Air-Sea Coupling at the Ocean Mesoscale: Some Reflections on the Challenges for Coupled DA

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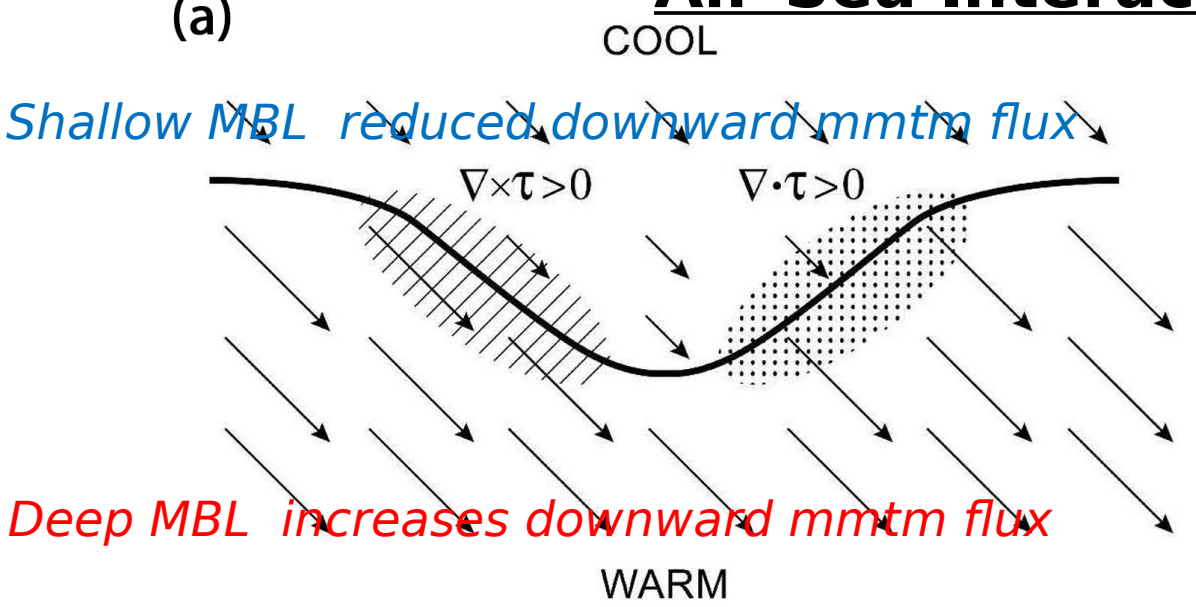
1: Rutgers University; 2: University of California Santa Cruz

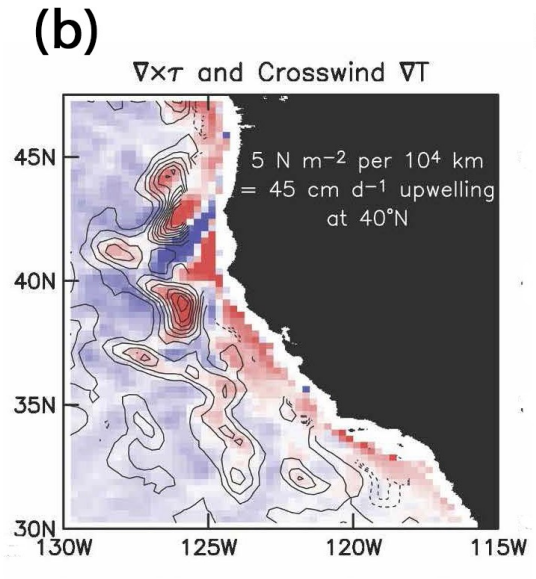
Acknowledgements: Jim Doyle, Sue Chen, Sergey Frolov and the COAMPS team at NRL

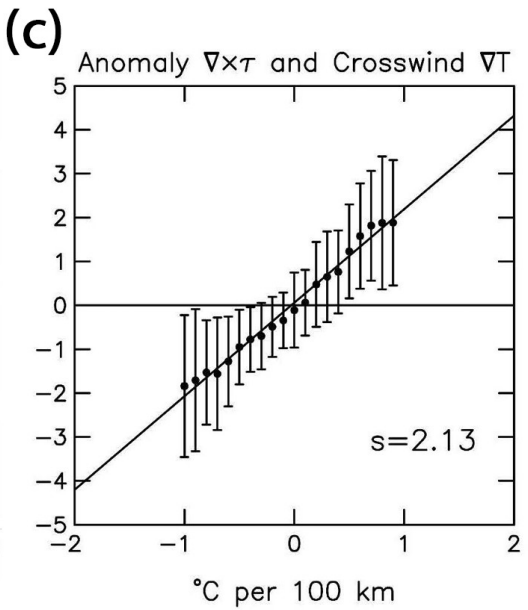
Outline

- **Review some aspects of air-sea interaction at the mesoscale**
- **Description of a regional coupled model**
- **Air-sea interactions captured by the coupled model**
- **Influence of DA on coupling strength**

Air-Sea Interactions at the Mesoscale







Chelton et al (2007) analysis of satellite derived SST and wind stress in the CA Current system:

