Distinct influence of air-sea coupling mediated by SST and current: California and Somali Current Systems

Hyodae Seo
Woods Hole Oceanographic Institution

Georgia Institute of Technology
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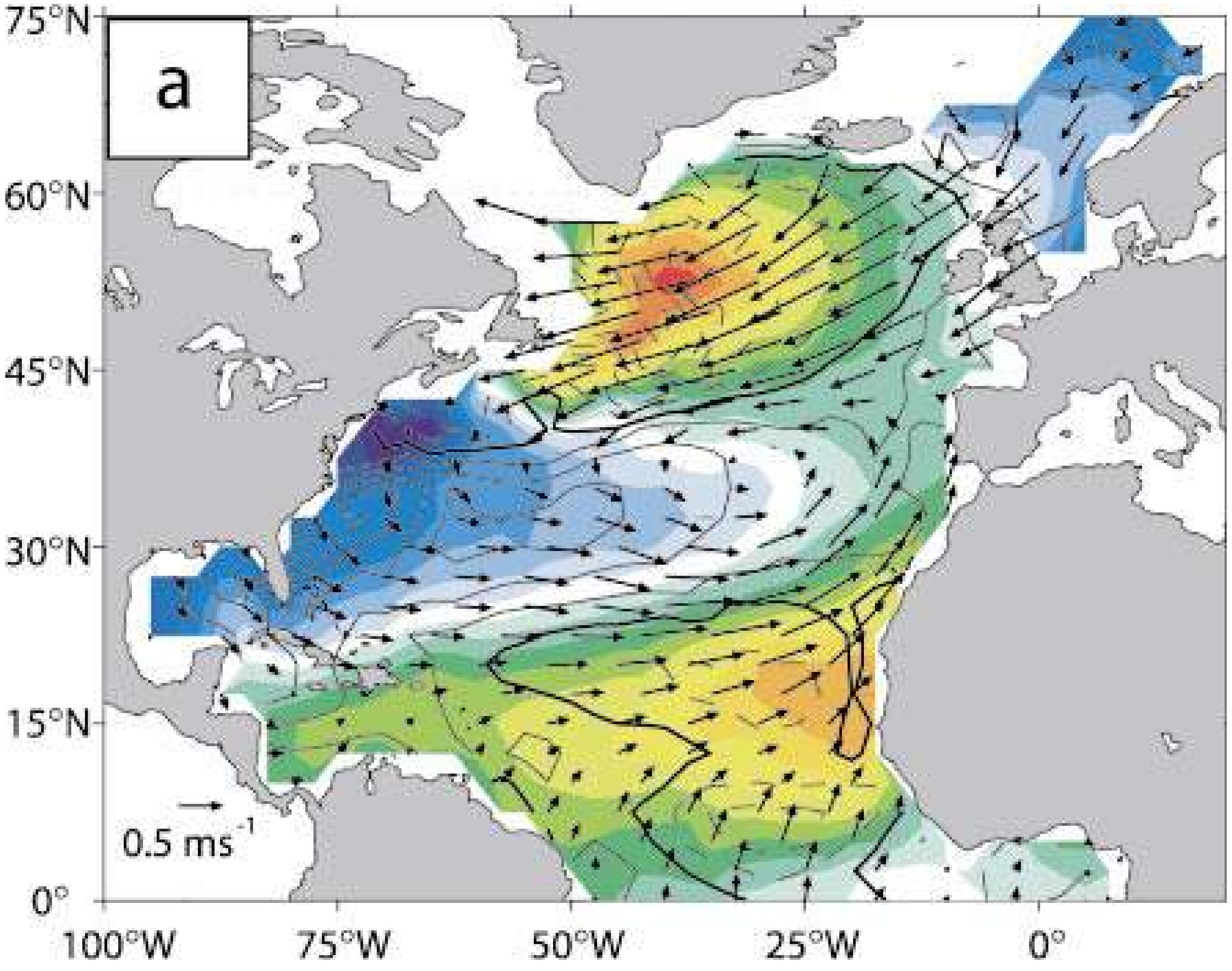
SeaWiFS surface chlorophyll concentration
O(>10³ km)
O(1-100 km)
Air-sea interaction
over different oceanic
scales?
http://earthobservatory.nasa.gov

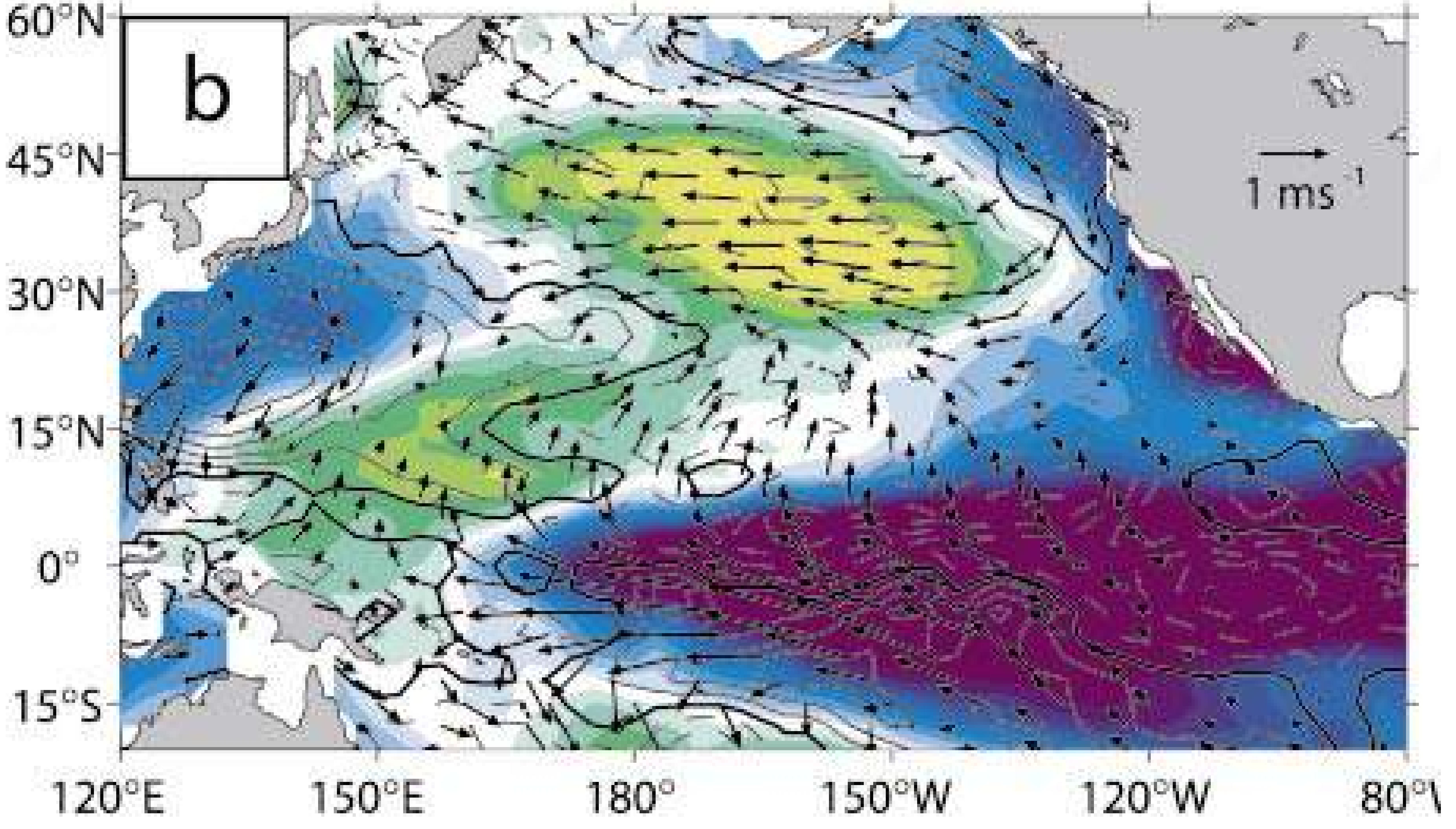
Large-scale air-sea interactions:

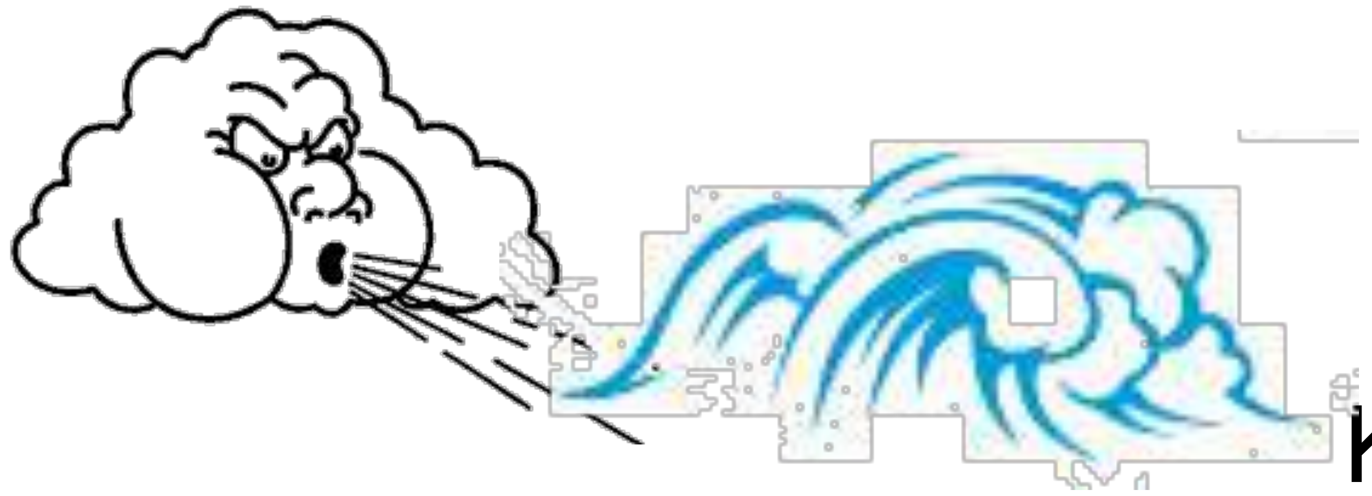
Winds over the slab ocean

North Atlantic Oscillation



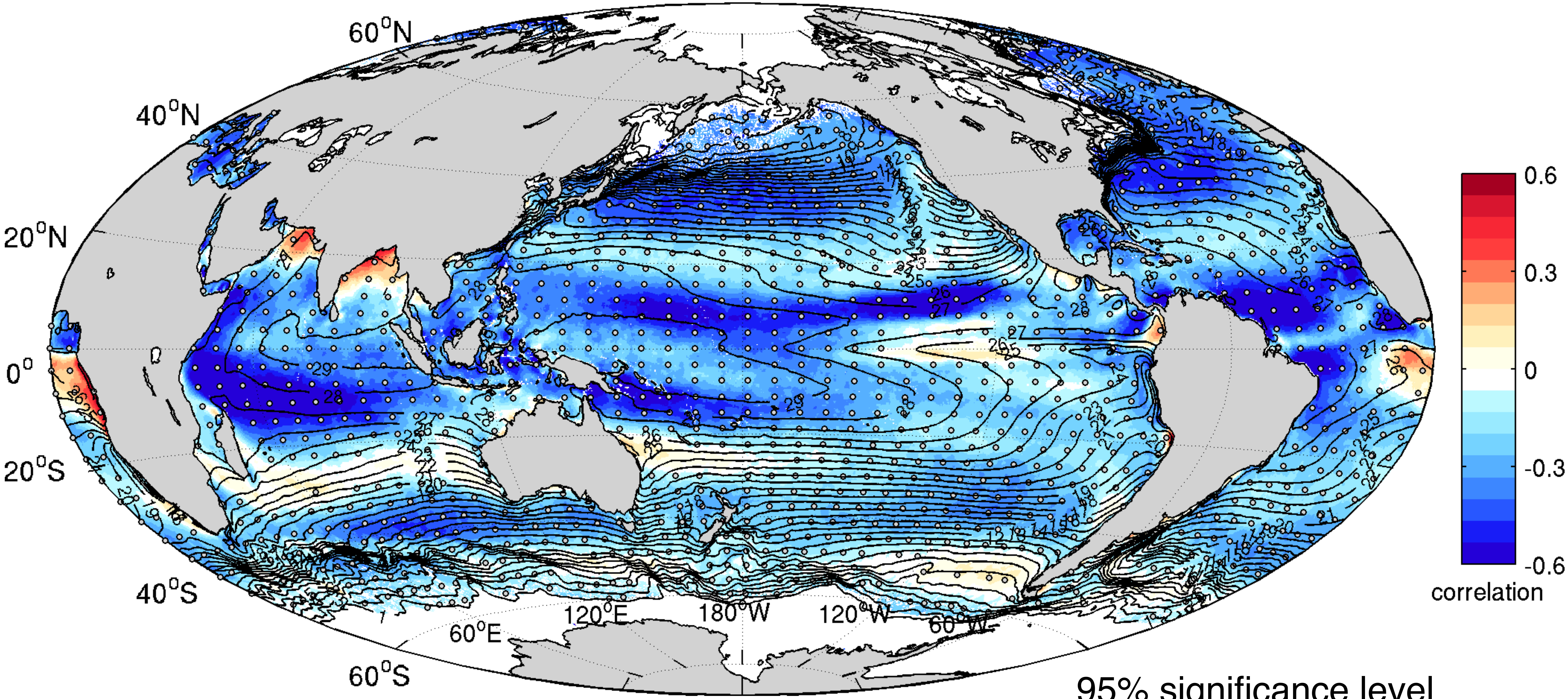
Pacific Decadal Oscillation





Kushnir et al. 2002

Air-sea interaction with no eddies/fronts
— Correlation between wind speed and SST



95% significance level

2000-2009 daily
QuikSCAT WS
NOAA-OI SST

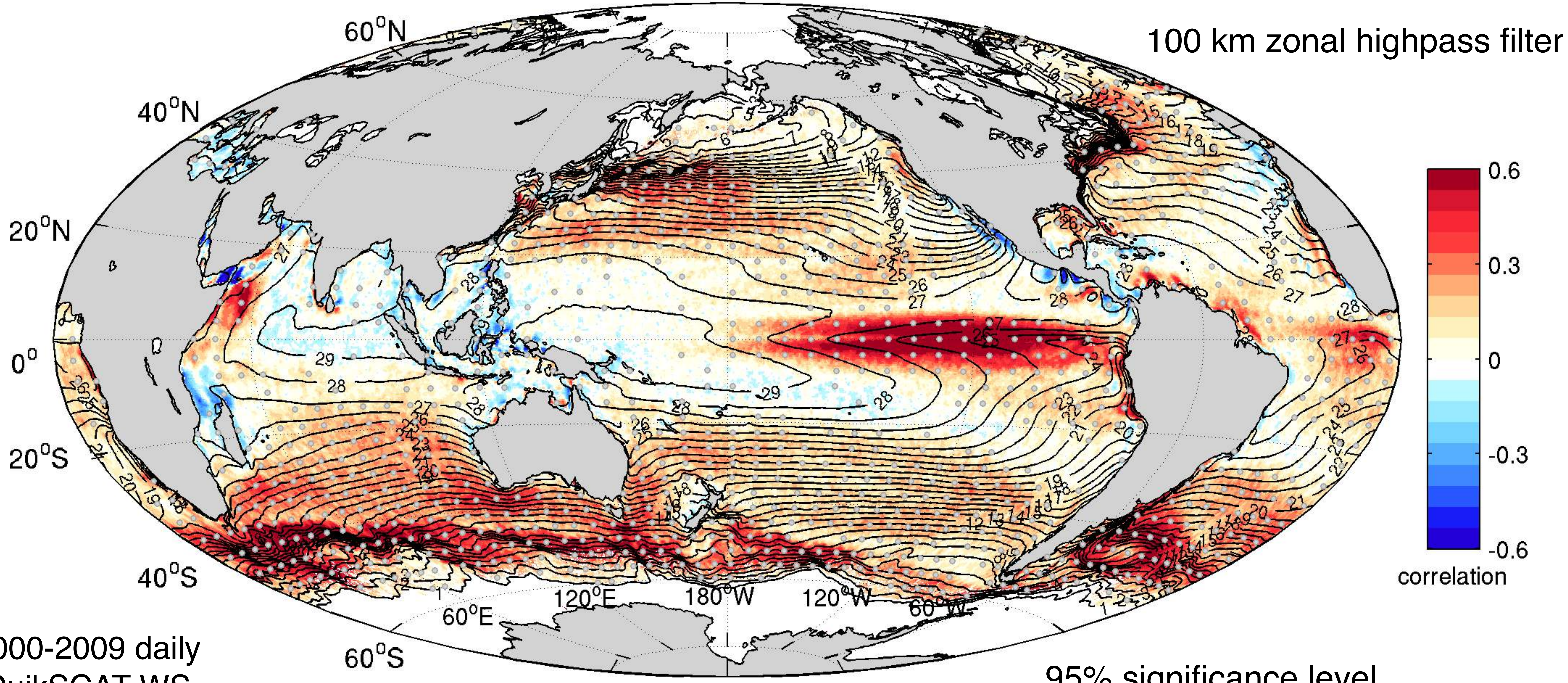
Negative correlation: Oceanic response to the atmosphere

