The Influence of Oceanic Mesoscale Eddies on Surface Stress

Dudley B. Chelton, Peter Gaube*, Vincent Coombs,
Ricardo P. Matano and Michael G. Schlax

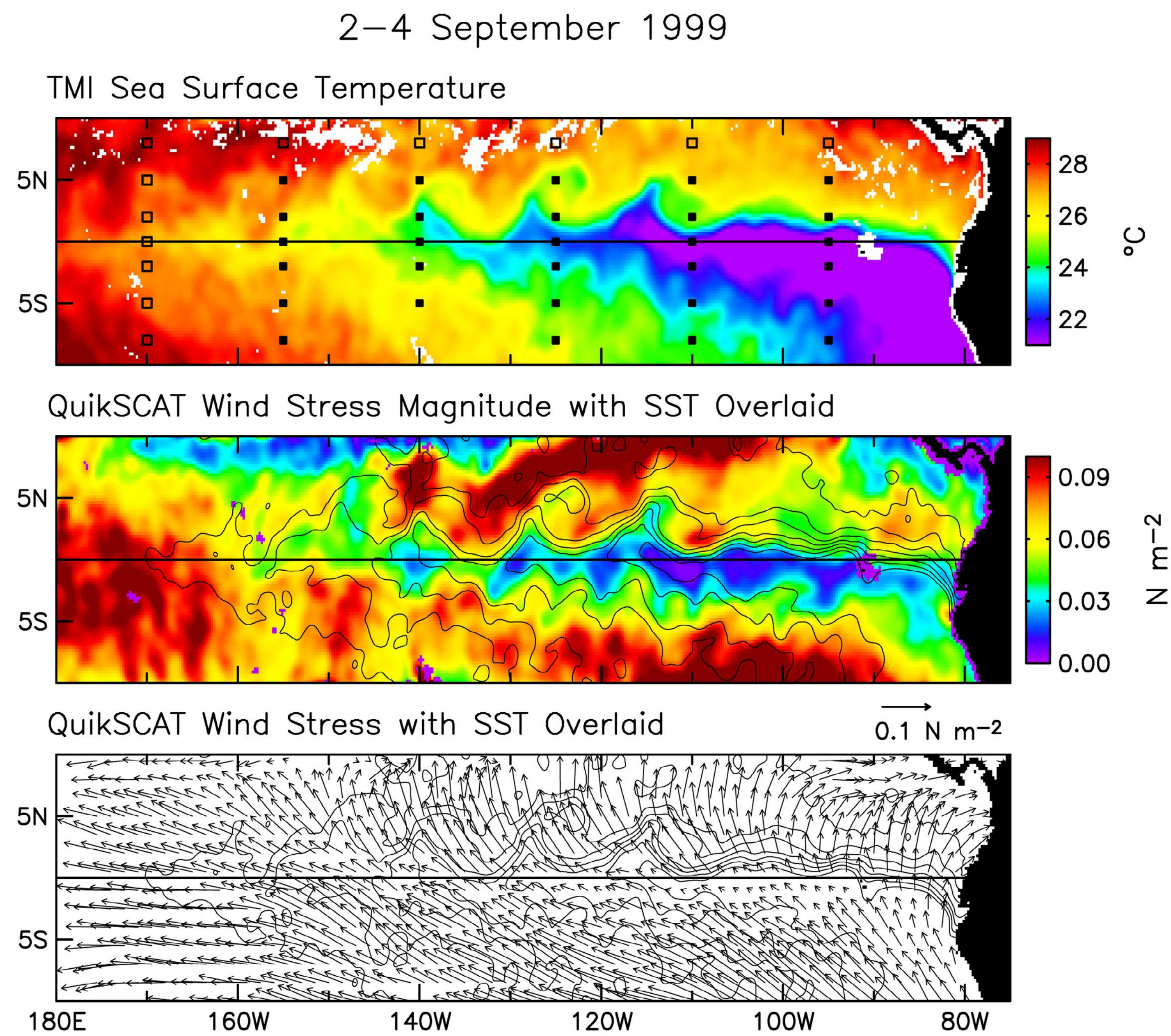
Oregon State University

Overview:

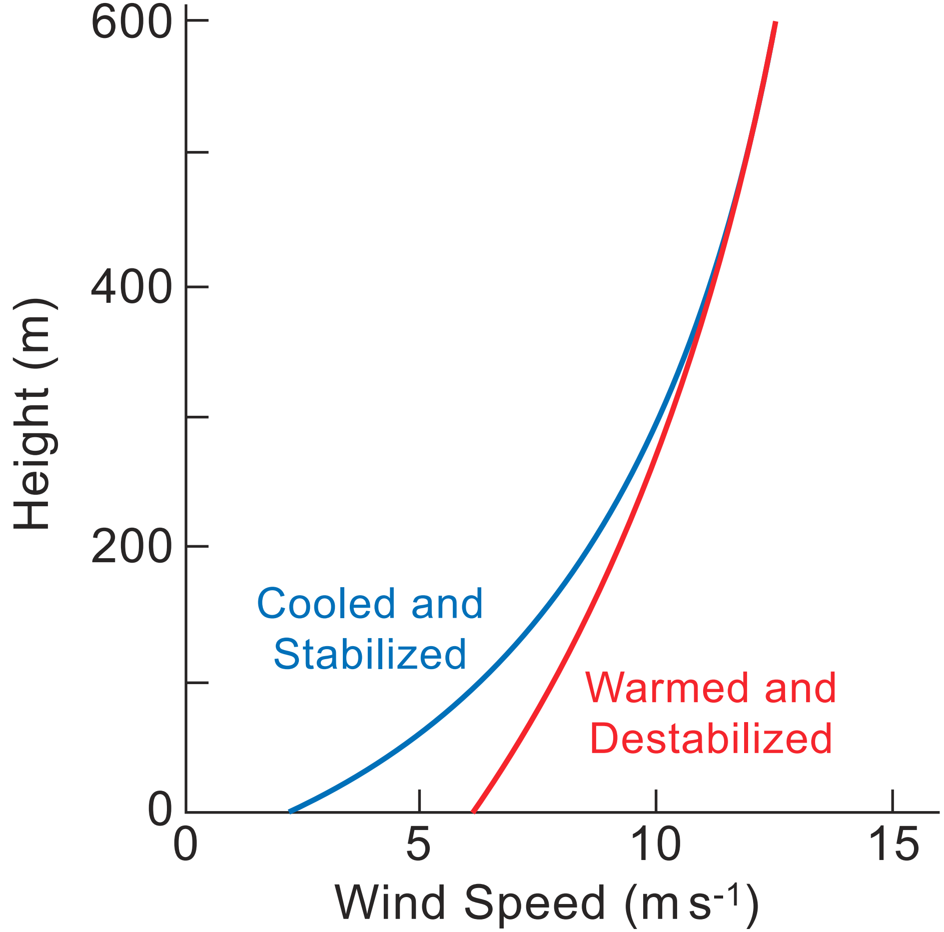
- Brief overview of air-sea interaction over SST frontal regions.
- A synergistic satellite observational investigation of mesoscale eddy-induced surface stress and Ekman pumping:
  - *from SST and air-sea interaction effects.*
  - *from ocean surface current effects.*
- Assessment of the relative importance of the two contributions to eddy Ekman pumping from:
  - *consideration of the two effects for idealized but realistic eddies.*
  - *analysis of the satellite observations.*
  - *numerical simulations in 3 experiments with the ROMS model run in a nested configuration with 1/12° grid resolution for the South Indian Ocean.*

* Much of the material in the middle and last parts of this presentation is from the PhD thesis of Peter Gaube, who is now a postdoc at Woods Hole Oceanographic Institution

Air-Sea Interaction in SST Frontal Regions


2–4 September 1999
TMI Sea Surface Temperature
QuikSCAT Wind Stress Magnitude with SST Overlaid
QuikSCAT Wind Stress with SST Overlaid
5N
5S
28
26
24
22
°C
0.09
0.06
0.03
0.00
N m^{-2}
0.1 N m^{-2}
180E
160W
140W
120W
100W
80W

Schematic Summary of SST Influence on the Wind Speed Profile in the Marine Atmospheric Boundary Layer



This is similar to diurnal variation of the atmospheric boundary layer over land:

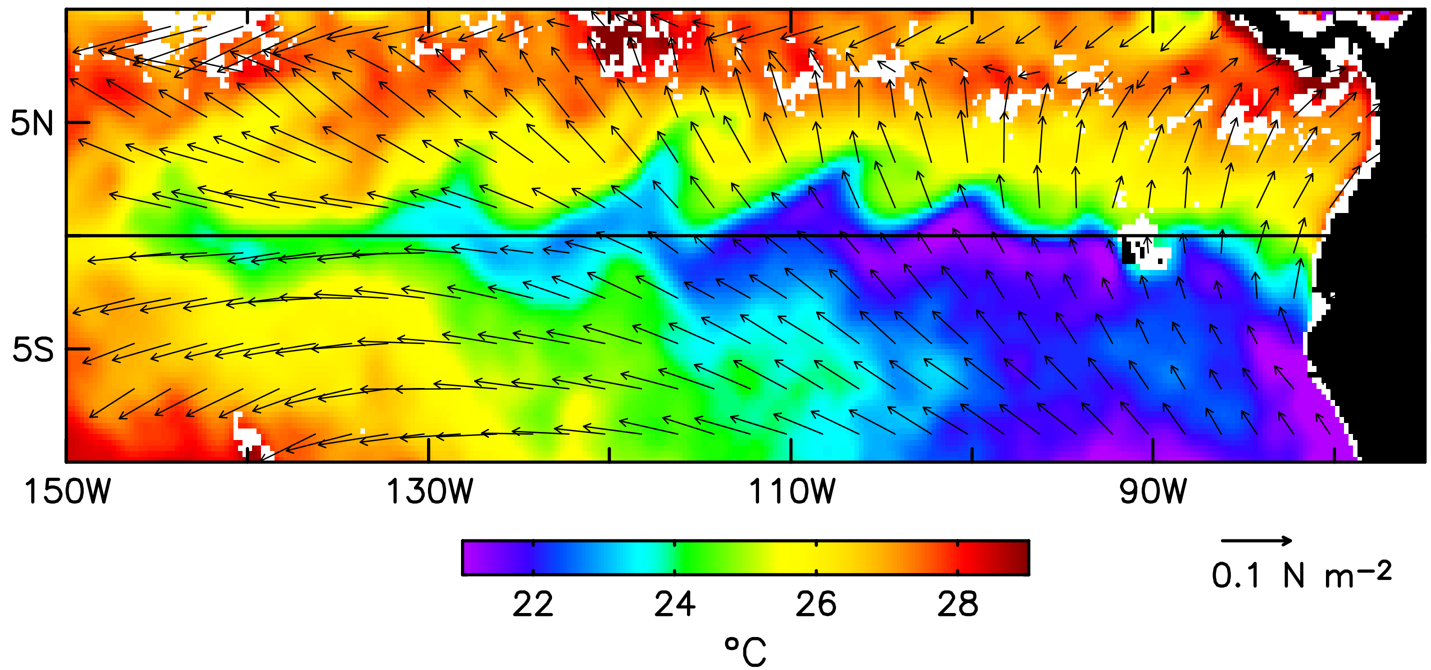
- *nocturnal stable boundary layer from radiative cooling*
- *daytime unstable boundary layer from solar heating of the land*

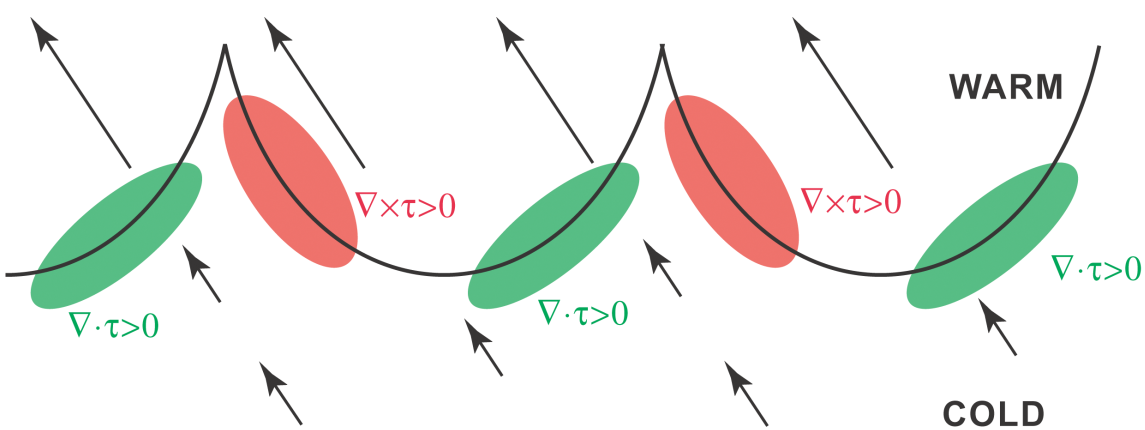
Note that vertical turbulent mixing is not the only term that is important in the momentum balance. The nonlinear advection and pressure gradient terms are also important, especially the latter.