(a) Changes in wind curl and divergence in the vicinity of an SST front due increase (decrease) in wind stress over warm (cool) water

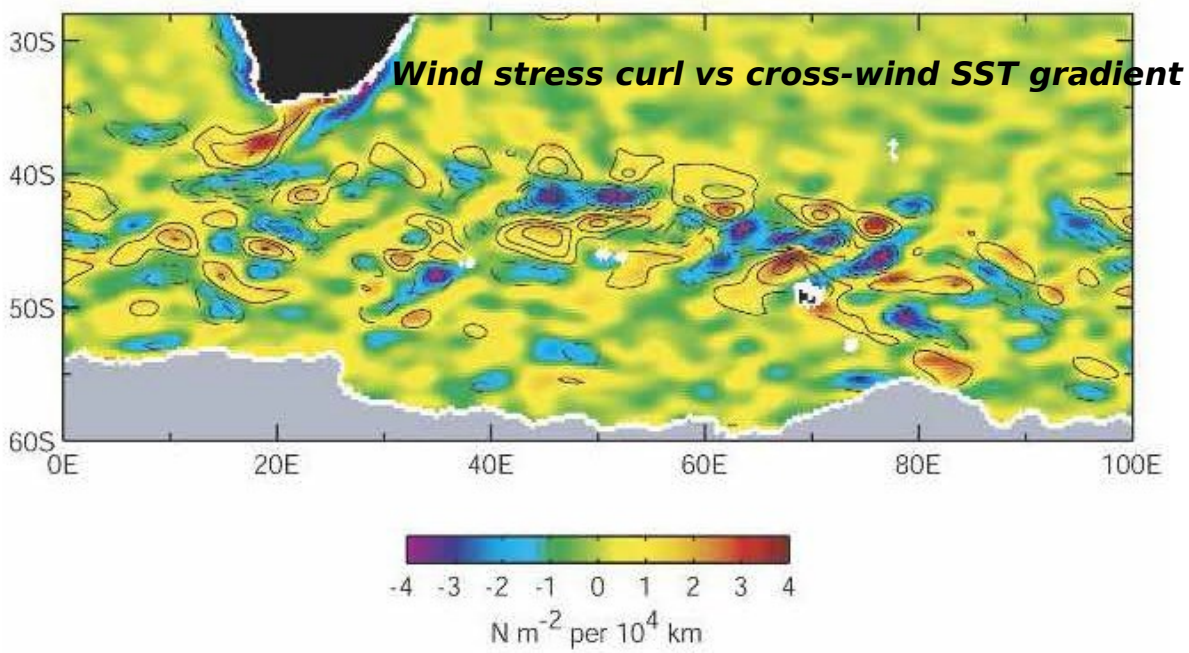
(b) Wind stress curl (colors) and cross-wind SST gradient (contours) - SST high pass filtered (75km)

(c) Binned scatterplot of summertime (June-September) wind stress curl and the crosswind SST gradient. Slope *s* often used a quantitative measure of air-sea coupling strength, and is ***maximum*** in the summer.

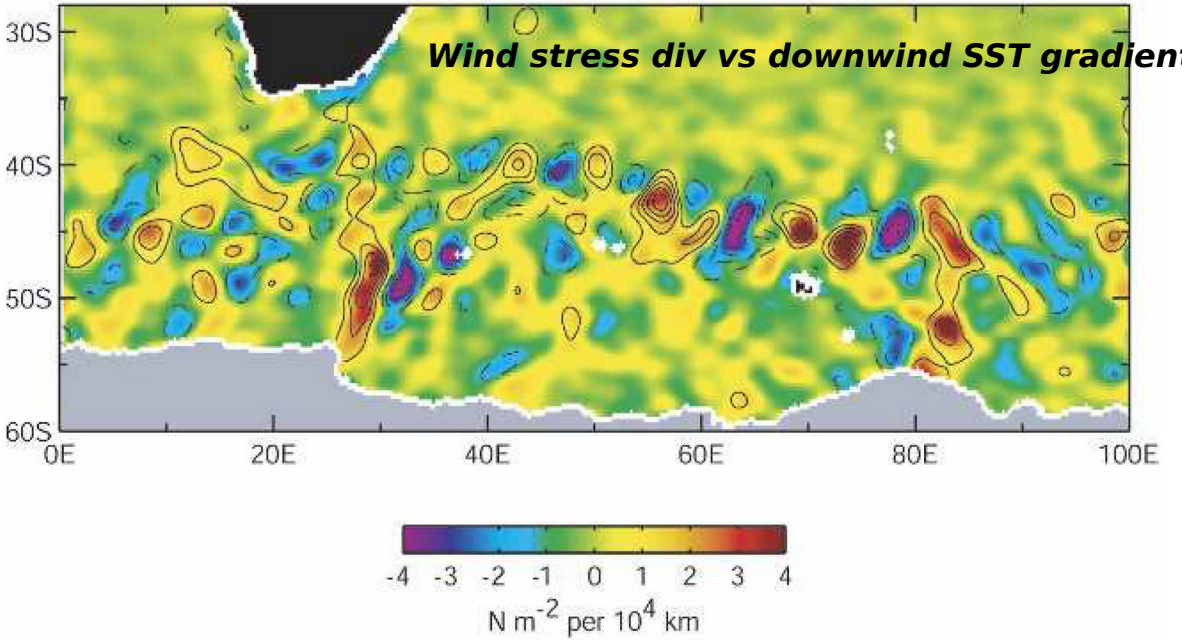
- Similar relationships found in coupled models (*e.g.* Seo et al, 2007; Haack et al, 2008; Small et al, 2008)

