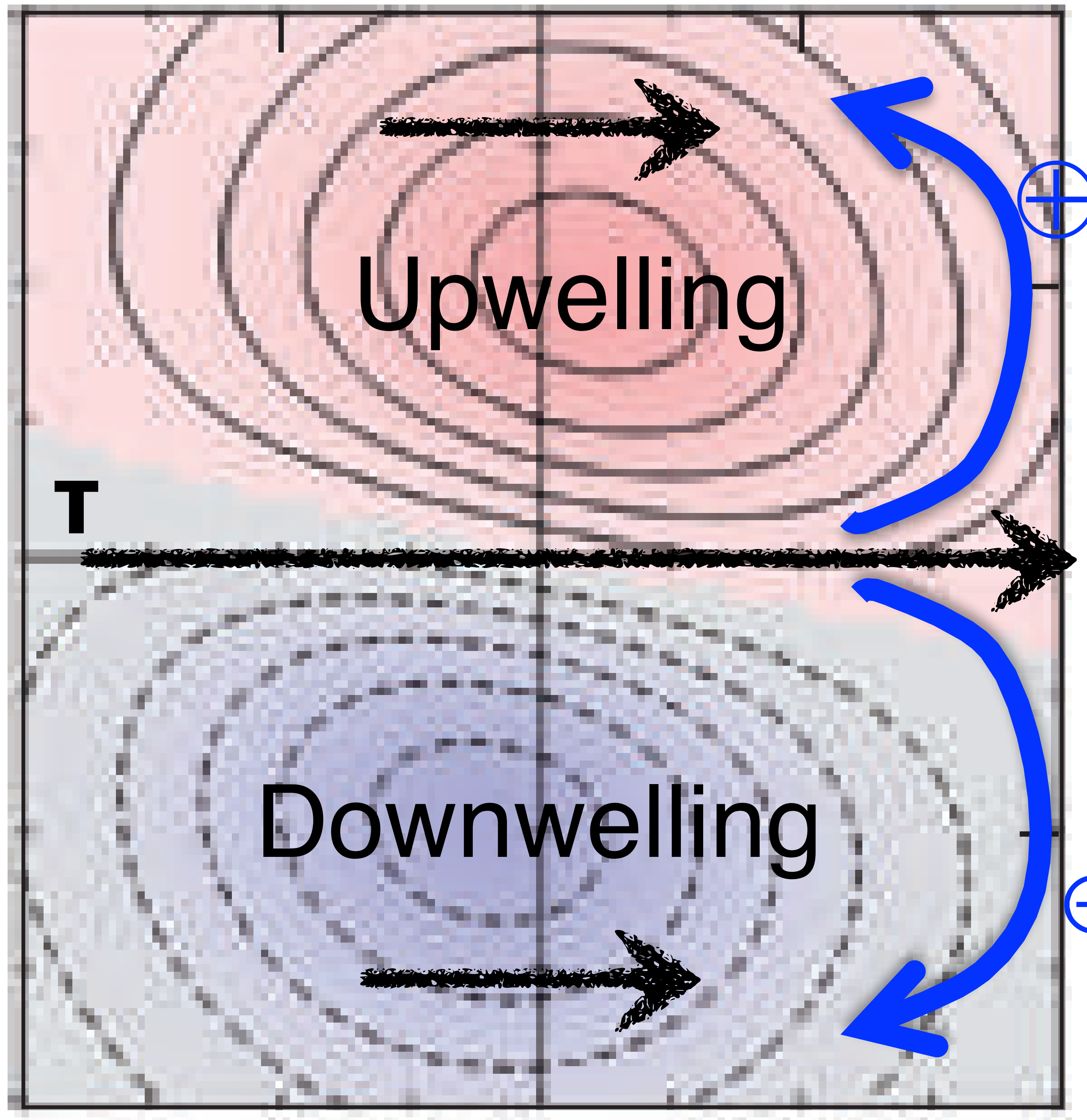
$\underline{W}$: 10m wind vector $\underline{W} = \underline{W}_b + \underline{W}_{SST}$

Consider an idealized anticyclonic warm-core eddy (e.g., Chelton 2013)

SST and SSH



Dipole Ekman pumping



⊕ curl

Ekman pumping anomaly in quadrature with SSH
→ equatorward propagation of a warm-core anticyclonic eddy

⊖ curl

Affect the position

Distinct dynamical influences of air-sea interaction

due to eddy SST vs surface current

$$\tau = \rho_a C_D (\underline{W} - \underline{U}) |\underline{W} - \underline{U}|$$

$\underline{U}$: surface current vector $\underline{U} = \underline{U_b} + \underline{U_e}$

$\underline{W}$: 10m wind vector $\underline{W} = \underline{W_b} + \underline{W_{SST}}$

Chelton 2013; Gaube et al. 2015

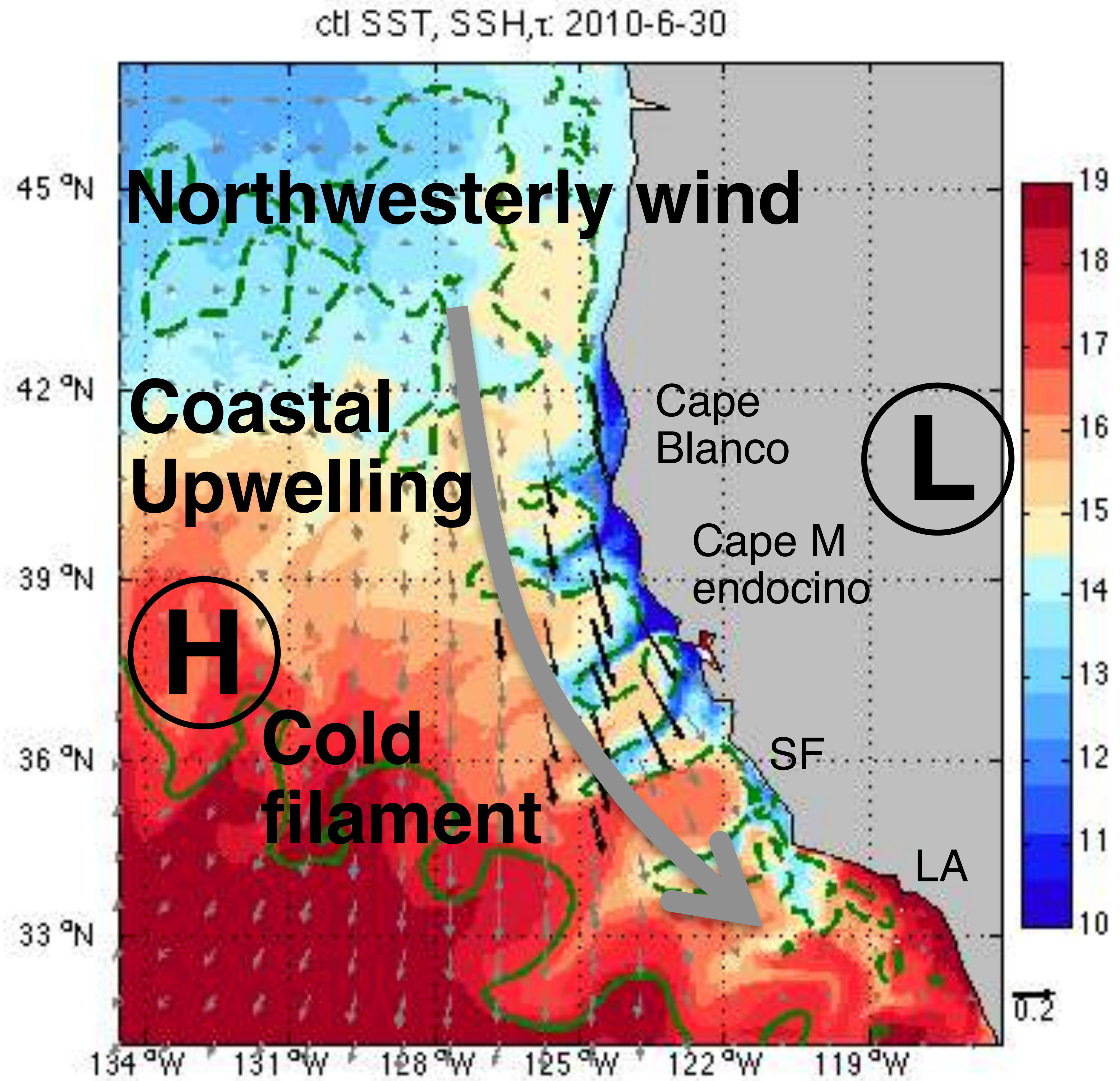
Affect the position

Reduce the eddy-amplitude

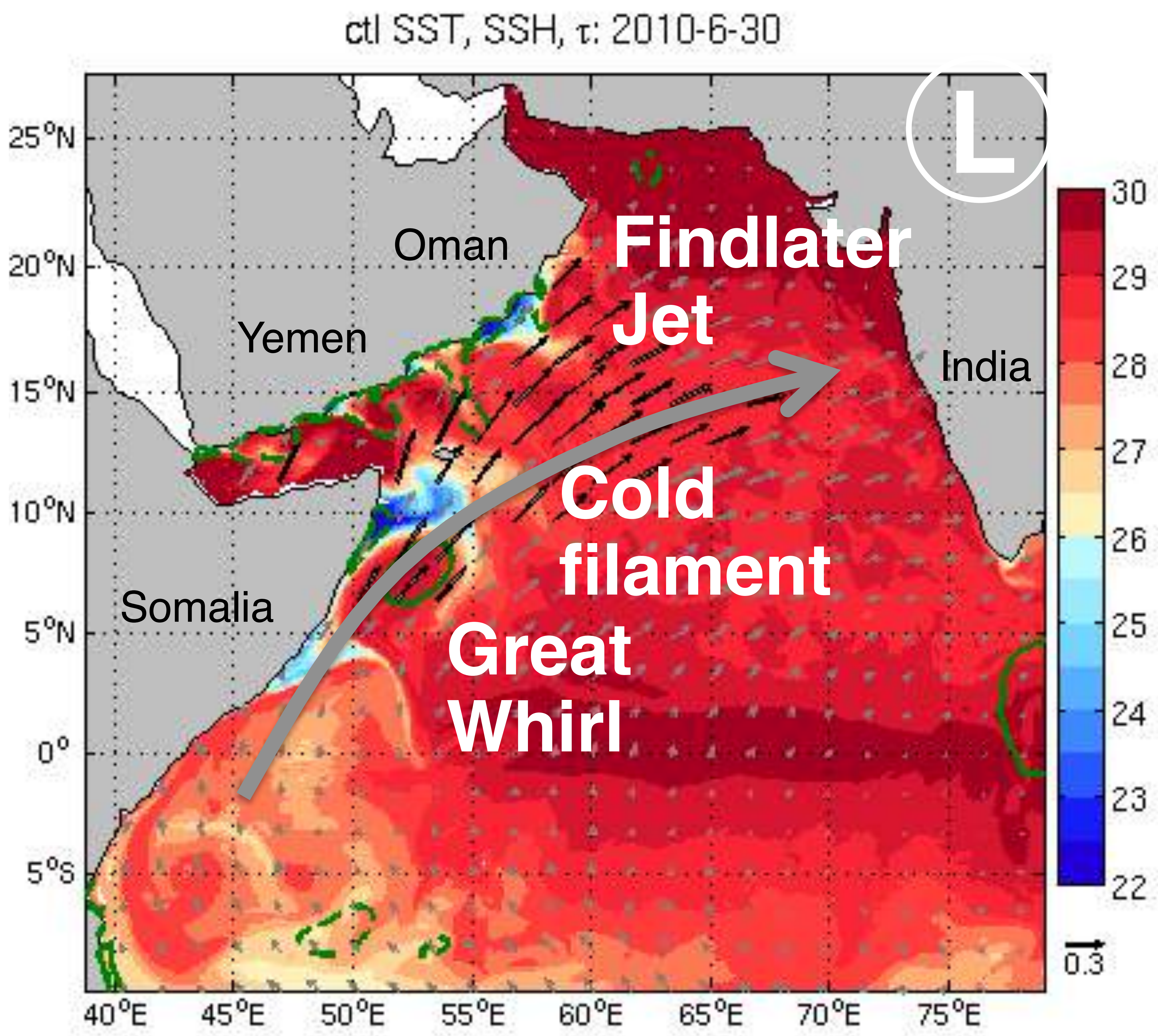
Objective

Examine effect of eddy-mediated air-sea interactions
through SST and surface current
on energetics of the two boundary current systems:
California Current System & Somali Current System

California Current System

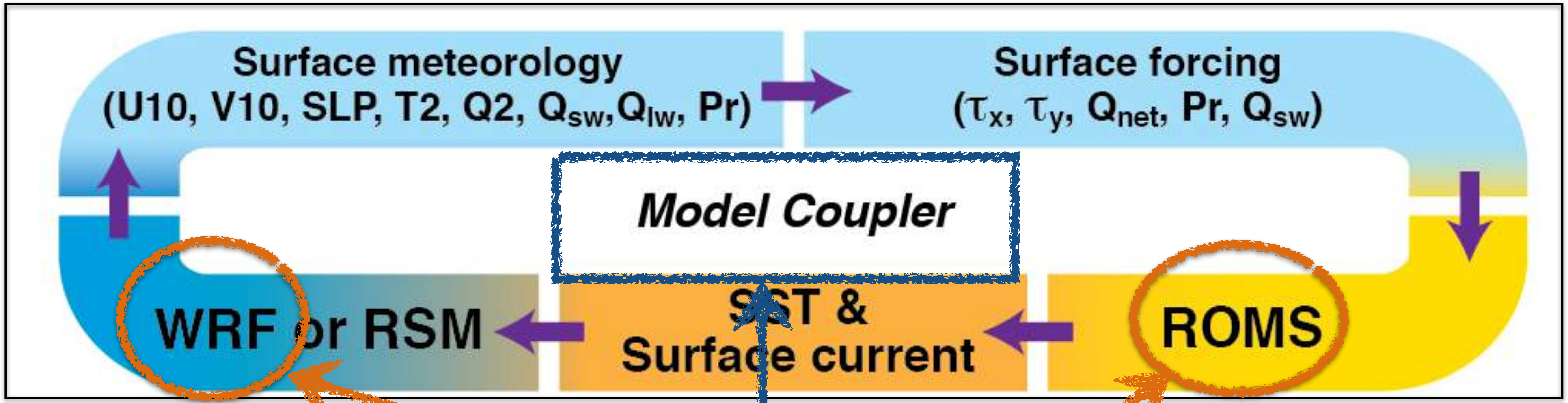


Somali Current System



EBC of the North Pacific	WBC of the Indian Ocean
Forcing: seasonal low-level atmospheric jets	
Upwelling favorable: Cold filaments, mesoscale variability, BGC responses	
Local mesoscale coupled feedback with potential downstream influences	

Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model



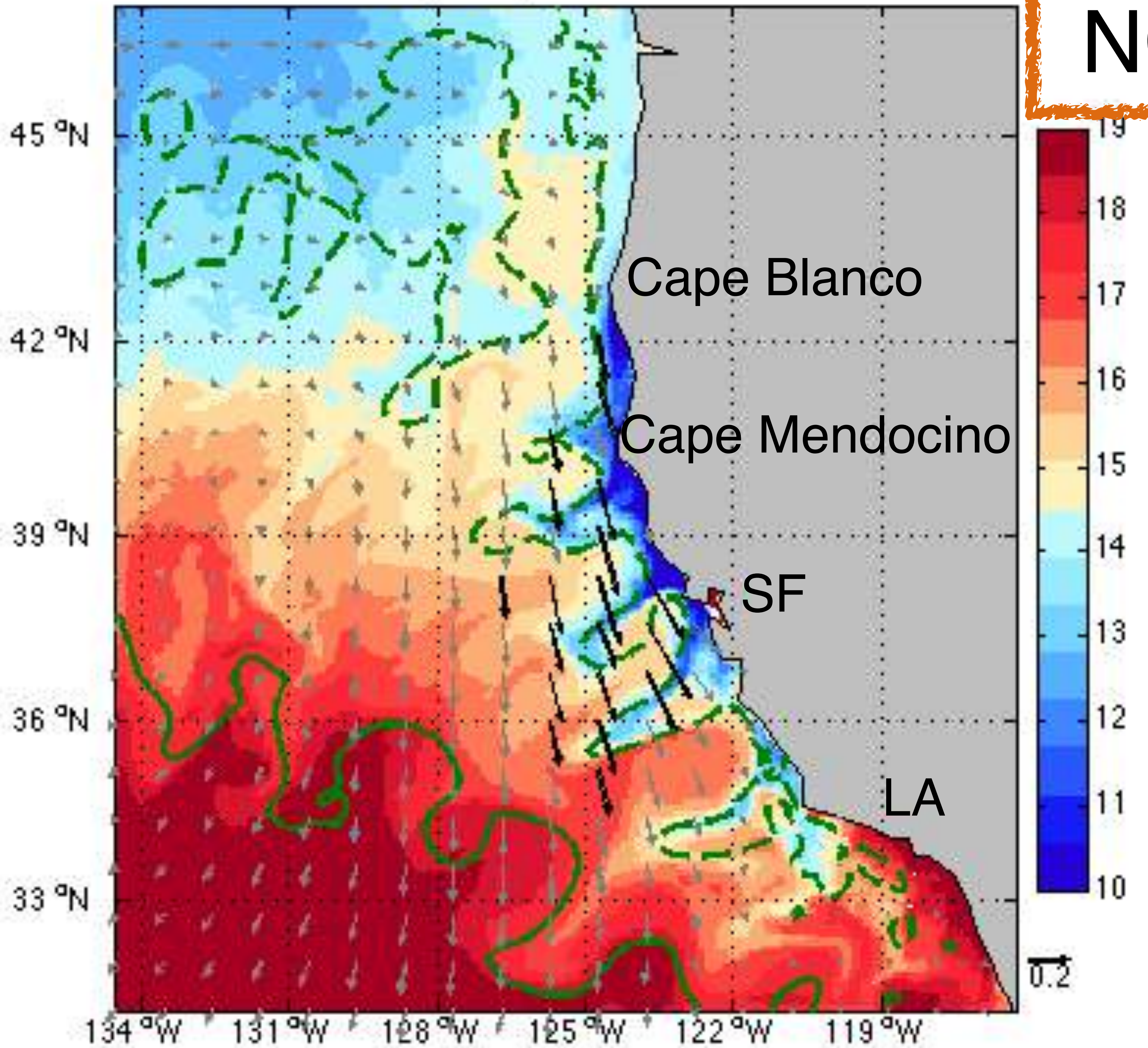
http://hseo.whoi.edu/scoar/

Seo et al. (2007; 2014; 2016, JCLI)

NCEP-FNL

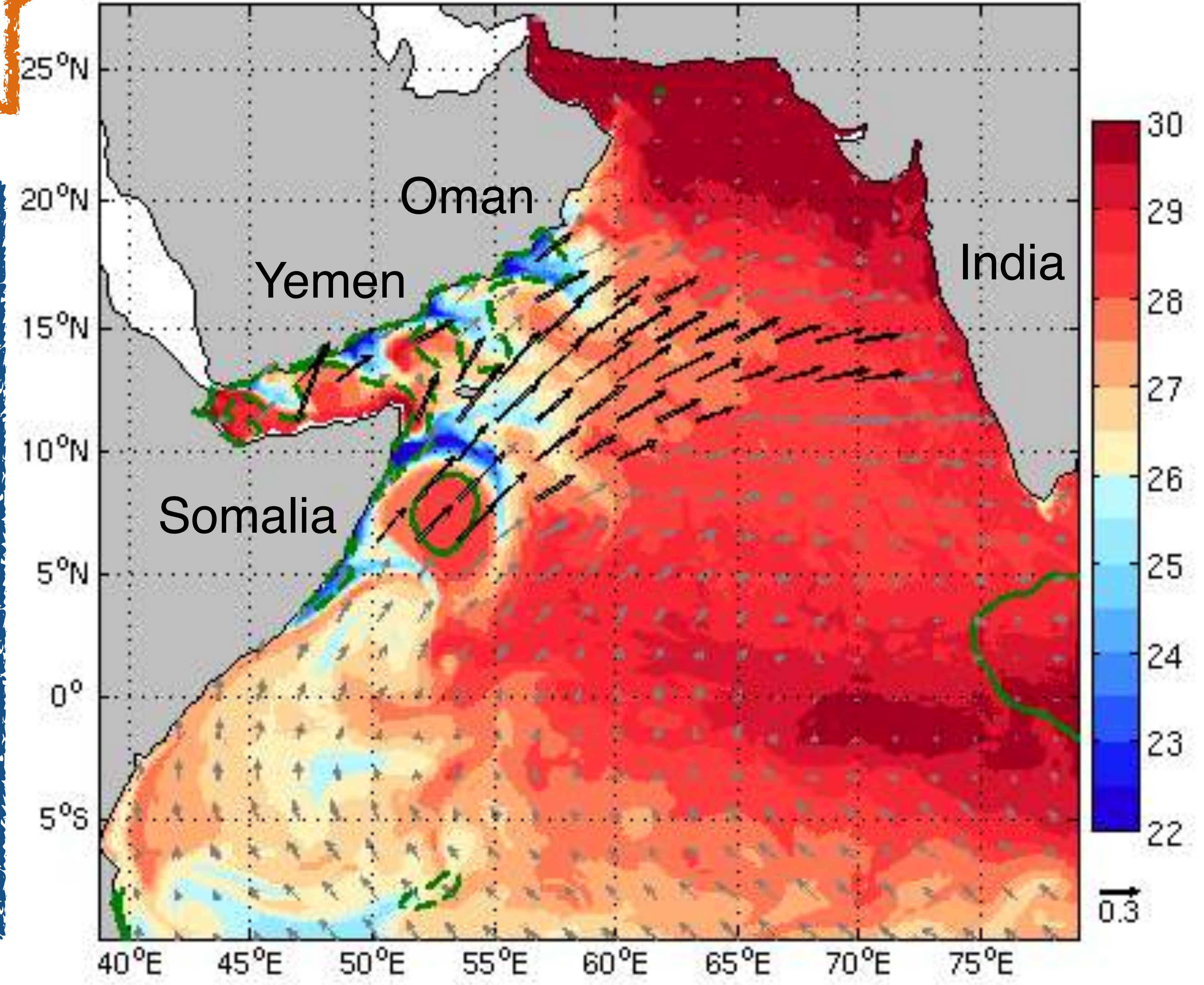
SODA

7km CCS



- Based on bulk formula
- 6-hourly coupling
- An input-output based coupler: portable, flexible, expandable
- Matching grids in the ocean and atmosphere

9km AS



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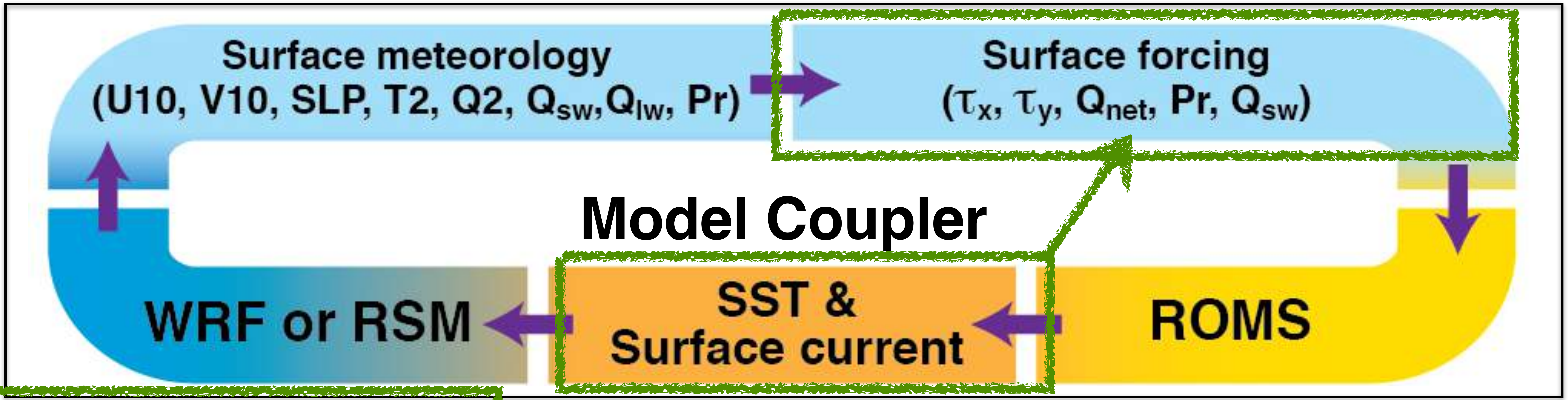

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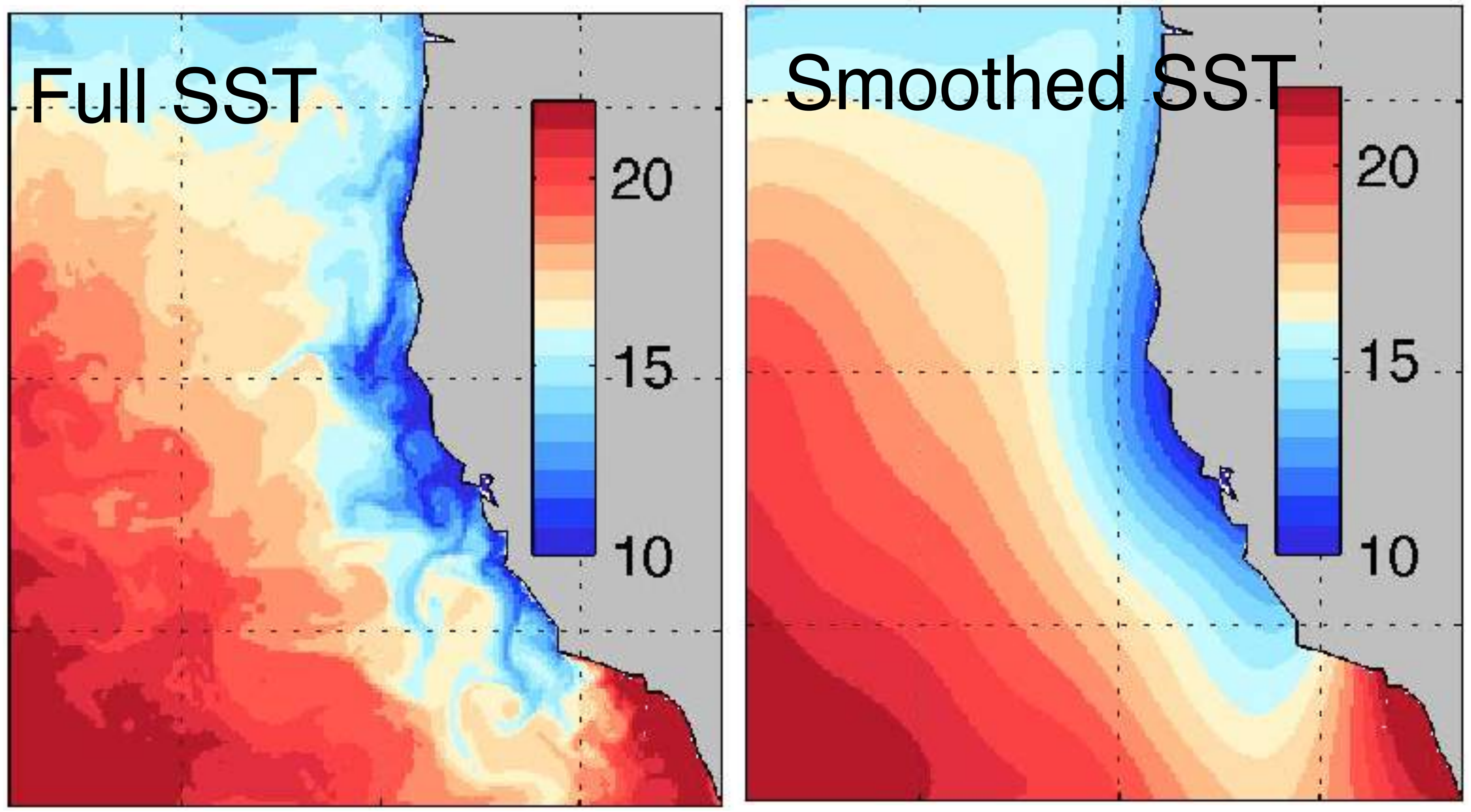
Seo et al. (2007; 2014; 2016, JCLI)

Online 2-D Loess smoothing (~3°×3°)

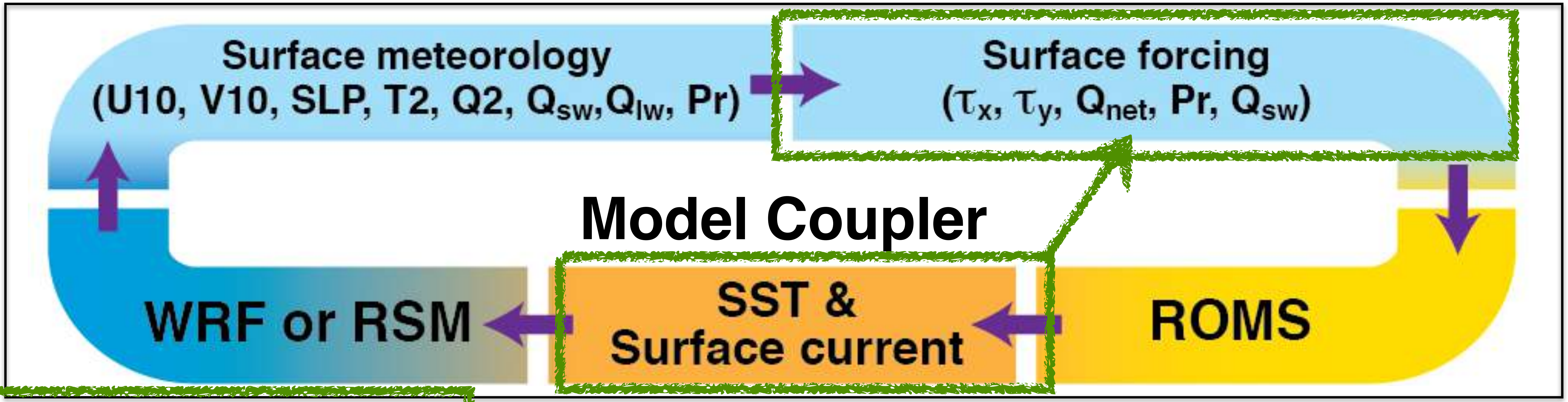
Separation of spatial-scale of air-sea coupling

Putrasahan et al. (2013); Seo et al. (2016)



Experiments	τ formulation			
CTL	T_b	T_e	U_b	U_e
noT_e	T_b		U_b	U_e
noU_e	T_b	T_e	U_b	
noU_{tot}	T_b	T_e		

Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model



Seo et al. (2007; 2014; 2016, JCLI)