This coupling between SST and winds on scales smaller than ~1000 km is opposite the negative correlation that occurs on basin scales:

- surface winds are <u>positively</u> correlated with SST on oceanic mesoscales.

Wind Stress Vectors and SST, 12 December 2001

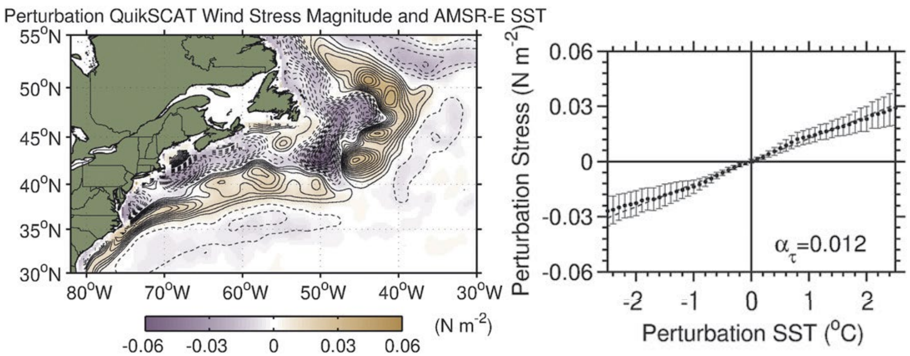


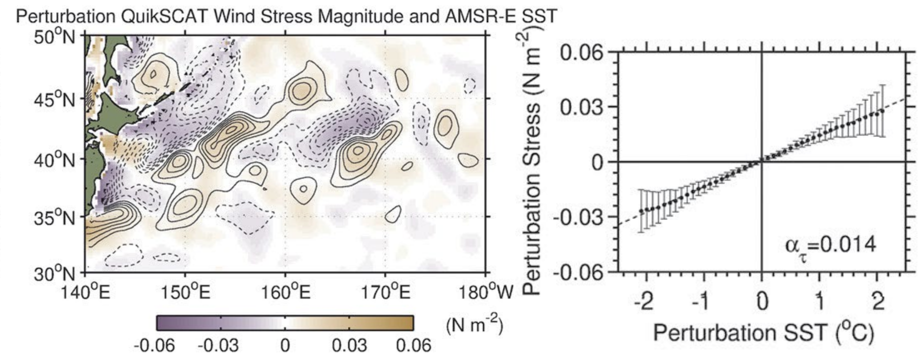


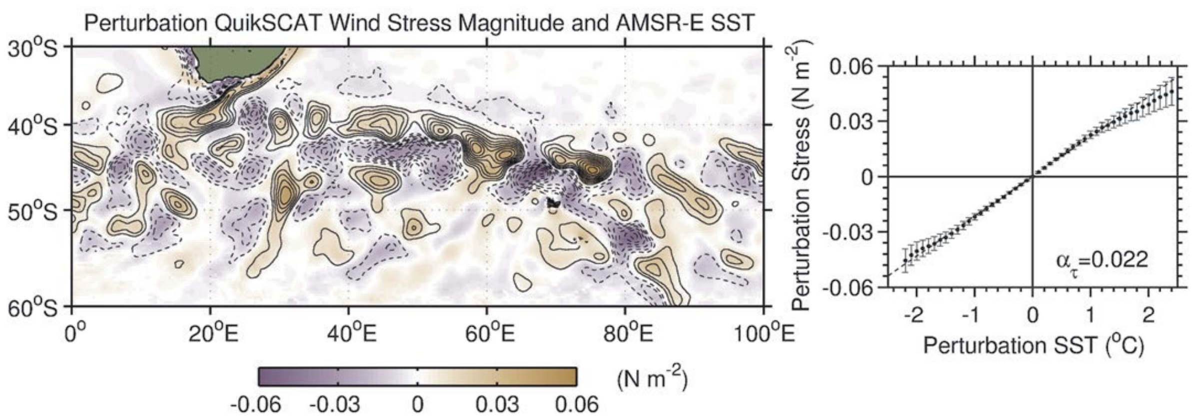
TMI SST and QuikSCAT Wind Stress Curl and Divergence

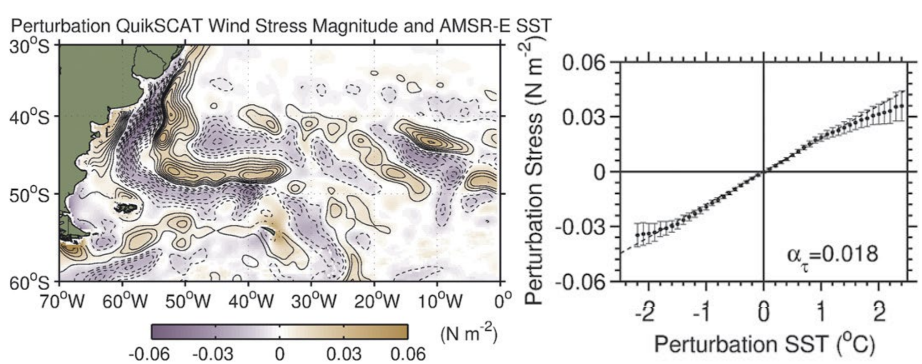
The Coupling Between SST and Wind Stress in 4 Frontal Regions

(Gulf Stream, Kuroshio Extension, Agulhas Return Current and Brazil-Malvinas Current)







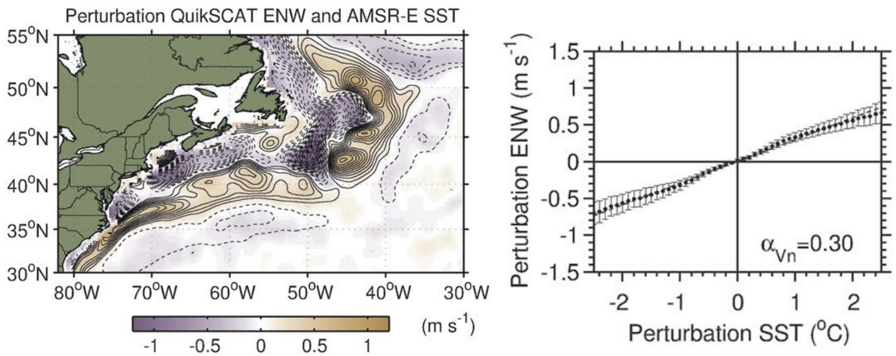


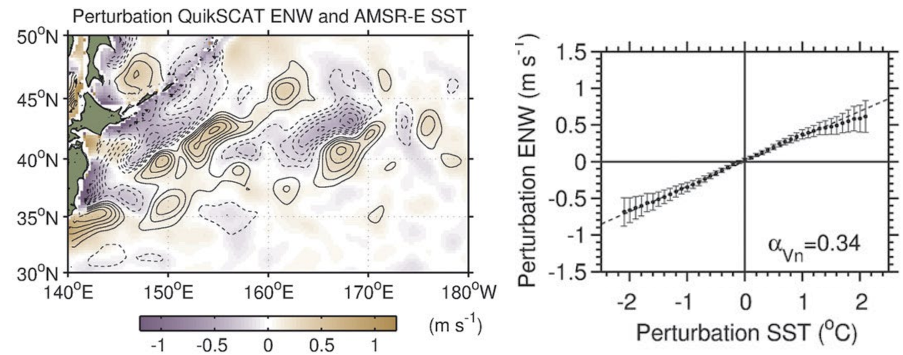
June 2002 - May 2009
Averages

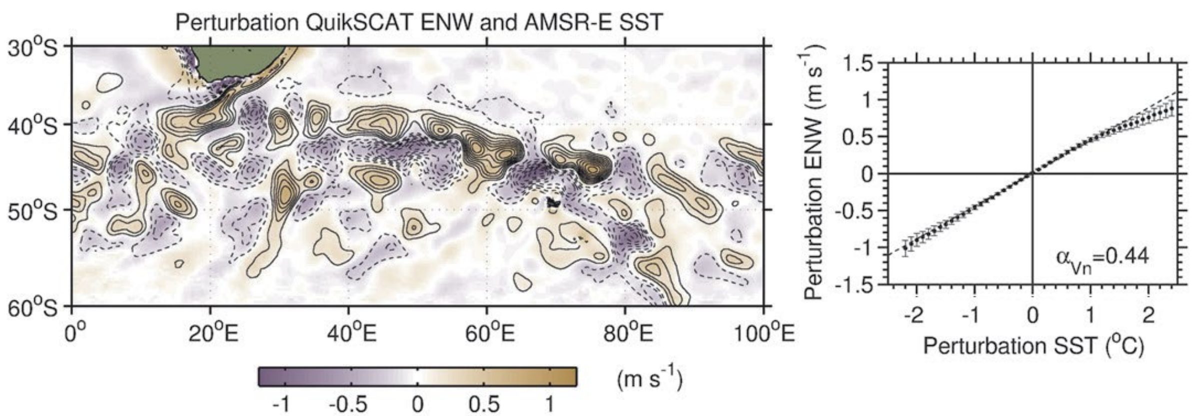
From O'Neill et al. (2012, J. Clim.)

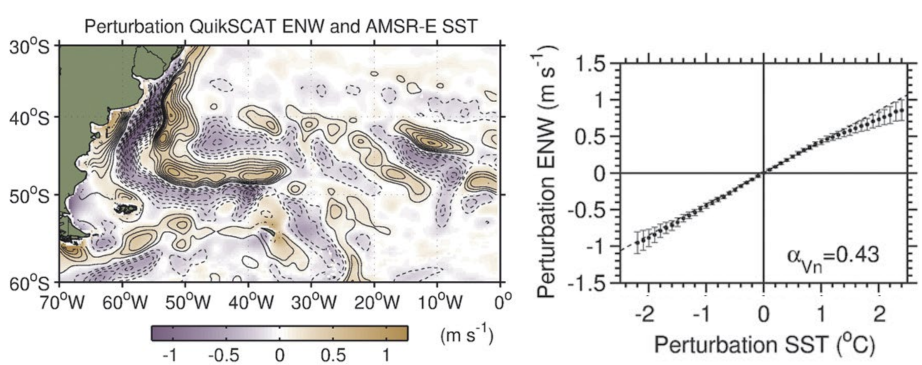
The Coupling Between SST and Wind Speed in 4 Frontal Regions

(Gulf Stream, Kuroshio Extension, Agulhas Return Current and Brazil-Malvinas Current)







