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

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KIOST
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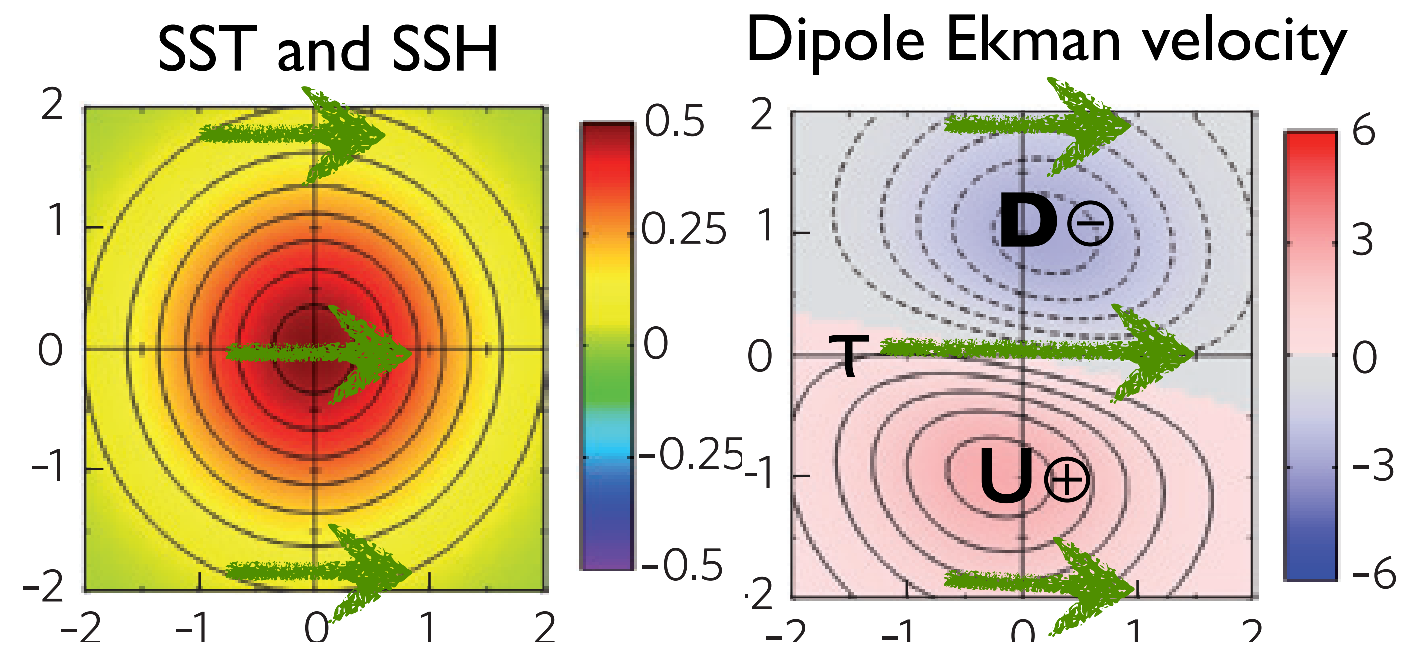
Eddy-wind interaction via SST

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

Uniform eastward wind over an anticyclonic eddy in the Southern Ocean (Chelton 2013)



Ekman pumping anomaly 90° out of phase with SSH → **Southward propagation** of an eddy (e.g., Dewar and Flierl 1987)

Eddy-wind interaction via SST

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

10m wind
$U_a = U_{ab} + \underline{U_{aSST}}$

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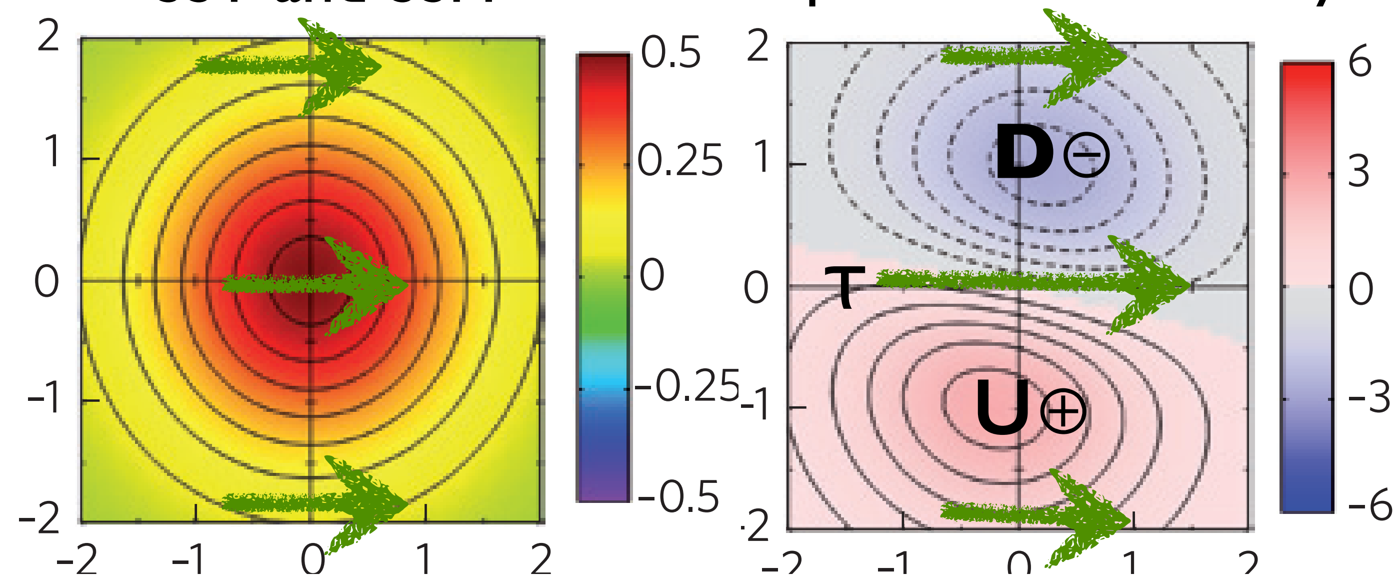
SST and SSH | Dipole Ekman velocity



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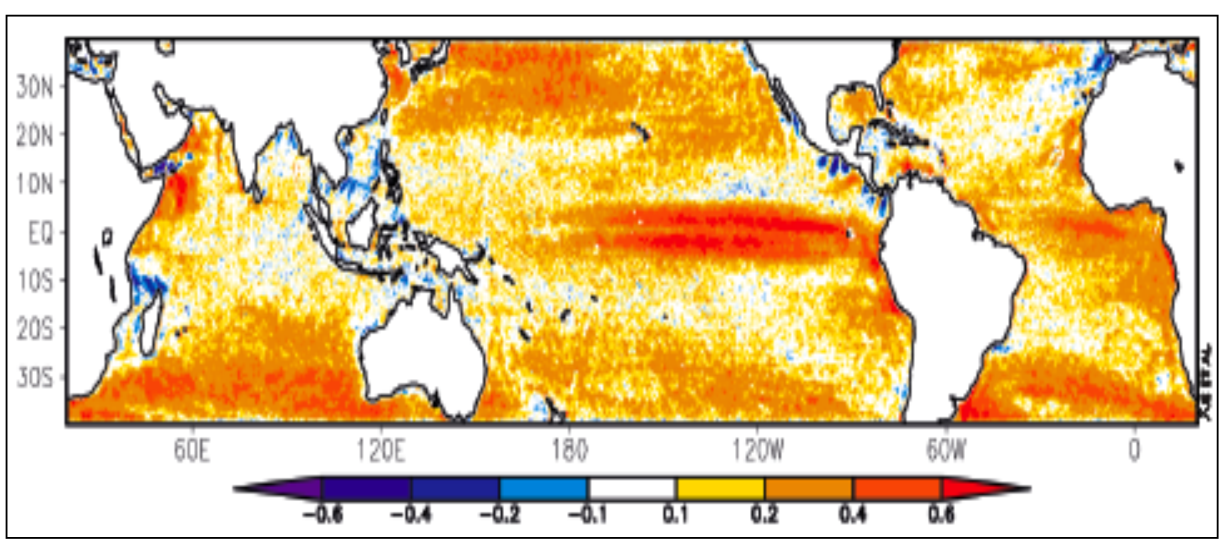
Correlation (SST & wind): high-passed



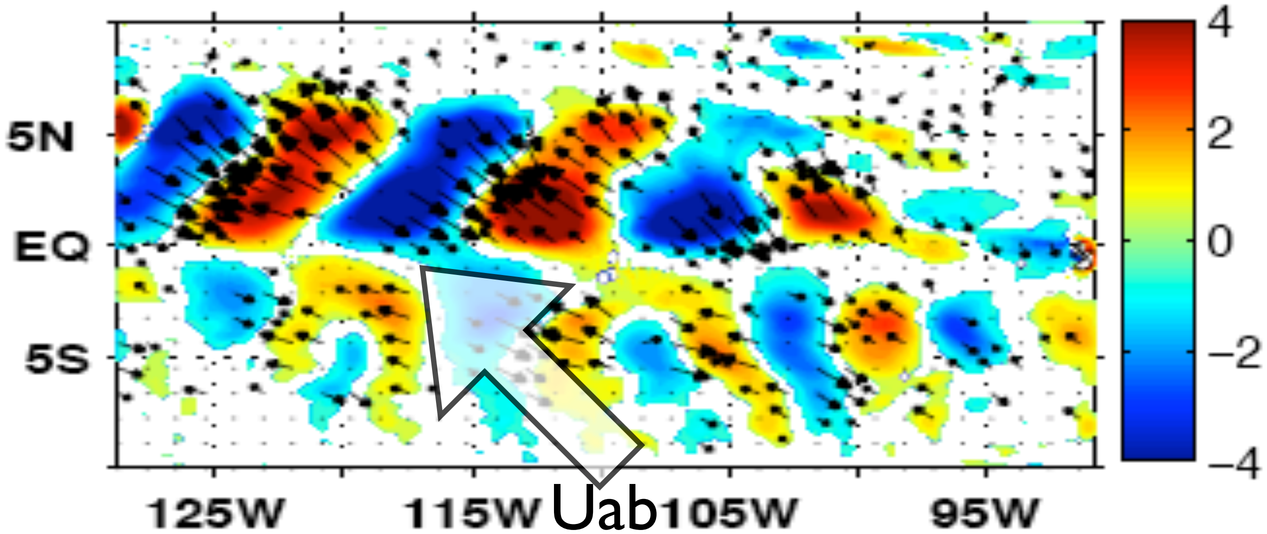
Satellite observations: Xie 2004

Eddy-wind interaction via SST

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

10m wind
$U_a = U_{ab} + \underline{U_{aSST}}$

stronger wind over warmer SST



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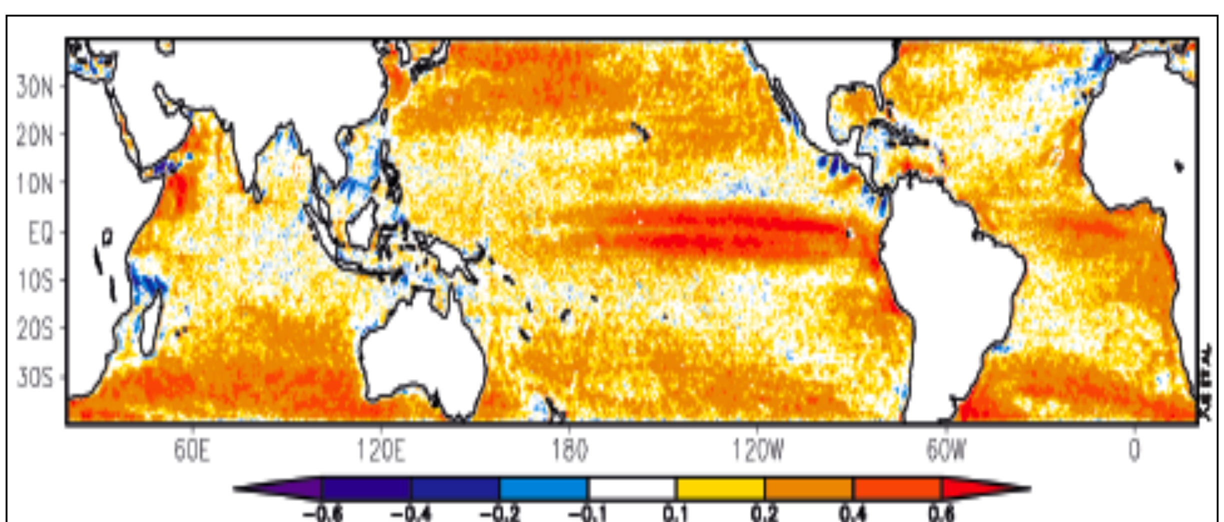