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 WS and SST



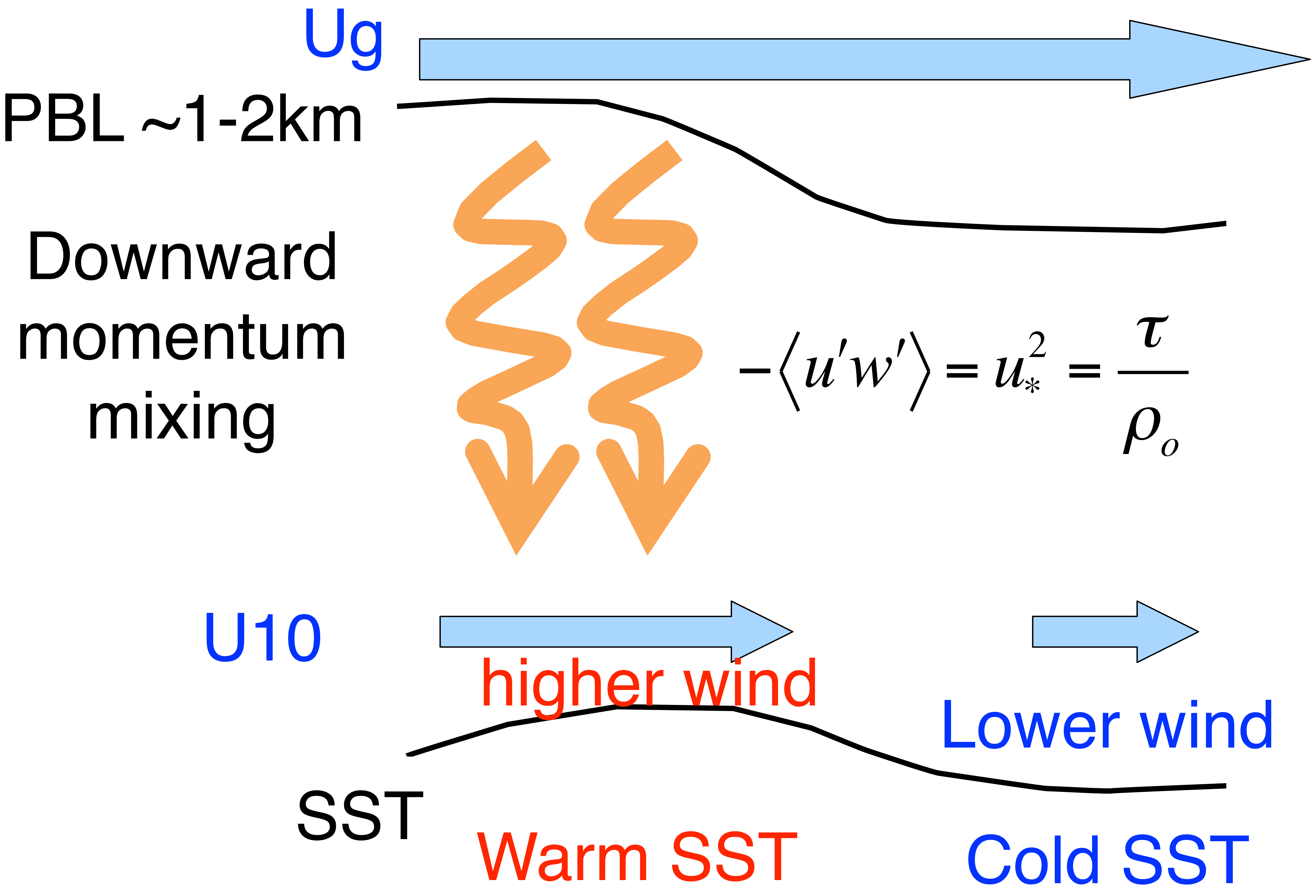
2000-2009 daily
QuikSCAT WS
NOAA-OI SST

95% significance level

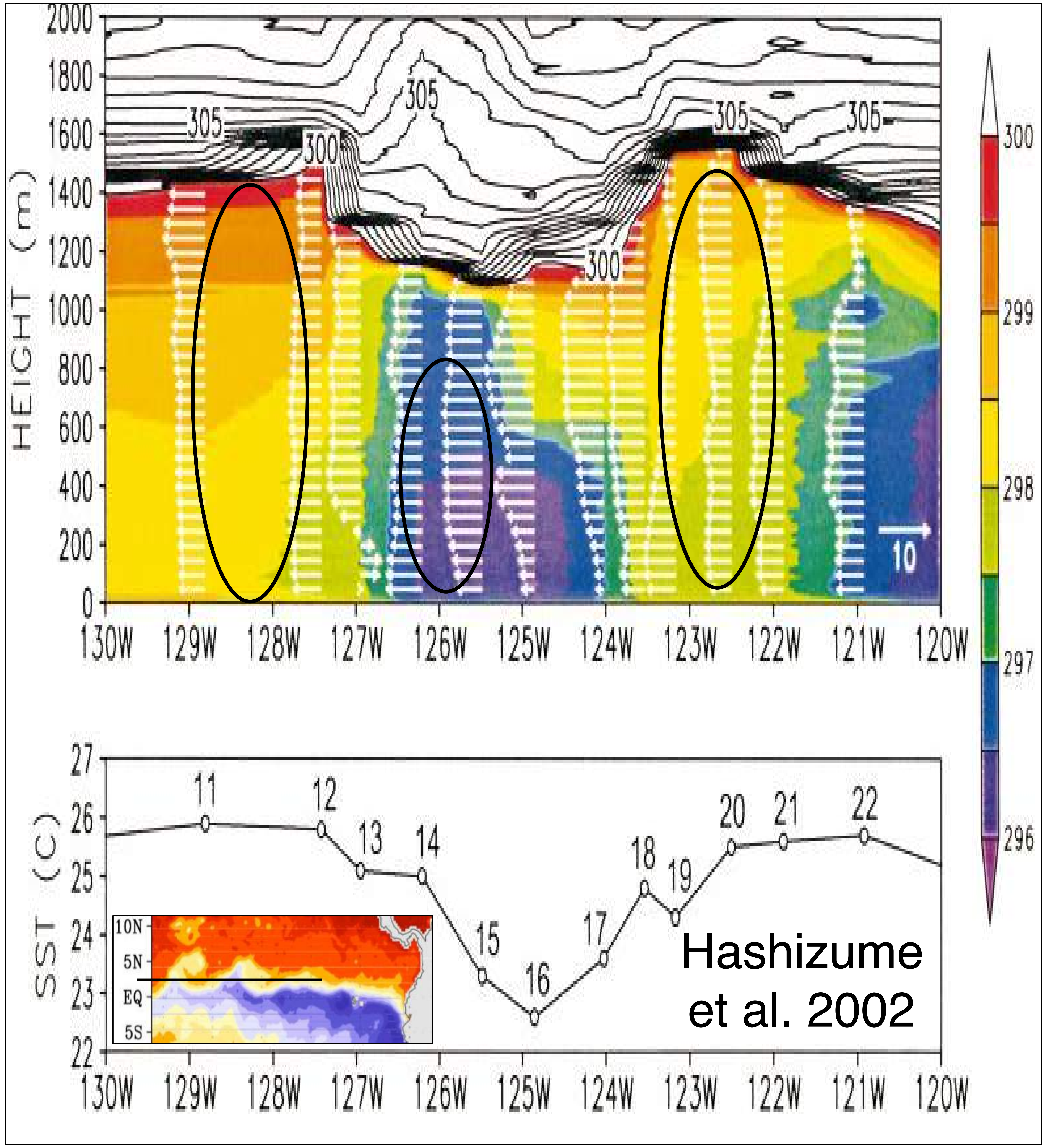
Oceanic forcing of the atmosphere on frontal and mesoscales.

Seo 2017

Mesoscale SST alters the vertical mixing in the MABL



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



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

How important is this mesoscale air-sea coupling to the ocean?

Let's look at the wind stress

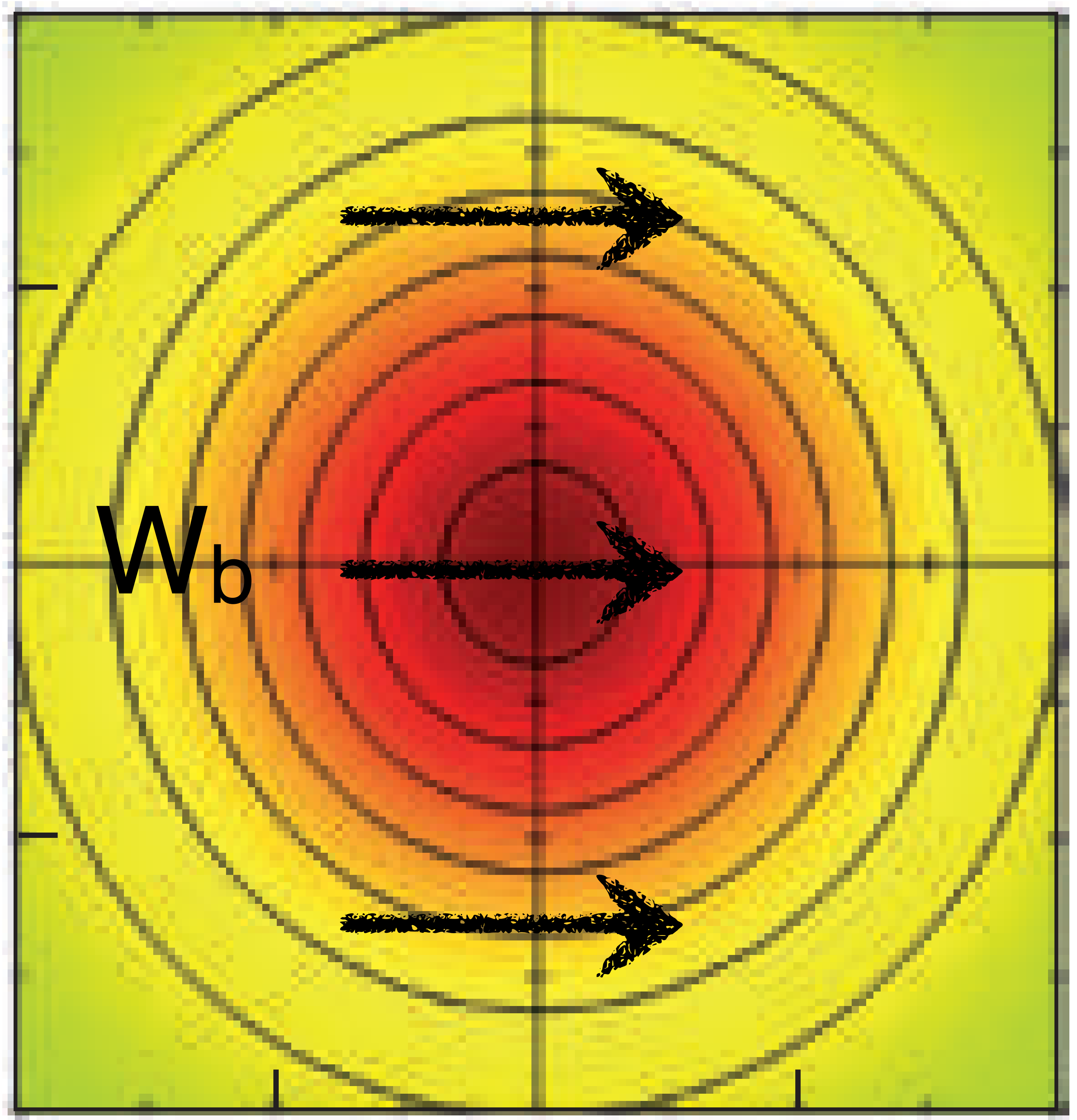
$$\tau = \rho_a C_D (\underline{W} - \underline{U})^2$$

U: surface current vector

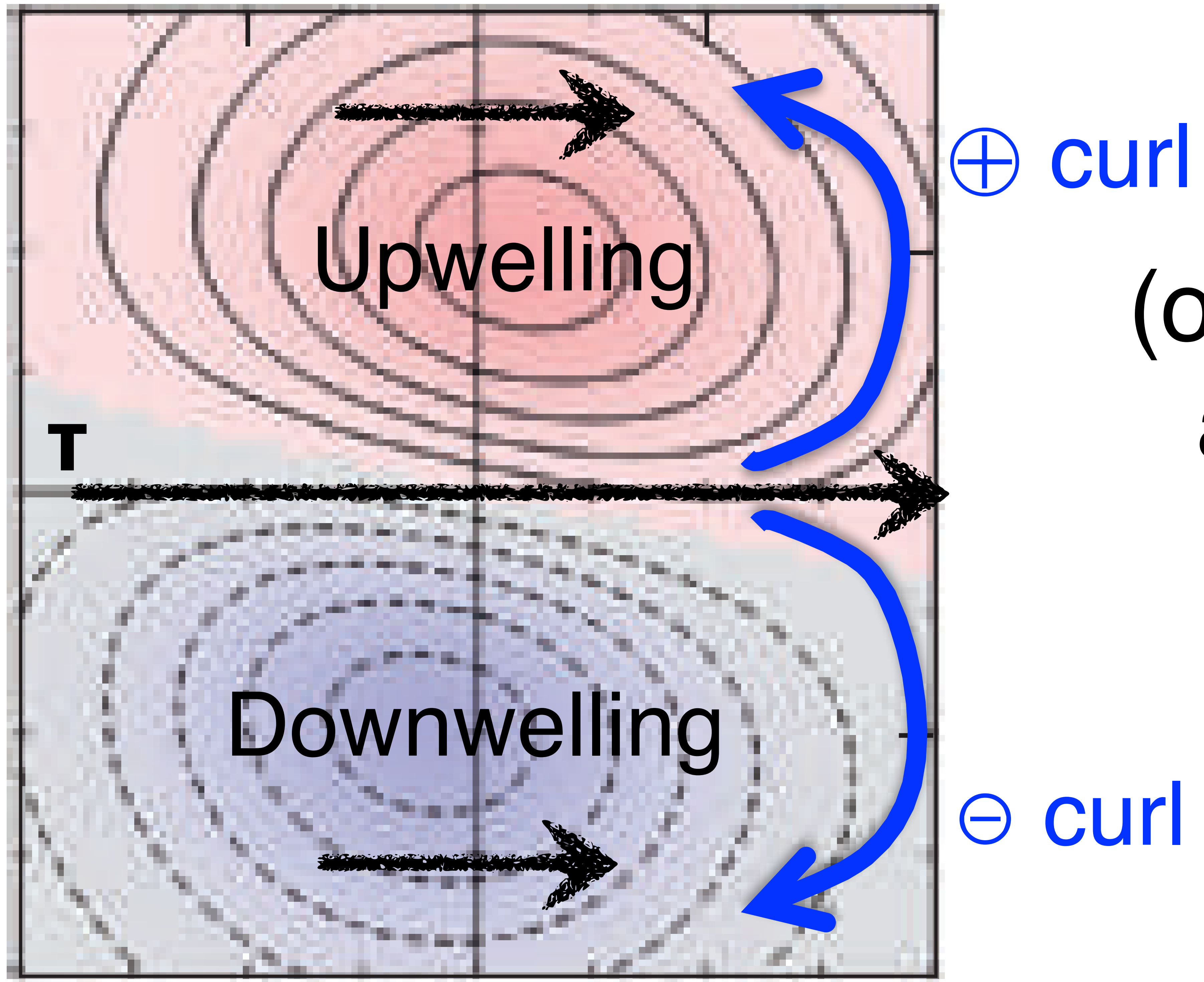
W: 10m wind vector $\underline{W} = \underline{W_b} + \underline{W_{SST}}$