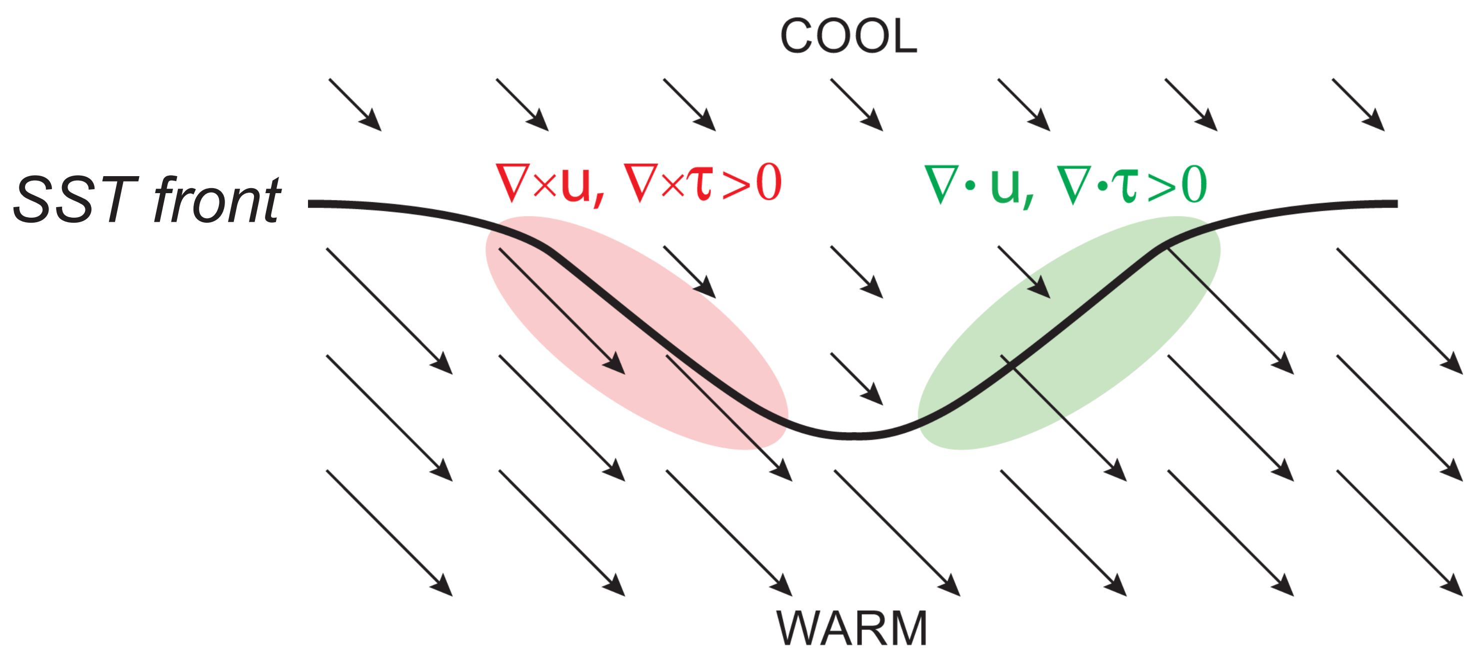


June 2002 - May 2009
Averages

From O'Neill et al. (2012, J. Clim.)

Why the SST influence on surface winds matters.....

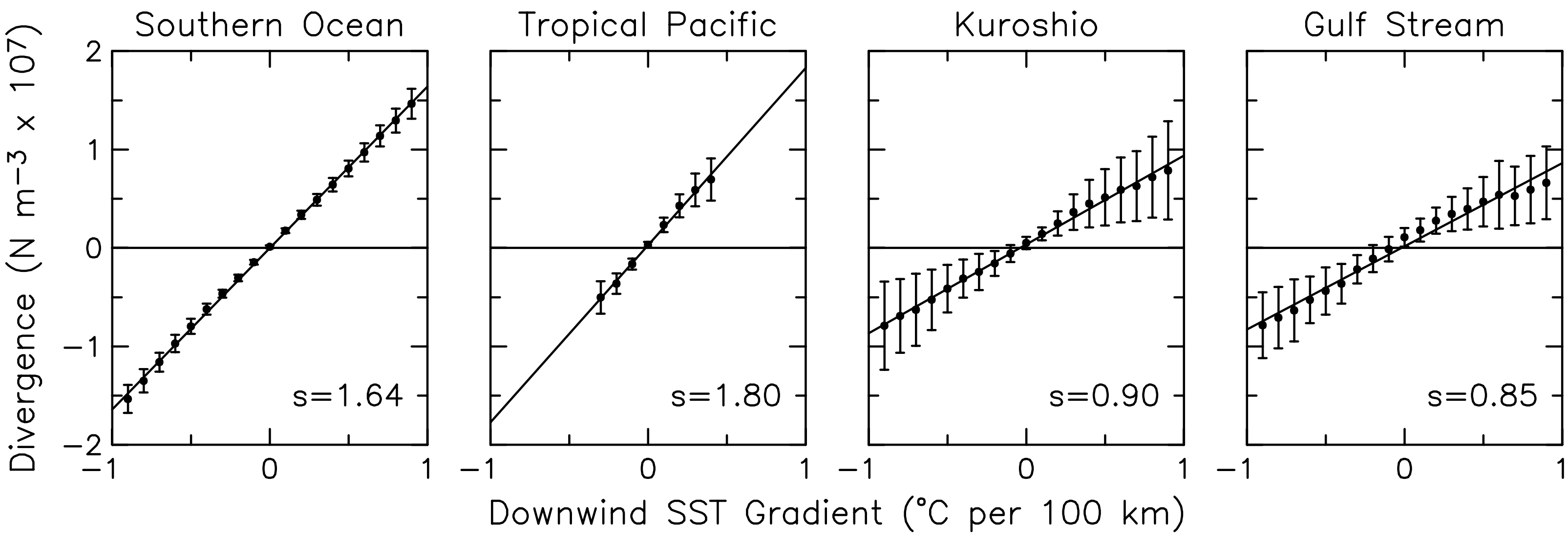
SST Effects on the Curl and Divergence of Surface Wind and Stress



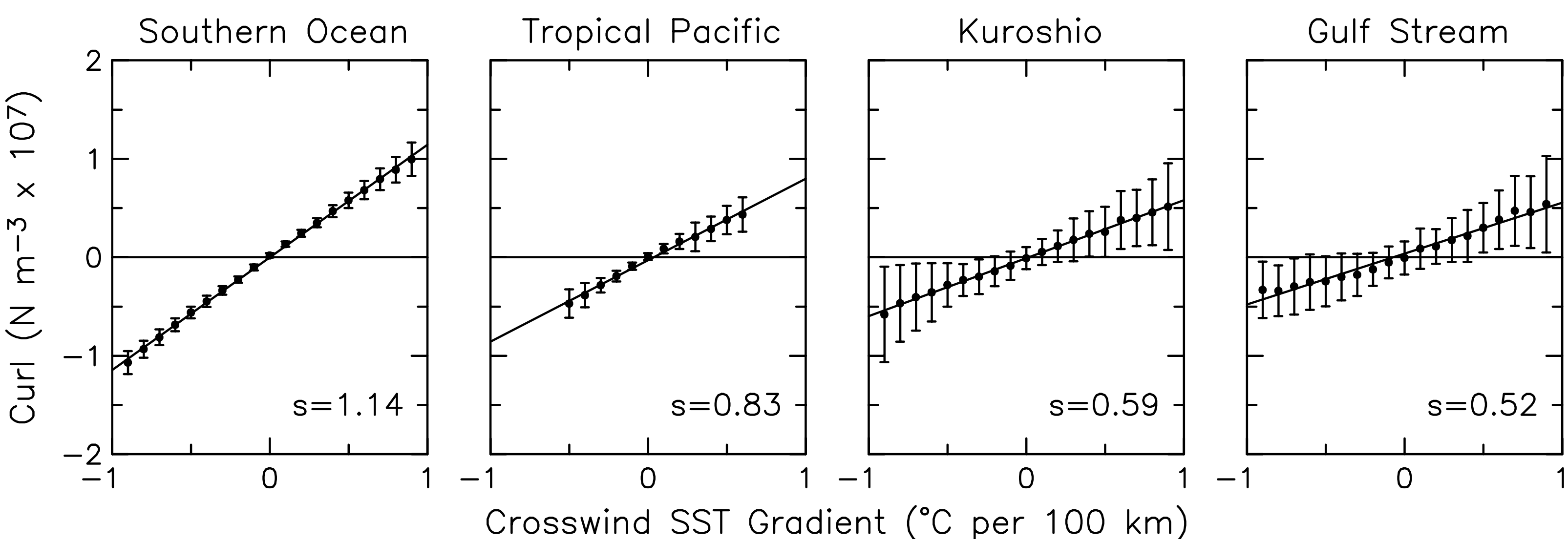
Wind vorticity and curl of the wind stress associated with crosswind SST gradients

Wind divergence and wind stress divergence associated with downwind SST gradients

