Dynamics and impacts of

Eddy-driven air-sea interaction

in the California Current System

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O-A interaction
on coastal upwelling
Broad-scale vs eddy-scale
SST vs surface current
O(10km)
O(10³km)
SeaWiFS surface
chlorophyll concentration
http://earthobservatory.nasa.gov

Eddy-driven air-sea interaction: wind and wind stress

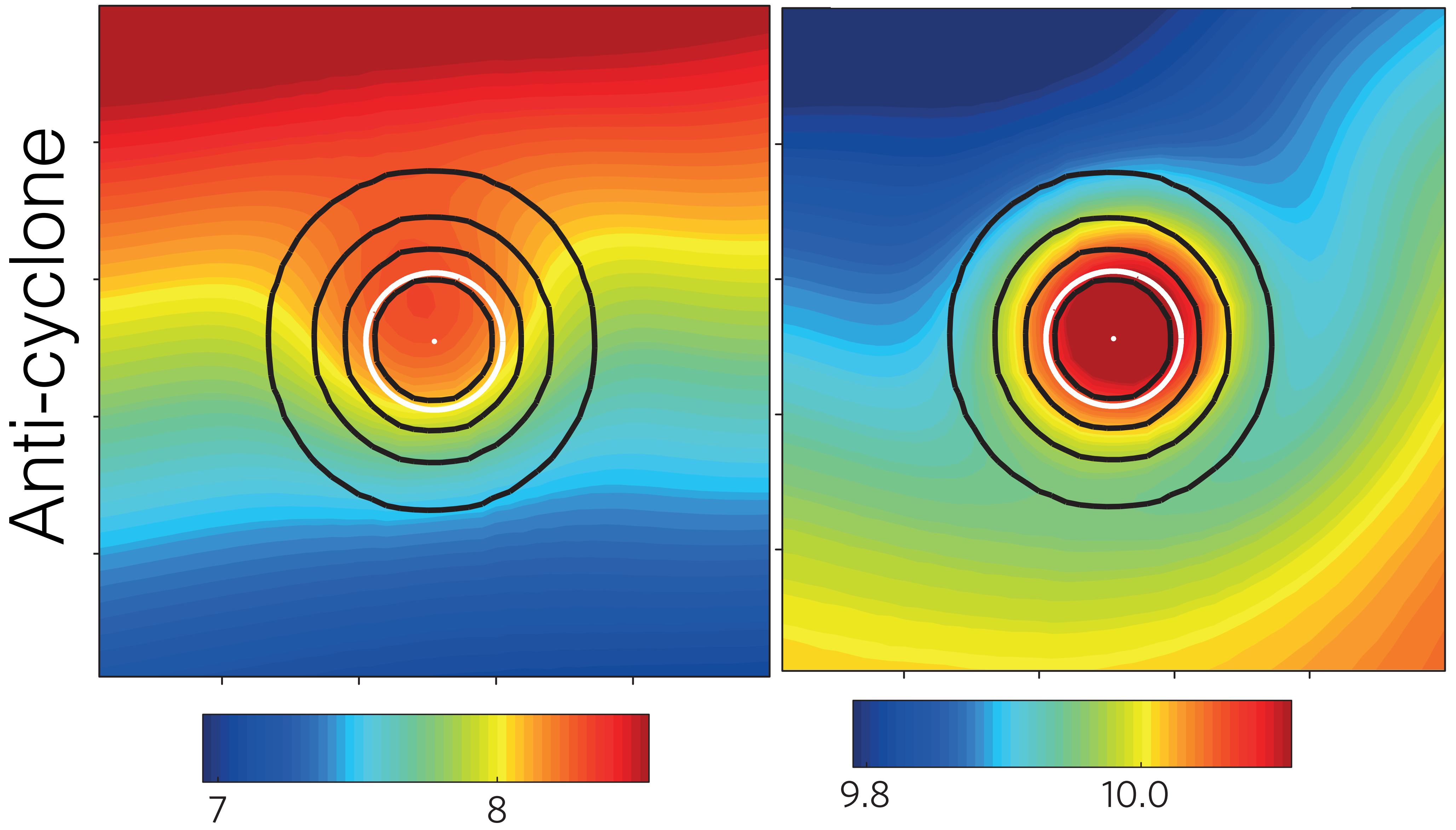
$$\tau = \rho_a C_D (W - U)\,|W - U|$$

surface current

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

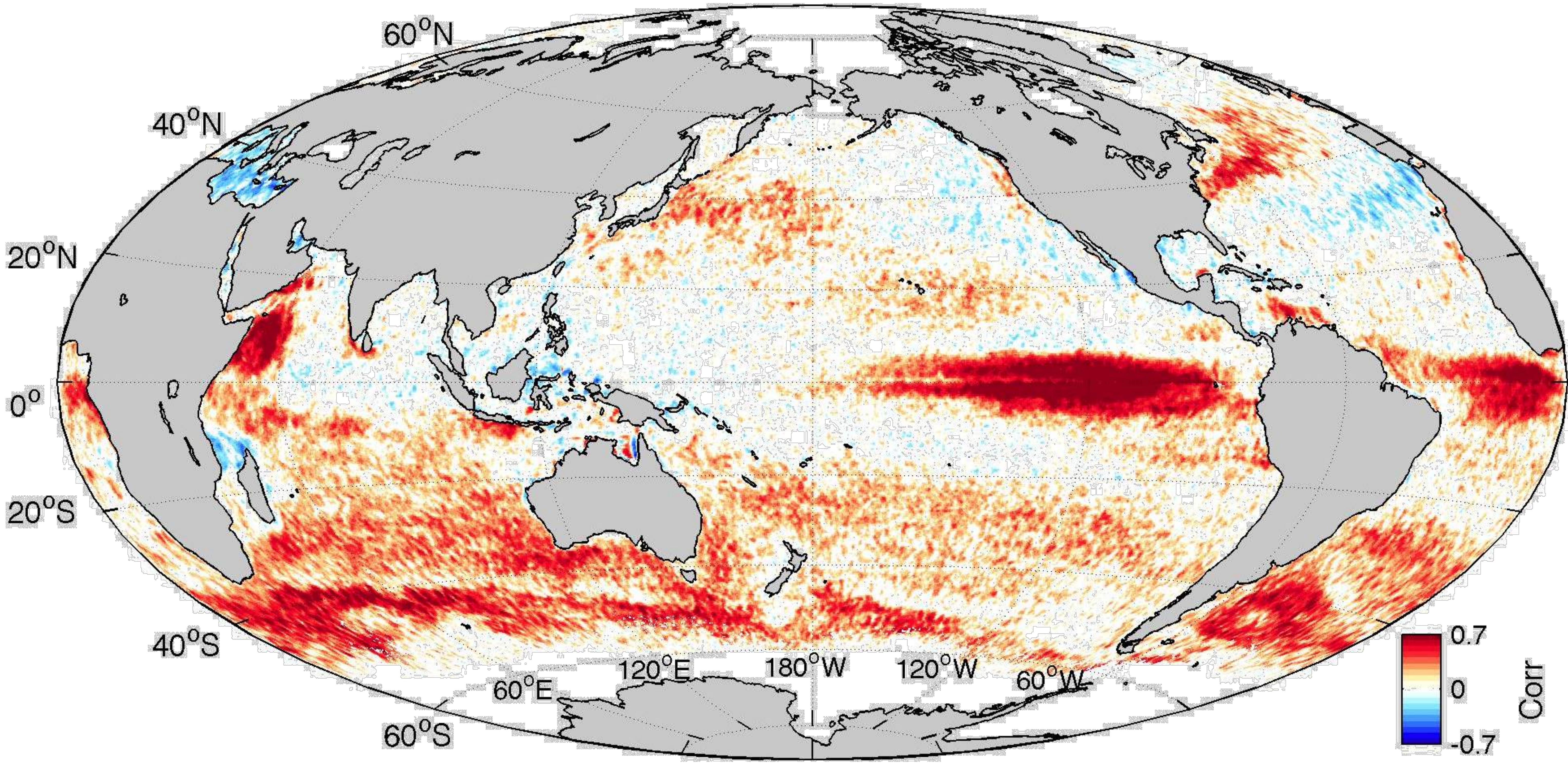
Eddy composites in the Southern Oceans

SST Wind speed



Frenger et al. 2013

Correlation bet'n highpass filtered SST & W



Eddy-driven air-sea interactions: Ekman pumping velocity

$$\tau = \rho_a C_D (W - U)\,|W - U|$$

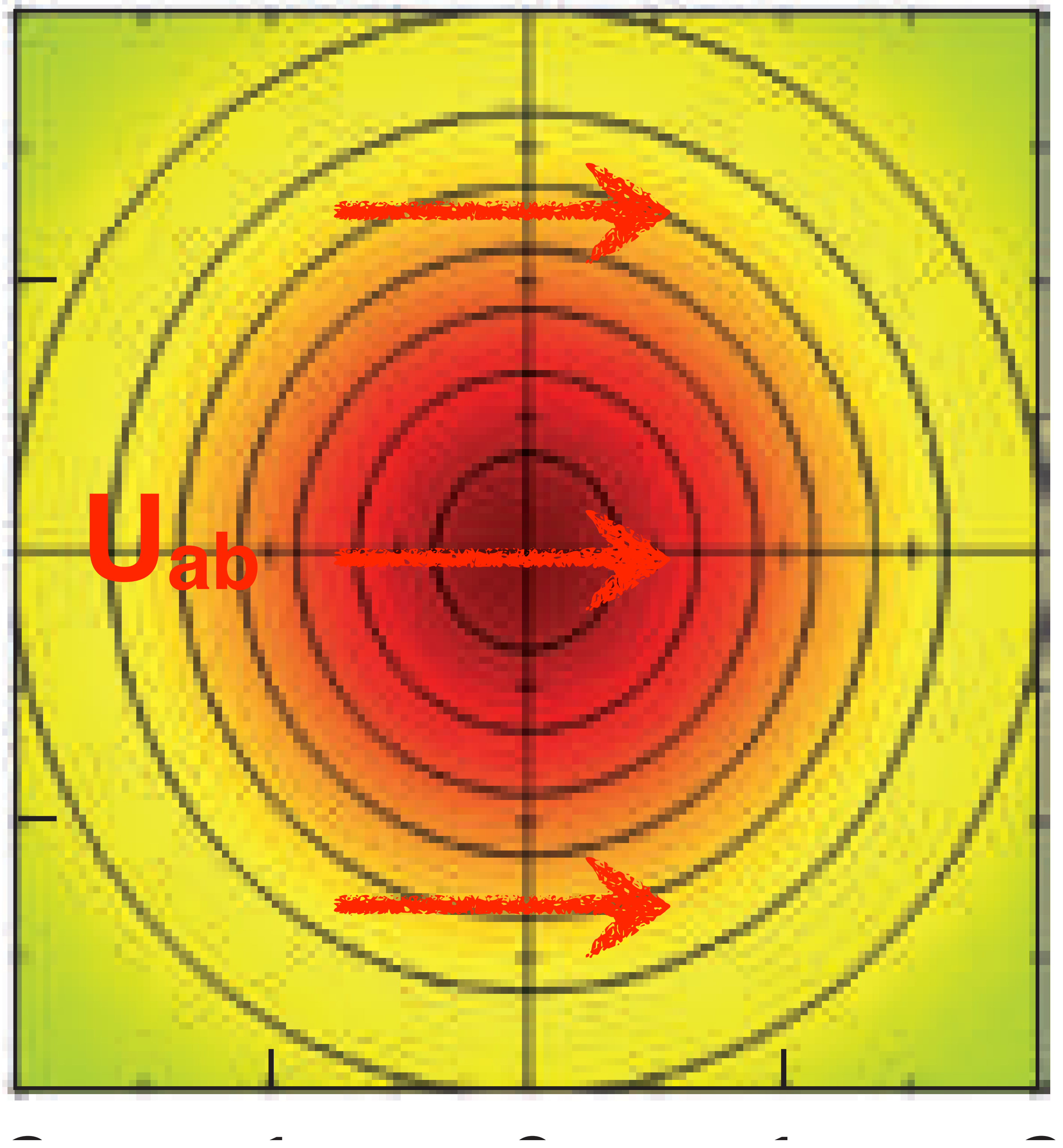
surface current

10m wind

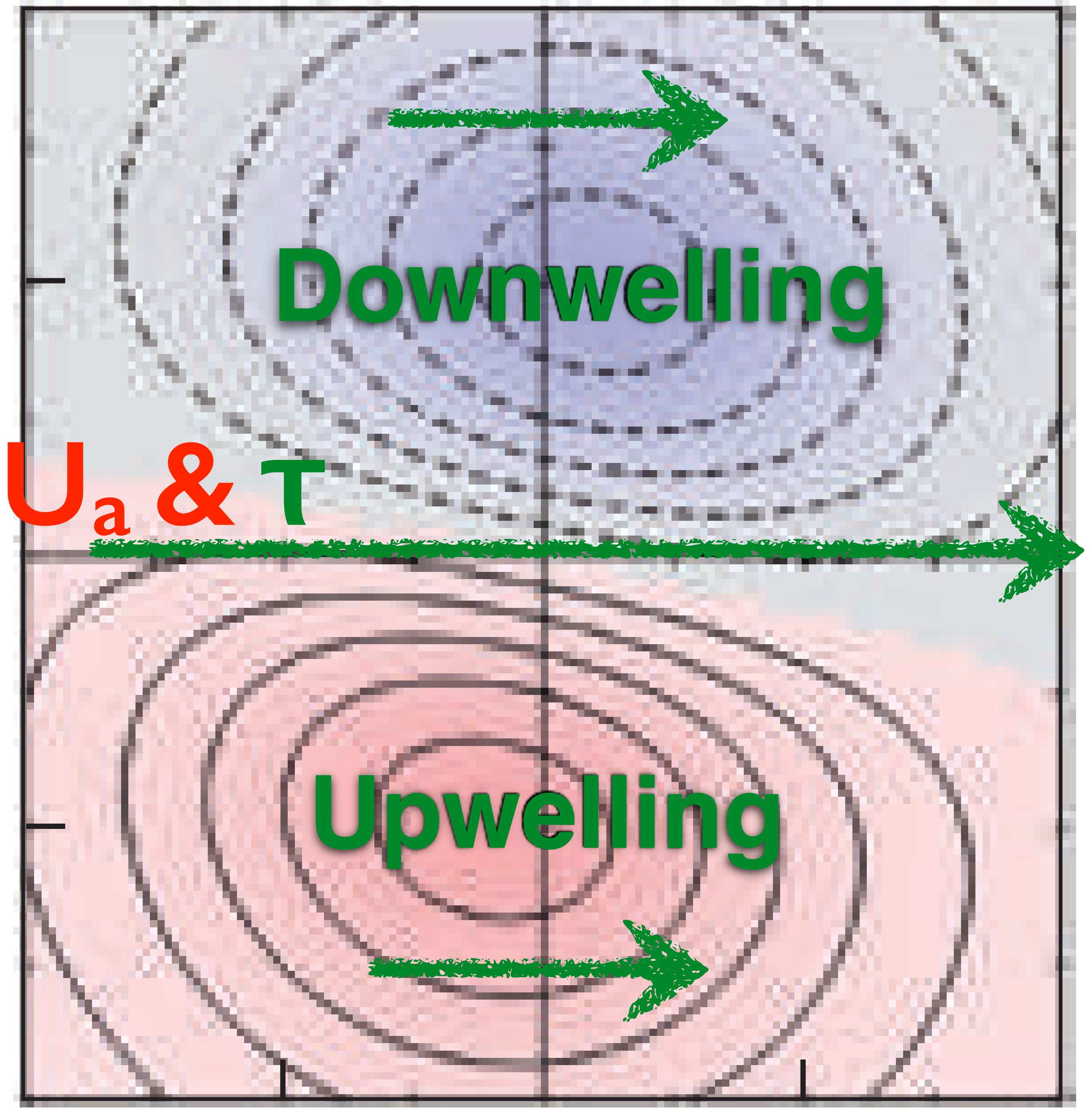
$W = W_b + \underline{W_{SST}}$

Consider an idealized anticyclonic warm-core eddy in the Southern Ocean (Chelton 2013)