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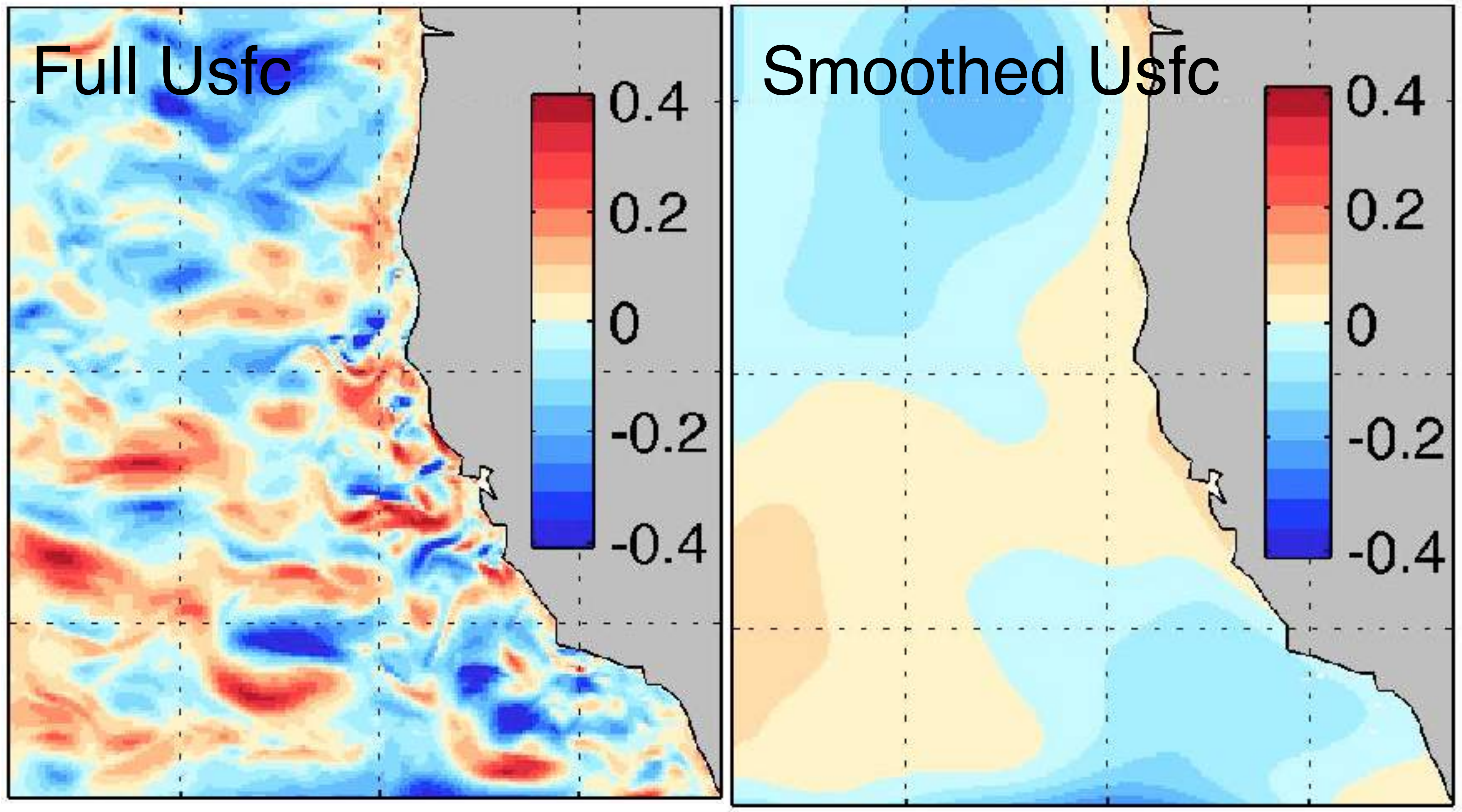

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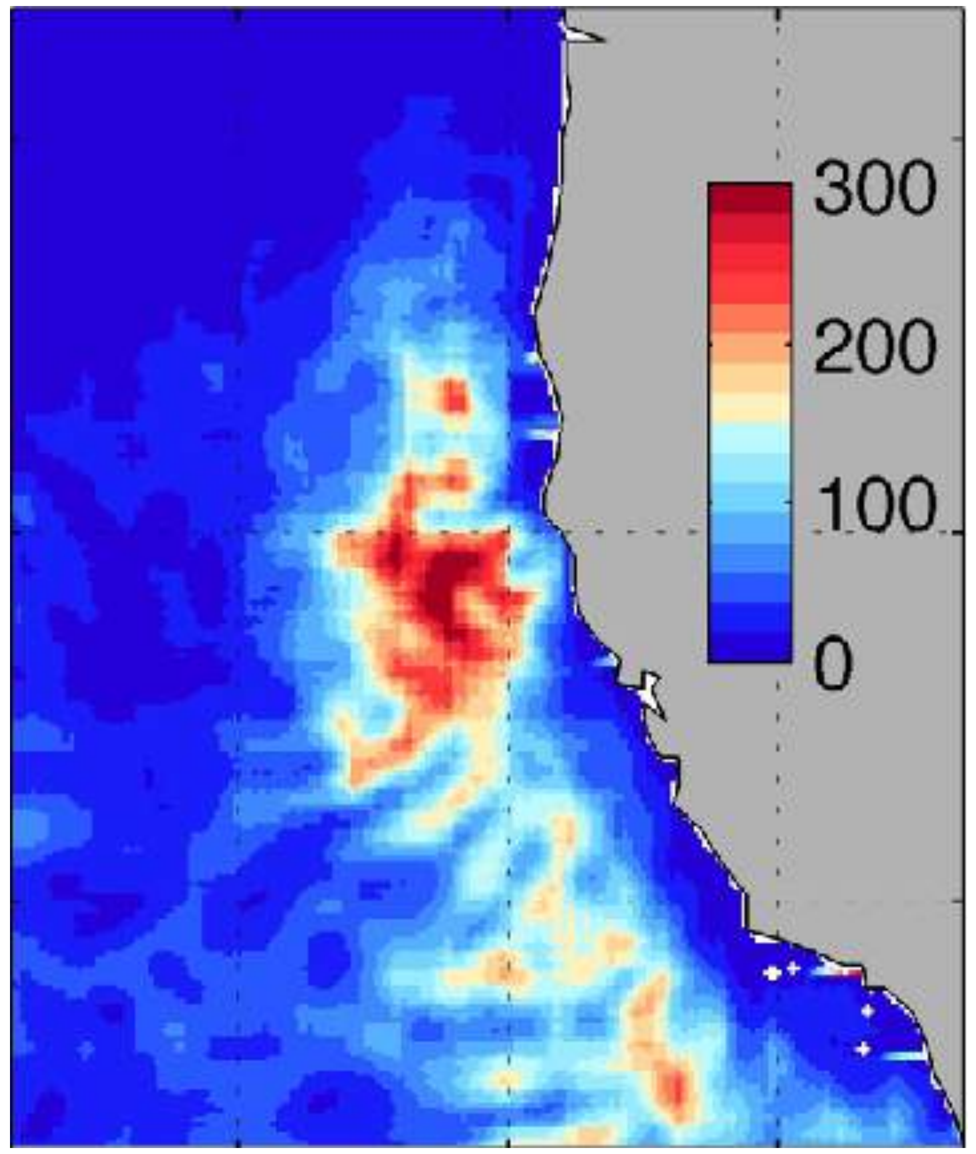
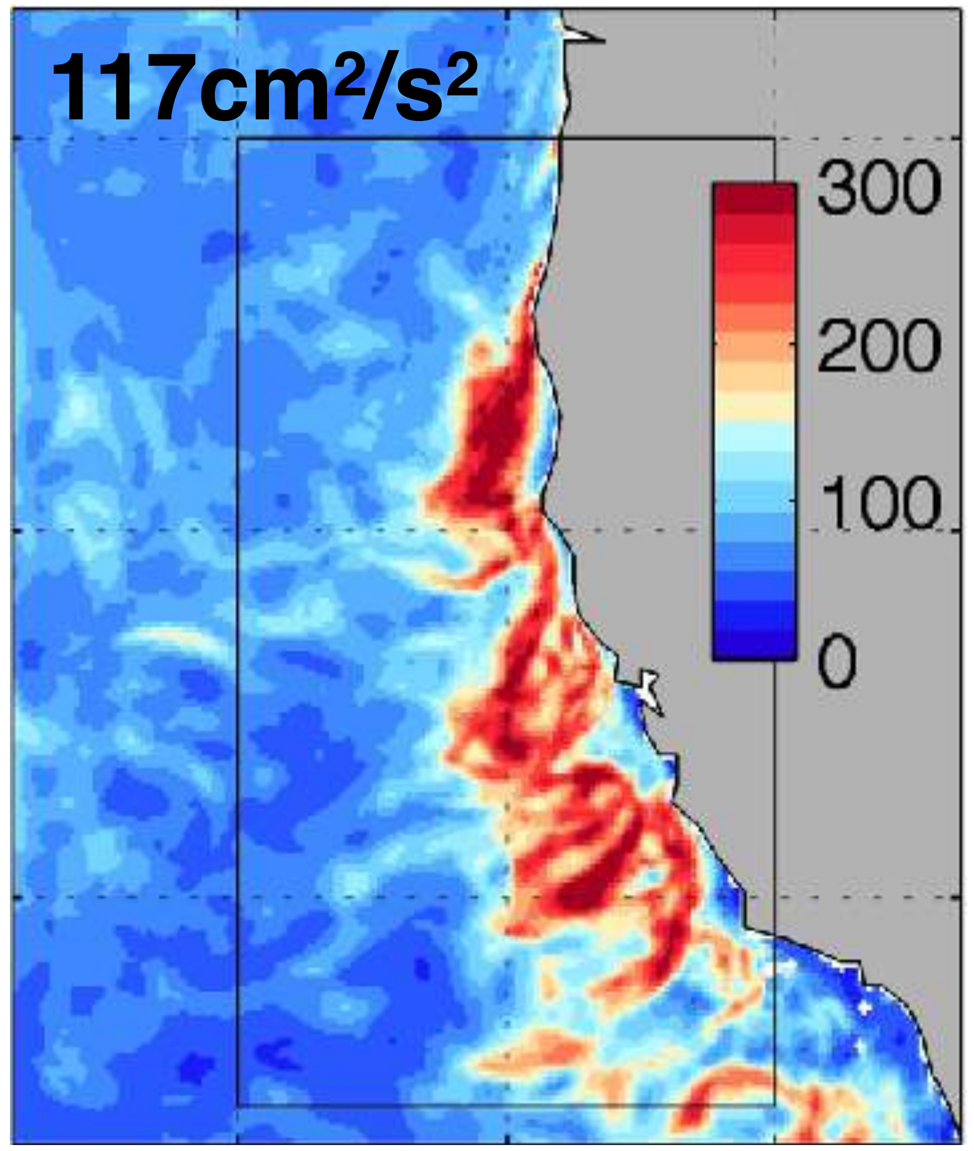
noT_e	T_b		U_b	U_e
noU_e	T_b	T_e	U_b	
noU_{tot}	T_b	T_e		

