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

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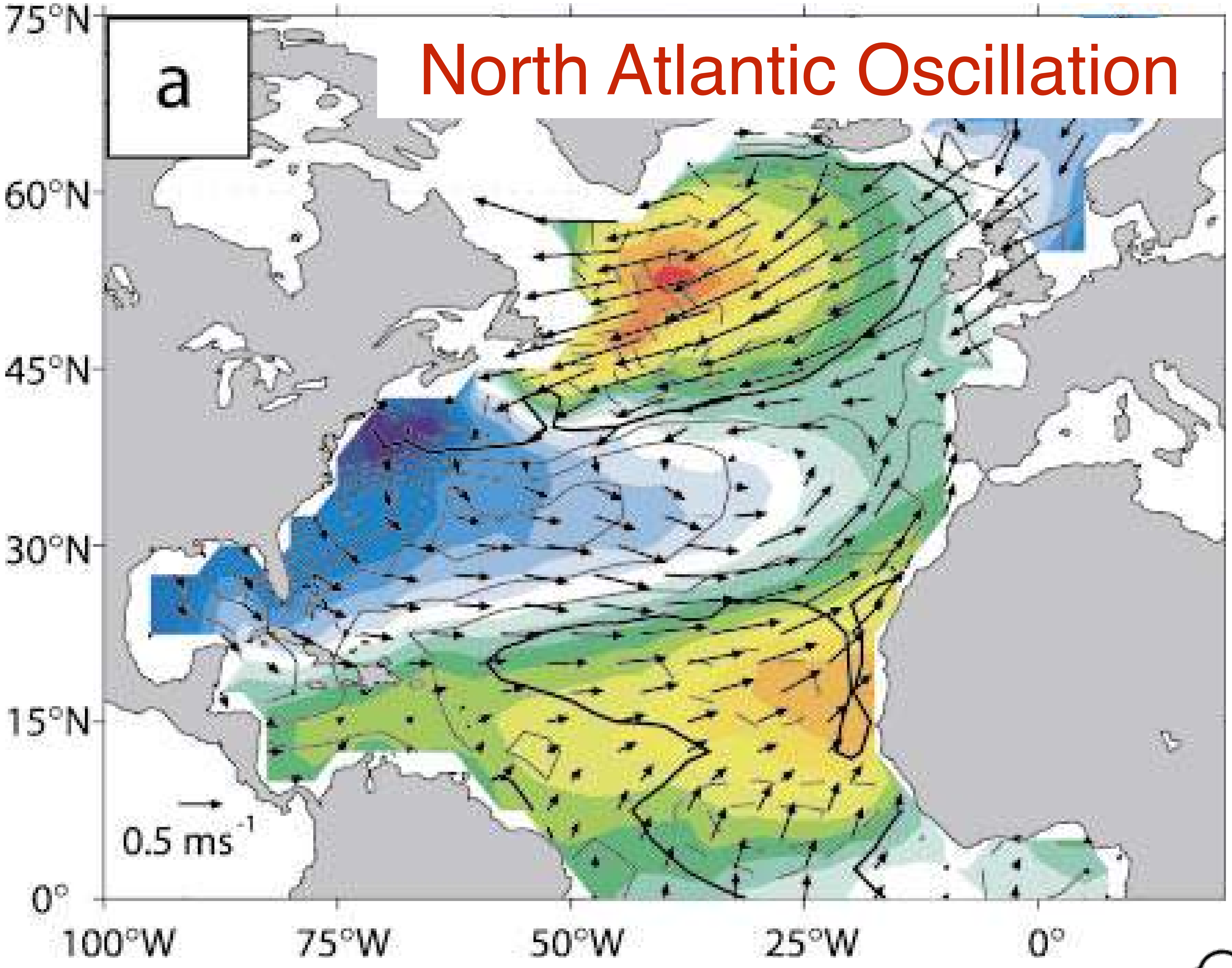
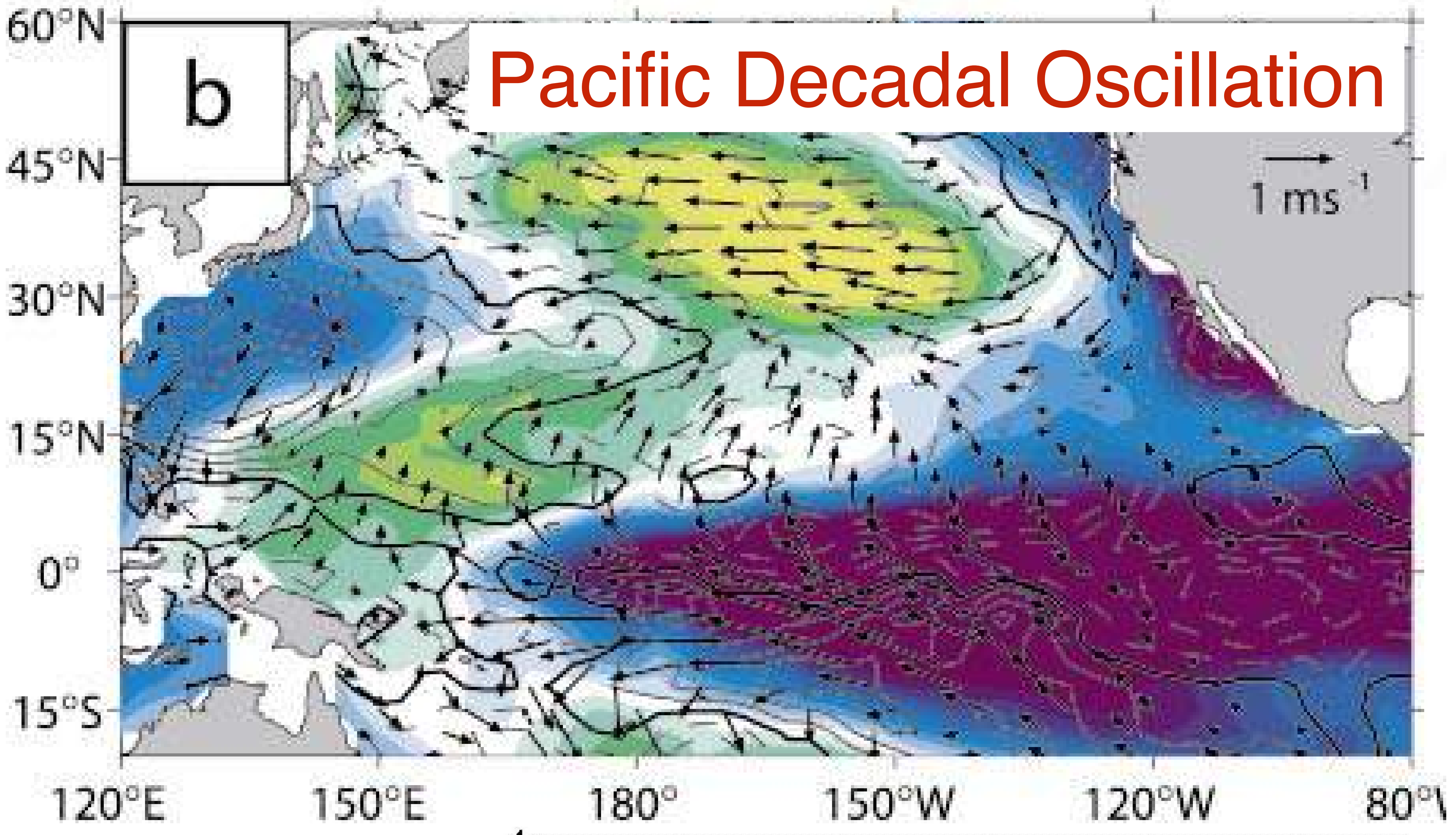
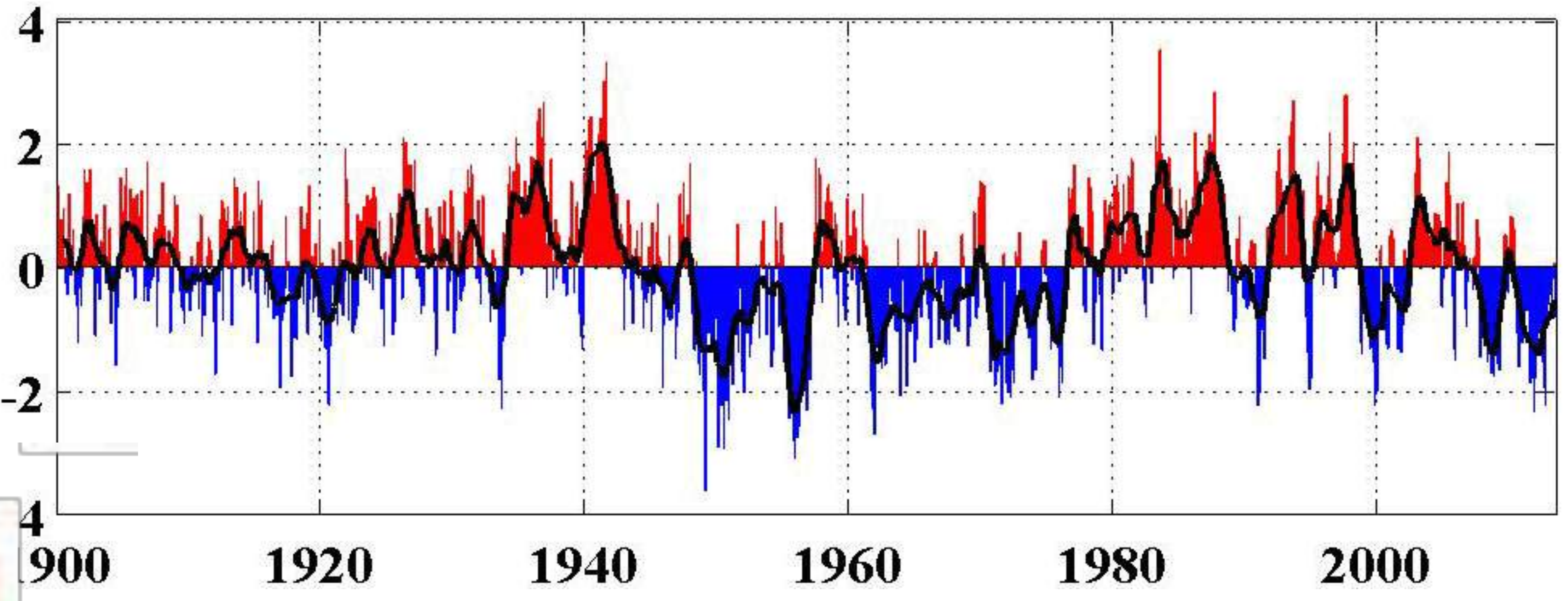
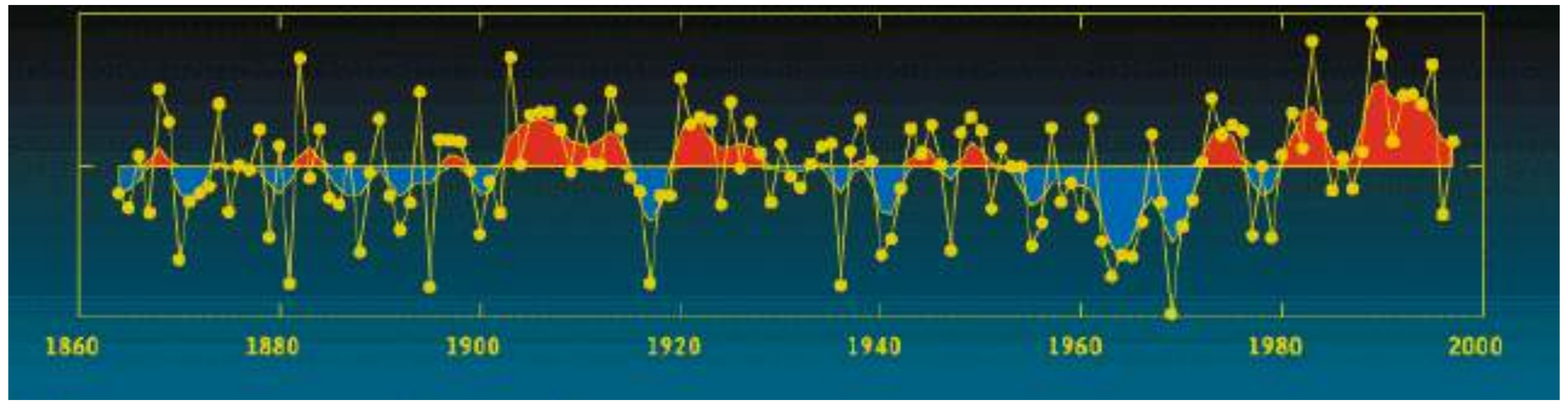
SeaWiFS surface chlorophyll concentration

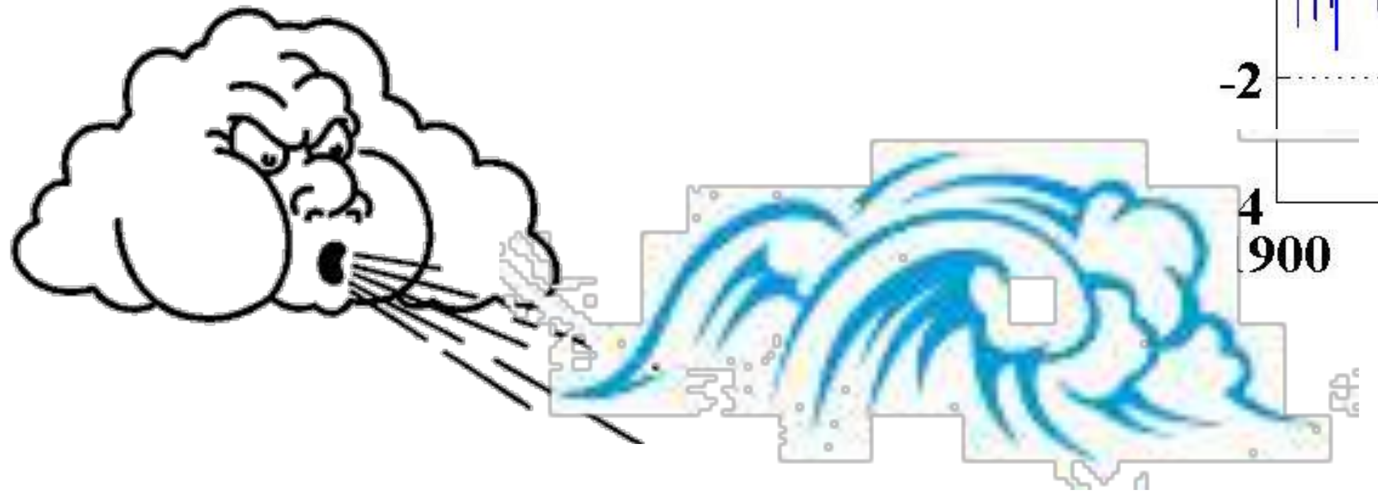
Large-scale air-sea interactions:
Winds over a slab ocean without dynamic eddies/fronts





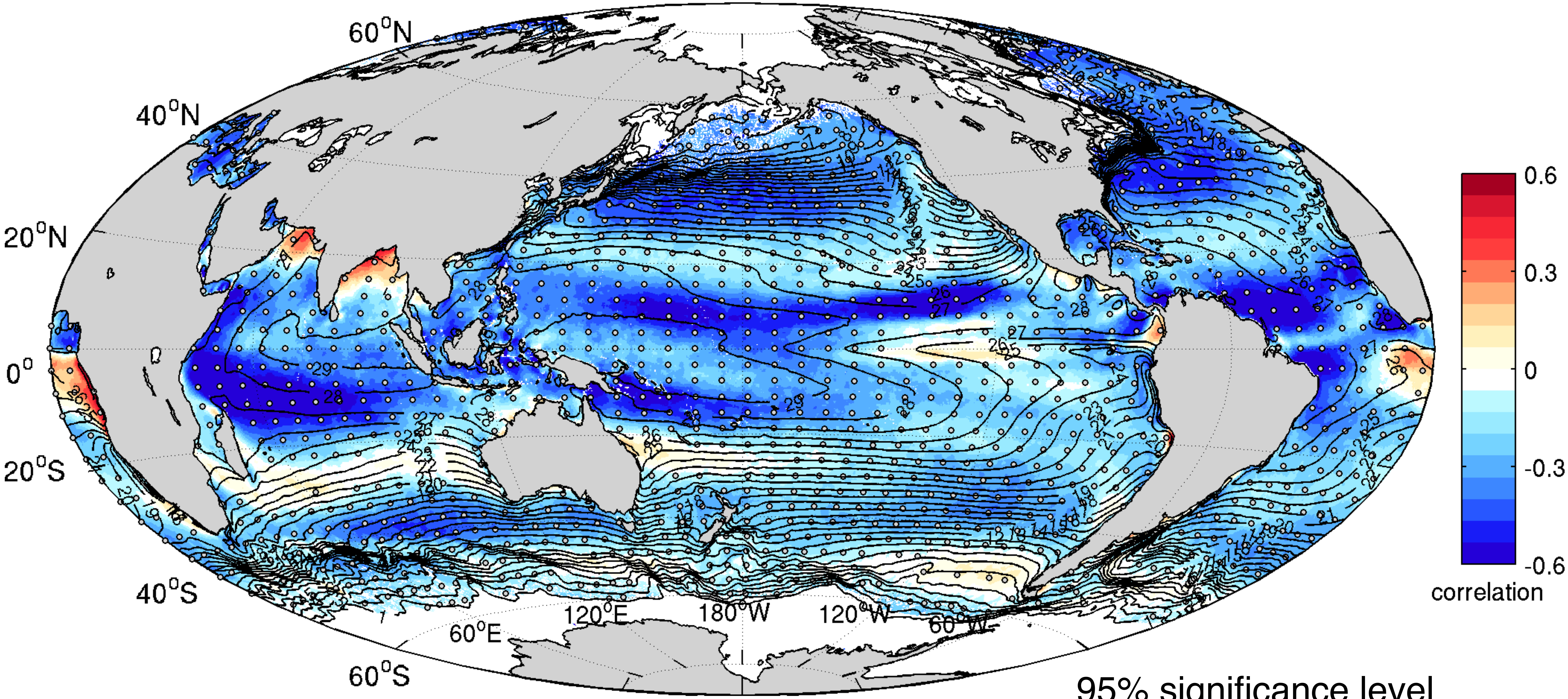






Kushnir et al. 2002

Air-sea interaction with no dynamic role of ocean eddies/fronts — 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