SST and SSH



Dipole Ekman pumping



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

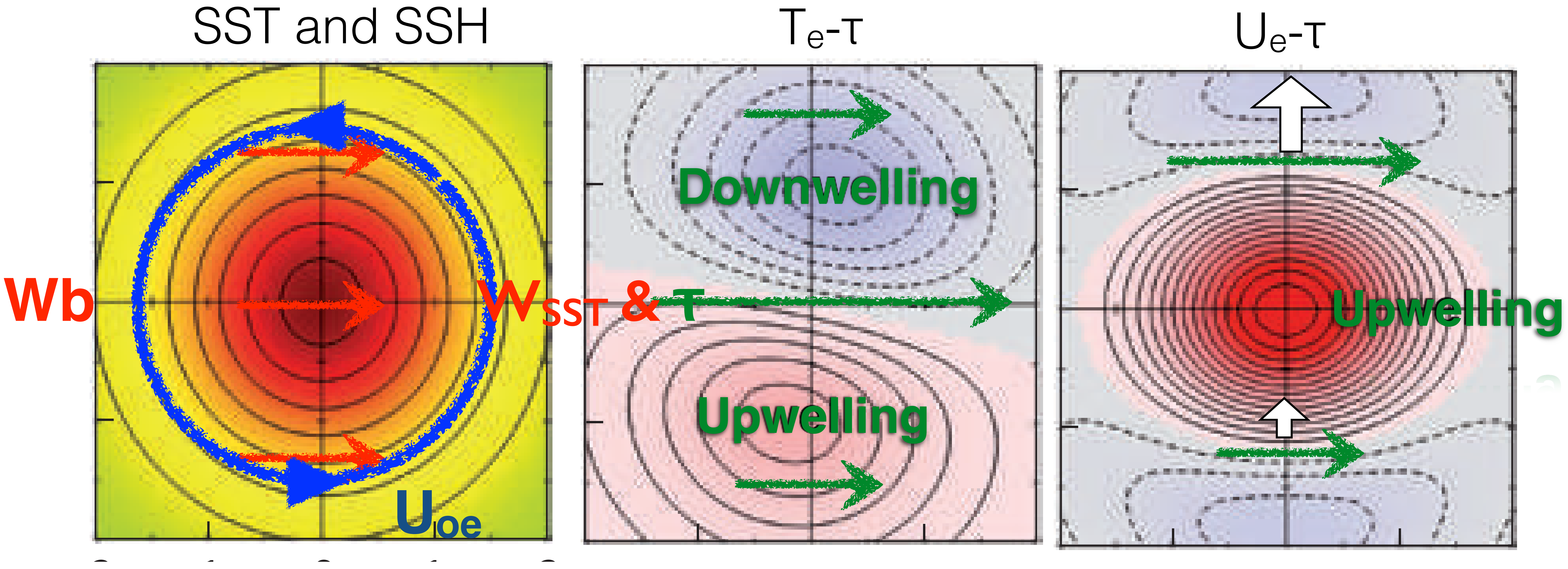
Eddy-driven air-sea interactions: under-stress

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

surface current
$U = U_b + U_e$

10m wind

$W = W_b + W_{SST}$



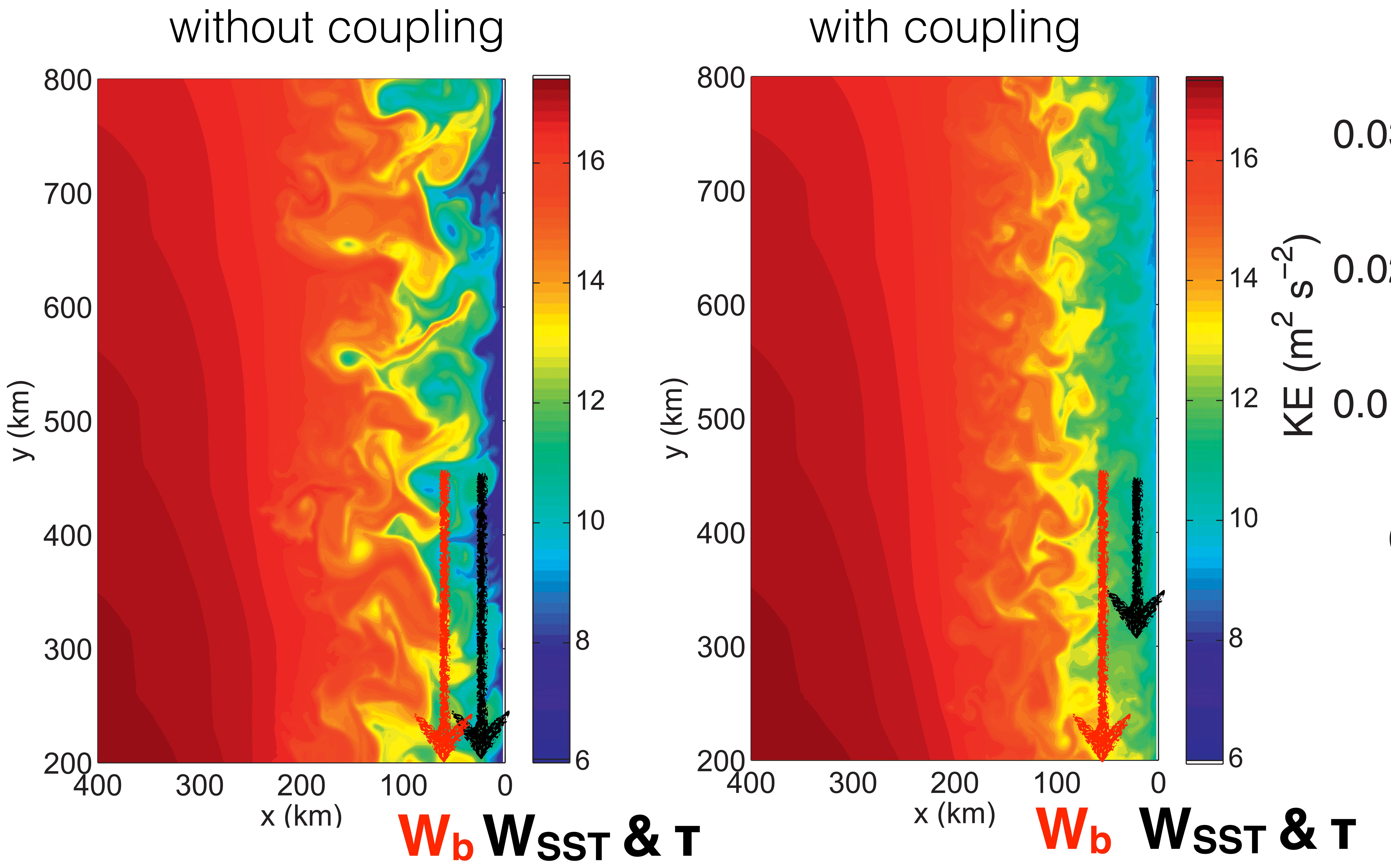
Affect the propagation

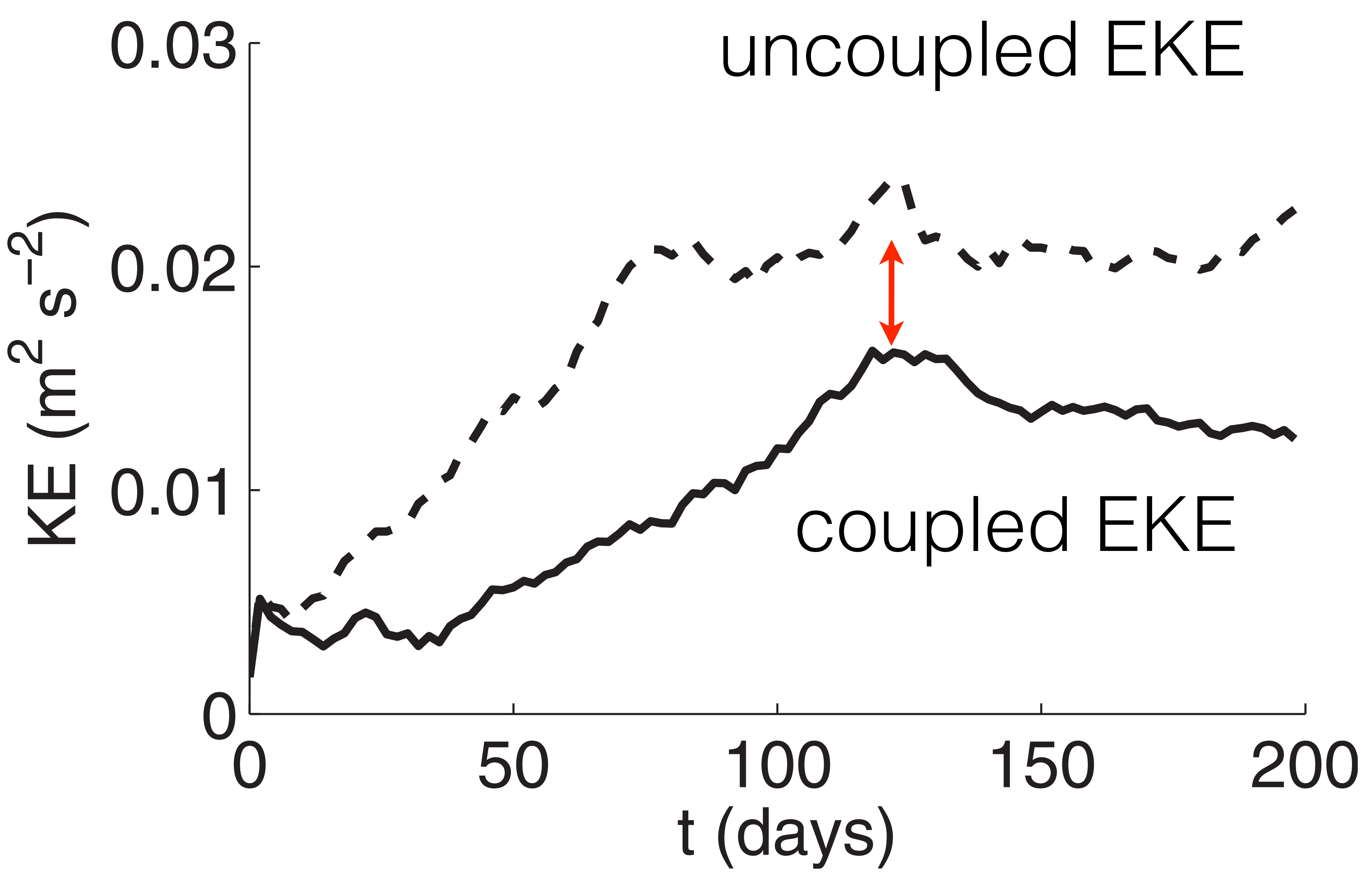
Reduce the eddy-amplitude

Chelton 2013

Previous studies: Jin et al. (2009)

SST-wind coupling weakens the EKE in an idealized ocean model



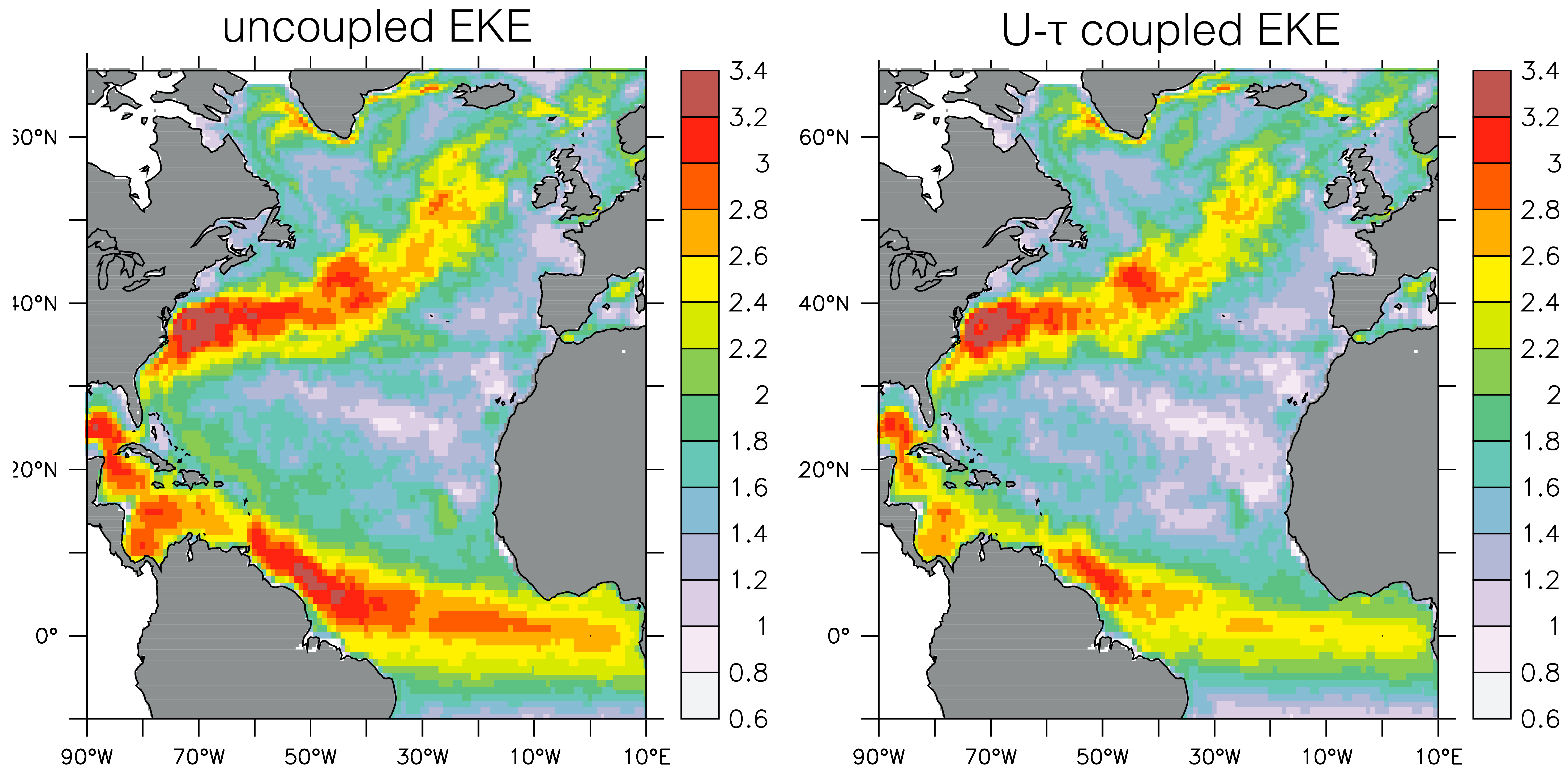


25% reduction of EKE
with SST-τ coupling

- SST-wind coupling weakens the alongshore wind stress, *baroclinic instability* and EKE.
- No distinction between the effects of background-scale and eddy-scale SSTs
- Wind speed is not allowed to vary with SST, only the stress.