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

SST and SSH



T_e-driven wind stress curl & W_e



Wind stress curl (or Ekman vertical velocity anomaly) in quadrature with SSH

→ Affect the position (southward)

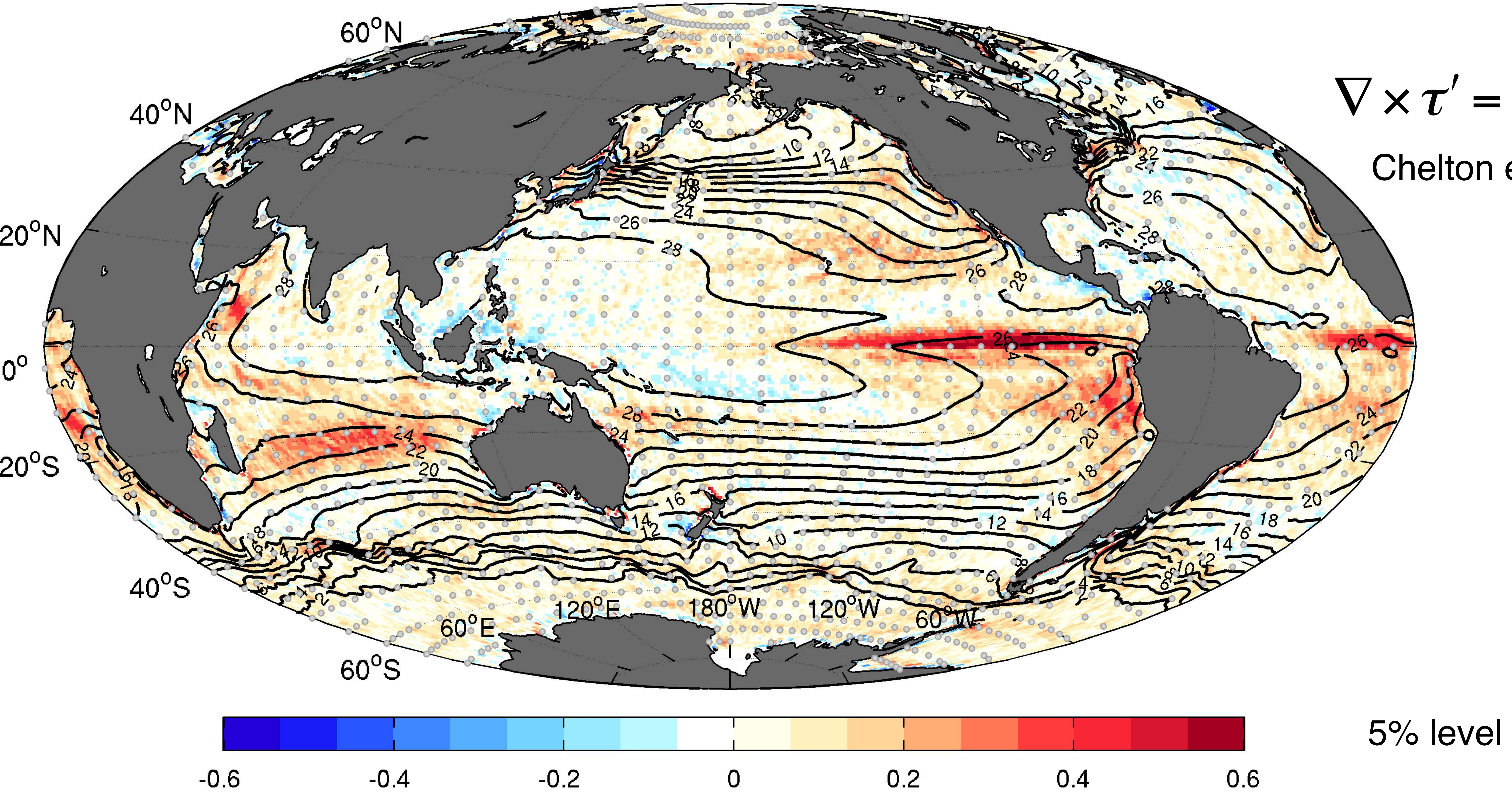
Wind stress curl associated with mesoscale SST gradients

Correlation bet'n wind stress curl and crosswind SST gradient

1993-2015, JJAS

$$\nabla \times \tau' = \alpha_c \nabla_c T'$$

Chelton et al. 2004



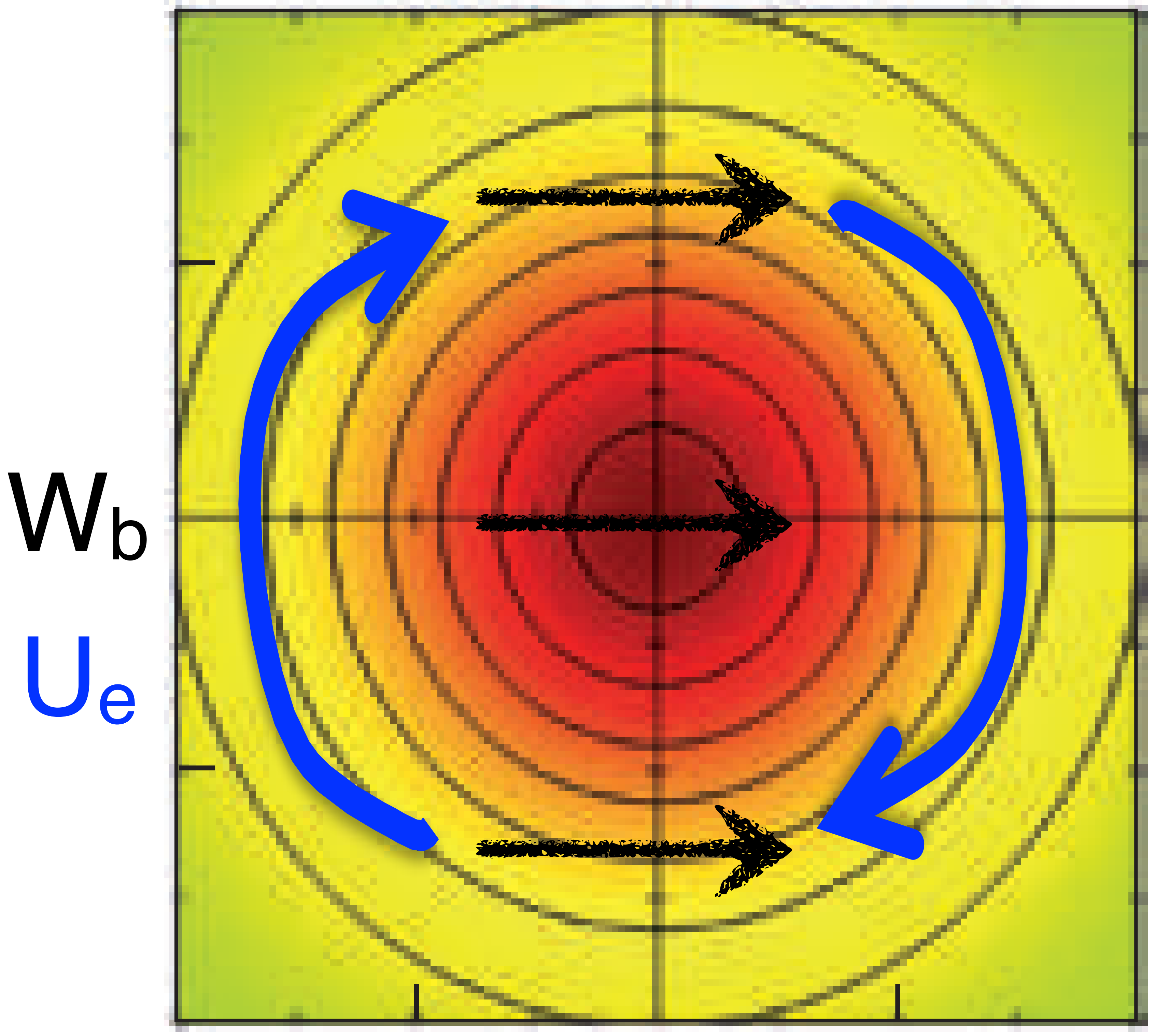
Surface current-induced wind stress curl

$$\tau = \rho_a C_D (\underline{W} - \underline{U})^2$$

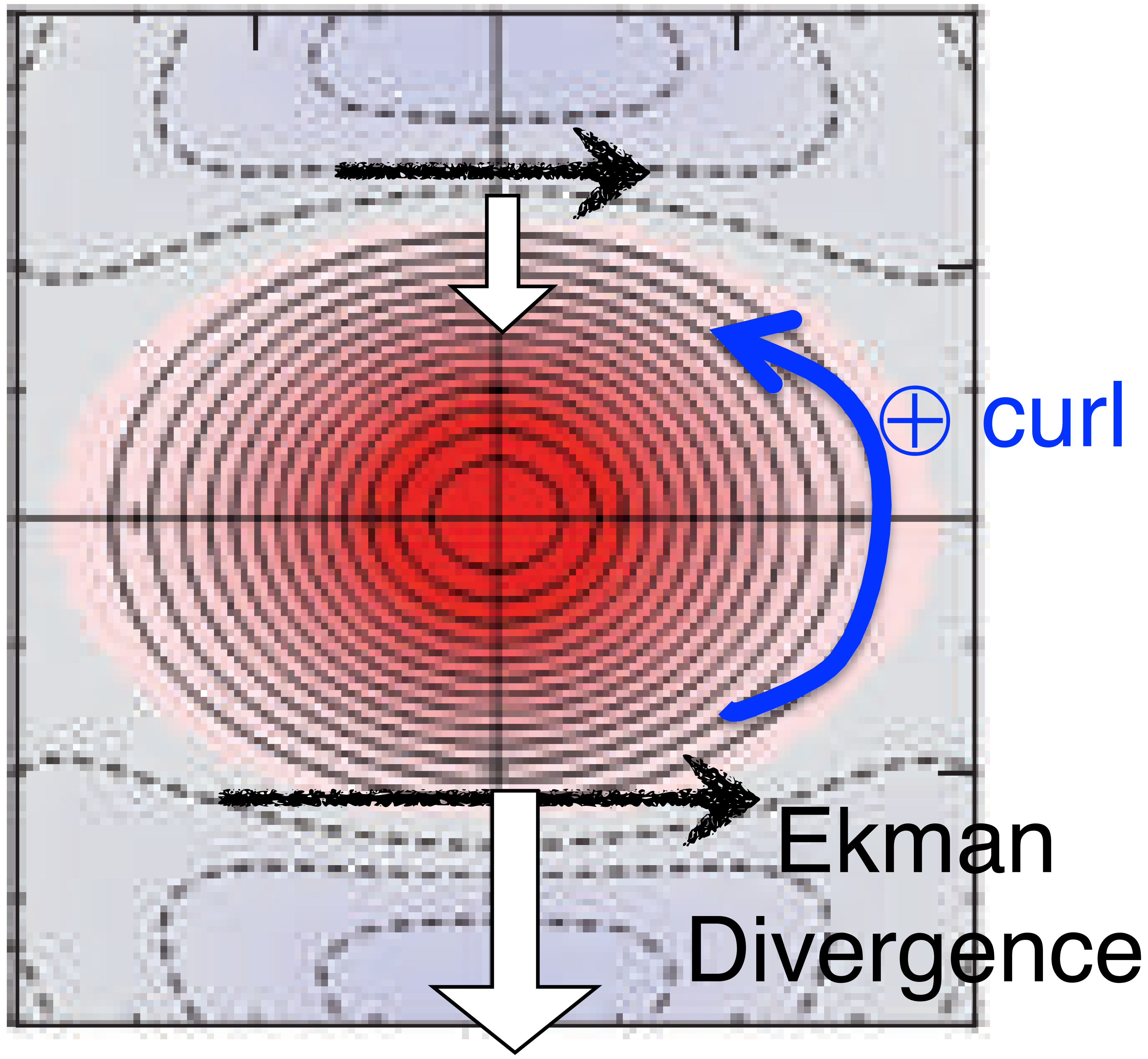
$\underline{U}$: surface current vector $\quad \underline{U} = \underline{U_b} + \underline{U_e}$