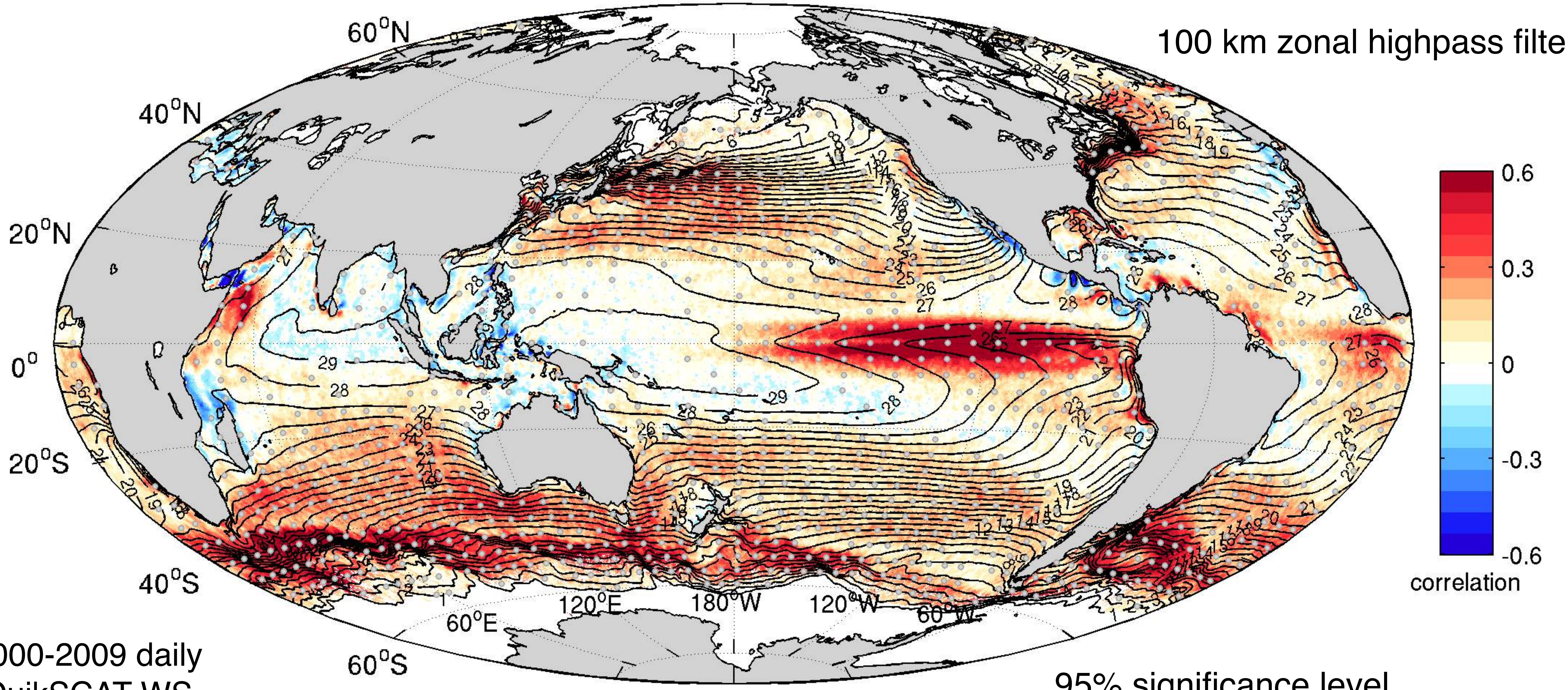
However, the oceans are filled with energetic eddies and fronts

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



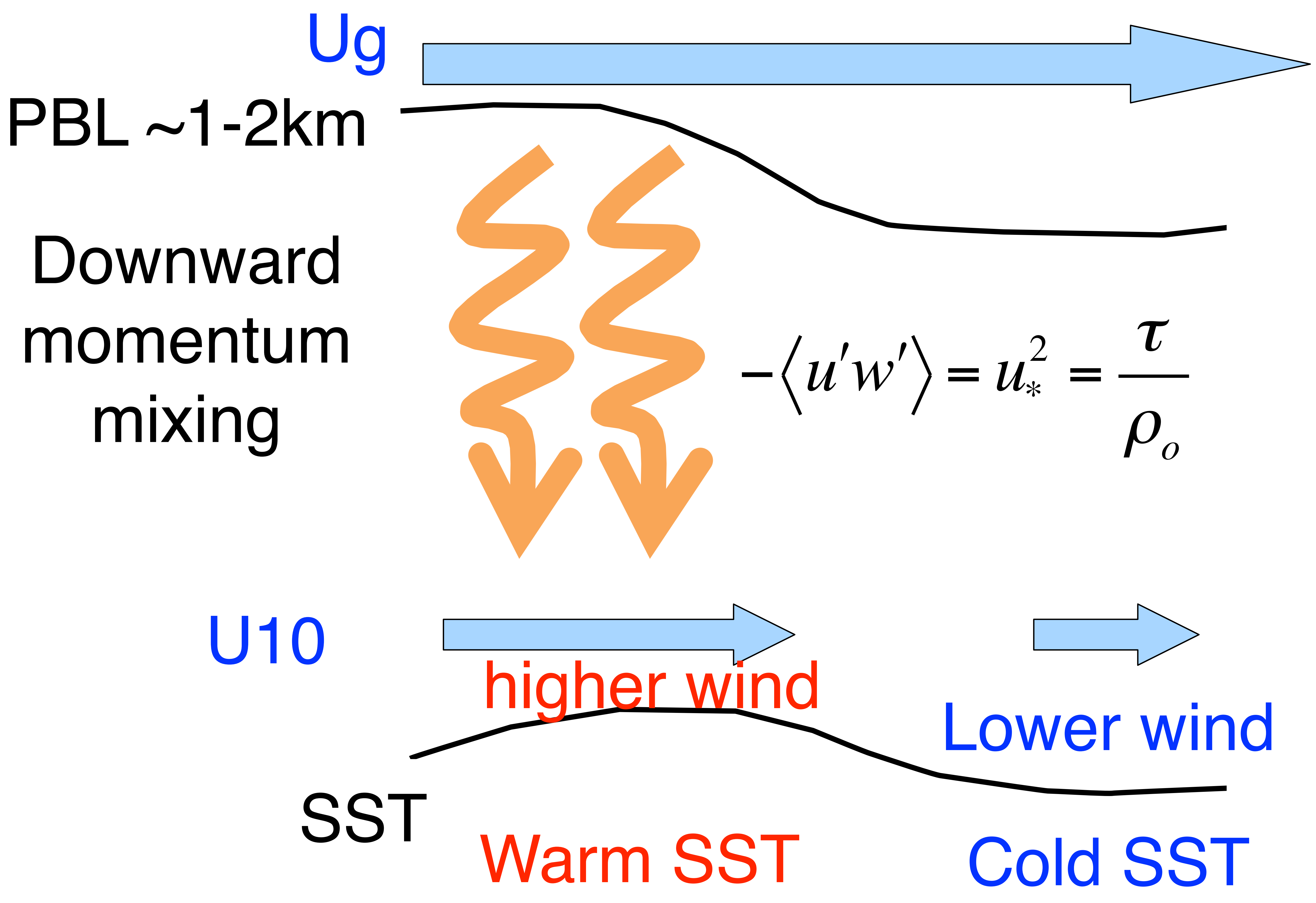
2000-2009 daily
QuikSCAT WS
NOAA-OI SST

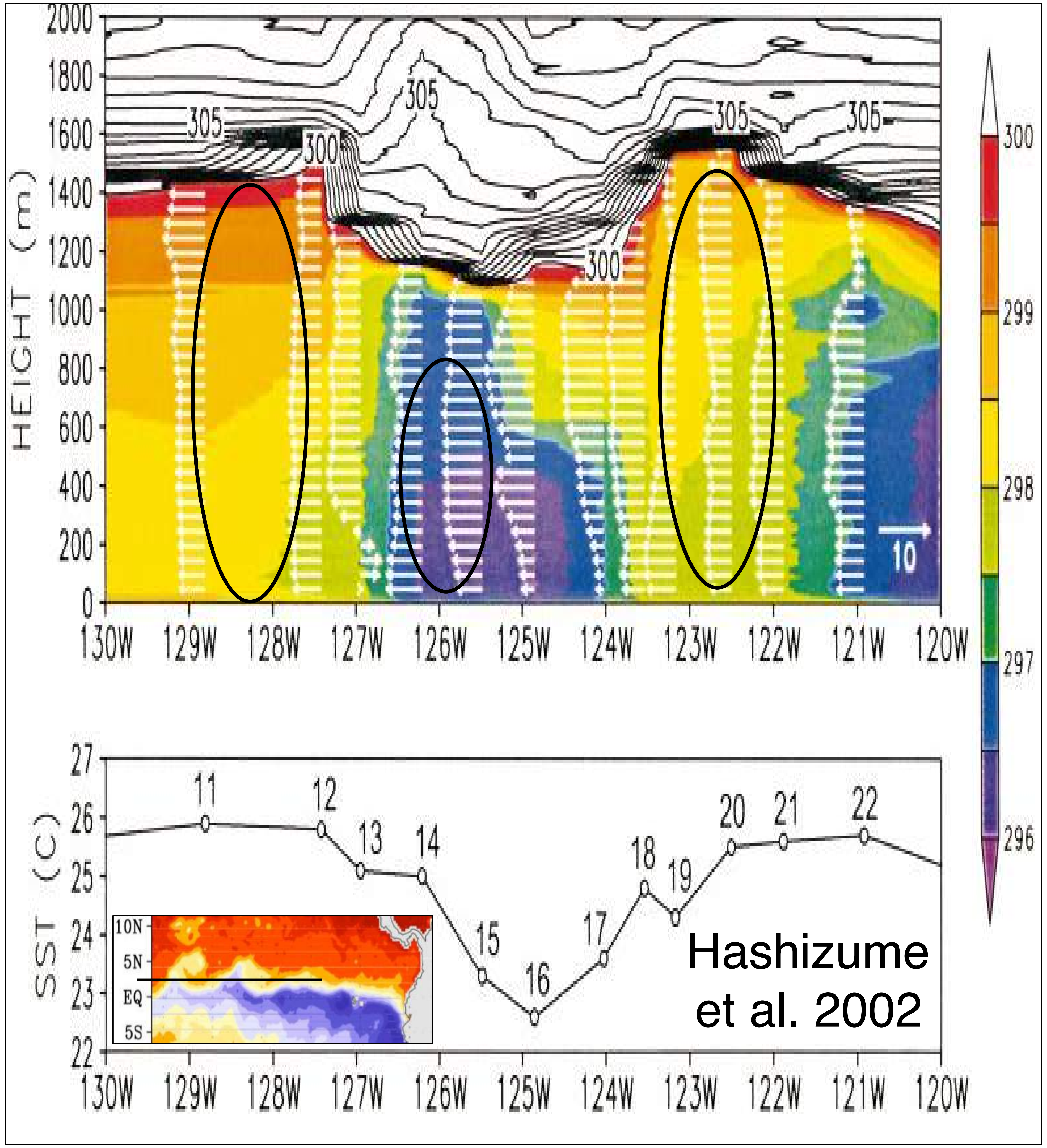
95% significance level

Oceanic forcing of the atmosphere on frontal and mesoscales.

Seo 2017

Mesoscale SST alters the vertical mixing in the ABL





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

How important is this mesoscale air-sea coupling on the ocean? Let's look at the wind stress

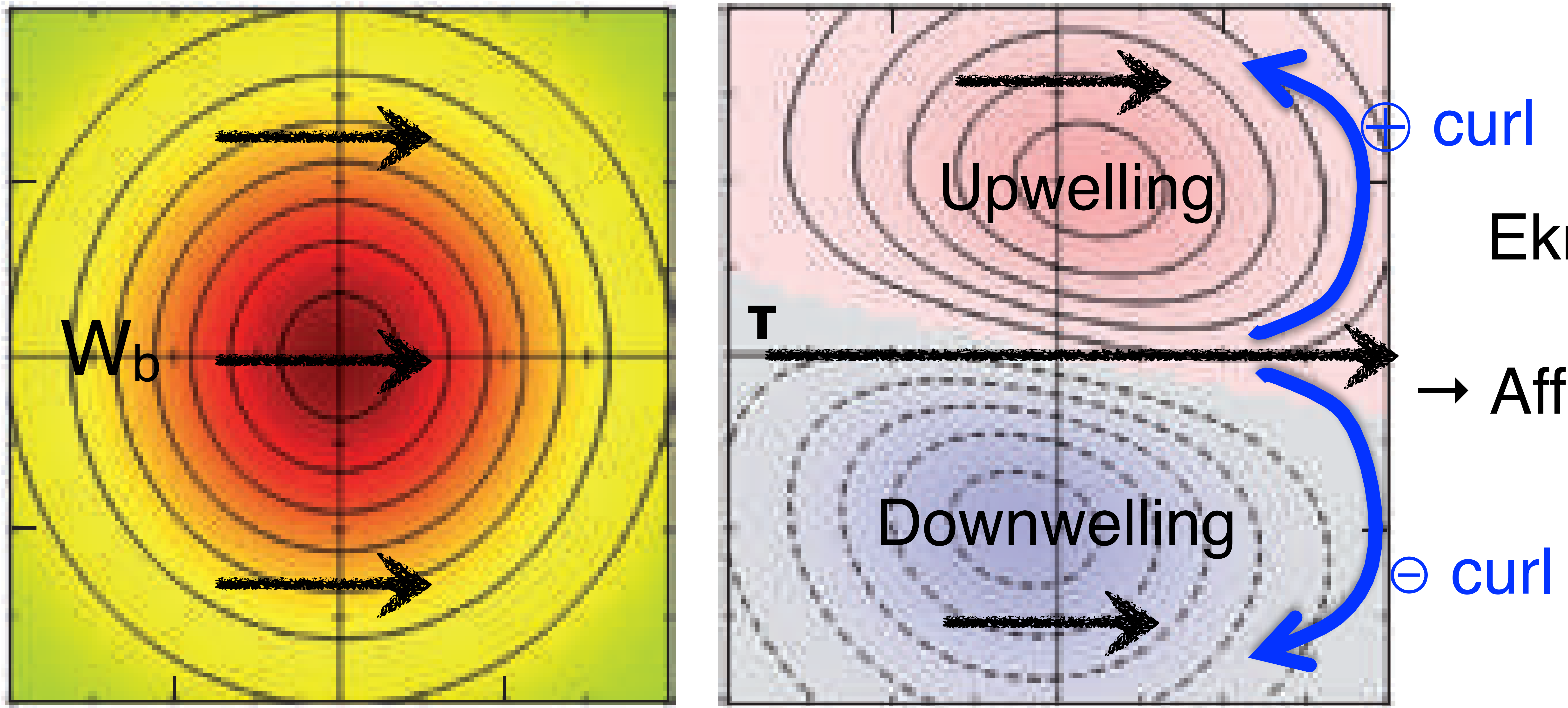
$$\tau = \rho_a C_D (\underline{W} - \underline{U}) |\underline{W} - \underline{U}|$$

$\underline{U}$: 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 T_e-driven wind stress curl or W_e



Ekman pumping anomaly in quadrature with SSH

→ Affect the position (southward)