Effect on Eddy Kinetic Energy

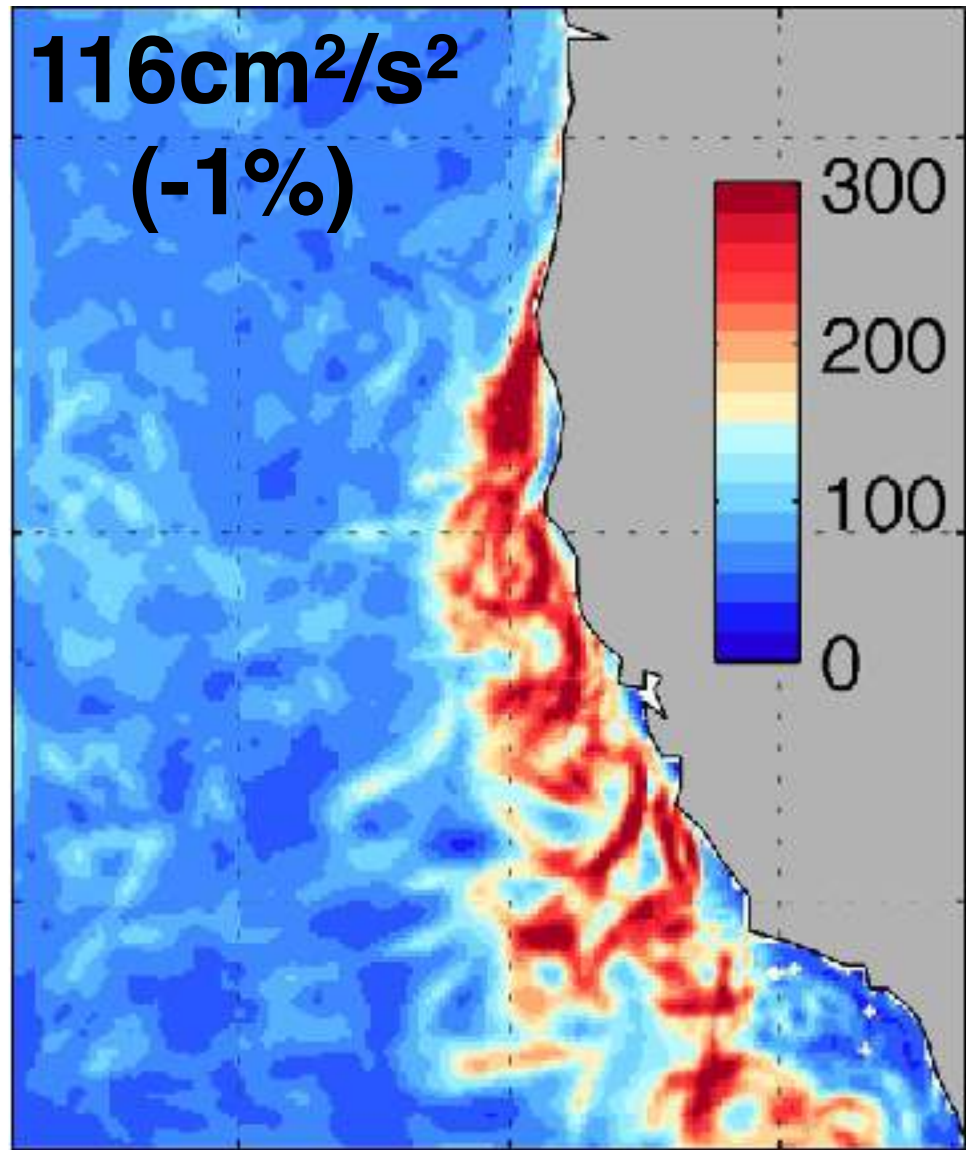
AVISO



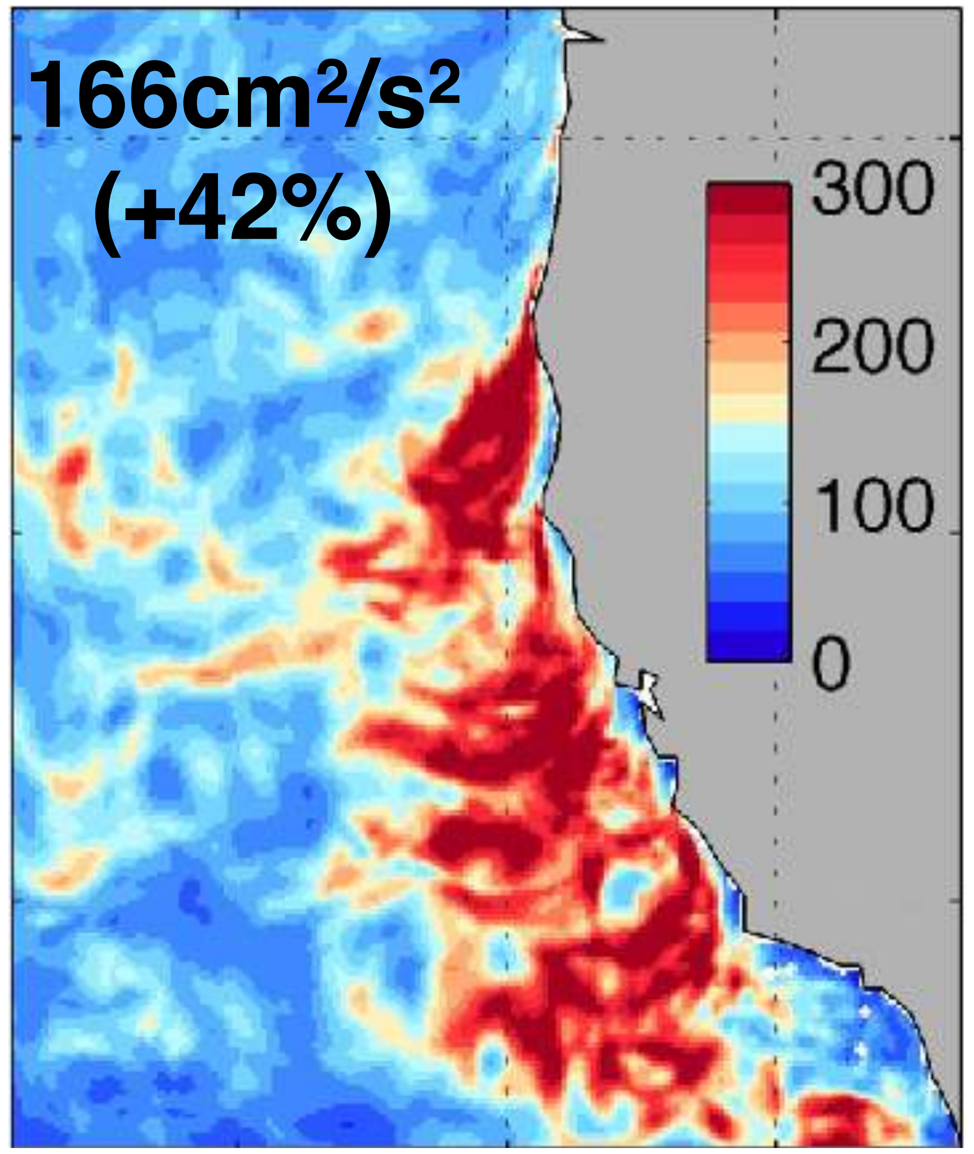
CTL: T_e & U_e



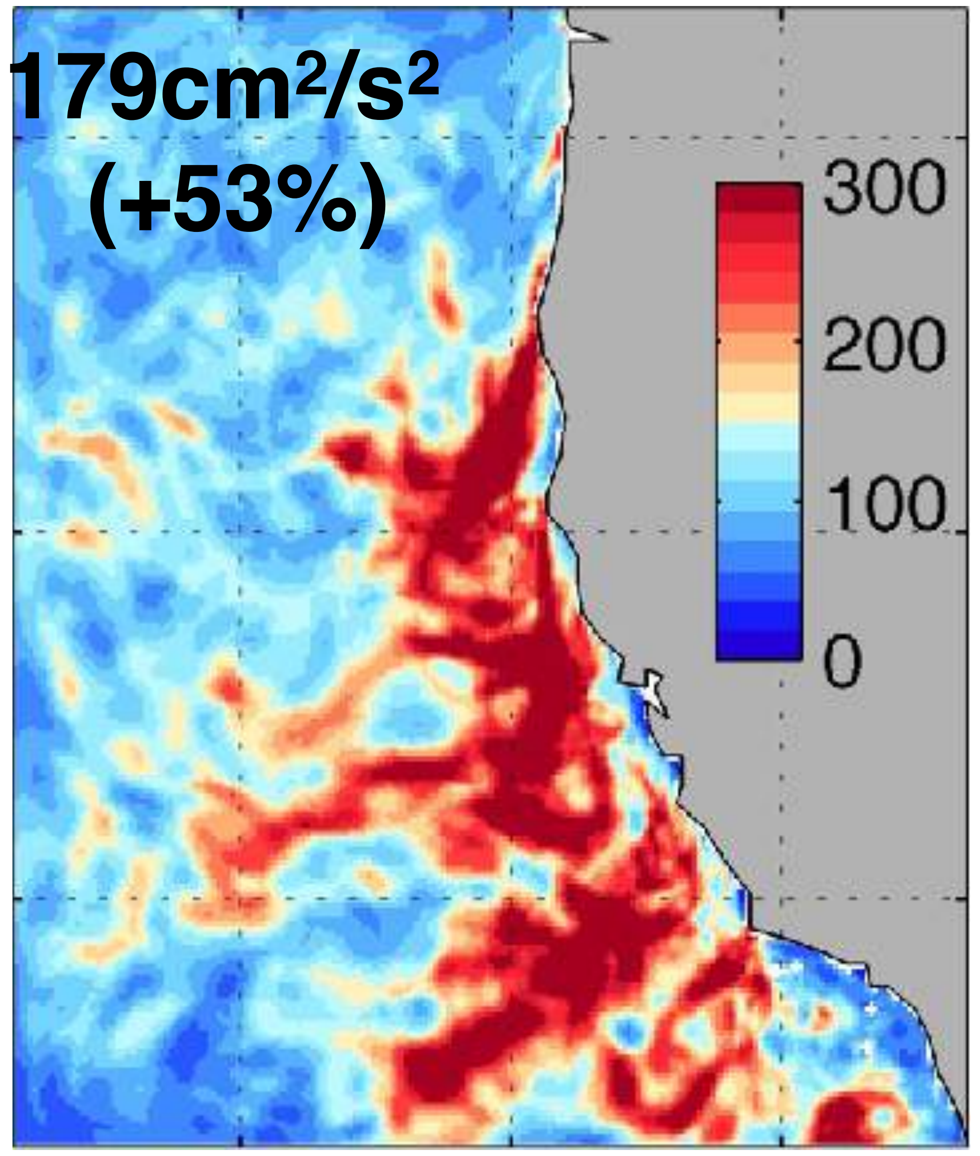
noT_e



noU_e



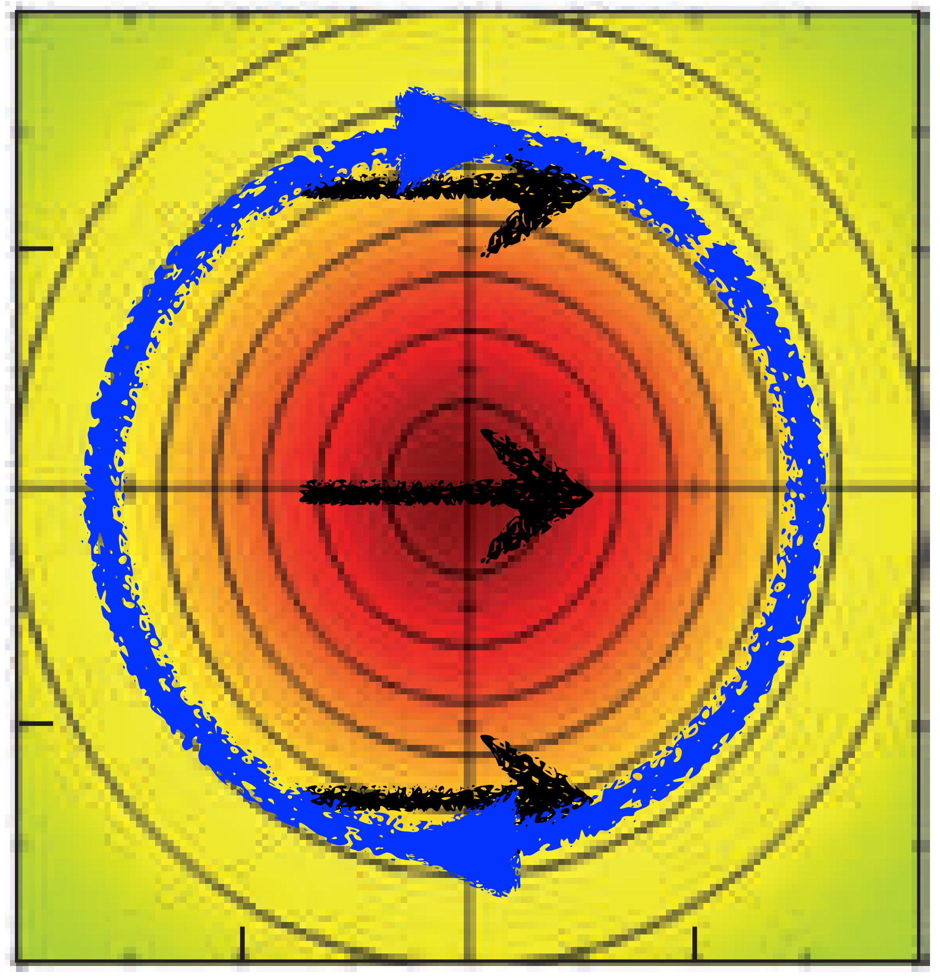
noU_{tot}



- T_e-τ has no impact on EKE
- U_e-τ reduces the EKE substantially
- U_{tot}-τ reduces the EKE only slightly more (additional 10%)
  - → The EKE reduction by under-stress occurs largely due to small-scale coupling

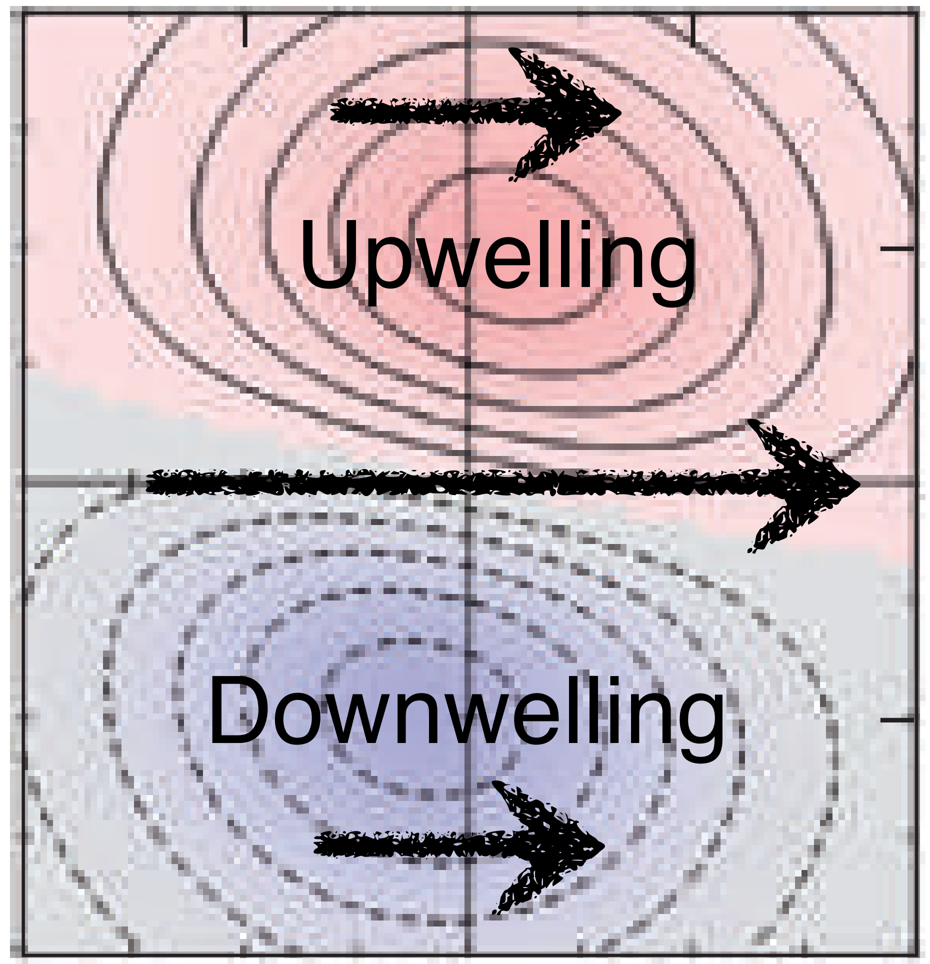
Seo et al. 2016 JPO

SST and SSH



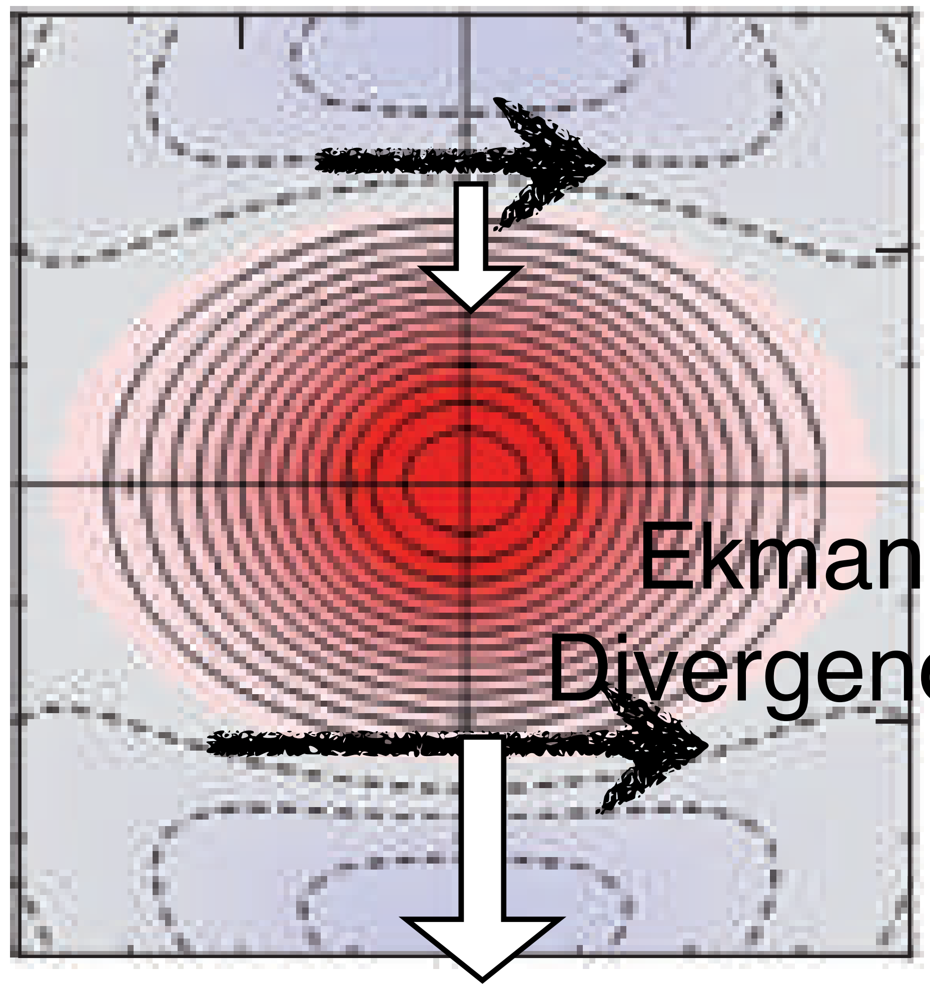
Chelton 2013

T_e-driven EkP



Affect the position

U_e-driven EkP



Reduce the eddy-amplitude

Depth-averaged EKE budget

$$\frac{\partial K_e}{\partial t} + U \cdot \nabla K_e + u' \cdot \nabla K_e = -\nabla \cdot (u'p') - g\rho' w' + \rho_o(-u' \cdot (u' \cdot \nabla U)) + u' \cdot \tau' + \varepsilon$$

$$P = \frac{1}{\rho_0}(\overline{u'\tau'_x} + \overline{v'\tau'_y}).$$

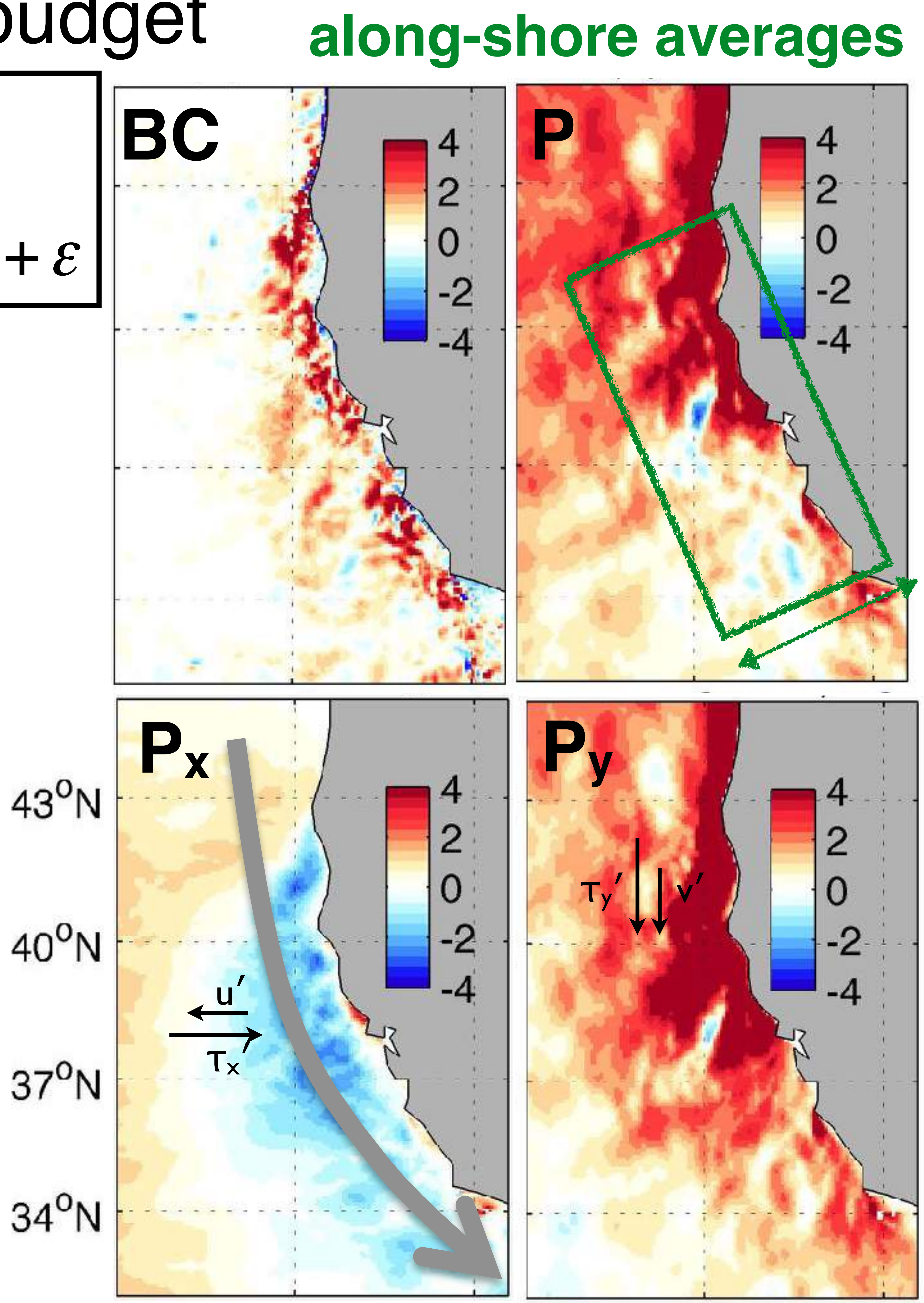
Wind work if positive, eddy drag if negative