From observations

O'Neill *et al.* (2005)



Southern Ocean



Sea Interaction and Ekman Pumping in the presence of Eddies

sed on the *excellent* review in Gaube et al, 2015)

- **At the gyre scale,**
- **At the mesoscale and sub-mesoscale, can be ~1.**
- **In general then, the Ekman pumping velocity is given by:**

$$w_c = \frac{\nabla \times \tilde{\boldsymbol{\tau}}}{\rho_o (f+\zeta)} = \frac{\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right)}{\rho_o (f+\zeta)}$$

$$\tilde{\boldsymbol{\tau}} = \rho_a c_d \left| (\boldsymbol{U_a} - \boldsymbol{u}_o) \right| (\boldsymbol{U_a} - \boldsymbol{u}_o)$$

Contribution of relative wind and surface current to Ekman pumping

- **Following Gaube *et al.* (2015, *JPO*, 45, 104) we can write as the sum of three different contributions, so that:**

$$w_\zeta = \frac{1}{\rho_o (f+\zeta)^2} \left(\tilde{\tau}_x \frac{\partial \zeta}{\partial y} - \tilde{\tau}_y \frac{\partial \zeta}{\partial x} \right)$$

Contribution of the interaction between wind stress and relative vorticity field to Ekman pumping

$$w_{SST} = \frac{\nabla \times \boldsymbol{\tau}'}{\rho_o (f+\zeta)}$$

Contribution of SST-induced wind stress curl to Ekman pumping

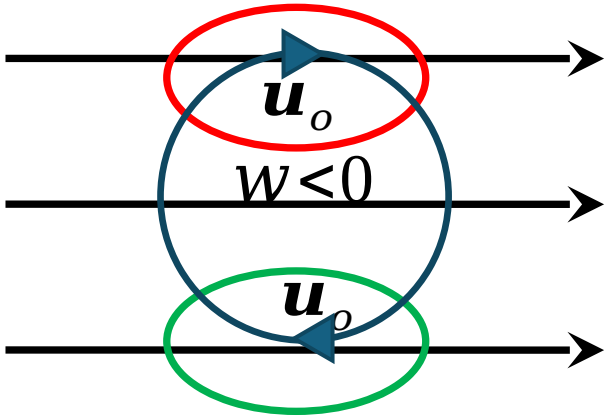
$$\nabla \times \boldsymbol{\tau}' = -\alpha \frac{\partial T}{\partial \boldsymbol{n}}$$

α $0.013\, N\, m^{-2} {}^{\circ}C^{-1}$ (or

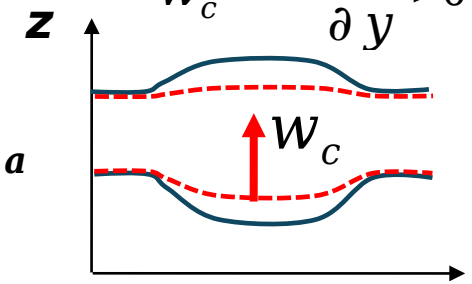
Empirically determined relationship (from satellite observations) between wind stress curl and the cross-front SST gradient

Relative wind and surface current

reduced here



U_a



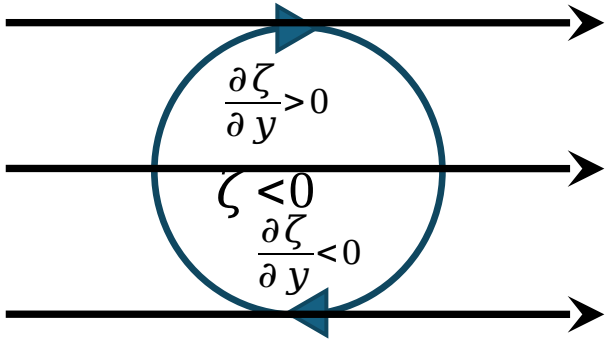
$$w_c \propto -\frac{\partial \tau_x}{\partial y} > 0$$

$$w_c = \frac{\nabla \times \tilde{\boldsymbol{\tau}}}{\rho_o (f+\zeta)}$$

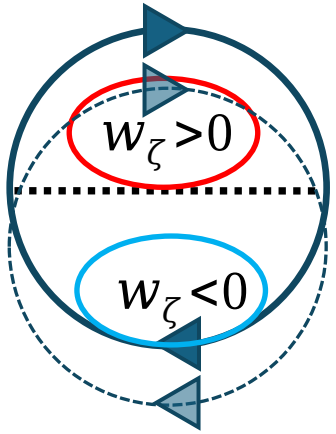
increases here

$$\tilde{\boldsymbol{\tau}} = \rho_a c_d \left| (\boldsymbol{U_a} - \boldsymbol{u_o}) \right| (\boldsymbol{U_a} - \boldsymbol{u_o})$$