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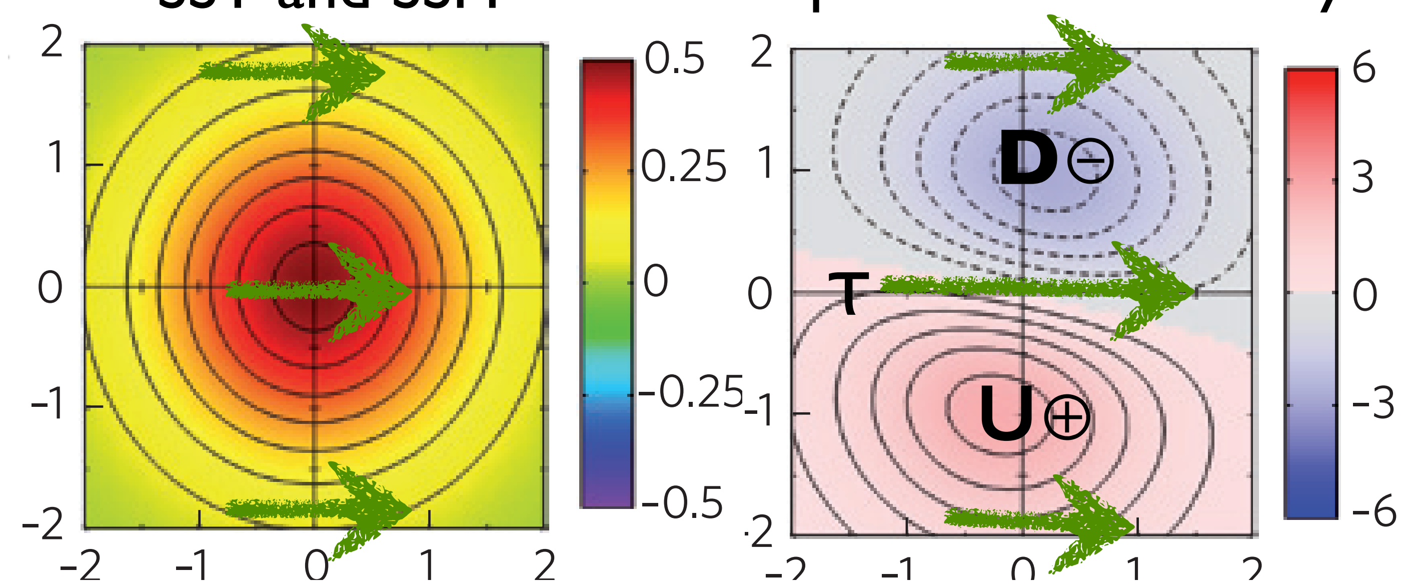


Ekman pumping anomaly 90° out of phase with SSH → **Southward propagation** of an eddy (e.g., Dewar and Flierl 1987)

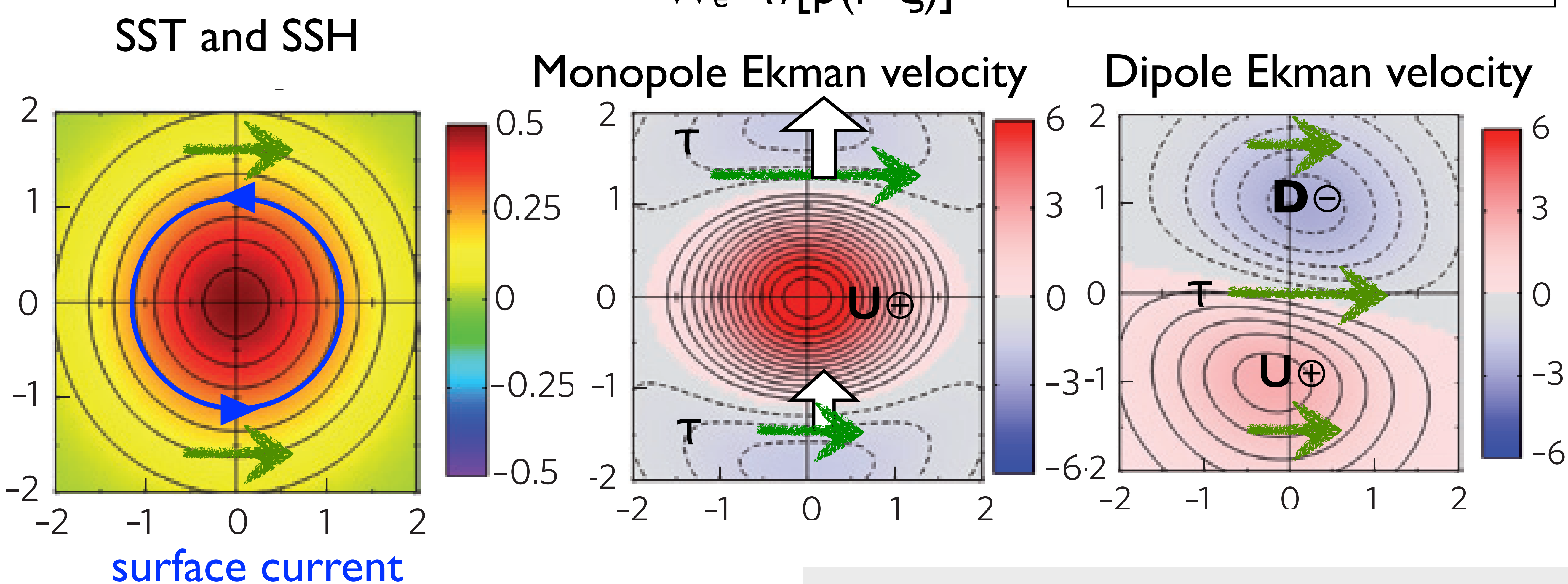
Eddy-wind interaction via current

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

Upwelling at the center of an anti-cyclonic eddy: **decaying of an anticyclonic eddy**

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

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



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

surface current

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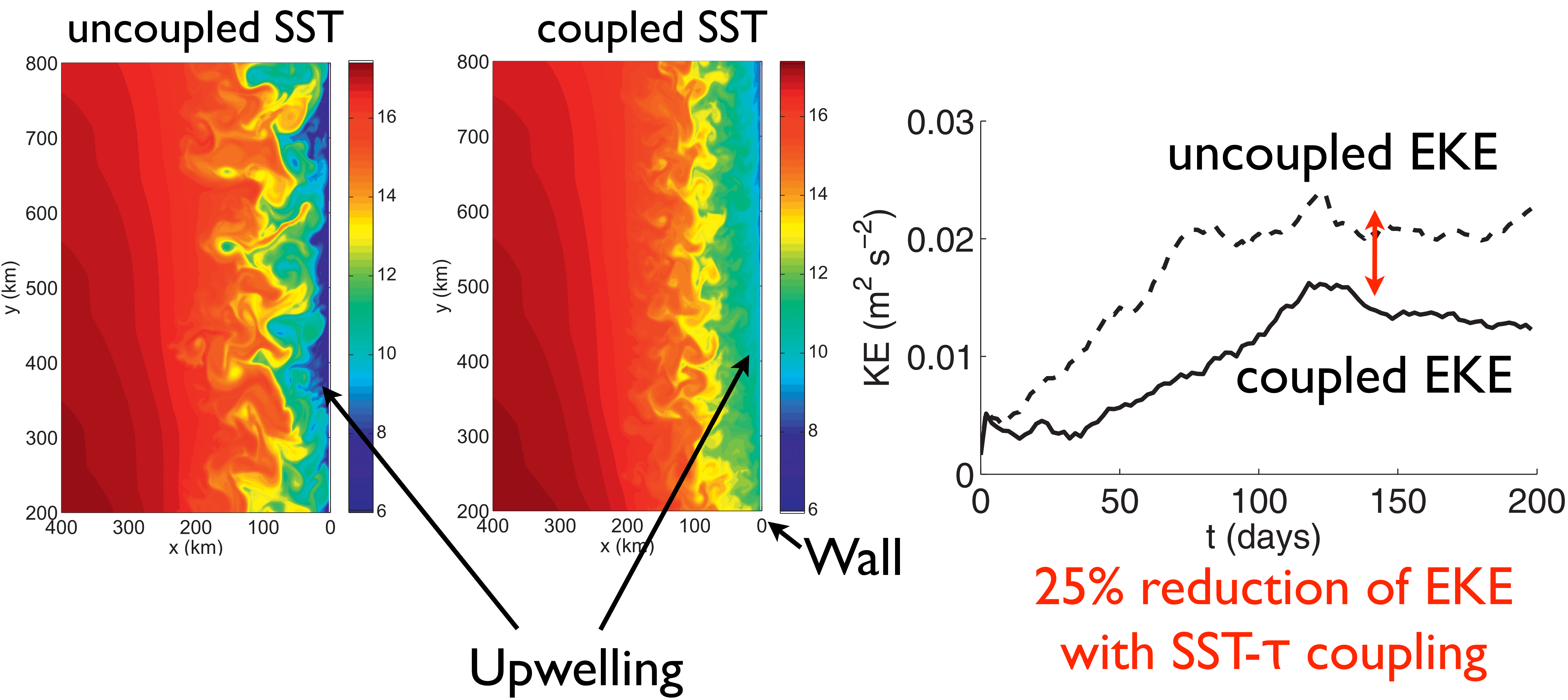
resulting wind stress

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

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

foci of this study: EKE and Ekman pumping

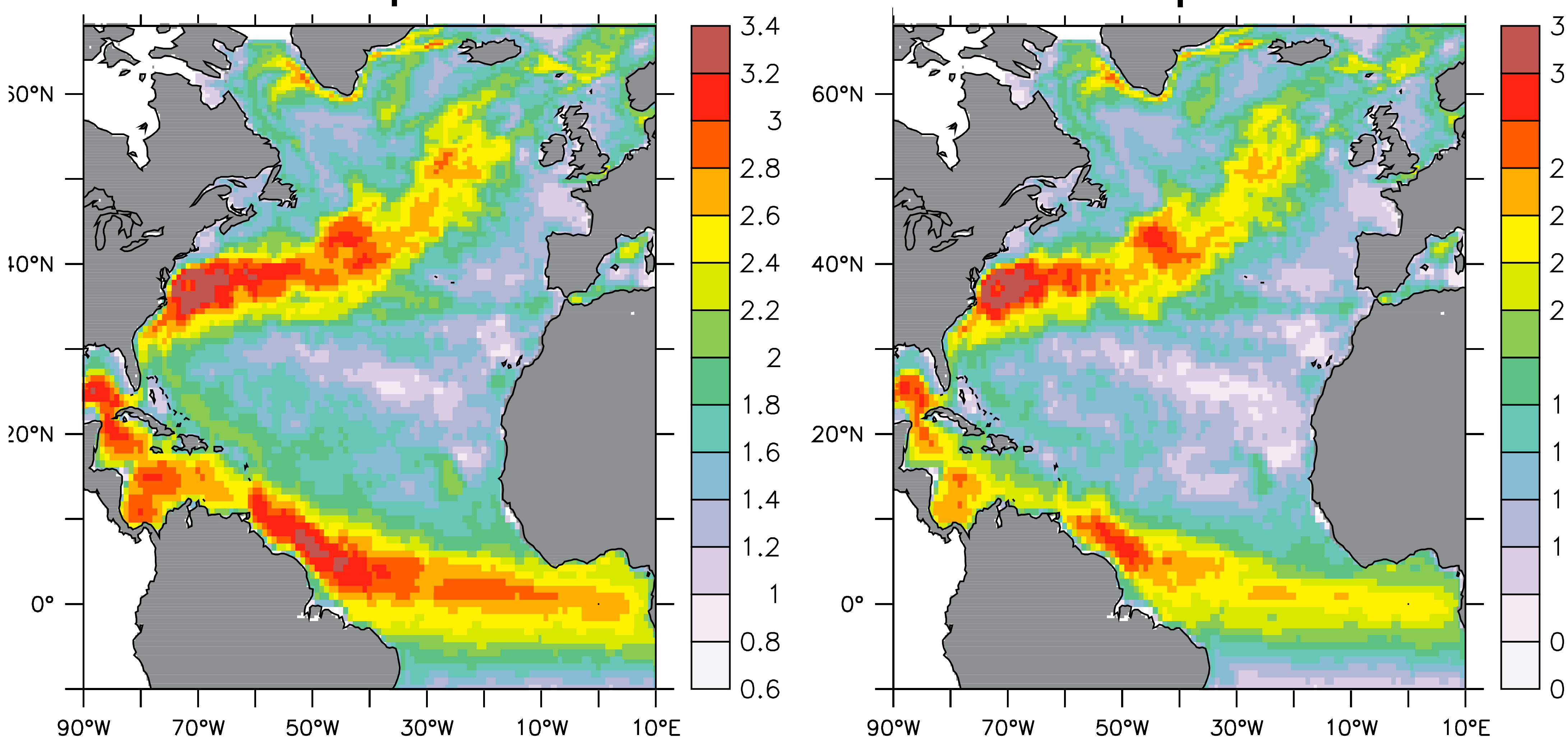
SST-τ coupling effect weakens the eddies: an idealized ocean model by Jin et al. (2009)