Previous studies: Eden and Dietze (2009)

U-τ coupling effect also damps the EKE in an OGCM



- 10% reduction in EKE in the mid-latitudes and ~50% in the tropics
- Primarily due to increased eddy drag (τ′·u′, direct effect)

- Again, no separation between background and small-scale currents.
- No air-sea interactions with the prescribed wind speed

Goal

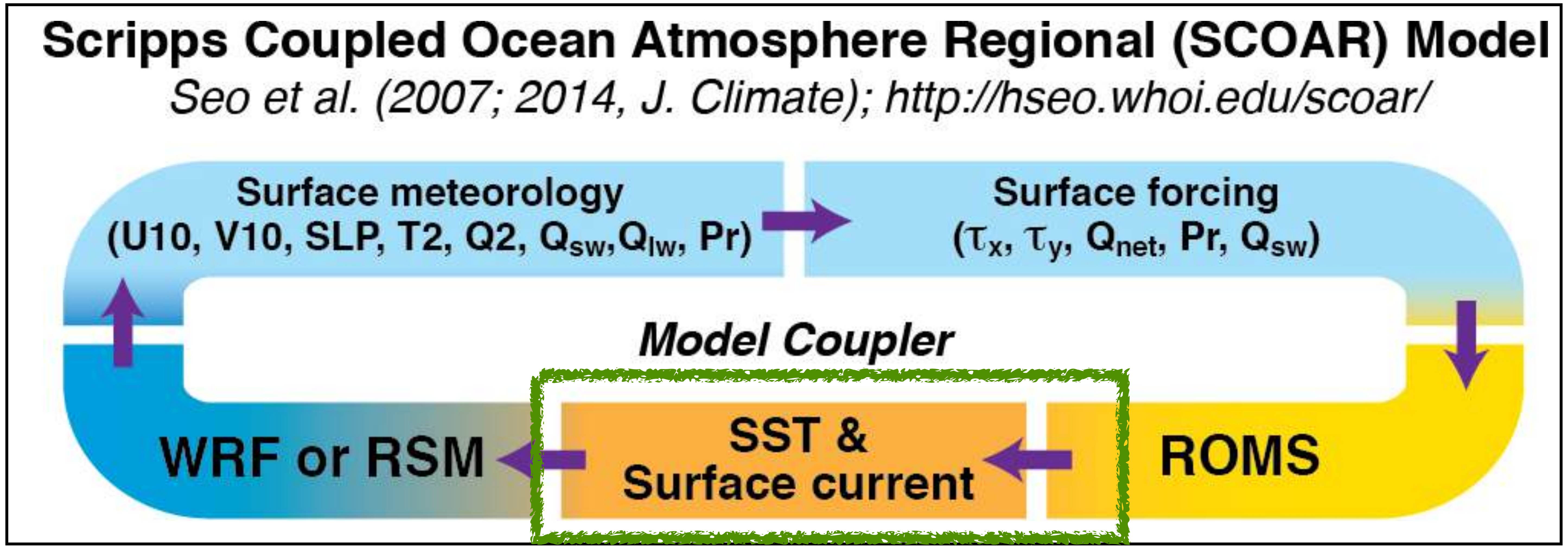
Examine effect of *eddy-driven* air-sea interaction
through SST and surface current
on energetics of the CCS and Ekman pumping

- 7 km O-A resolutions
- Driven by NCEP-FNL and SODA

- Suppresses the small-scale coupling but retain the large-scale coupling
- Up to 300 or 150km are considered small-scale

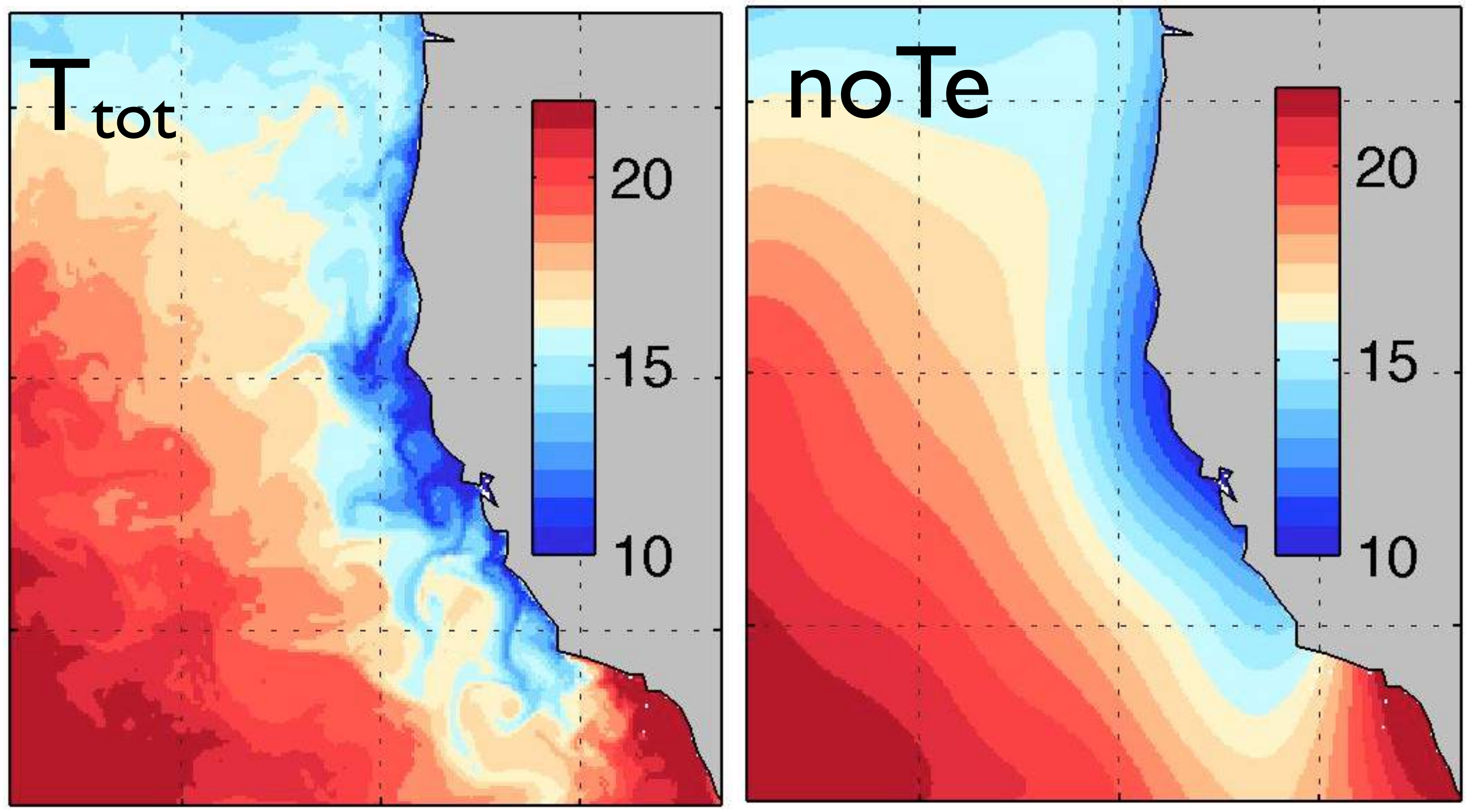
Experiments

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

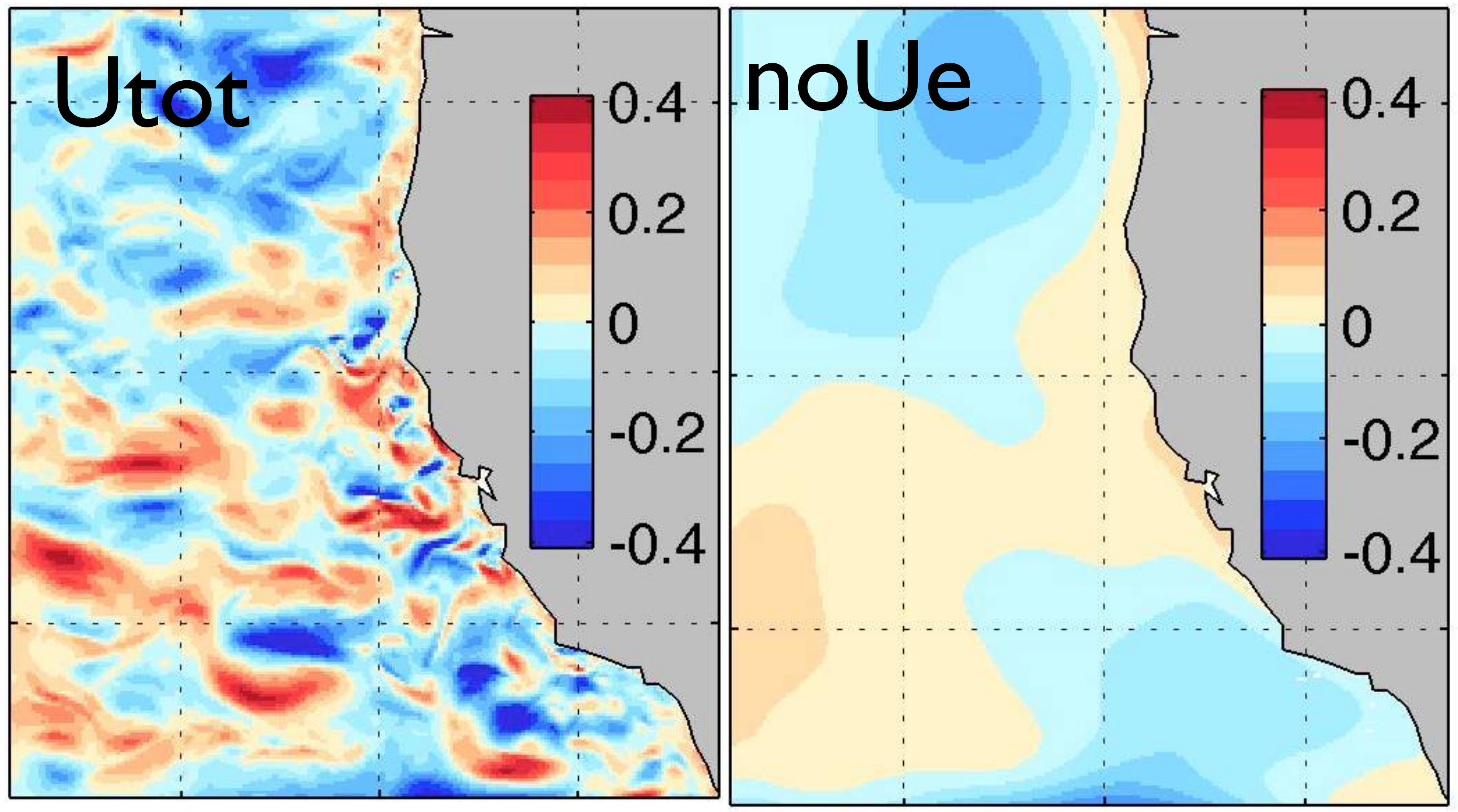


Experiments	τ formulation			
CTL	T_b	T_e	U_b	U_e
noT$_e$	T_b		U_b	U_e
noU$_e$	T_b	T_e	U_b	
noT$_e$U$_e$	T_b		U_b	
noU$_{tot}$	T_b	T_e		

