Eddy-wind interaction in the California Current System
— Eddy kinetic energy and Ekman pumping

Hyodae Seo
Woods Hole Oceanographic Institution

RIAM, Kyushu University
December 15, 2014

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Eddy-wind interaction via SST

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10m wind

$U_a = U_{ab} + \underline{U_{aSST}}$

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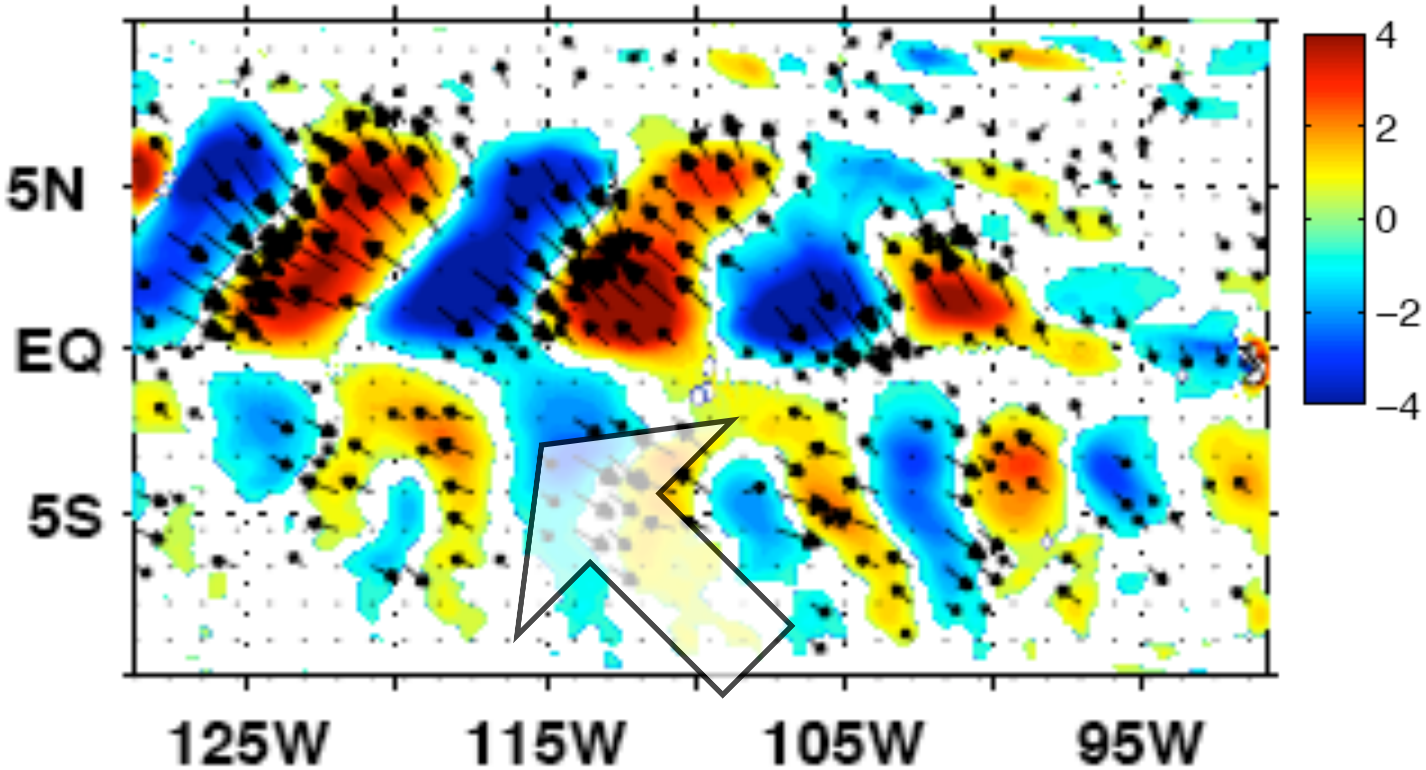
higher wind over warmer SST



U_{ab}: background south easterlies

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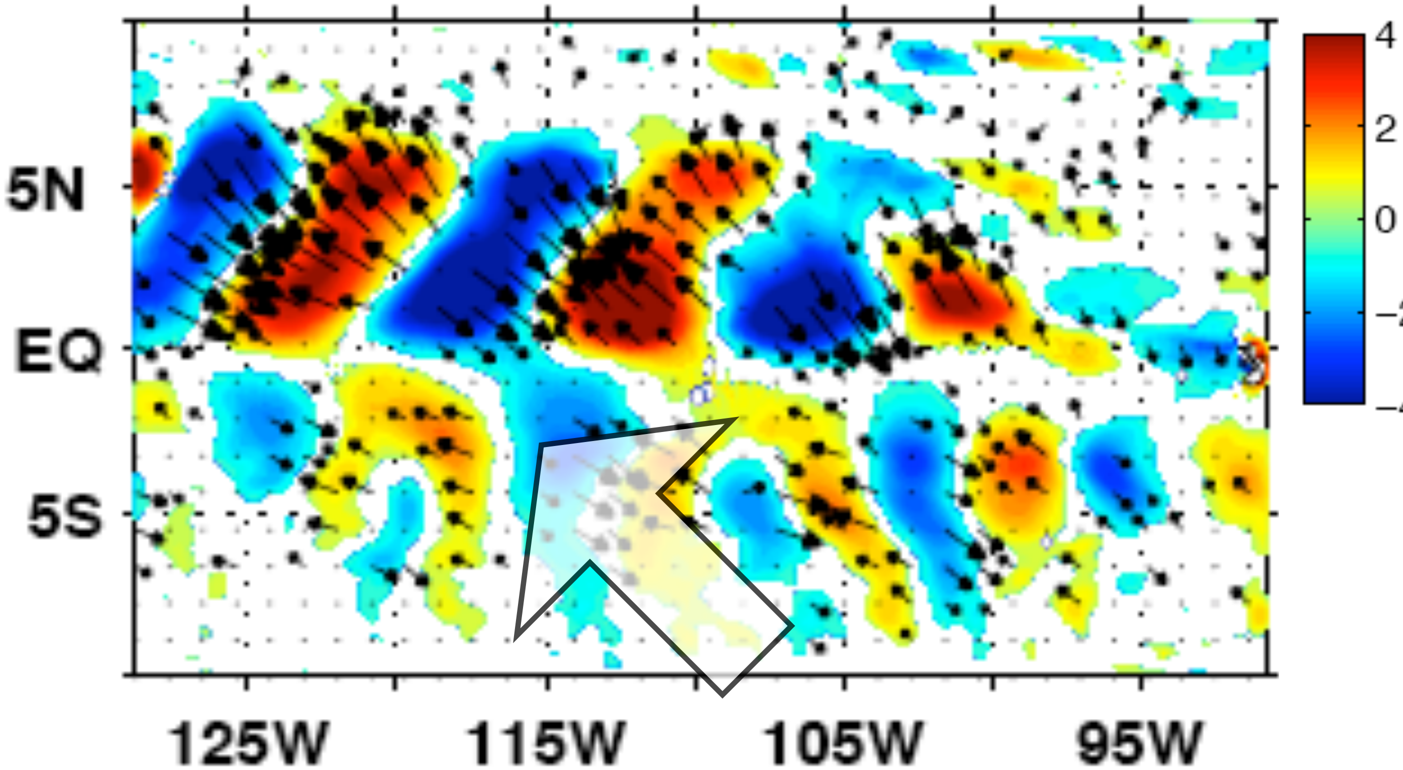

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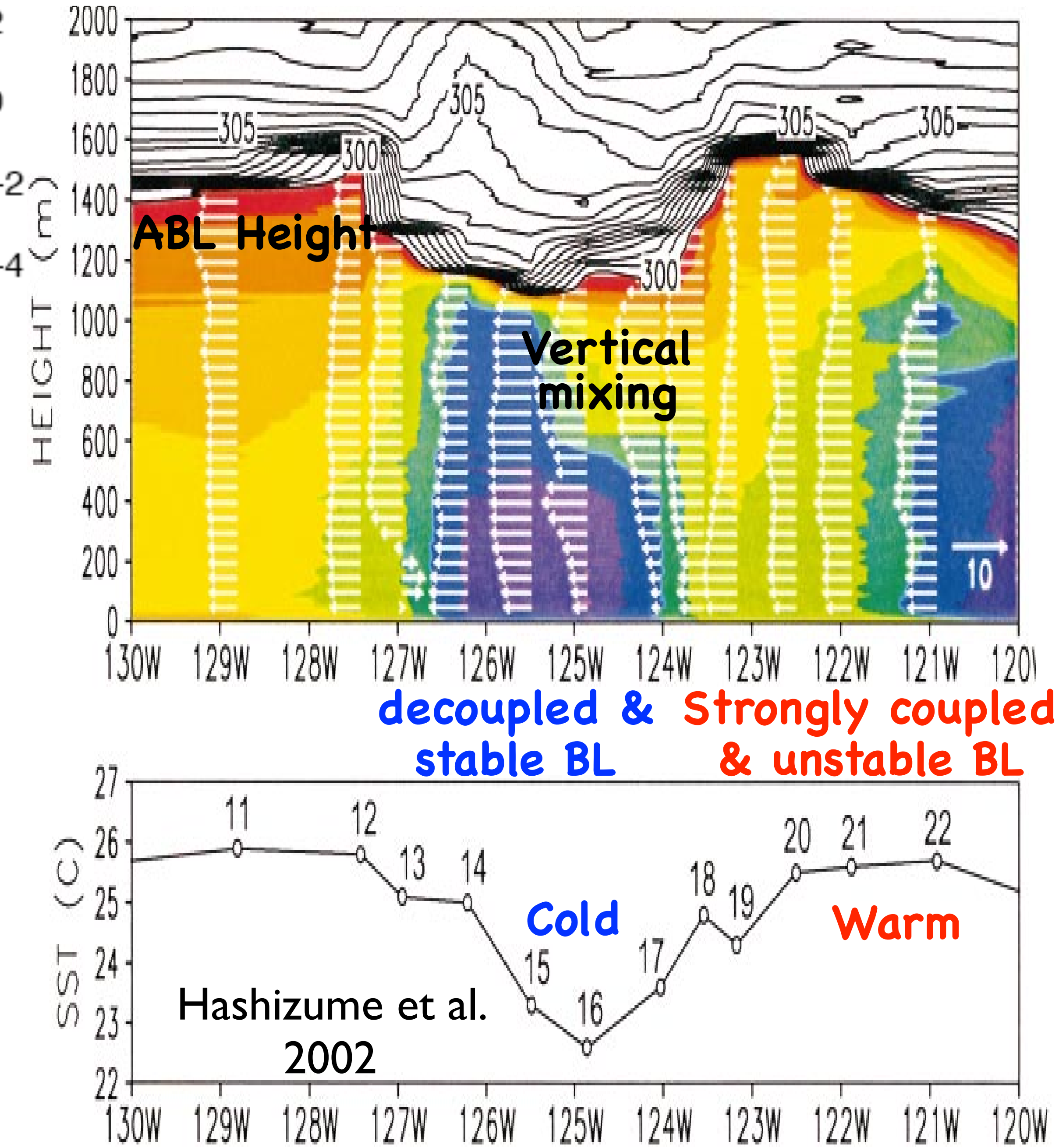

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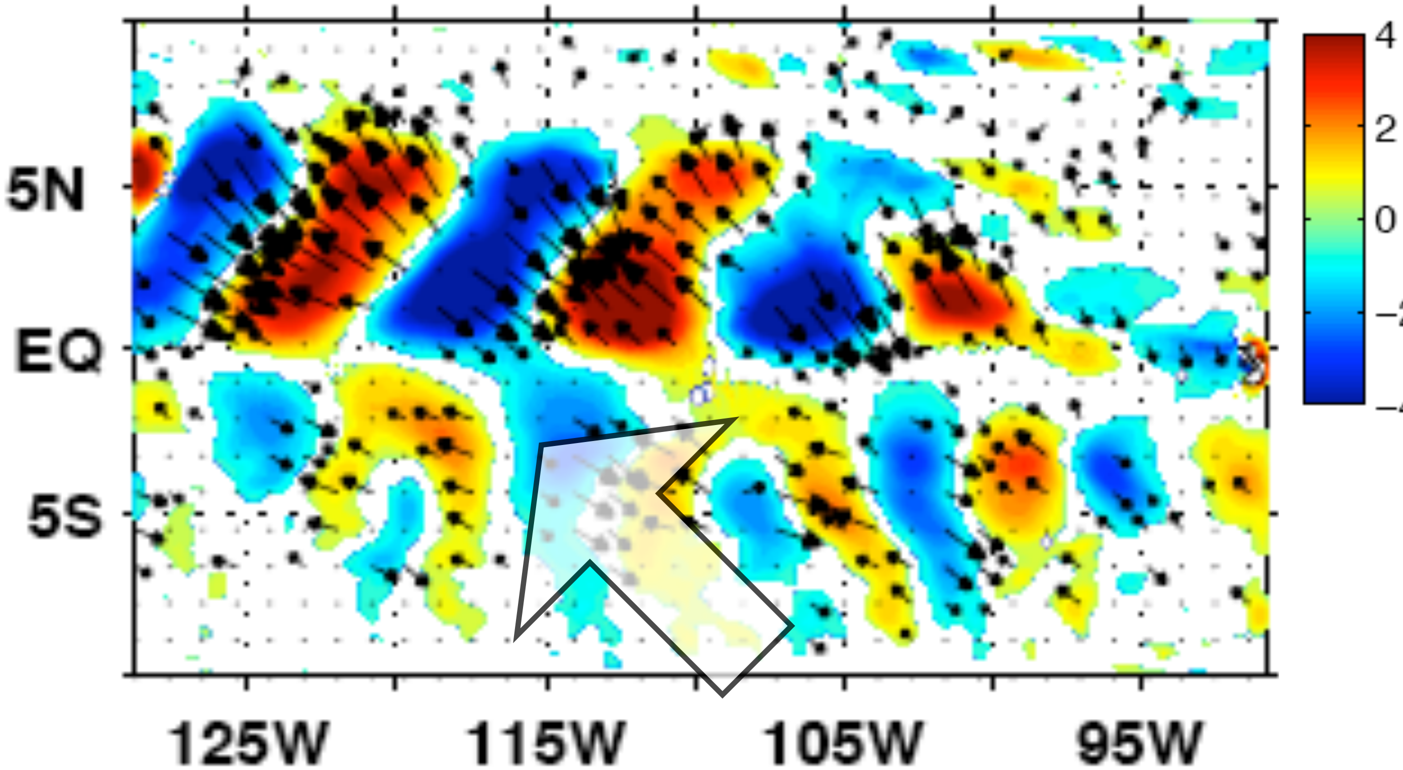
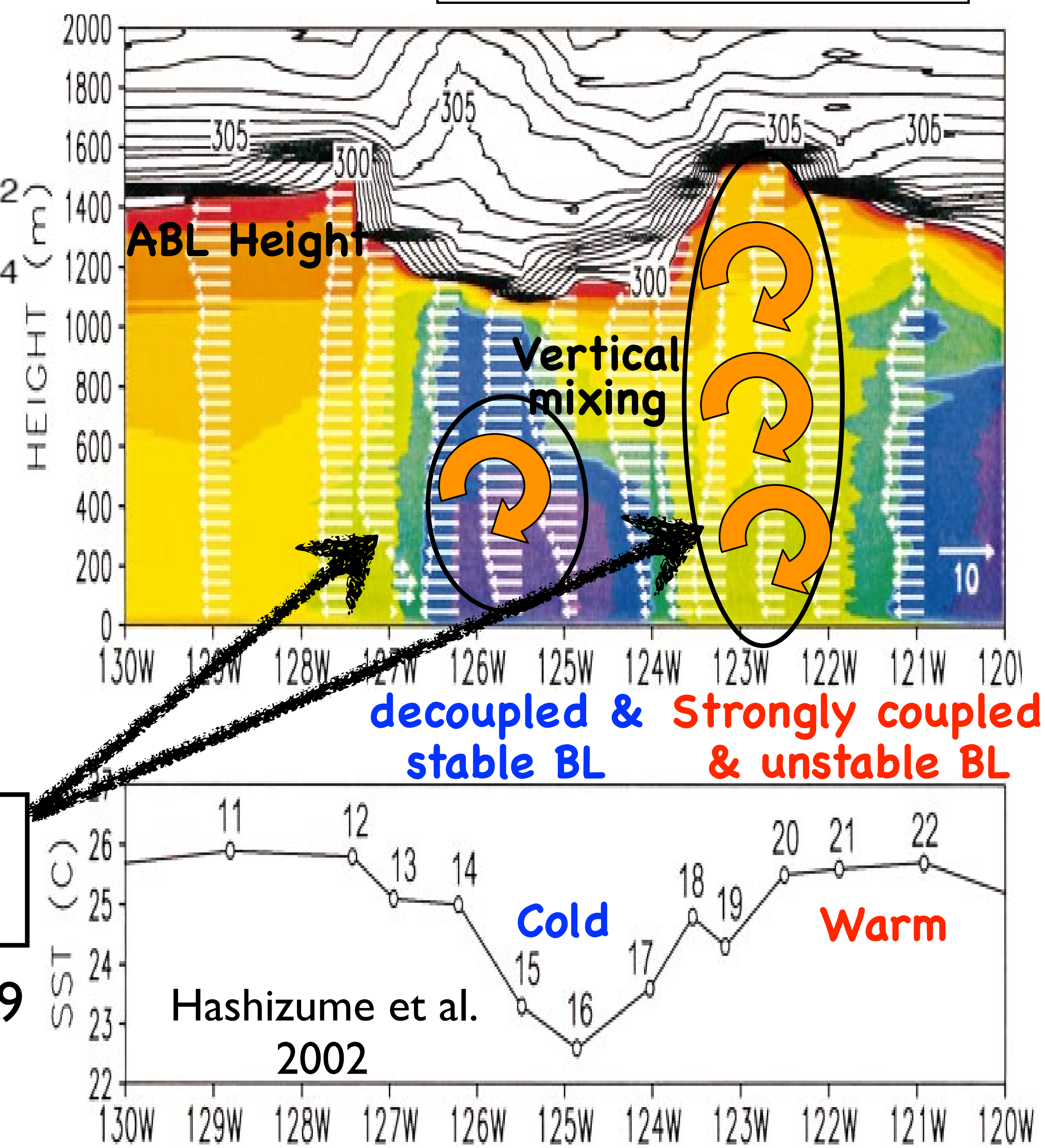