- 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)

uncoupled EKE / coupled EKE

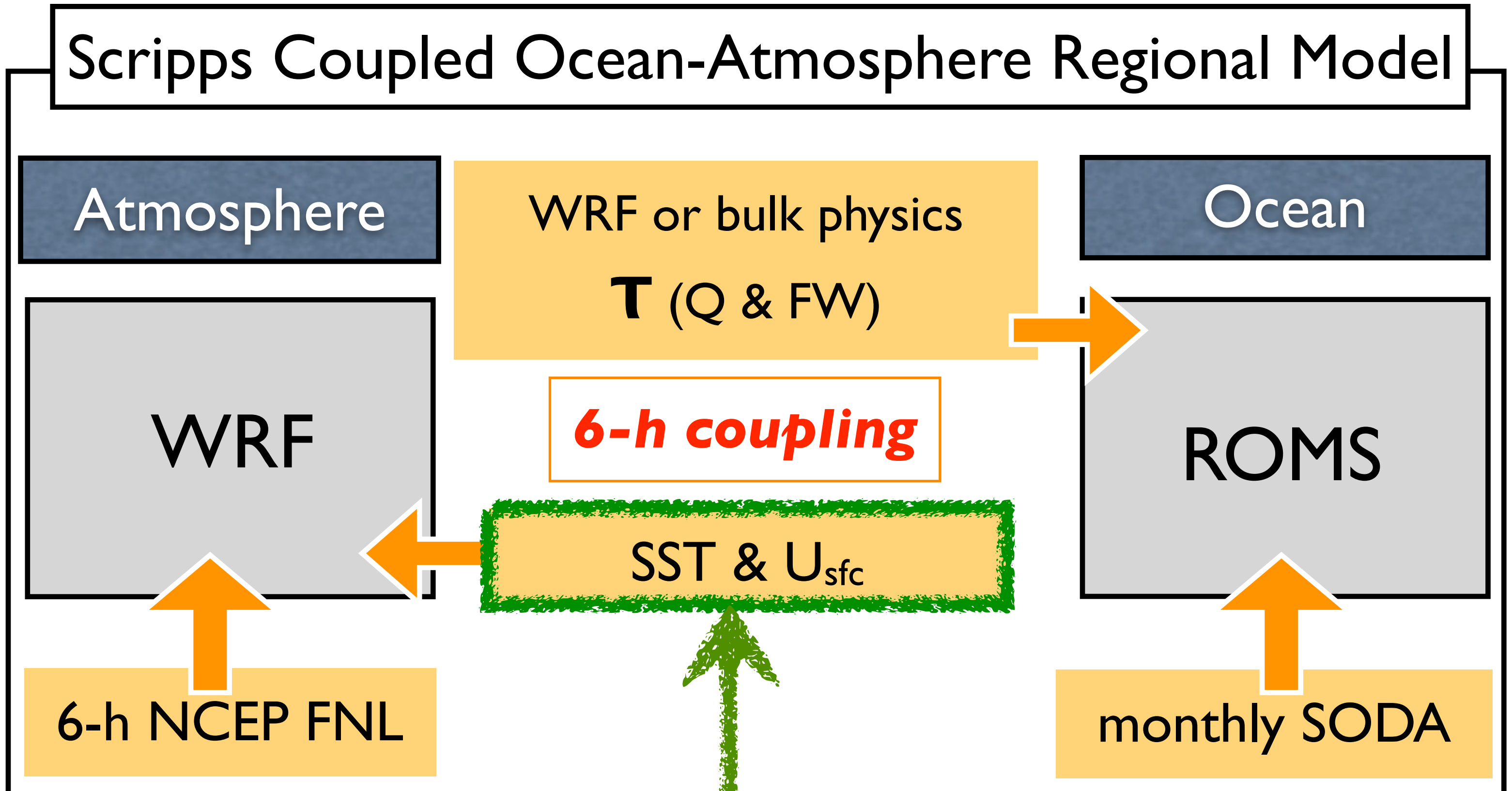


- 10% reduction in EKE in the mid-latitudes and ~50% in the tropics
- Primarily due to increased eddy drag ($\tau' \cdot u'$, direct effect)
- Change in baroclinic and barotropic instability (indirect effect) of secondary importance

Result from previous studies and goal of this study

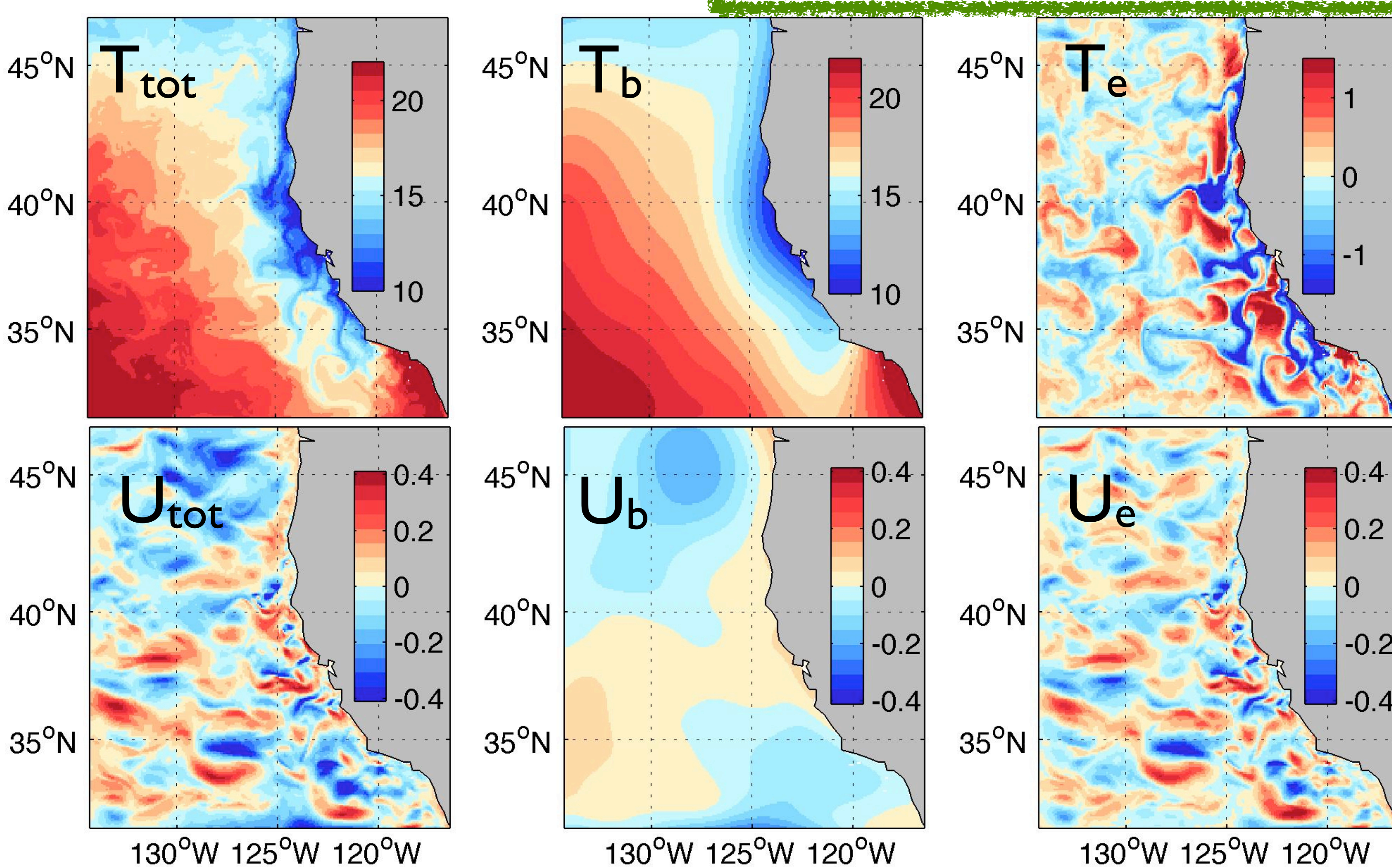
- Previous studies considered either SST or U_o in τ formulation in ocean-only models and saw weakened eddy variability.
- This study examines the relative magnitudes of SST and u_{sfc} effects in a fully coupled regional model.

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

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

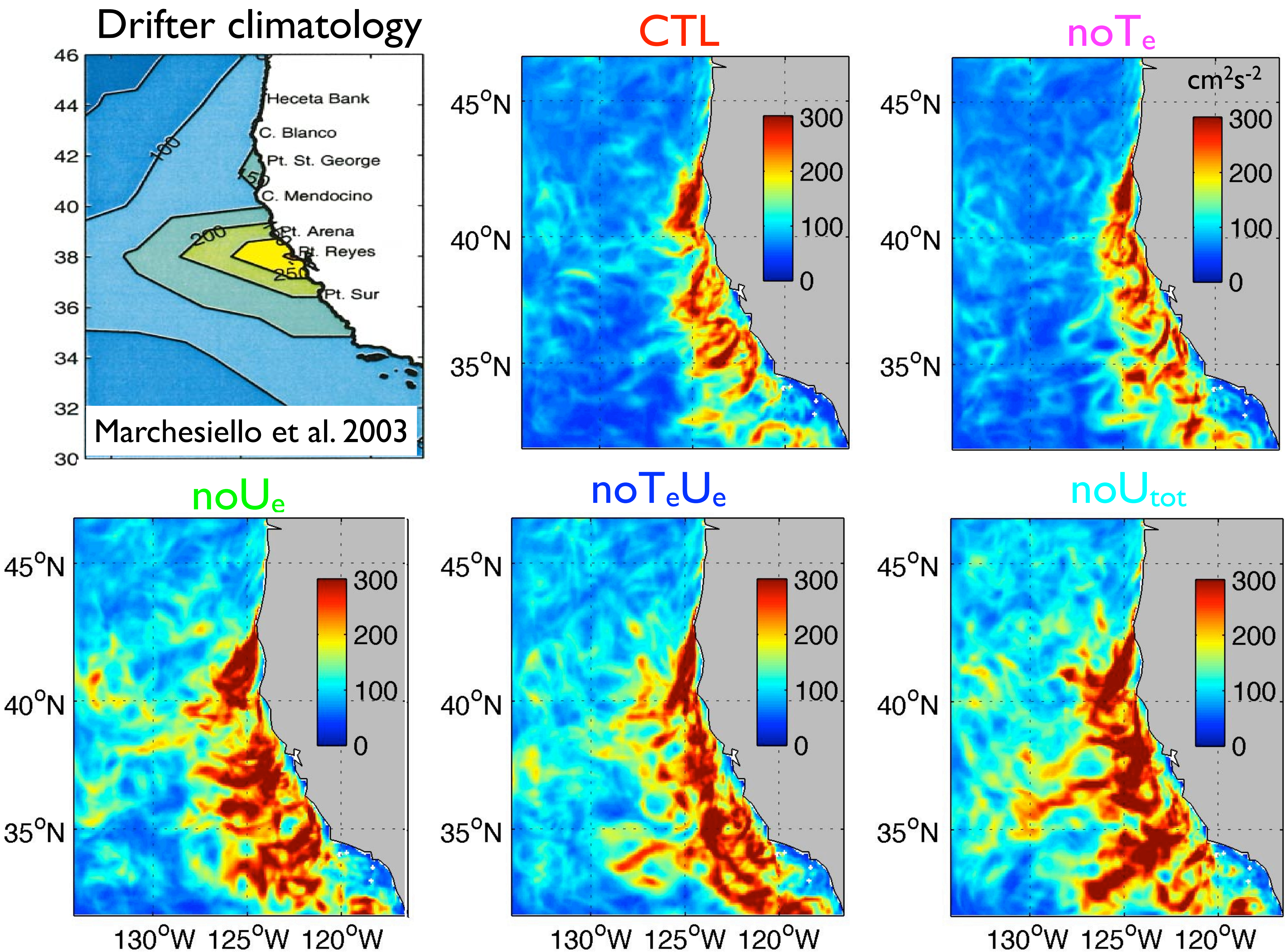
$T_{tot} = T_b + T_e$

$U_{tot} = U_b + U_e$ 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
noT_eU_e	T_b	T_e	U_b	U_e
noU_{tot}	T_b	T_e	U_b	U_e