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

SST and SSH



Ue-driven wind stress curl & We

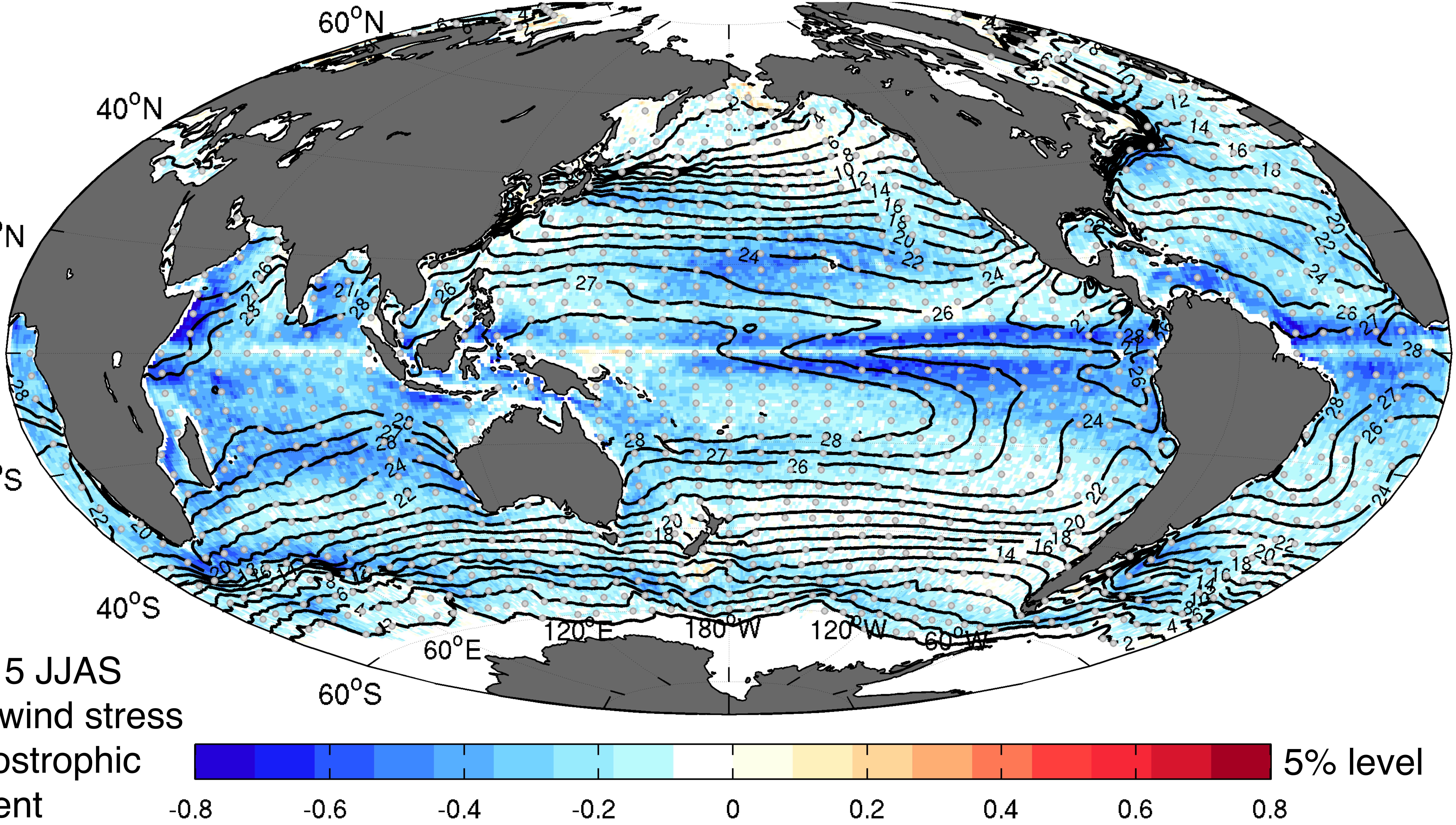


Cyclonic wind stress curl over anticyclonic eddy

→ Attenuate the eddy amplitude

Imprints of surface current in wind stress curl

—Correlation between wind stress curl and surface relative vorticity



1993-2015 JJAS
ERA-Interim wind stress
AVISO geostrophic current

Distinct influences of air-sea interaction due to SST and current

T_e-τ coupling

Anticyclonic eddy

U_e-τ coupling

Dipolar wind stress curl or W_e
→ Affect the position of the eddy

Positive correlation bet'n
wind stress curl and SST gradient

Monopole wind stress curl or W_e
→ Affect the amplitude of the eddy

Negative correlation bet'n
wind stress curl and relative vorticity

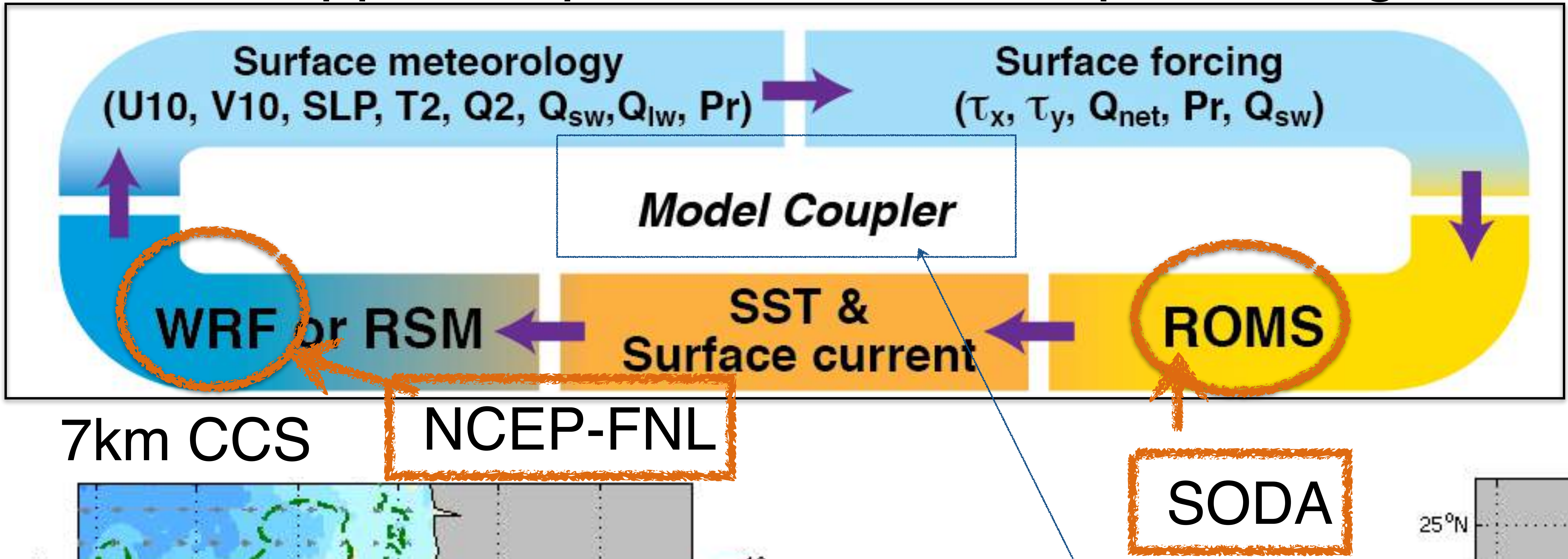
Objective

Can we quantify the effects of the two distinctive feedback process?

Let's look at the two summertime boundary current systems:
California & Somali Current Systems

EBC of the North Pacific	WBC of the Indian Ocean
Forcing: Summertime atmospheric jet	
Upwelling favorable: Cold filaments, mesoscale variability	
Mesoscale coupled feedback with potential downstream influences	

Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model

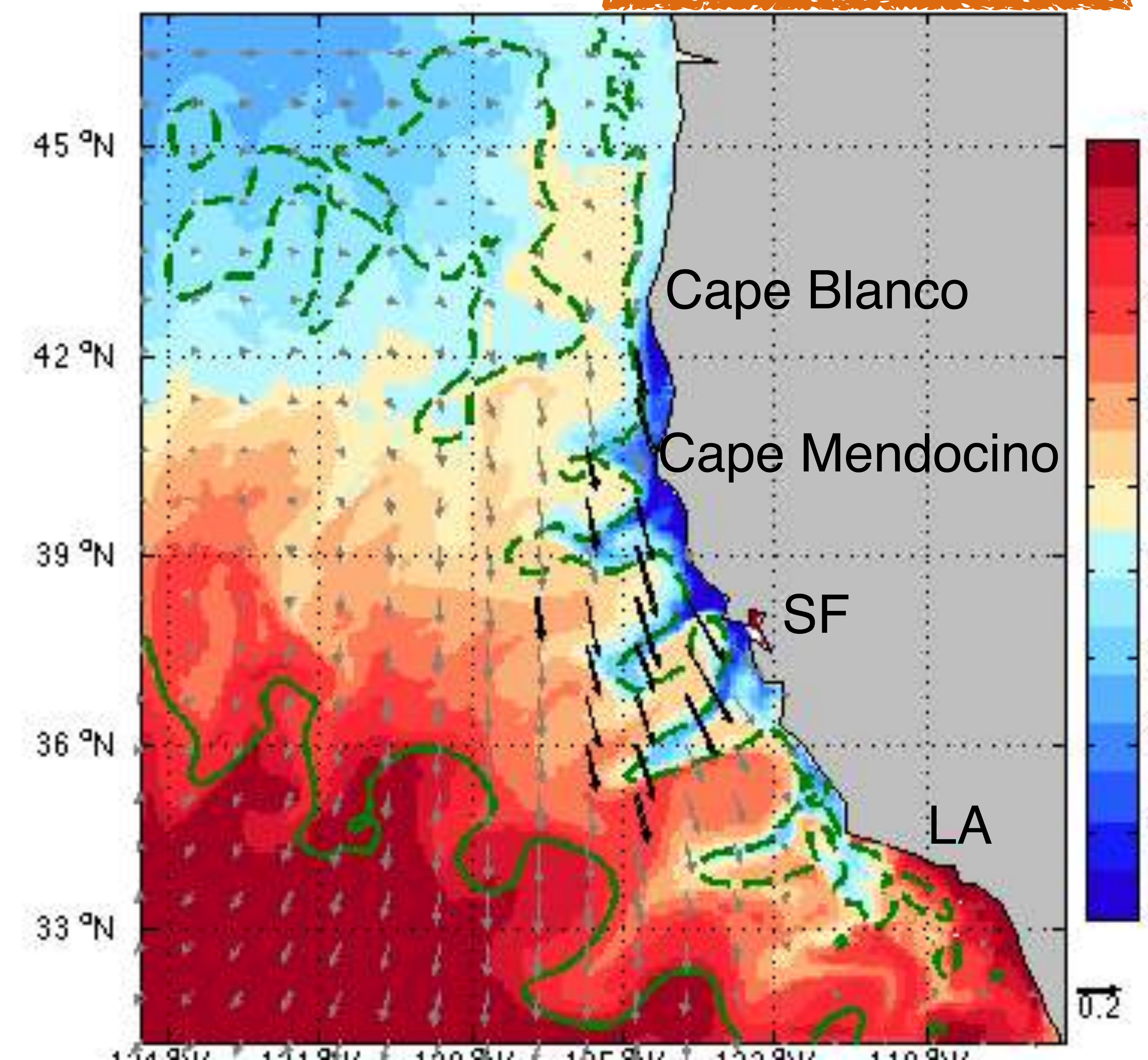


http://hseo.whoi.edu/scoar/

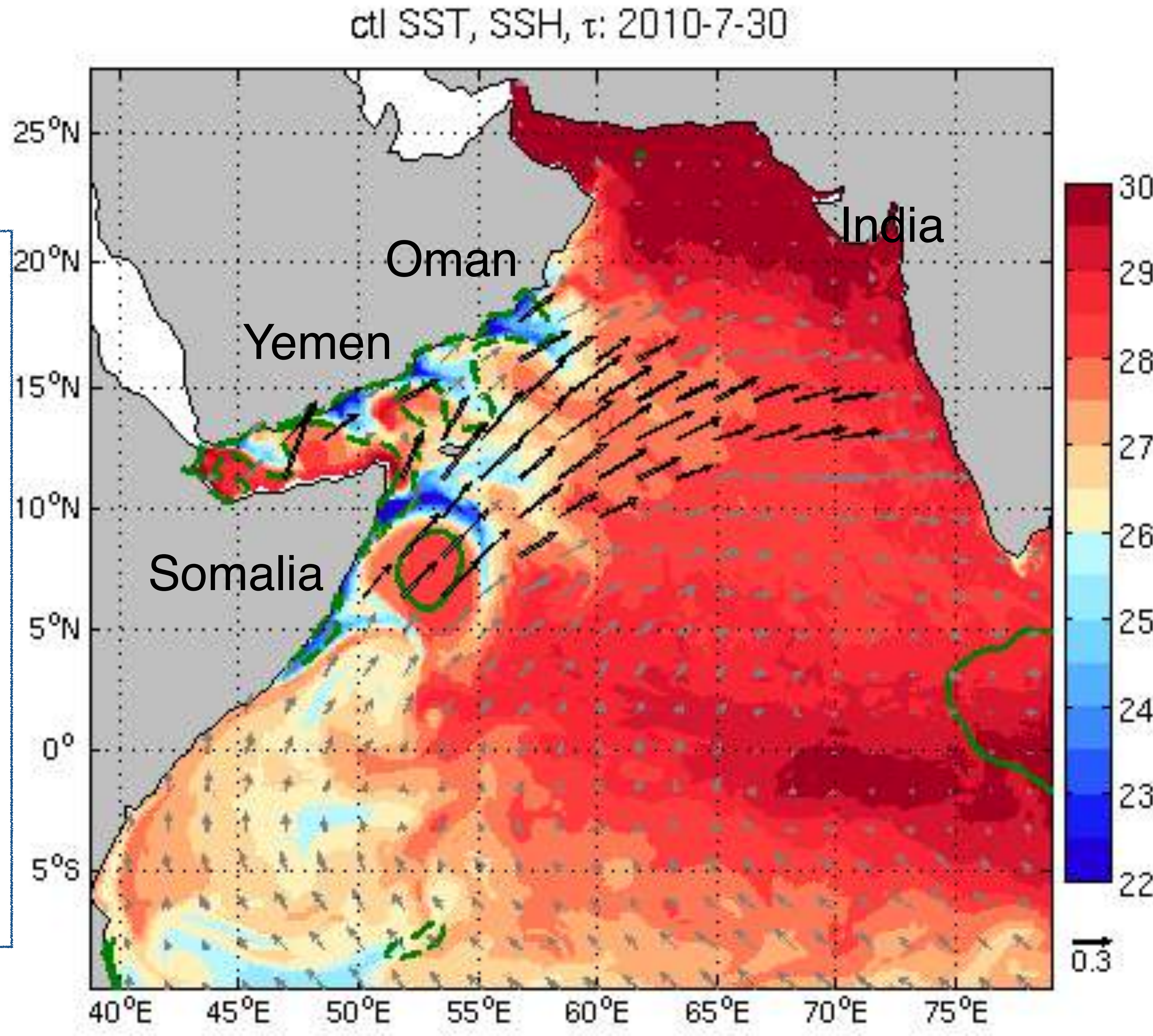
Seo et al. (2007; 2014; 2016, JCLI)