Coupling Between Wind Stress Divergence and Downwind SST Gradient

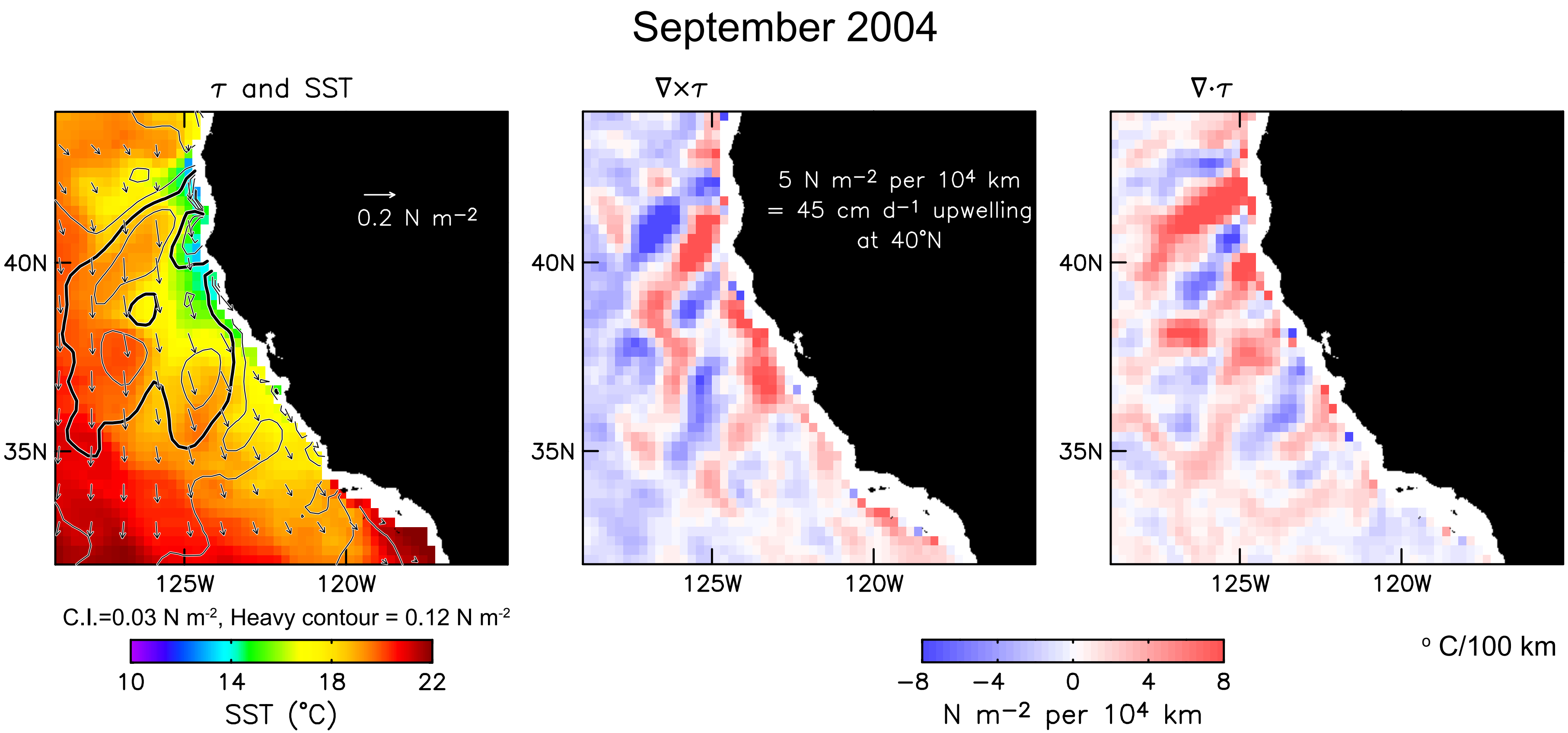


Coupling Between Wind Stress Curl and Crosswind SST Gradient

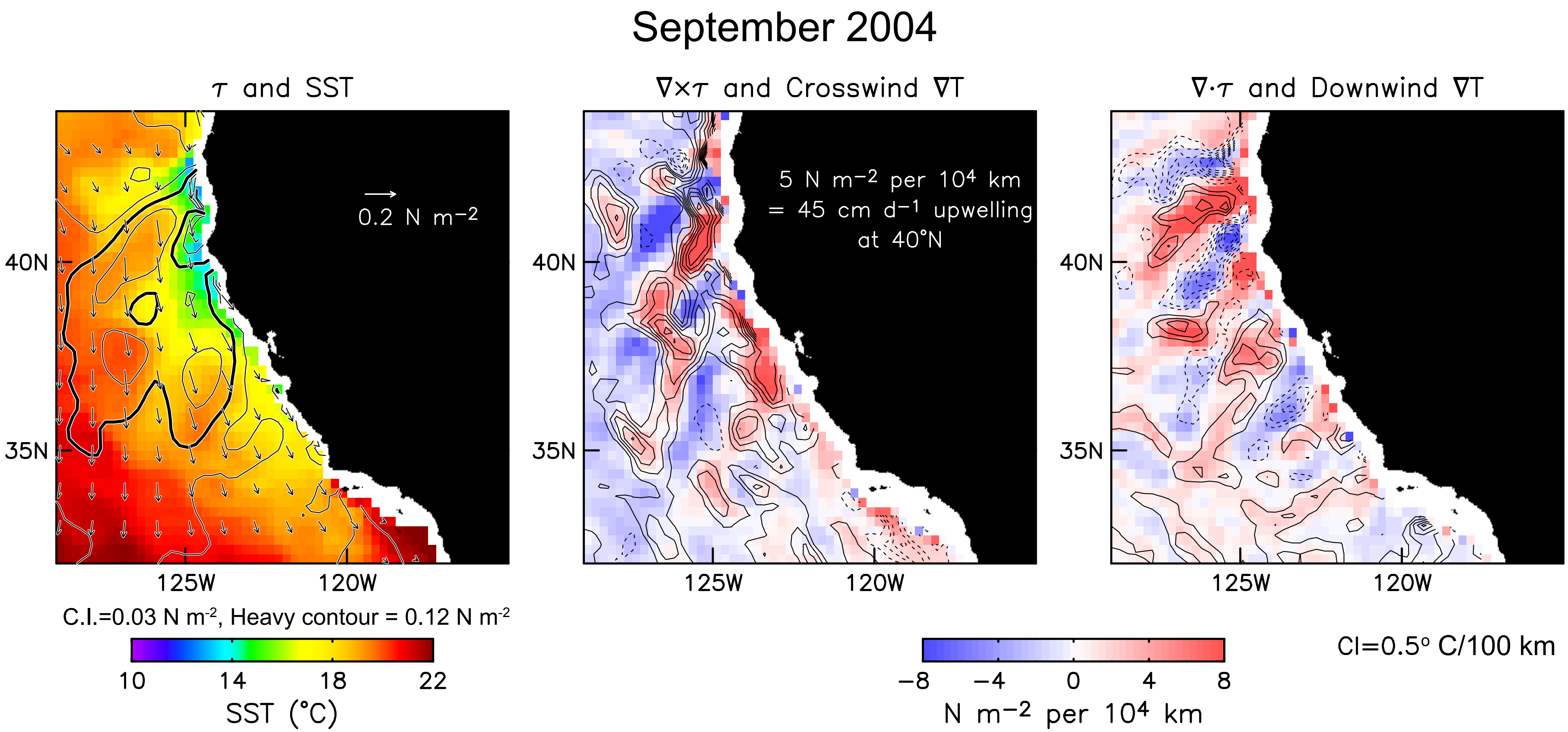


Note that divergence response is consistently stronger than curl response.

A regional example: The California Current System



A regional example: The California Current System



SST-induced wind stress curl feedback effects on the large-scale ocean circulation from empirically coupled models

The Effects of Mesoscale Ocean–Atmosphere Coupling on the Large-Scale Ocean Circulation

ANDREW MCC. HOGG
Australian National University, Canberra, Australian Capital Territory, Australia

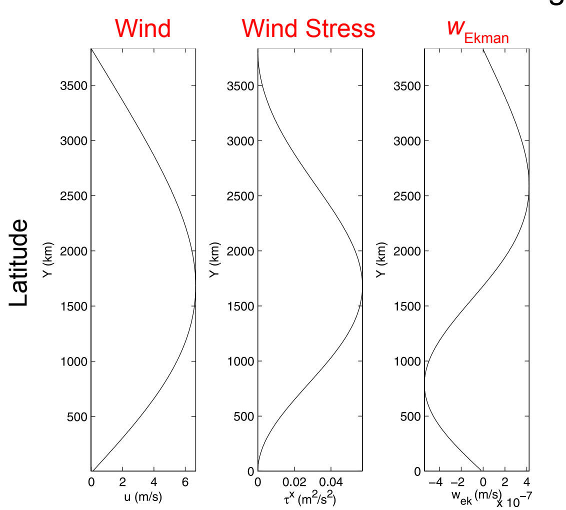
WILLIAM K. DEWAR
The Florida State University, Tallahassee, Florida

PAVEL BERLOFF
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, and Cambridge University, Cambridge, United Kingdom

SERGEY KRAVTSOV
University of Wisconsin—Milwaukee, Milwaukee, Wisconsin

DAVID K. HUTCHINSON
Australian National University, Canberra, Australian Capital Territory, Australia

Meridional Profiles of Wind Forcing



Empirical SST-induced changes in the atmospheric wind stress:

constant

$$({}^a\tau^x, {}^a\tau^y) = C_D(1 + \alpha \Delta T)|{}^\mathbf{a}\mathbf{u_m}|({}^a u_m, {}^a v_m),$$

coupling coefficient chosen to match coupling deduced from QuikSCAT observations

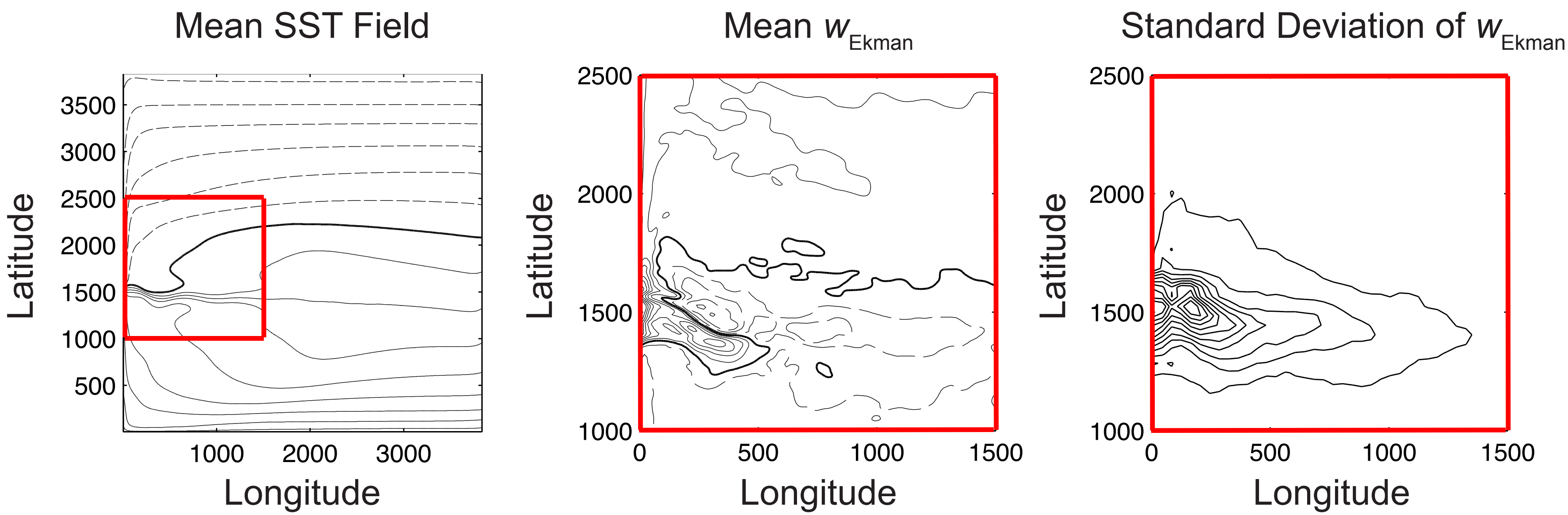
$$\Delta T = {}^oT_m - {}^aT_m$$

where the subscript m denotes mixed layer and the superscripts a and o denote atmosphere and ocean.

The Ekman-pumping velocity from the ocean stress ${}^o\tau = ({}^a\rho\,/\,{}^o\rho)\,{}^a\tau$ is

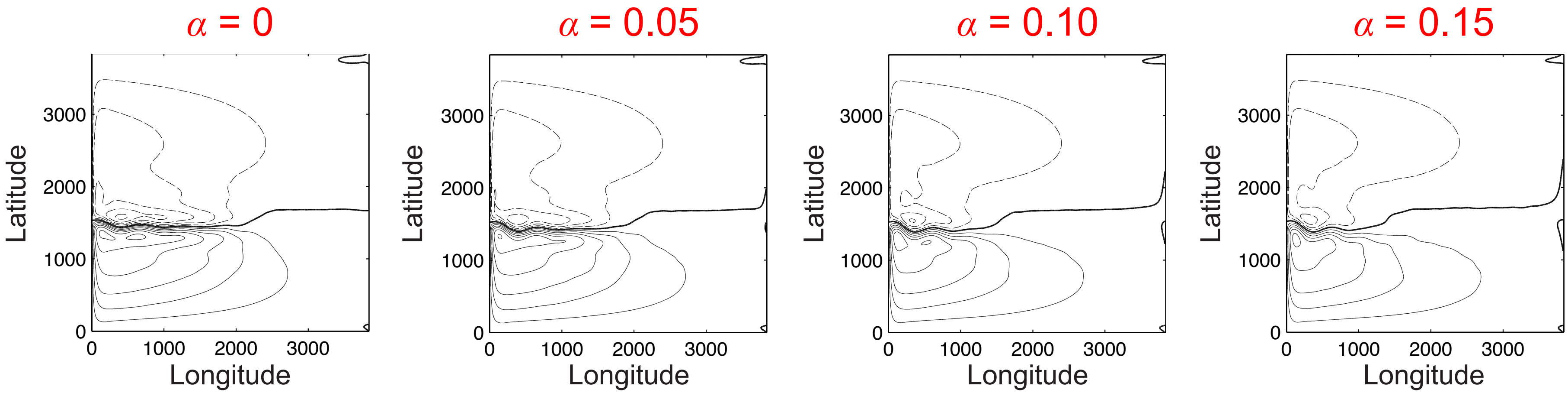
$$w_{\mathrm{Ek}} = \frac{1}{f_0}({}^o\tau^y_x - {}^o\tau^x_y),$$

Small-Scale, SST-Induced Perturbations of Ekman-Pumping Velocity, w_{Ekman}

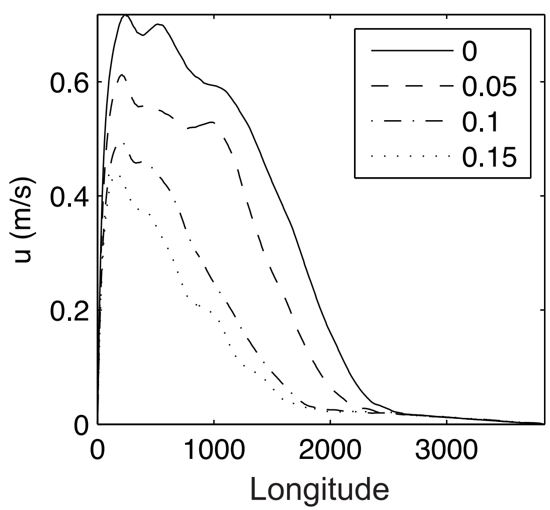


Hogg et al. (2009, J. Phys. Oceanogr.)

Sensitivity of Upper-Layer Streamfunction to the Coupling Coefficient, α



Maximum Zonal Velocity of Jet for α = 0, 0.05, 0.10 and 0.15



Hogg et al. (2009, J. Phys. Oceanogr.)