SST



Surface currents

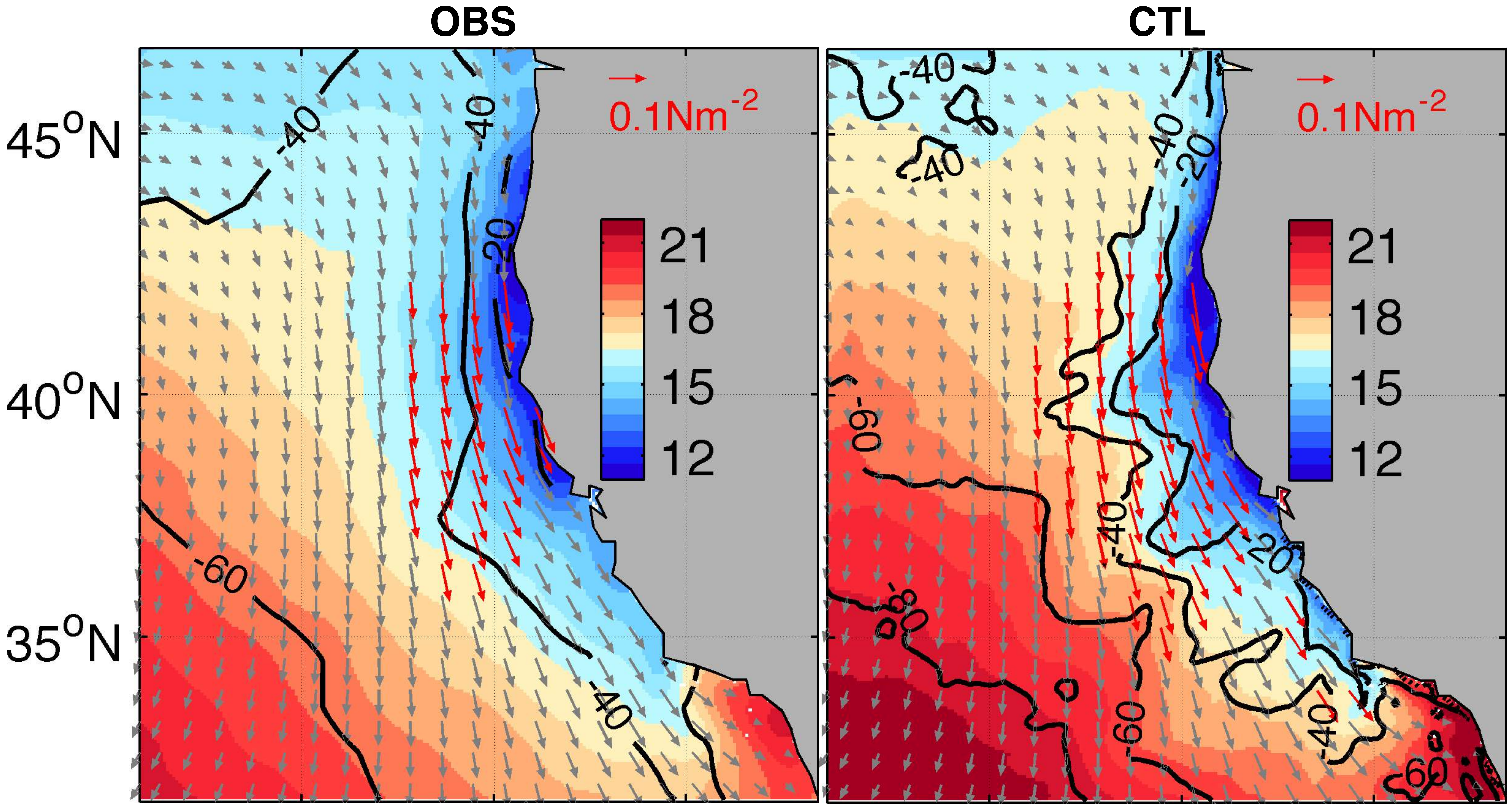


6-yr simulations:
2005-2010

CTL-noT$_e$: effect of T$_e$
CTL-noU$_e$: effect of U$_e$

Simulated summertime climatology in CTL

SST, wind stress, and latent heat flux



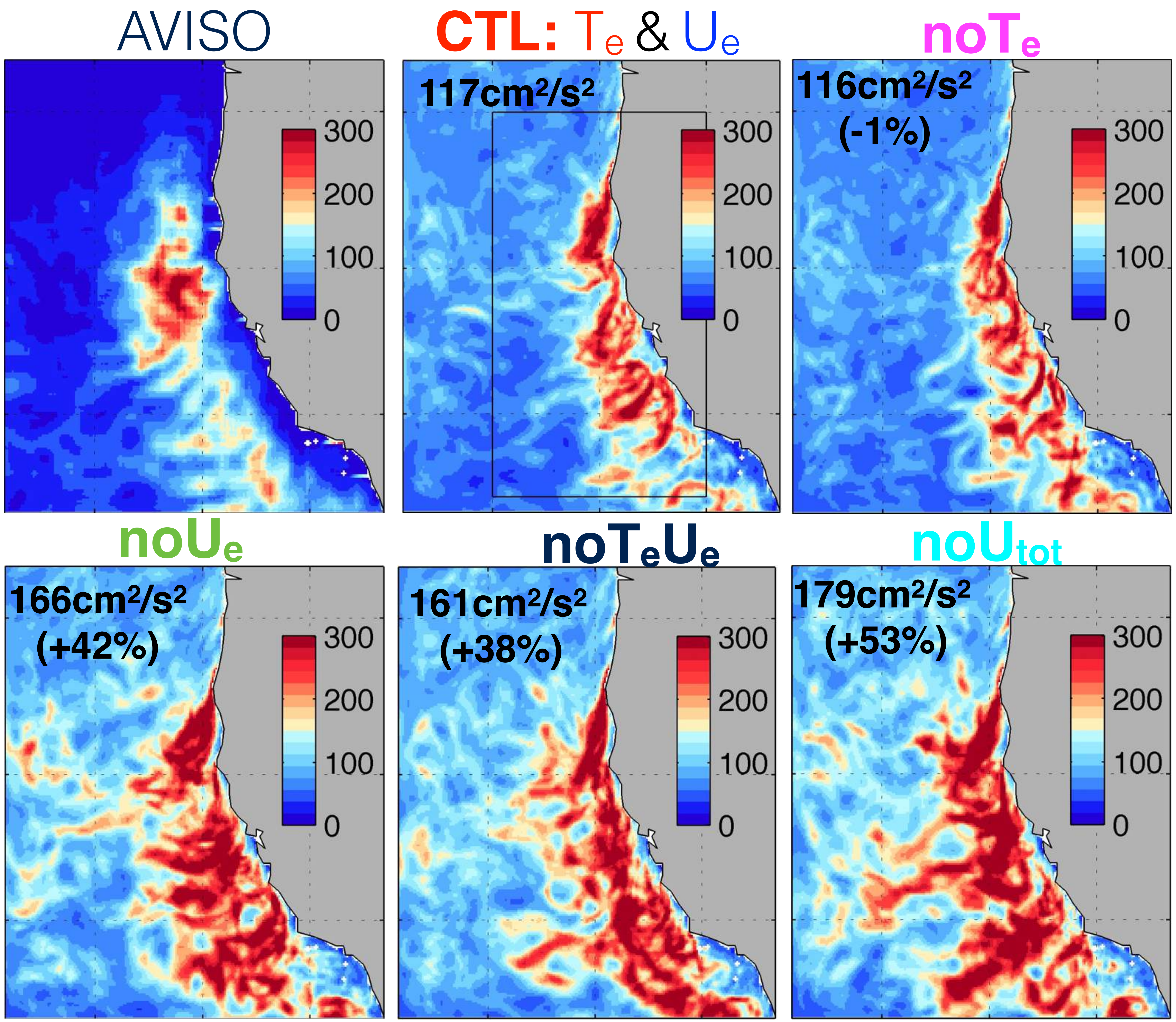
2005-2010 JJAS

SODA SST, QuikSCAT wind stress and OAFLUX LH

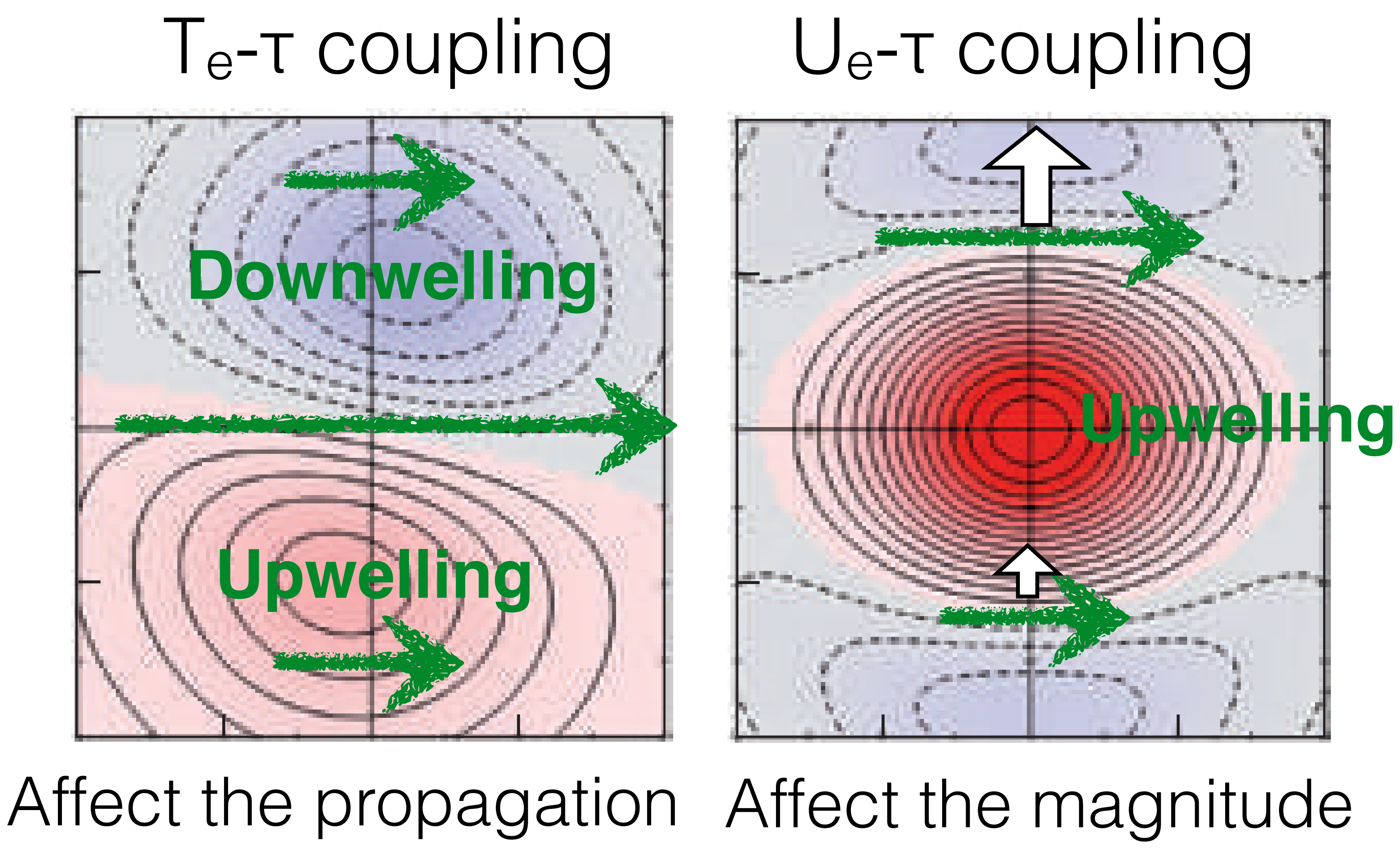
Summertime eddy kinetic energy

(eddies defined as deviation from time-mean)

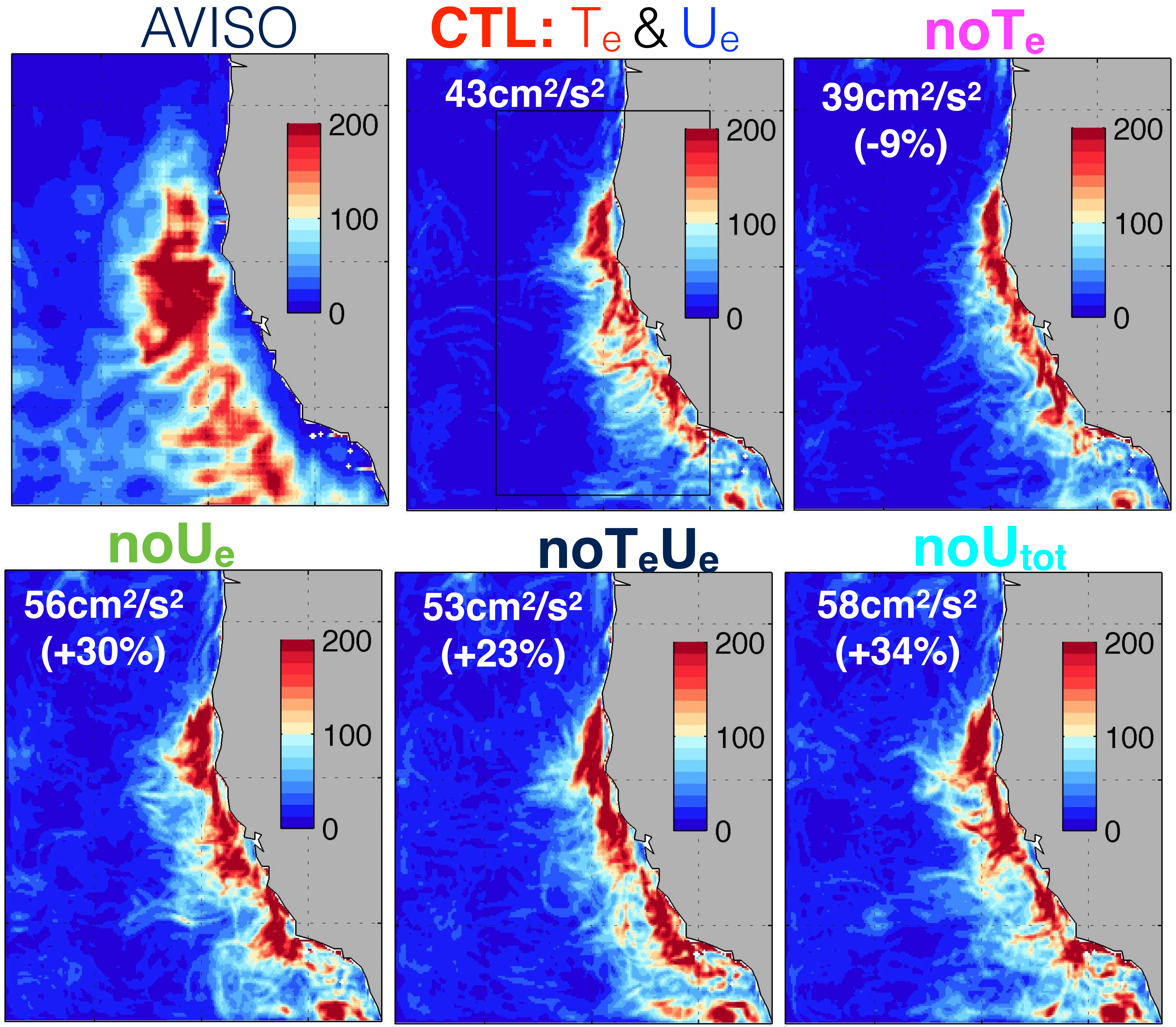
JAS 2005-2010



- Te-τ has no impact on EKE
- Ue-τ reduces the EKE substantially
- Utot-τ reduces the EKE only slightly more (additional 10%)
  - → The EKE reduction by under-stress occurs largely due to small-scale coupling



Summertime eddy kinetic energy;
(eddies defined as deviation from 3°×3° mean)



- Same result;
- Eddy-wind coupling reduces the EKE through surface currents,
- The damping is largely on eddy-scales.