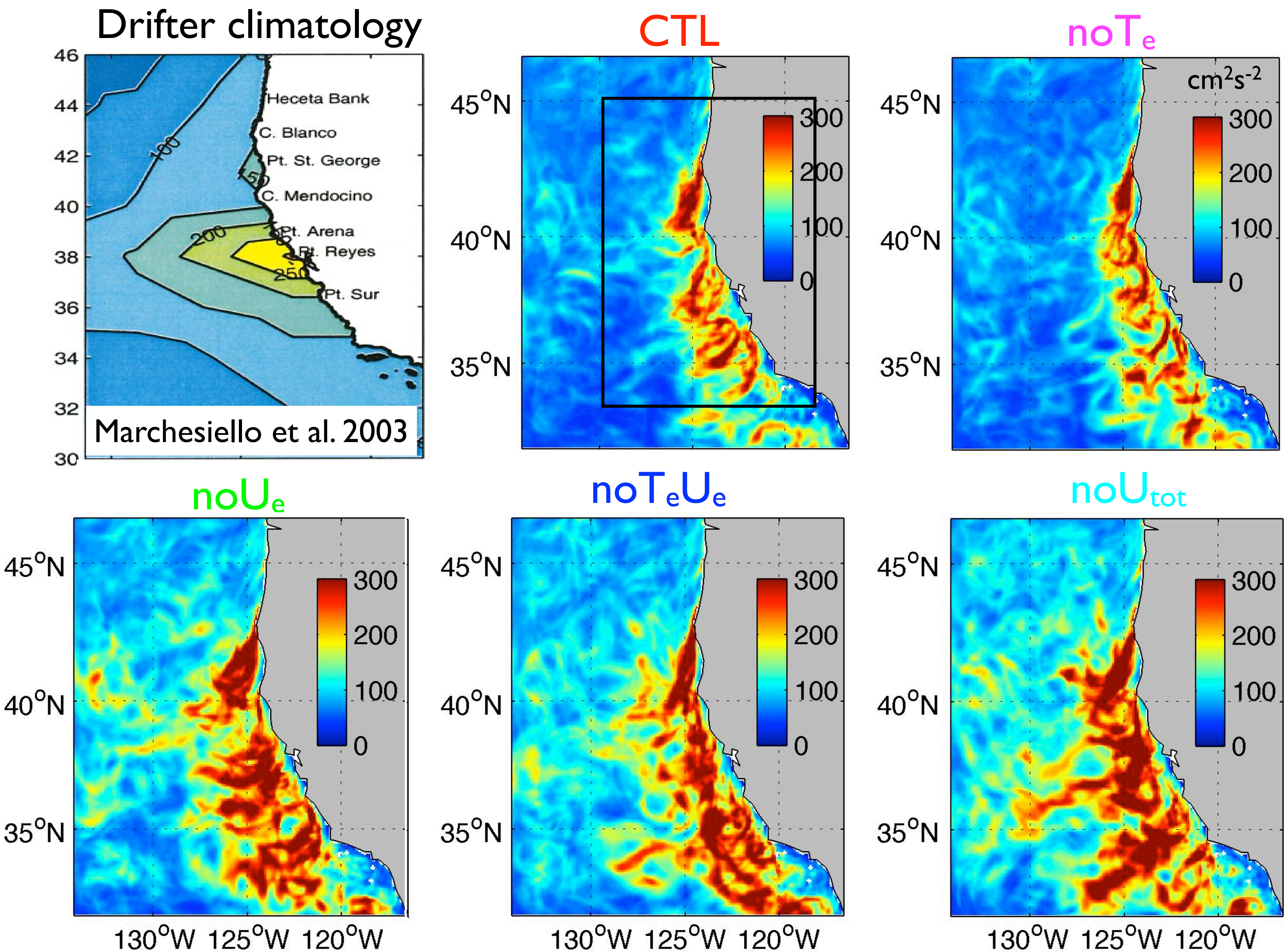
Eddy kinetic energy

Eddy kinetic energy JAS 2005-2010



• T_e no impact • <u>25% weaker</u> EKE with U_e • <u>30% weaker</u> EKE with U_b+U_e

Eddy kinetic energy JAS 2005-2010



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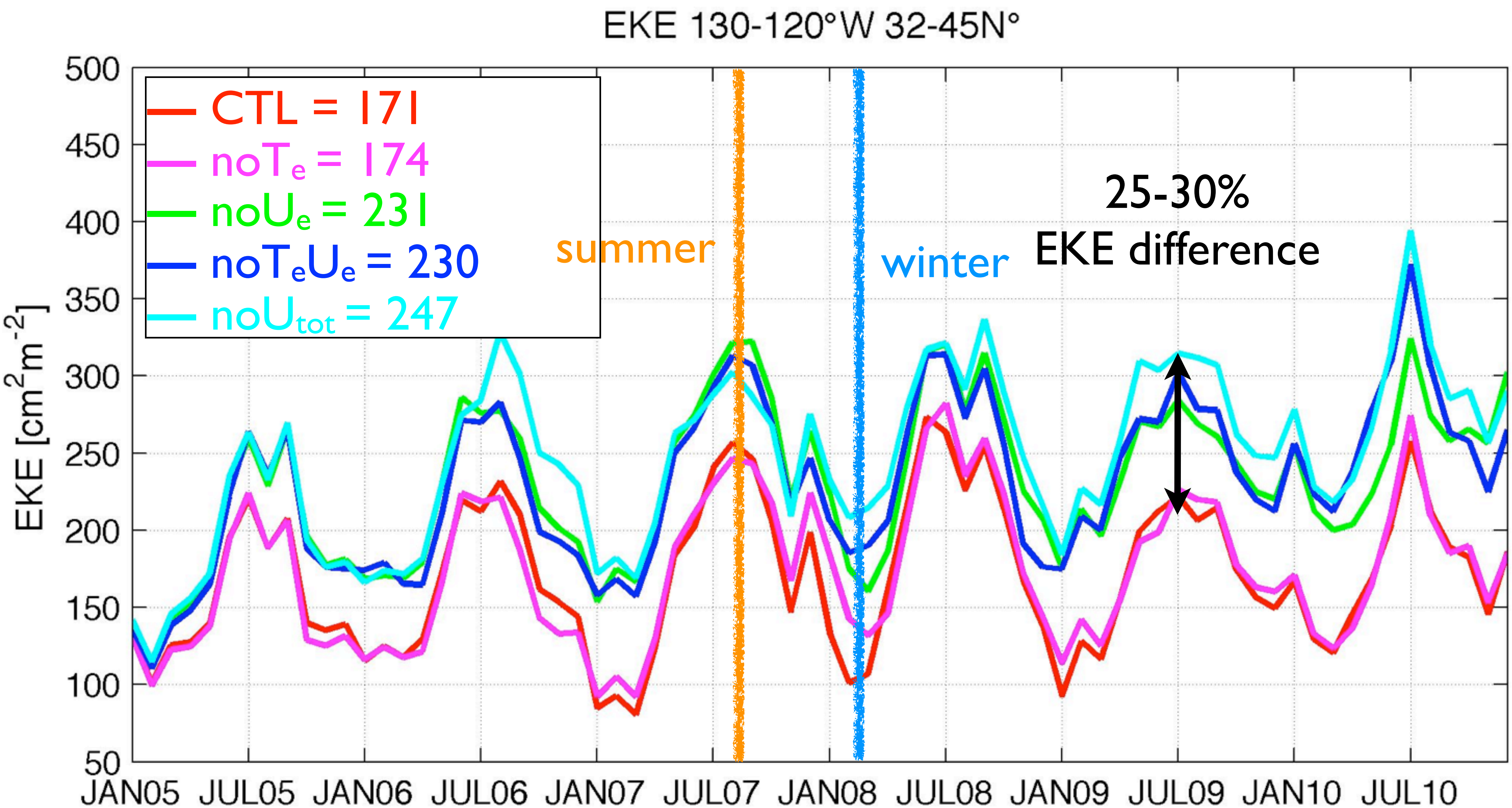
Monthly EKE time-series



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)

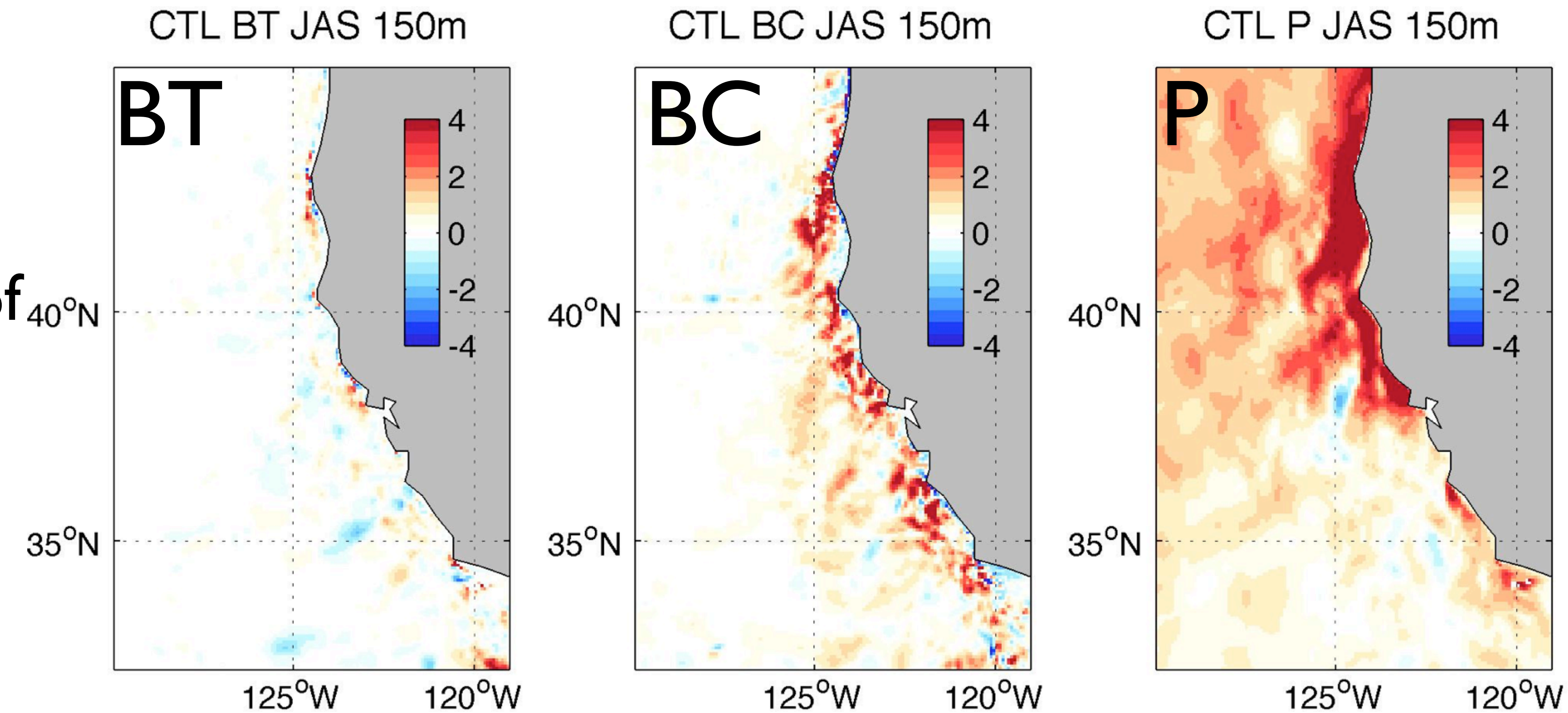
$K_m \rightarrow K_e$ barotropic conversion (BT)