Distinct influences of air-sea interaction

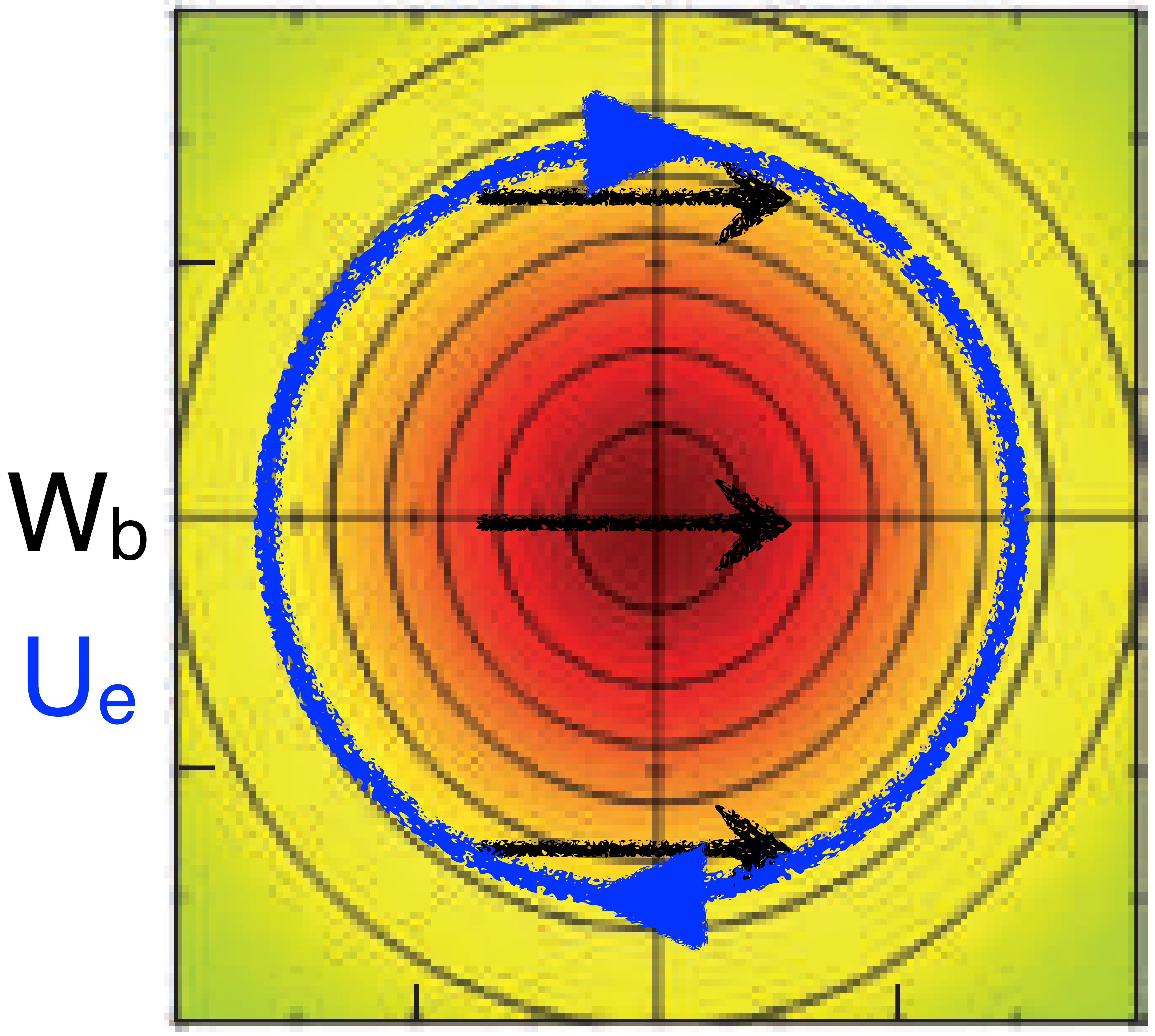
due to eddy SST vs surface current

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

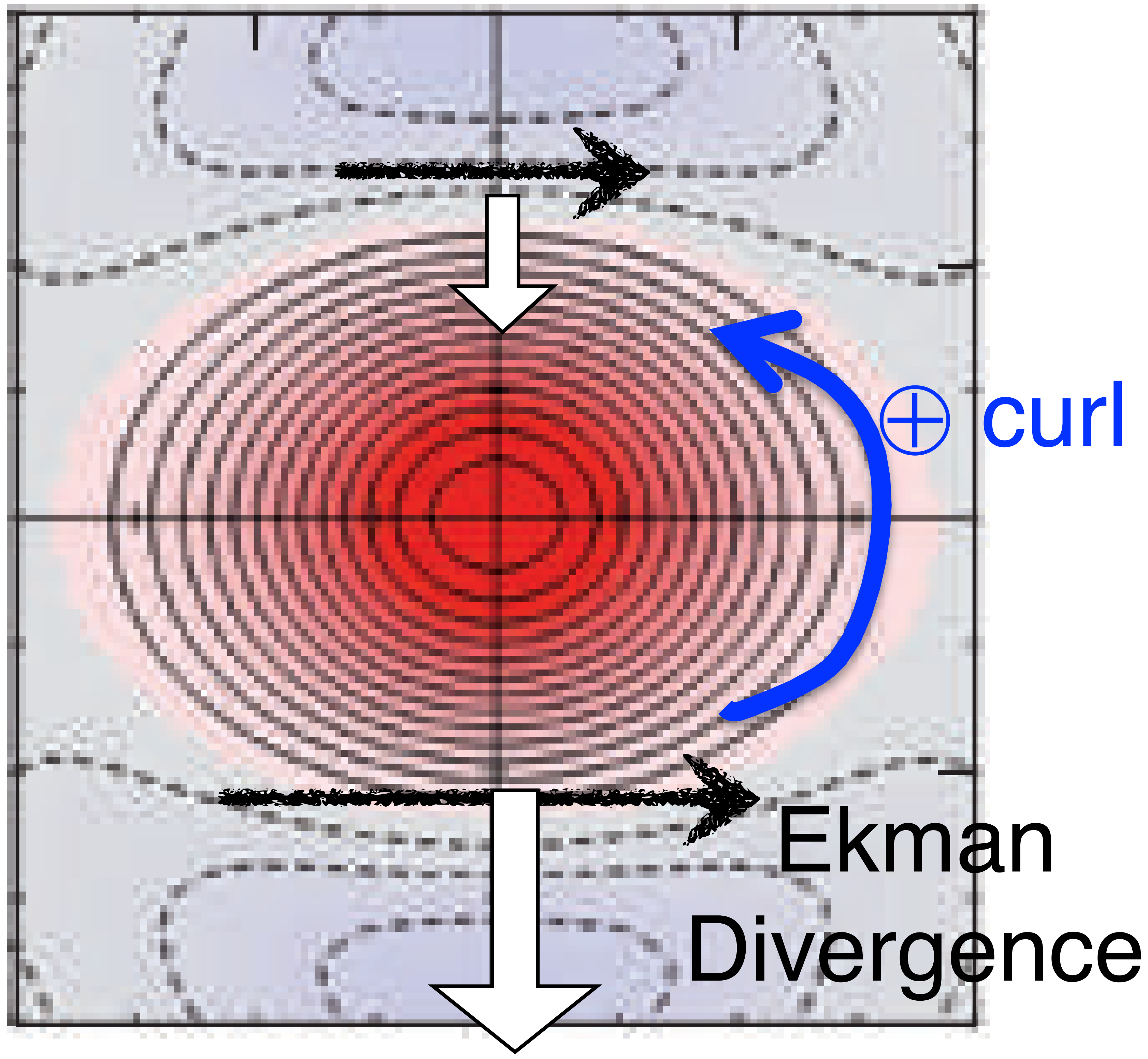
$\underline{U}$: surface current vector $\quad \underline{U} = \underline{U_b} + \underline{U_e}$

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

SST and SSH



U_e-driven wind stress curl or W_e



cyclonic wind stress curl over anticyclonic eddy

→ Attenuate the eddy amplitude

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

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

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

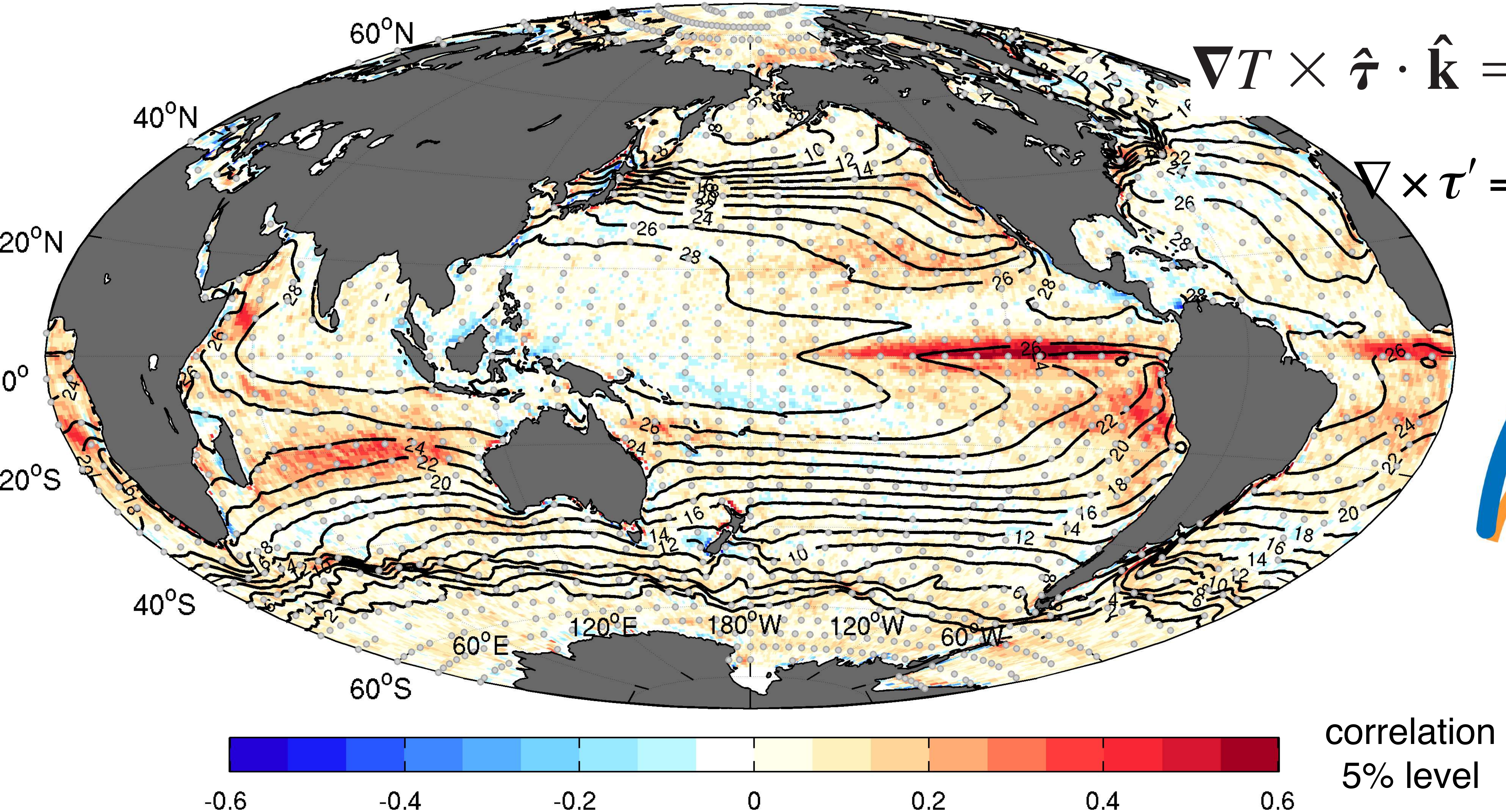
Positive correlation bet'n wind stress curl and SST gradient

Negative correlation bet'n wind stress curl and surface vorticity

Wind stress curl associated with mesoscale SST gradients

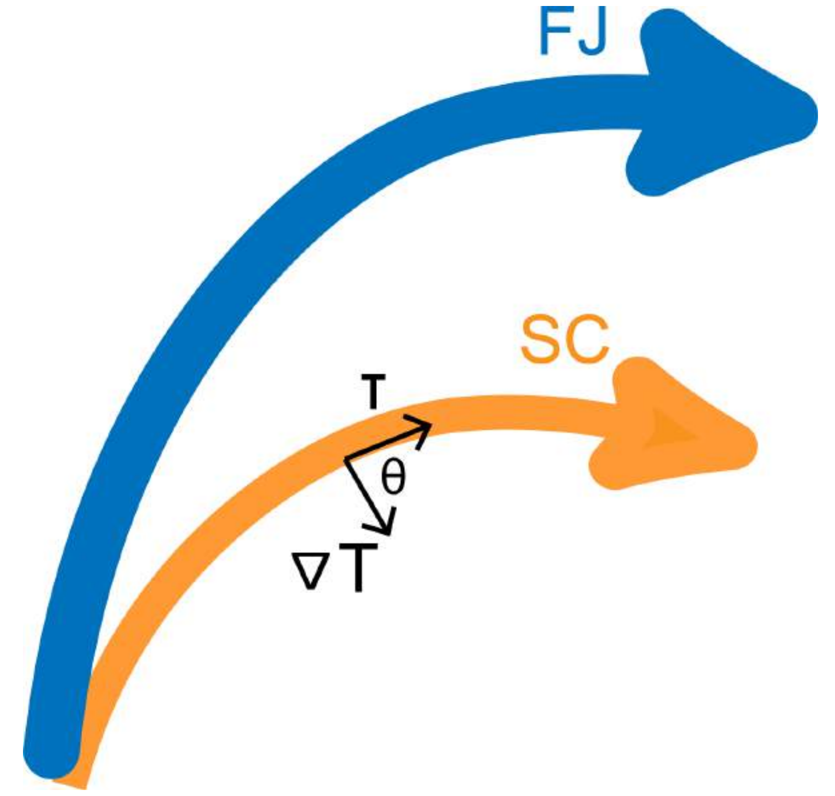
Correlation bet’n wind stress curl and crosswind SST gradient

1993-2015, JJAS



$$\nabla T \times \hat{\boldsymbol{\tau}} \cdot \hat{\mathbf{k}} = |\nabla T| \sin\theta$$

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



Imprints of surface vorticity in wind stress curl

—Correlation between wind stress curl and surface vorticity

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

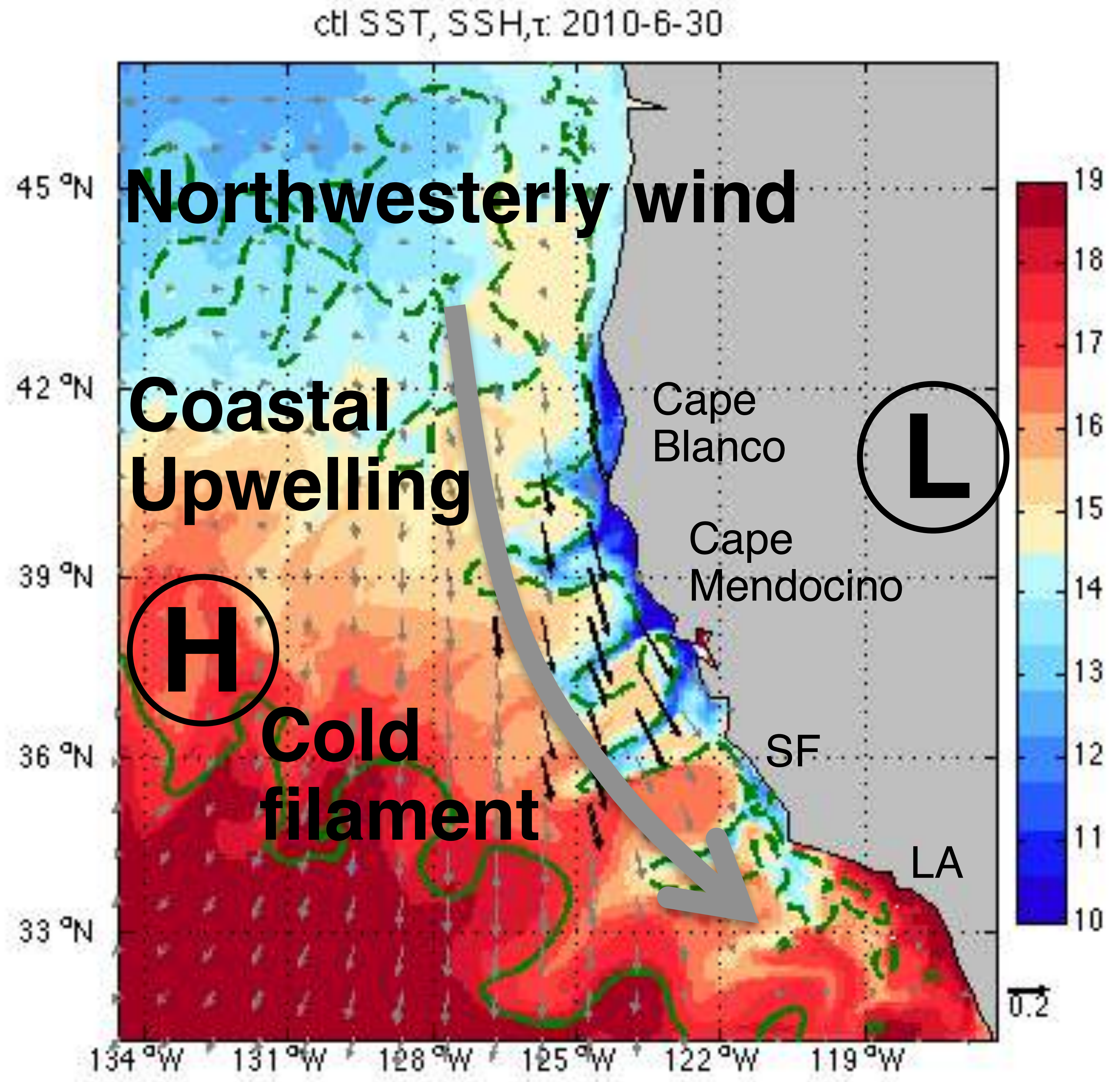
correlation
5% level

Objective

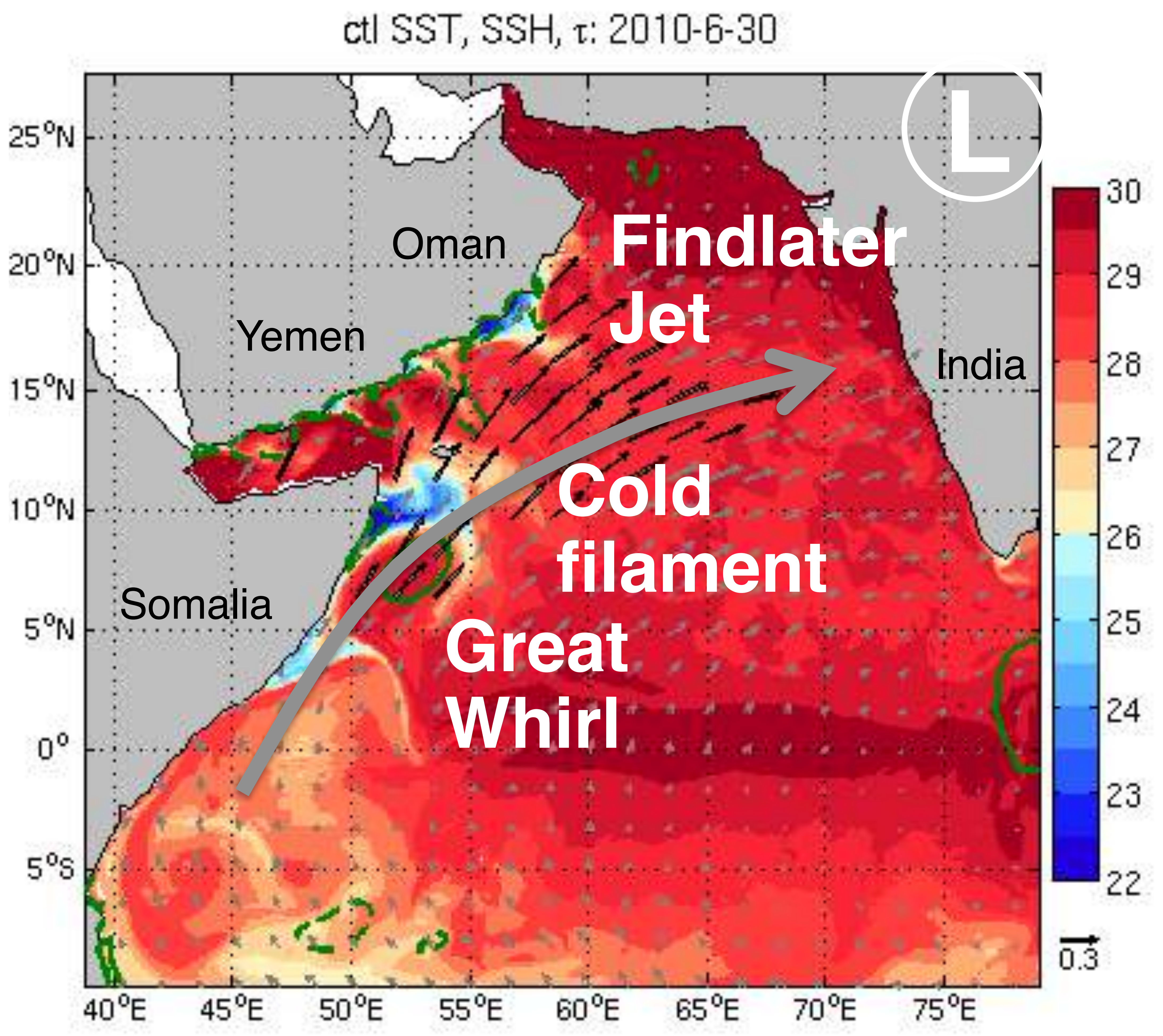
Can we quantify the effects of the two distinctive feedback process?