Weakened EKE with U_e-τ:
EKE budget and Ekman pumping

Eddy energetics in CTL

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

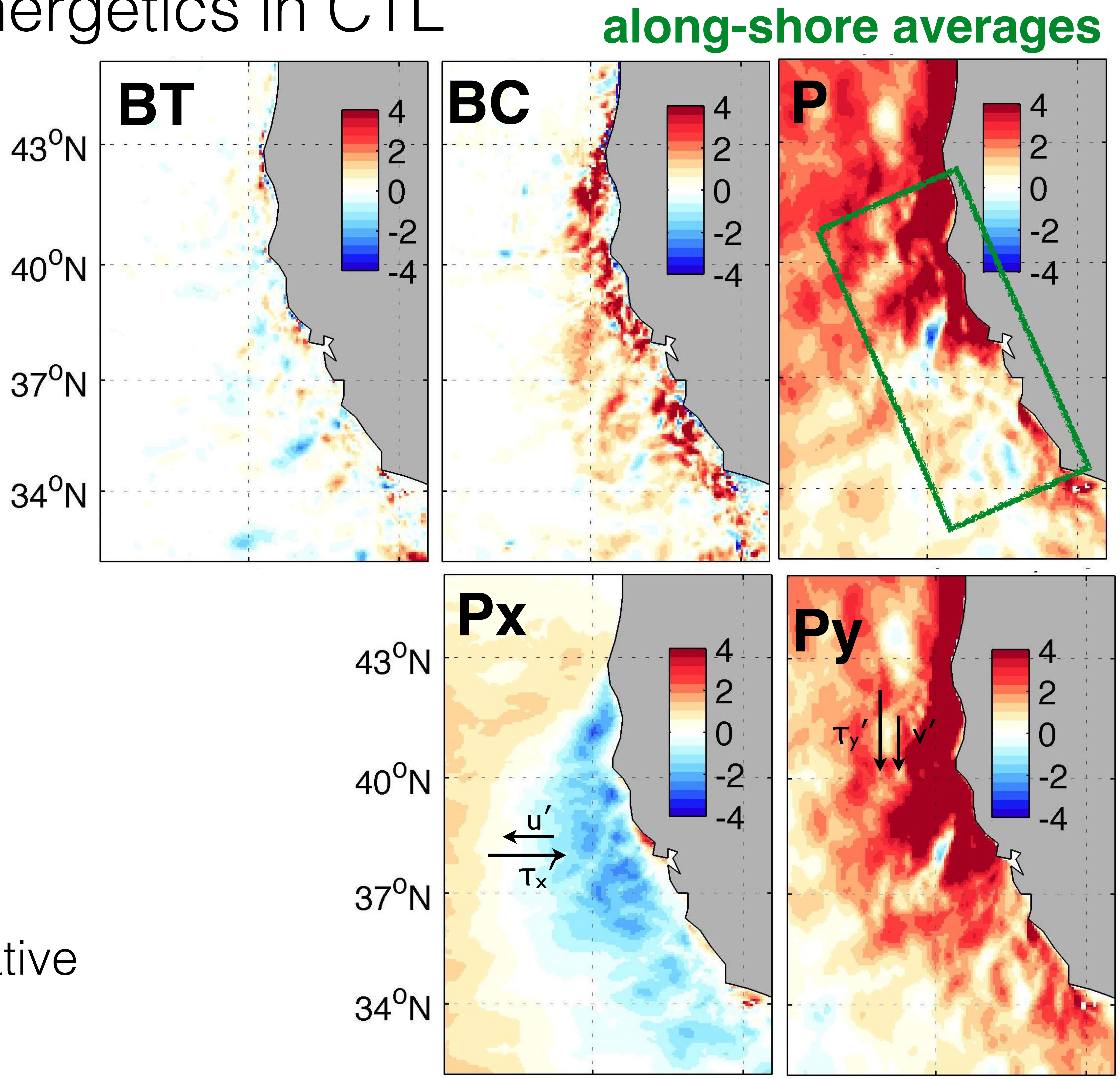
$K_m \rightarrow K_e$ barotropic conversion (BT)

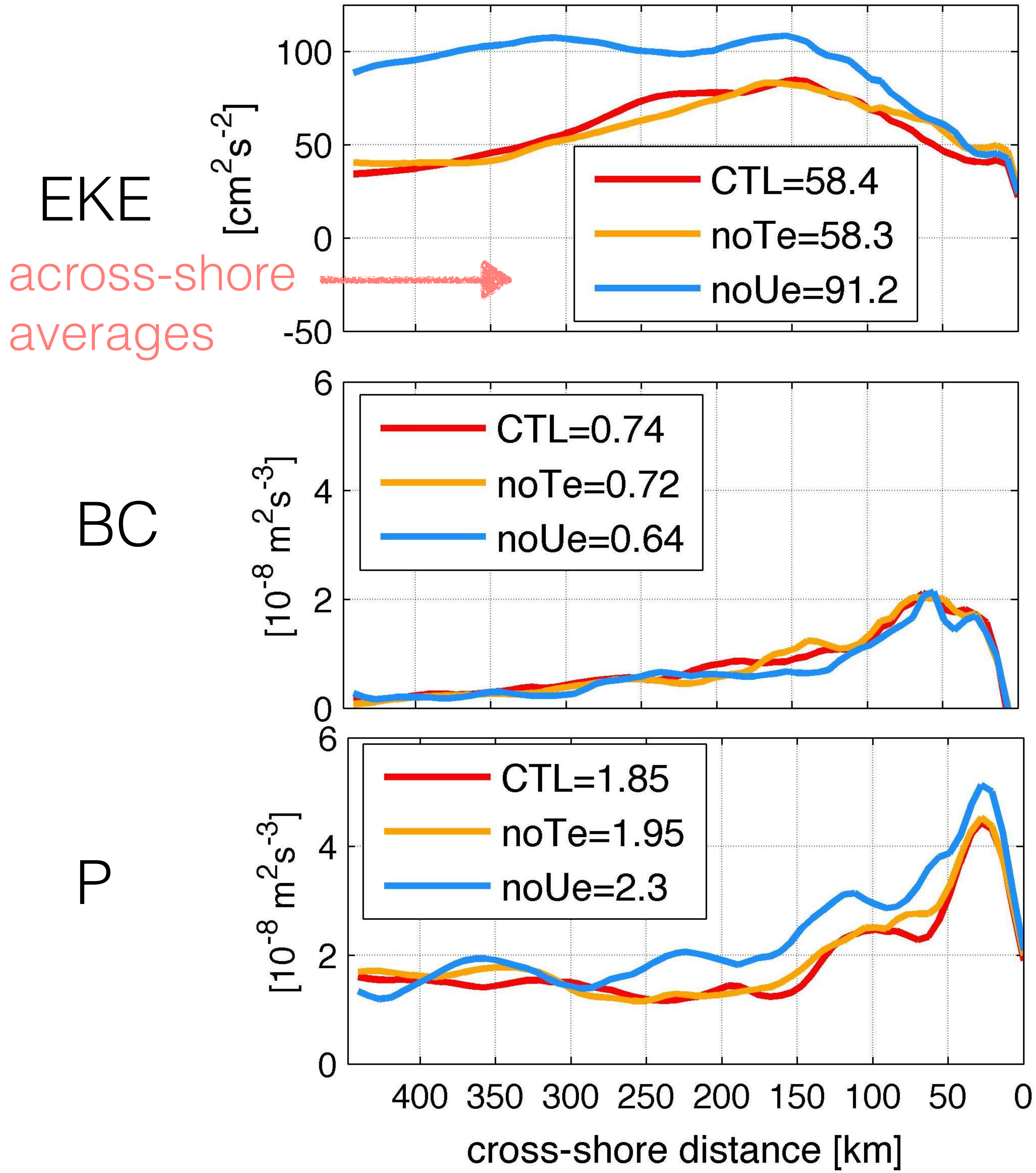
$$\mathrm{BC} = -\frac{g}{\rho_0}\overline{\rho' w'},$$

$P_e \rightarrow K_e$ baroclinic conversion (BC)

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

Wind work if positive, eddy drag if negative

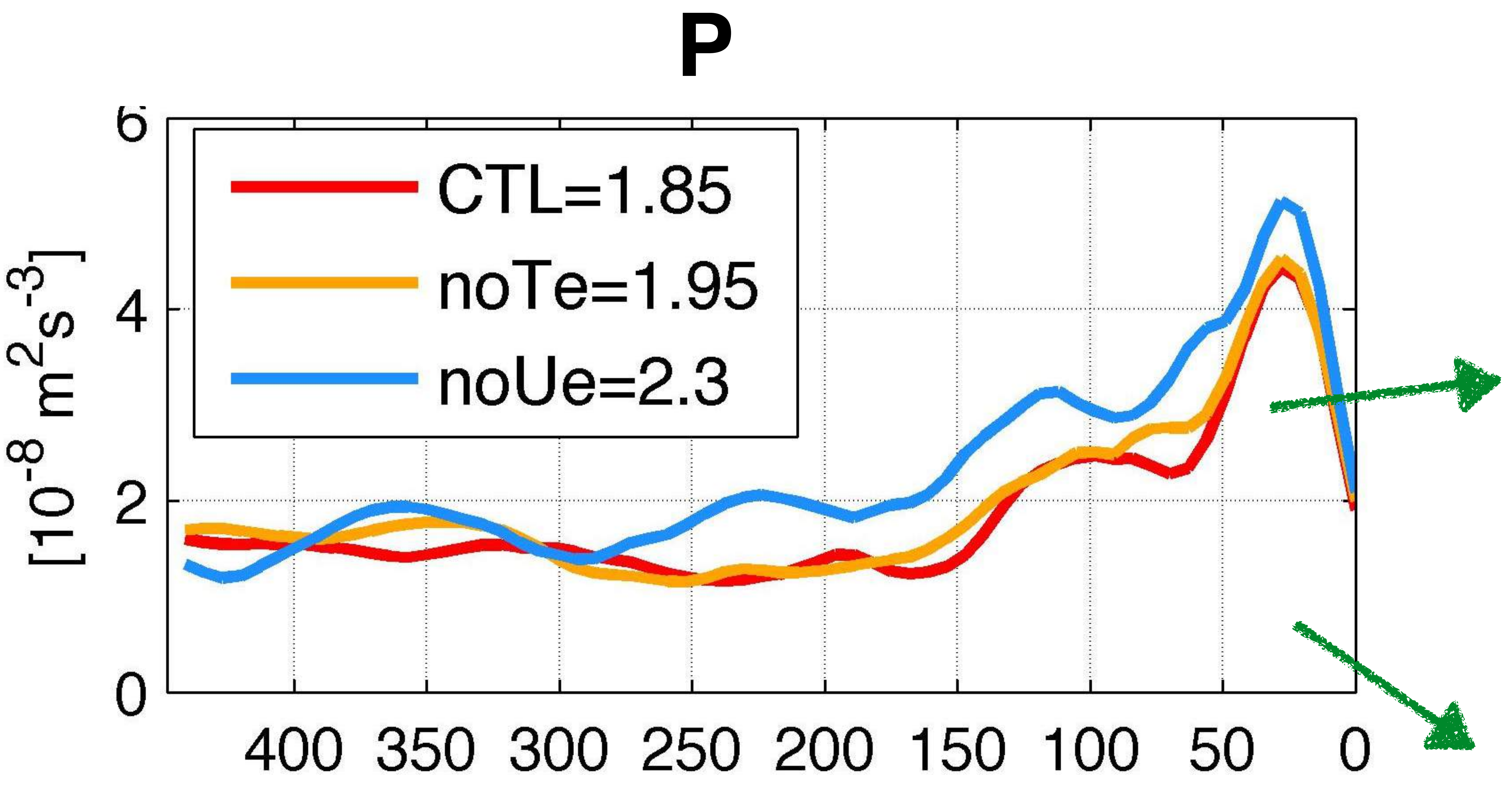


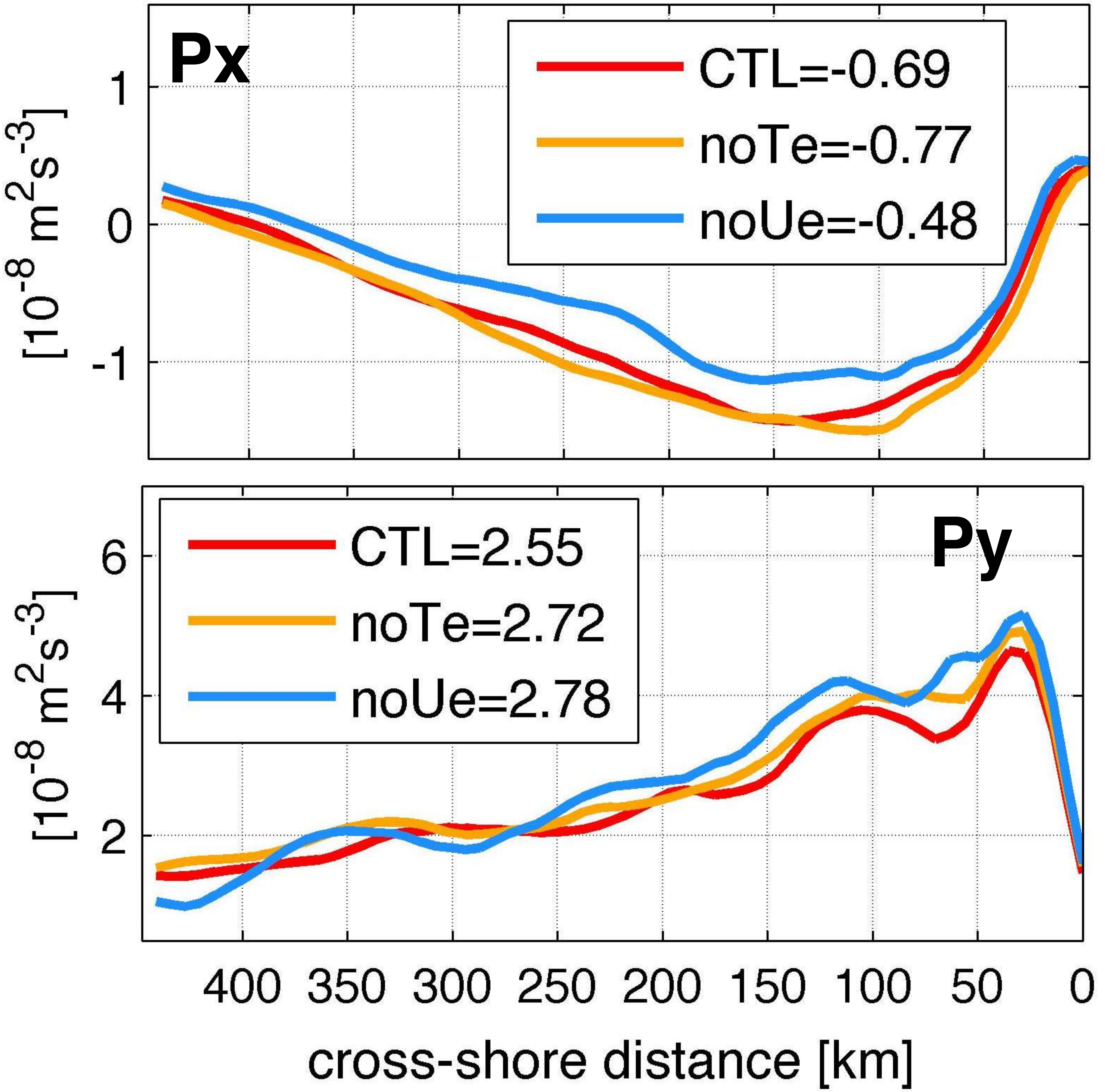


Across-shore distribution of EKE budget terms

- **Baroclinic conversion**
  - Only a small reduction in noUe → can't explain the higher EKE
- **Eddy-wind interaction**
  - 24% increase in noUe over the eddy-rich coastal zone (up to ~300 km) → Ue-τ reduces the wind work