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

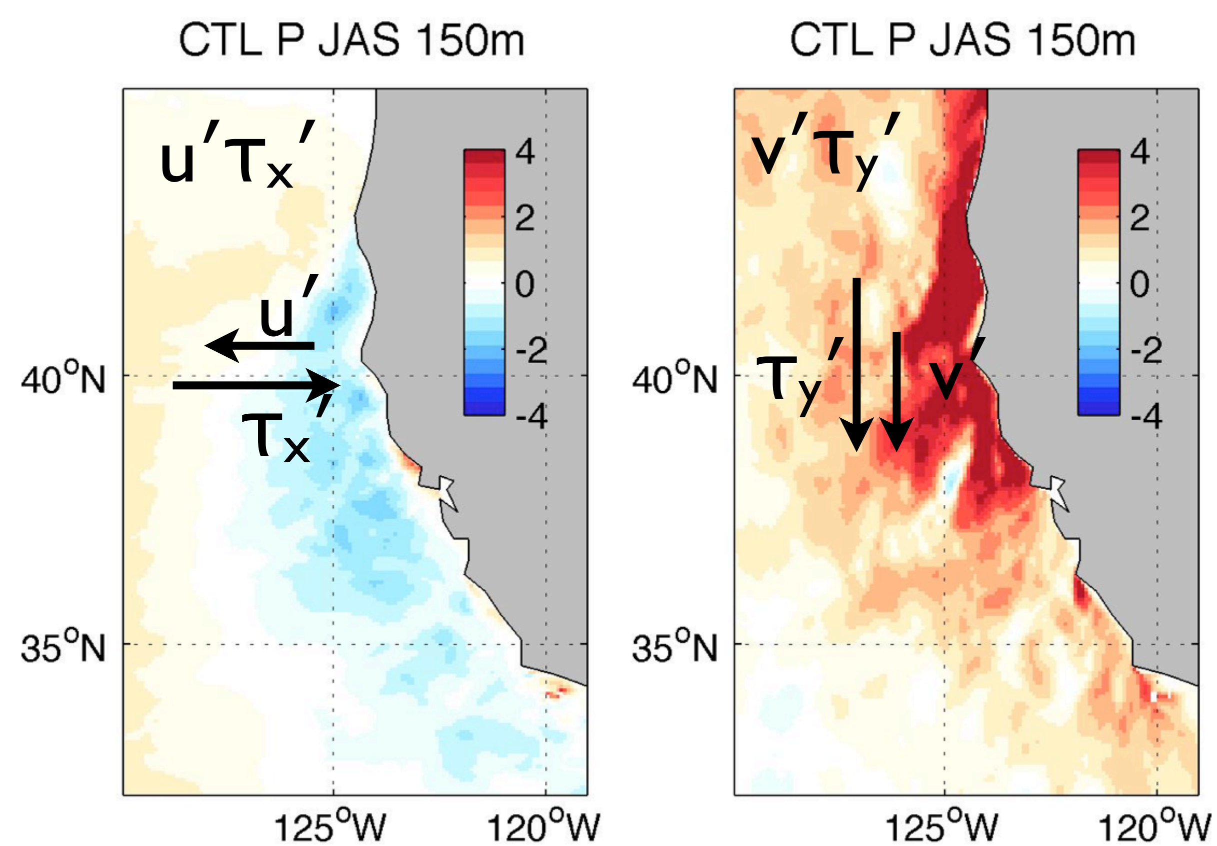
Upper 100 m average

H~fL/N, where $f=10^{-4}$, $L=10^4$m, $N=10^{-2}$ → $H=10^2$m

Summertime EKE budget in CTL



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

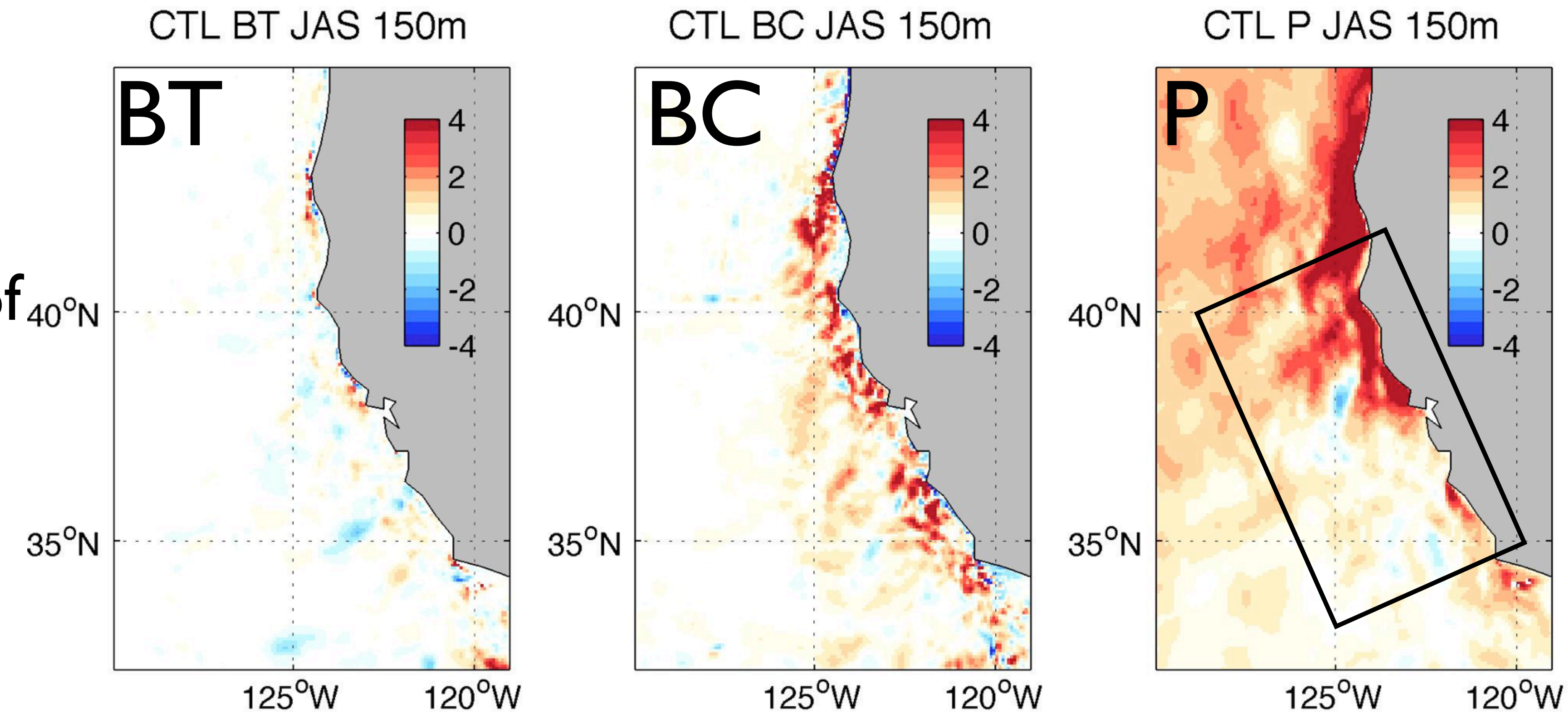


- v'τ_y': Source of EKE
  - v' is a linear response to nearshore τ_y'
- u'τ_x': Dissipating EKE
  - Eddies (via u') "systematically" oppose τ_x' in the upwelling zone

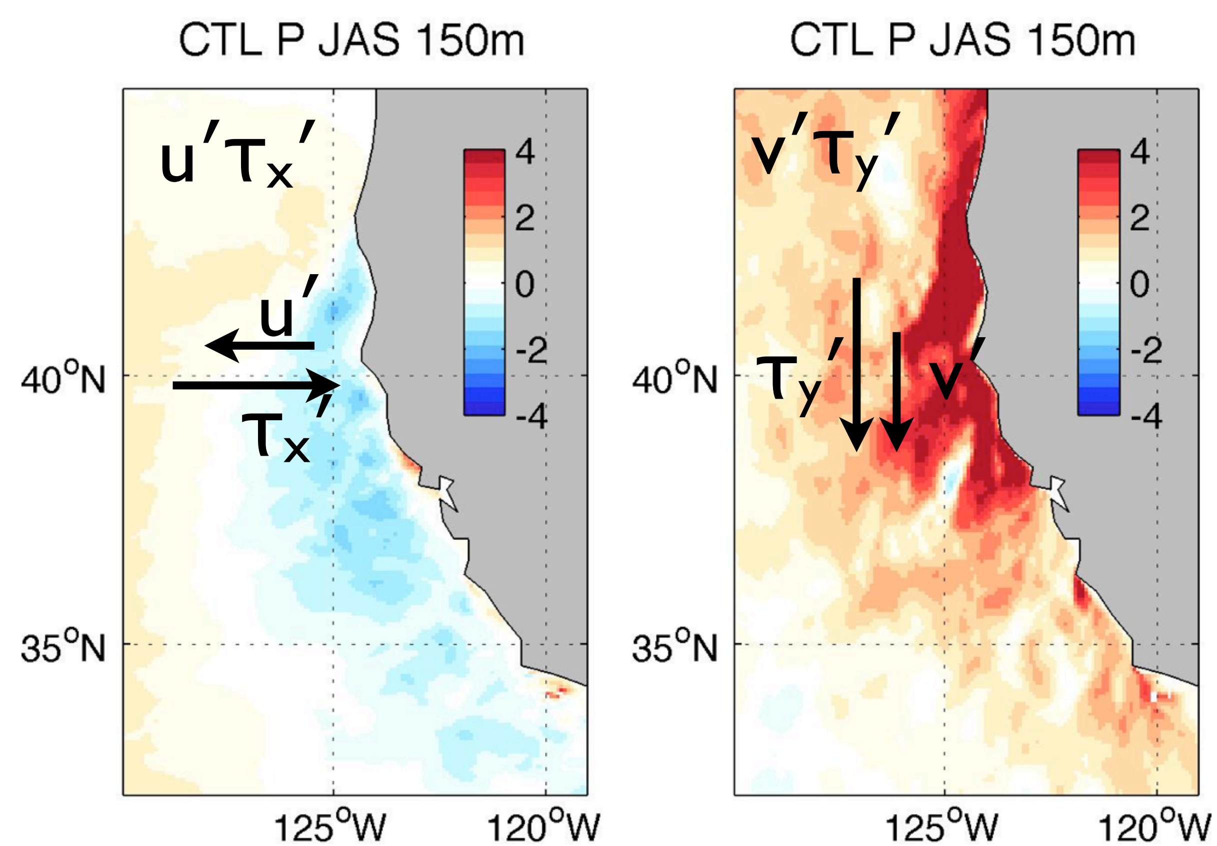
150 m average

Summertime EKE budget in CTL along-shore mean

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

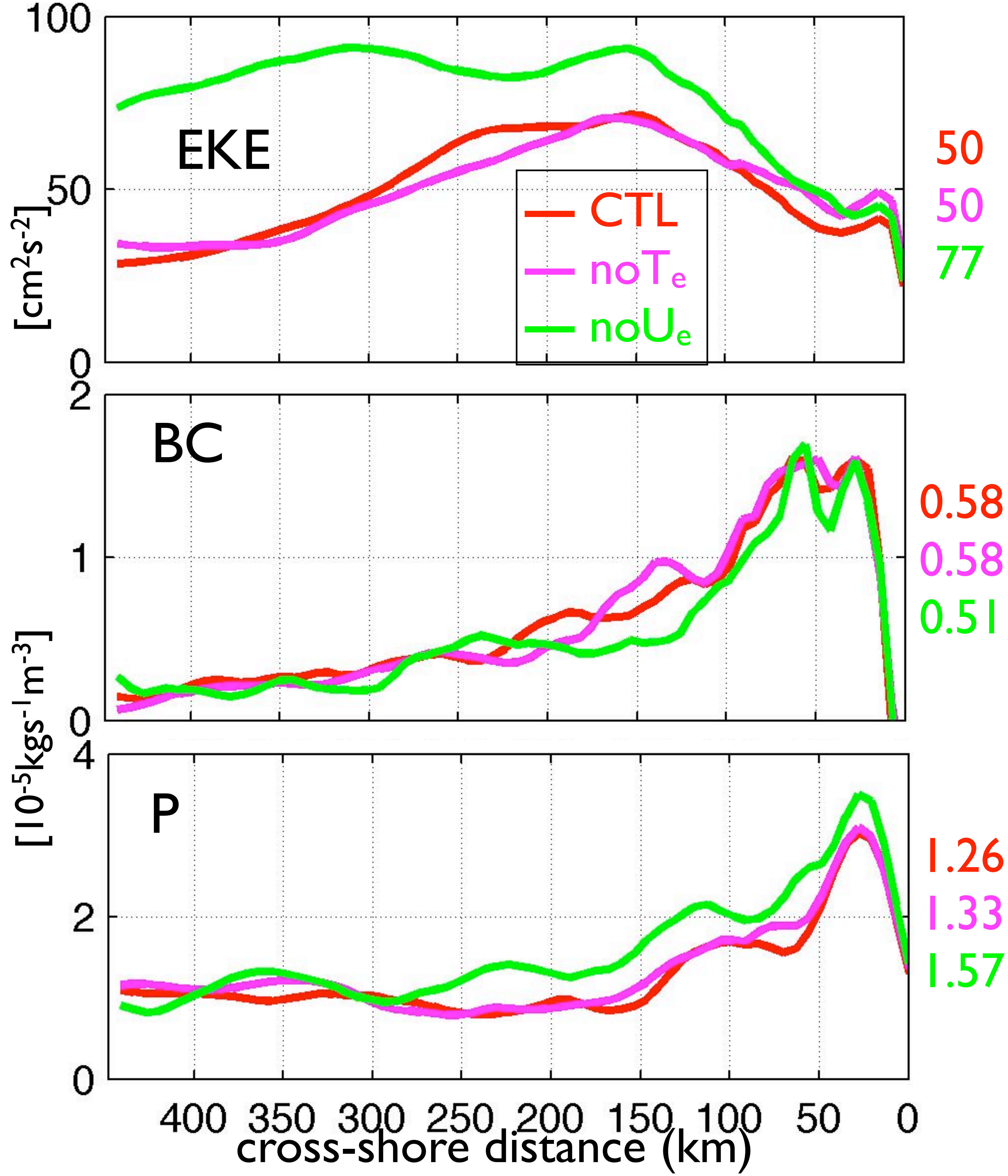


- $v'\tau_y'$: Source of EKE
  - v' is a linear response to nearshore τ_y'
- $u'\tau_x'$: Dissipating EKE
  - Eddies (via u') "systematically" oppose τ_x' in the upwelling zone