9km AS

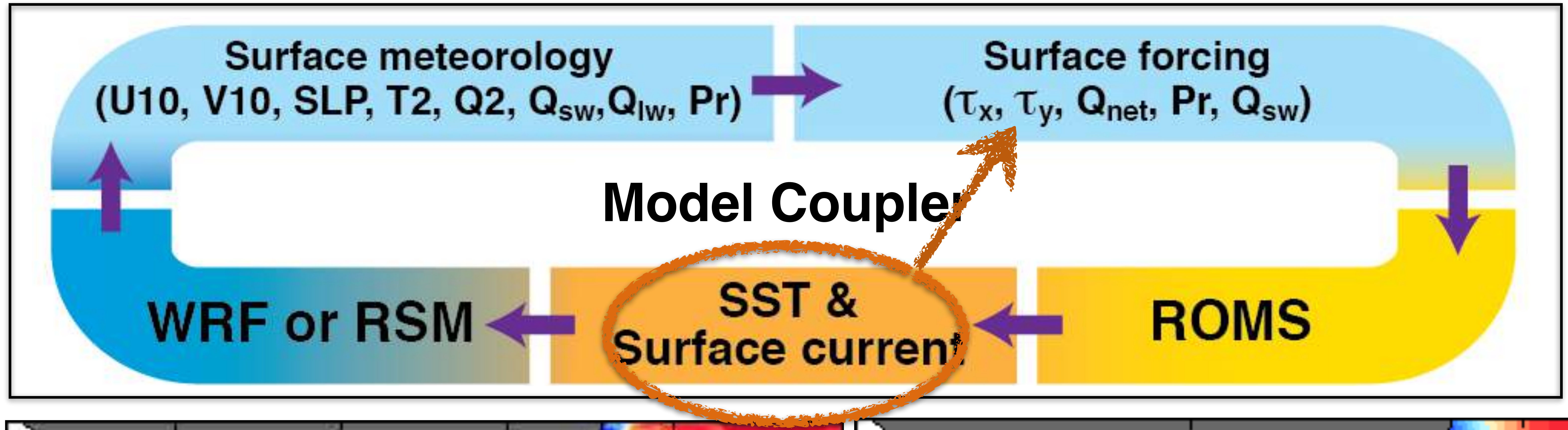
7km CCS



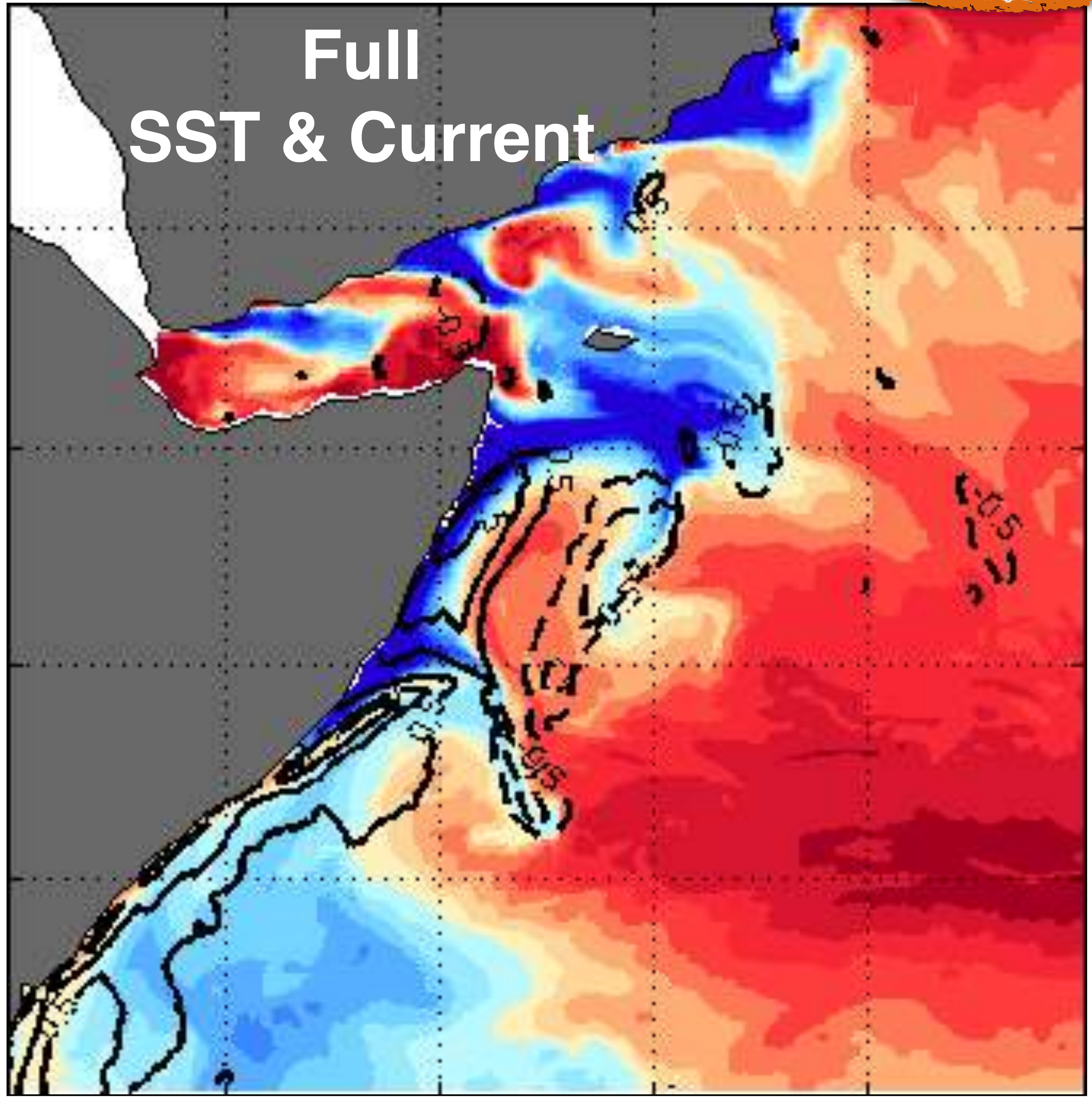
- Bulk formula or WRF PBL physics
- An input-output based coupler: portable & flexible
- Matching grids in the ocean and atmosphere

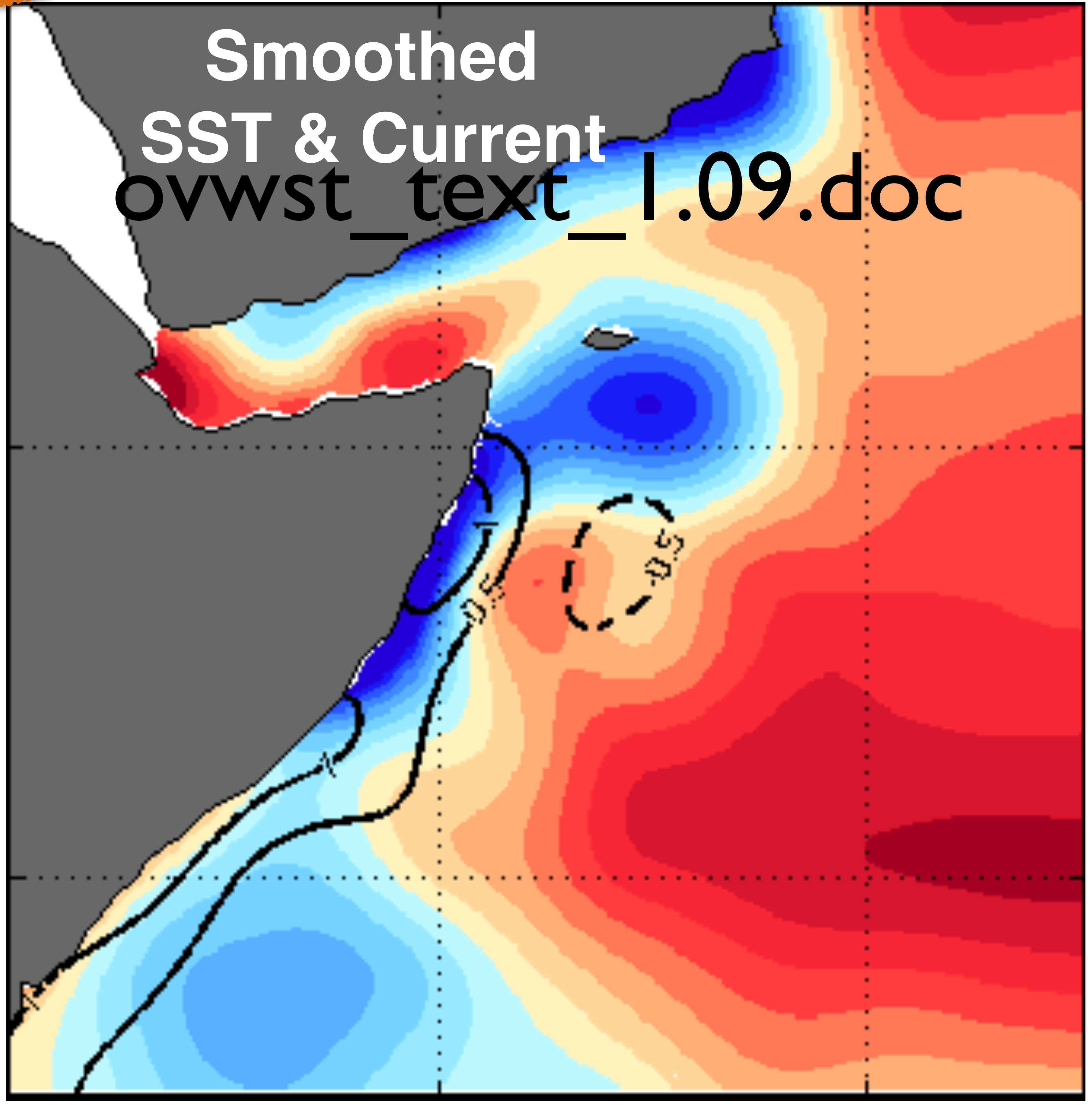


Scale separation of air-sea coupling



Online 2-D Loess smoothing
(e.g., ~3°×3°)
at each coupling time-step
Putrasahan et al. (2013); Seo et al. (2016); Seo (2017)



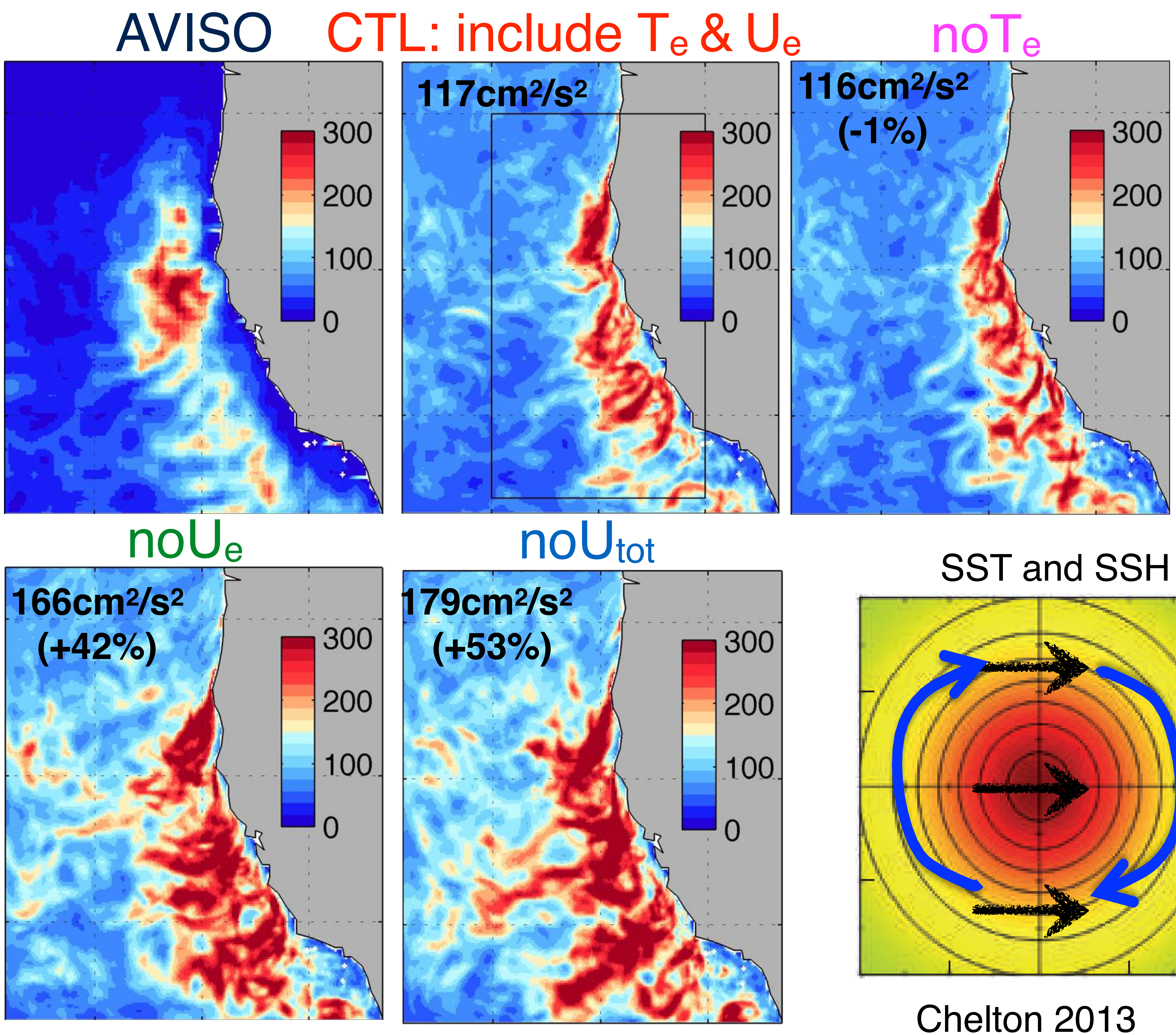


$\tau = \rho_a C_D (W - U)^2$

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

CCS: Effect on Eddy Kinetic Energy

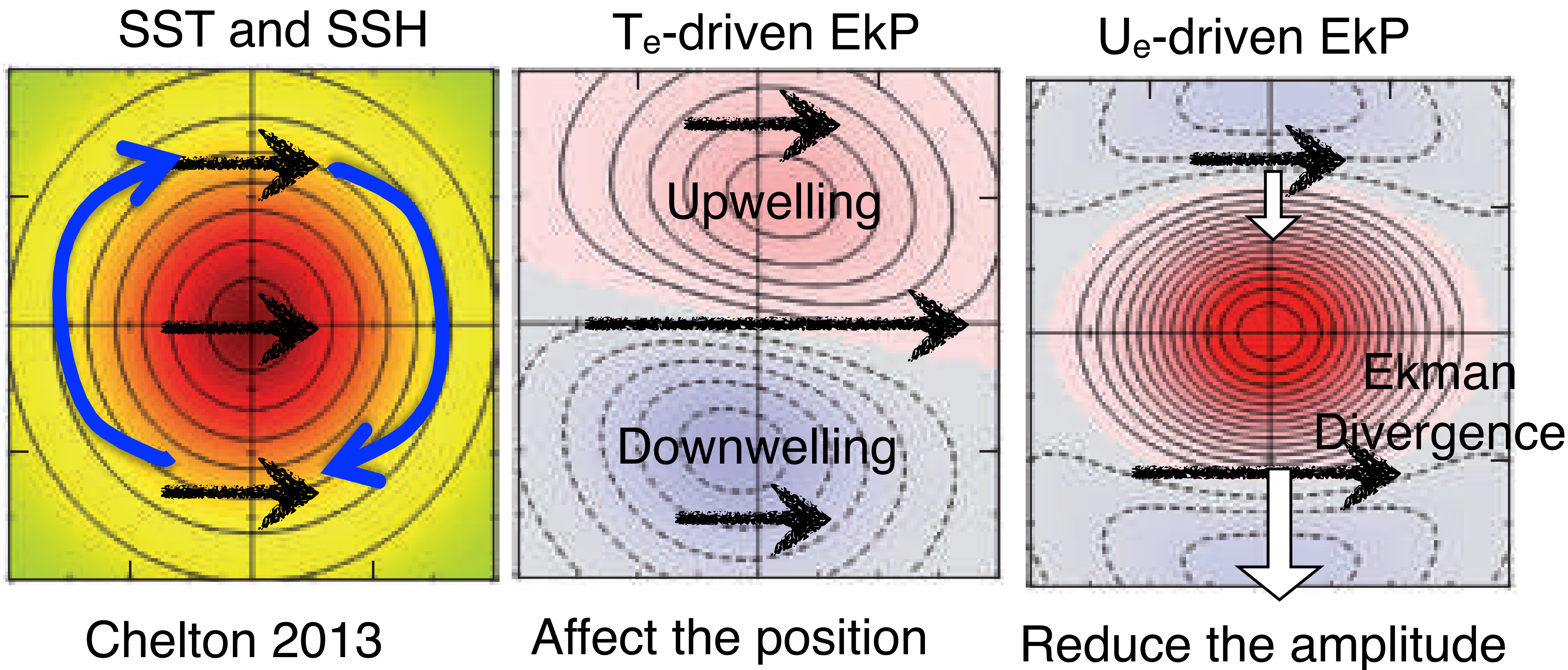
JAS 2005-2010



- T_e-τ has no impact on EKE
- U_e-τ reduces the EKE by 40%
- 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