NOVEMBER 2009 JOURNAL OF PHYSICAL OCEANOGRAPHY VOLUME 39

SST–Wind Interaction in Coastal Upwelling: Oceanic Simulation with Empirical Coupling

XIN JIN, CHANGMING DONG, JAISON KURIAN, AND JAMES C. MCWILLIAMS

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, California

DUDLEY B. CHELTON

College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

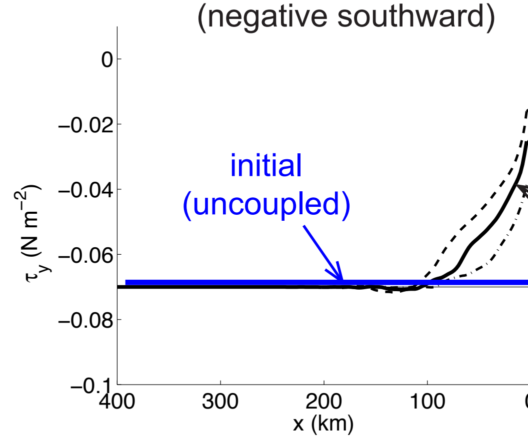
ZHIJIN LI

NASA Jet Propulsion Laboratory, Pasadena, California

A "25-Cent" Empirical Coupled Model:

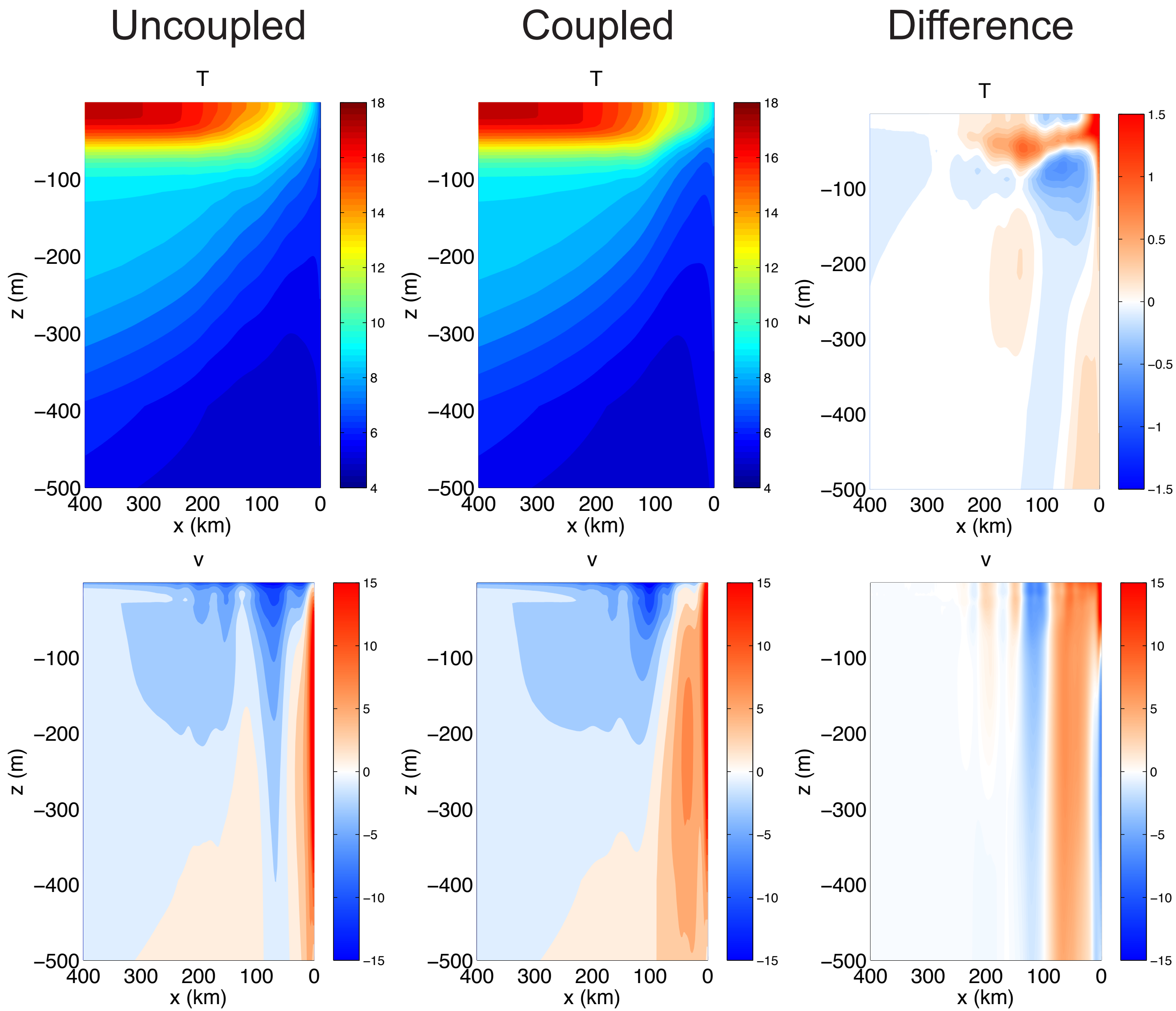
- *Based on:*
  - *the ROMS model of an idealized eastern boundary current system with a straight coastline.*
  - *QuikSCAT-based empirical coupling coefficients for the feedback on the ocean.*
- *The winds are modified at each time step to conform to the empirical coupled relations among SST gradients, wind direction, and the local curl and divergence of the wind stress.*
- *This leads to an evolving modified wind obtained by inverting the diagnosed curl and divergence fields, while maintaining the original wind values on the open-ocean boundary.*

Average Wind Stress
Days 40-80
(negative southward)



Coupled, based on 1x, 2x and 0.5x the empirically observed coupling deduced from QuikSCAT observations

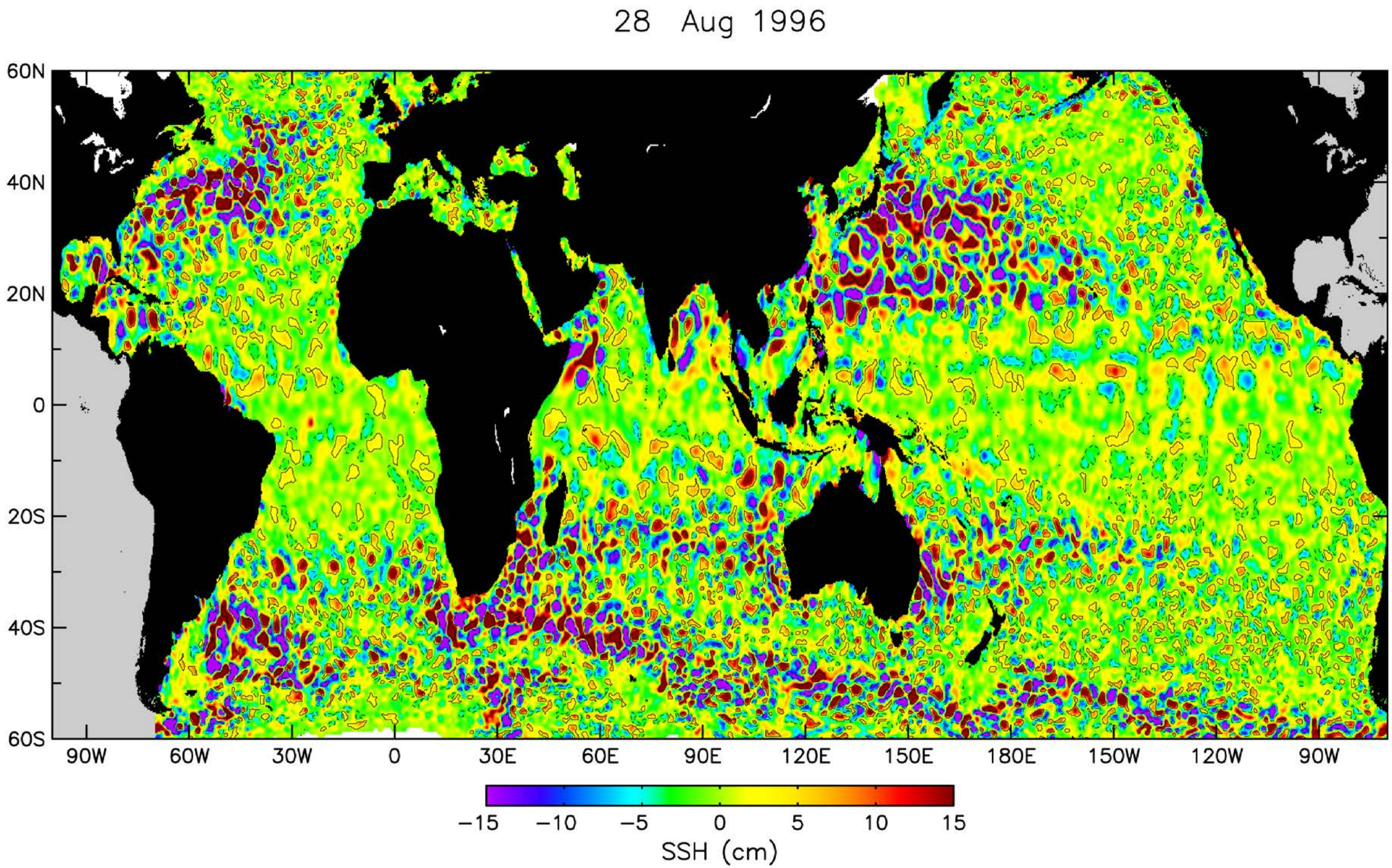
Temperature and Alongshore Velocity



Jin et al. (2009, J. Phys. Oceanogr.)

Mesoscale eddy-induced wind stress curl feedback on the ocean circulation

Merged TOPEX and ERS-1 Spatially High-Pass Filtered SSH with contours of eddies with lifetimes ≥ 4 weeks



There are 2495 eddies in this map

(http://cioss.coas.oregonstate.edu/eddies/)

Animation of Global Altimeter Measurements of Oceanic Eddies

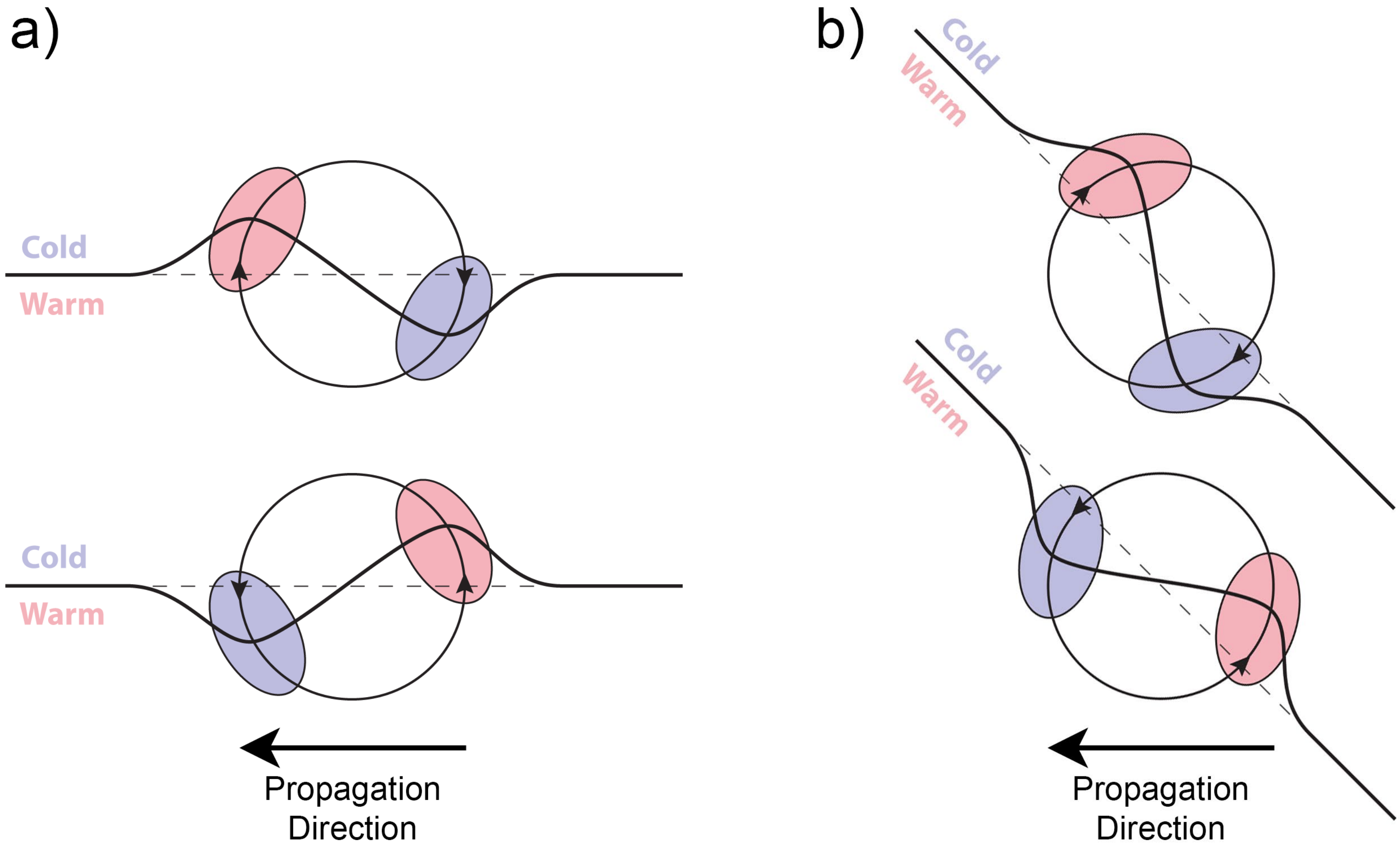
October 1992 - December 2008

Oceanic eddies can trap parcels of water and transport water properties, including nutrients and heat, to distant locations. They therefore play important roles in the global heat budget and ocean biology.