Ue-τ coupling increases the eddy drag and reduces the momentum input





- In noUe, 30% weaker eddy drag
- In noUe 7-10% stronger wind work

  → Changes in absolute magnitude are comparable

Eddy-driven Ekman pumping velocity

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

$$\approx \frac{\nabla \times \boldsymbol{\tau}_{SST}}{\rho_0(f+\zeta)} - \frac{1}{\rho_0(f+\zeta)^2}\left(\tilde{\tau}_y \frac{\partial \zeta}{\partial x} - \tilde{\tau}_x \frac{\partial \zeta}{\partial y}\right) + \frac{\nabla \times \tilde{\boldsymbol{\tau}}}{\rho_0(f+\zeta)} + \frac{\beta \tau^x}{\rho_0(f+\zeta)^2}$$

Stern 1965
Gaube et al. 2015

W_{SST}: SST induced Ekman pumping
Chelton et al. (2001)

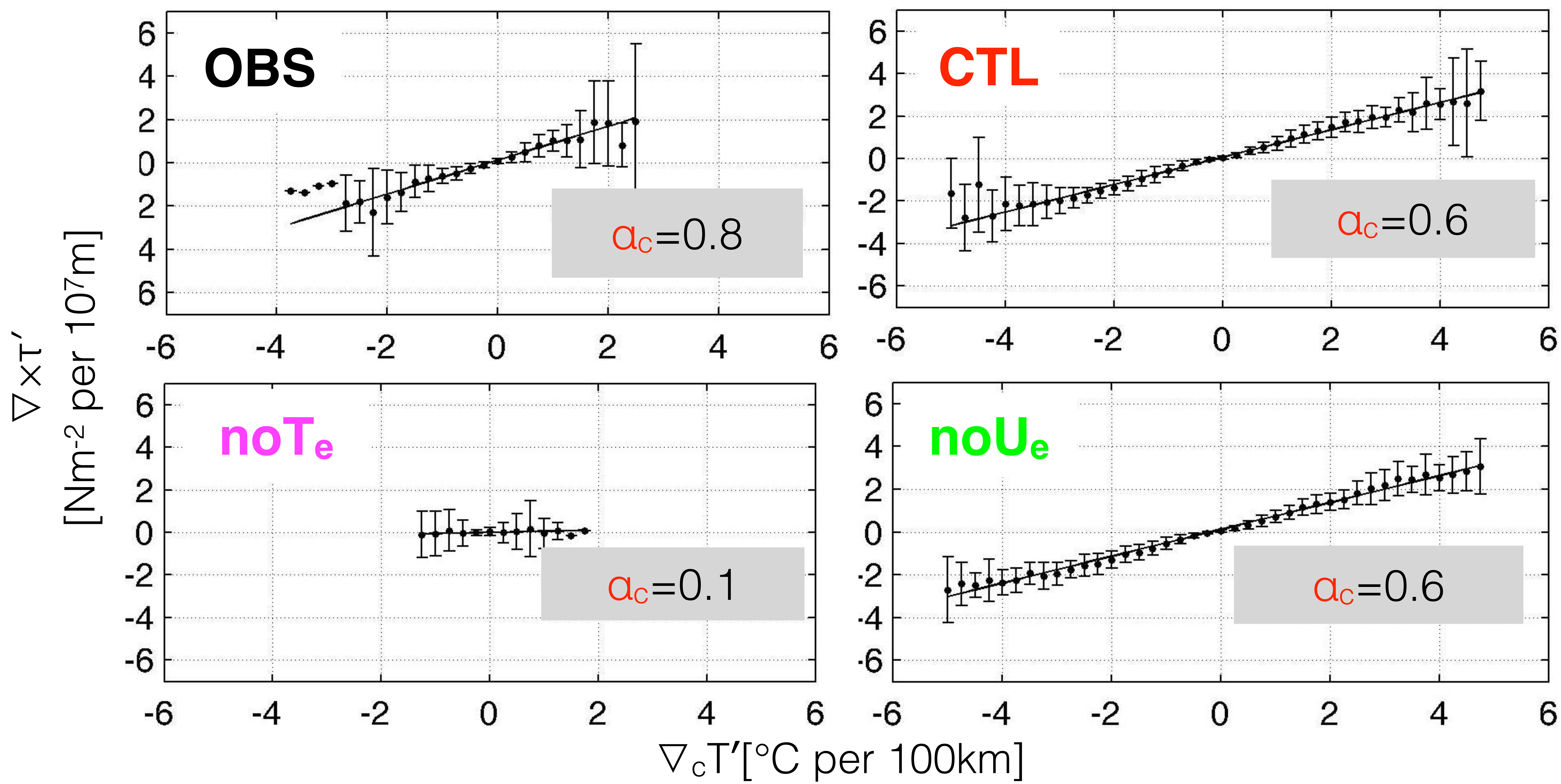
W_{ζ}: Surface vorticity gradient-induced nonlinear Ekman pumping

W_{LIN}: Curl-induced linear Ekman pumping

W_{β}: β Ekman pumping (negligible)

Estimating eddy SST-driven Ekman pumping velocity

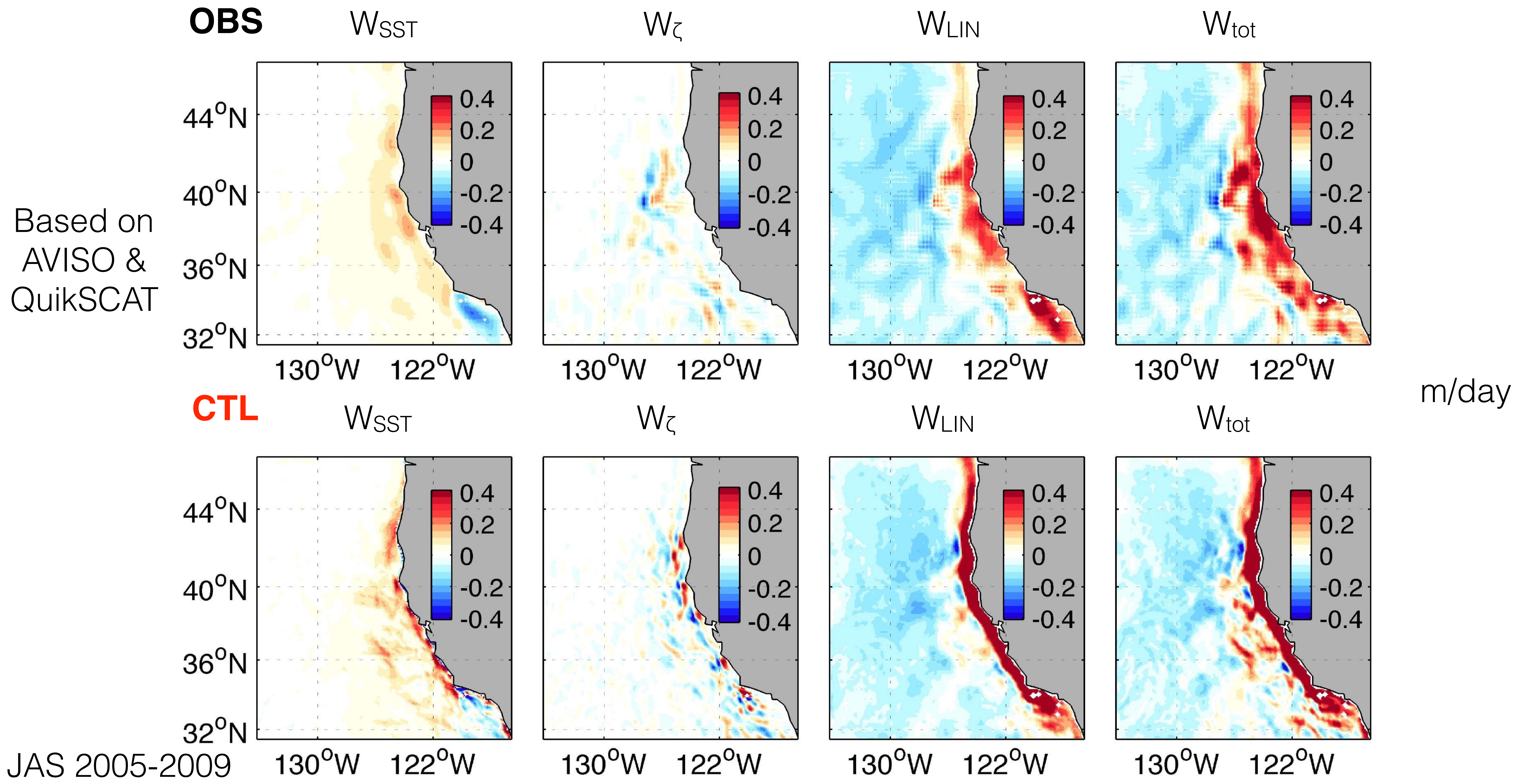
$$W_{SST} = \frac{\nabla \times \tau'_{SST}}{\rho_o(f+\zeta)} \approx \frac{\alpha_c \nabla_c SST}{\rho_o(f+\zeta)}$$