Depth-averaged key EKE budget terms

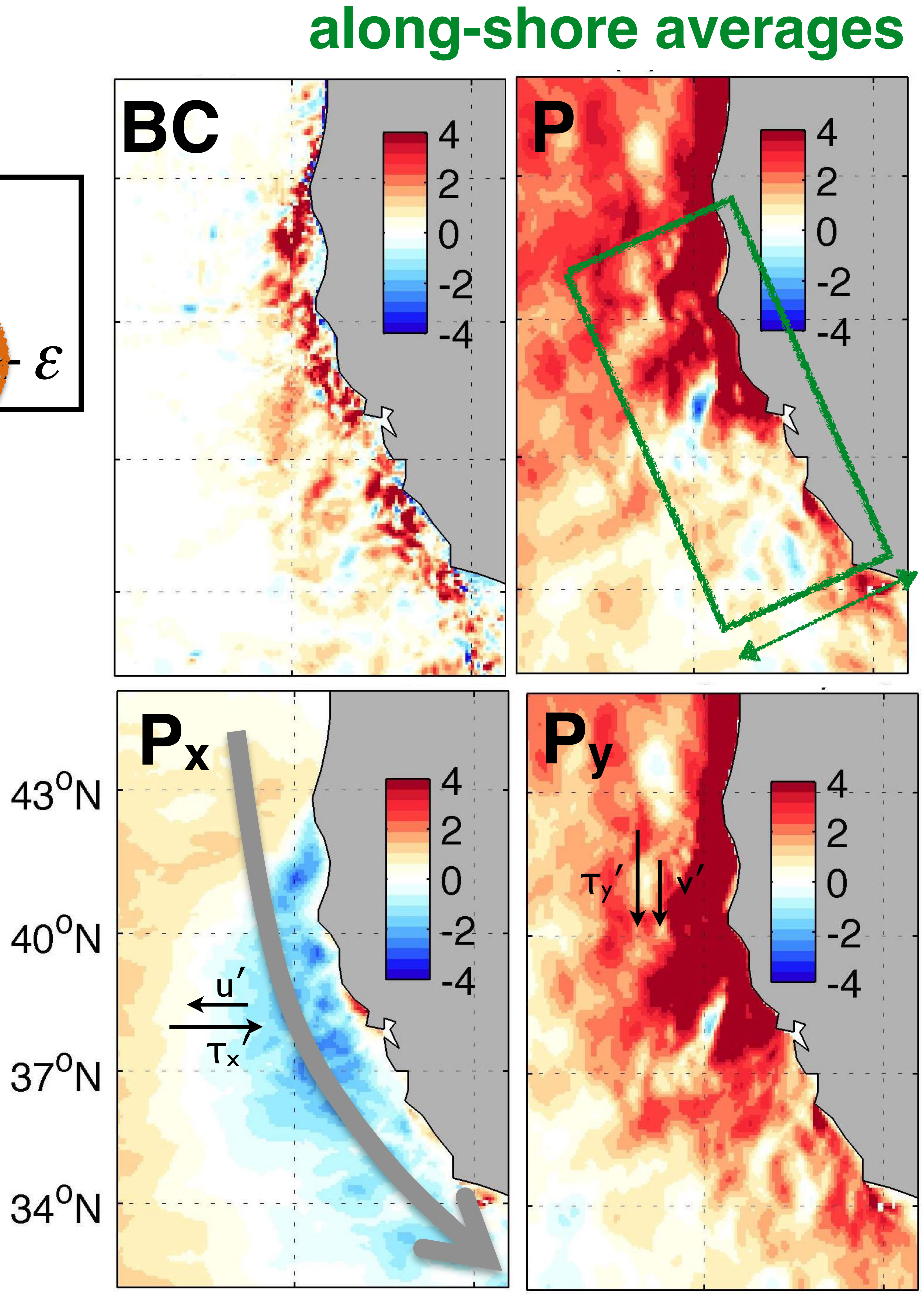
$$\frac{\partial K_e}{\partial t} + U \cdot \nabla K_e + u' \cdot \nabla K_e = -\nabla \cdot (u'p') - g\rho' w' + \rho_o(-u' \cdot (u' \cdot \nabla U)) + u' \cdot \tau' - \varepsilon$$

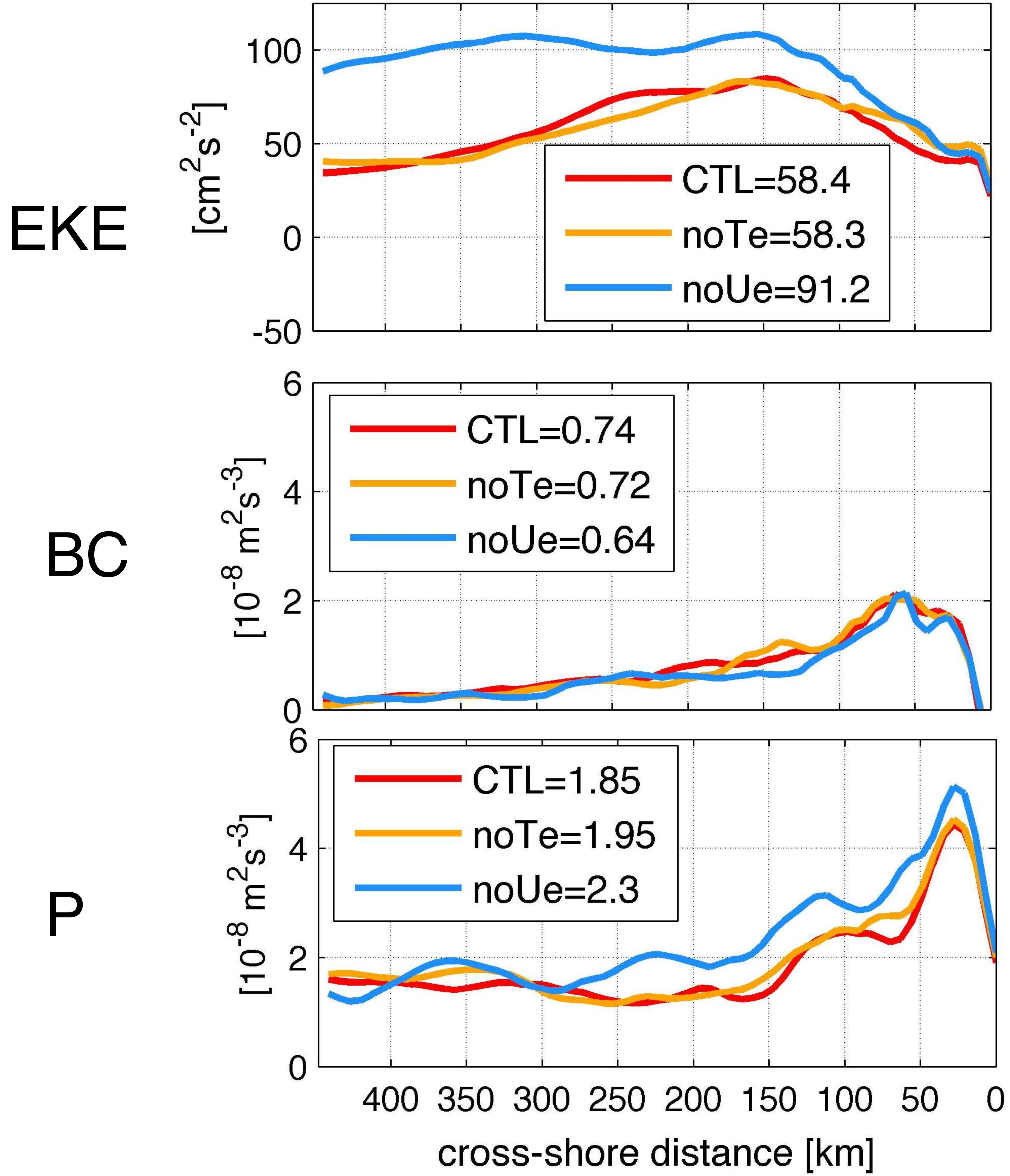
$$P = \frac{1}{\rho_0}(\overline{u'\tau'_x} + \overline{v'\tau'_y}).$$

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)





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

Eddy-driven Ekman pumping velocity

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

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

Stern 1965
Gaube et al. 2015
Seo et al. 2016

W_{LIN}: Curl-induced linear Ekman pumping

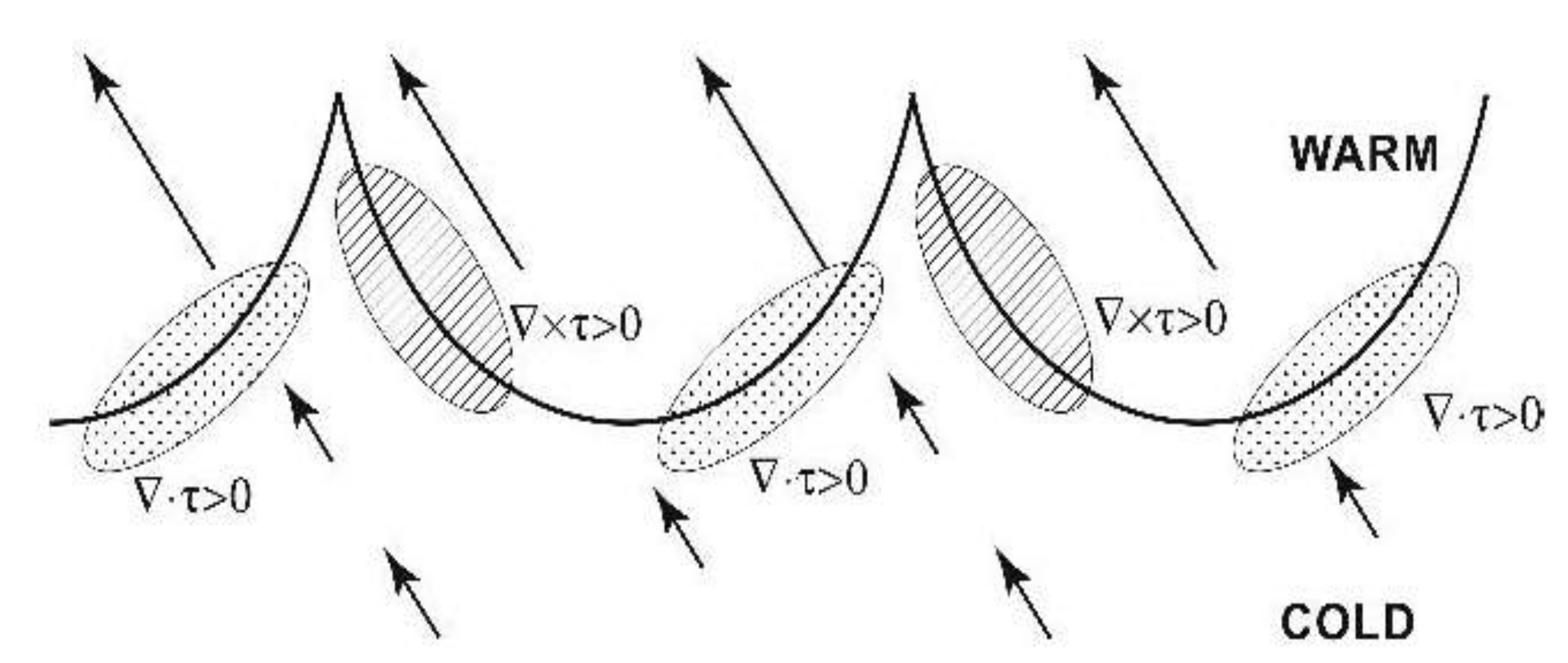
W_{ζ}: Relative vorticity gradient-induced nonlinear Ekman pumping

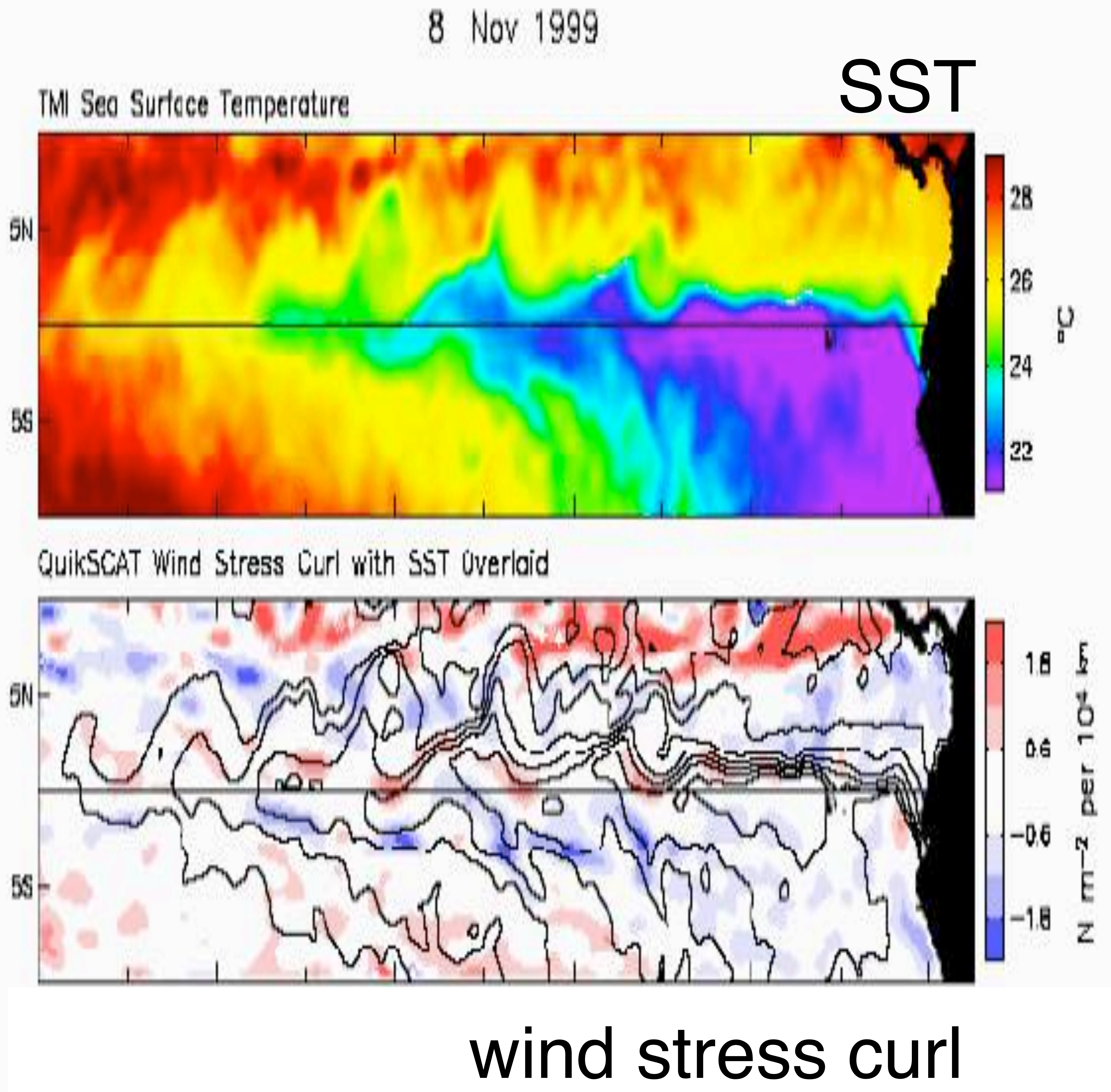
W_{SST}: SST induced Ekman pumping (Chelton et al. 2007)