Procedure for Composite Averaging SST, Wind Speed, Wind Stress Curl and Chlorophyll in Eddy-Centric Coordinates: Synergy Between 4 Complimentary Satellite Datasets

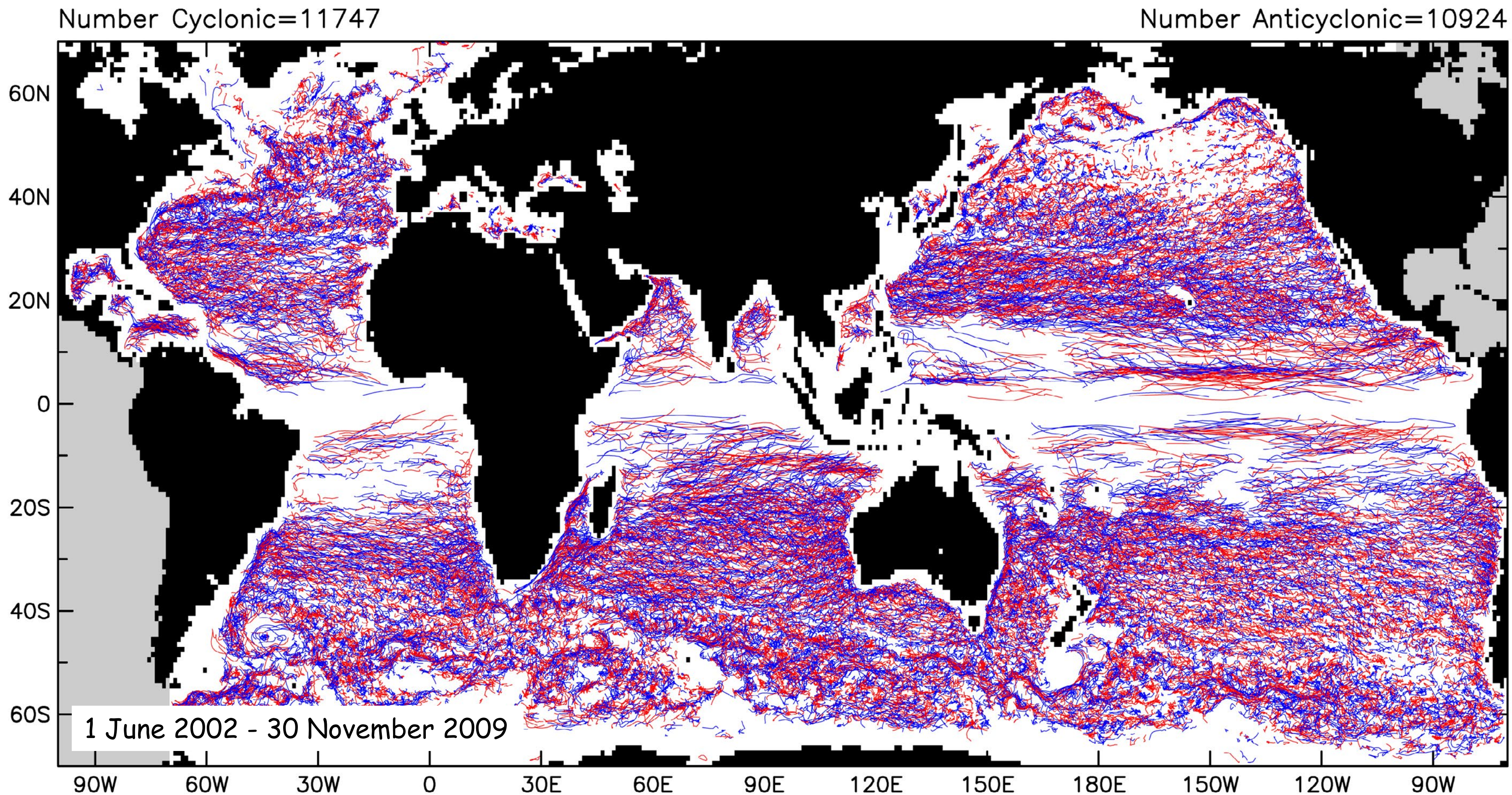
- Identify mesoscale eddies by altimetry from their SSH signatures.
- Composite average the other satellite datasets in an "eddy-centric" translating reference frame with (Δx,Δy) coordinates relative to the eddy centroid normalized by the radius L_s of maximum rotational speed at each location along its trajectory.
  - AMSR+AVHRR measurements of SST (Reynolds OI2 analyses)
  - QuikSCAT measurements of wind speed and wind stress
  - SeaWiFS estimates of oceanic chlorophyll
- Because the dominant mechanism for eddy-induced SST variability is horizontal advection by the rotational velocity of the eddy, SST and wind speed must be composite averaged in a coordinate system that is rotated by an amount determined from the large-scale background SST gradient.

Schematic of Eddy Influence on SST Showing the Dependence on Rotational Sense and the Large-Scale SST Gradient



Trajectories of the ~22,000 Mesoscale Eddies with Lifemes ≥16 Weeks During the 7.5 Years of Overlap of the Four Satellite Datasets

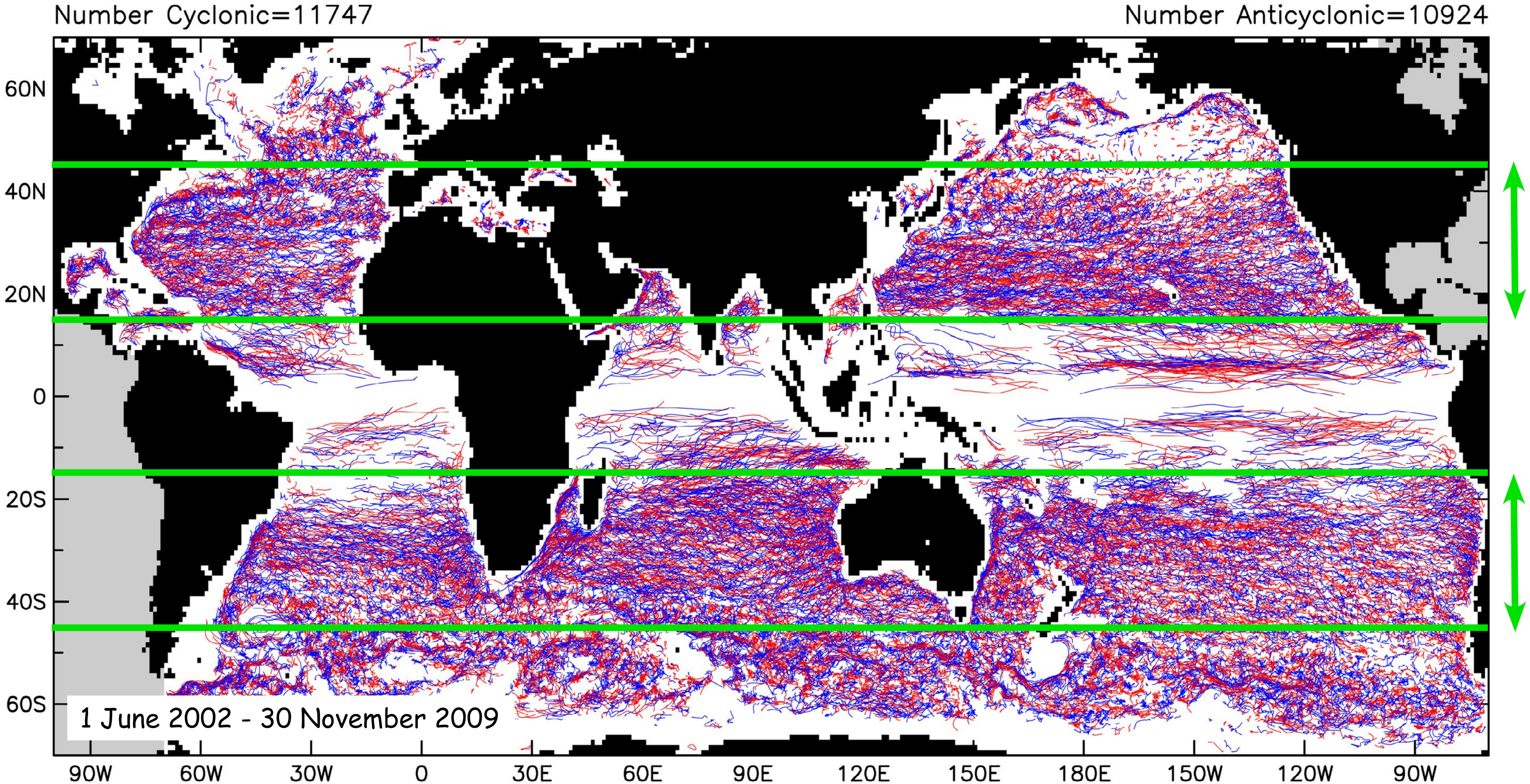
1 June 2002 - 30 November 2009



http://cioss.coas.oregonstate.edu/eddies/

Trajectories of the ~22,000 Mesoscale Eddies with Lifemes ≥16 Weeks During the 7.5 Years of Overlap of the Four Satellite Datasets