U_{ab}: background south easterlies

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

Wallace et al. 1989



Hashizume et al. 2002

Eddy-wind interaction via SST

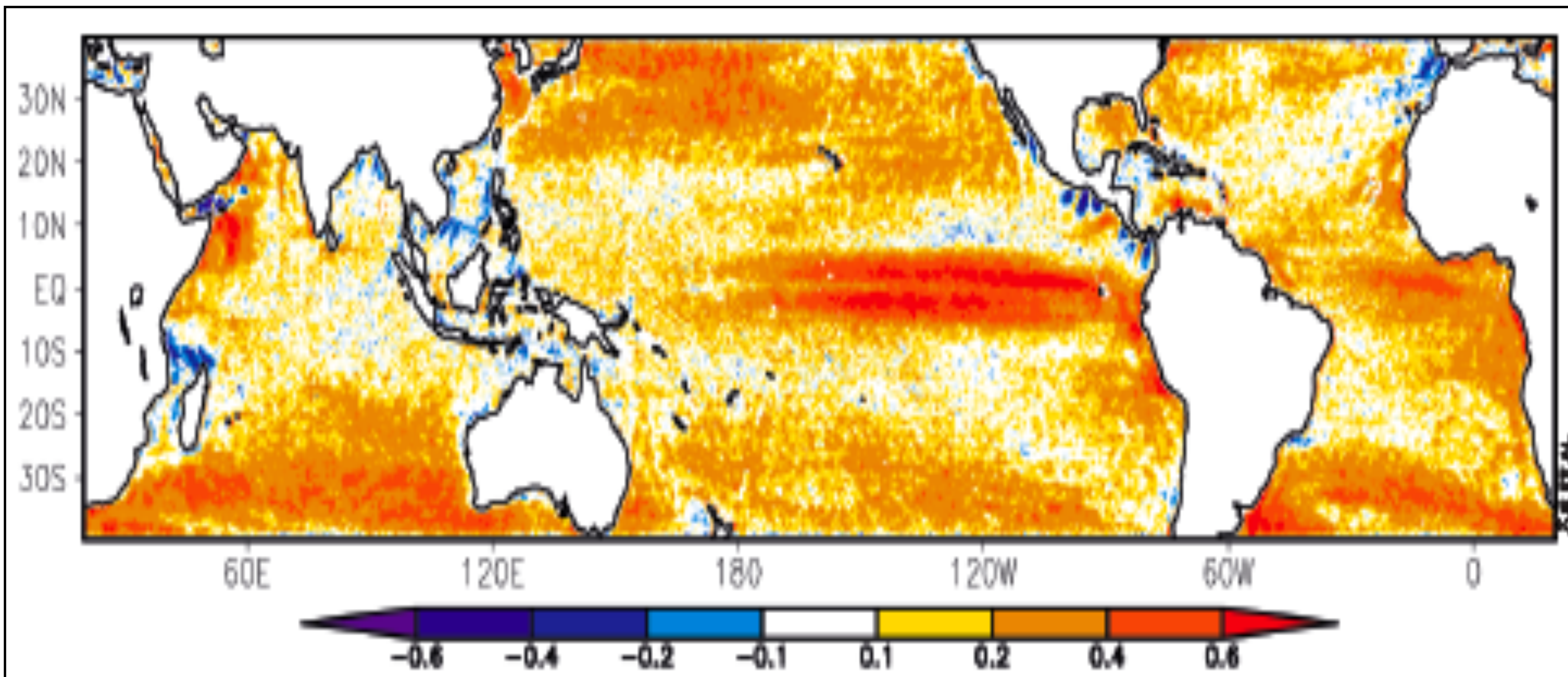
$$\tau = \rho\, C_D\, (U_a - U_o)\, |U_a - U_o|$$

10m wind

$U_a = U_{ab} + \underline{U_{aSST}}$

Ubiquitous positive correlation between wind speed and SST on oceanic mesoscales

Correlation (SST and wind speed): high-passed filtered



Xie 2004

Eddy-wind interaction via SST

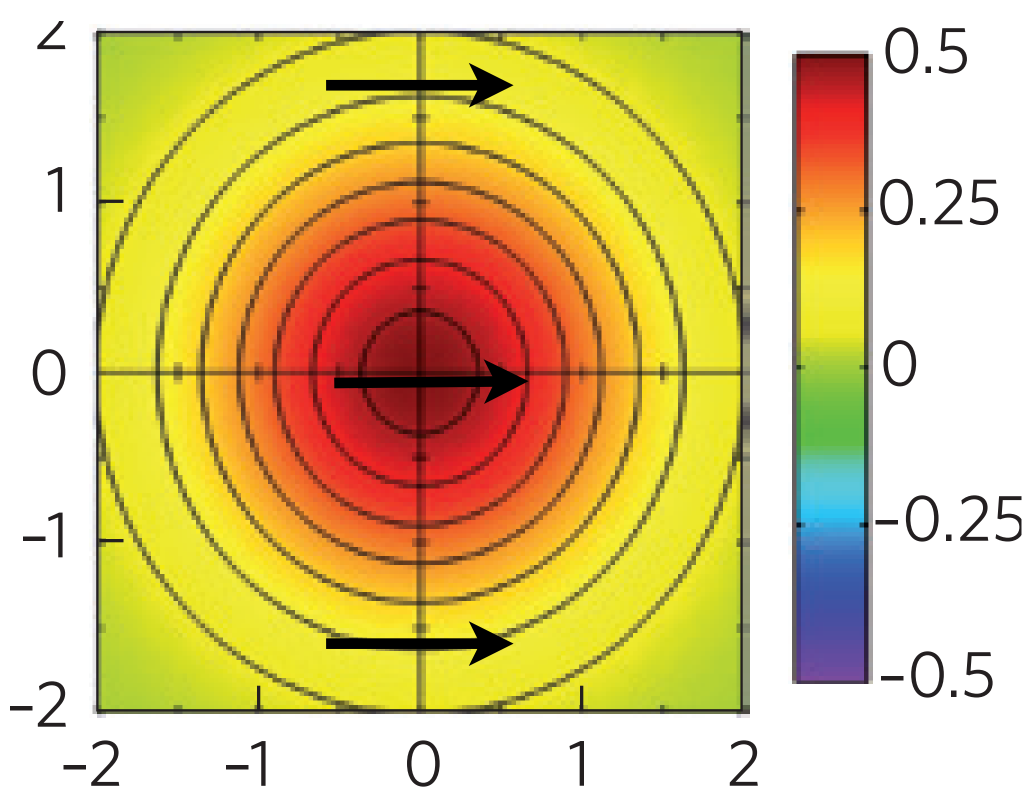
$$\tau = \rho\, C_D\, (U_a - U_o)\, |U_a - U_o|$$

10m wind

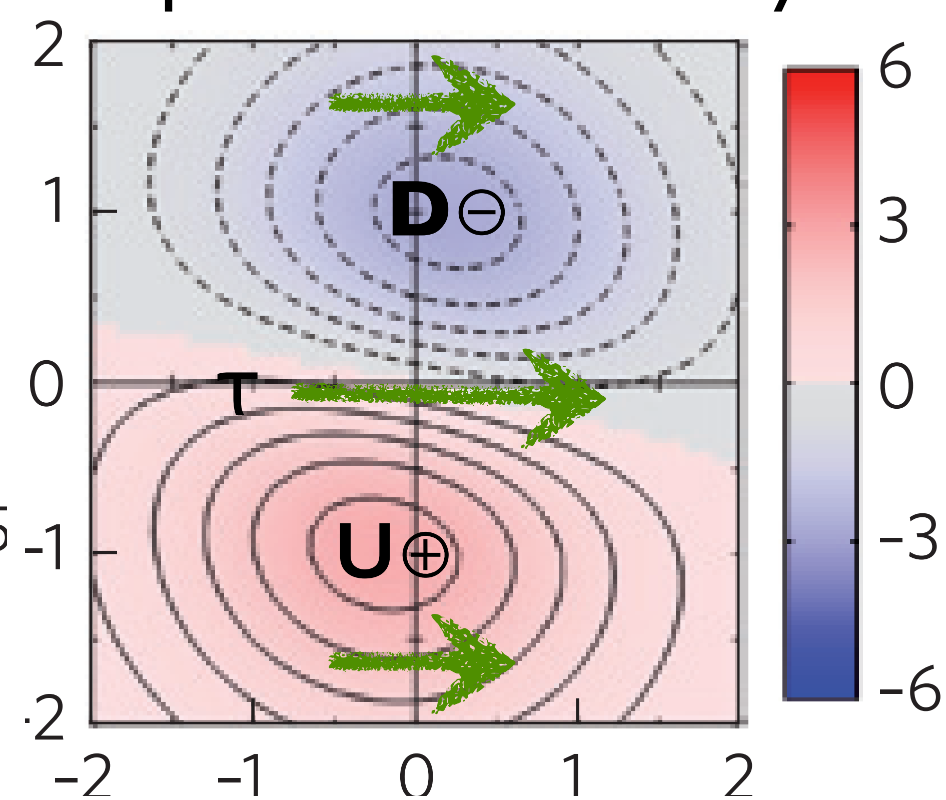
$U_a = U_{ab} + \underline{U_{aSST}}$

Uniform wind over an anticyclonic eddy in the Southern Ocean

SST and SSH



Dipole Ekman velocity



Ekman pumping anomaly 90° out of phase with SSH → propagation of an eddy

Chelton 2013

Eddy-wind interaction via current

$$\tau = \rho C_D (U_a - U_o) |U_a - U_o|$$

Upwelling at the center of an anti-cyclonic eddy: damping of an eddy

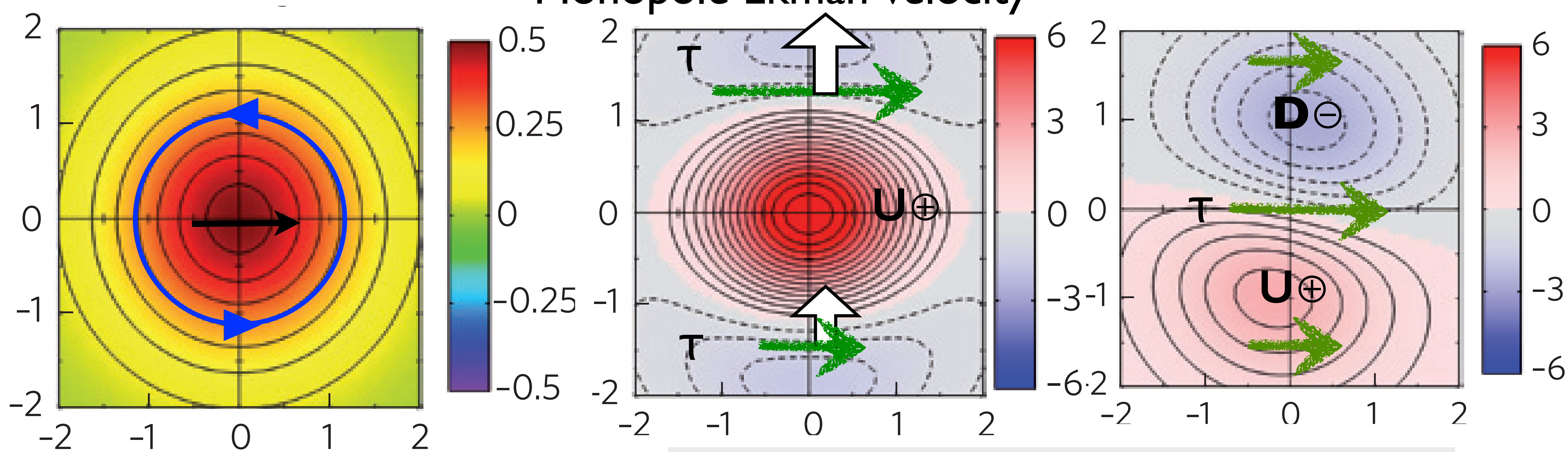
surface current
$U_o = U_{ob} + U_{oe}$

$W_e = \tau/[\rho(f+\zeta)]$

SST and SSH

Monopole Ekman velocity

Dipole Ekman velocity



surface current

Feedback to ocean would be different!