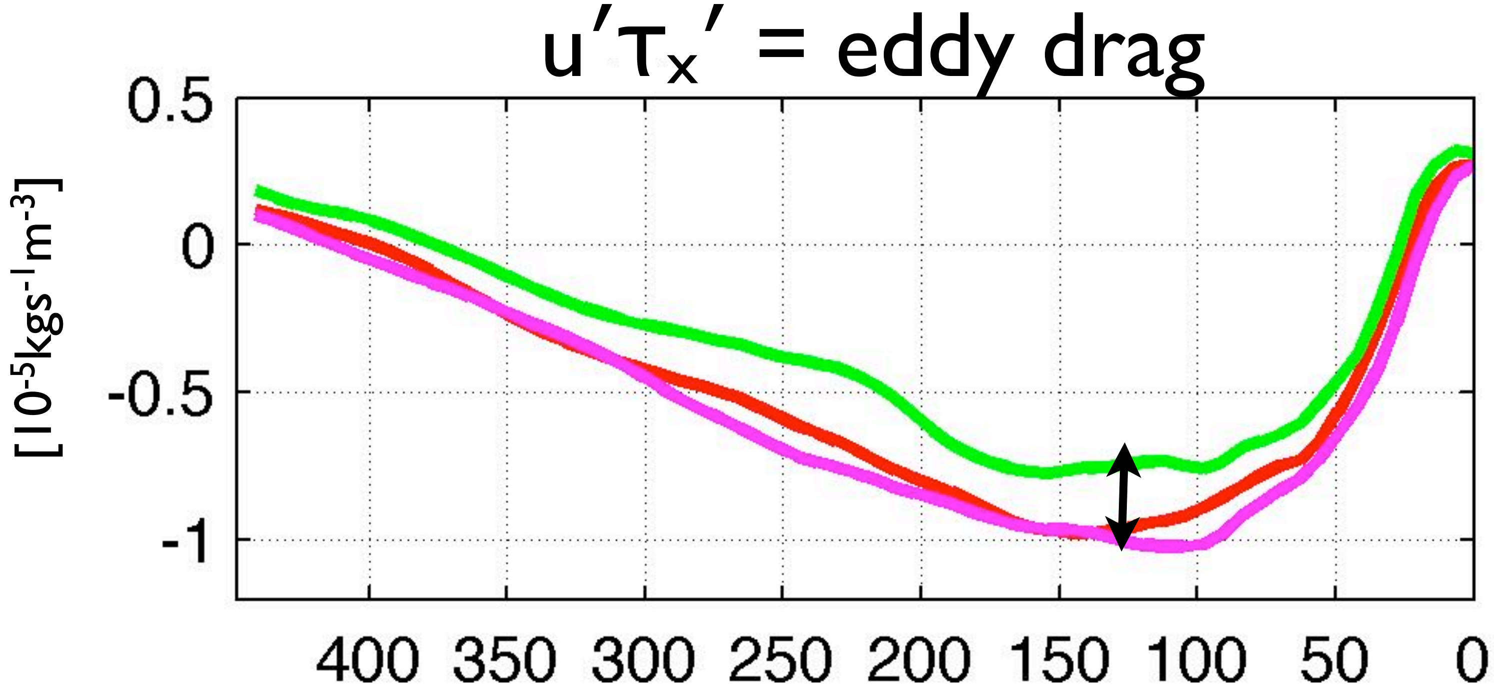
150 m average

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$_e$ → CTL: 20% reduction

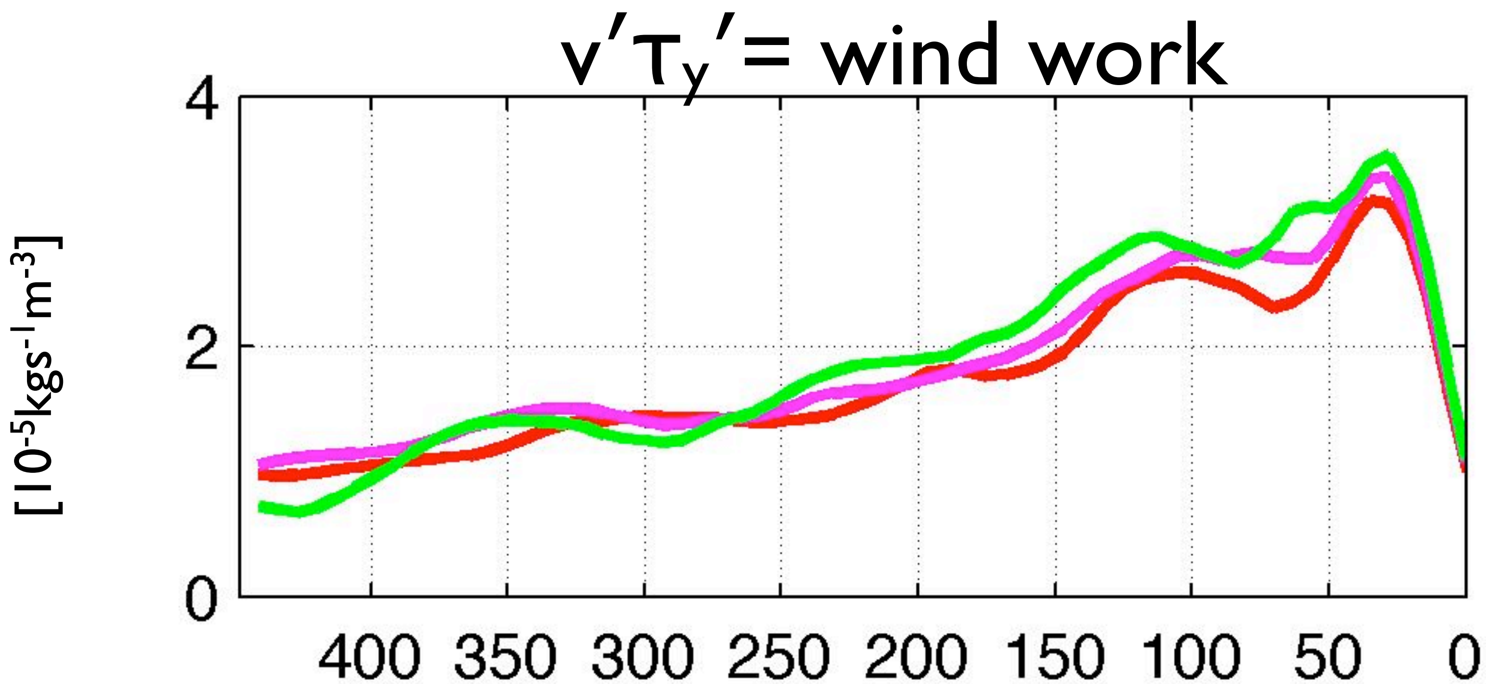
Eddies increase the eddy drag and reduce the momentum input.



eddy drag

CTL=−0.47
noTe=−0.53
noUe=−0.33

42% stronger eddy drag



wind work

CTL=1.74
noTe=1.86
noUe=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

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

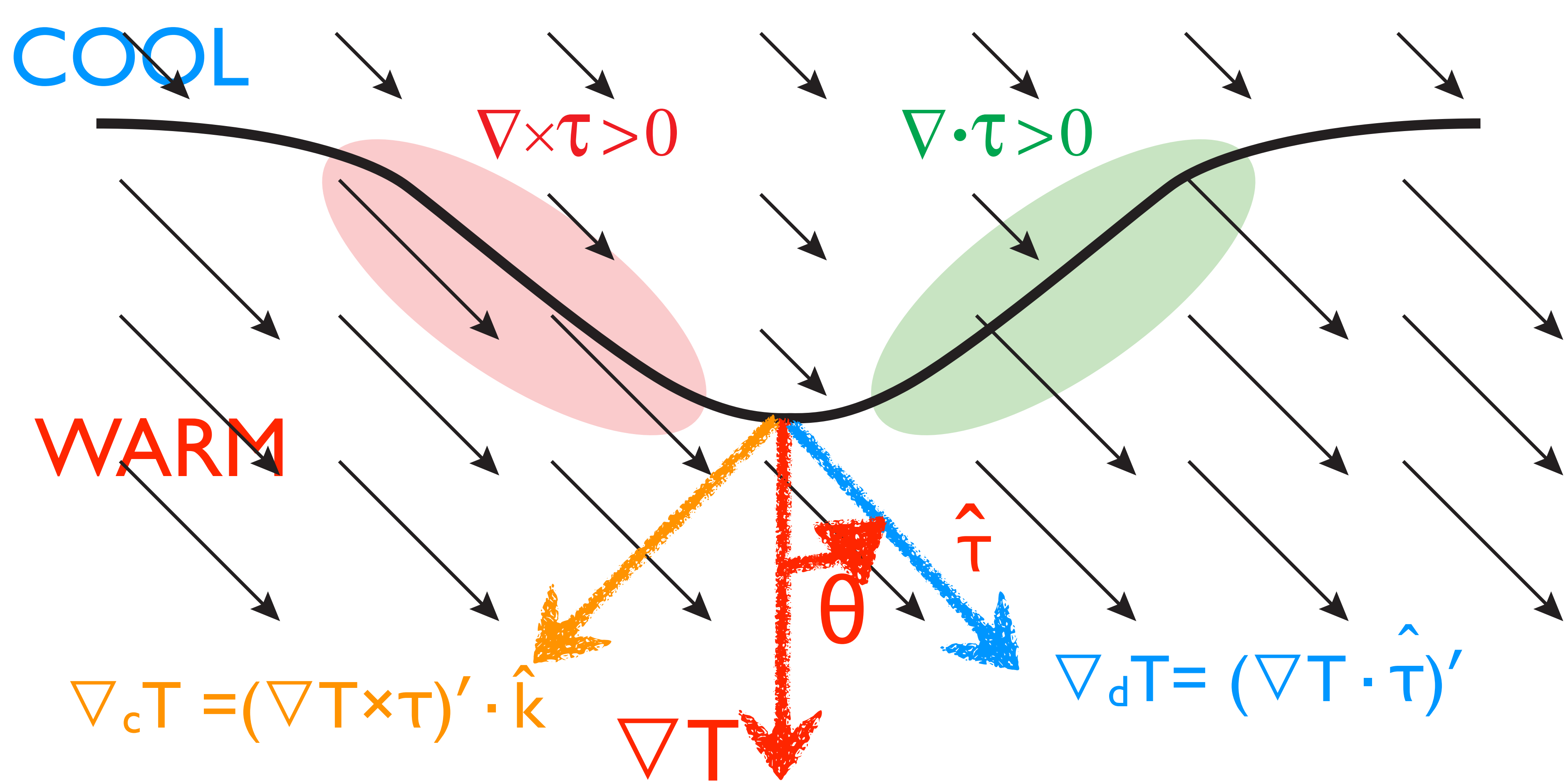
Curl-induced
linear Ekman pumping

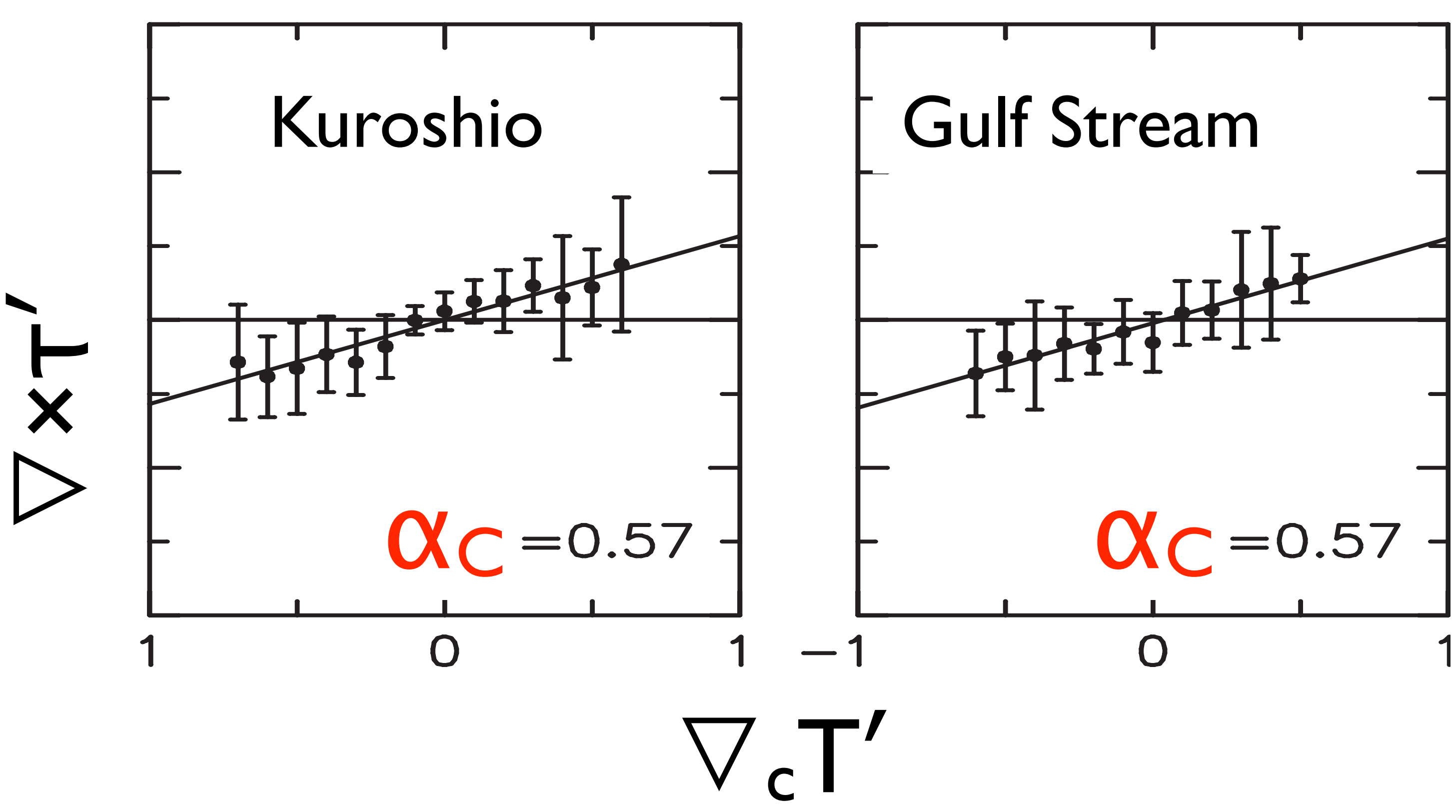
Vorticity gradient-induced
nonlinear Ekman pumping