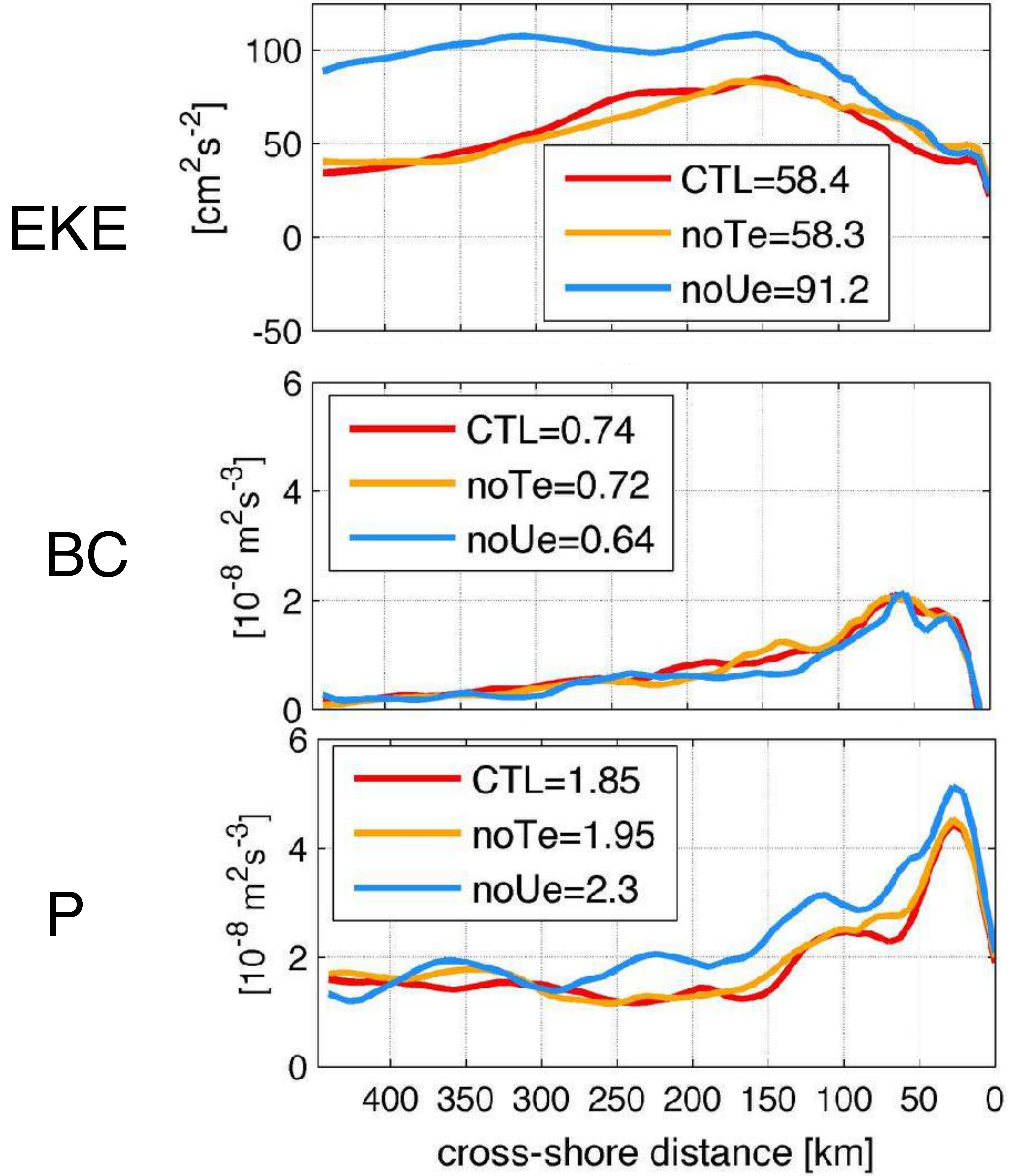
$$\mathrm{BC} = -\frac{g}{\rho_0}\overline{\rho' w'},$$

$P_e \rightarrow K_e$ baroclinic conversion (BC)

$$\mathrm{BT} = -(\overline{u'u'}\overline{U}_x + \overline{u'v'}\overline{U}_y + \overline{u'w'}\overline{U}_z + \overline{v'u'}\overline{V}_x + \overline{v'v'}\overline{V}_y + \overline{v'w'}\overline{V}_z),$$

$K_m \rightarrow K_e$ barotropic conversion (BT)



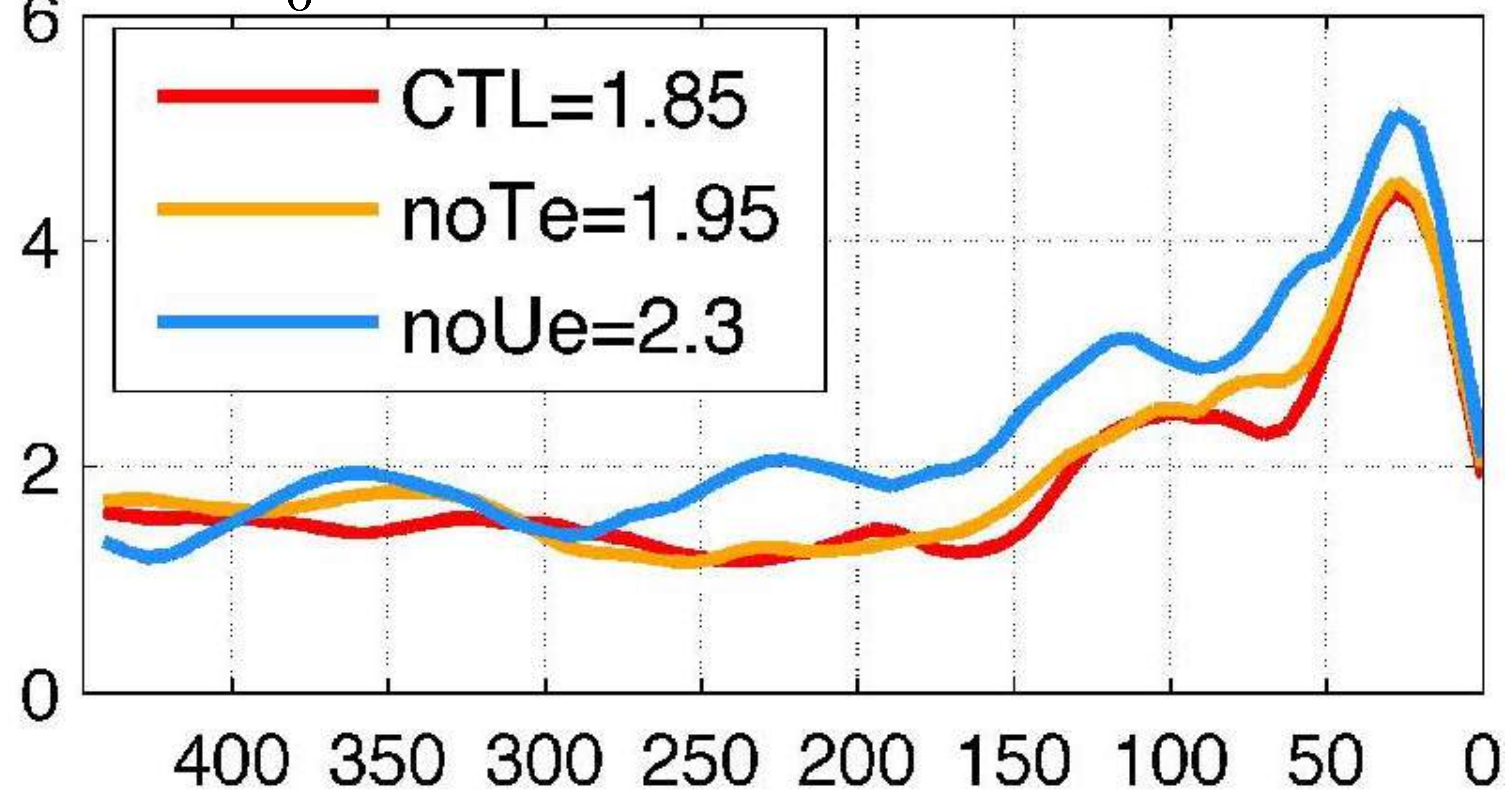


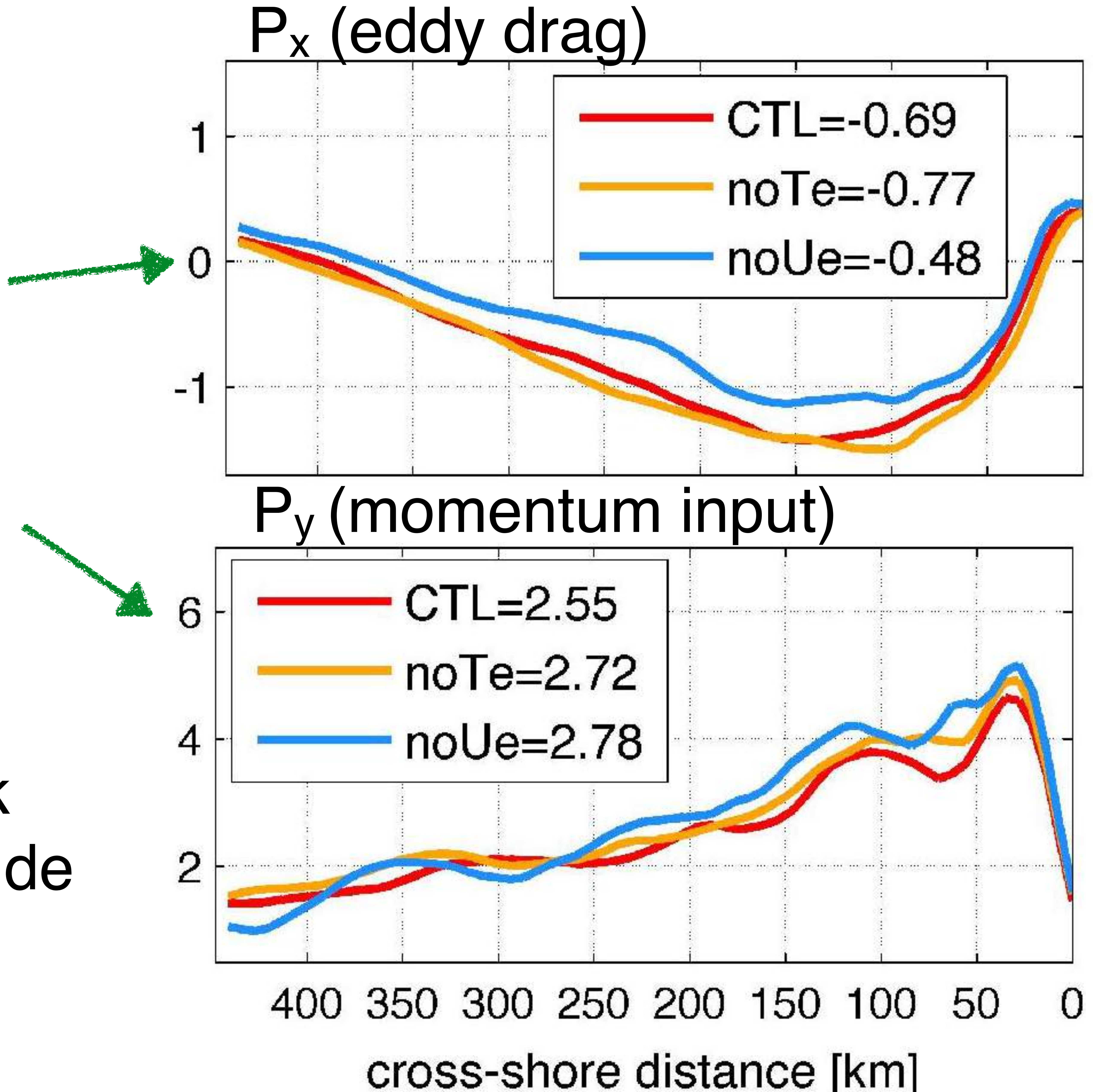
Across-shore distribution of EKE budget terms

- **Baroclinic conversion**
  - Only a small reduction in noU$_e$
    → can't explain the higher EKE
- **Eddy-wind interaction**
  - 24% increase in noU$_e$ over the eddy-rich coastal zone
    → U$_e$-τ reduces the wind work

U_e-τ reduces the momentum input and increases the eddy drag

$$P = \frac{1}{\rho_0}\left(\overline{u'\tau'_x} + \overline{v'\tau'_y}\right).$$





- In noU_e, ~30% weaker eddy drag
- In noU_e ~10% stronger wind work

  → Changes in absolute magnitude are comparable

Eddy-driven Ekman pumping velocity

$$W_{tot} = \frac{1}{\rho_o}\nabla \times \left(\frac{\boldsymbol{\tau}}{(f+\zeta)}\right)$$ when Ro~O(1)

Stern 1965
Gaube et al. 2015

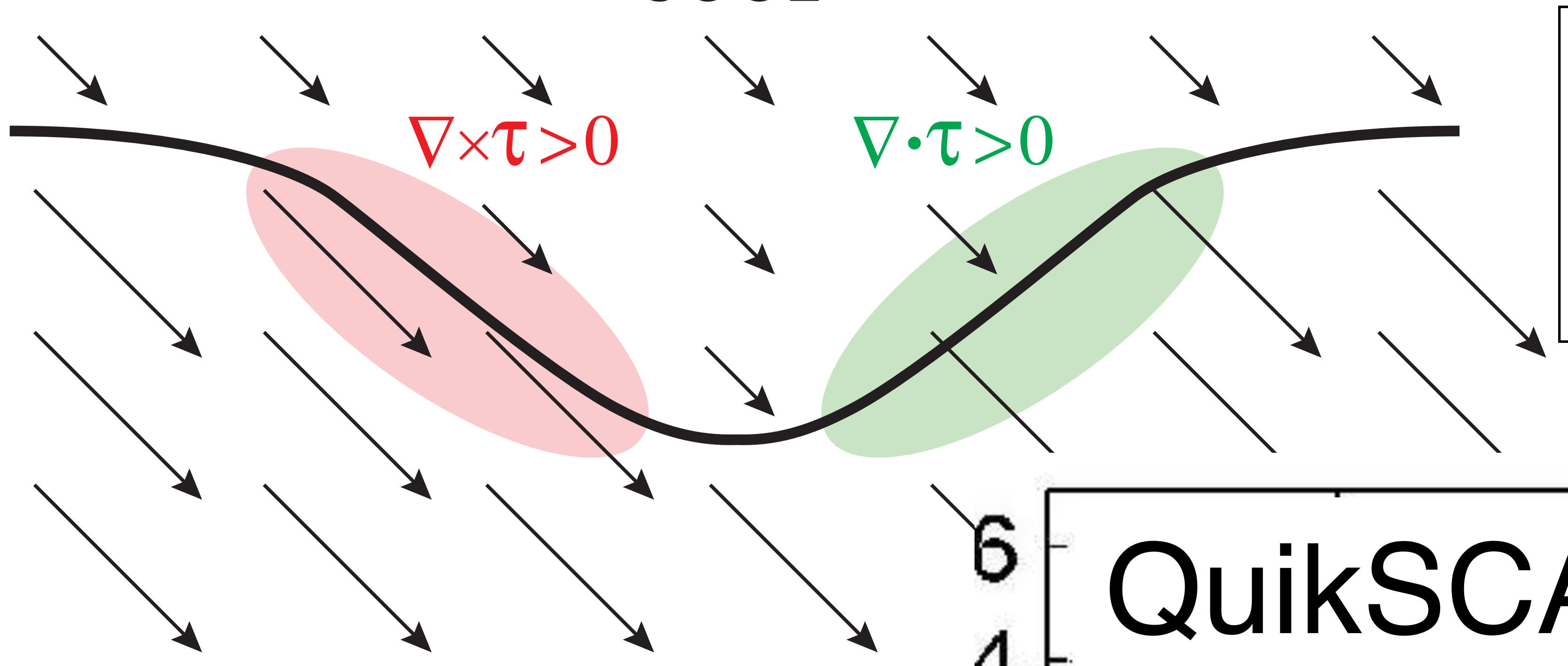
$$= \underbrace{\frac{\bar{\nabla} \times \tilde{\boldsymbol{\tau}}}{\rho_o(f+\zeta)}}_{W_{LIN}} - \underbrace{\frac{1}{\rho_o(f+\zeta)^2}\left(\tilde{\tau}^y\frac{\partial\zeta}{\partial x} - \tilde{\tau}^x\frac{\partial\zeta}{\partial y}\right)}_{W_{\zeta}} + \underbrace{\frac{\nabla \times \boldsymbol{\tau}'_{SST}}{\rho_o(f+\zeta)}}_{W_{SST}}.$$