Interaction between wind stress and Ekman pumping



$\tilde{\tau}_x$

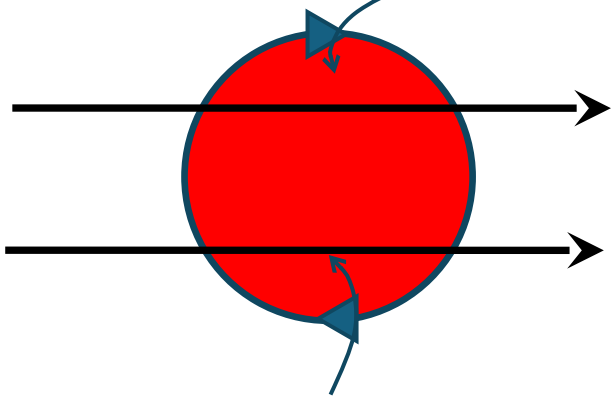


$$w_\zeta = \frac{1}{\rho_o (f+\zeta)^2} \tilde{\tau}_x \frac{\partial \zeta}{\partial y}$$

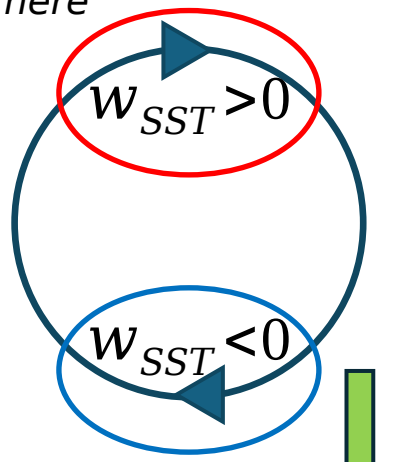
$$w_\zeta = \frac{1}{\rho_o (f+\zeta)^2} \left(\tilde{\tau}_x \frac{\partial \zeta}{\partial y} - \tilde{\tau}_y \frac{\partial \zeta}{\partial x} \right)$$