Let’s look at two summertime boundary current systems:
California Current System & Somali Current System

California Current System

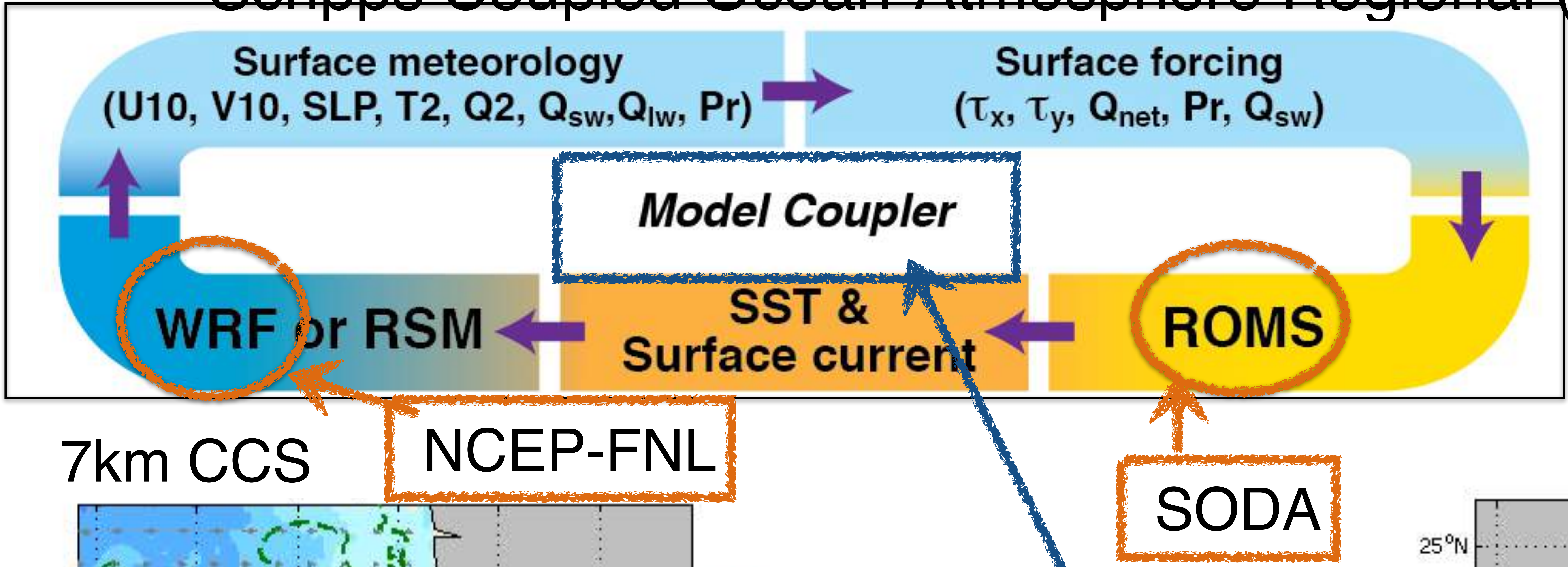


Somali Current System



EBC of the North Pacific	WBC of the Indian Ocean
Forcing: Summertime 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

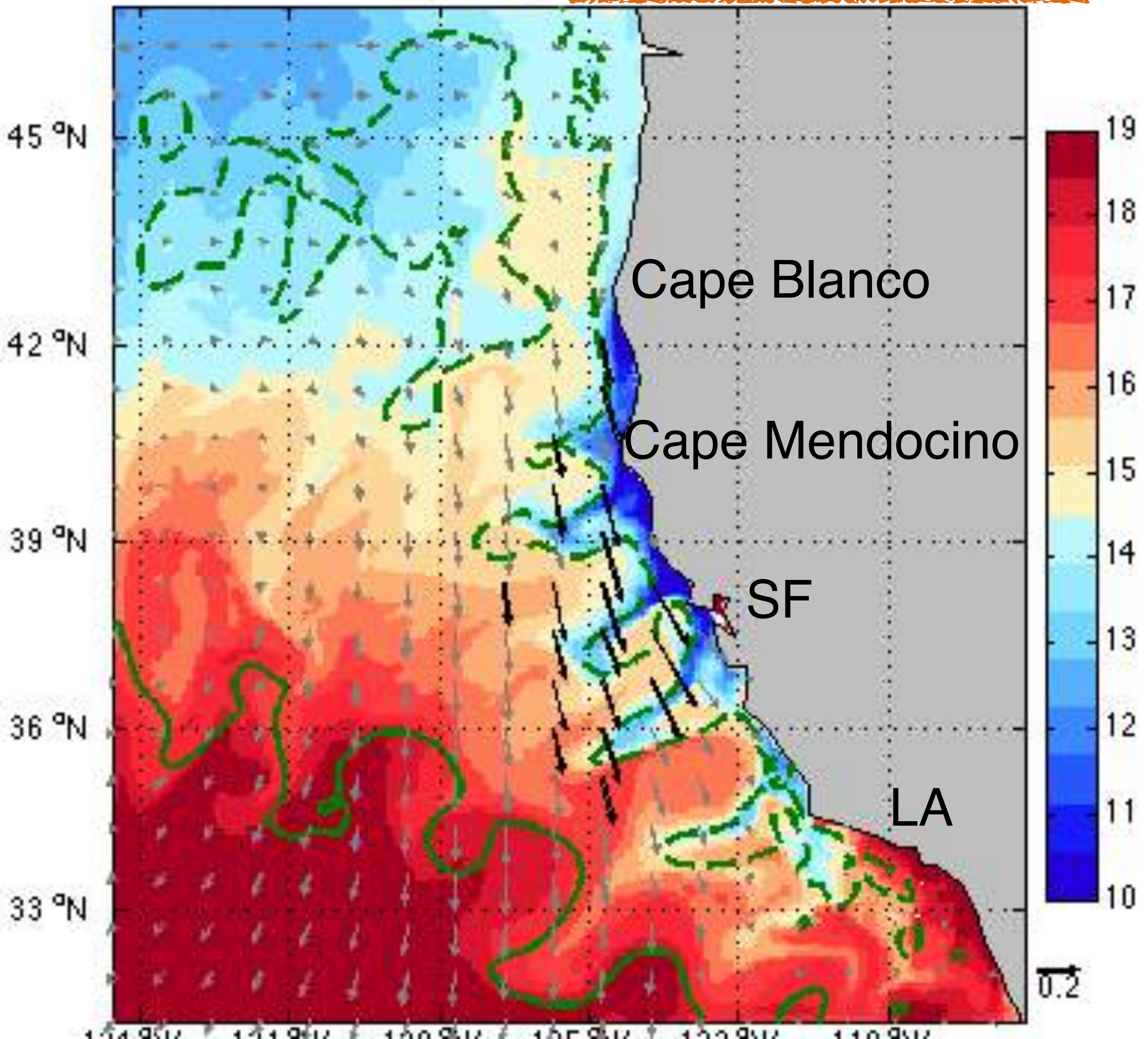


http://hseo.whoi.edu/scoar/

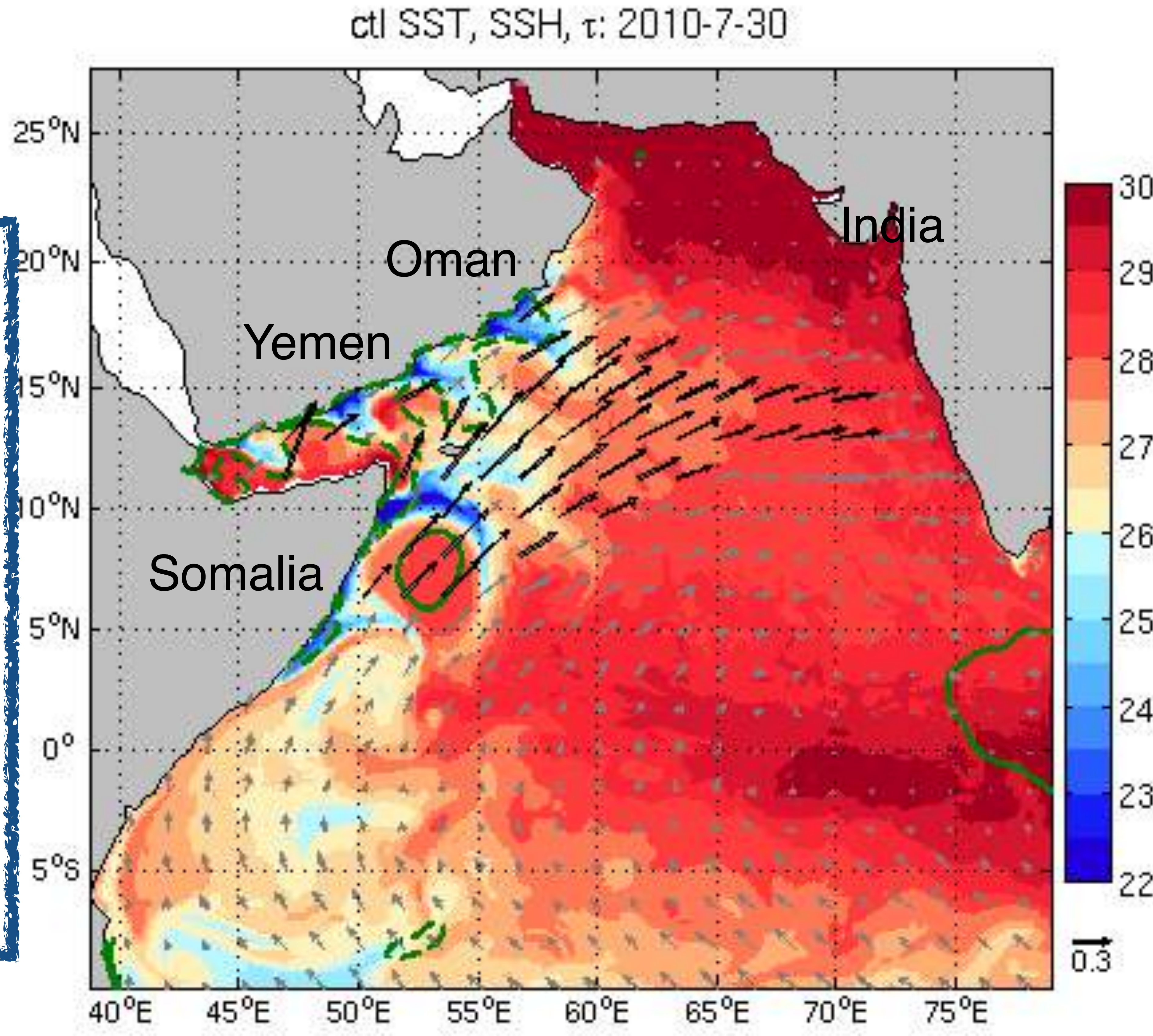
Seo et al. (2007; 2014; 2016, JCLI)

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

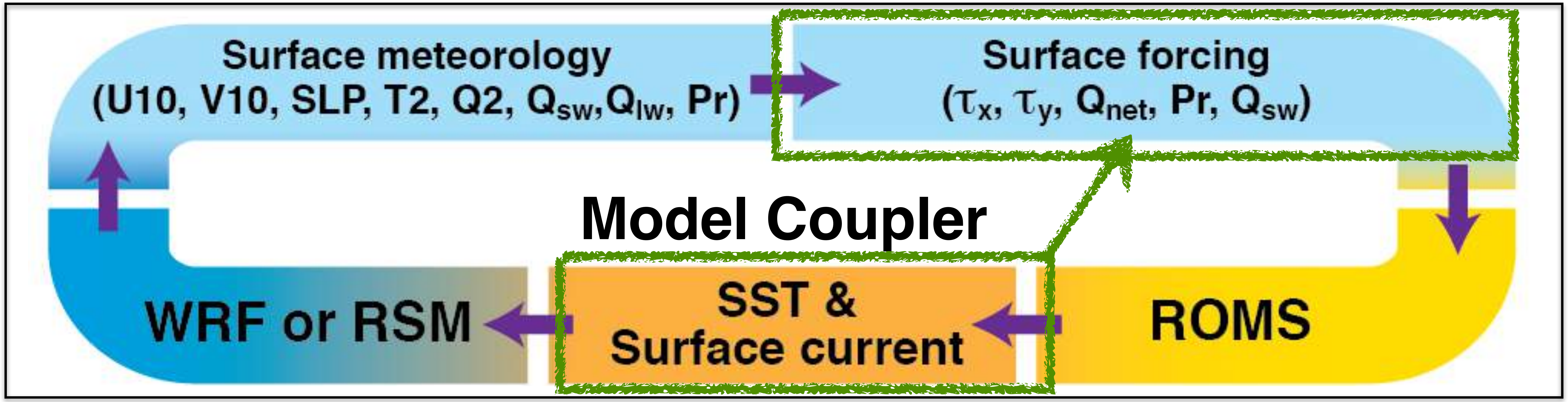
7km CCS



9km AS



Scripps Coupled Ocean-Atmosphere Regional (SCOAR) Model

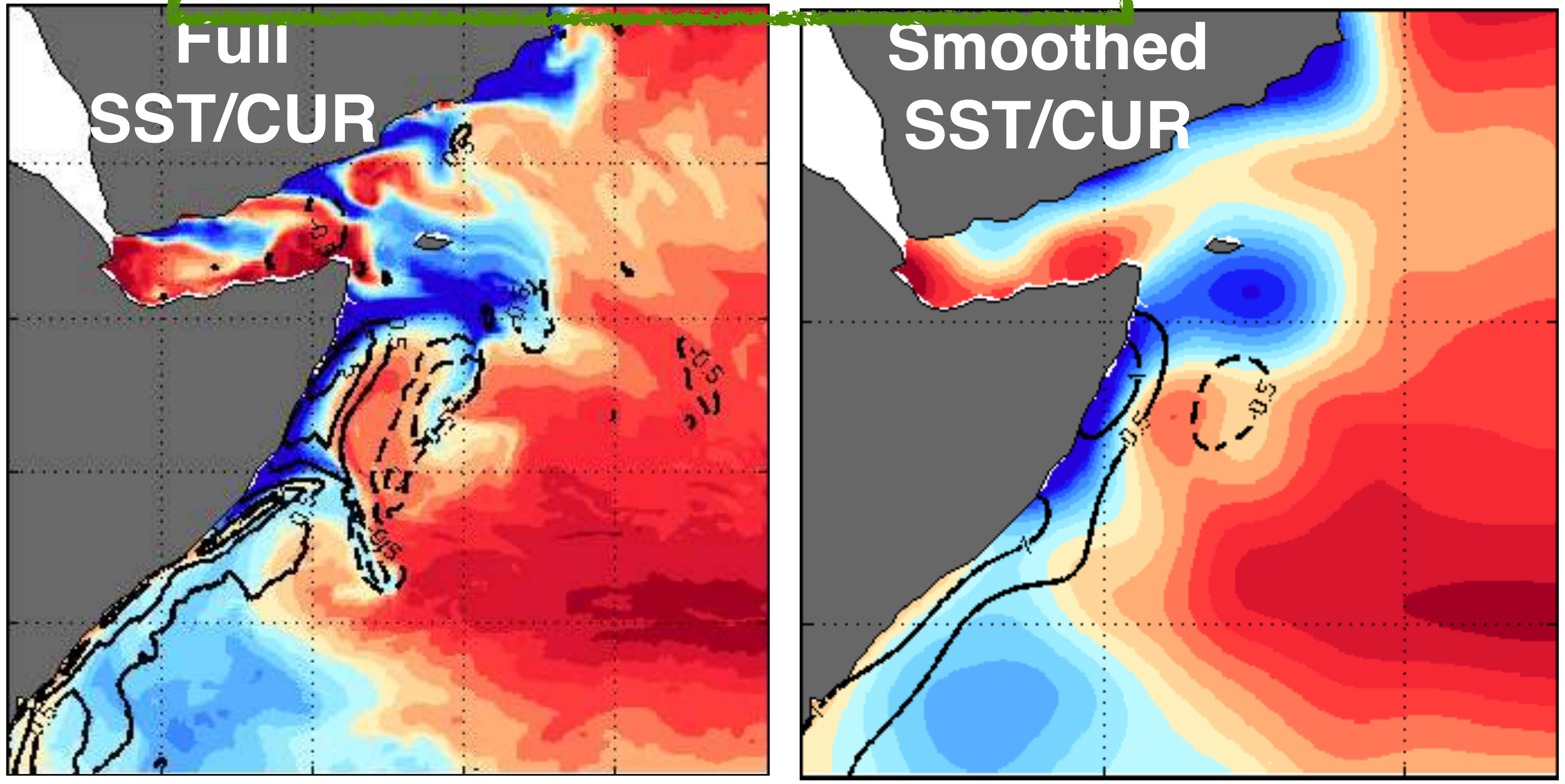


http://hseo.whoi.edu/scoar/

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

Online 2-D Loess smoothing (~3°×3°)