Estimating eddy SST-driven Ekman pumping velocity

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

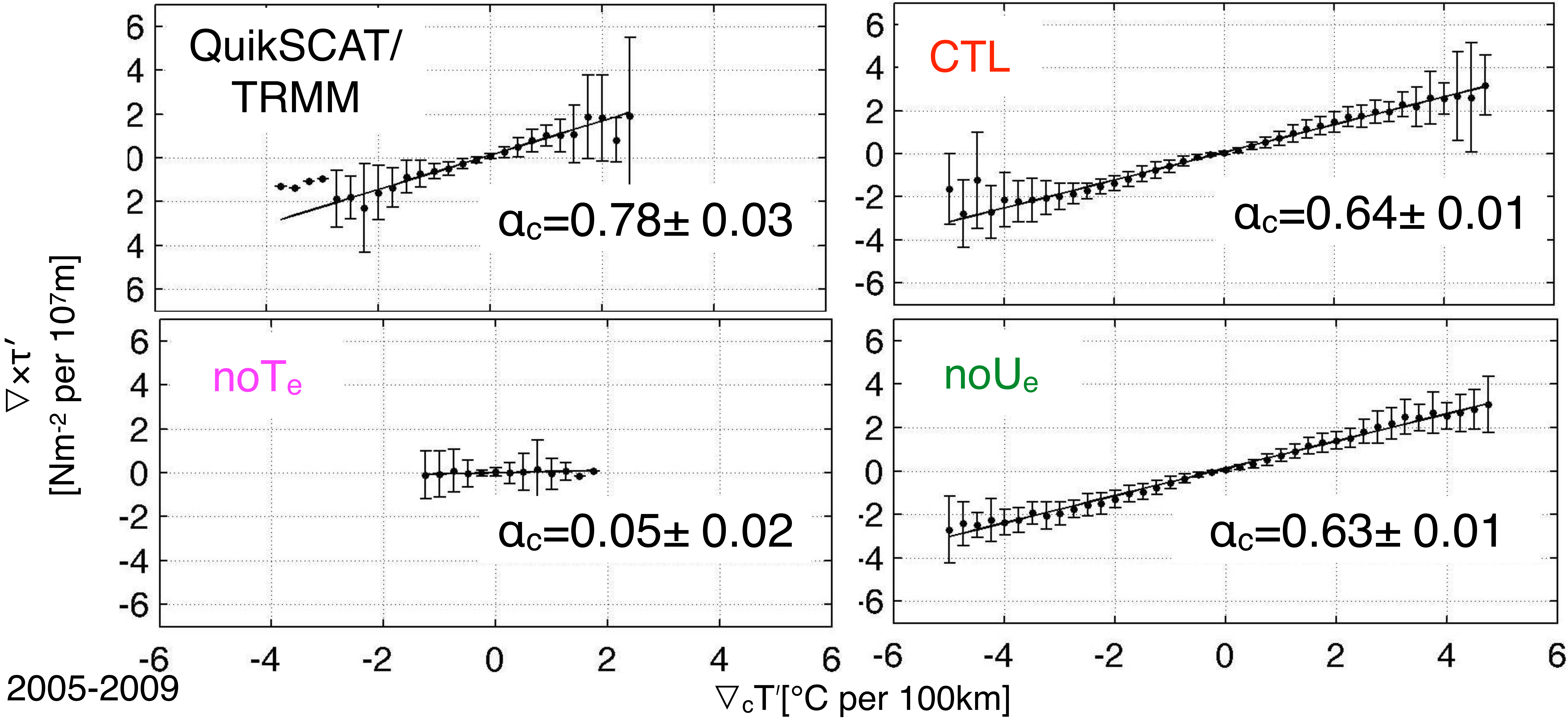
Chelton et al. (2001)





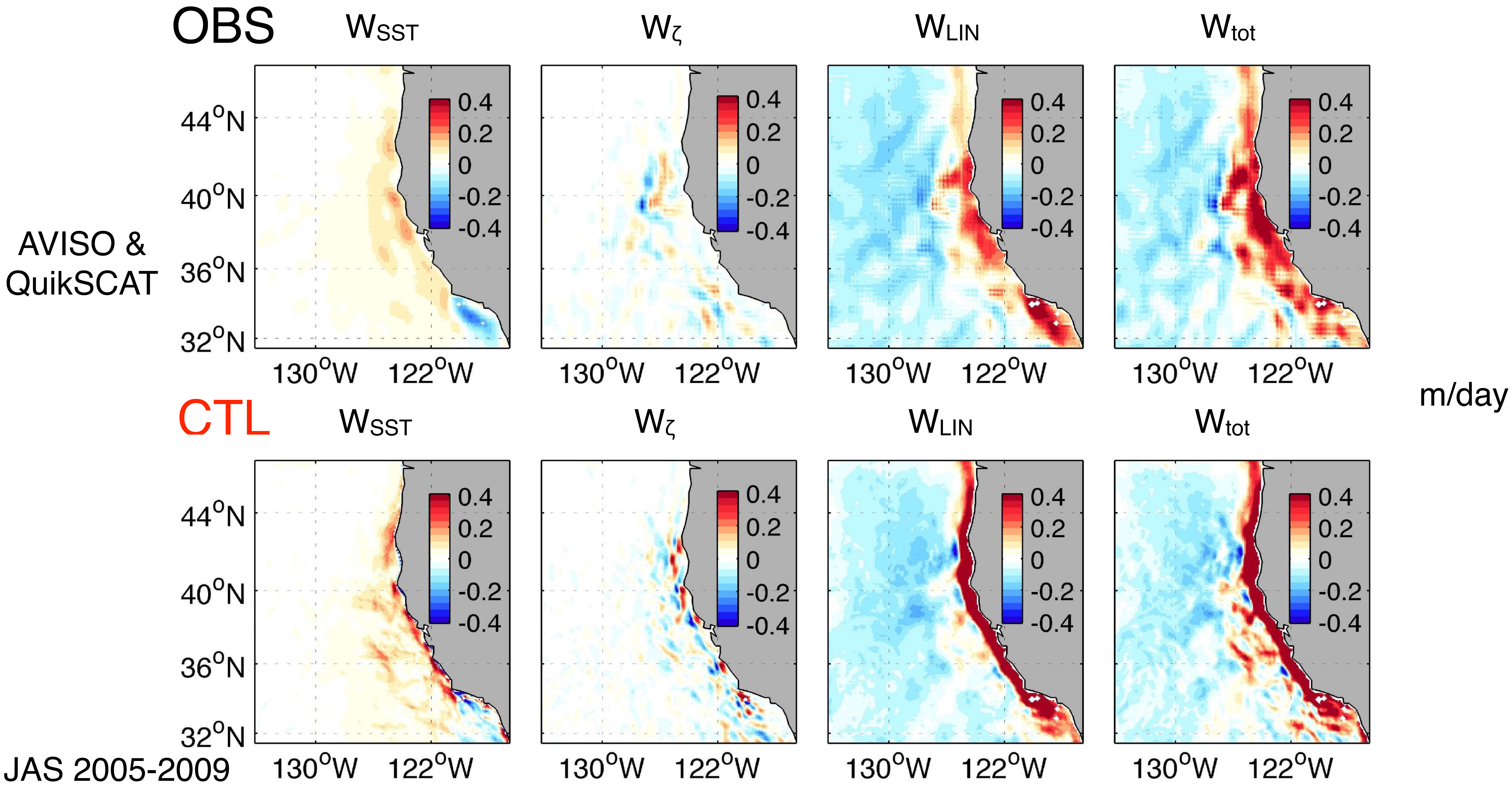
$$W_{SST} = \frac{\nabla \times \tau'_{SST}}{\rho_o (f+\zeta)} \approx \frac{\alpha_c \nabla_c SST}{\rho_o (f+\zeta)}$$