SST-induced wind stress curl

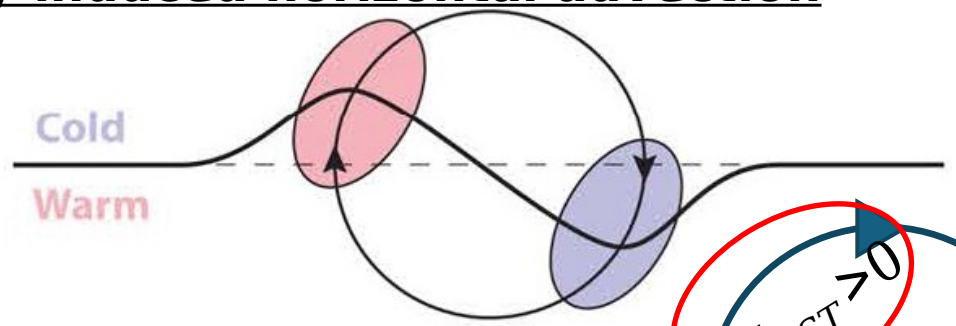
wind curl stress increases here

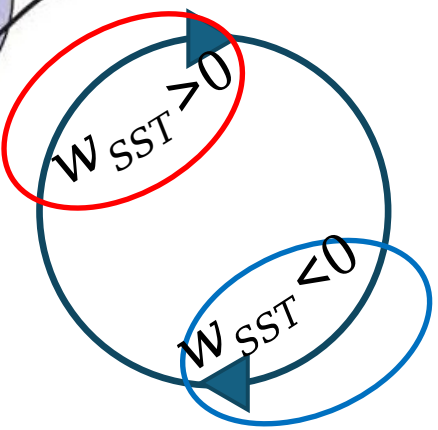


wind curl stress decreases here

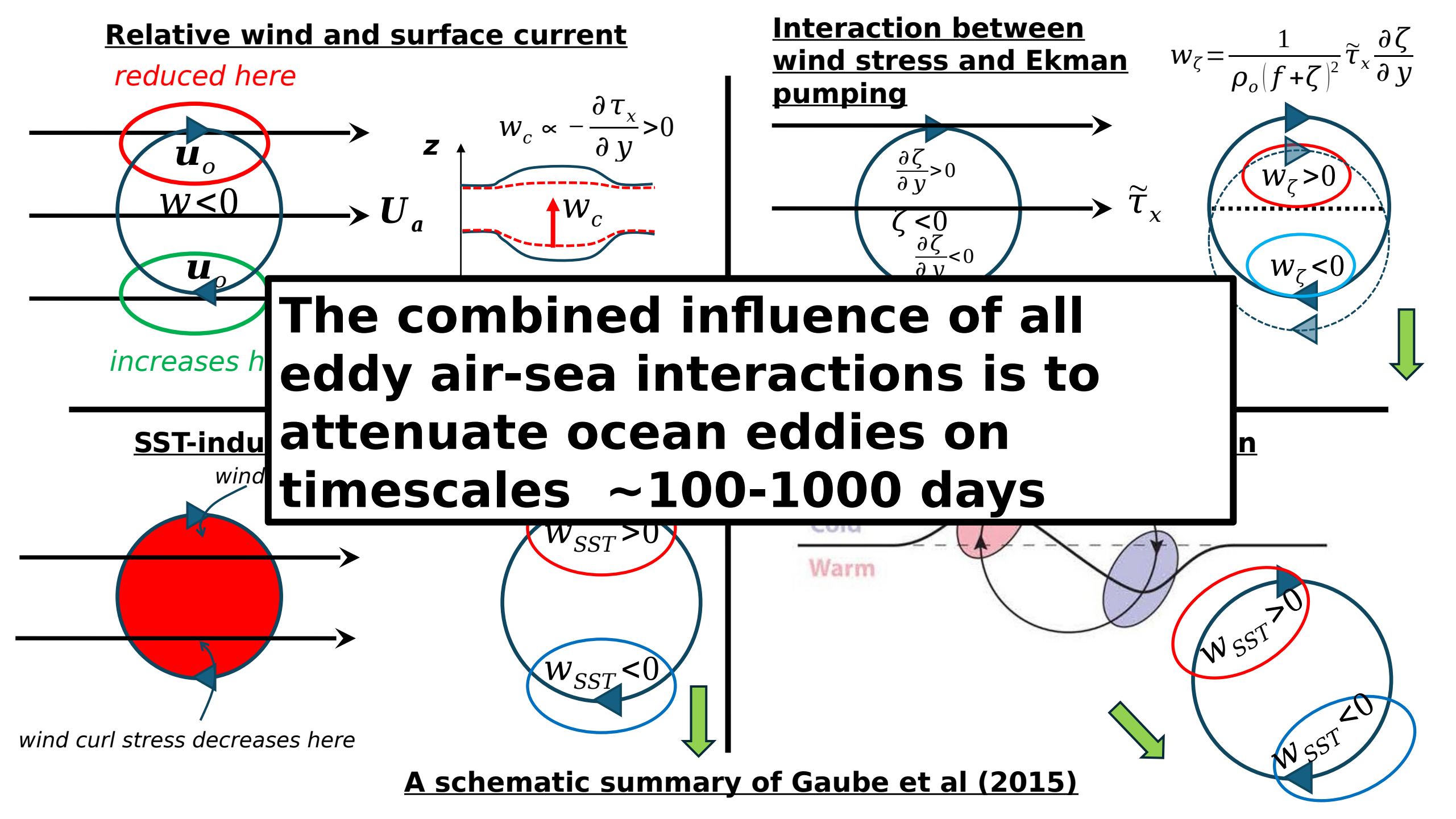


Eddy-induced horizontal advection

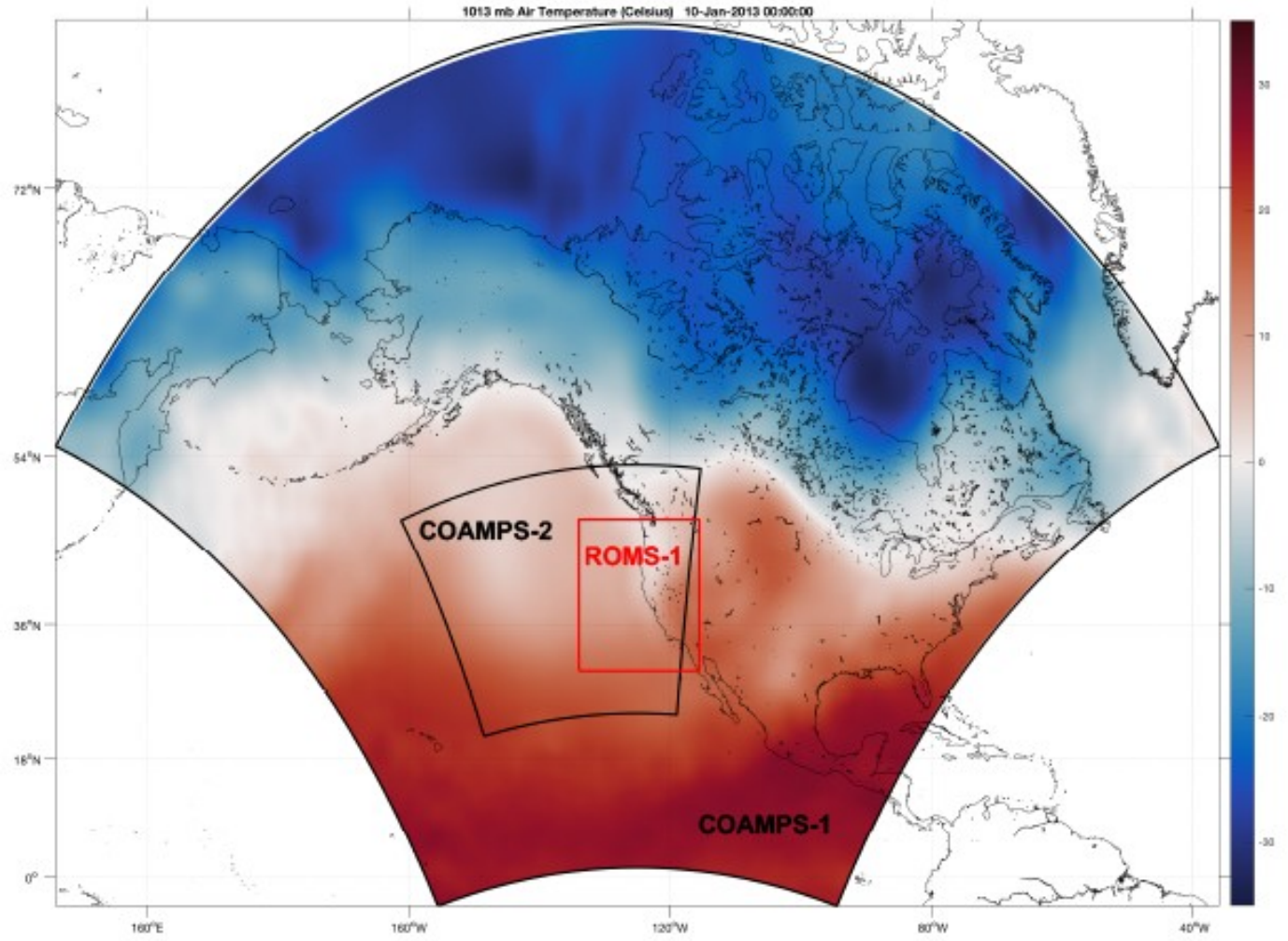




A schematic summary of Gaube et al (2015)


Relative wind and surface current
reduced here
u_o
$w<0$
u_o
increases h
U_a
z
$w_c \propto -\frac{\partial \tau_x}{\partial y} > 0$
w_c
Interaction between wind stress and Ekman pumping
$w_\zeta = \frac{1}{\rho_o (f+\zeta)^2} \tilde{\tau}_x \frac{\partial \zeta}{\partial y}$
$\frac{\partial \zeta}{\partial y} > 0$
$\zeta < 0$
$\frac{\partial \zeta}{\partial y} < 0$
$\tilde{\tau}_x$
$w_\zeta > 0$
$w_\zeta < 0$