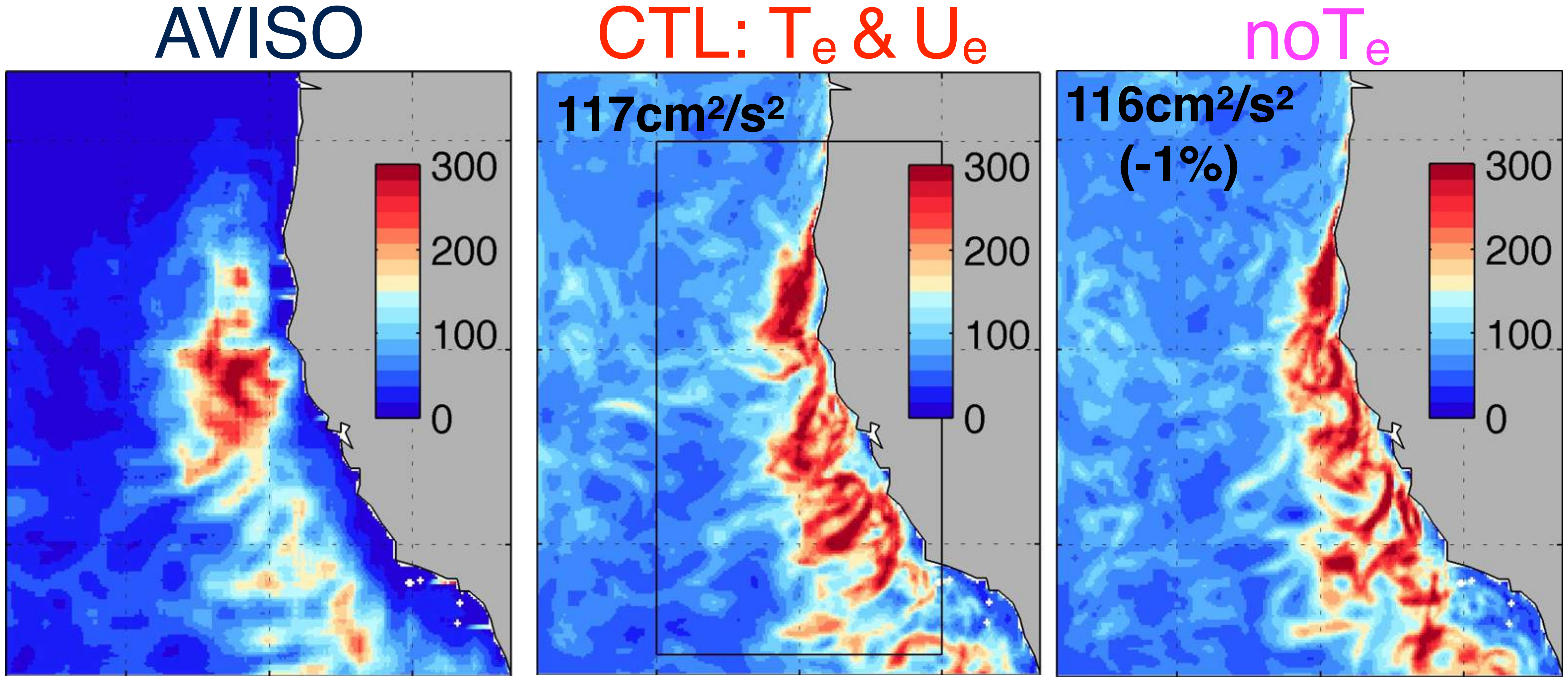
Separation of spatial-scale of air-sea coupling
Putrasahan et al. (2013); Seo et al. (2016); Seo (2017)

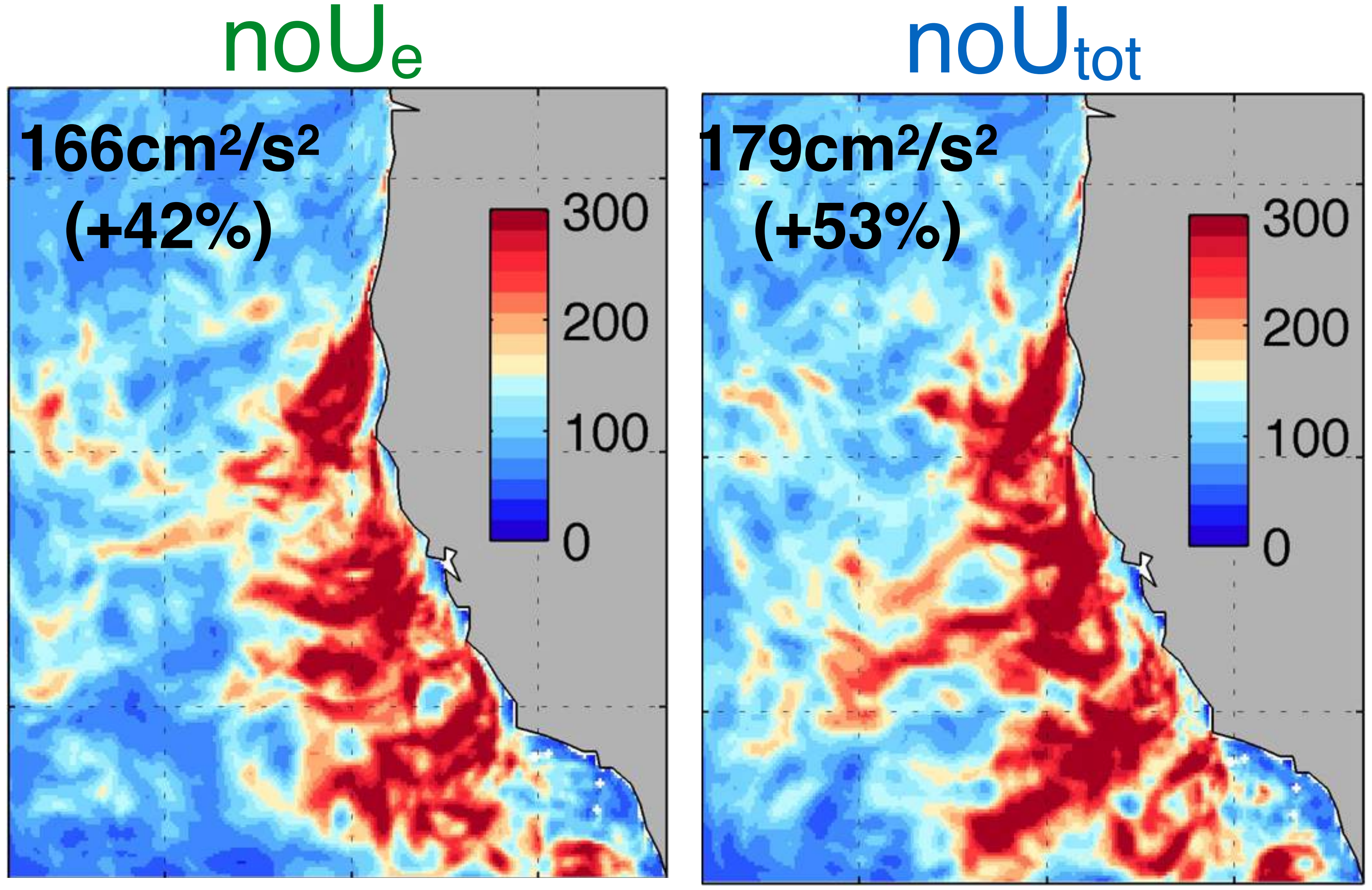


Experiments	τ formulation			
CTL	T_b	T_e	U_b	U_e
noT$_e$	T_b		U_b	U_e
noU$_e$	T_b	T_e	U_b	
noU$_{tot}$	T_b	T_e		

CCS: Effect on Eddy Kinetic Energy

JAS 2005-2010

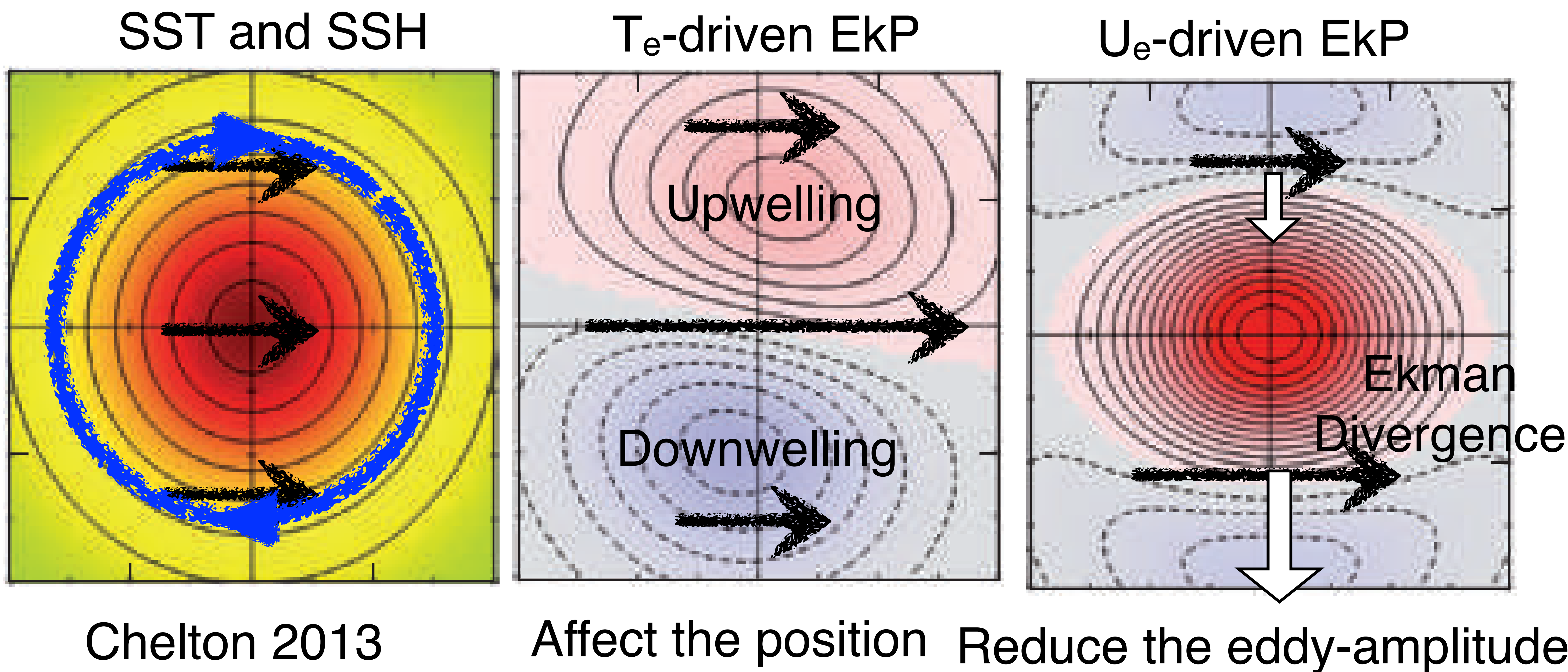




- T_e-τ has no impact on EKE
- U_e-τ reduces the EKE by 40%
- U_{tot}-τ reduces the EKE only slightly more (additional 10%)

→ The EKE reduction by under-stress occurs largely due to small-scale coupling

Seo et al. 2016 JPO



Depth-averaged EKE budget

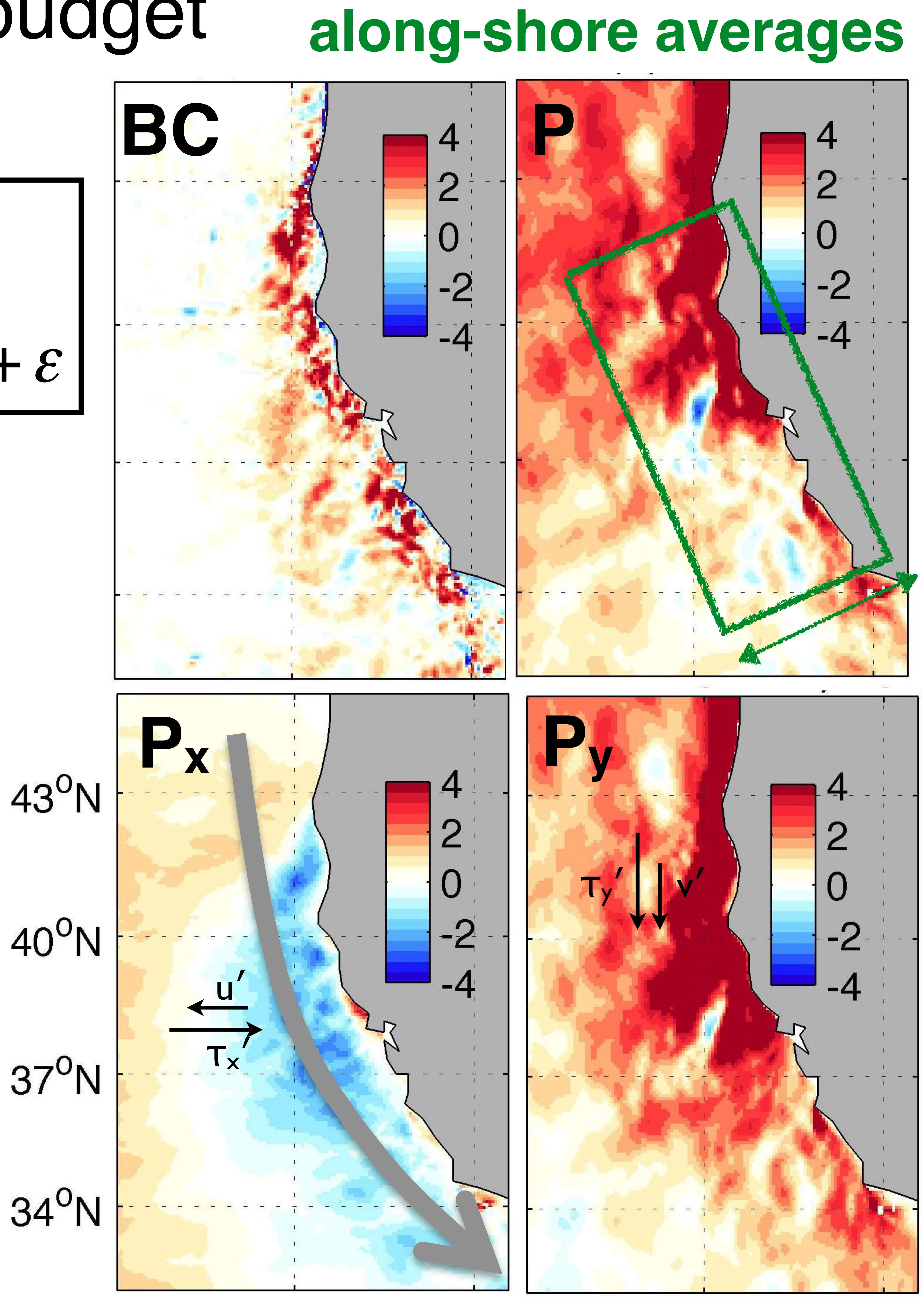
$$\frac{\partial K_e}{\partial t} + U \cdot \nabla K_e + u' \cdot \nabla K_e = -\nabla \cdot (u'p') - g\rho' w' + \rho_o(-u' \cdot (u' \cdot \nabla U)) + u' \cdot \tau' + \varepsilon$$

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

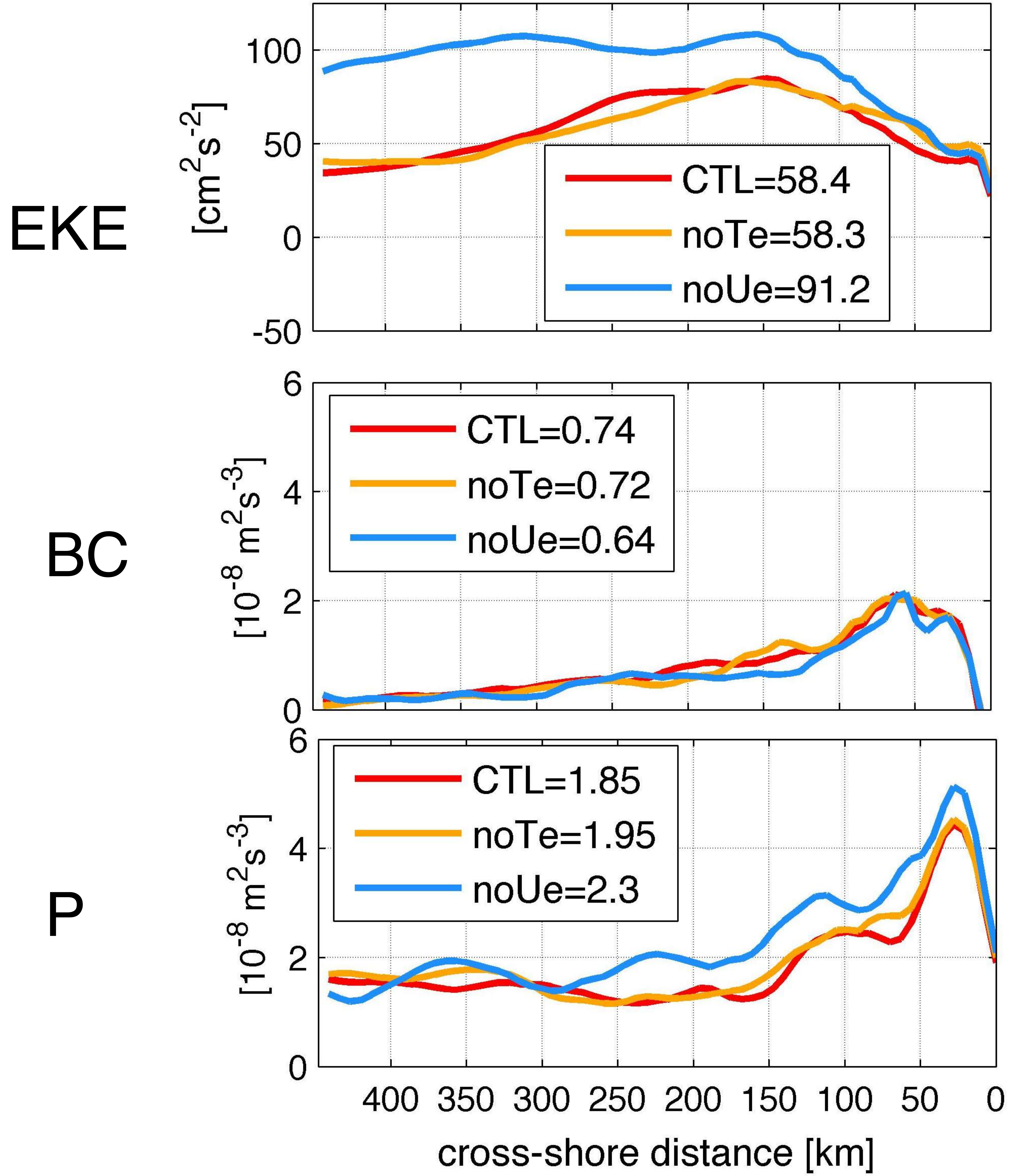
Wind work if positive, eddy drag if negative