Eddy-wind interaction: SST and current

$$\tau = \rho\, C_D\, (U_a - U_o)\, |U_a - U_o|$$

10m wind

$U_a = U_{ab} + \underline{U_{aSST}}$

surface current

$U_o = U_{ob} + U_{oe}$

resulting wind stress

$\tau \approx \tau_b + \tau_{SST} + \tau_{cur}$

Eddy-wind interaction: SST and current

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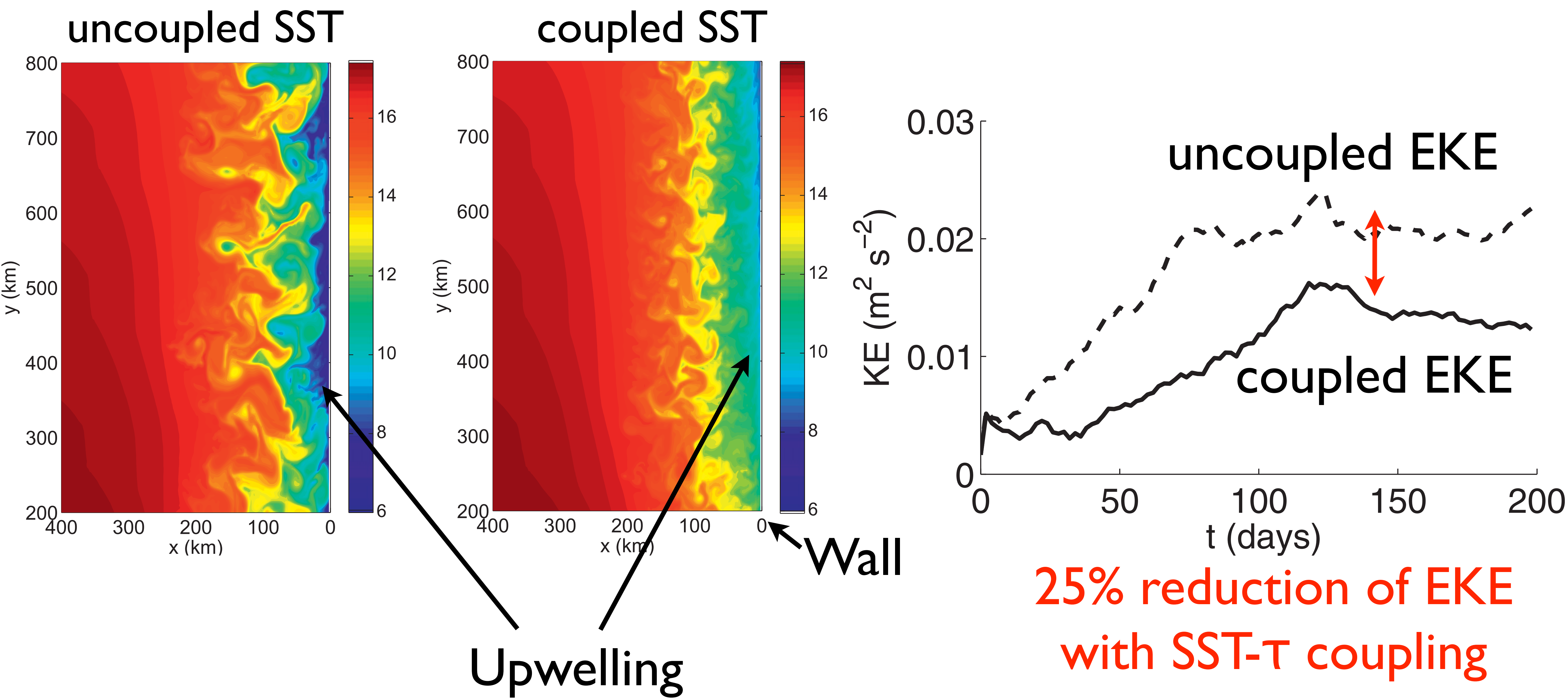
$\tau \approx \tau_b + \tau_{SST} + \tau_{cur}$

Relative effects of τ_{SST} and τ_{cur} on the ocean?

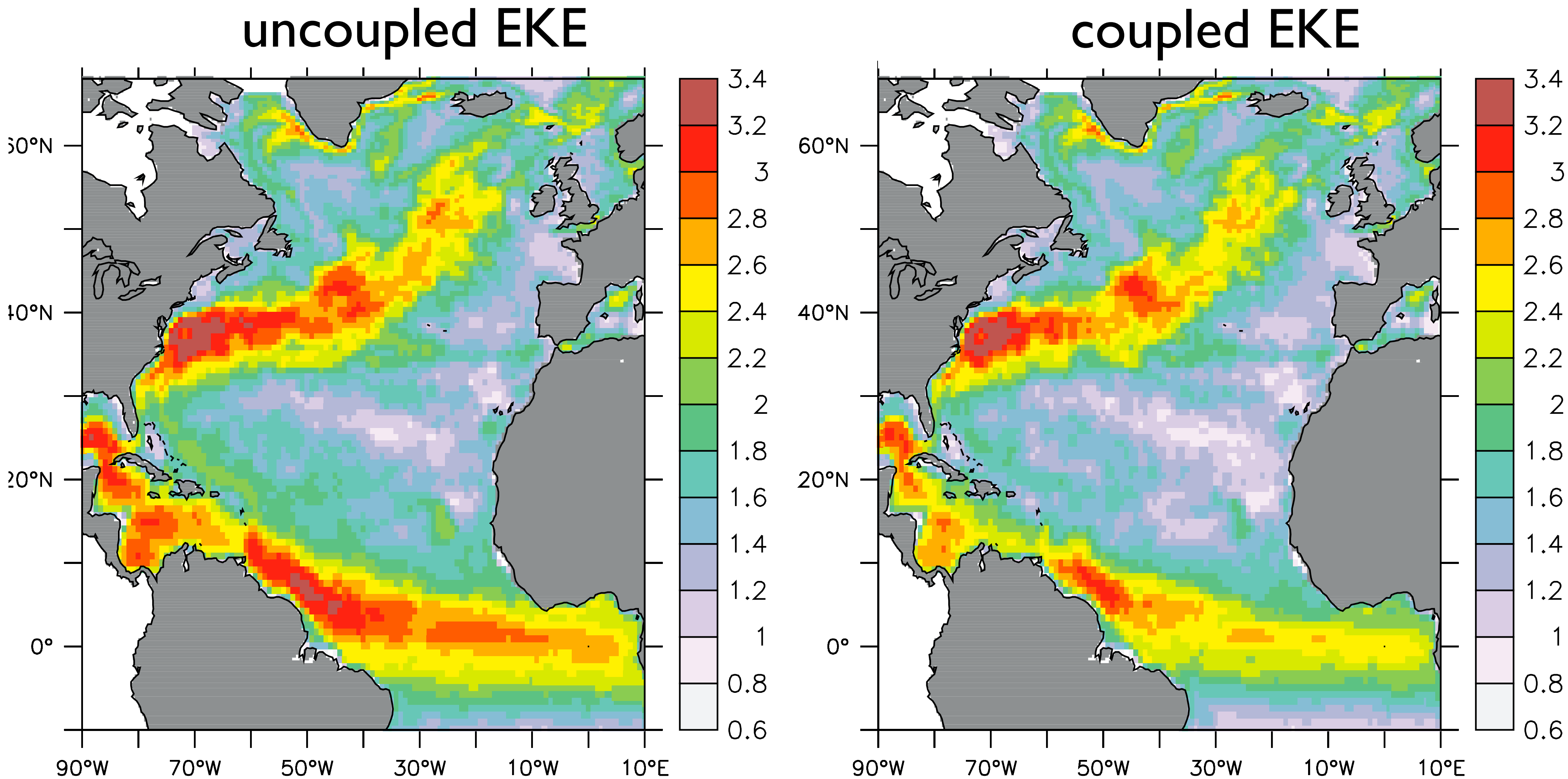
foci of this study: EKE and Ekman pumping

SST-τ coupling effect weakens the eddies: an idealized ocean model by Jin et al. (2009)



- SST-τ coupling reduces the alongshore wind stress, baroclinic instability and offshore Ekman transport.

U_o-τ coupling effect also damps the EKE: an OGCM study by Eden and Dietze (2009)

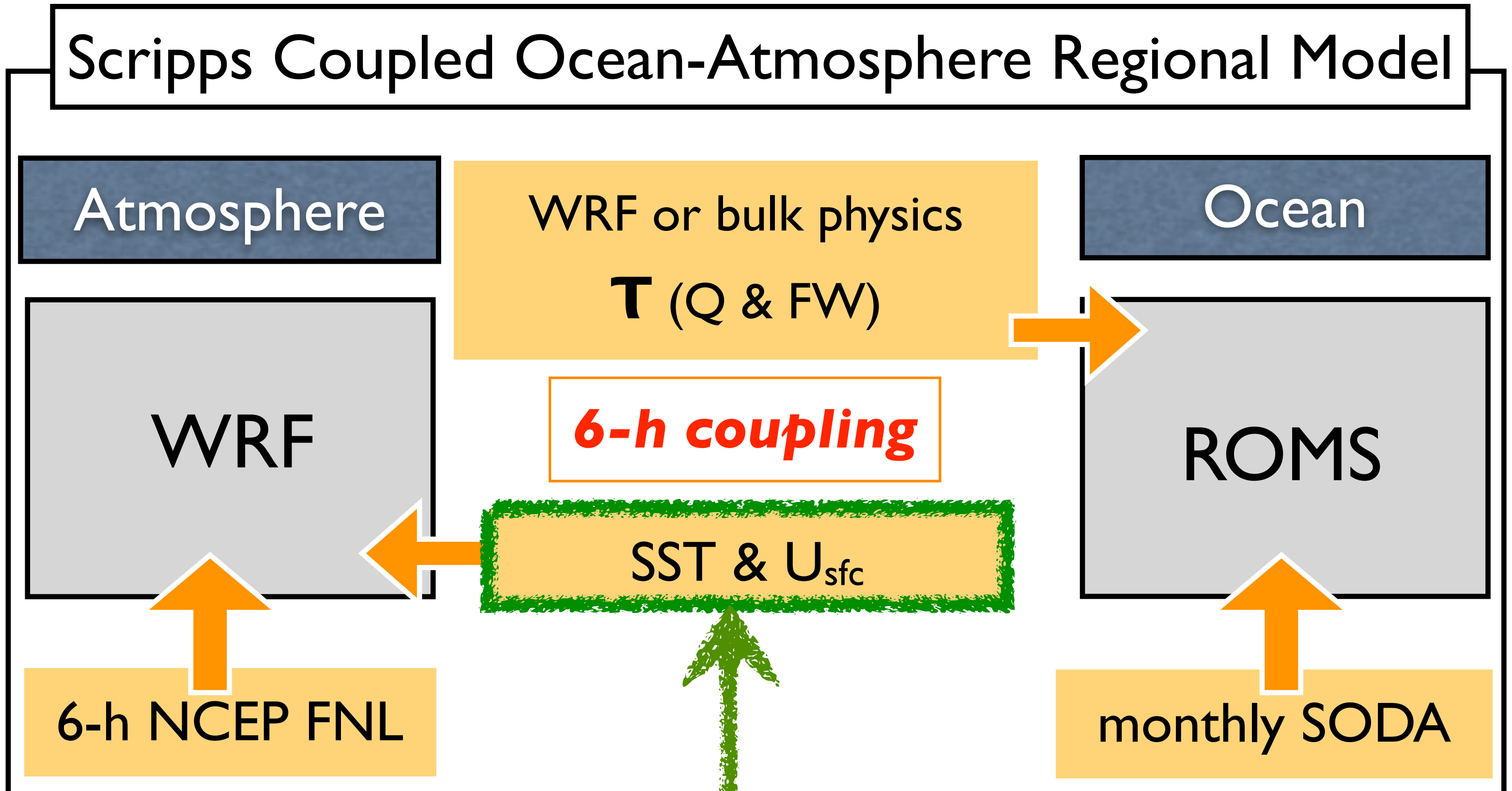


- 10% reduction in EKE in the mid-latitudes and ~50% in the tropics
- Primarily due to increased eddy drag ($\tau' \cdot u'$, direct effect)
- Change in baroclinic and barotropic instability (indirect effect) of secondary importance

Result from previous studies and goal of this study

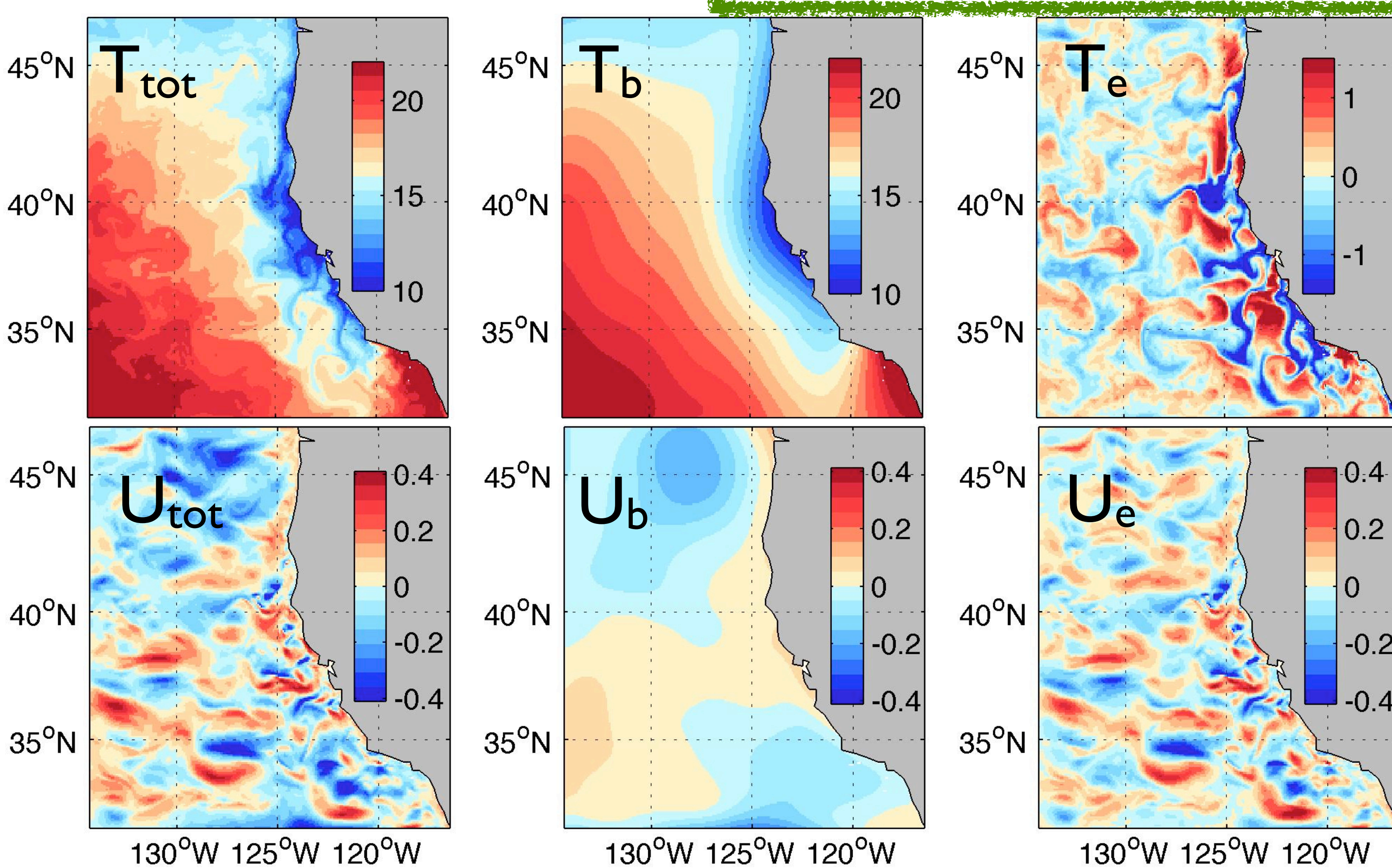
- Previous studies considered either SST or U_o in τ formulation in ocean-only models and saw weakened eddy variability.
- This study examines the relative importance of SST and u_{sfc} in a fully coupled regional model.