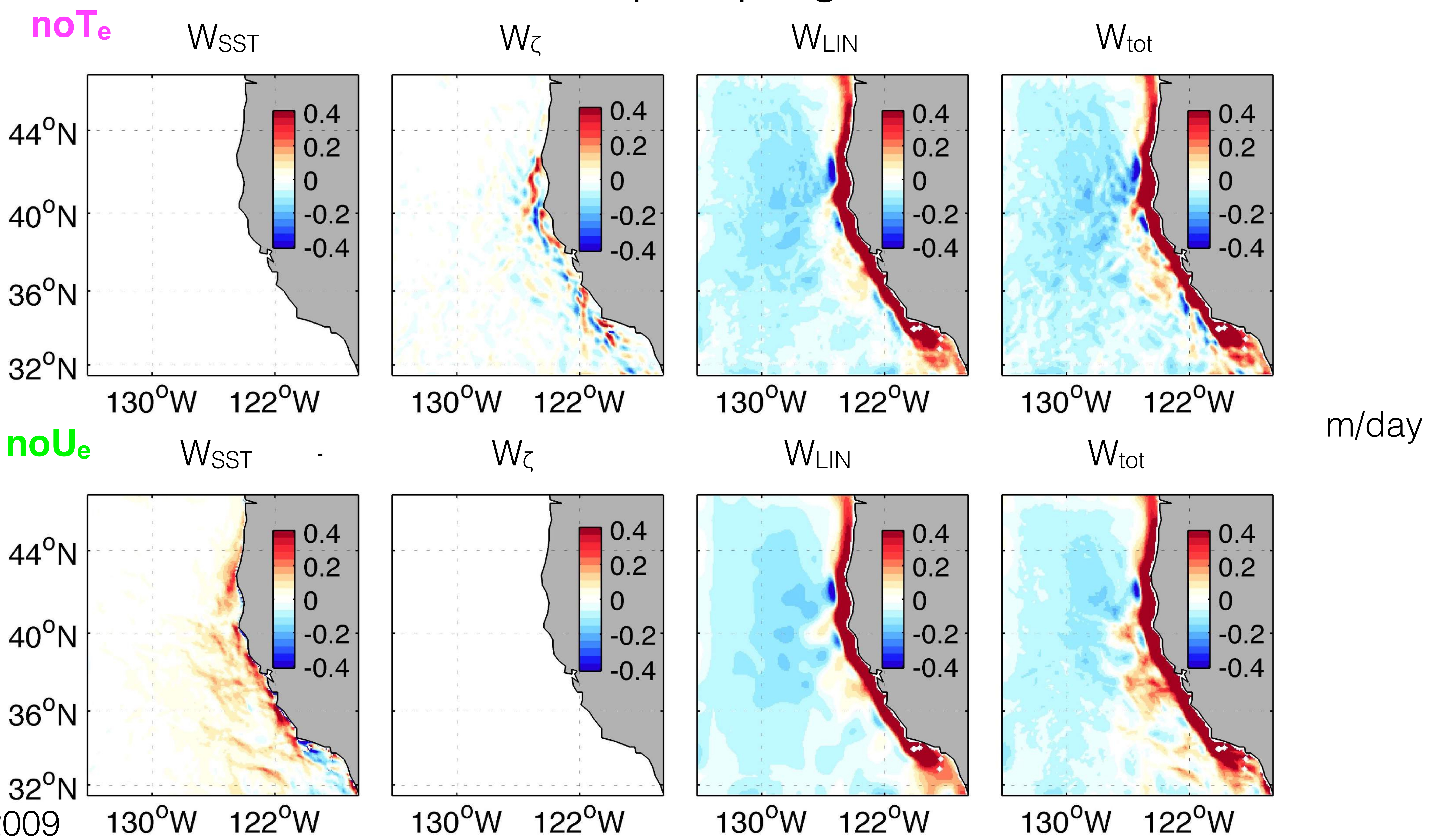
JAS 2005-2009

OBS based on QuikSCAT wind stress and TRMM SST

Estimated Ekman pumping velocities



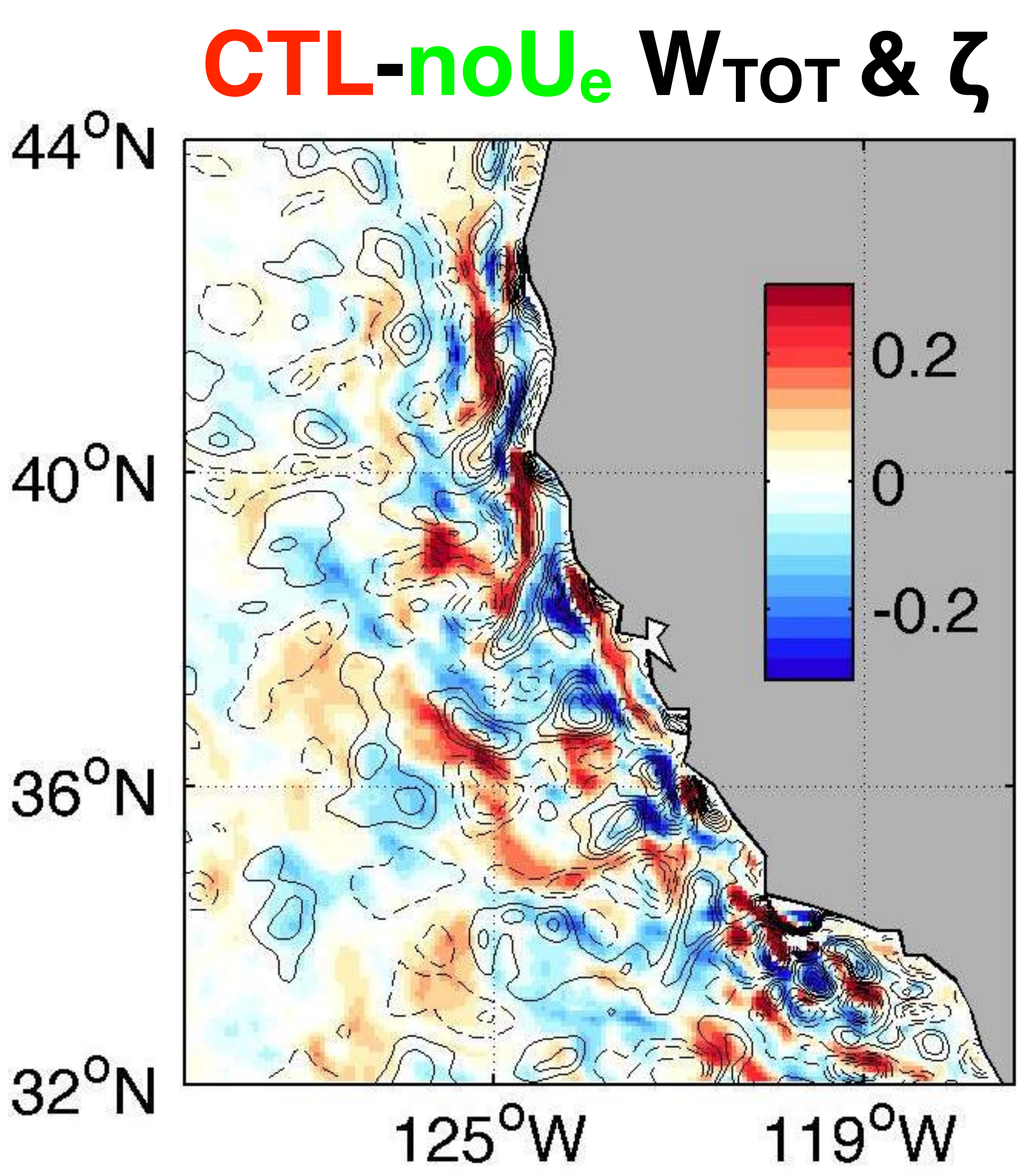
Estimated Ekman pumping velocities

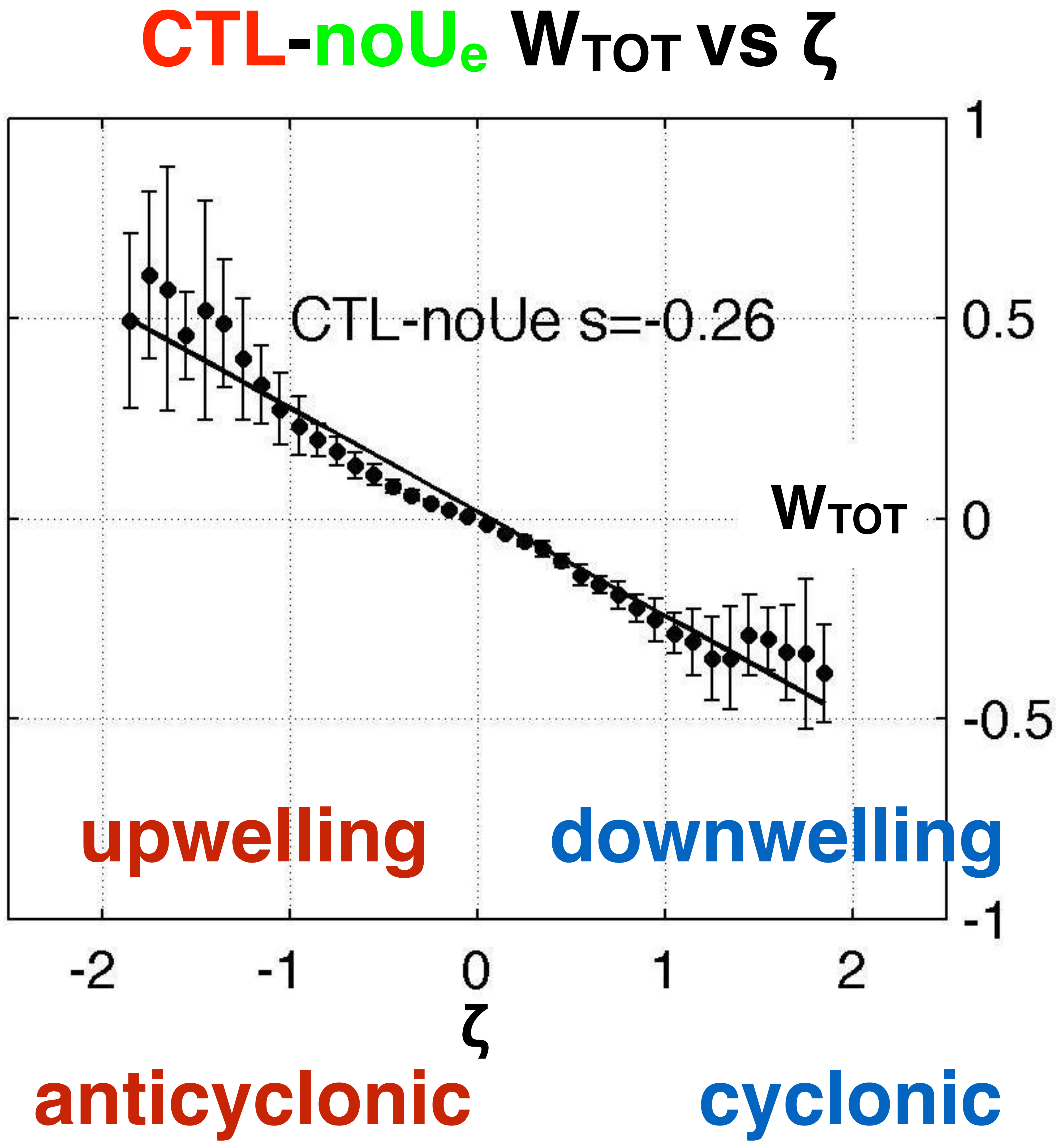


JAS 2005-2009

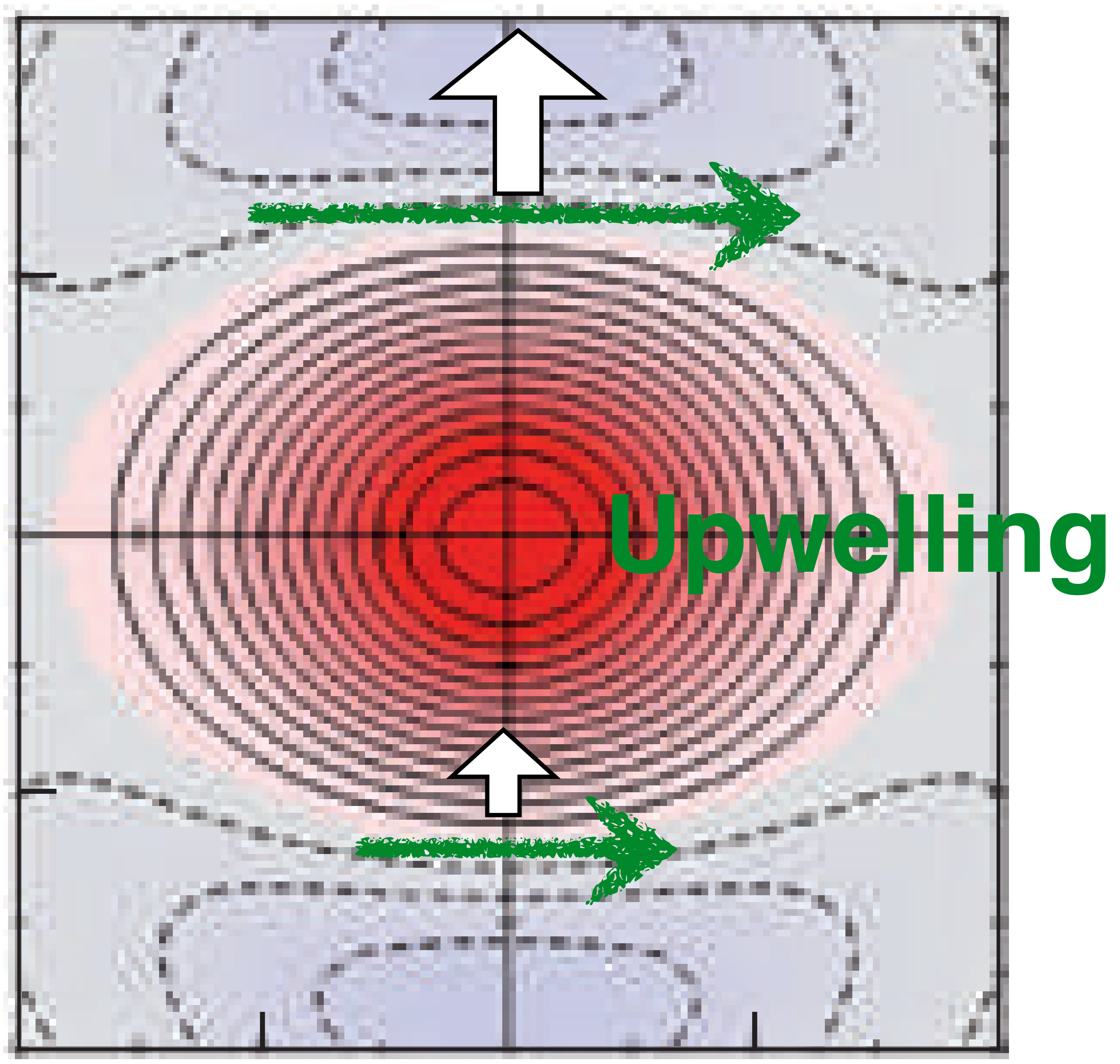
Inferred feedback to eddy activity through Wζ

Total Ekman pumping velocity difference





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

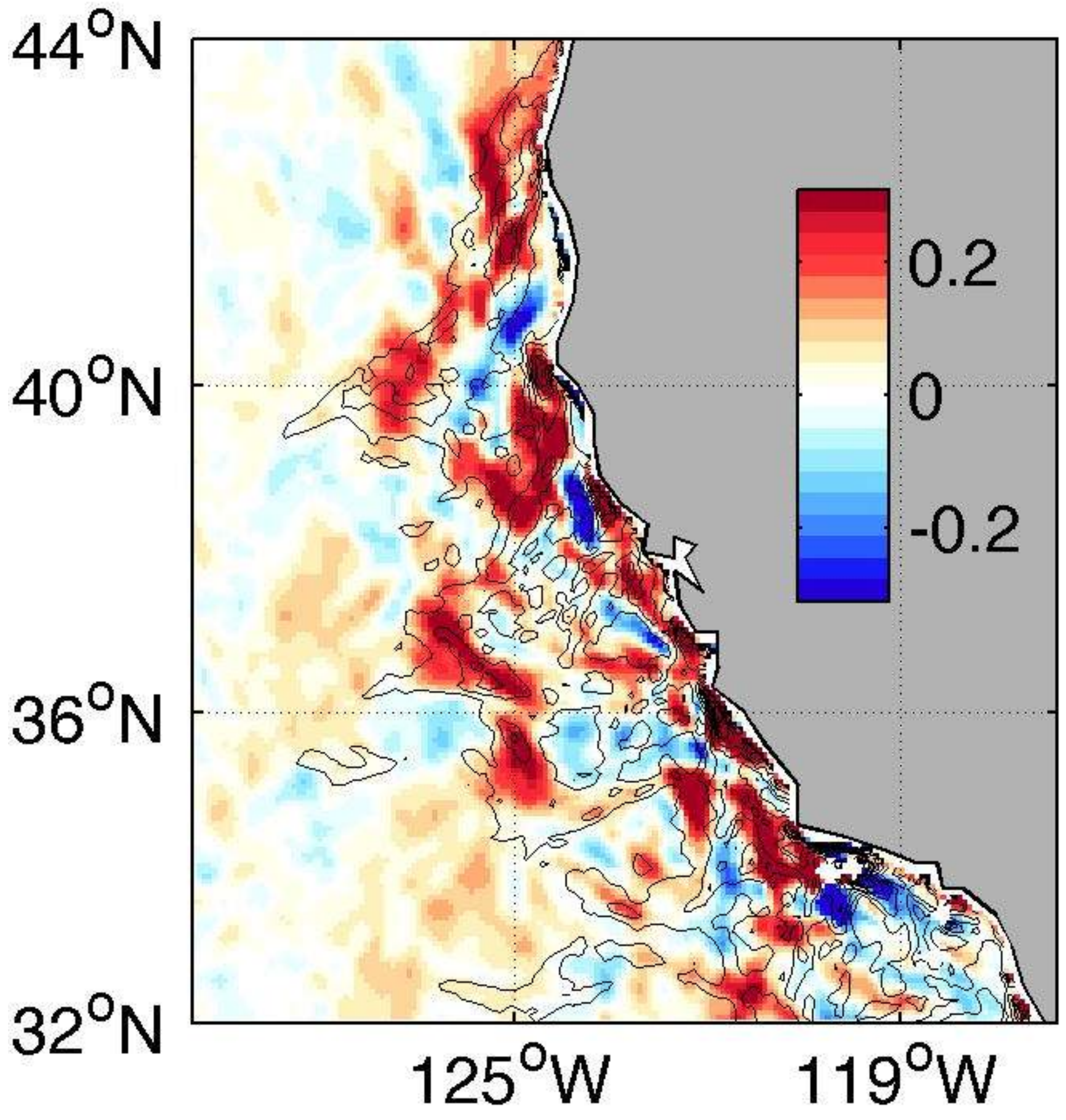


JAS 2005-2010

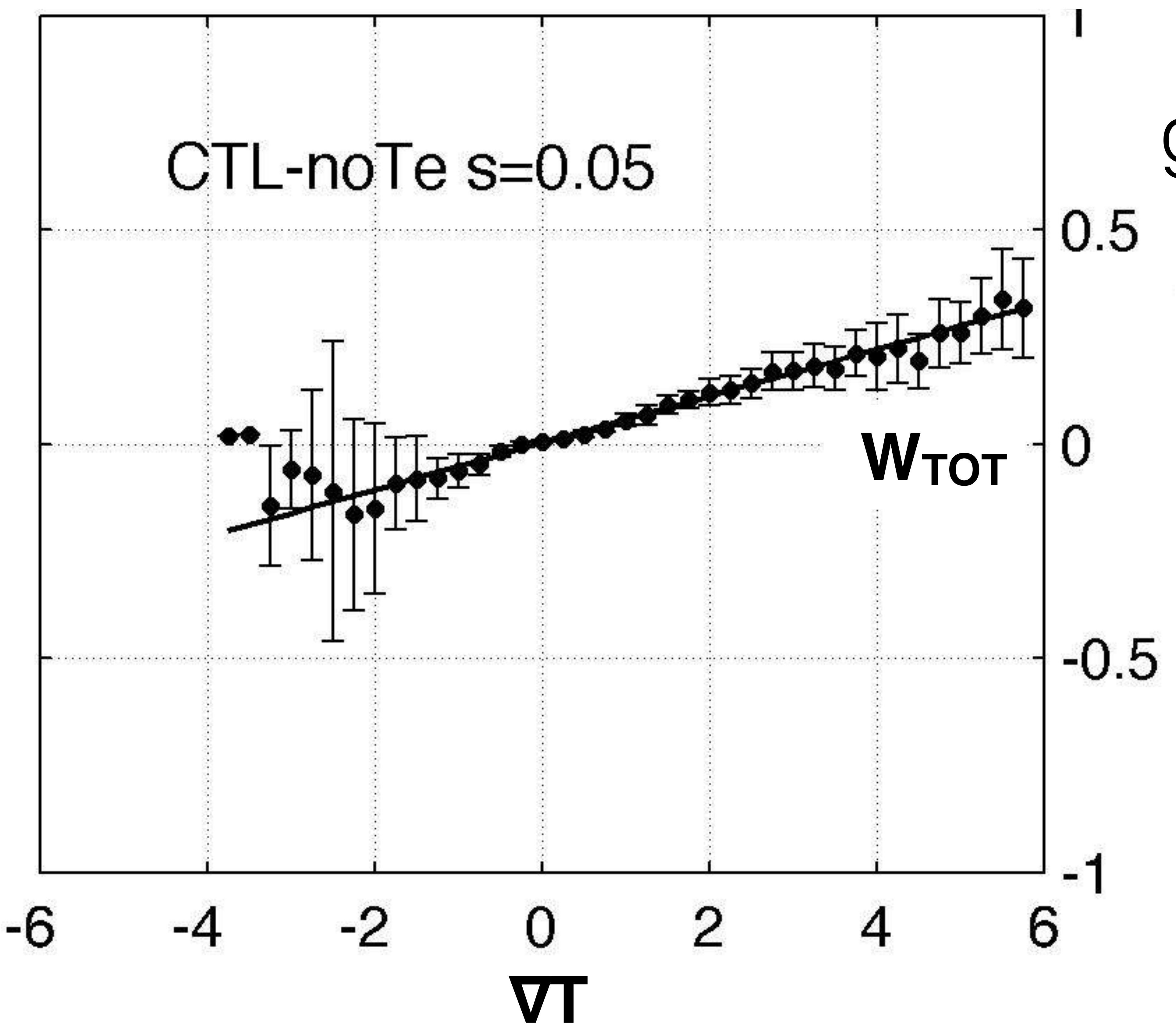
Inferred Feedback to eddy activities through W_{SST}