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

$P_e \rightarrow K_e$ baroclinic conversion (BC)



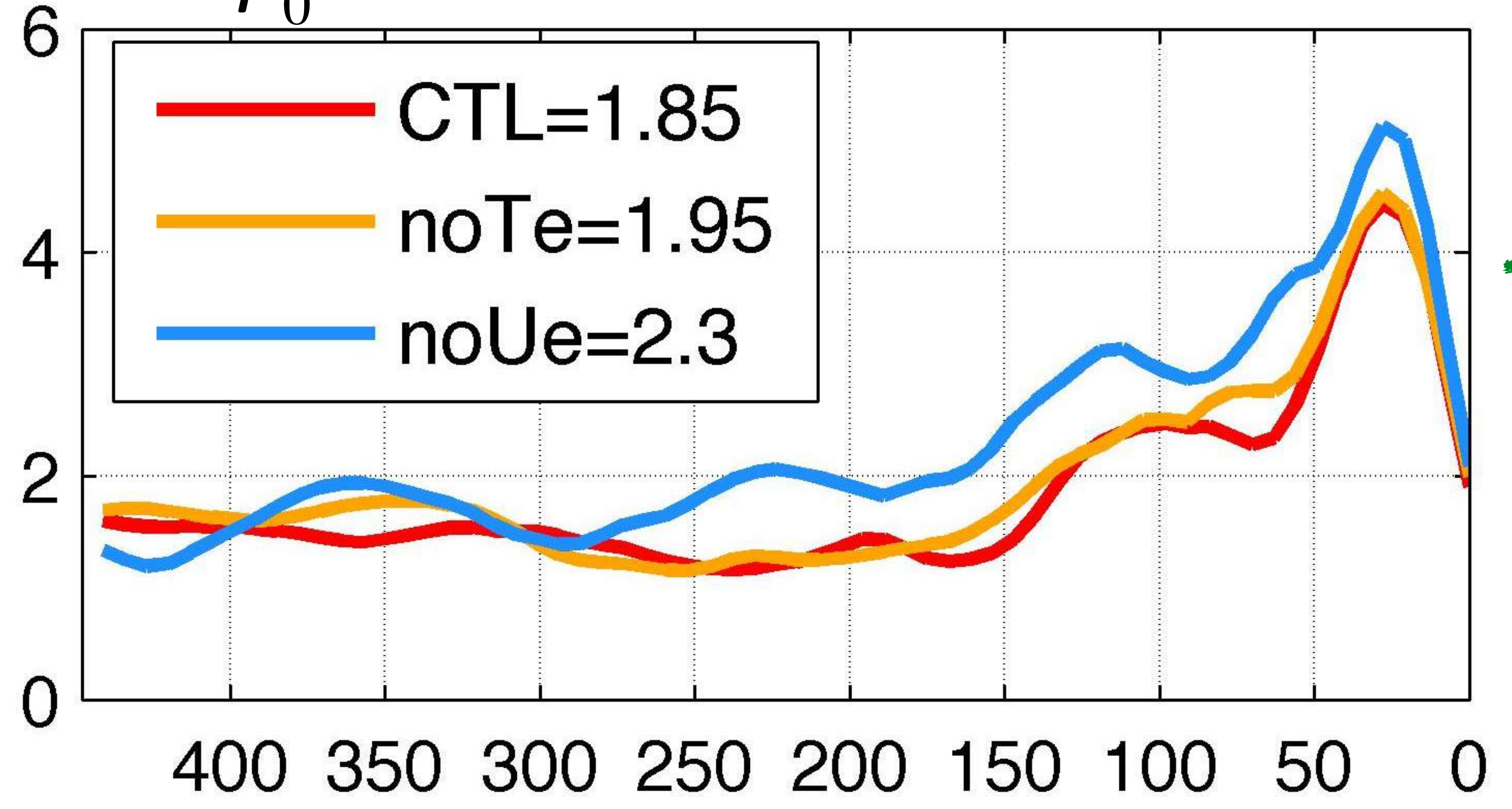
Across-shore distribution of EKE budget terms



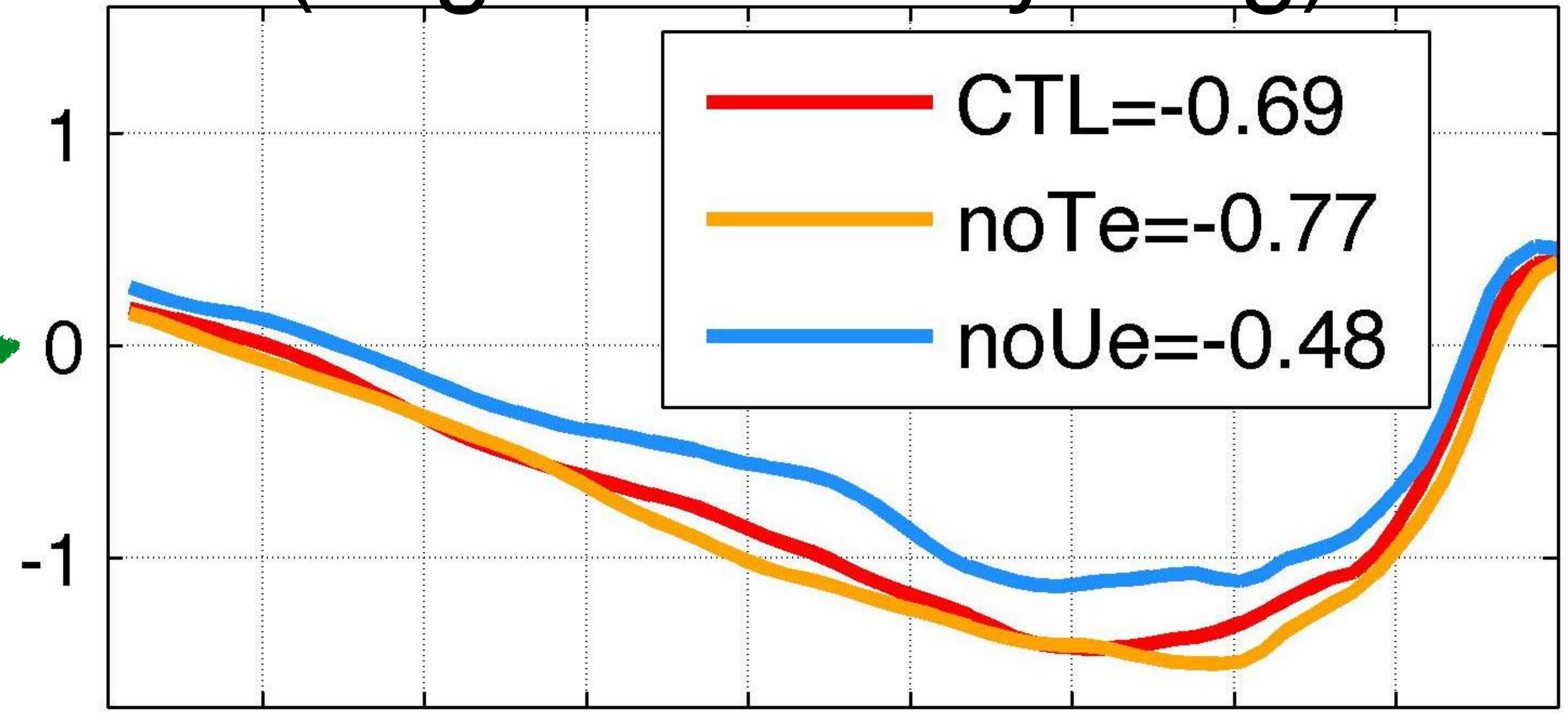
- **Baroclinic conversion**
  - Only a small reduction in noU_e
    → can't explain the higher EKE
- **Eddy-wind interaction**
  - 24% increase in noU_e over the eddy-rich coastal zone
    → U_e-τ reduces the wind work

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

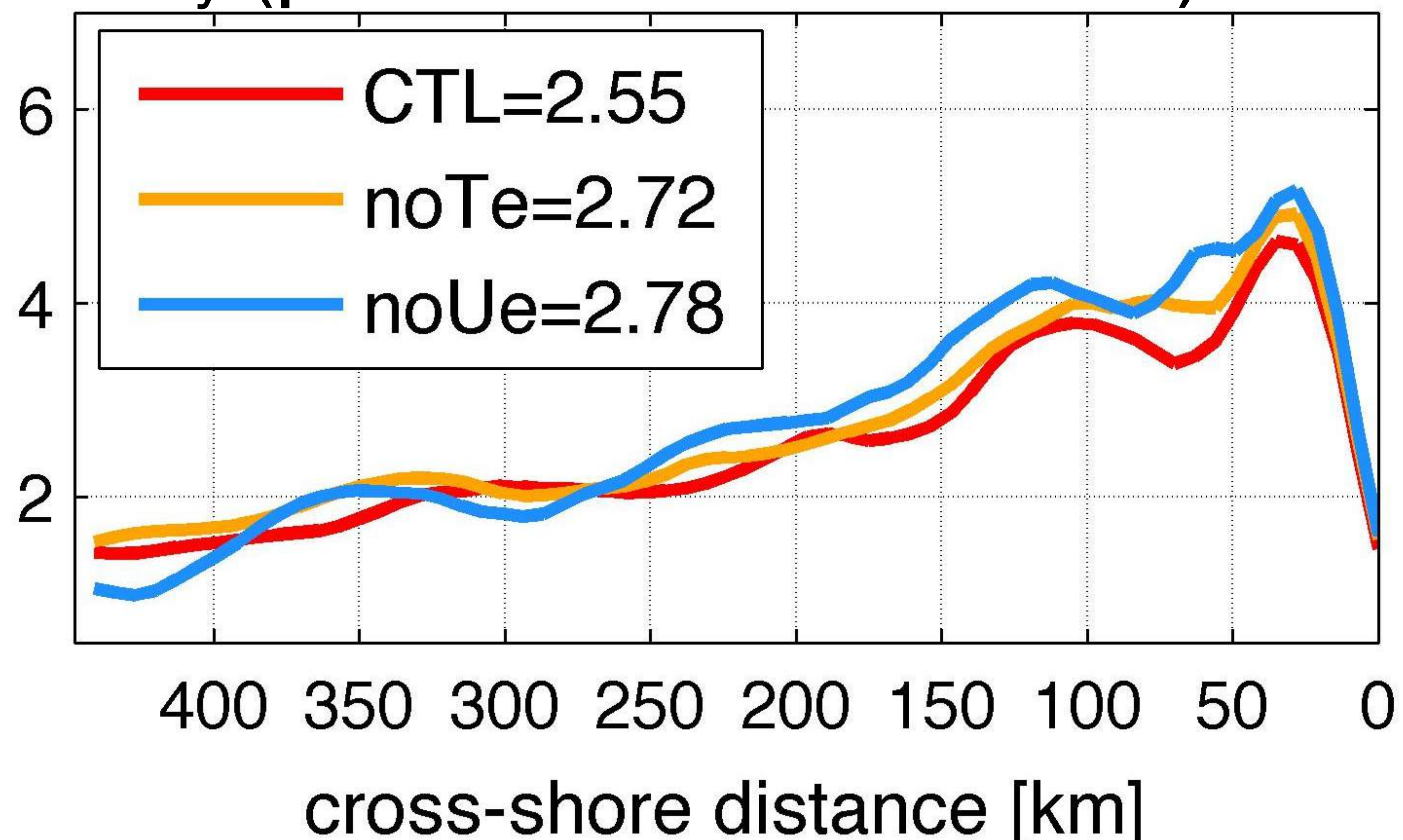
$$P = \frac{1}{\rho_0}\left(\overline{u'\tau'_x} + \overline{v'\tau'_y}\right).$$



P_x (negative→eddy drag)



P_y (positive → wind work)



- 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

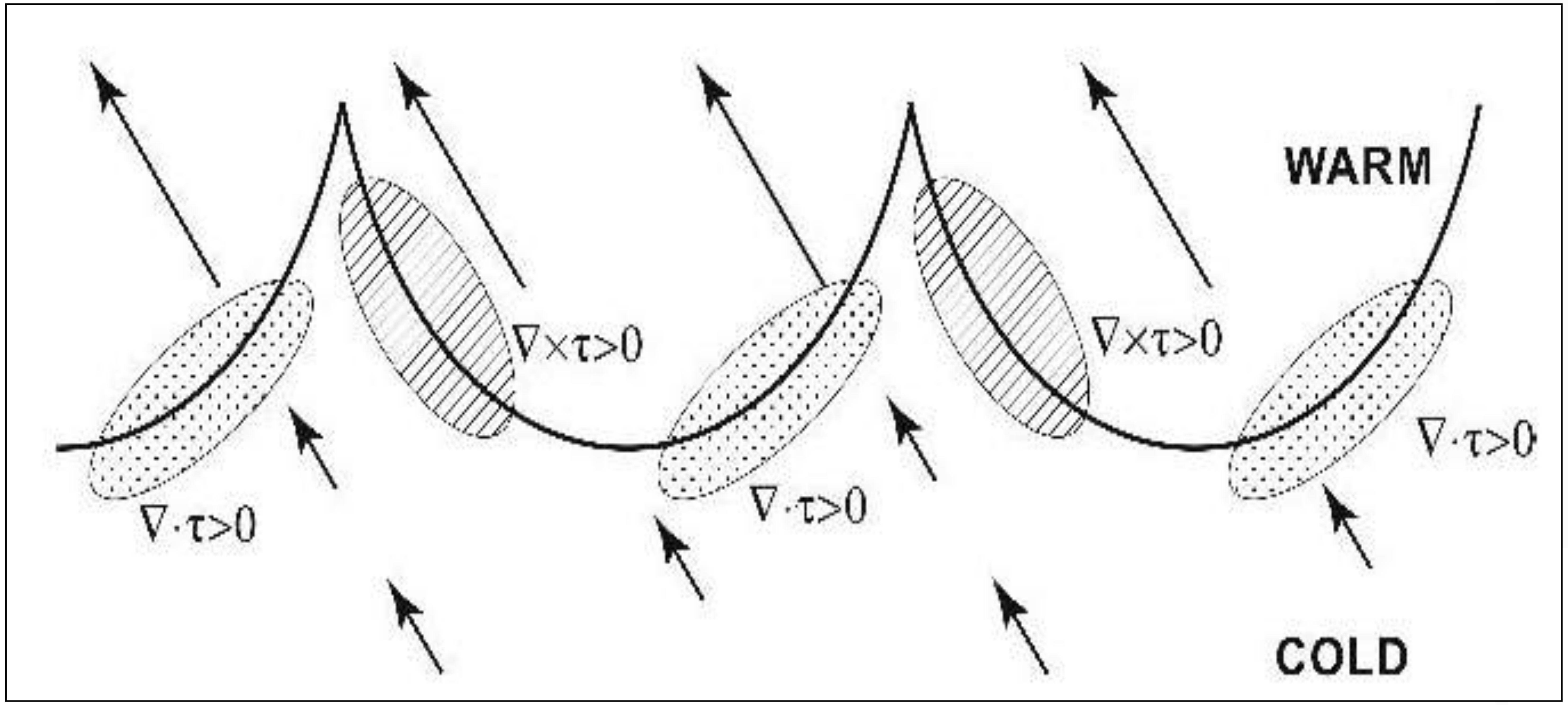
W_{ζ}: Surface vorticity gradient-induced nonlinear Ekman pumping

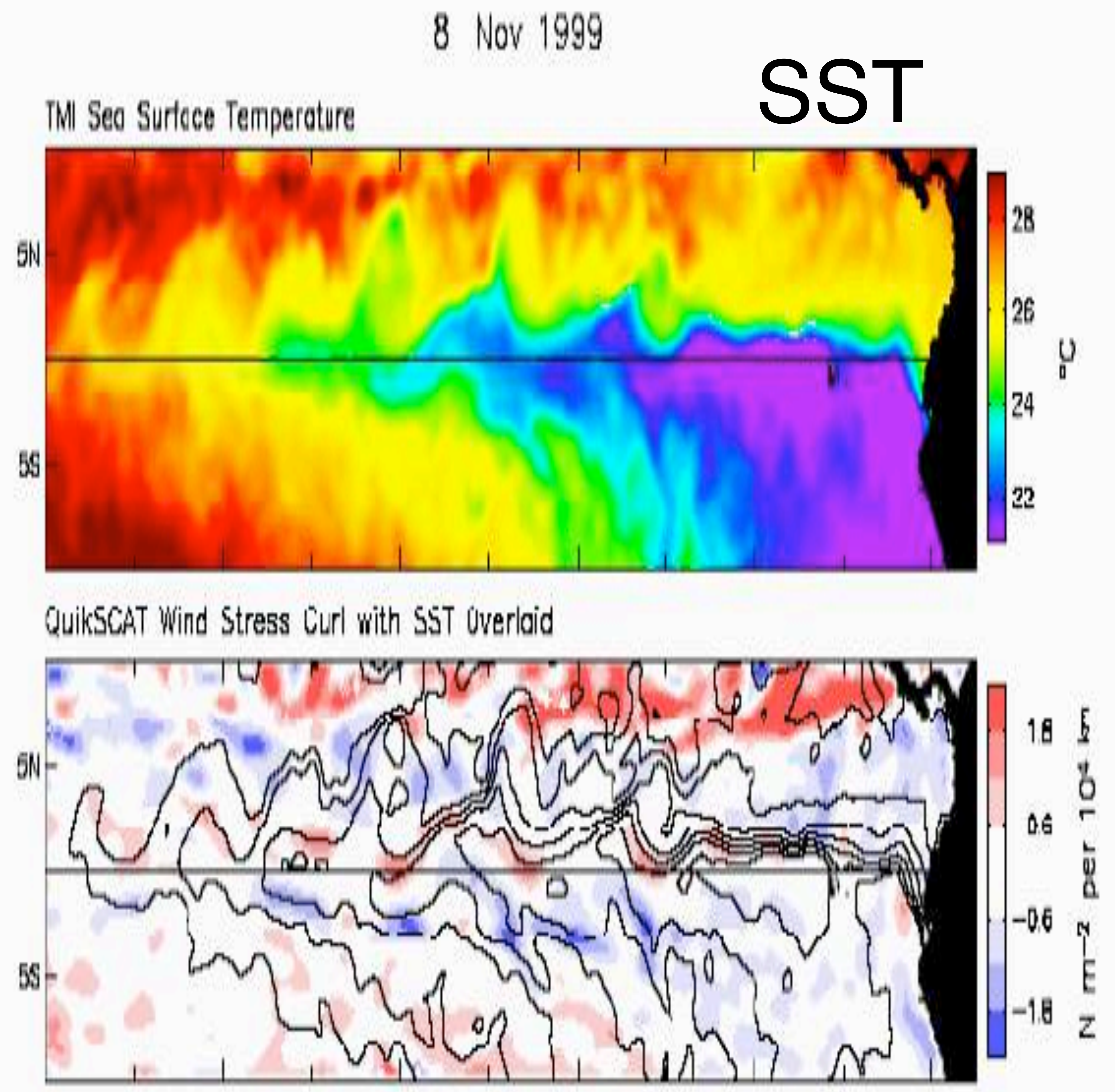
W_{SST}: SST induced Ekman pumping (Chelton et al. 2007)