Regional coupled model



- Seo et al. 2007, 2014
- An input-output based coupler; portable & flexible

- 7 km O-A resolutions & matching mask
- 6-yr integration (2005-2010)



Smoothing of mesoscale SST and U_o (Putrasahan et al. 2013)

5° loess smoothing (~3° boxcar smoothing)

Similar results with different smoothing (e.g, 3° loess smoothing)

Experiments

$$\tau=\rho C_D(U_a-U_o)|U_a-U_o|$$

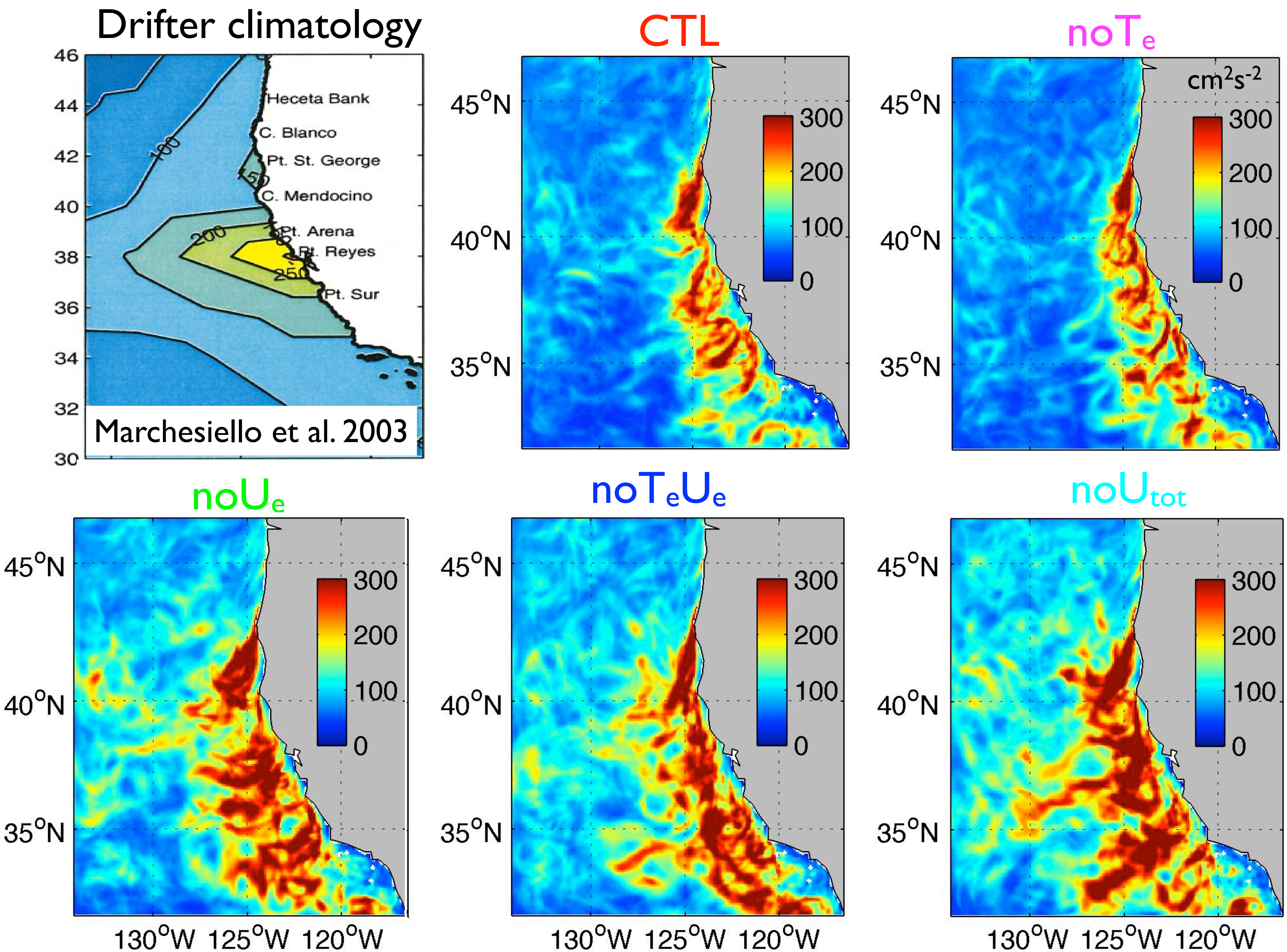
$T_{tot} = T_b + T_e$

$U_{tot} = U_b + U_e$ 5° loess filtering (≈ 3° boxcar smoothing)

Experiments	τ formulation includes			
✔ CTL	T_b	T_e	U_b	U_e
✔ noT_e	T_b	T_e	U_b	U_e
✔ noU_e	T_b	T_e	U_b	U_e
no$T_e U_e$	T_b	T_e	U_b	U_e
noU_{tot}	T_b	T_e	U_b	U_e

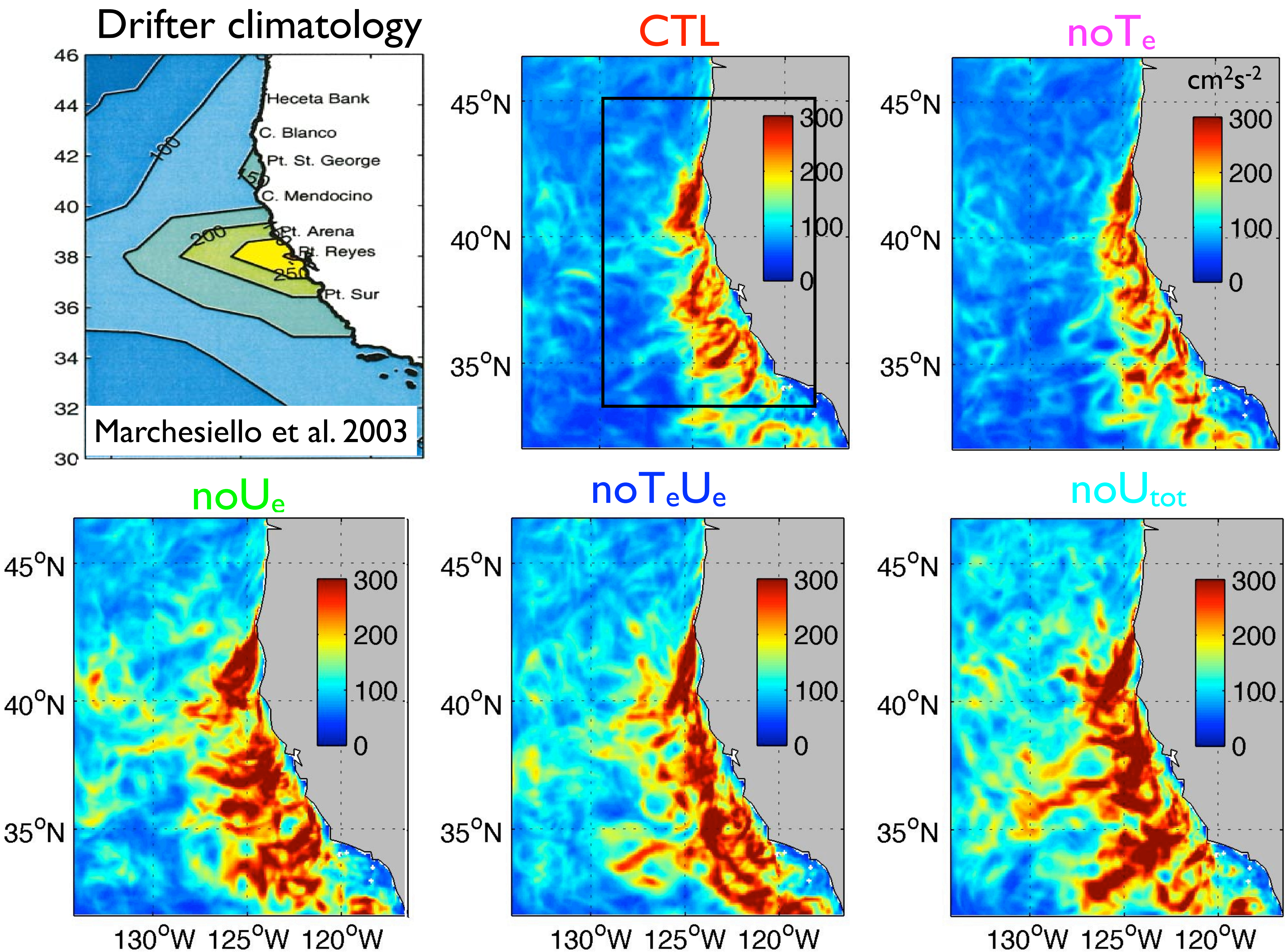
Eddy kinetic energy

Eddy kinetic energy JAS 2005-2010



• T$_e$ no impact • 25% weaker EKE with U$_e$ • 30% weaker EKE with U$_b$+U$_e$

Eddy kinetic energy JAS 2005-2010



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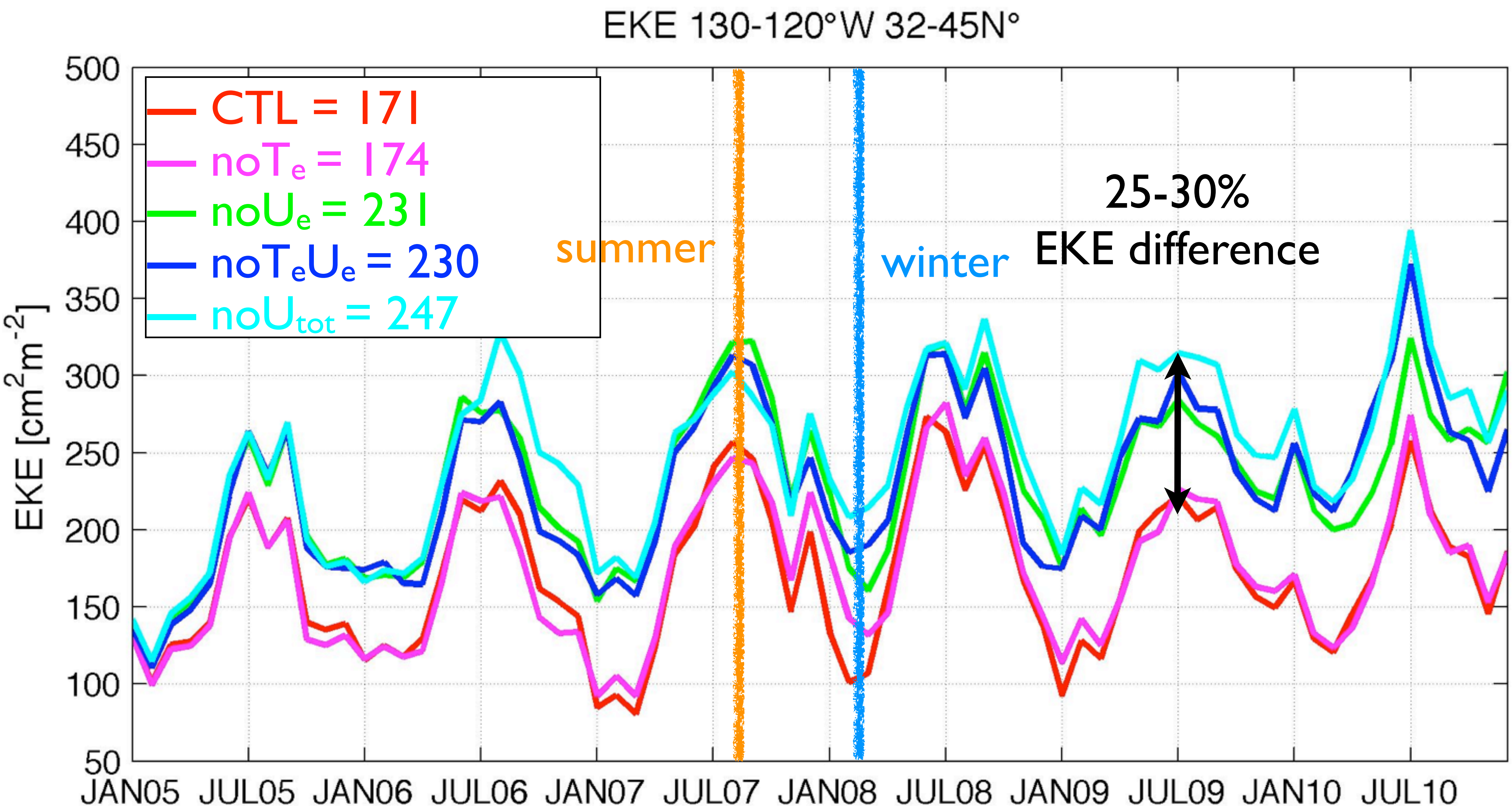
Monthly EKE time-series



High EKE in summer, low in winter

Reduced eddy activity in both seasons!