β Ekman pumping
(negligible)

SST induced Ekman pumping

SST-induced Ekman pumping velocity





Positive empirical relationship

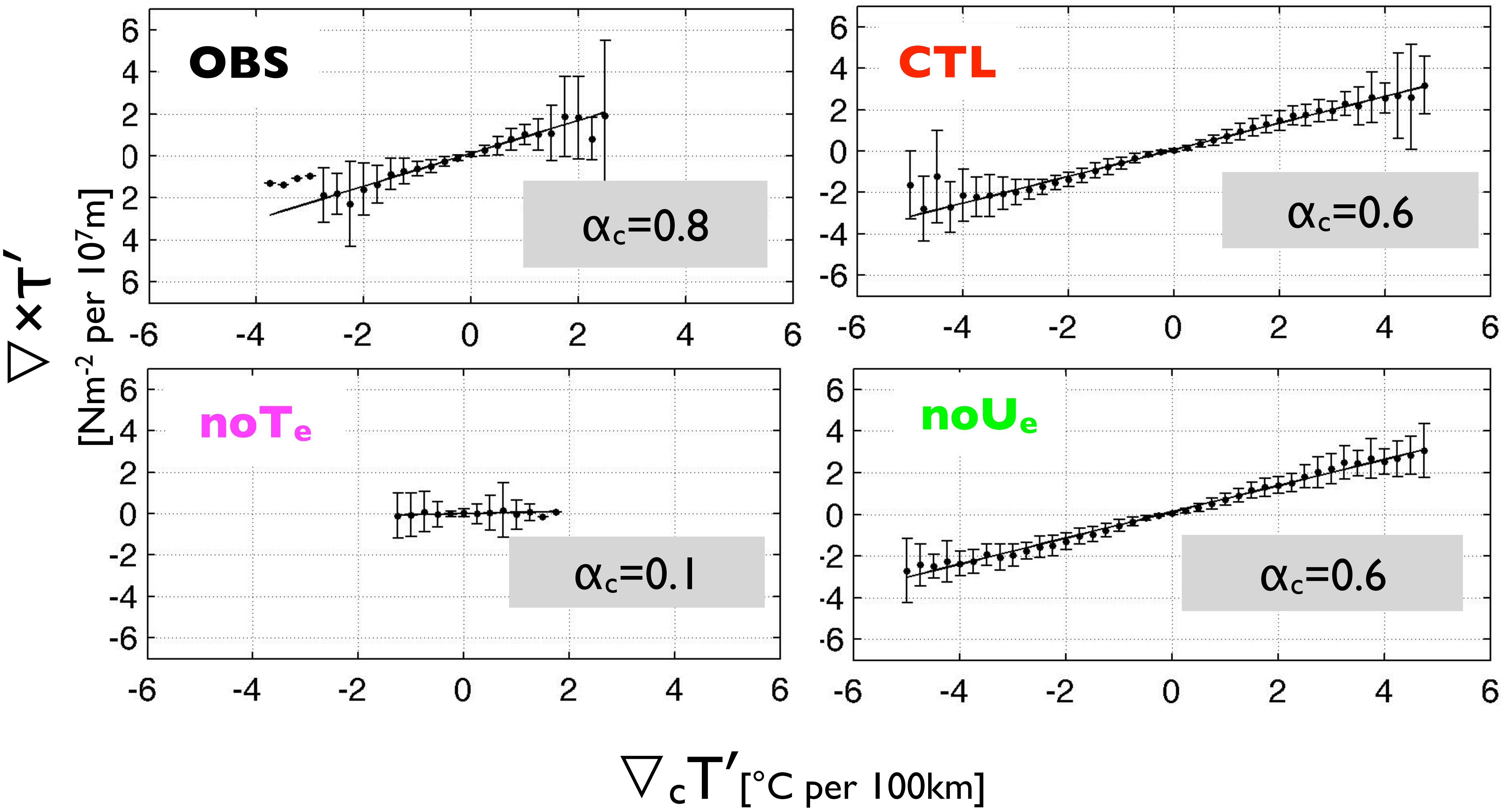
$$\nabla \times \tau' = \alpha_C \nabla_c T'$$

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

Chelton et al. 2004

Wind stress curl and cross-wind SST gradient

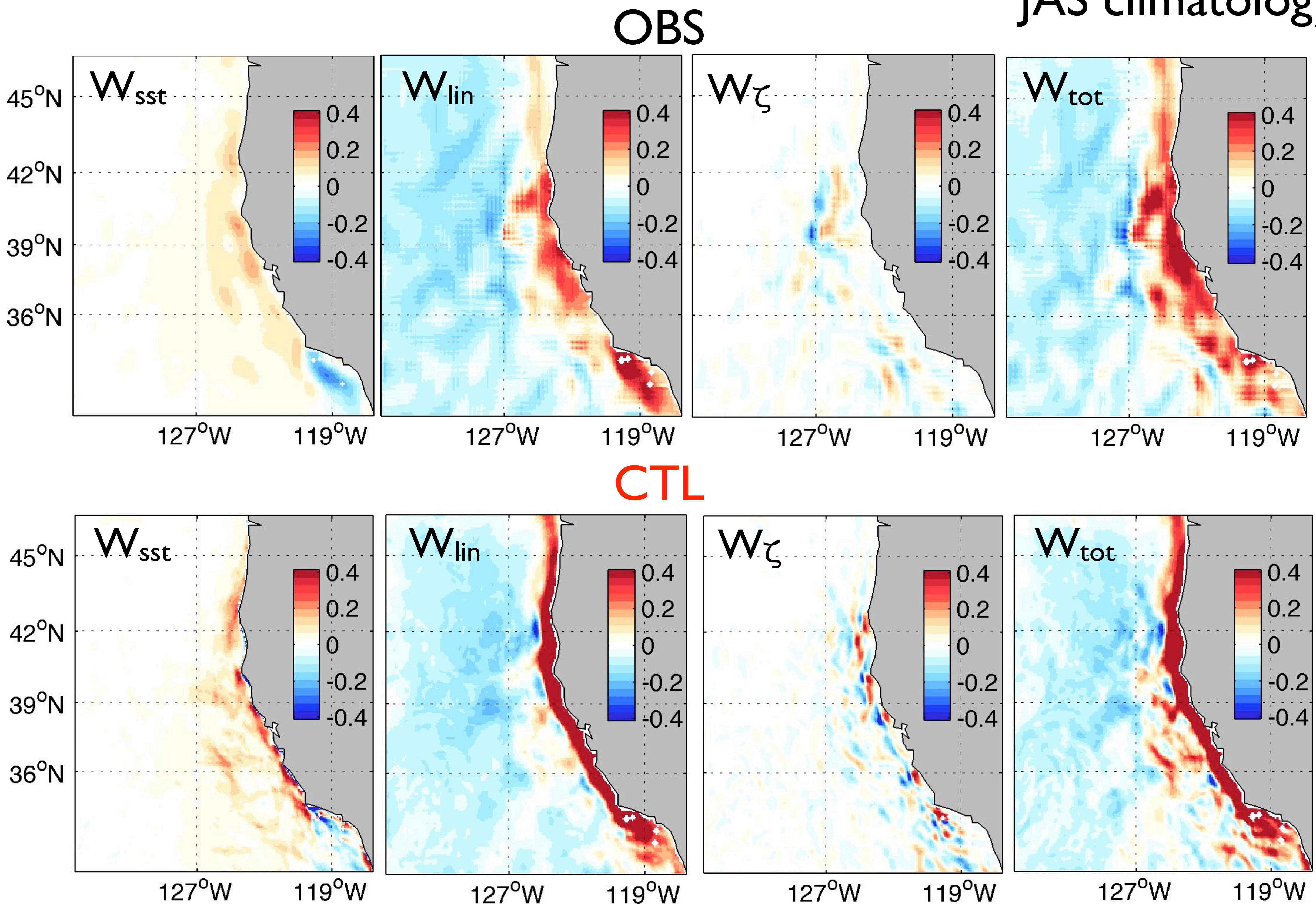
$$W_{SST} = \frac{\nabla \times \tau'_{SST}}{\rho_o (f + \zeta)} \approx \frac{\alpha_c \nabla_c SST}{\rho_o (f + \zeta)}$$