1 June 2002 - 30 November 2009

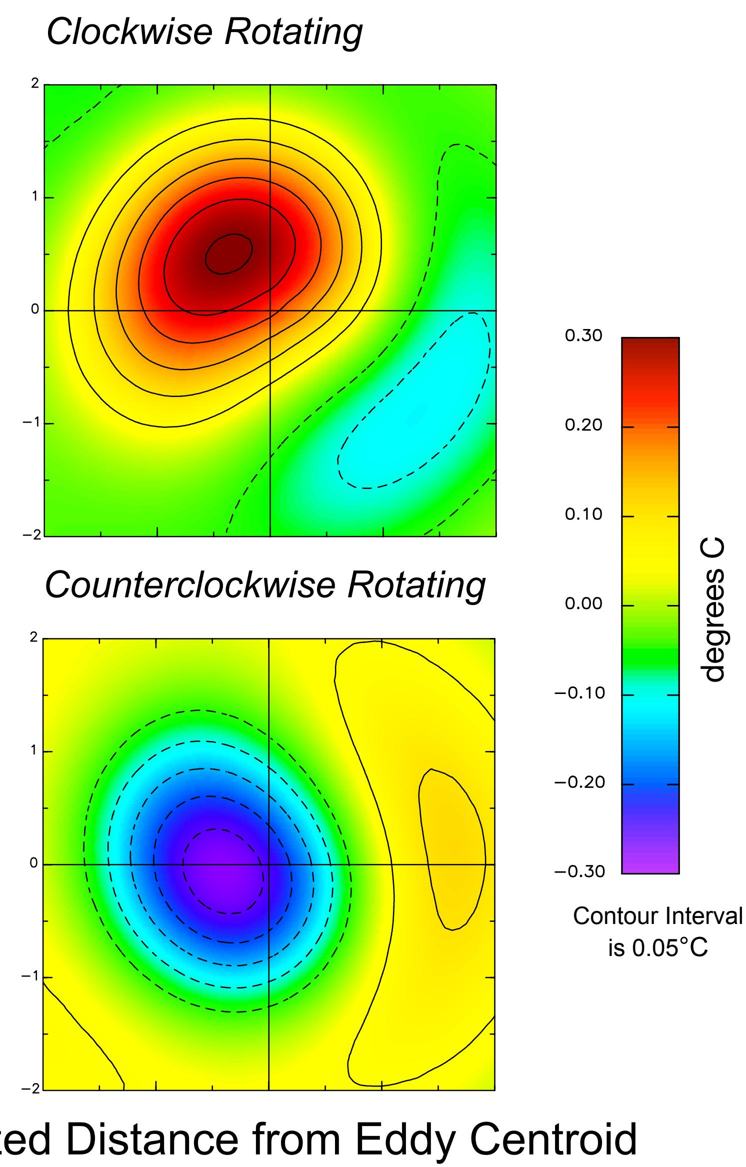


http://cioss.coas.oregonstate.edu/eddies/

Mesoscale eddy influence on SST and wind speed

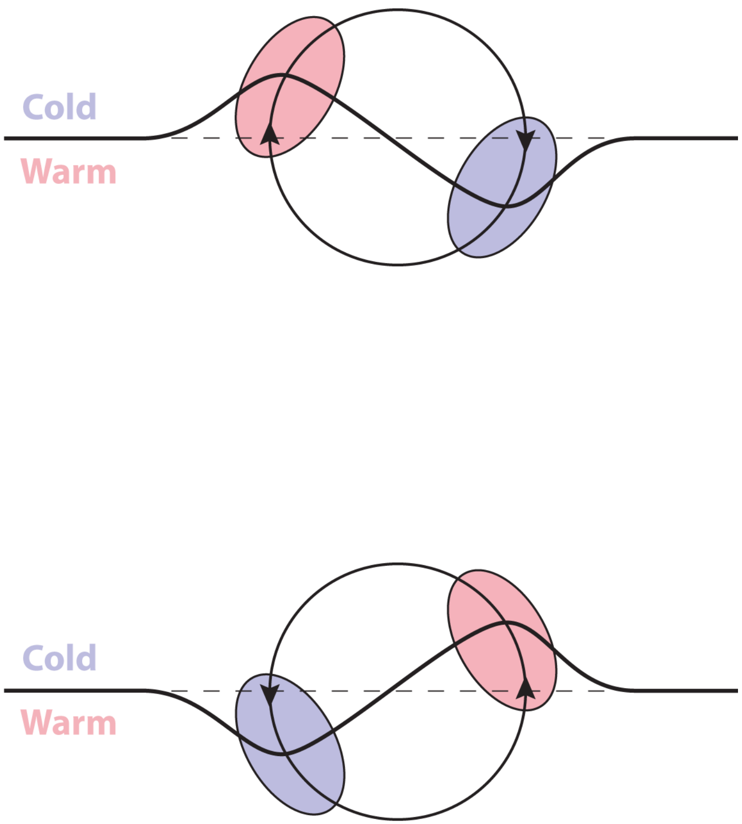
Global Composite Averages of SST in Eddy-Centric Coordinates