W_{LIN}: Curl-induced linear Ekman pumping

W_{ζ}: Surface vorticity gradient-induced nonlinear Ekman pumping

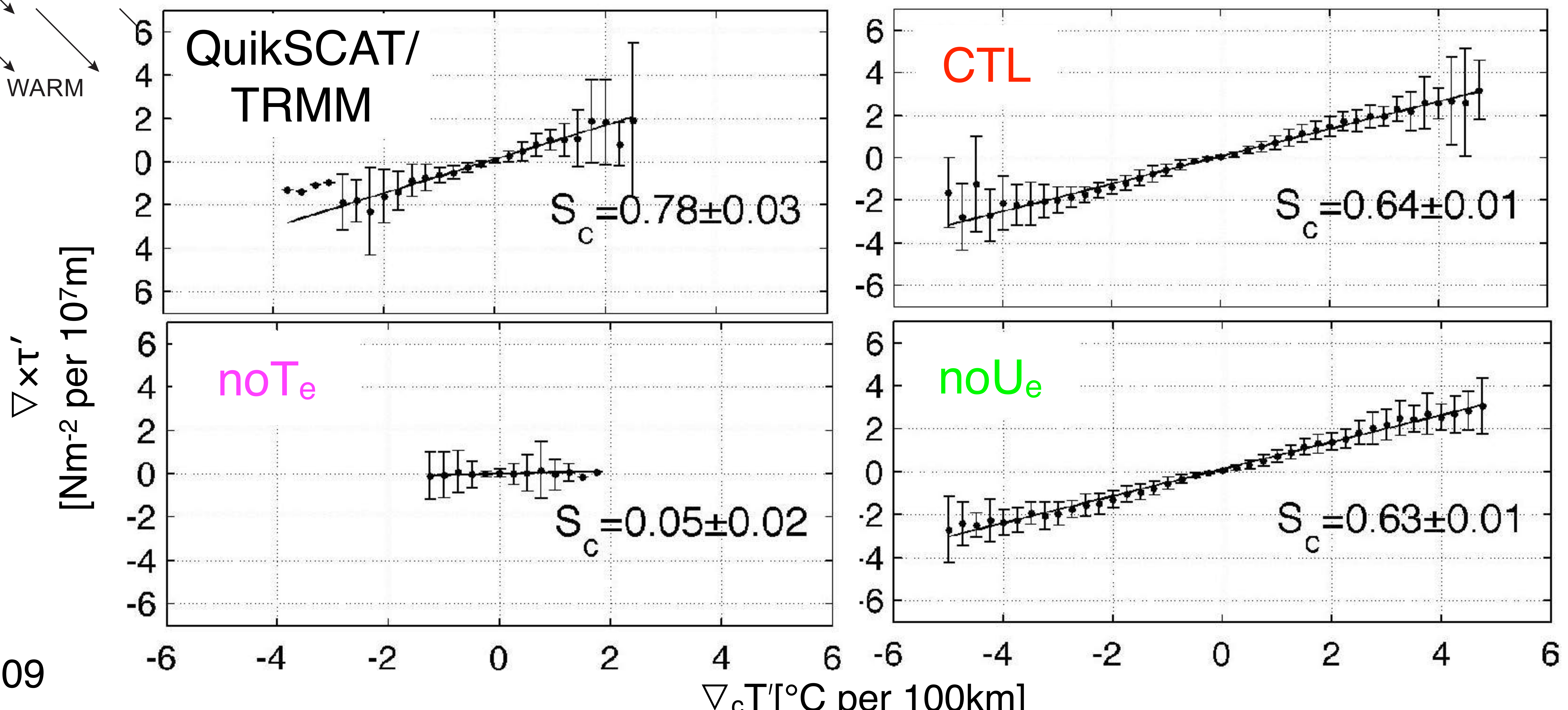
W_{SST}: SST induced Ekman pumping (Chelton et al. 2007)

Estimating eddy SST-driven Ekman pumping velocity



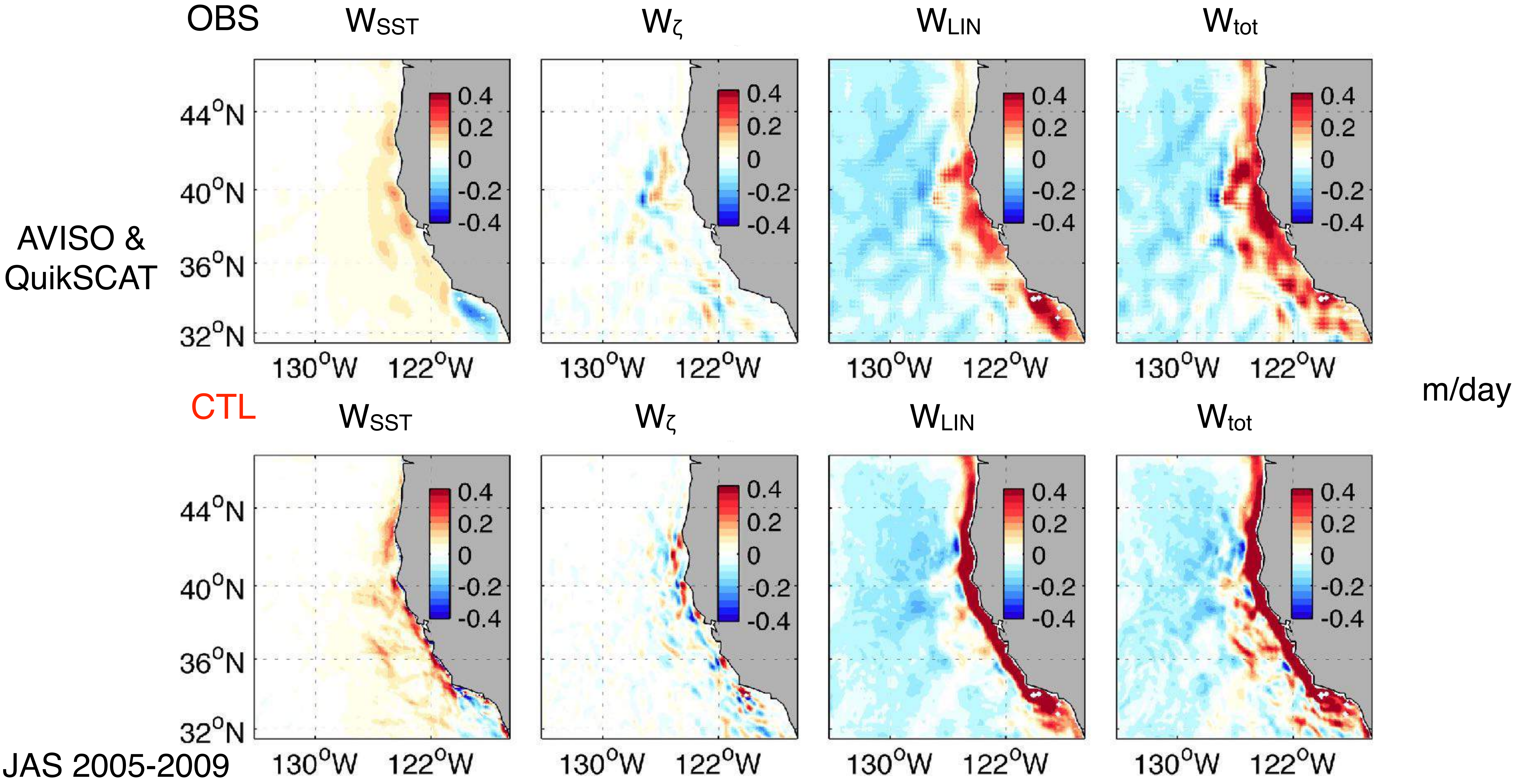
$$W_{SST} = \frac{\nabla \times \tau'_{SST}}{\rho_o (f+\zeta)} \approx \frac{\alpha_c \nabla_c SST}{\rho_o (f+\zeta)}$$

Chelton et al. (2001)



JAS 2005-2009

Estimated Ekman pumping velocities



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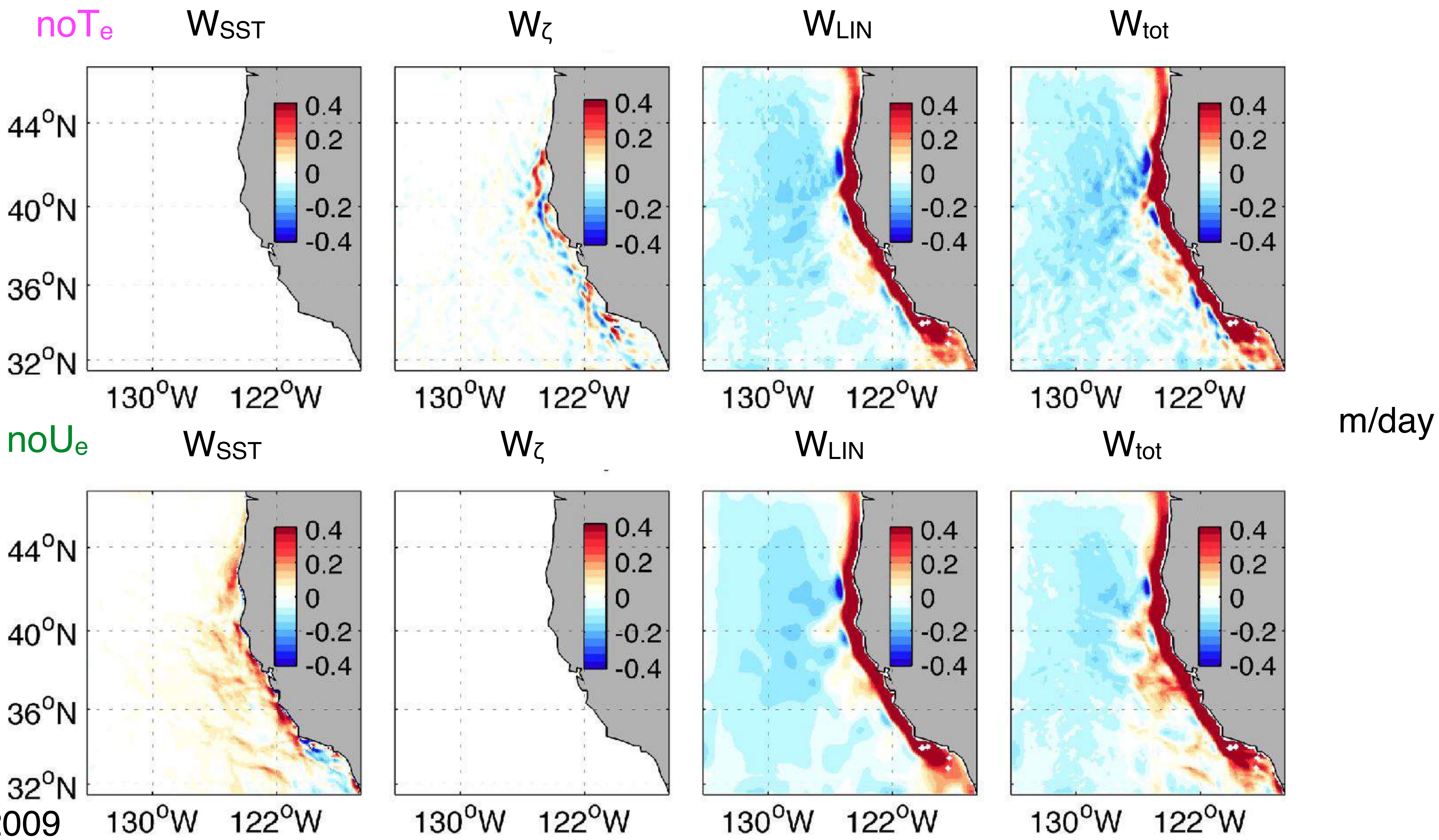
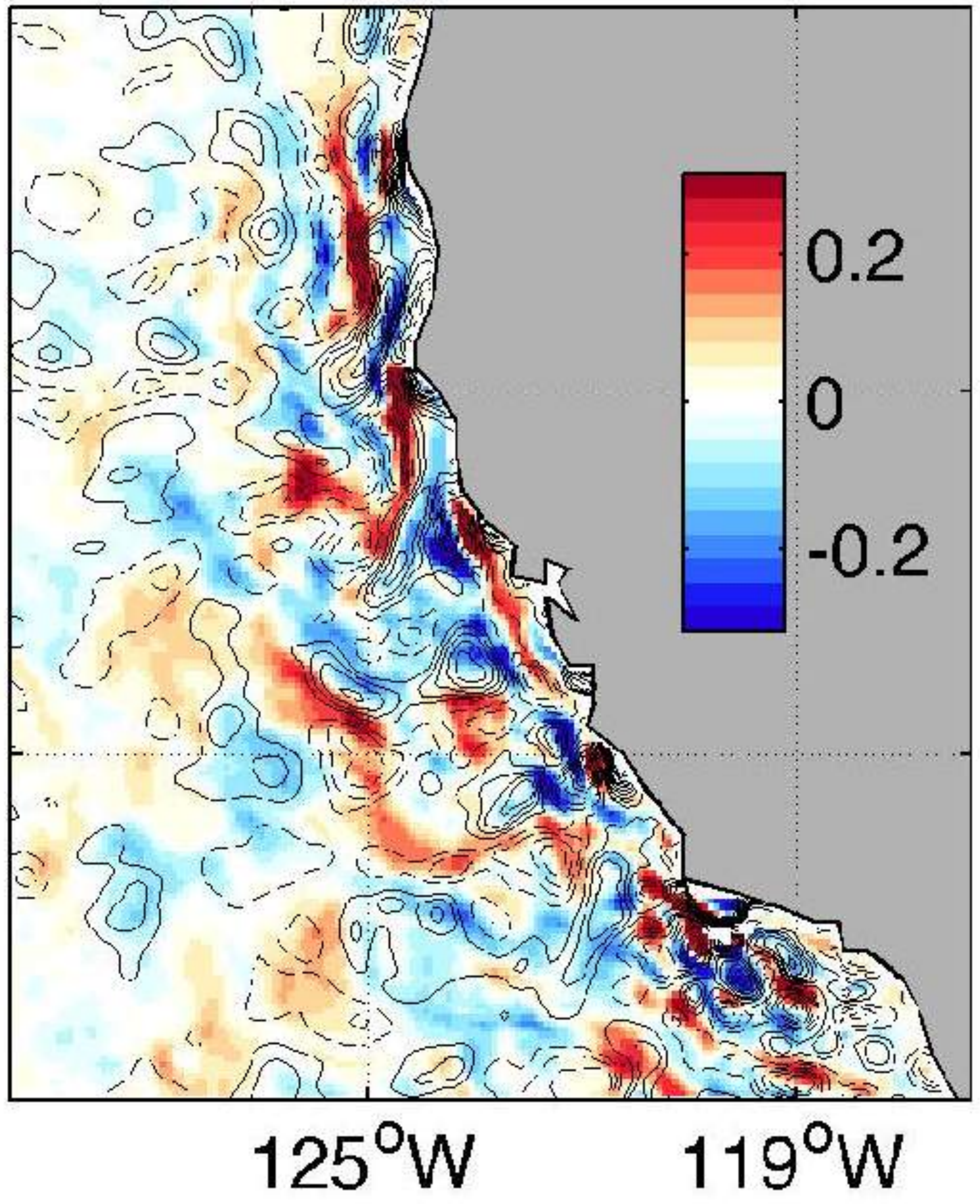