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)



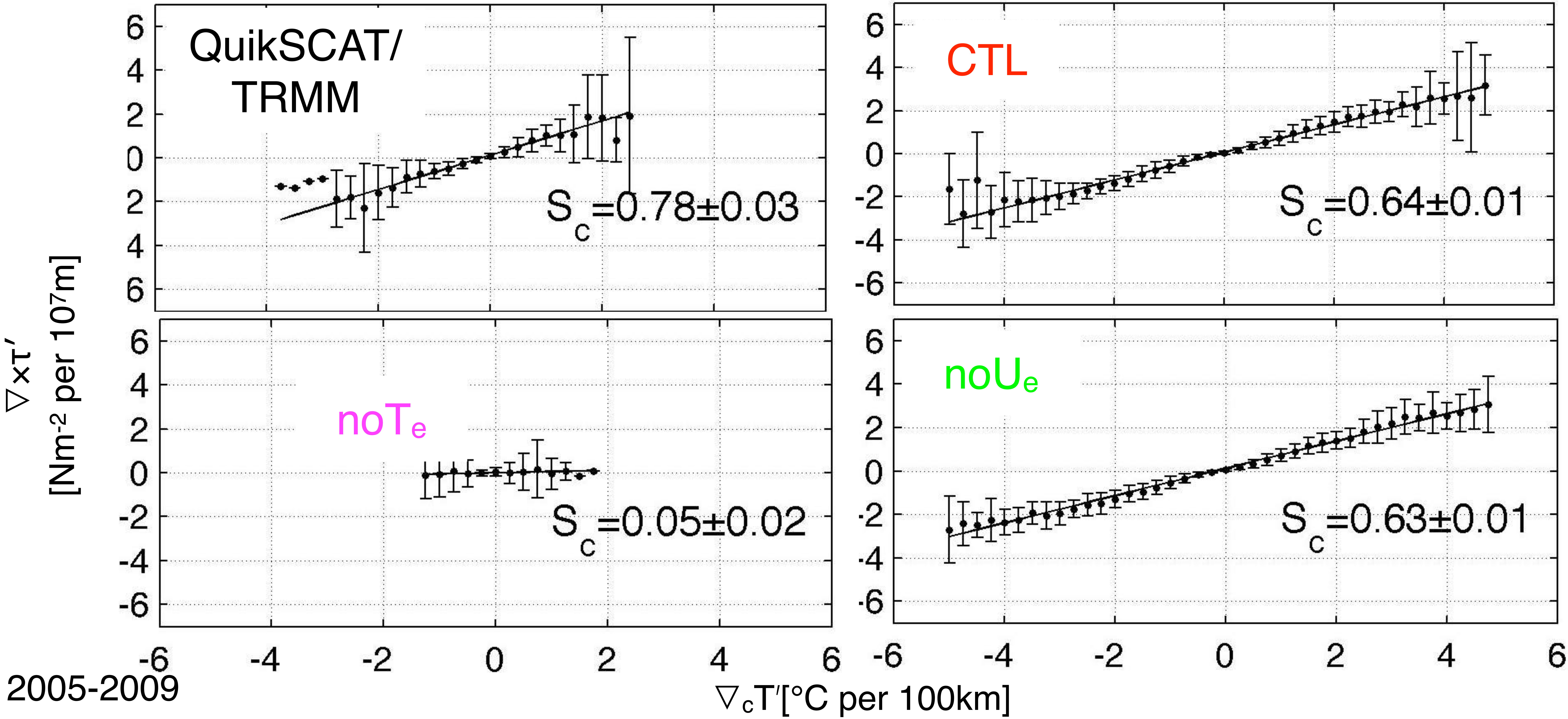


SST

wind stress curl

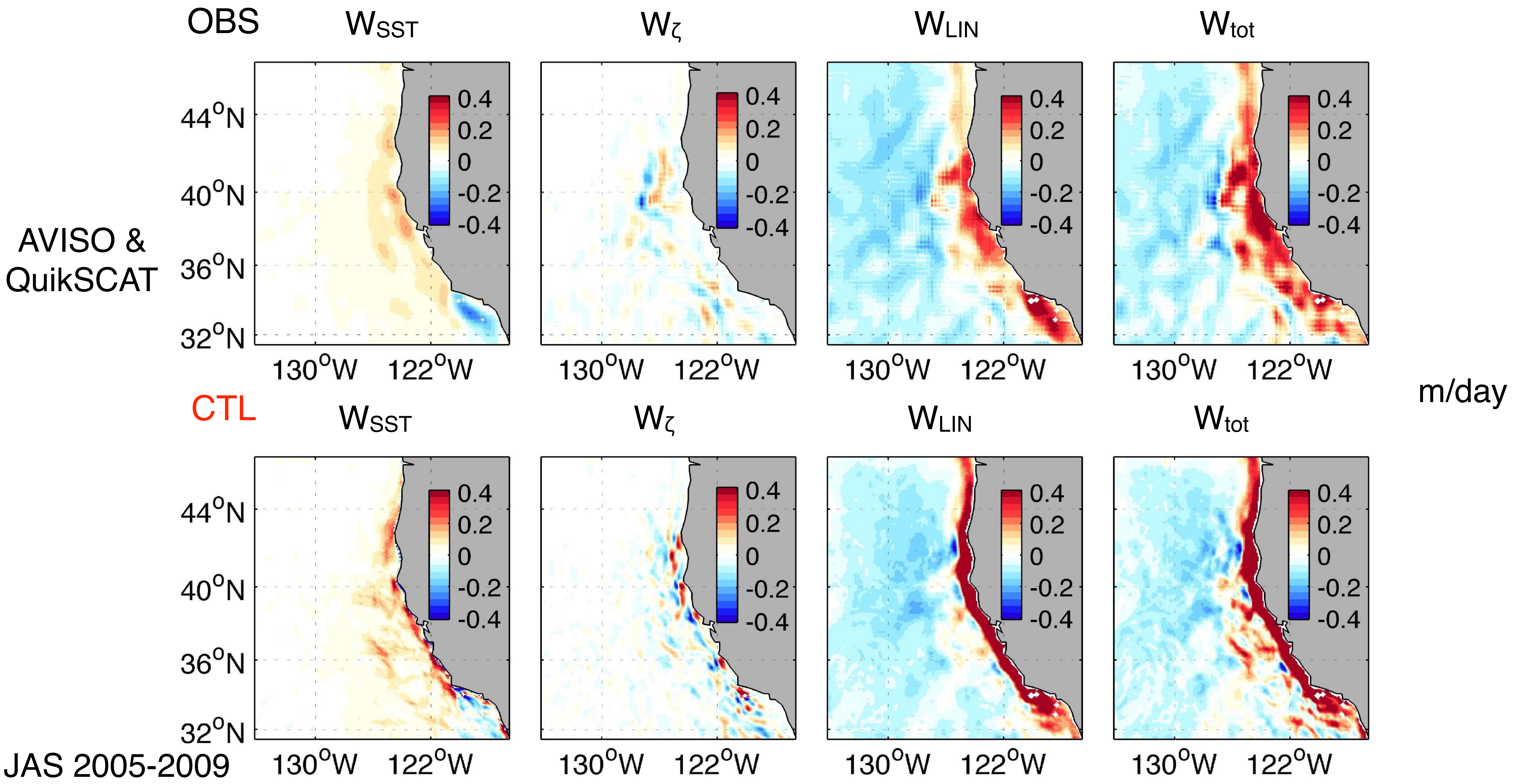
$$W_{SST} = \frac{\nabla \times \tau'_{SST}}{\rho_o (f + \zeta)} \approx \frac{\alpha_c \nabla_c SST}{\rho_o (f + \zeta)}$$