Empirical estimation of SST-driven Ekman vertical velocity

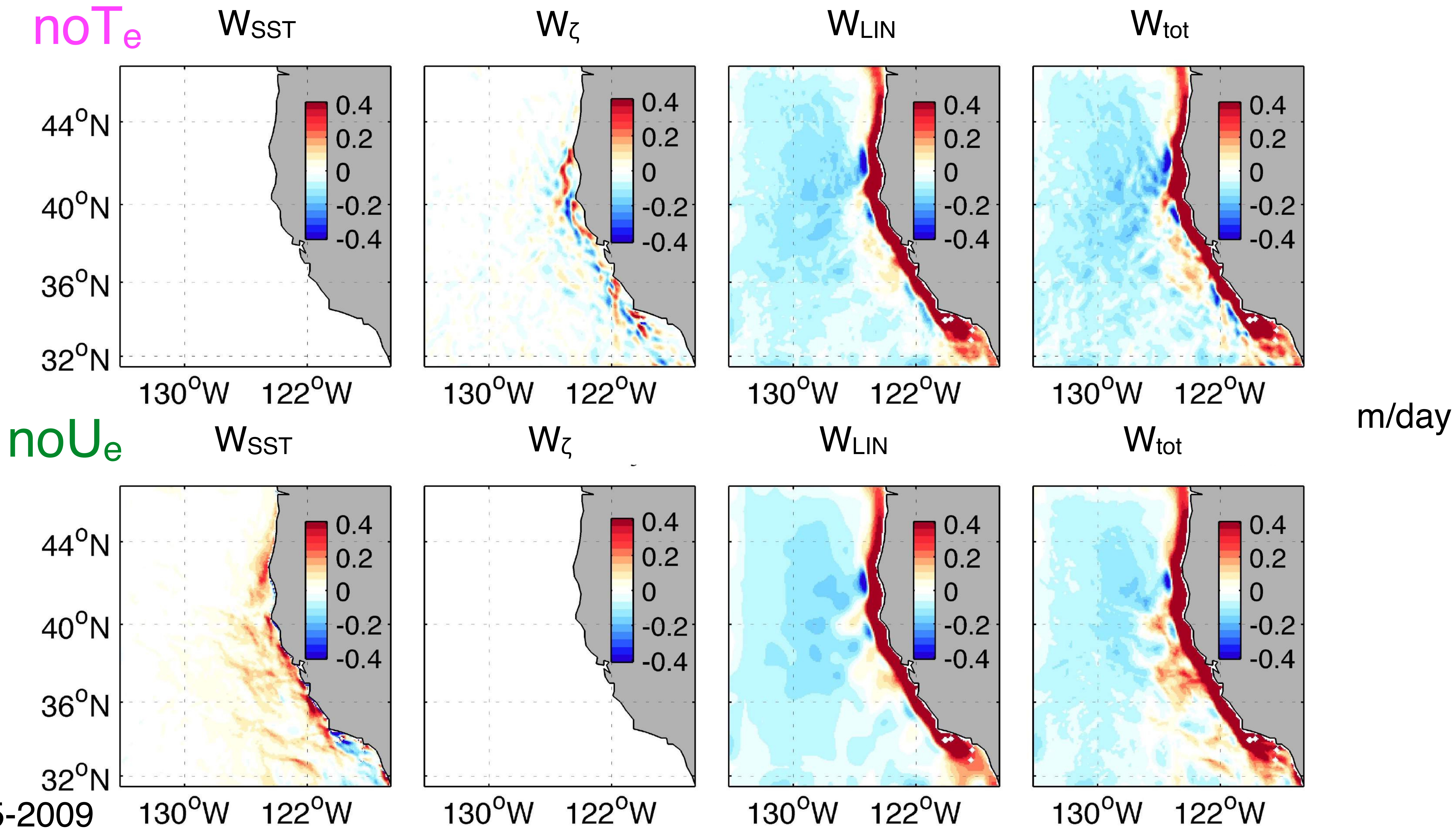


JAS 2005-2009

Estimated Ekman vertical velocities

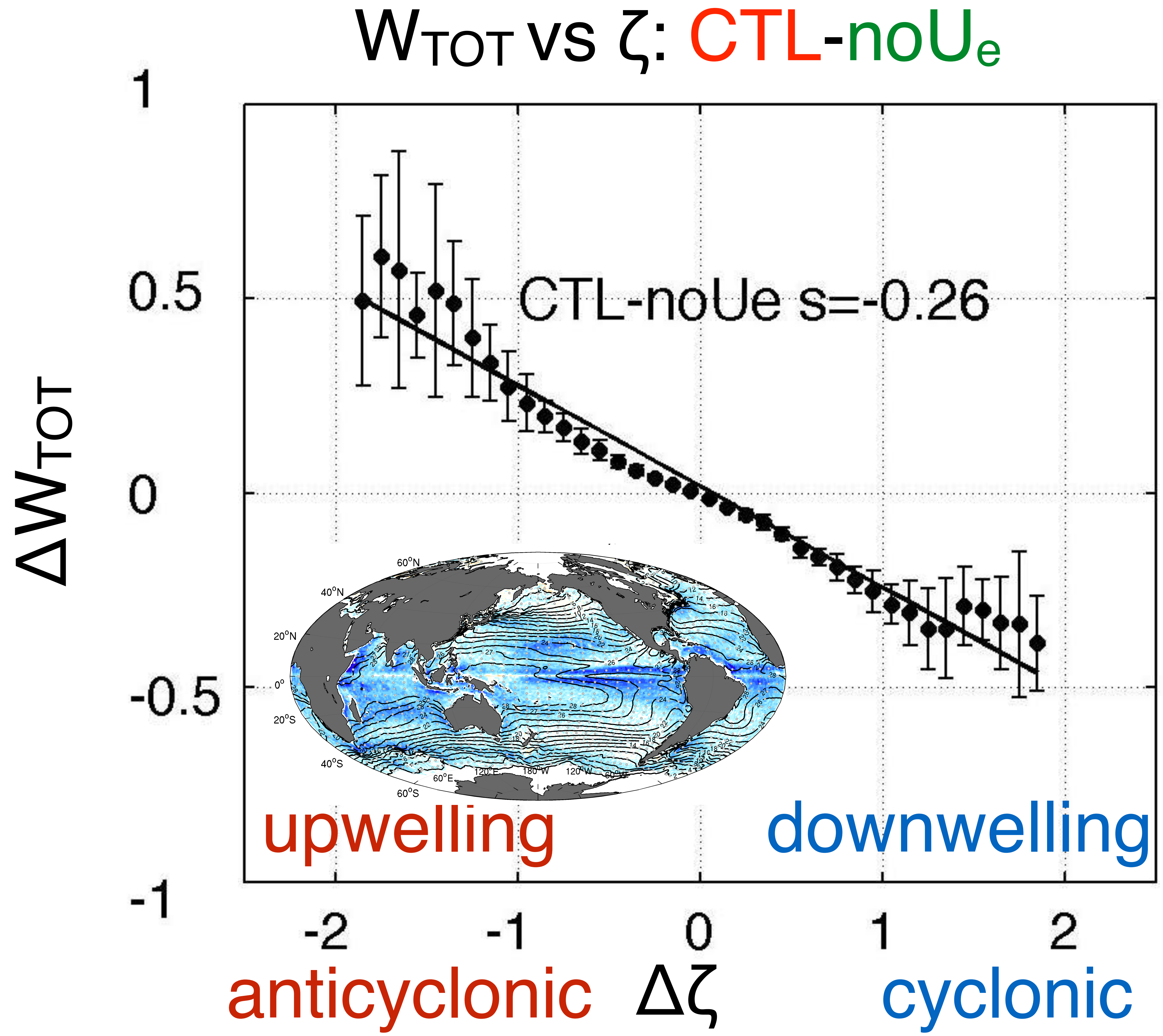


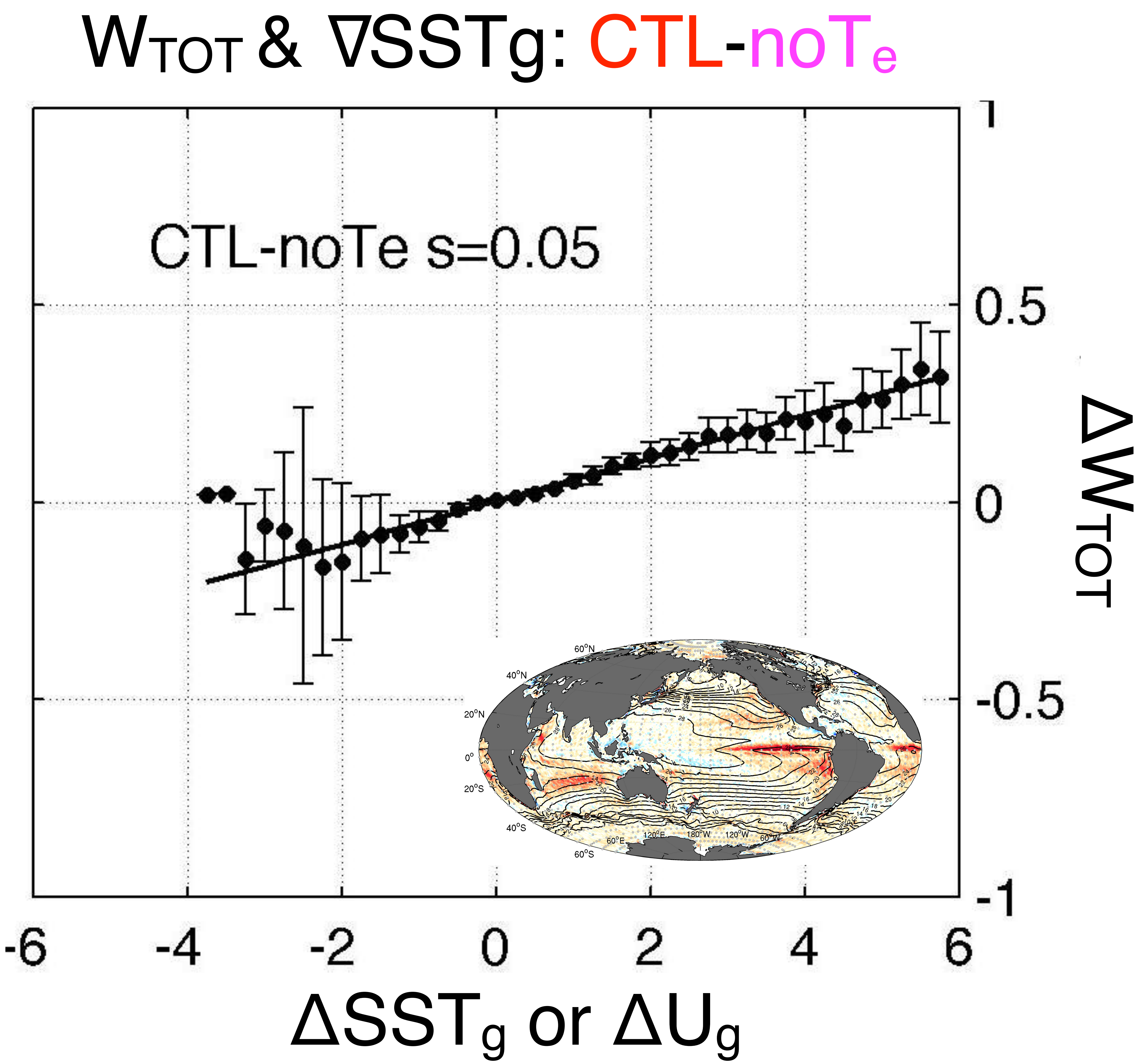
Estimated Ekman vertical velocities



JAS 2005-2009

Feedback effects



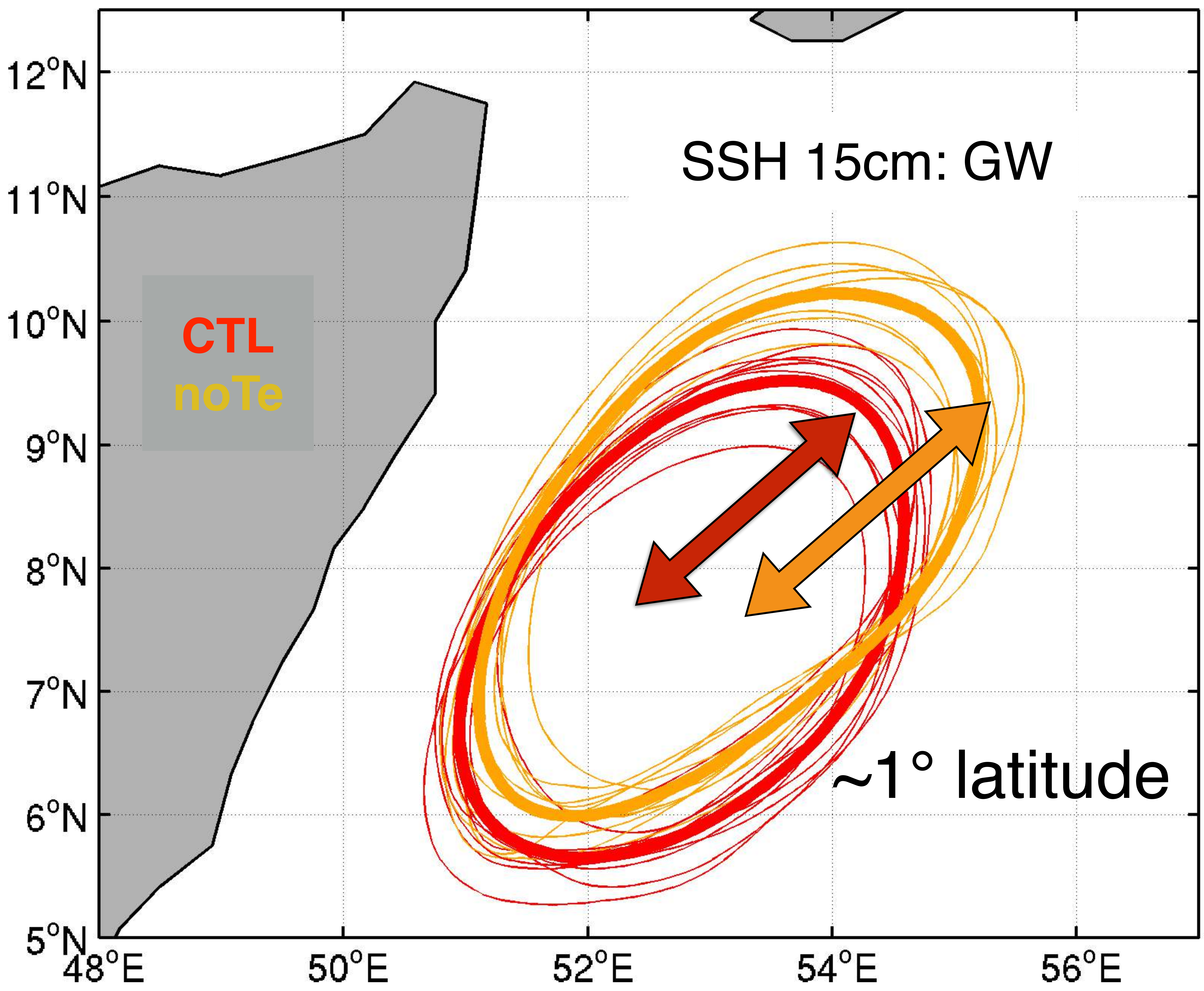


Downwelling over cyclonic anomaly → U_e-τ weakens the amplitude of the eddies

W_e acting on the maximum SST_g → T_e-τ influences the eddy interior U_g

Confirming two distinct influences of air-sea coupling:

2001-2010 JJAS climatology



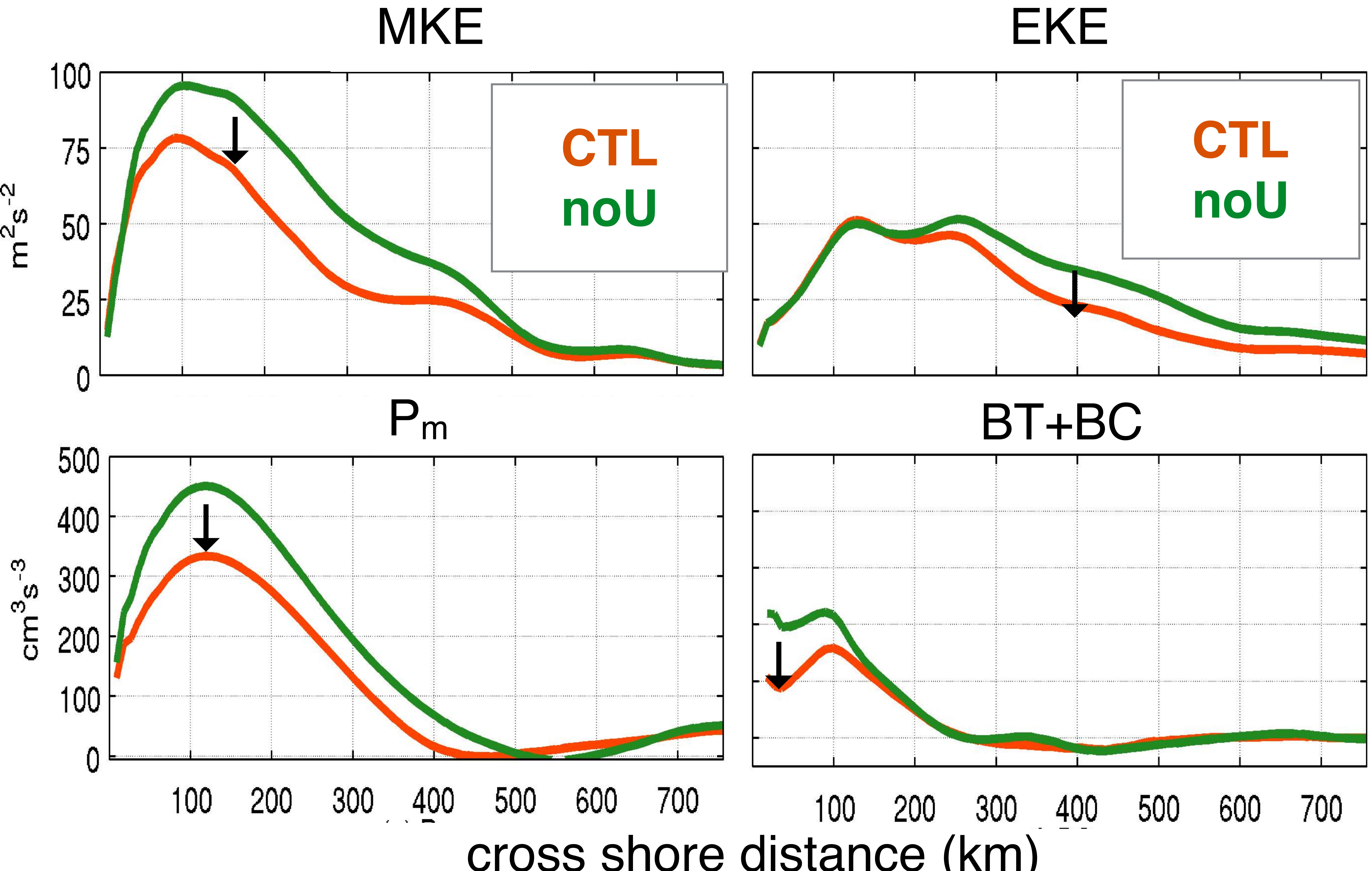
T_e-τ influences the position of the Great Whirl (GW)

About 1° downstream shifts of the GW when T_e-τ is suppressed

Seo 2017 JCLI

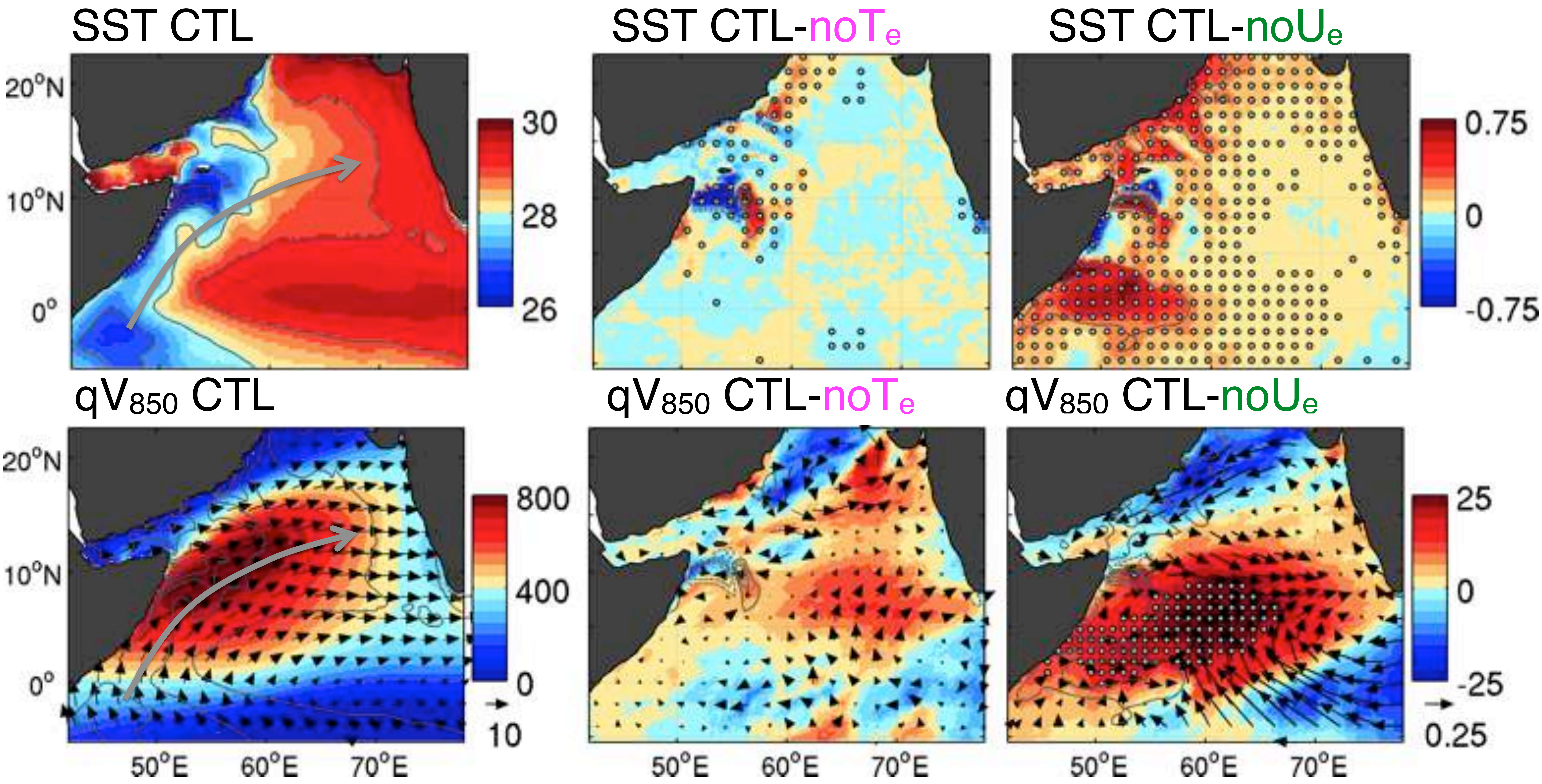
U-τ coupling influences the amplitude but not the position

Alongshore profiles of energy input and conversions



- Reduced MKE by 35% due to reduced P_m
- Weakened EKE due to reduced BT/BC

Some downstream influence in the Arabian Sea



- Small (~5%) but significant changes in the axis of the FJ and the moisture transport

Summary and Discussion

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

- T_e-τ coupling affects the position of eddy fields through Ekman pumping
  → E.g., Great Whirl is shifted by ~1° downstream.
- U_e-τ coupling attenuates the kinetic energy
  → by reducing wind work and increasing eddy-drag.
  → Negative correlation between W_ζ and the relative vorticity of the eddy
- Some evidence of downstream atmospheric response
 → Air–sea interaction study should consider both the thermal and mechanical coupling effects

Comments, questions?

hseo@whoi.edu

Thanks!