Eddy kinetic energy budget

advection by mean and eddy current (offshore)

$$Ke_t + \vec{U}\cdot\vec{\nabla}\vec{K}e + \vec{u}'\cdot\vec{\nabla}\vec{K}e + \vec{\nabla}\cdot(\vec{u}'p') =$$

$$-g\rho' w' + \rho_o(-\vec{u}'\cdot(\vec{u}'\cdot\vec{\nabla}\vec{U})) + \vec{u}'\cdot\vec{\tau}' + \varepsilon$$

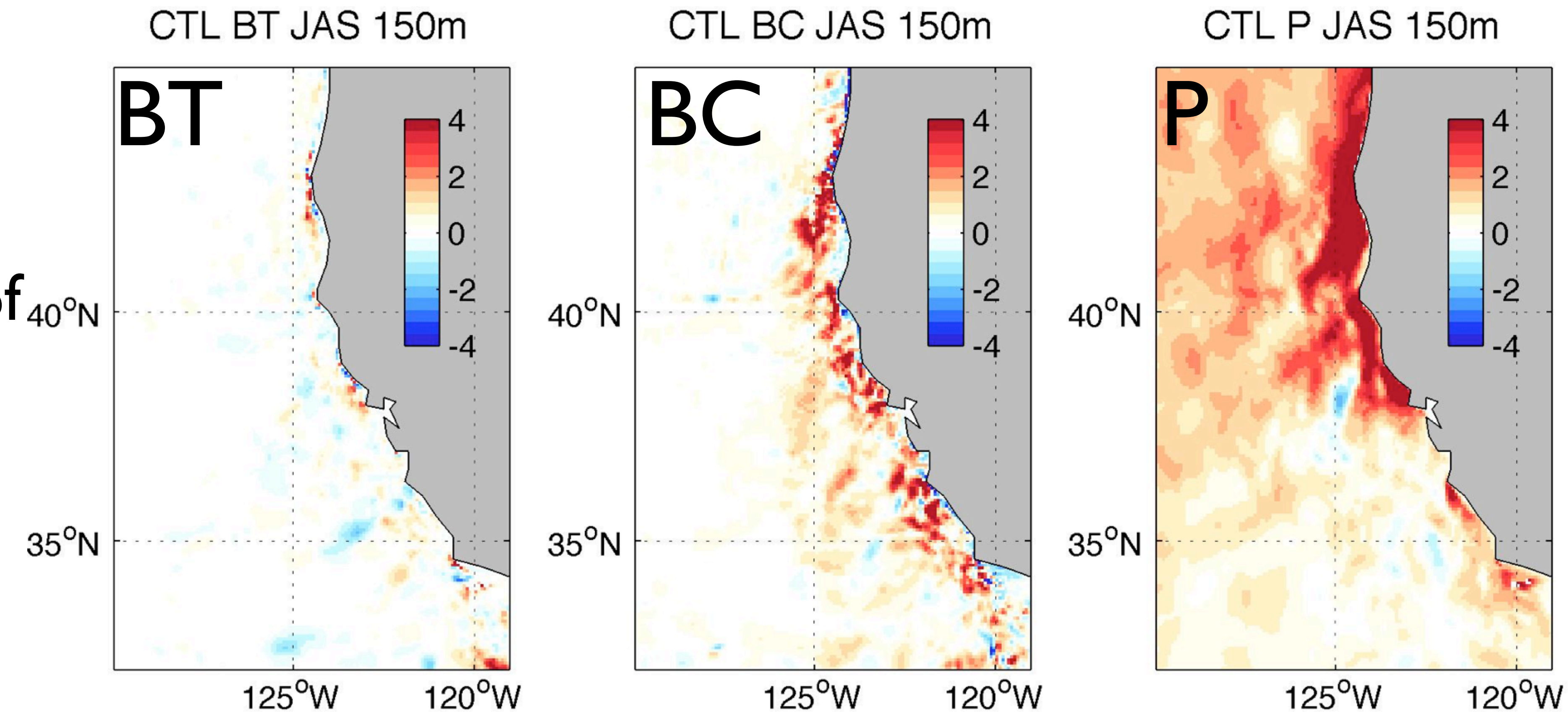
$P_e \rightarrow K_e$ baroclinic conversion (BC)

$K_m \rightarrow K_e$ barotropic conversion (BT)

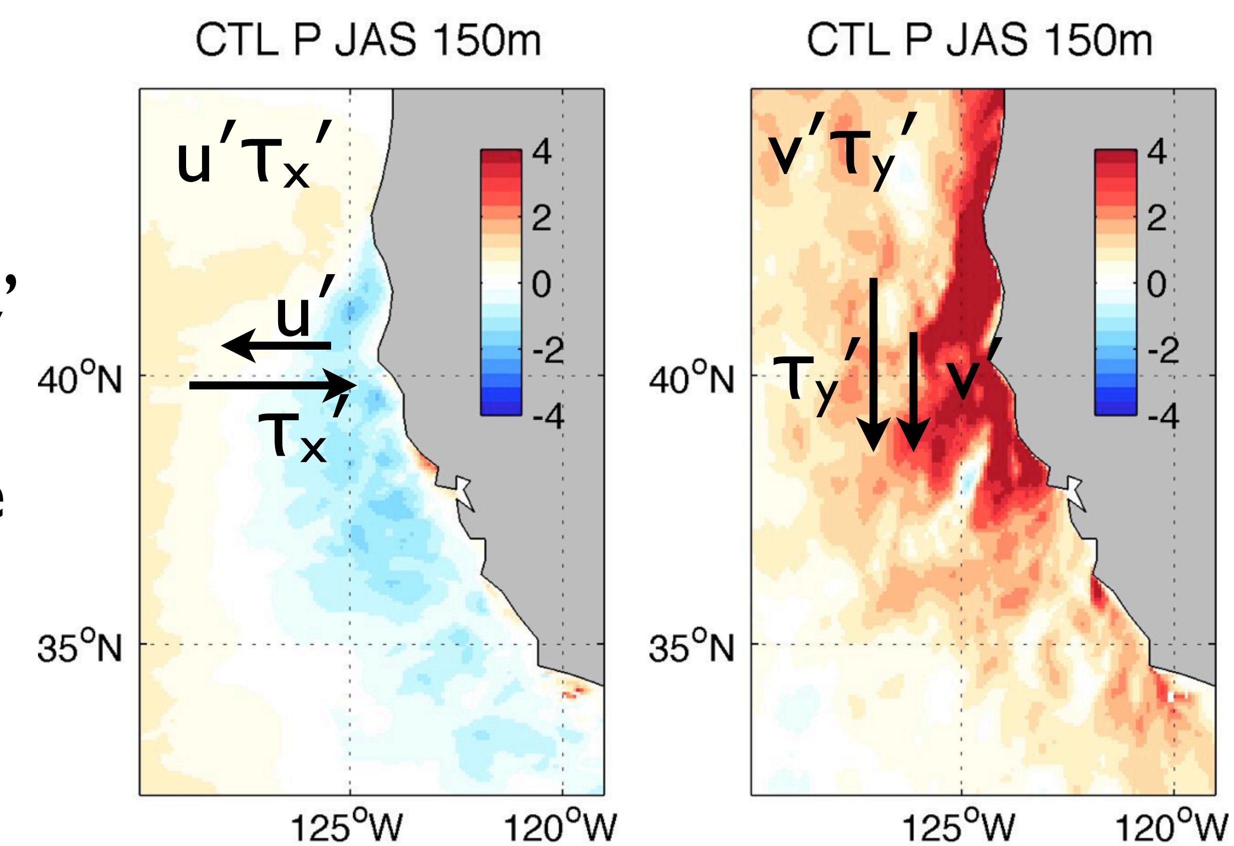
Wind work (P)
EKE source if positive
Eddy drag and dissipation (ε) if negative

Upper 100 m average
H~fL/N, where $f=10^{-4}$, $L=10^{4}$m, $N=10^{-2} \rightarrow H=10^{2}$m

Summertime EKE budget in CTL



- P a primary source of EKE.
  - BC secondary and BT negligible

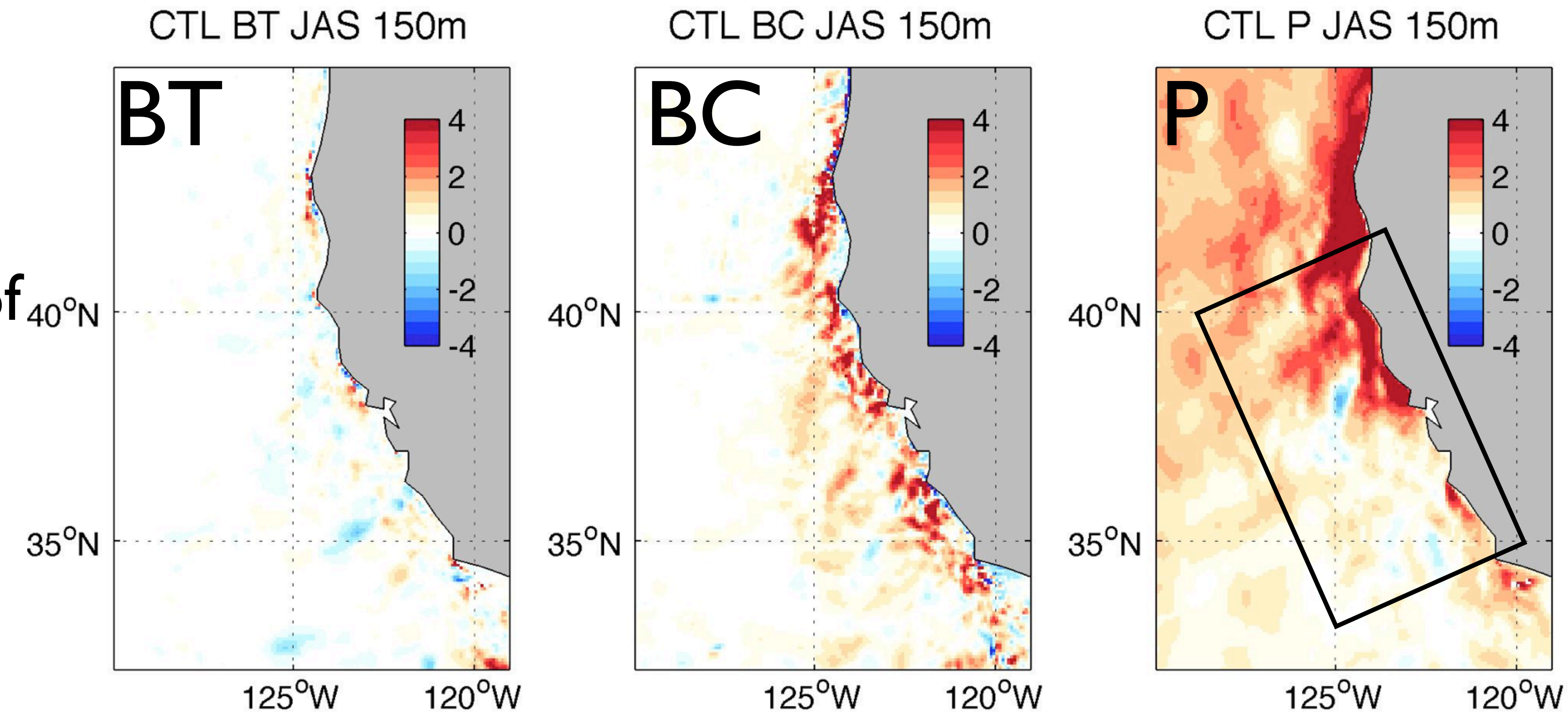


150 m average

- $v'\tau_y'$: Source of EKE
  - v' is a linear response to nearshore τ_y'
- $u'\tau_x'$: Dissipating EKE
  - Eddies (via u') "systematically" oppose τ_x' in the upwelling zone