The combined influence of all eddy air-sea interactions is to attenuate ocean eddies on timescales ~100-1000 days
SST-indu
n
wind
wind curl stress decreases here
$w_{SST} > 0$
$w_{SST} < 0$
Warm
$w_{SST} > 0$
$w_{SST} < 0$
A schematic summary of Gaube et al (2015)

oupled COAMPS-ROMS Model for the CA Current System



COAMPS nested grids:
(a) COAMPS-1, 45km grid, 60 levels
(b) COAMPS-2, 15km grid, 60 levels

ROMS:
10km grid, 42 levels

Period: Jan-Dec, 2017

Where COAMPS and ROMS do not overlap HYCOM global SST assimilation product used.

NOGAPS analysis at the open boundaries.

Coupled model run for 5-day intervals – COAMPS reinitialized every 5-days using a 4D-Var analysis.

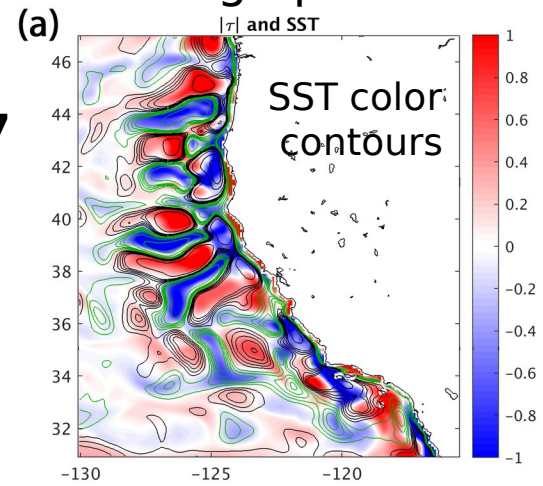
Experiment name	COAMPS grid	ROMS i.c.	Wind stress
Exp1	45 km	Continuous	
Exp2	45 km	Continuous	
Exp3	15 km	Continuous	
Exp4	15 km	4D-Var	