Total Ekman pumping velocity difference

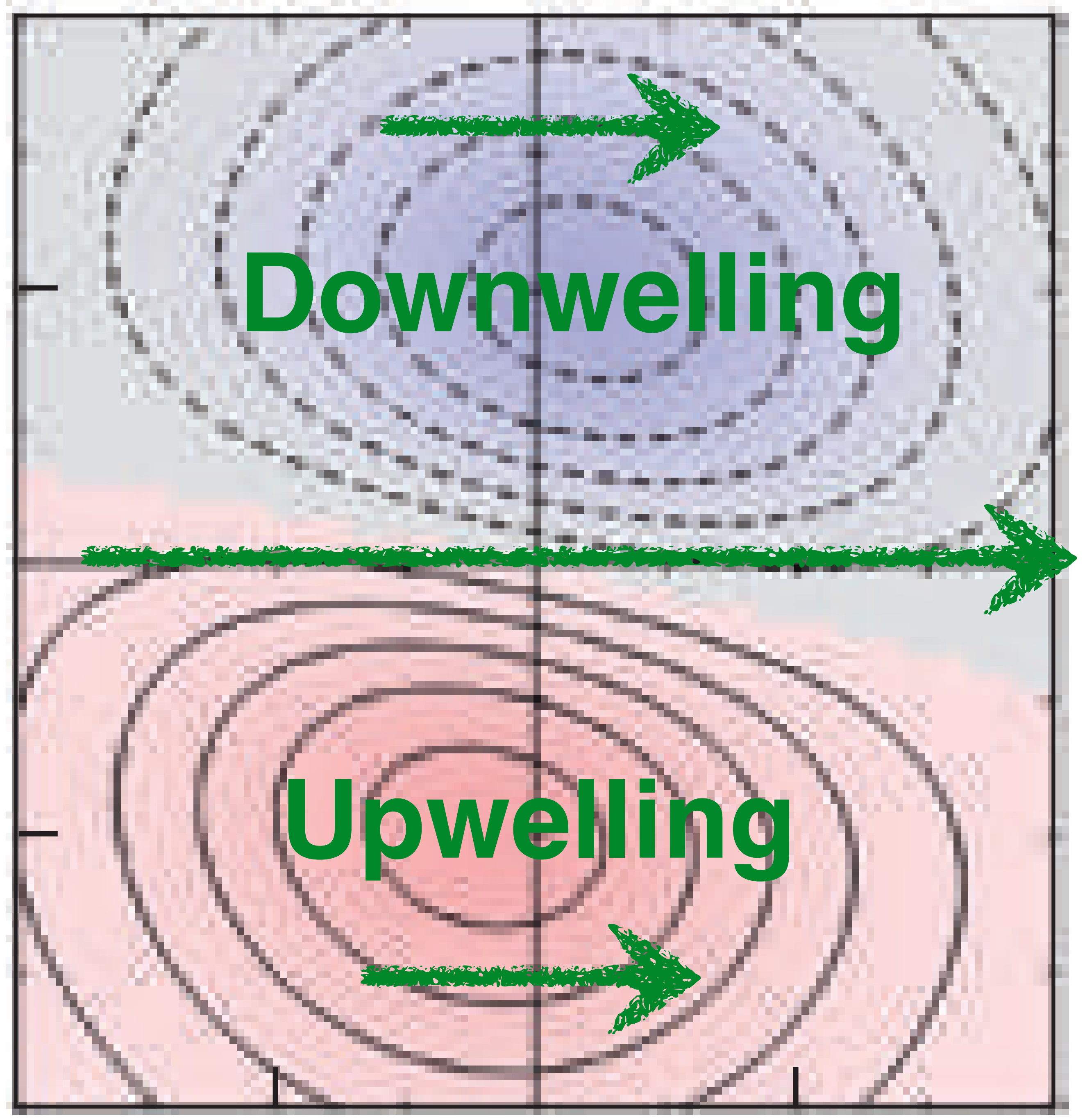
CTL-noT$_e$ W_{TOT} & ∇T



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

Summary and Discussion

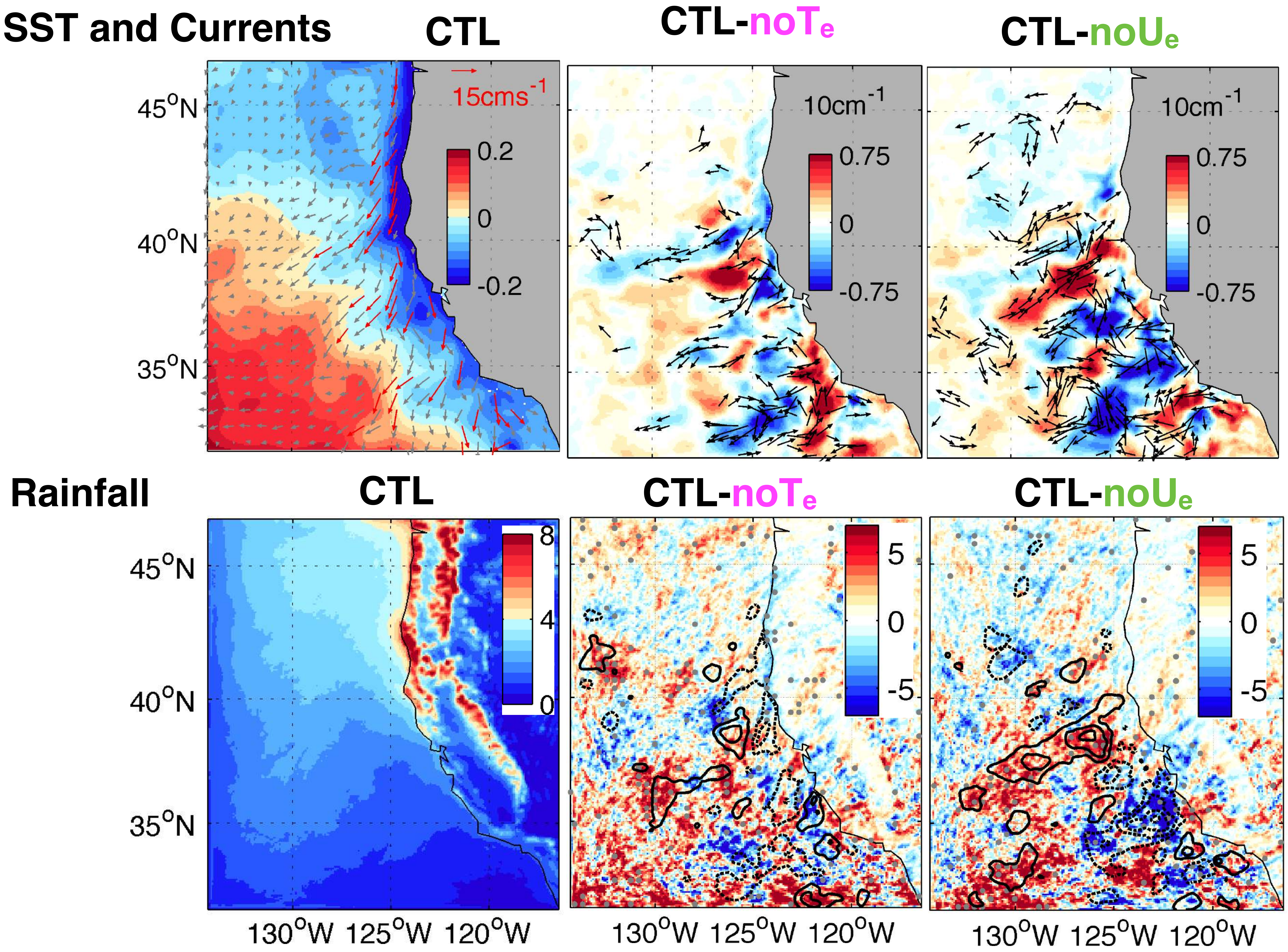
A significant role of eddy-driven air-sea interaction through surface currents in the energetics of the CCS and the Ekman pumping velocity

- The weakened EKE due to reduced wind momentum input and enhanced eddy drag (of nearly equal importance).

- Eddies modify the Ekman vertical velocities
  - W_ζ suppresses the eddy activity
  - W_{SST} may influences the eddy propagation
    - Eddy-centric analysis to examine the changes in propagation characteristics of the eddies (e.g., Gaube et al. 2015; Renault et al. 2016)

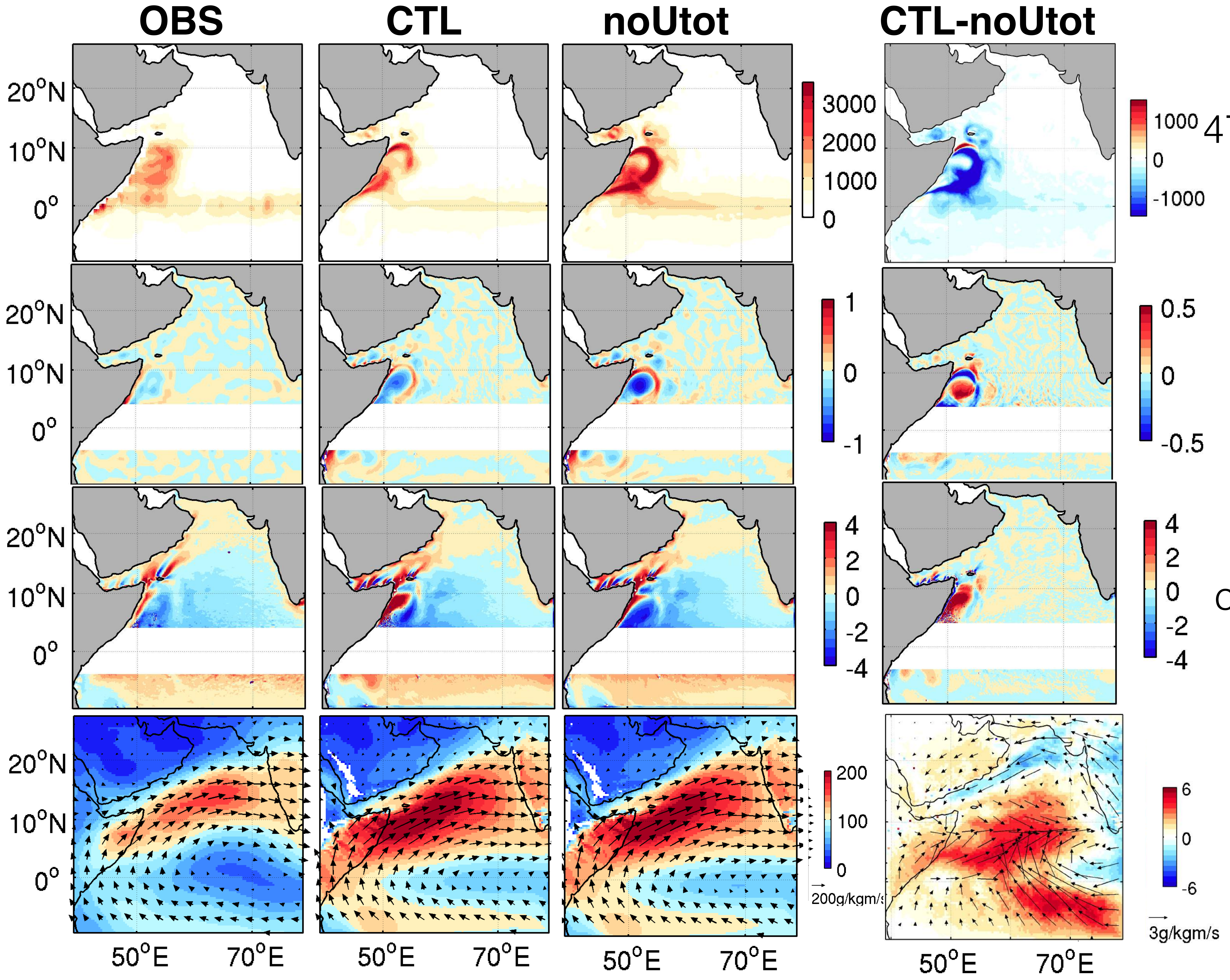
- Would the eddy-wind interactions affect the atmosphere beyond the boundary layer?

Rectified changes in SST and rainfall



- SST anomalies are driven by the changes in offshore temperature advection in the mixed layer.
- Small (3-5%) change in rainfall, but it does reflect the local SST anomaly.

Ongoing work: Arabian Sea circulation system and the Findlater Jet



EKE (Somali Current) — 47% weaker flow fields

ζ/f — Weaker Great Whirl anticyclone

total Ekman pumping — Stronger cyclonic forcing over the GW

Moisture transport by the Findlater Jet — Some intensification and shift in the FJ moisture transport

Planned work: WBCs and the midlatitude storm track

WBC downstream influence on the weather system development

Thanks!

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Seo, Miller, Norris, 2016:
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