Summertime EKE budget in CTL along-shore mean

- P a primary source of EKE.
  - BC secondary and BT negligible



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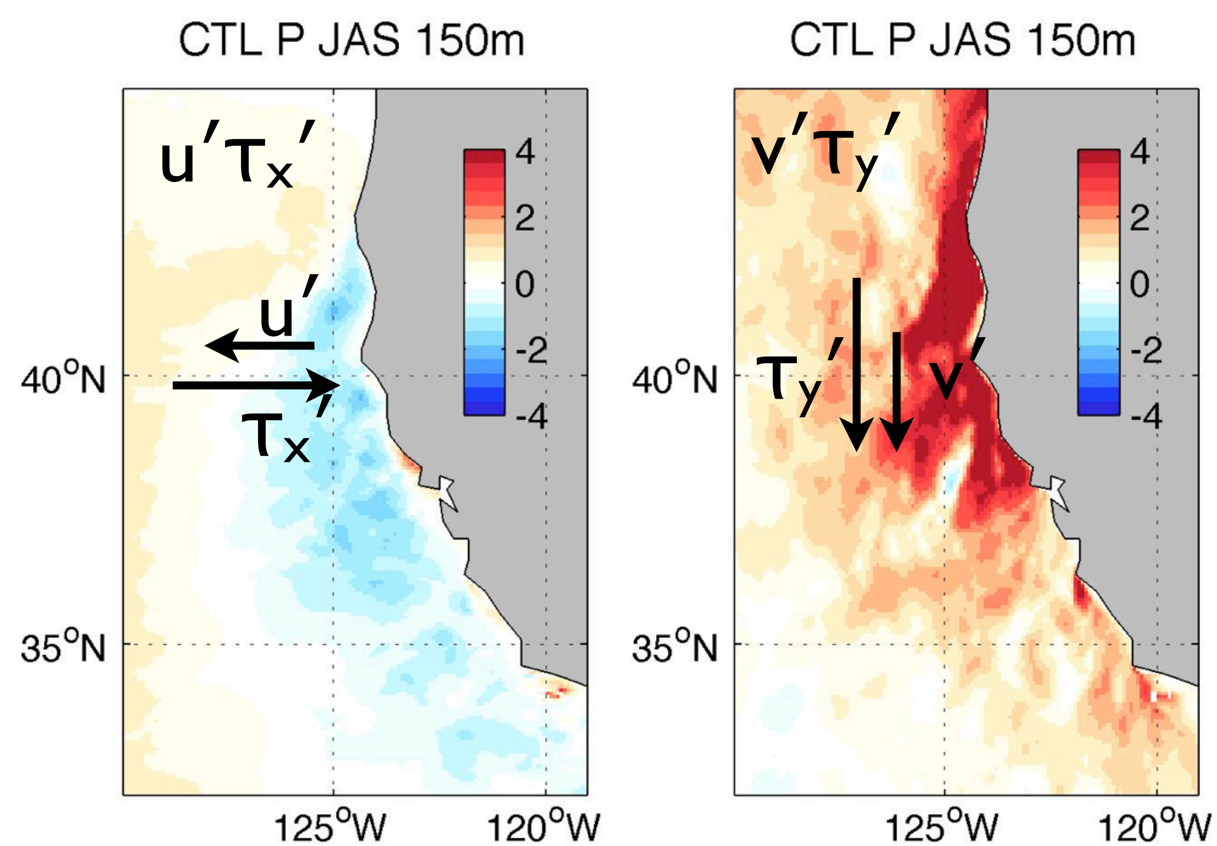
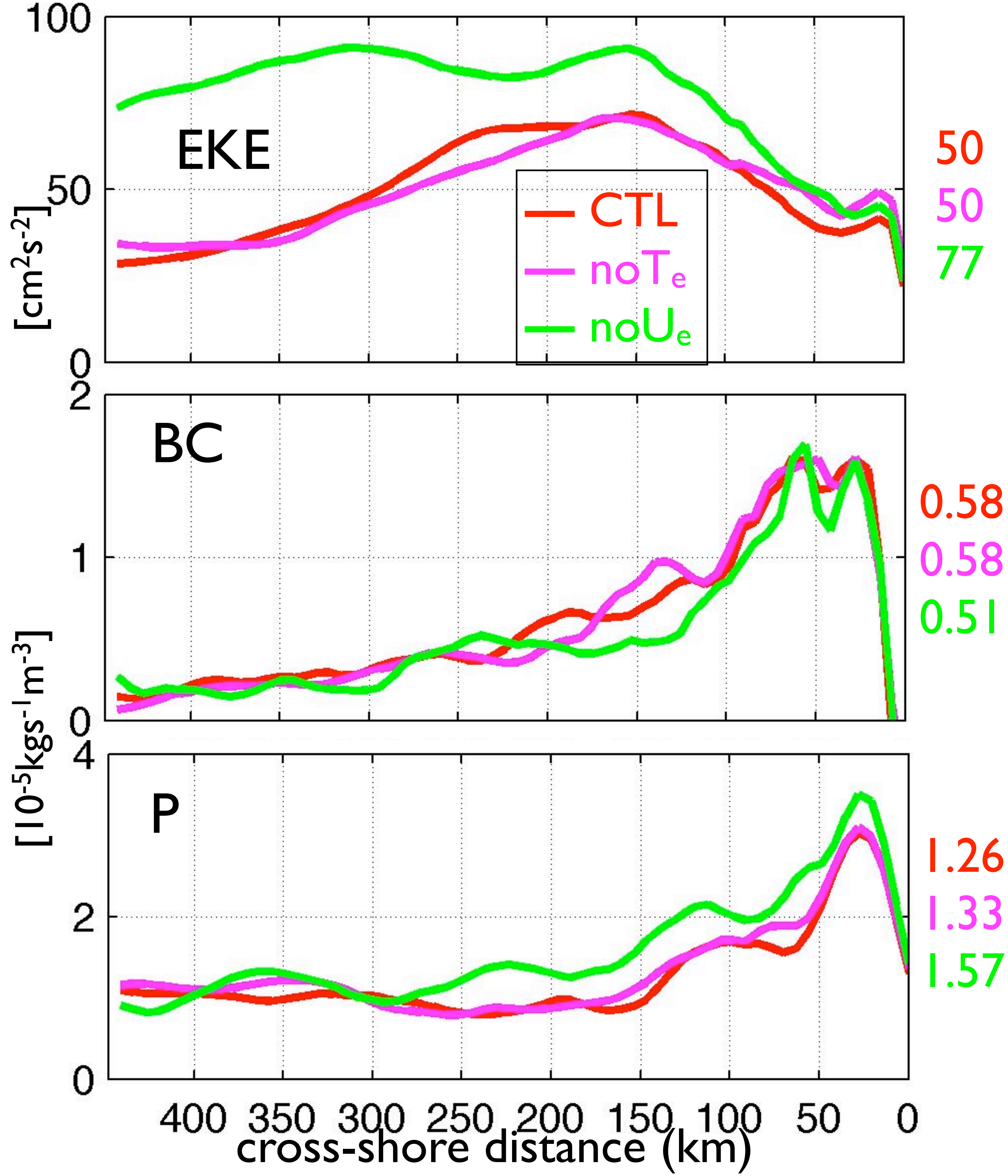


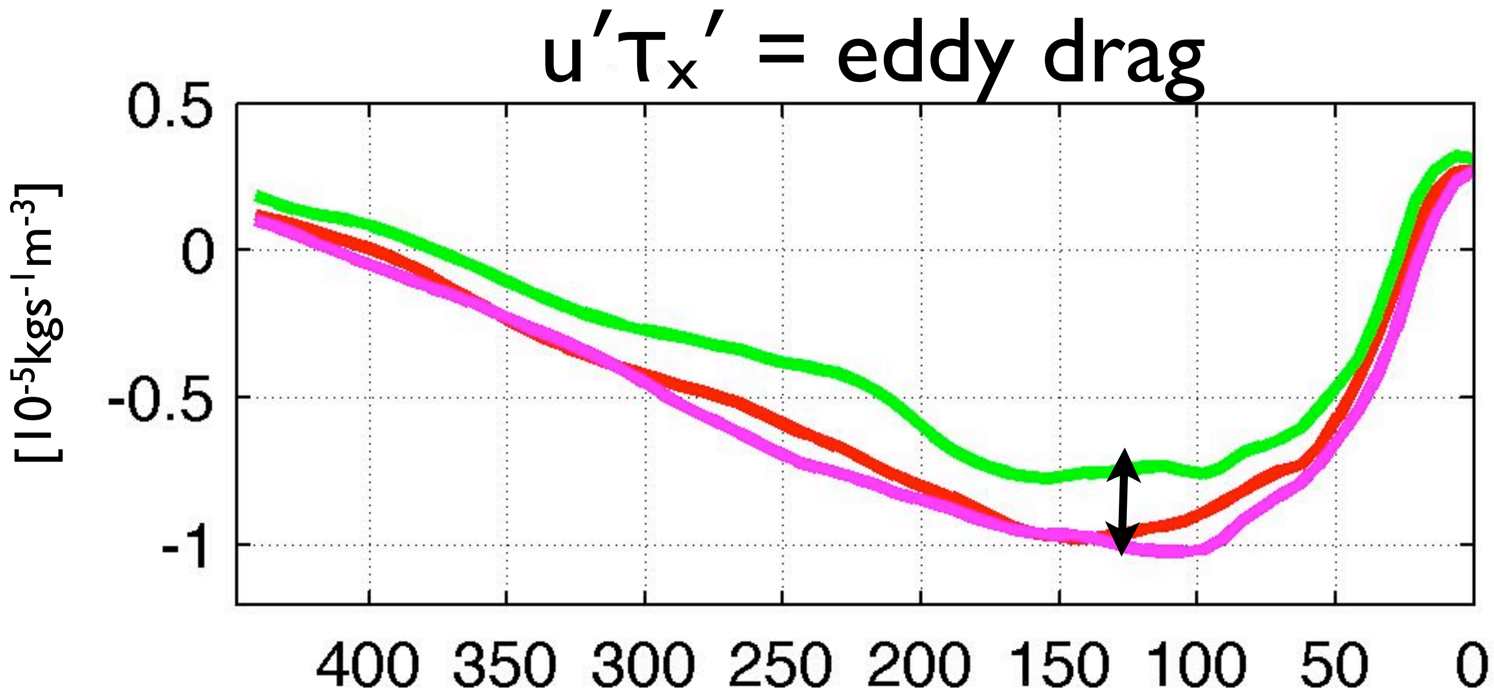
150 m average

Cross-shore distribution of EKE and key EKE budget terms



- EKE maximum offshore at 150km
- P maximum near the coast (20-30 km) by offshore advection
- No significant change in BC bet'n CTL noTe
  - Some reduction of BC in noUe
- Decreased wind work
  - $noU_e \rightarrow$ CTL: 20% reduction

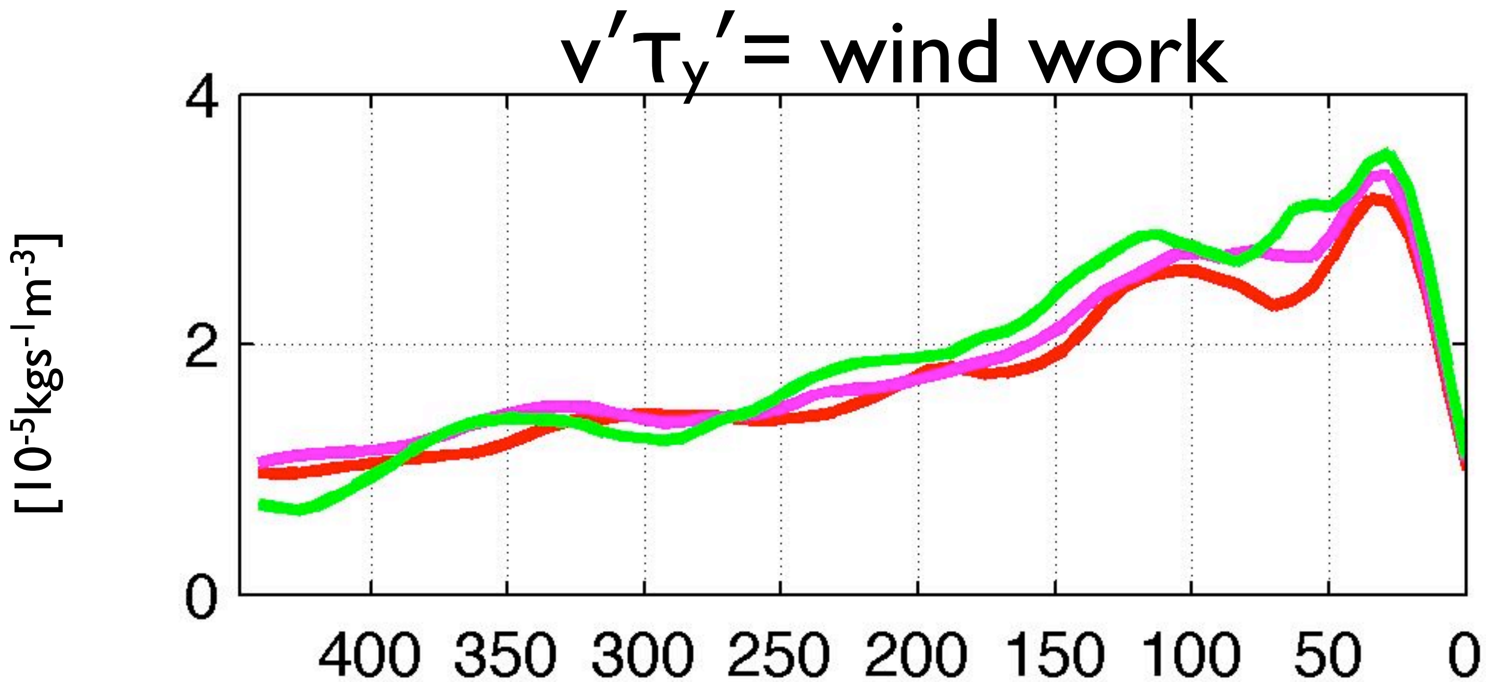
Eddies increase the eddy drag and reduce the momentum input.