SST Influence on Wind Stress

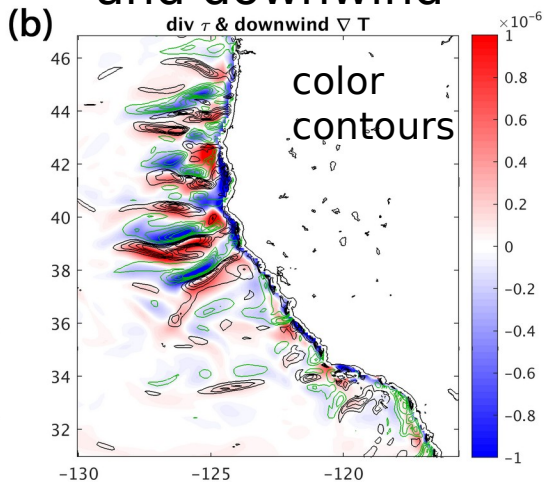
August 2017

Spatial high pass filtered SST using a lowess smoother (75km)

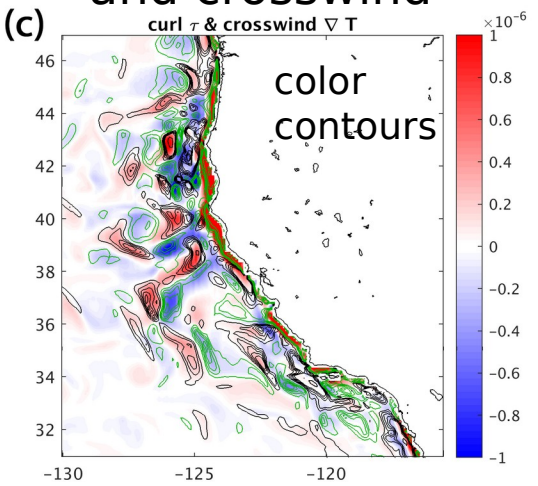
and high pass SST



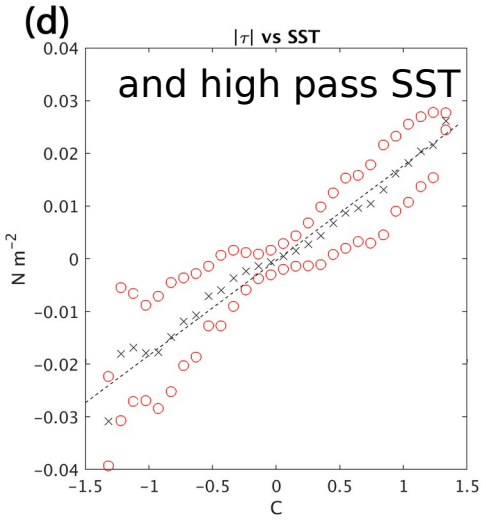
and downwind

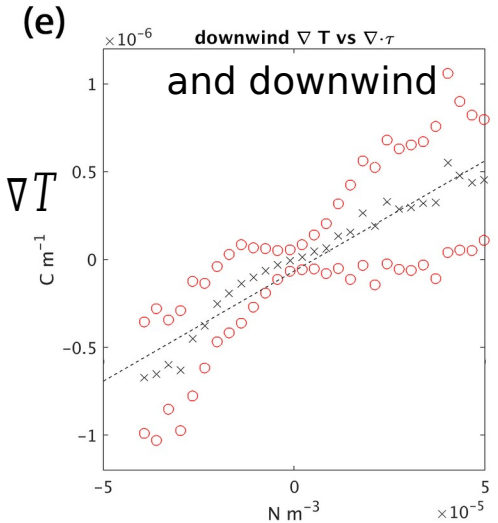


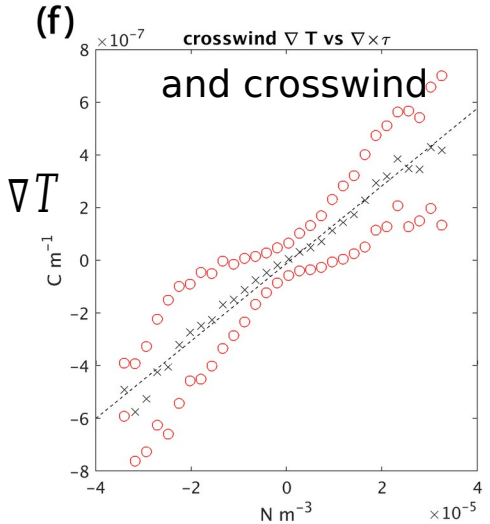
and crosswind



In all panels red colors and black lines indicate positive values while blue colors and green lines indicate negative values.