JAS 2005-2009; QuikSCAT wind stress and TRMM SST

Ekman pumping velocity

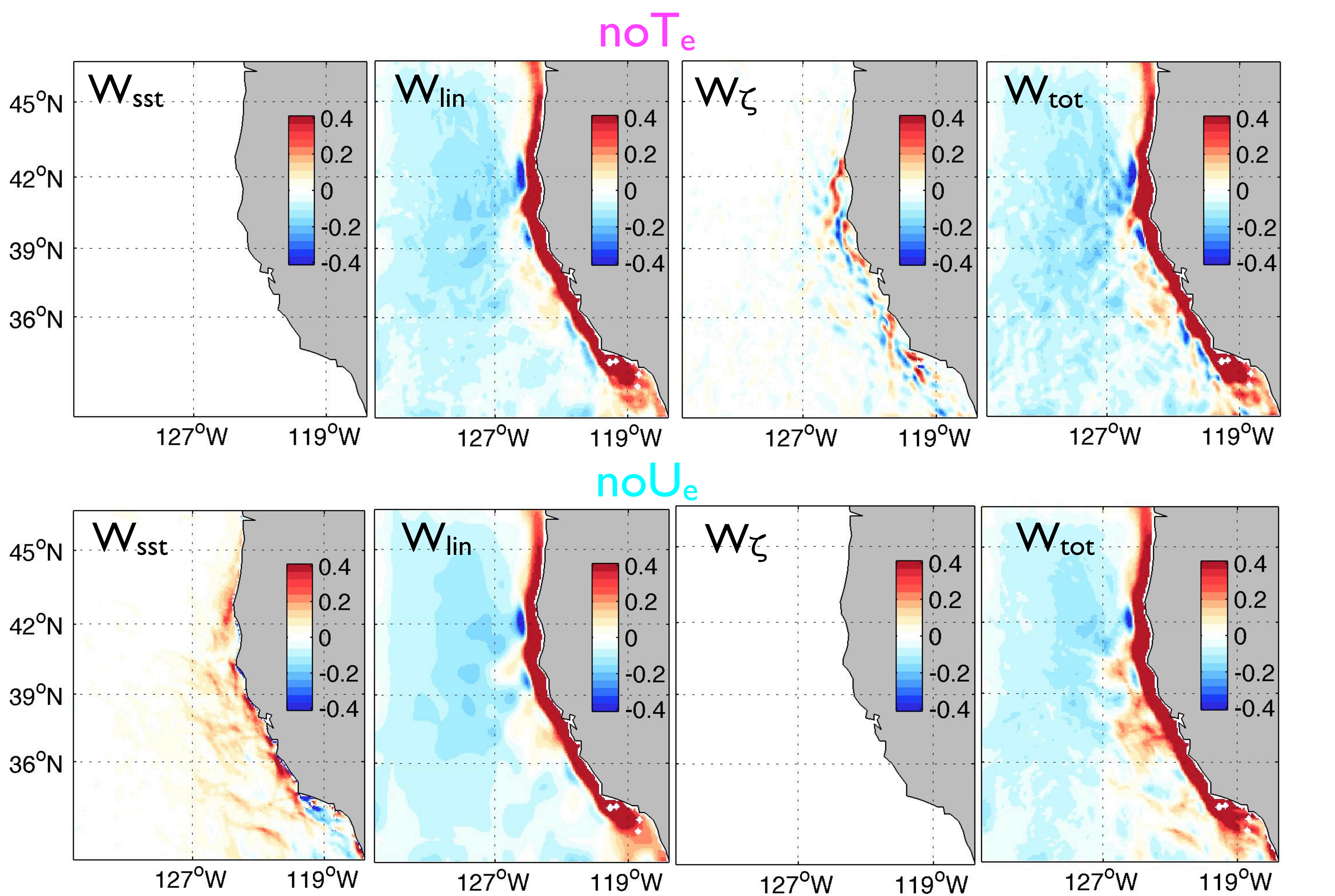
JAS climatology



m/day

JAS 2005-2009

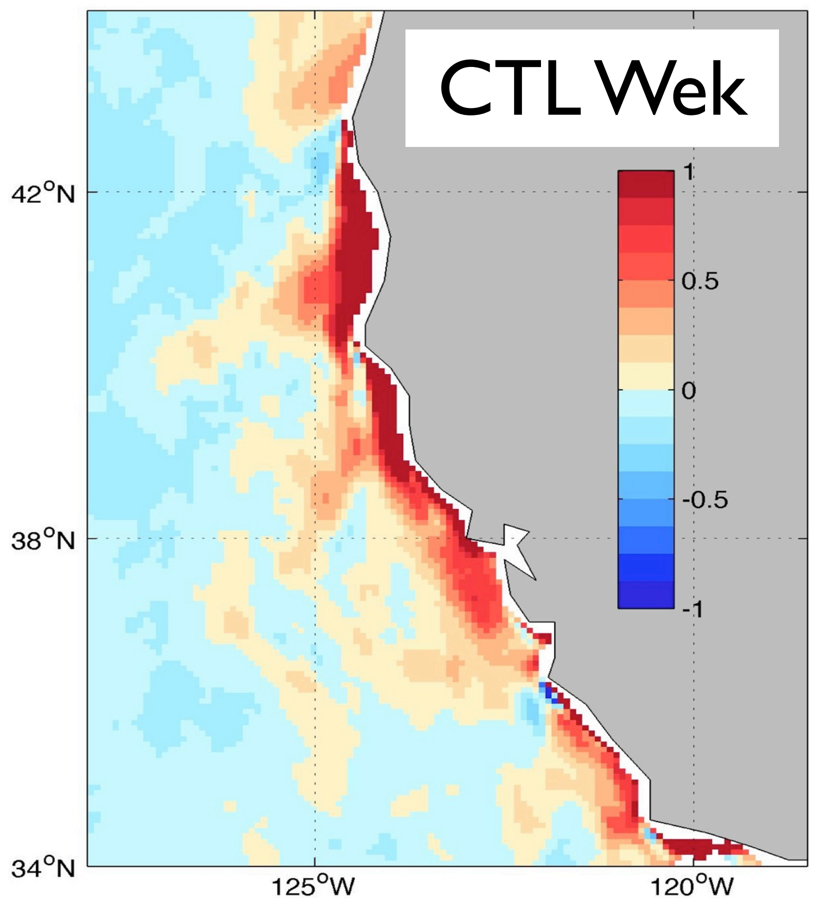
Ekman pumping velocity JAS climatology

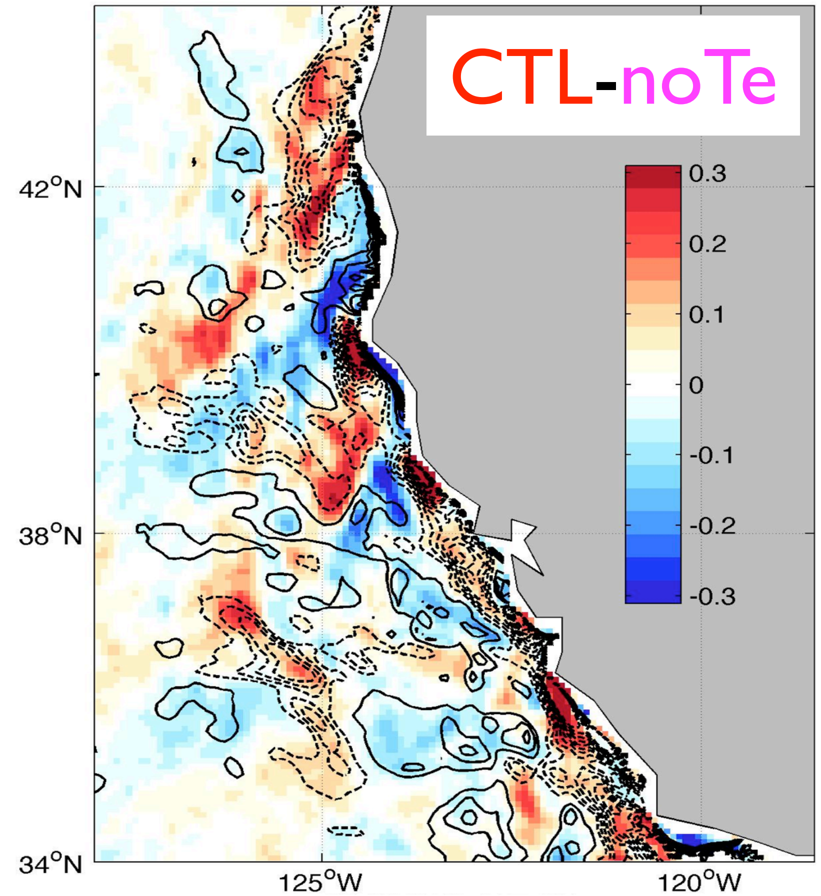


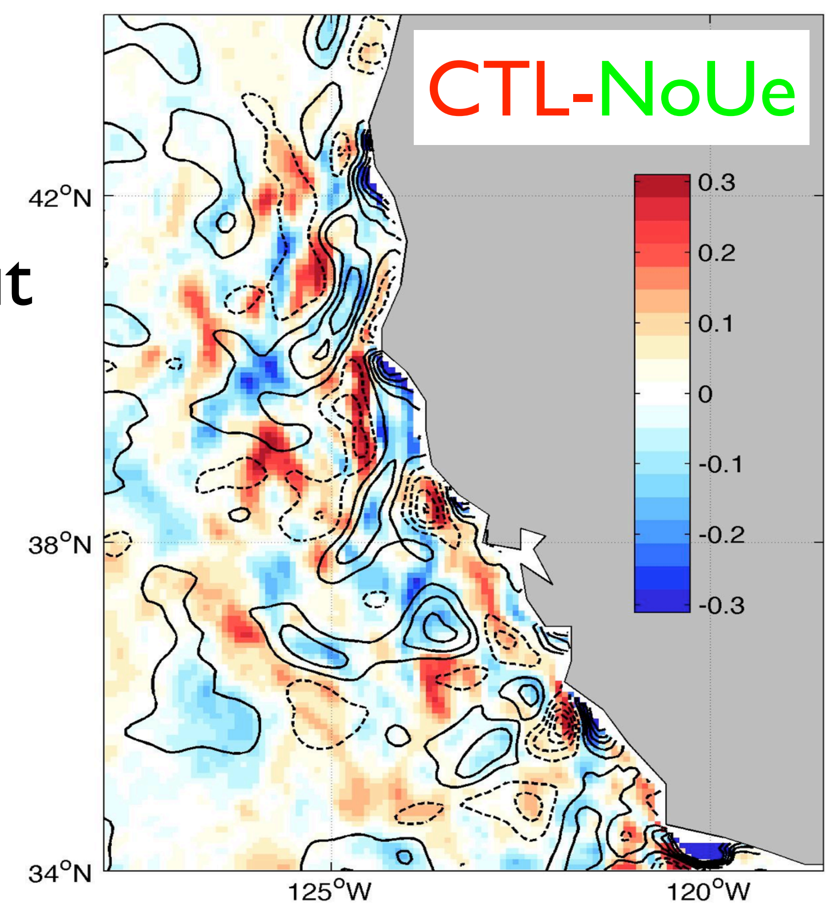
m/day

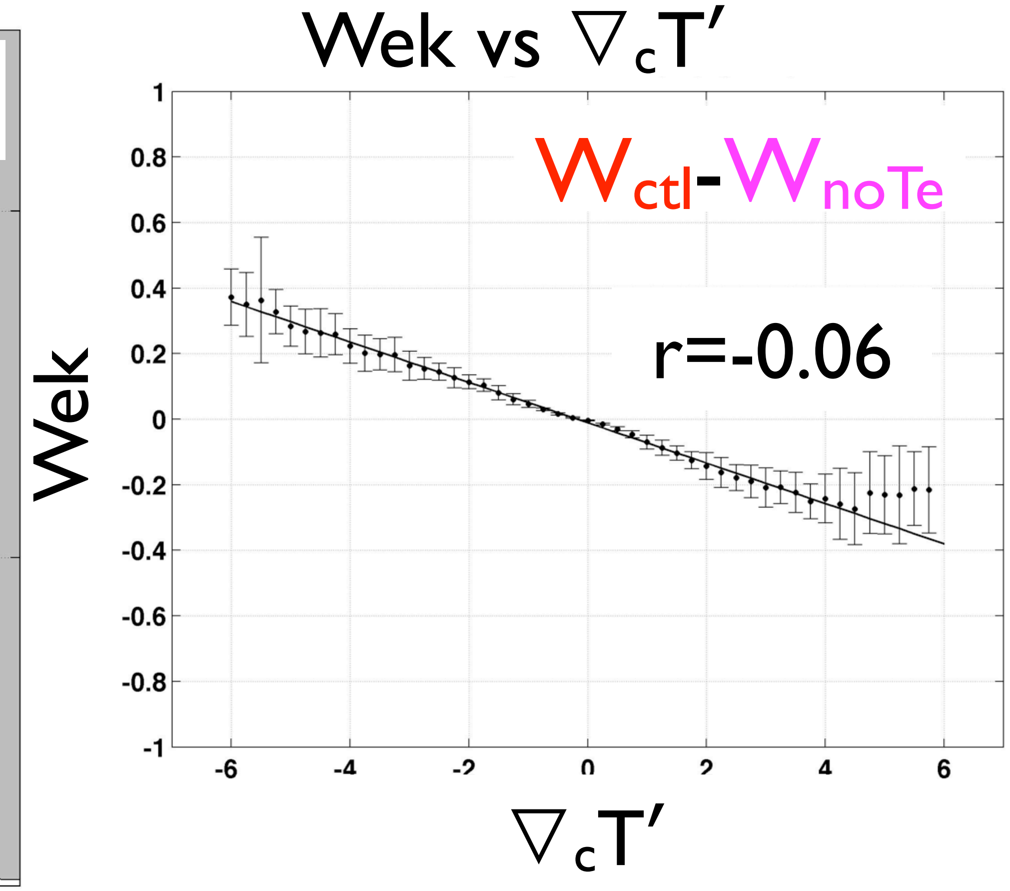
JAS 2005-2009

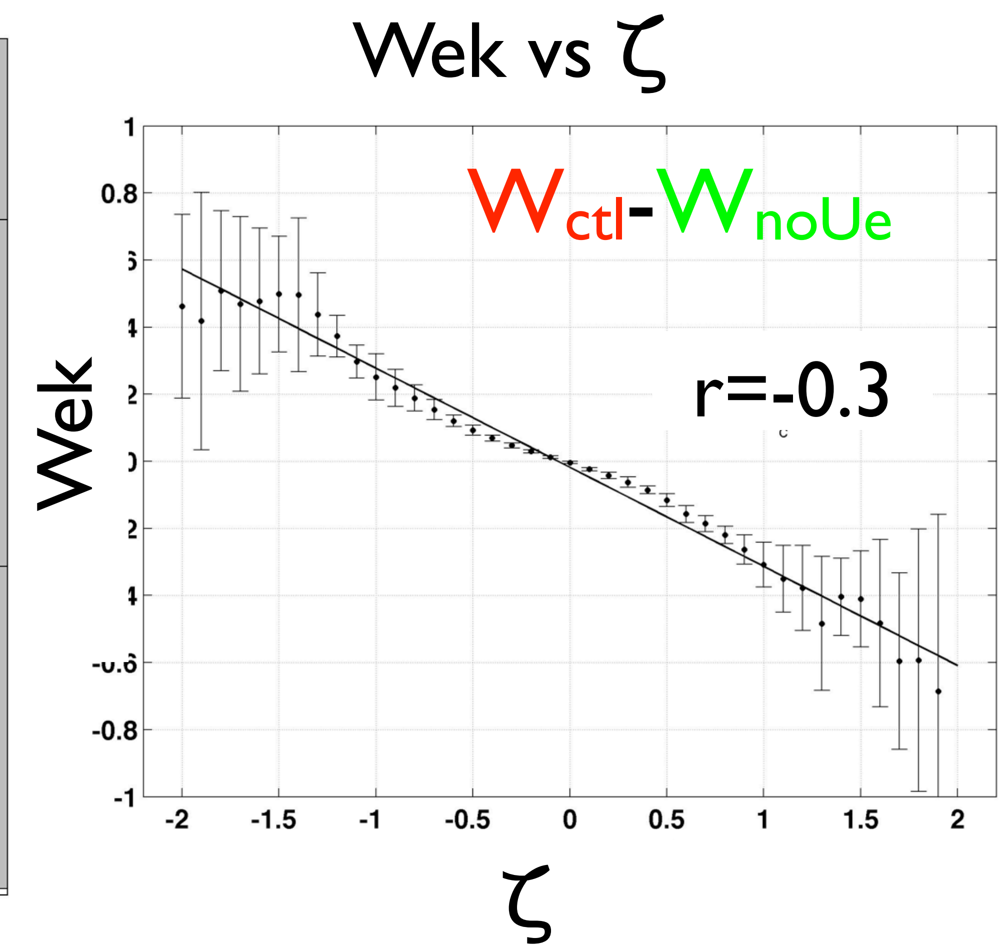
SST-induced and current-induced Ekman pumping velocity











- 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!