Estimating SST-driven Ekman pumping velocity

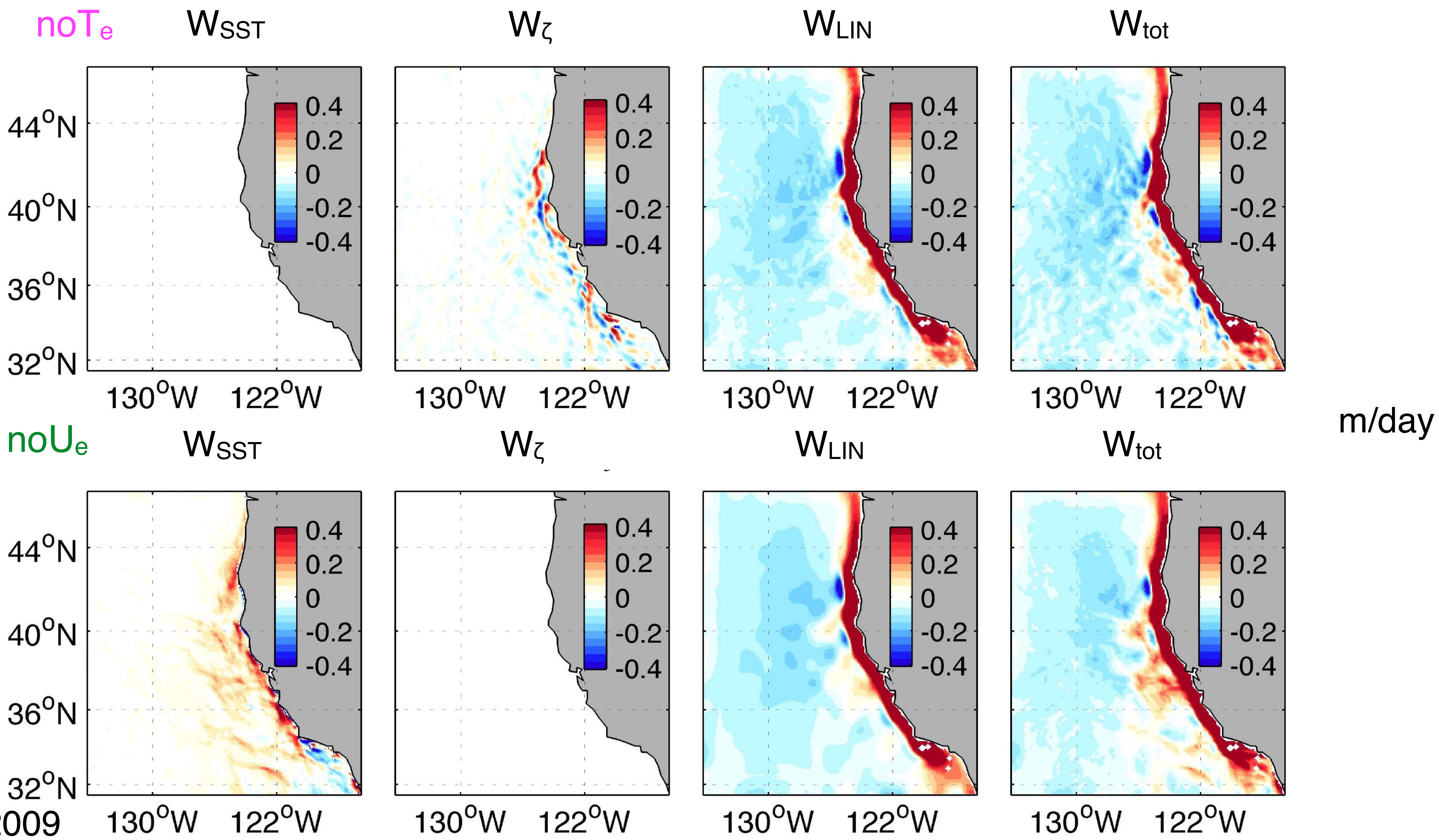


JAS 2005-2009

Estimated Ekman pumping velocities

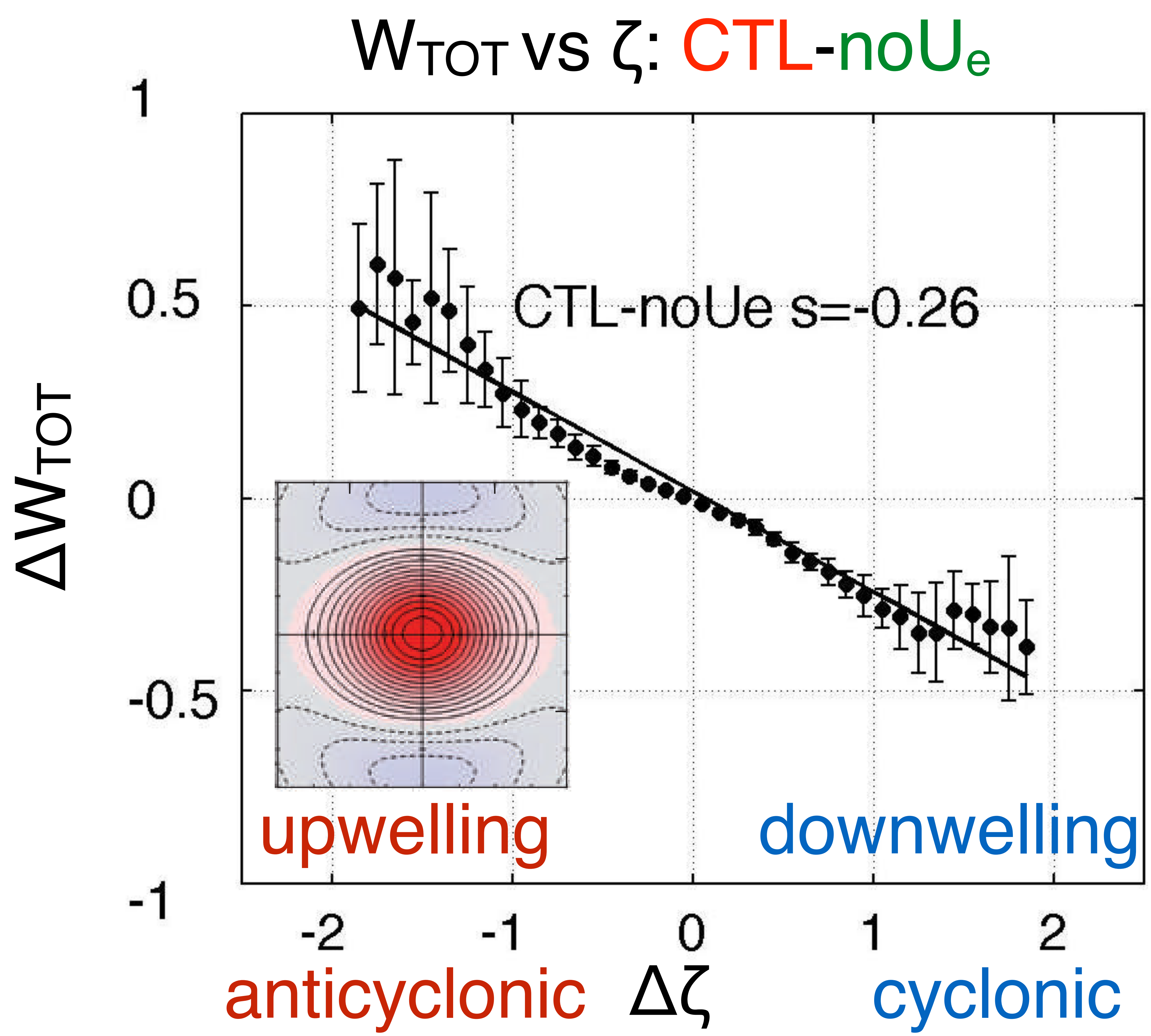


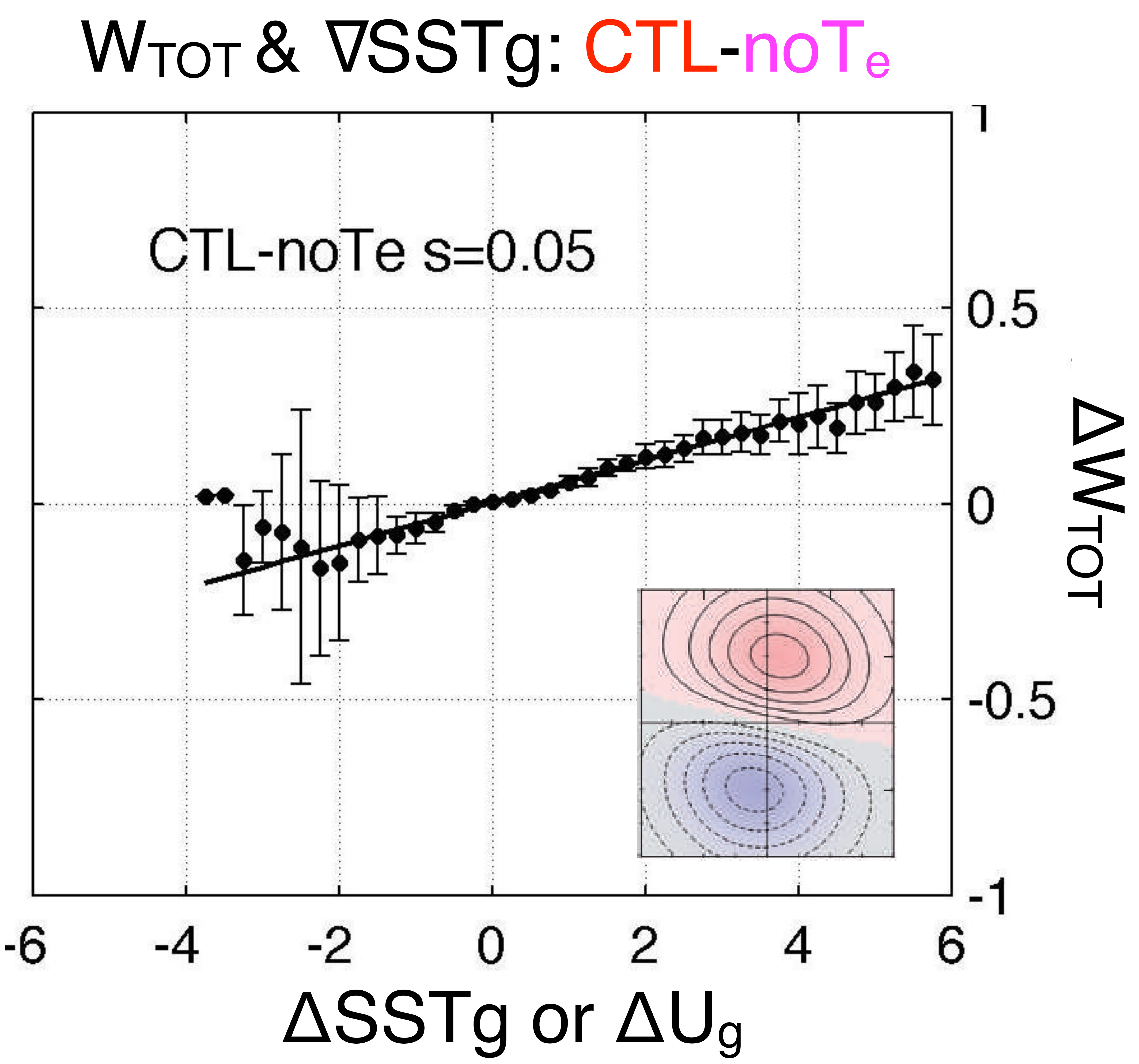
Estimated Ekman pumping velocities



JAS 2005-2009

Inferred feedback effects



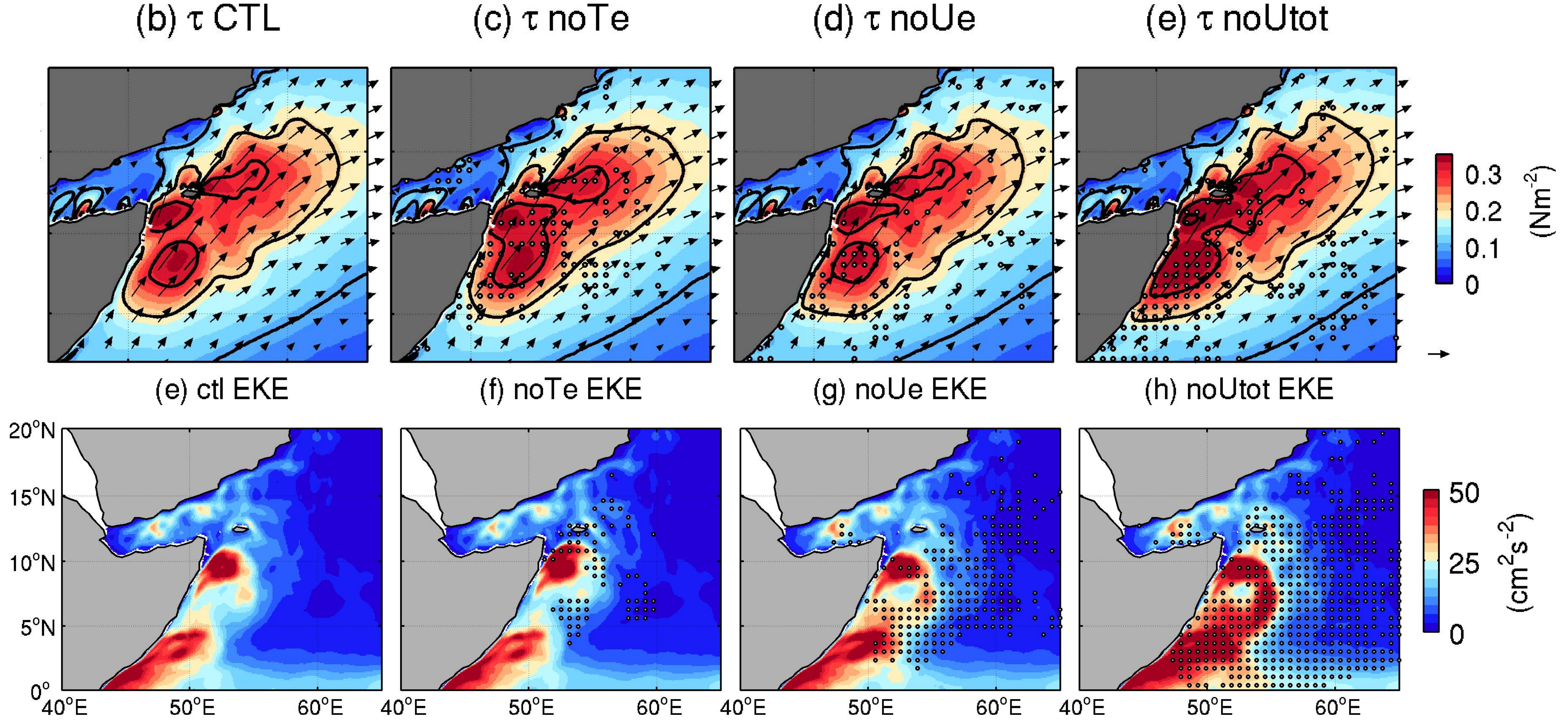


Downwelling over cyclonic vorticity anomaly → U_e-τ weakens the amplitude of the eddies

W_e acting on the maximum SST gradients → T_e-τ influences the Ug within the eddy interior

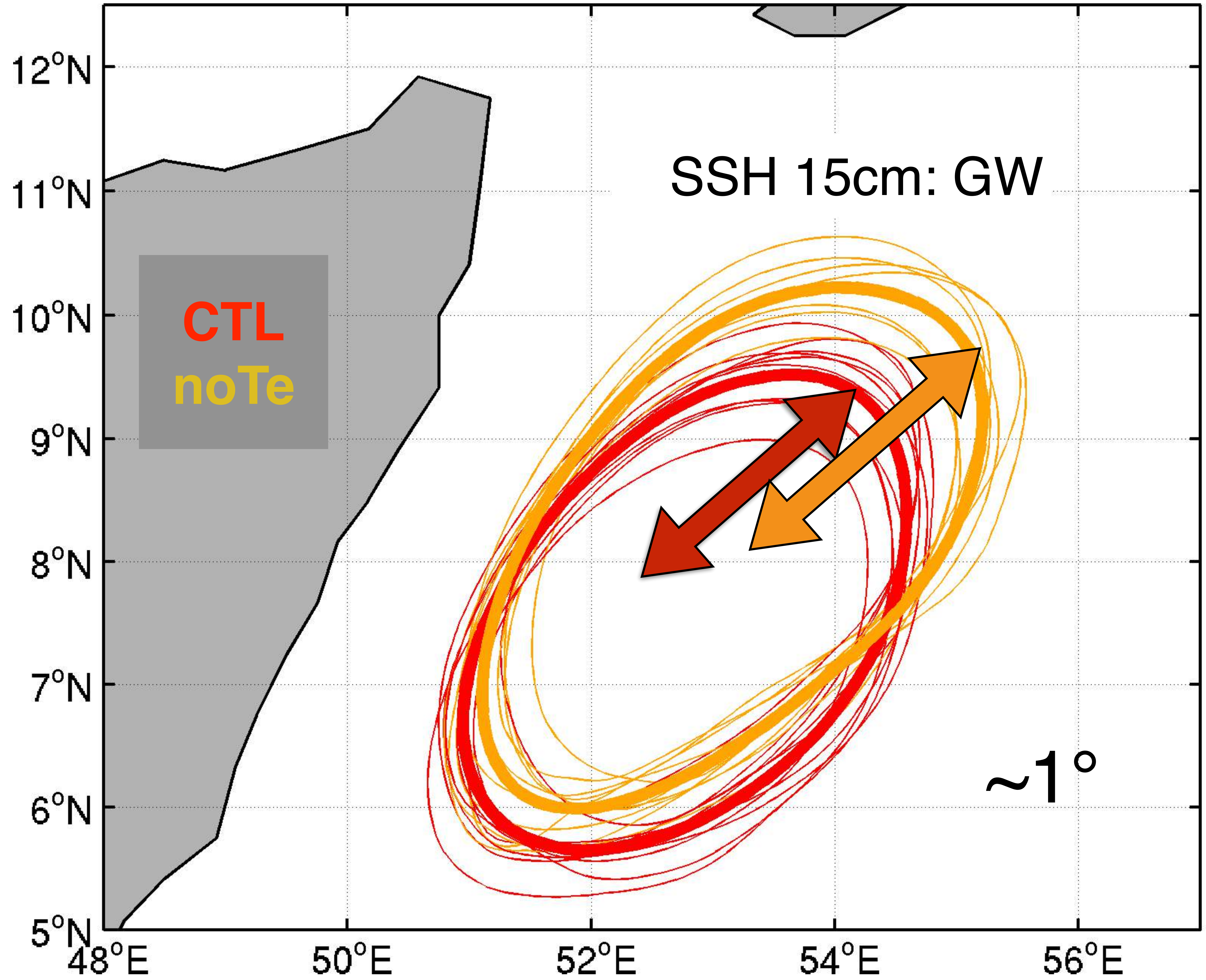
Confirming two distinct influences of air-sea coupling:

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



2001-2010 JJAS climatology

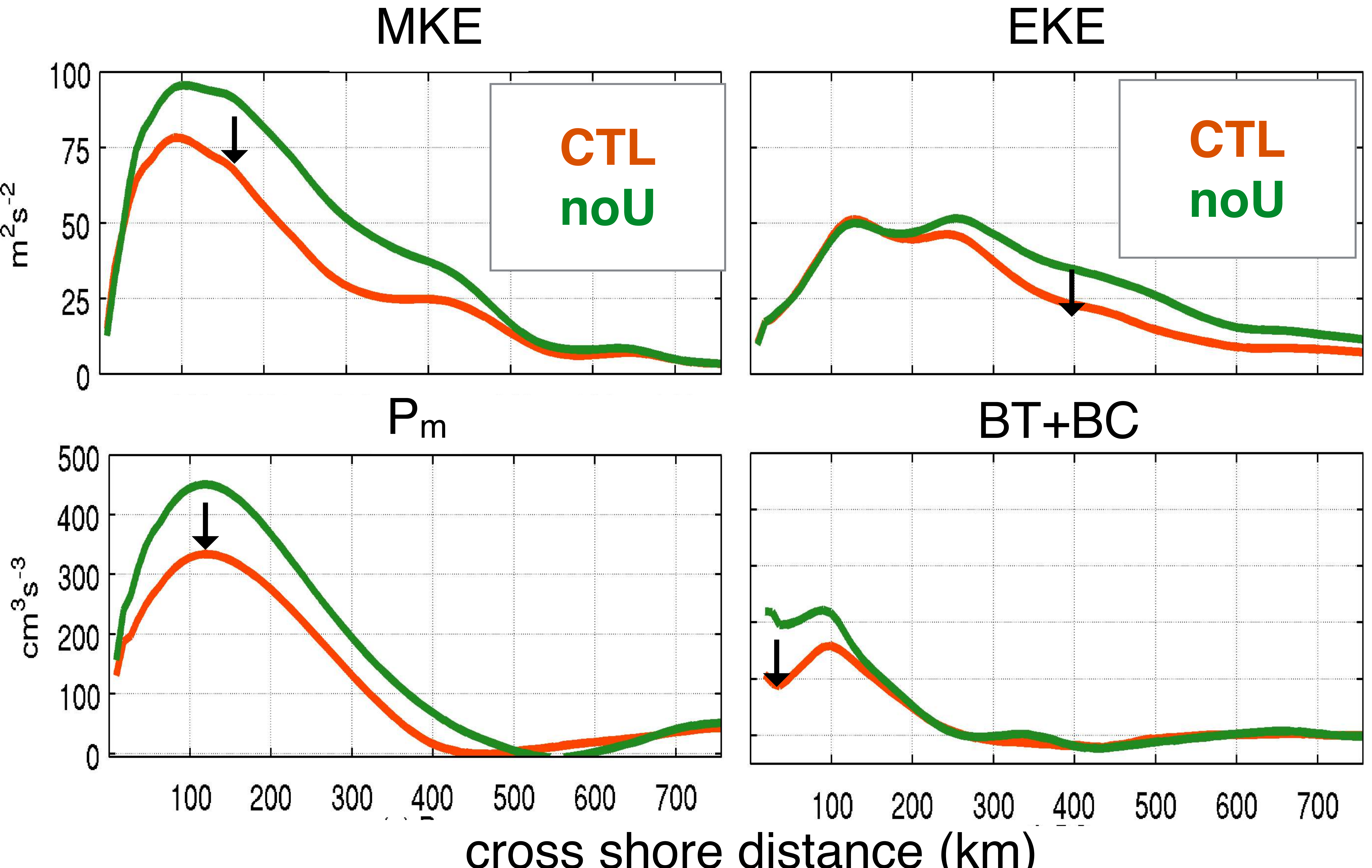
T_e-τ influences the position of the Great Whirl (GW)



- About 1° downstream shifts o the GW in noT_e

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

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 vorticity of the eddy

- (not discussed today) Some evidence of downstream atmospheric response → Air–sea interaction study should consider both the thermal and mechanical coupling effect on the oceanic mesoscales and frontal-scales.

Thanks

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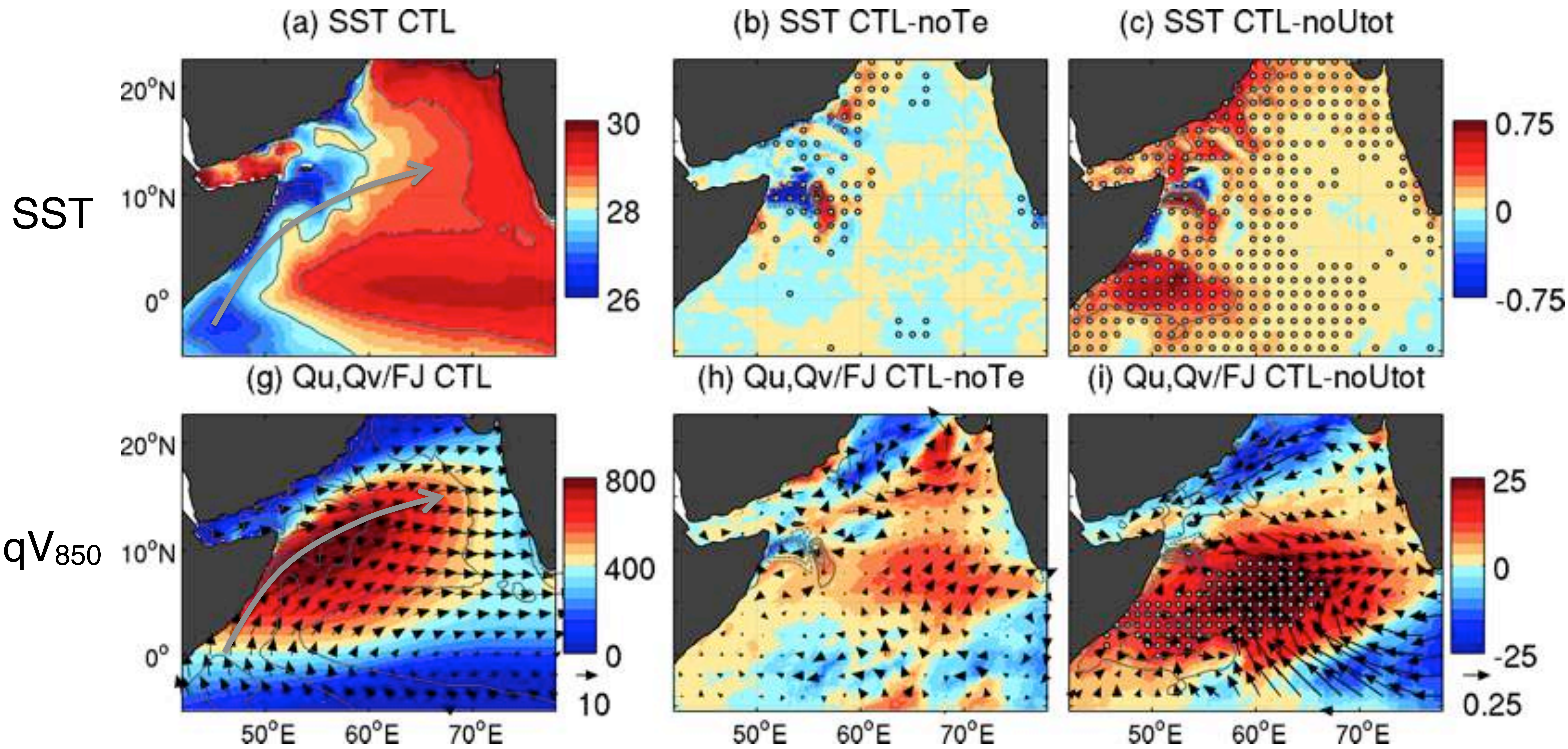
Some downstream influence



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