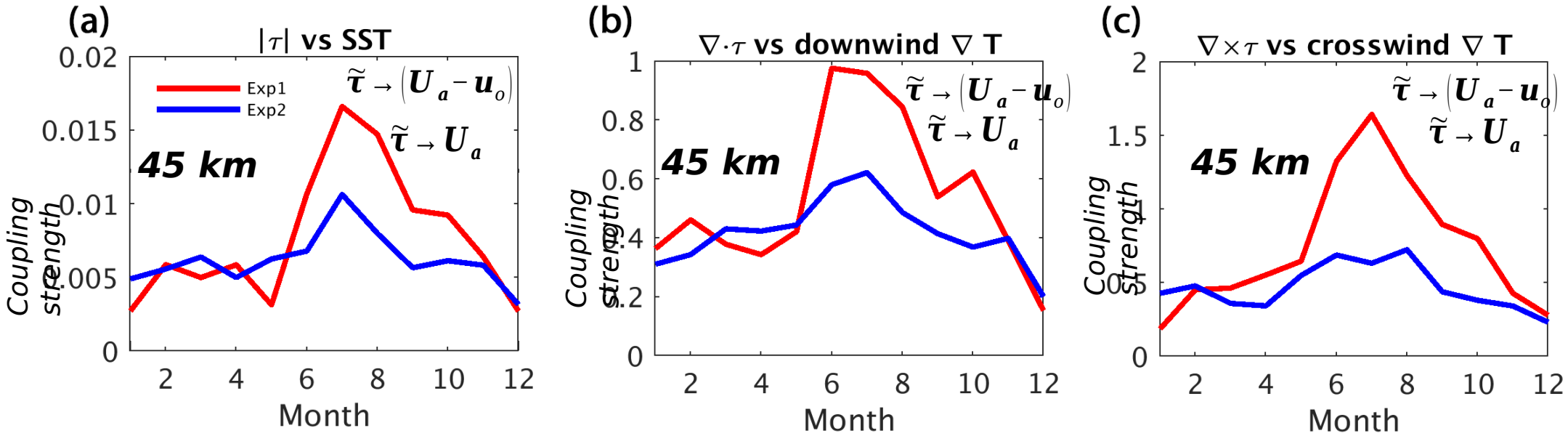




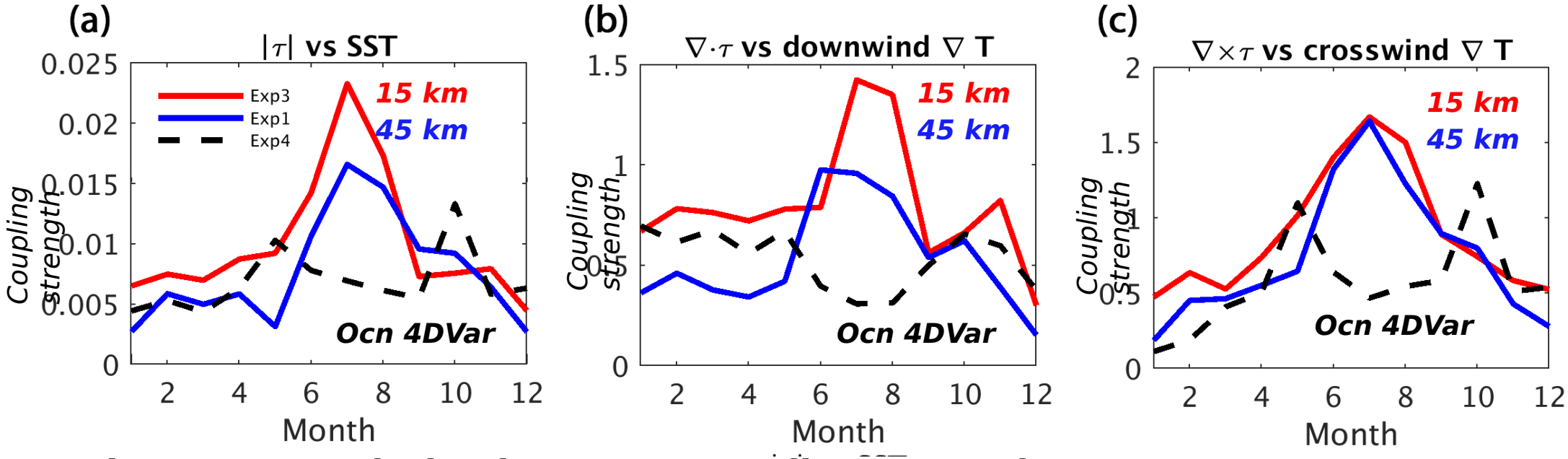
- bin mean
- bin std

lowess=locally weighted scatter plot smoothing

Coupled model captures observed relationships between wind stress and SSTA



ccounting for relative motions of ocean and atmos increases summer & autumn coupling stren



)Increase in atmos resolution increases coupling strength: Exp3 vs Exp 1

)Ocean DA reduces coupling strength and destroys the seasonal dependence: Exp4 vs Exp3

Summary and Reflections

- **Preliminary experiments with a regional coupled atmos-ocean model reproduce the observed relationship between SST and surface wind stress at the ocean mesoscale.**
- **Accounting for relative motion between the wind and surface current appears to be a critical ingredient.**
- **Higher horizontal resolution in the atmosphere also improves the efficacy of the model.**
- **Weakly coupled data assimilation (*i.e.* without due regard to the air-sea interface) weakens the coupling strength and destroys the seasonal variations.**
- **This highlights the challenges of respecting important dynamical constraints at the air-sea interface during coupled DA.**
- **Strongly coupled DA may be required that accounts covariances between the atmos and ocean variables in the marine boundary layer – likely to be very challenging…**
- **Perhaps this is a good candidate for ML in coupled DA?**