eddy drag

CTL=−0.47
noT_e=−0.53
noU_e=−0.33

42% stronger eddy drag



wind work

CTL=1.74
noT_e=1.86
noU_e=1.90

16% weaker wind work

Ekman pumping velocity

Ekman pumping velocity

Stern 1965

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

$$\tilde{W}_{tot} = W_{cur} + W_{SST}$$

background wind stress

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

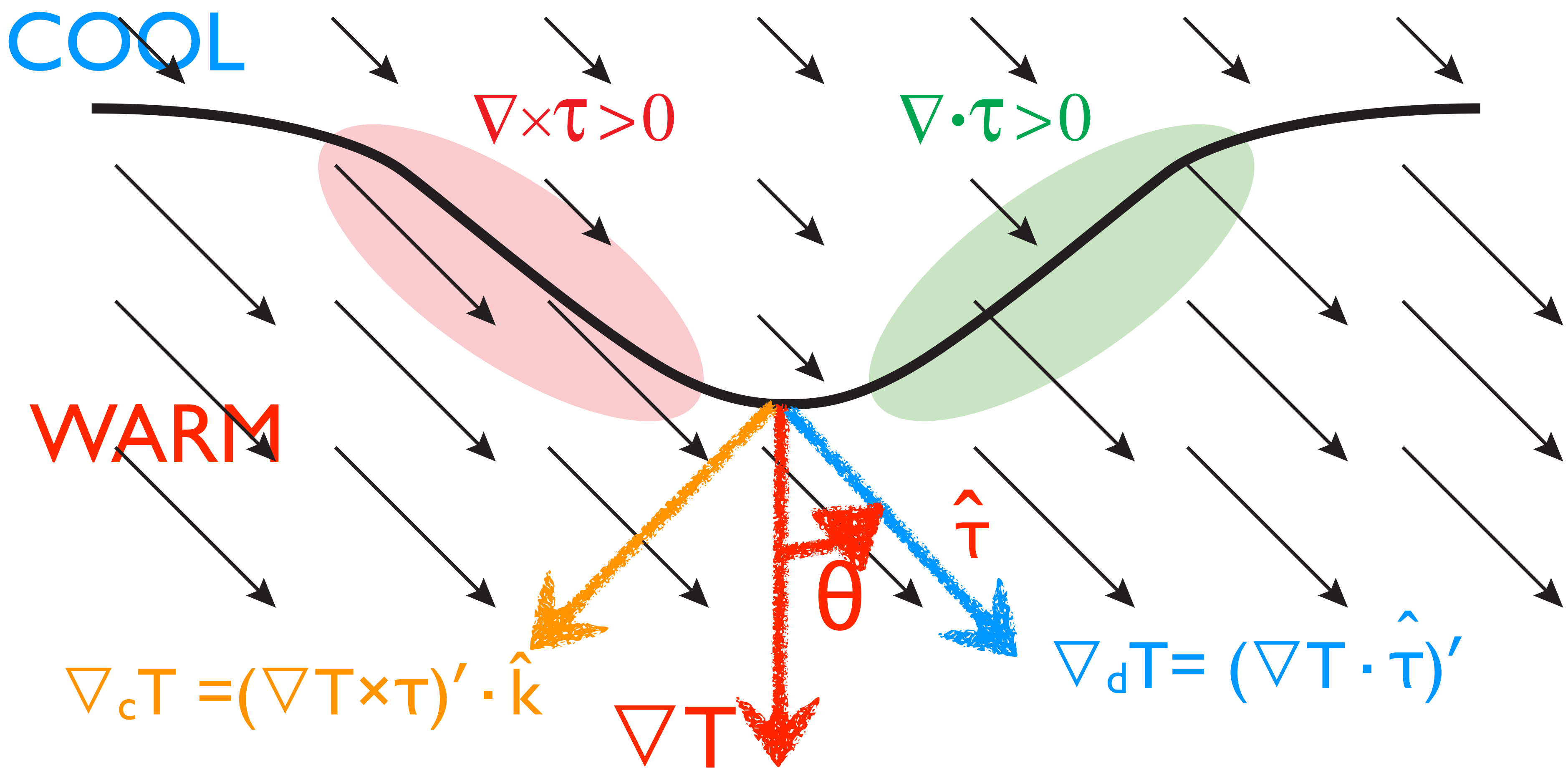
Curl-induced **linear** Ekman pumping

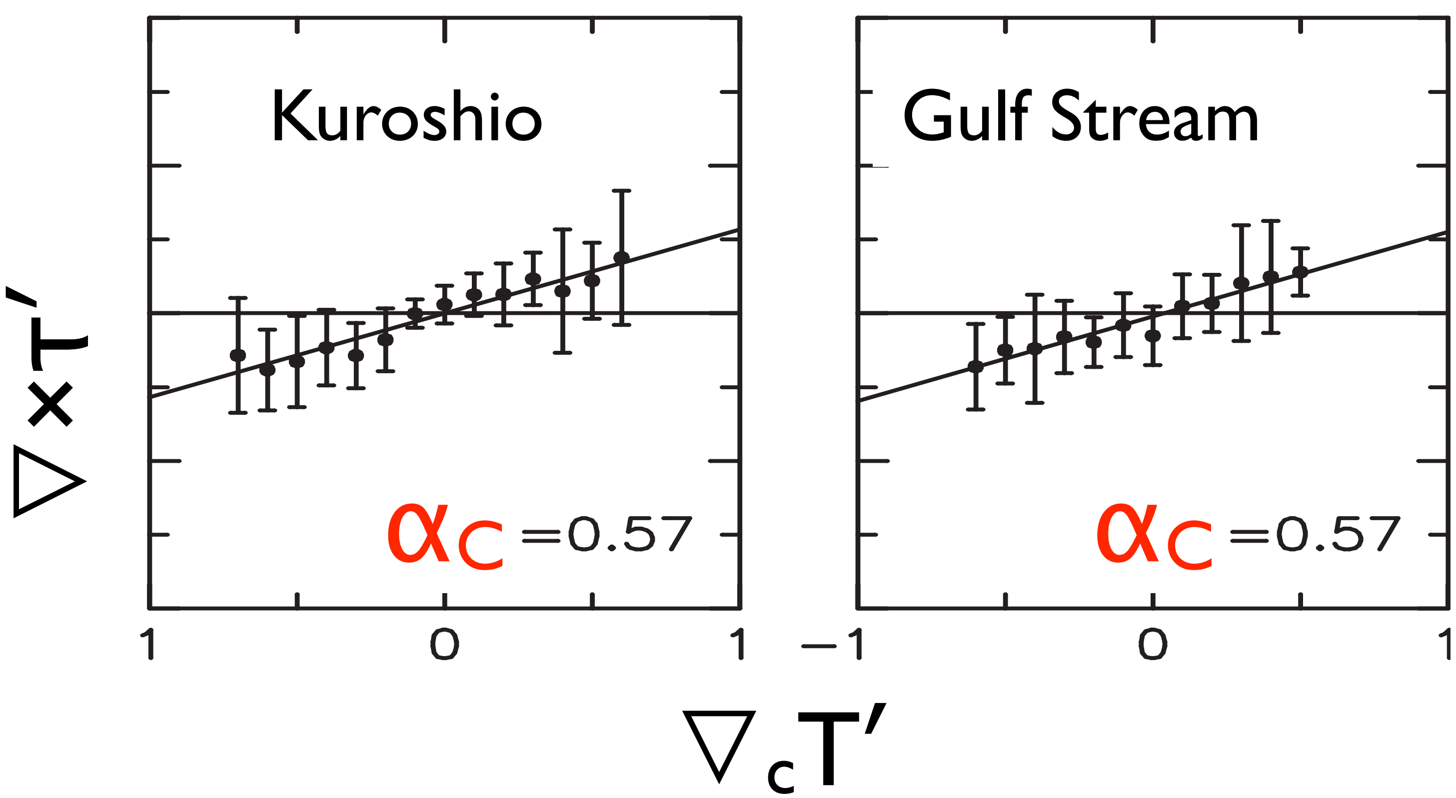
Vorticity gradient-induced **nonlinear** Ekman pumping

β Ekman pumping (negligible)

SST induced Ekman pumping

SST-induced Ekman pumping velocity





Positive empirical relationship

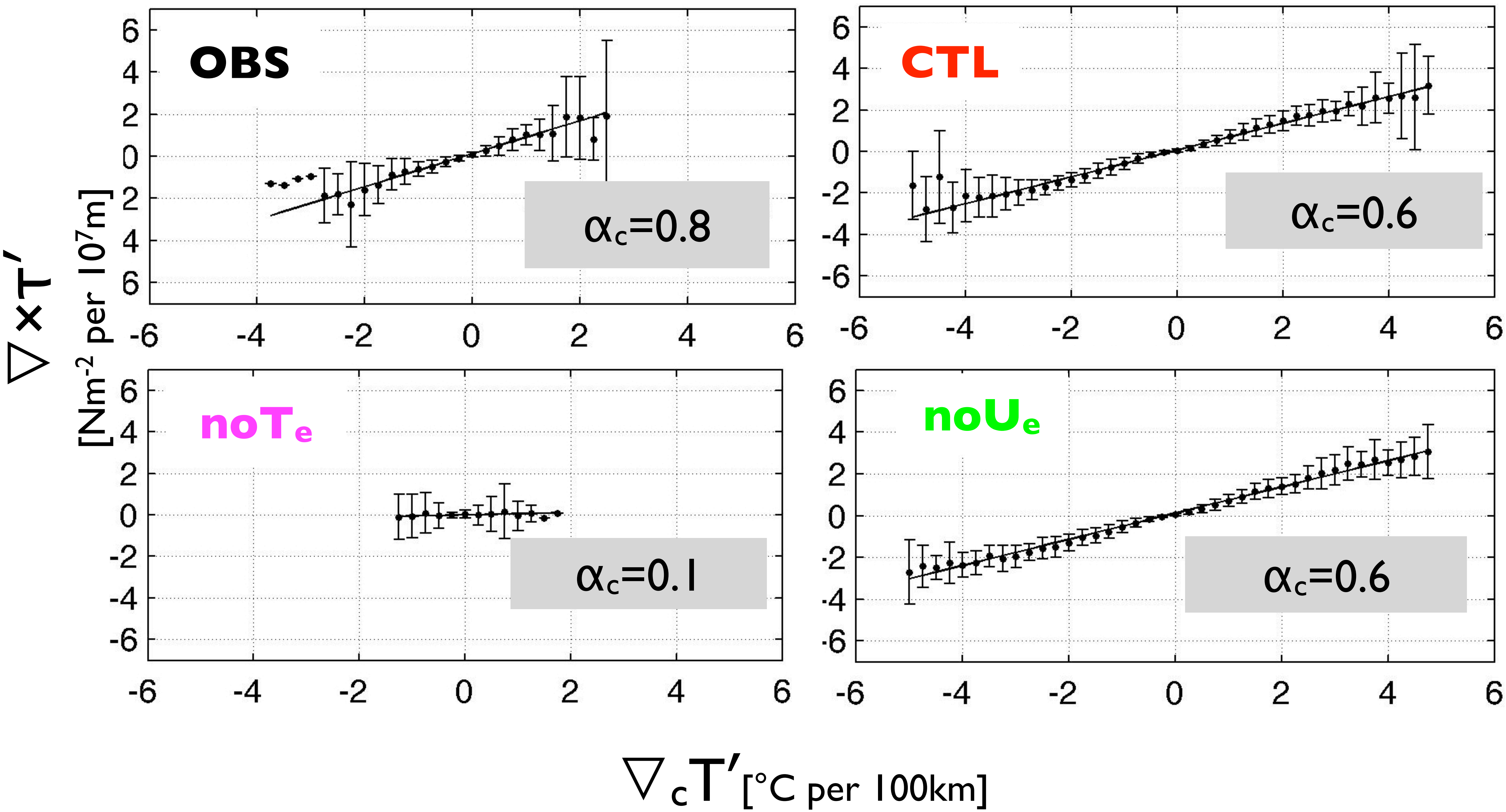
$$\nabla \times \tau' = \alpha_C \nabla_c T'$$

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

Chelton et al. 2004

Wind stress curl and cross-wind SST gradient

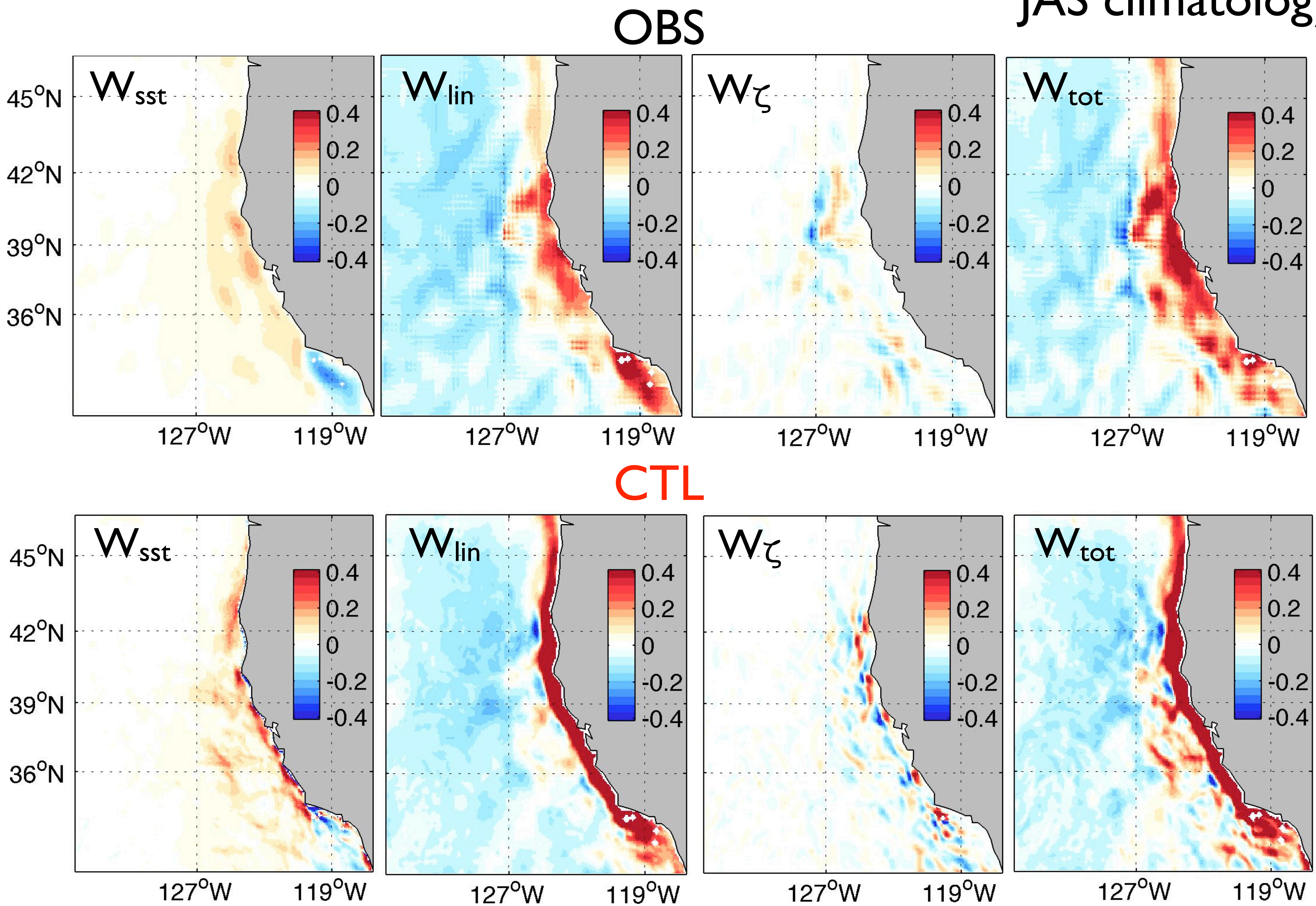
$$W_{SST} = \frac{\nabla \times \tau'_{SST}}{\rho_o(f+\zeta)} \approx \frac{\alpha_c \nabla_c SST}{\rho_o(f+\zeta)}$$