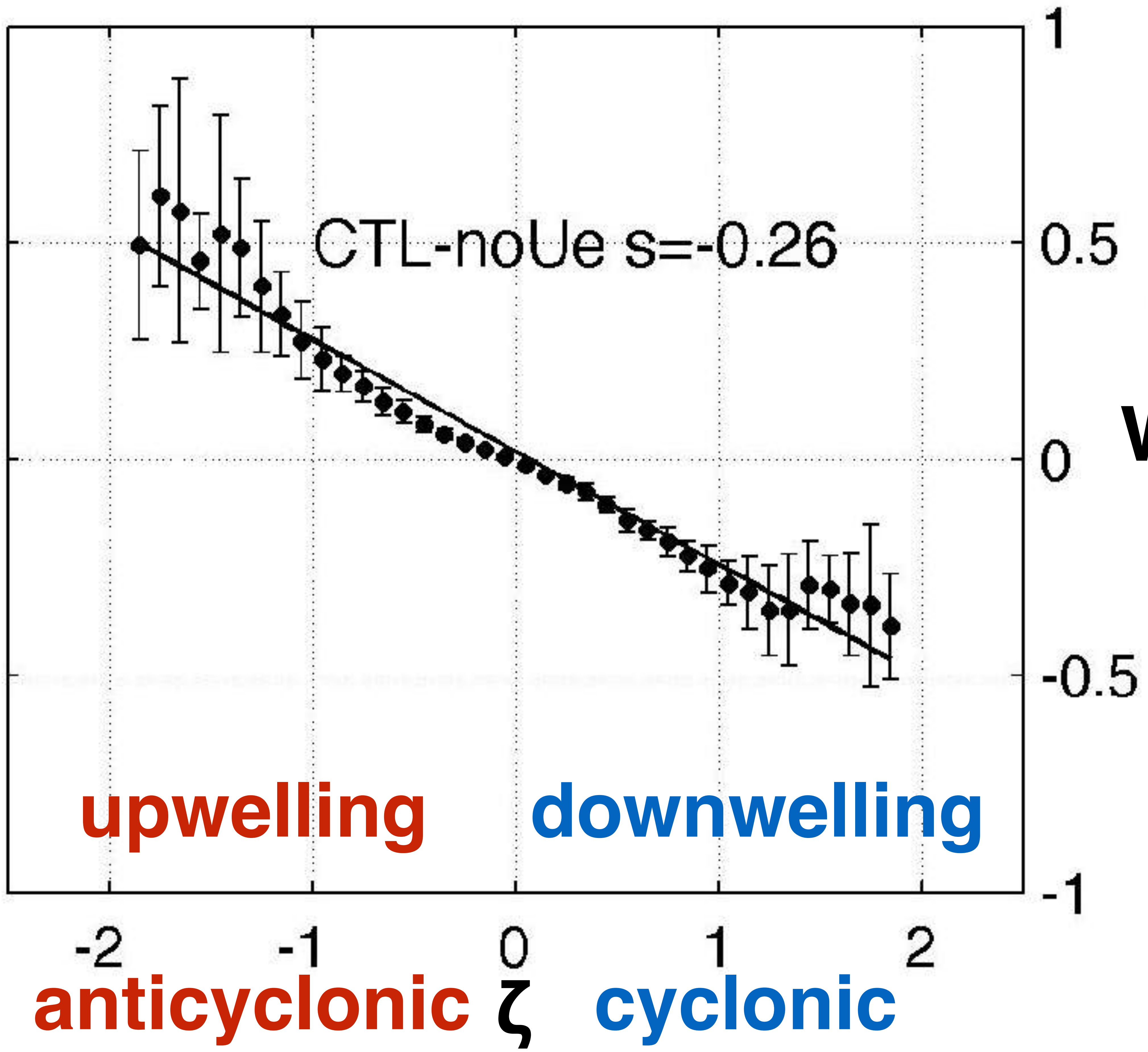
JAS 2005-2009

Inferred feedback to eddy activity through W_ζ

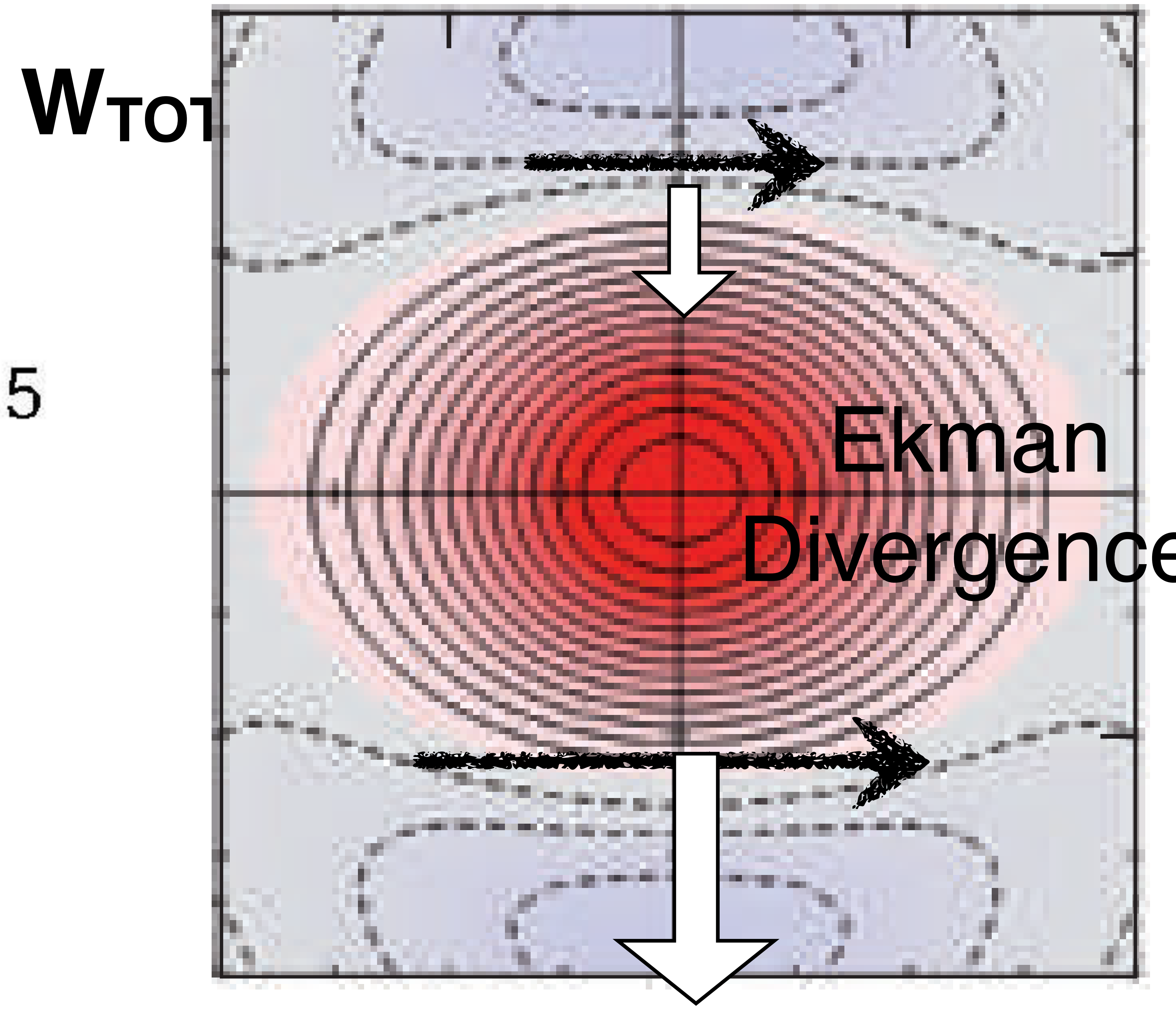
CTL-noU$_e$ W_{TOT} & ζ



CTL-noU$_e$ W_{TOT} vs ζ



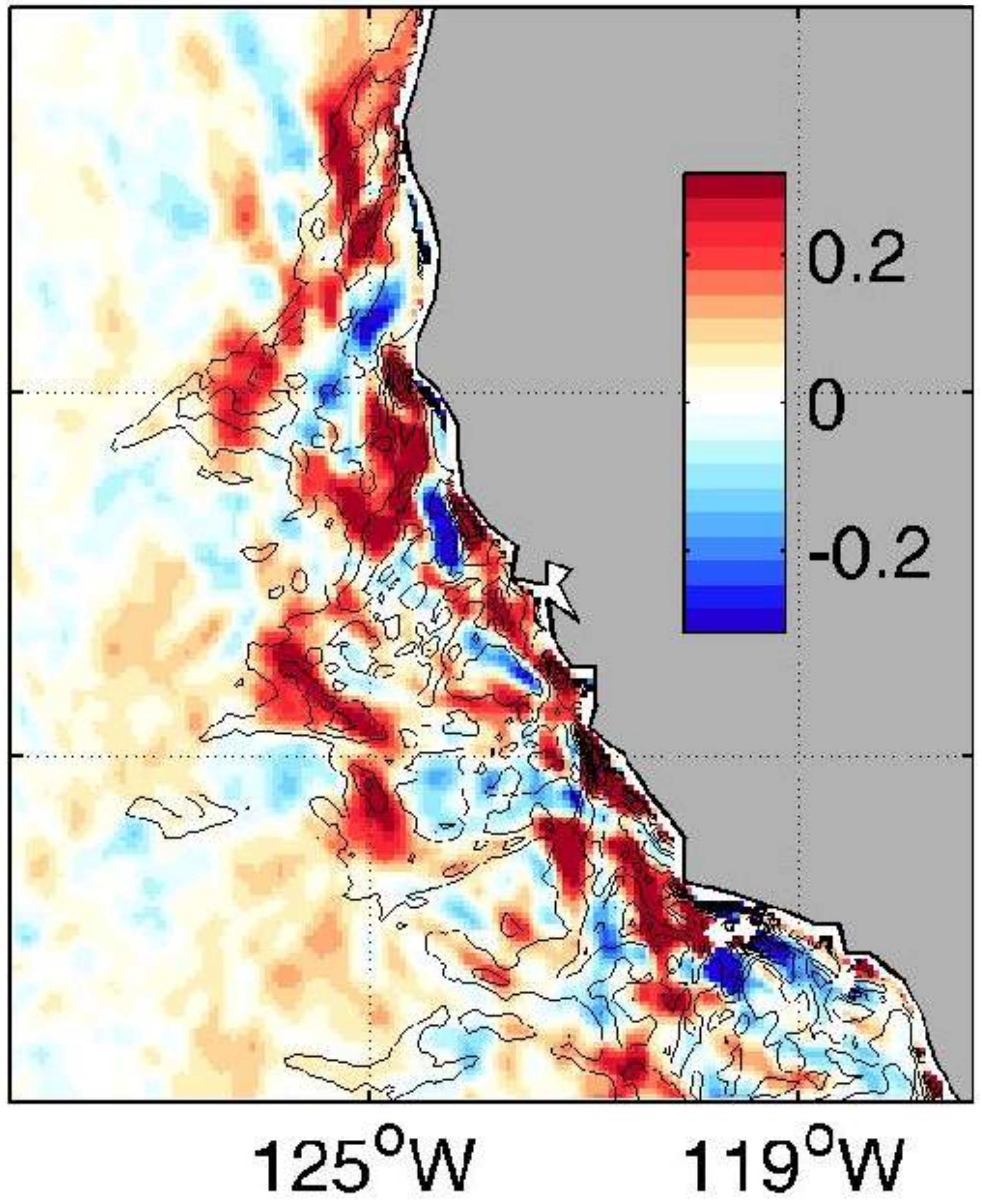
Downwelling over cyclonic vorticity anomaly
→ U$_e$-τ weakens the amplitude of the eddies



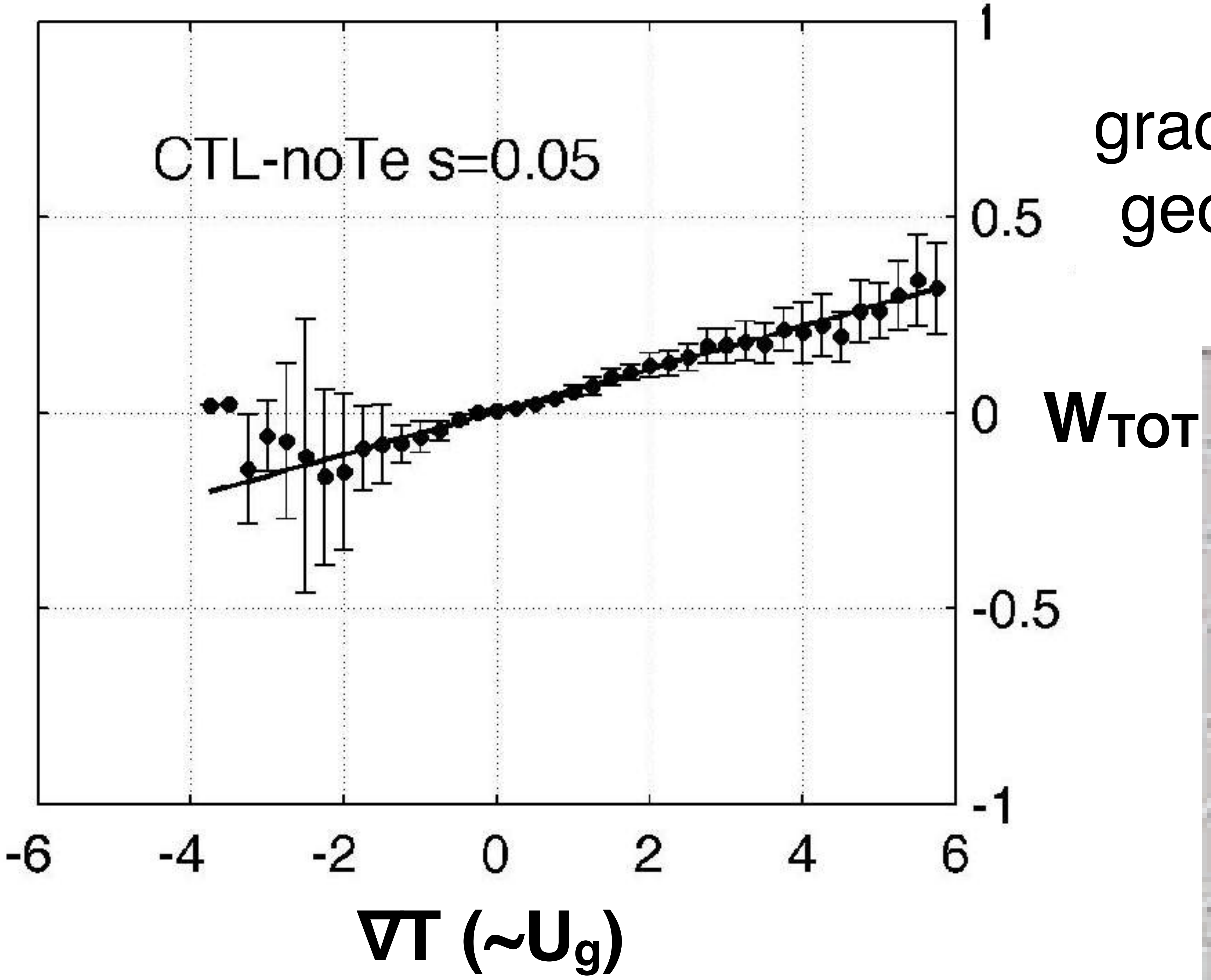
JAS 2005-2010

Inferred Feedback to eddy activities through W_{SST}

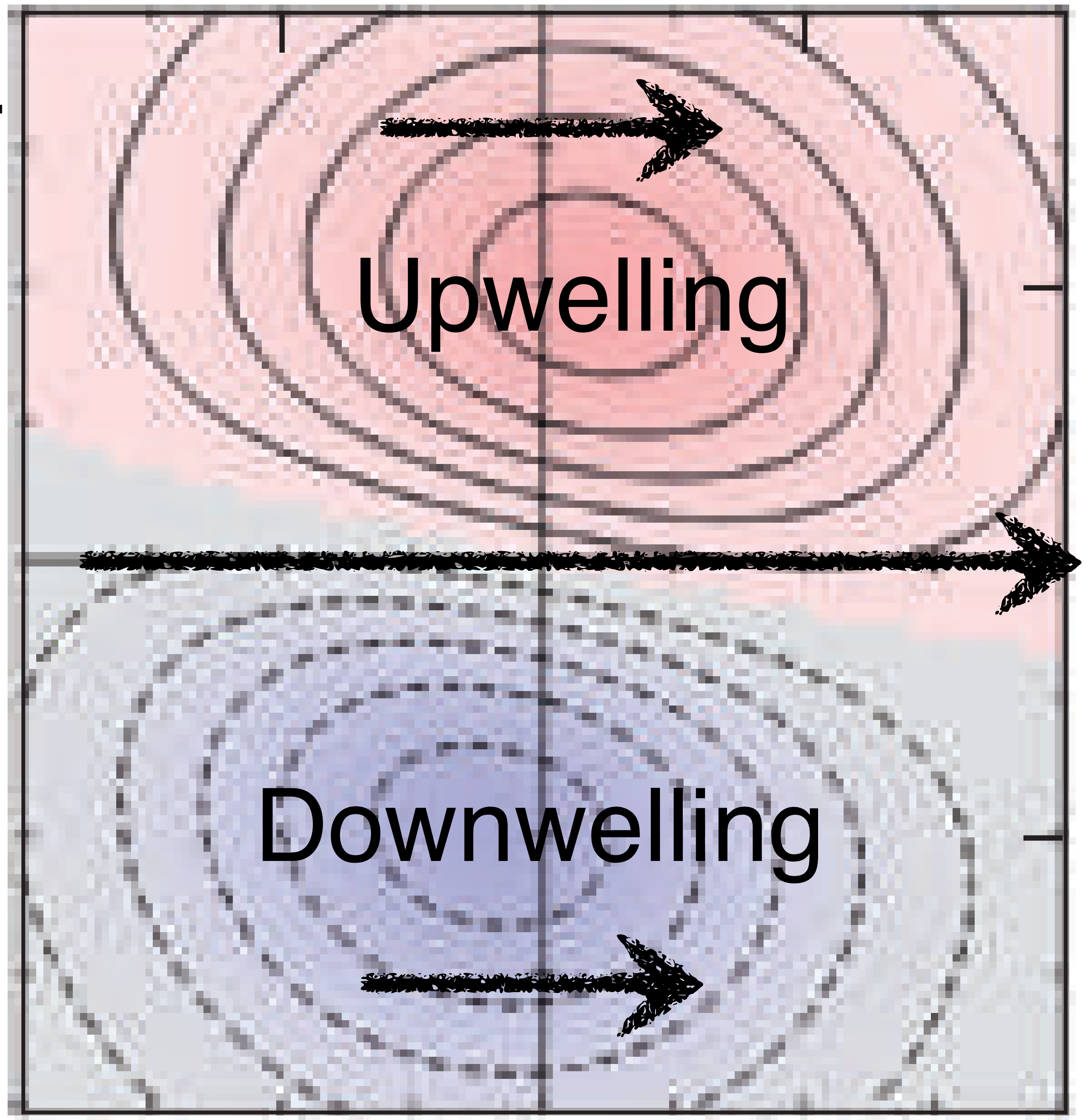
CTL-noT$_e$ W_{TOT} & ∇T



CTL-noT$_e$ W_{TOT} vs ∇T



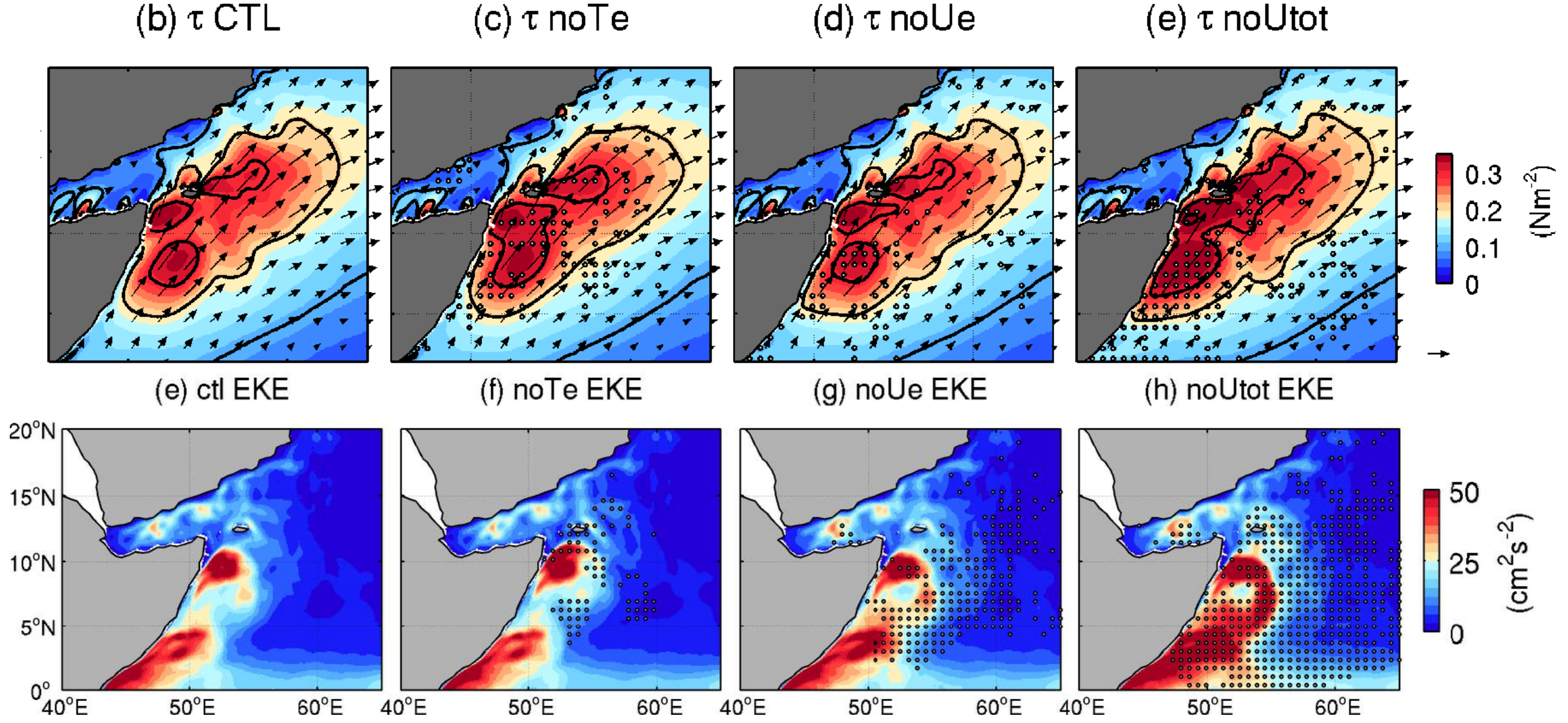
Ekman pumping acting on the maximum SST gradients → influences the geostrophic speed within the eddy interior



JAS 2005-2010

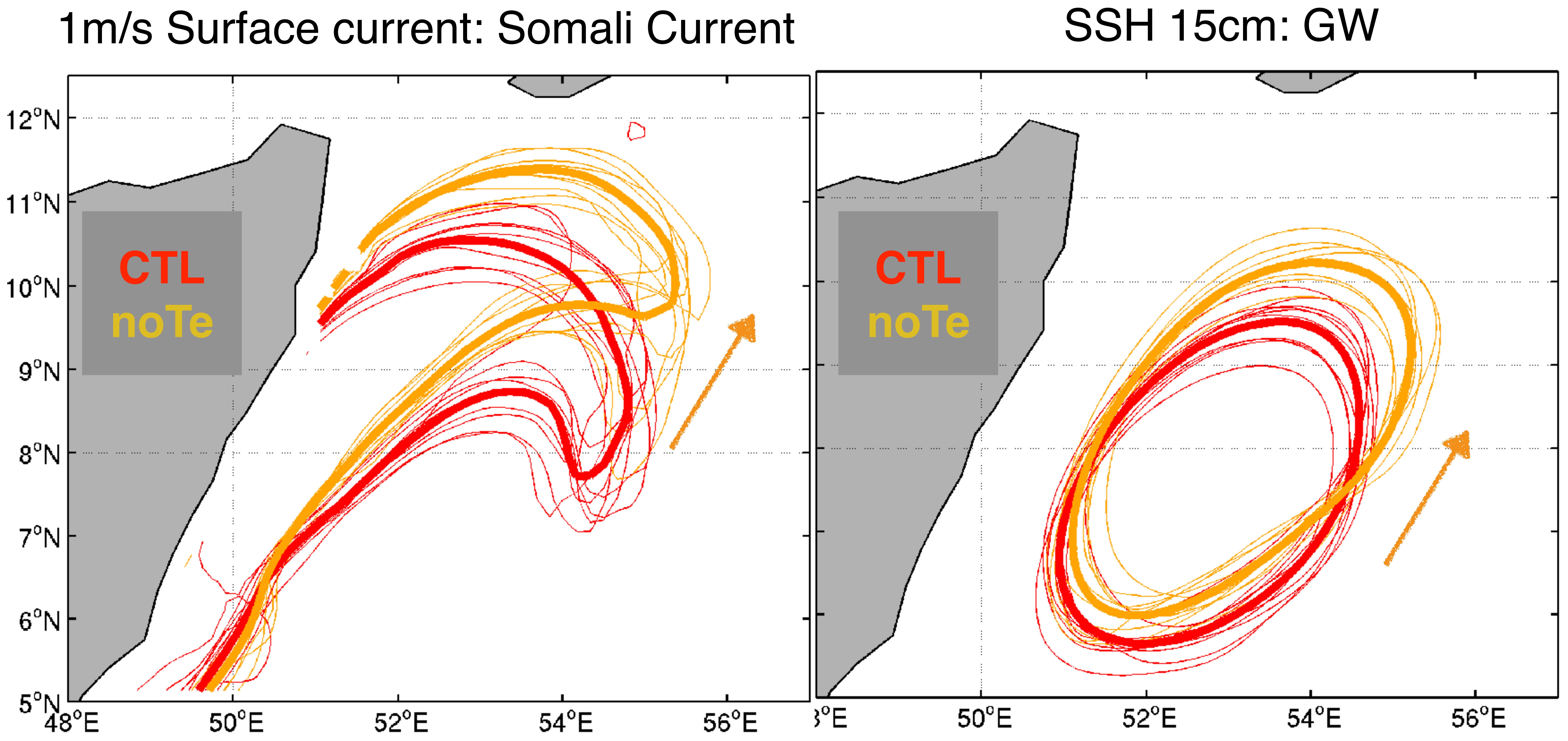
Confirming two distinct dynamical influences of air-sea coupling

U-τ coupling decreases the KE by reducing the momentum input



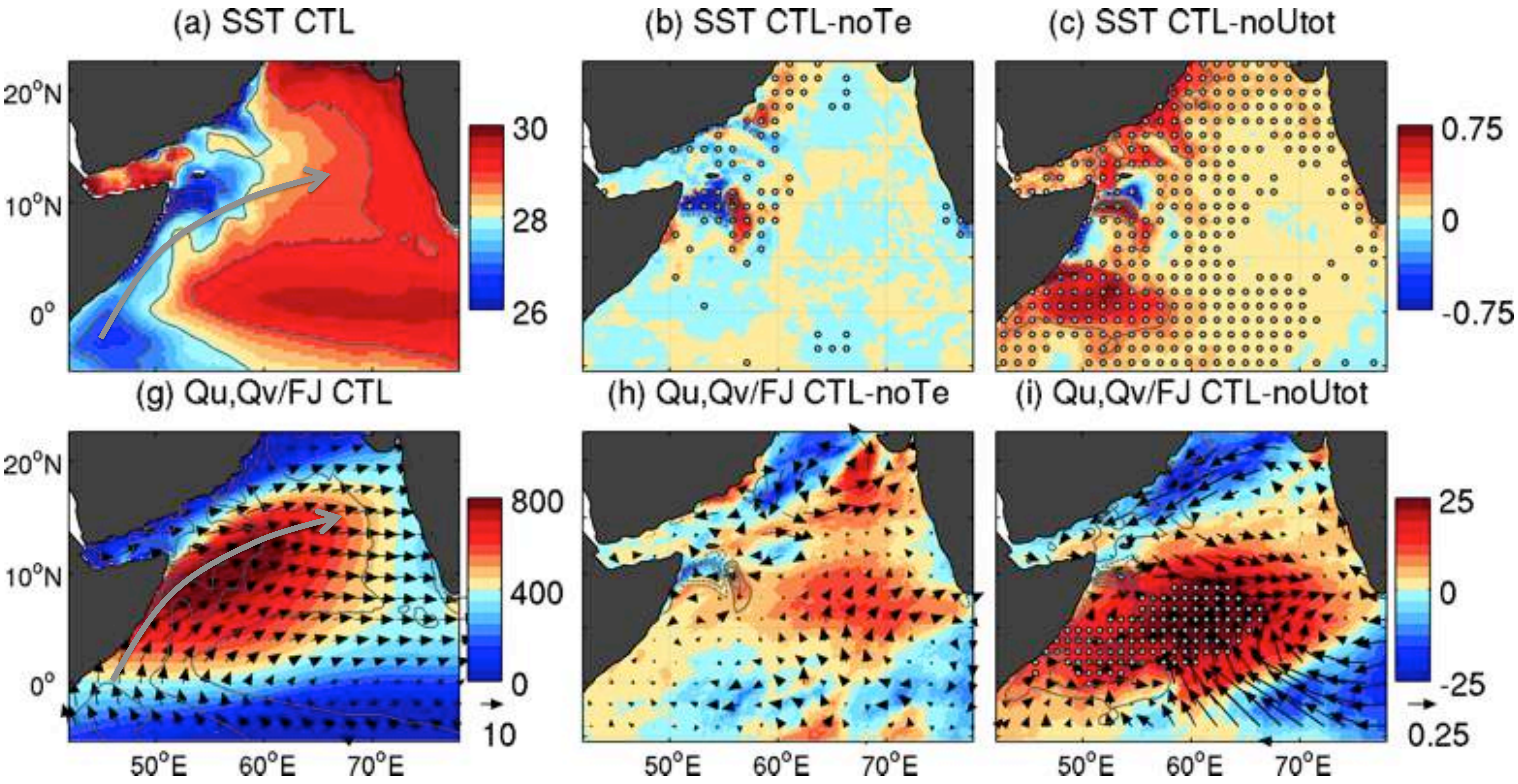
2001-2010 JJAS climatology

T_e-τ influences the position of GW and the Somali Current overshooting



- About 1° downstream shifts in eastward jet in SC and GW in noT_e

Some downstream influence on the moisture transport



SST

qV_{850}

- Small (~5%) but significant change in the axis of the Findlater Jet and the associated moisture transport

Summary and Discussion

Distinct impacts of air-sea interaction mediated by SST vs surface current on the energetics of the two boundary current systems

- T_e-τ coupling affects the position of eddy fields through Ekman pumping velocity
  → E.g., the Great Whirl is shifted northeastward by ~1°.
- U_e-τ coupling attenuates the kinetic energy
  → by reducing wind work and increasing eddy-drag. W_ζ further suppresses the eddy amplitude
- Some geographical difference
  → In the AS, U_{tot}-τ coupling is more important than U_e-τ coupling
- Some evidence of potentially important downstream influence
  → The so-called "frontal-scale air–sea interactions" should consider beyond the thermal coupling the mechanical coupling arising from the boundary currents and eddies.

Thanks!

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