JAS 2005-2009; QuikSCAT wind stress and TRMM SST

Ekman pumping velocity

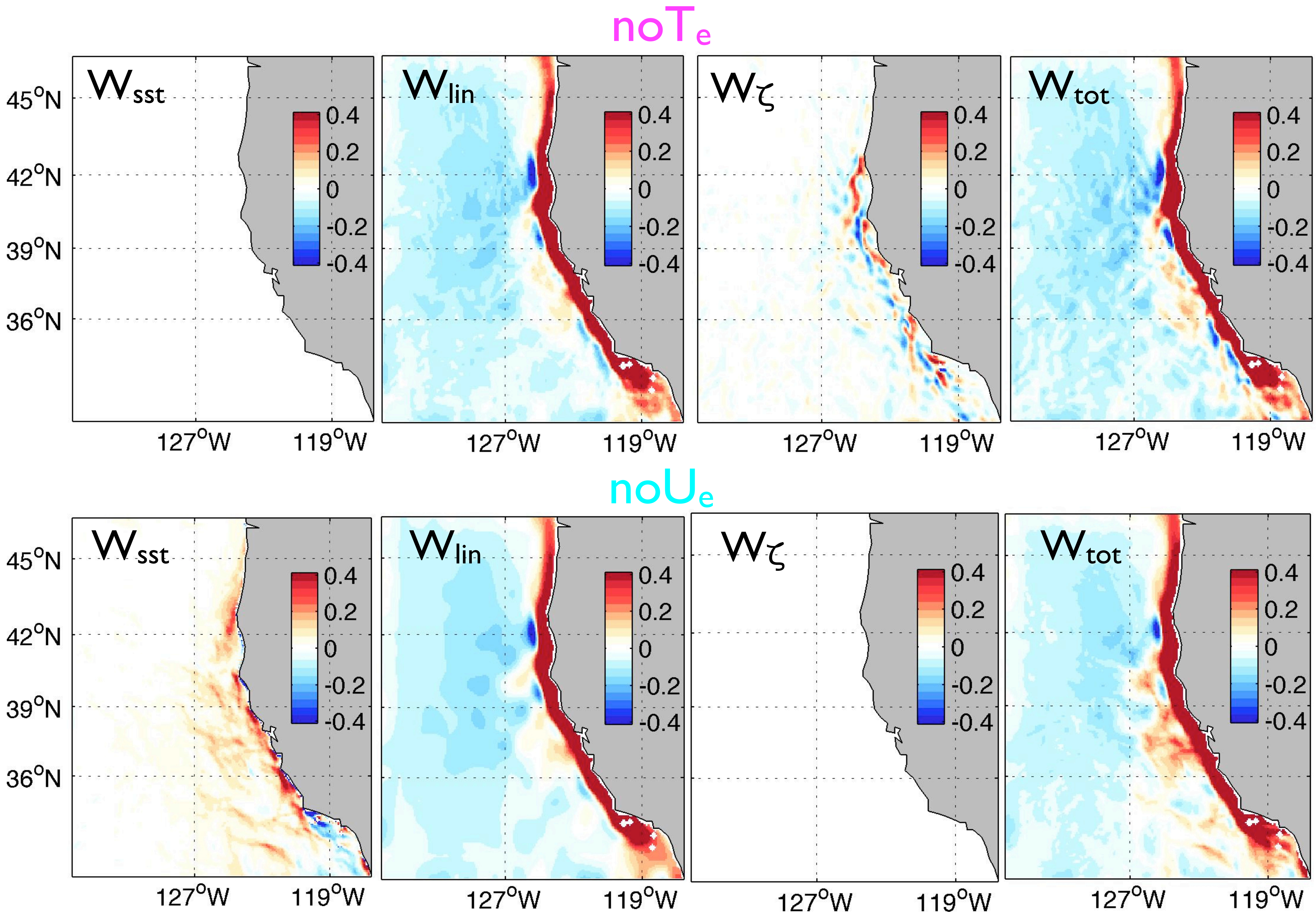
JAS climatology



m/day

JAS 2005-2009

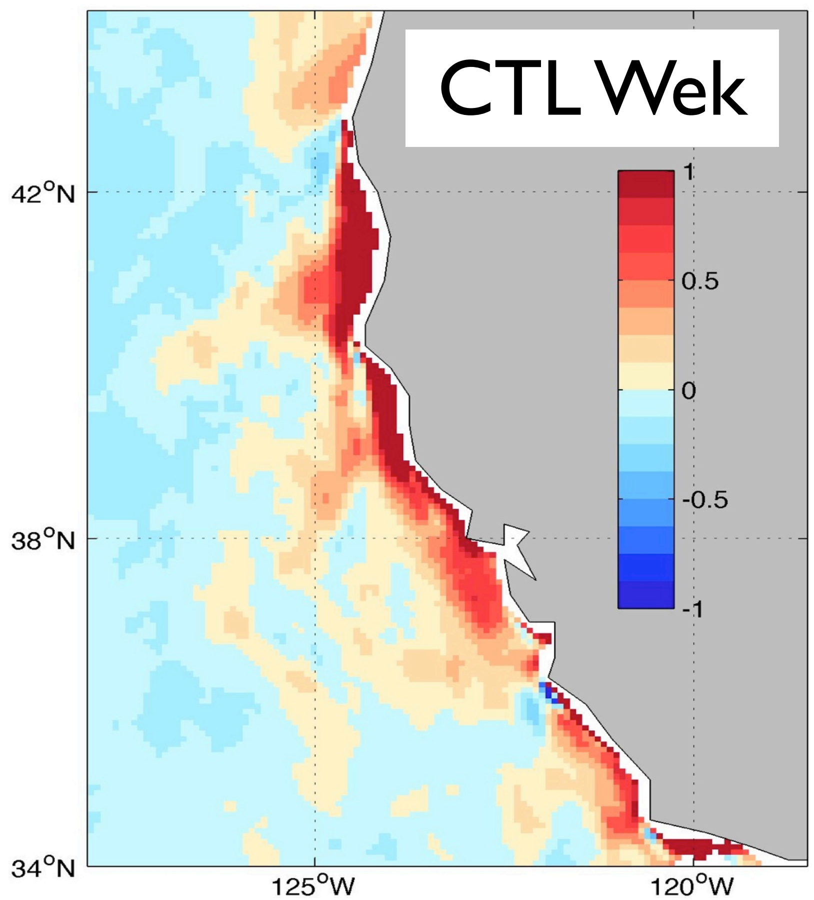
Ekman pumping velocity JAS climatology

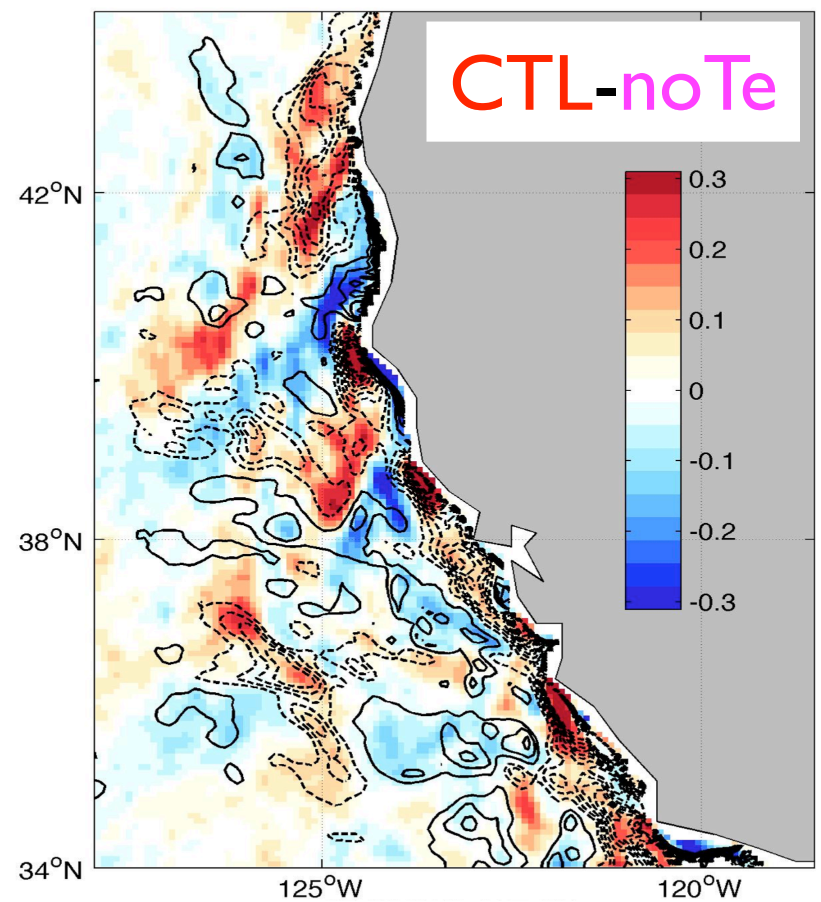


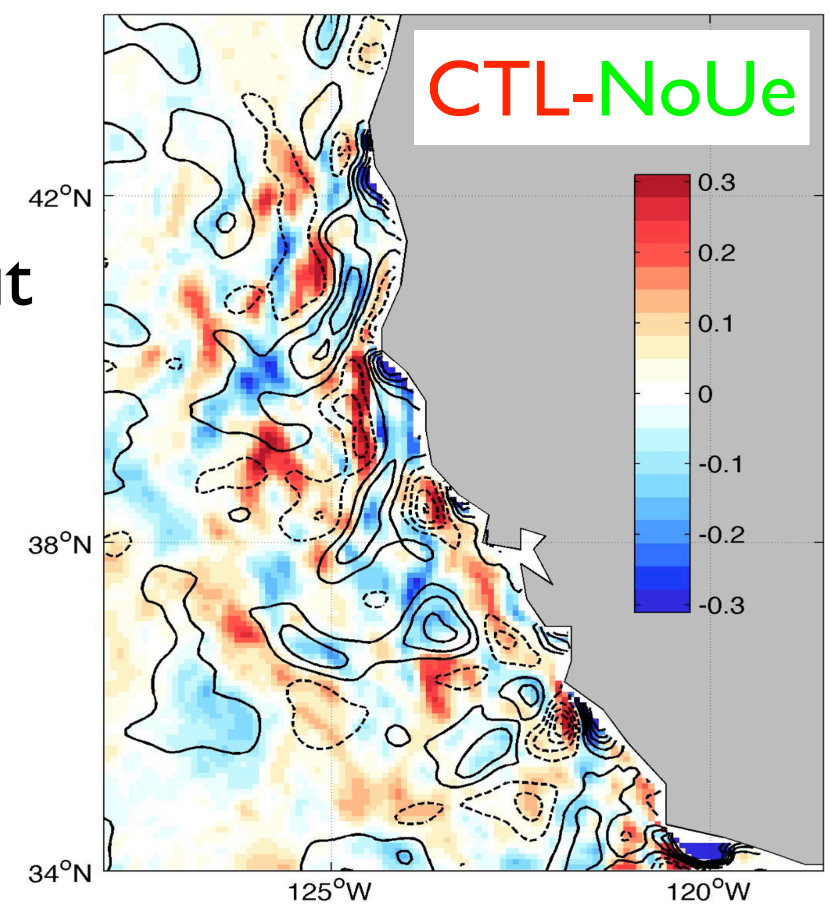
m/day

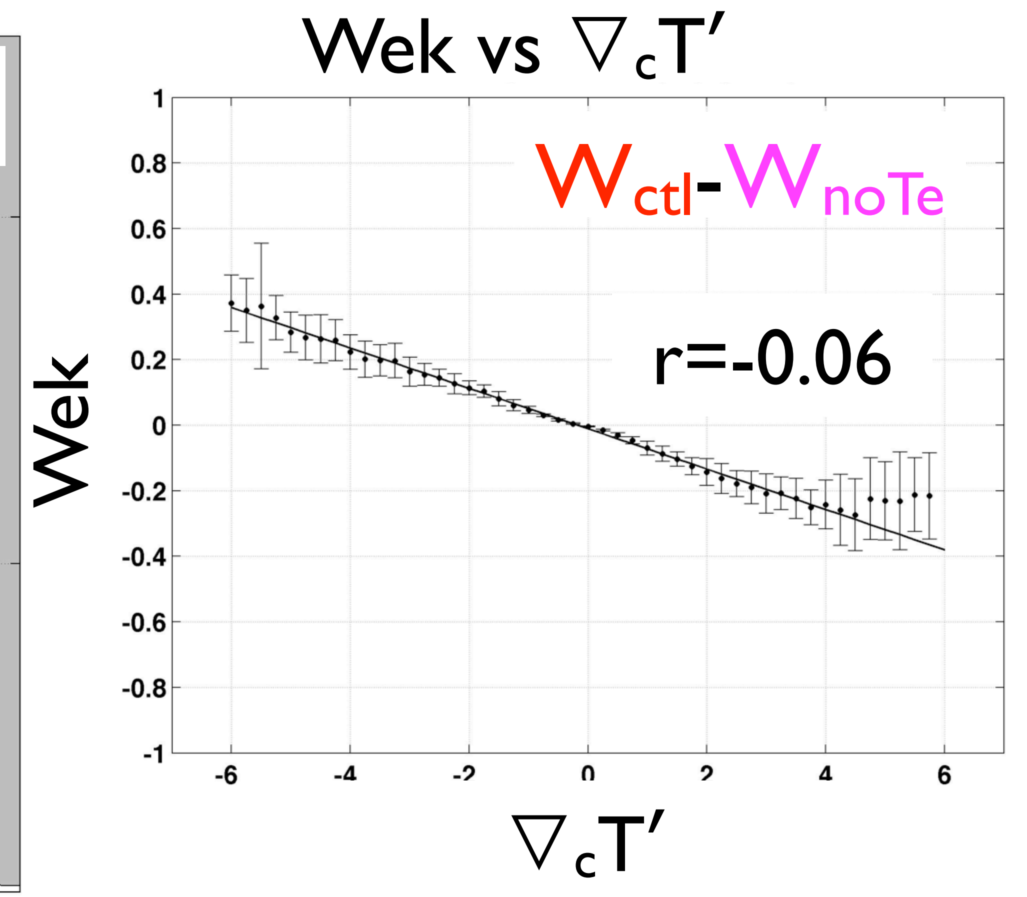
JAS 2005-2009

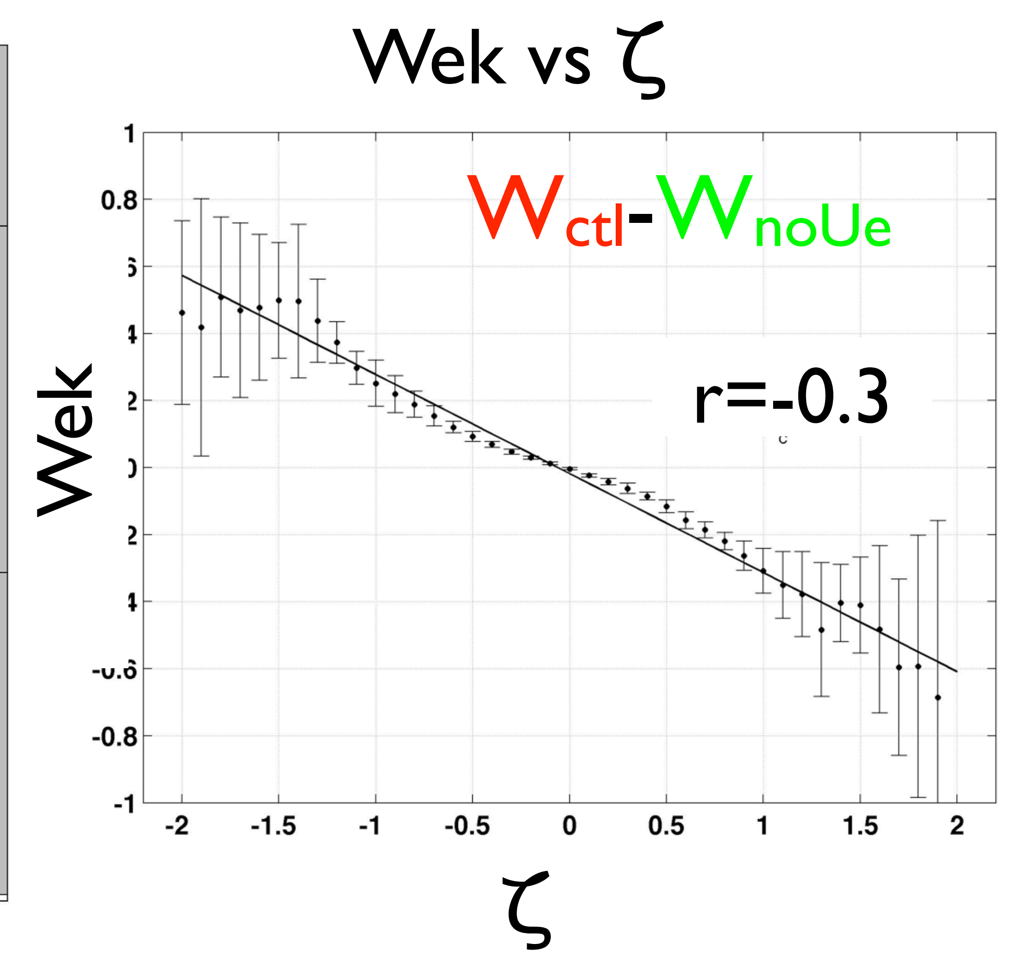
SST-induced and current-induced Ekman pumping velocity











- SST and vorticity induce the Wek responses of comparable magnitudes but with distinctive spatial pattern.
  - indicative of different feedback processes

JAS 2005-2009

Summary

- Surface EKE is weakened almost entirely due to mesoscale current effect on wind stress.
  - SST has no impact (at odds with some previous studies)
- EKE budget: eddies enhance the eddy drag and weaken the wind work.
  - Thus eddies have both direct and indirect impact.

- Eddies modify Ekman pumping velocity.
  - SST via a linear relationship between $\nabla \times \tau'$ and $\nabla_c T'$.
  - Current via gradient of surface vorticity.
  - Ekman pumping velocities due to SST and current are comparable in magnitude but different in spatial pattern.
    - Implying different feedback processes
    - Subject of ongoing study.

Thanks!