Regions of Southward ∇T

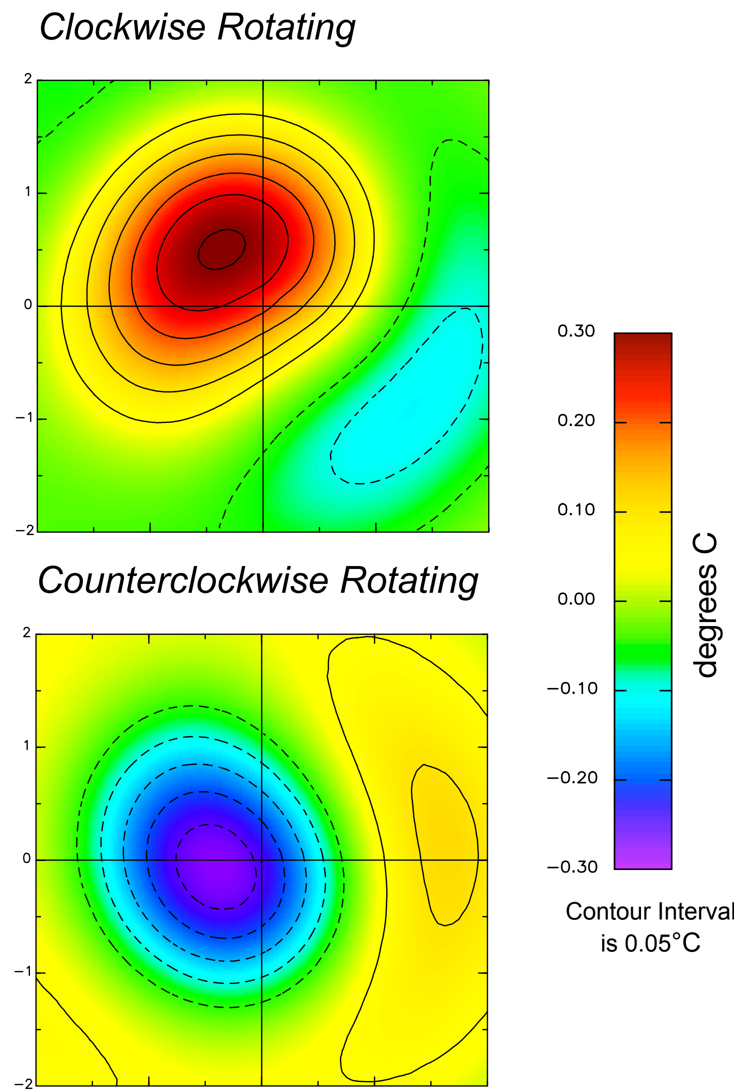


Global Composite Averages of SST in Eddy-Centric Coordinates

Schematic of Horizontal Advection

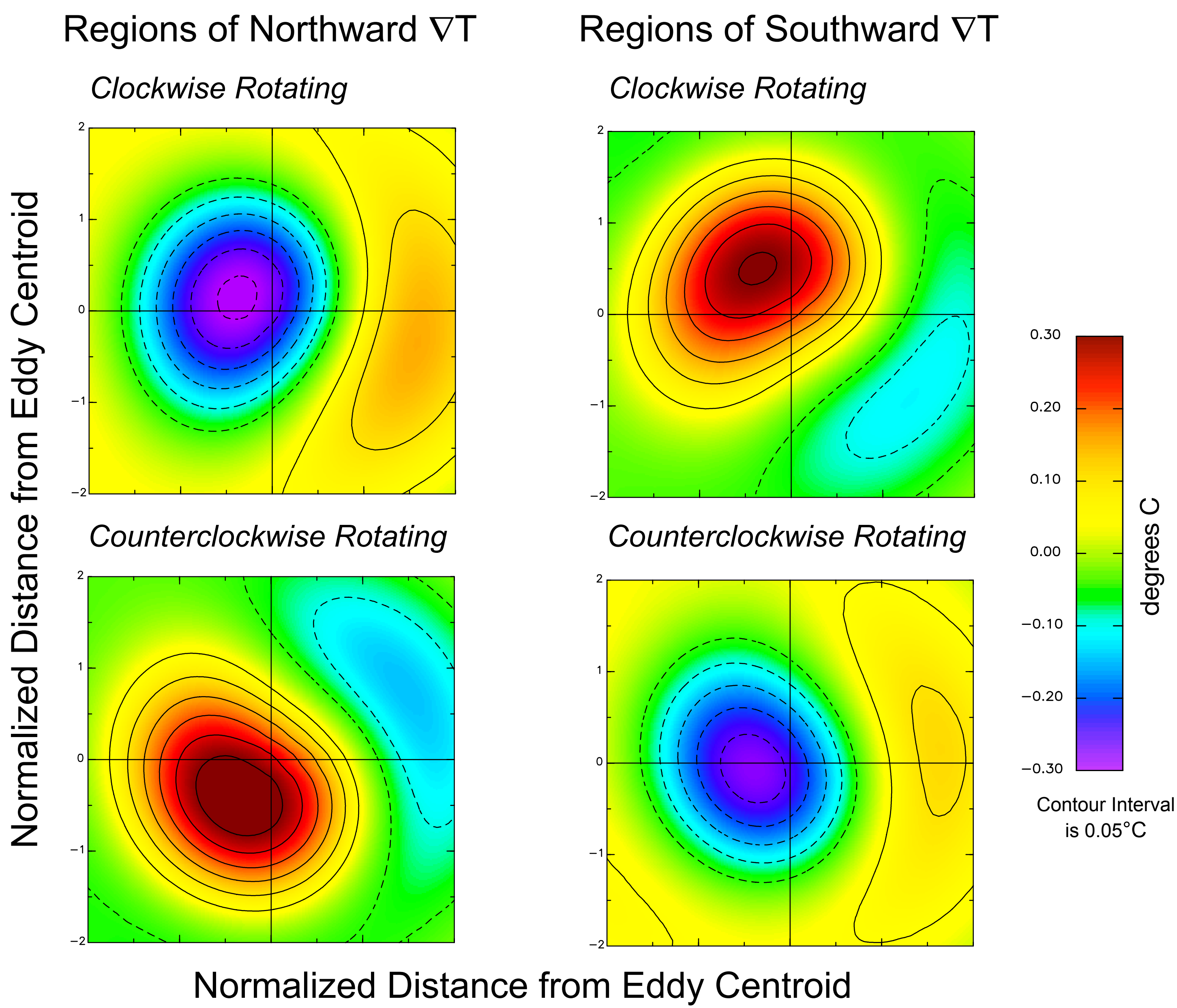


Regions of Southward ∇T

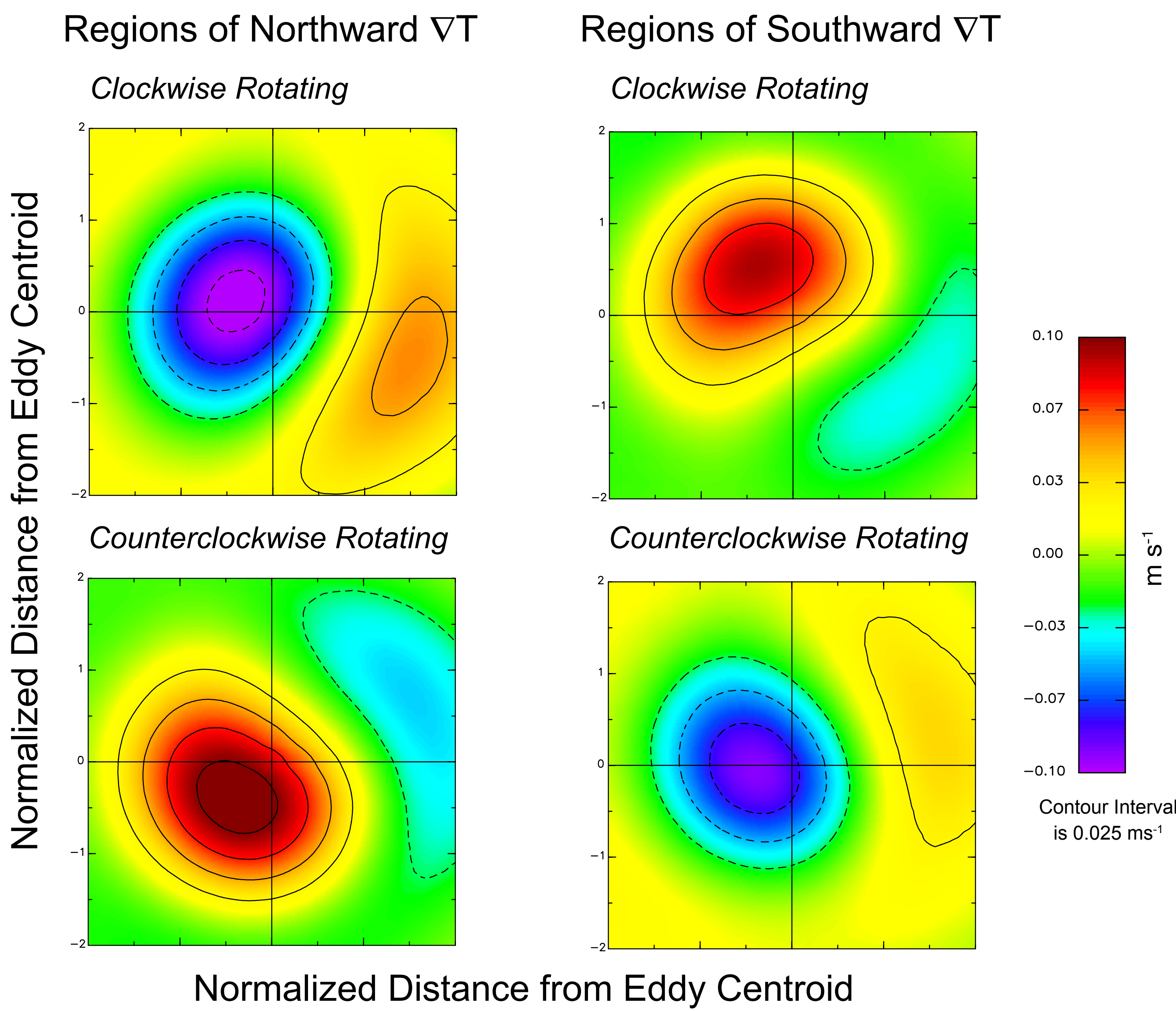


Normalized Distance from Eddy Centroid

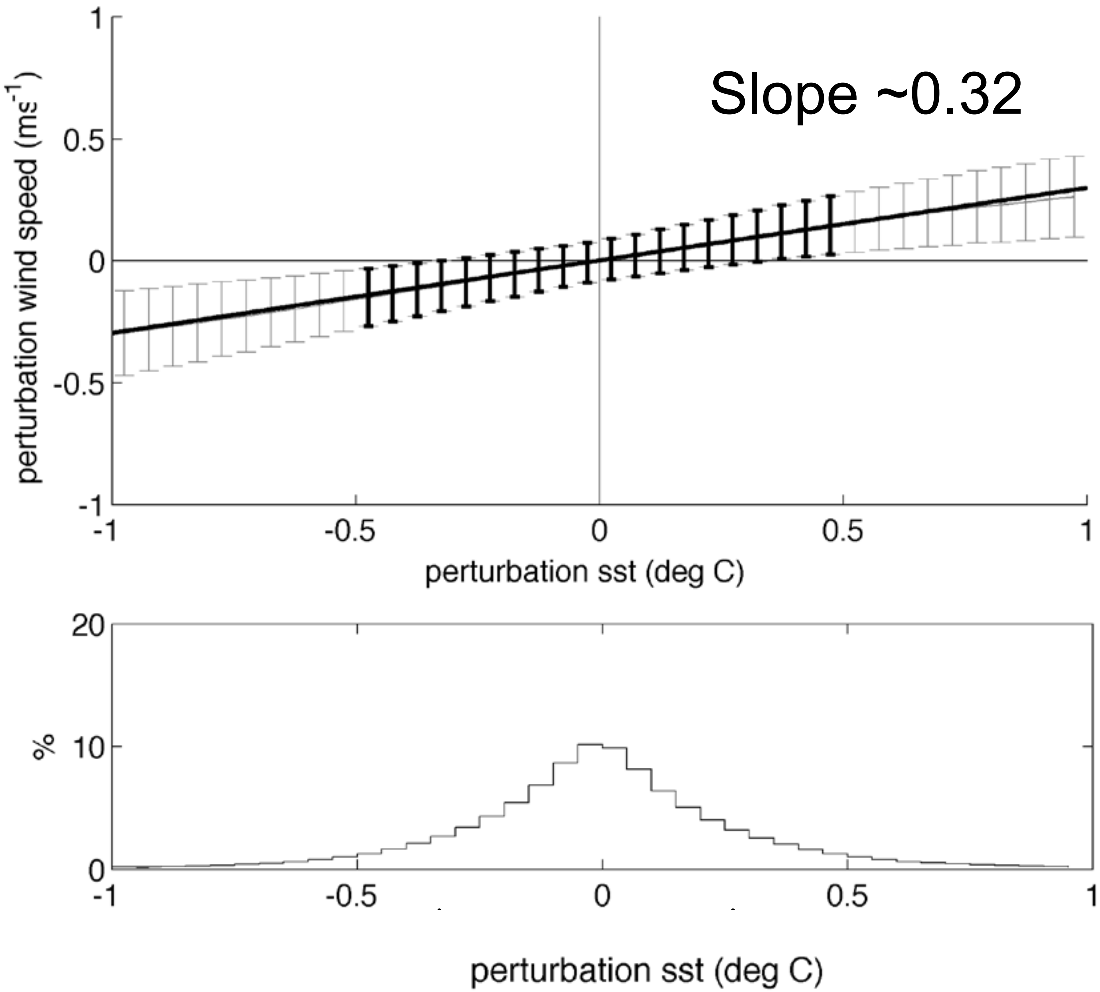
Global Composite Averages of SST in Eddy-Centric Coordinates



Global Composite Averages of Wind Speed in Eddy-Centric Coordinates



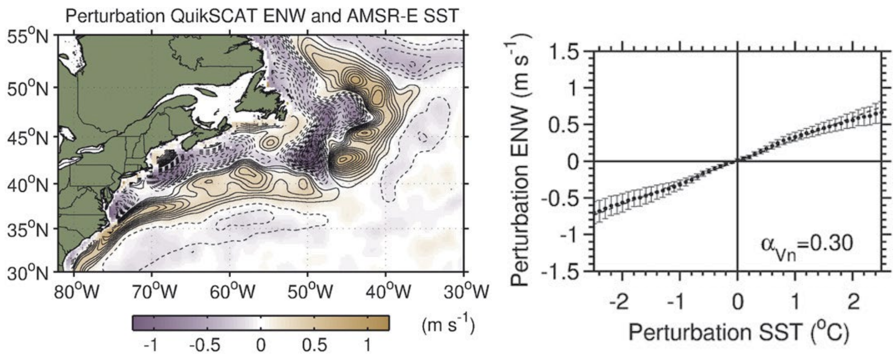
Coupling Coefficient Between Wind Speed and SST over Globally Distributed Mesoscale Eddies

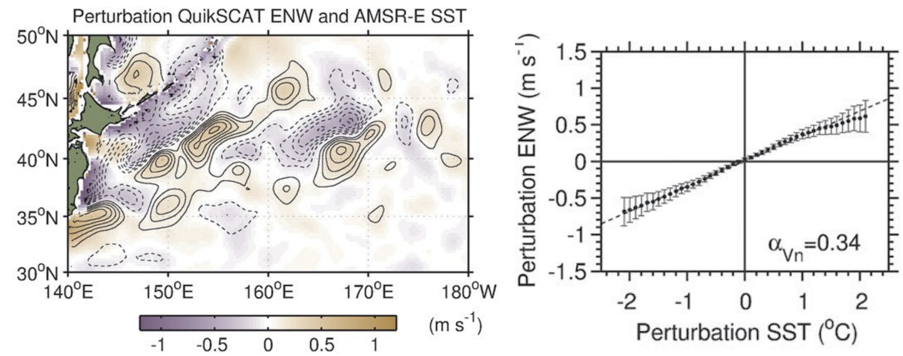


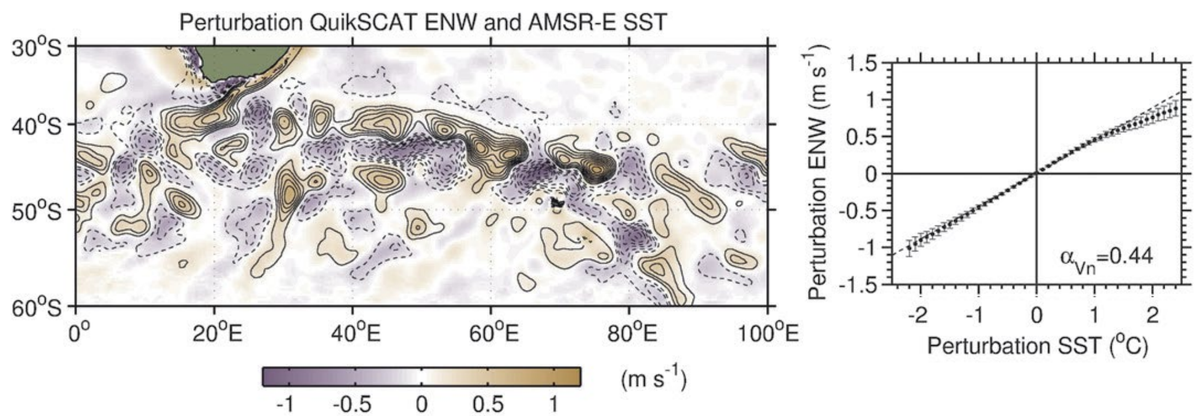
This wind speed response to SST over eddies is consistent with the coupling deduced previously over frontal regions by O'Neill et al. (2010; 2012)

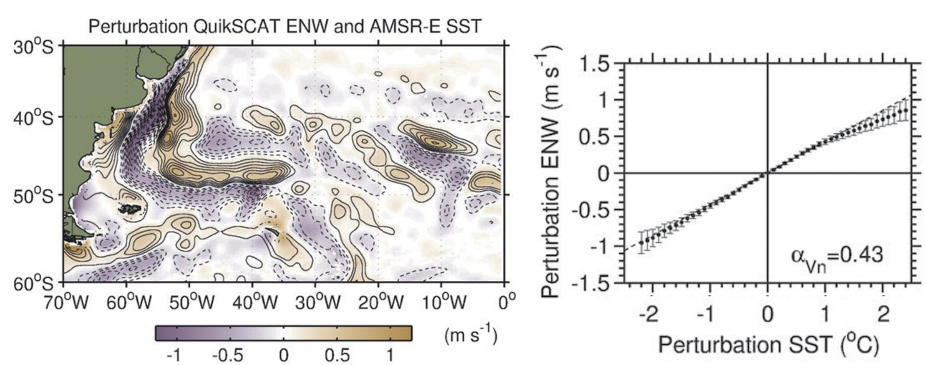
The Coupling Between SST and Wind Speed in 4 Frontal Regions

(Gulf Stream, Kuroshio Extension, Agulhas Return Current and Brazil-Malvinas Current)









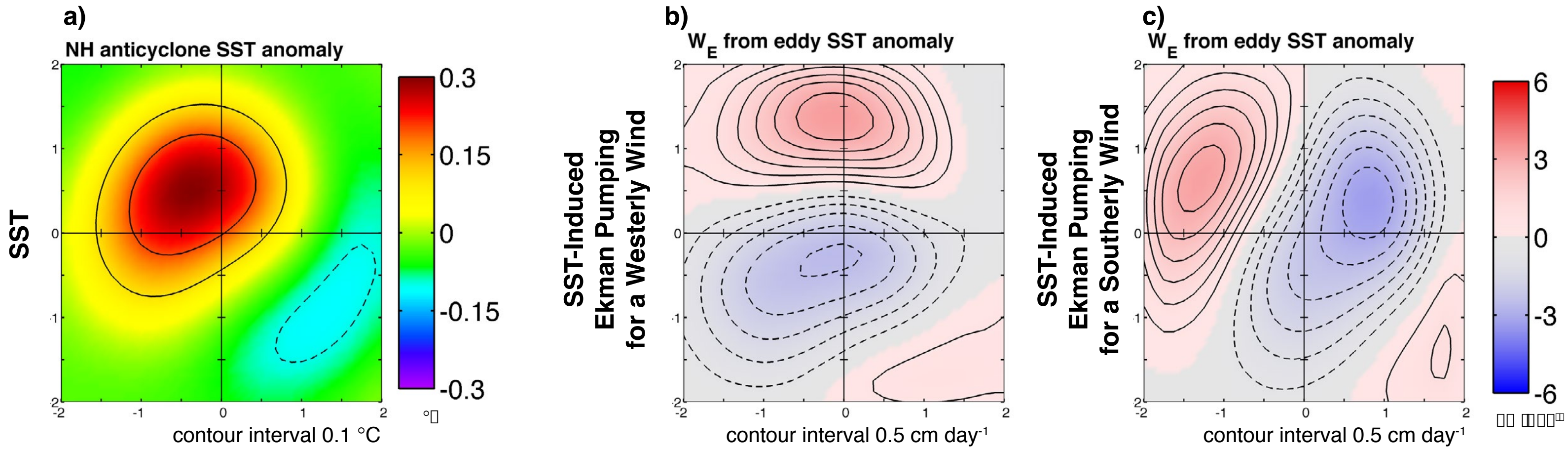
June 2002 - May 2009
Averages

From O'Neill et al. (2012, J. Clim.)

Eddy-induced SST influence on Ekman pumping

Eddy-Induced Ekman Pumping for an Idealized Anticyclone

From SST influence on Surface Winds at 30°N
for an Eddy-Induced SST Anomaly of 0.3°C and a Wind Speed of 7 m/s



Mesoscale eddy SST-induced wind stress curl feedback on the ocean circulation from an empirically coupled model (Jin et al., 2009)

SST–Wind Interaction in Coastal Upwelling: Oceanic Simulation with Empirical Coupling

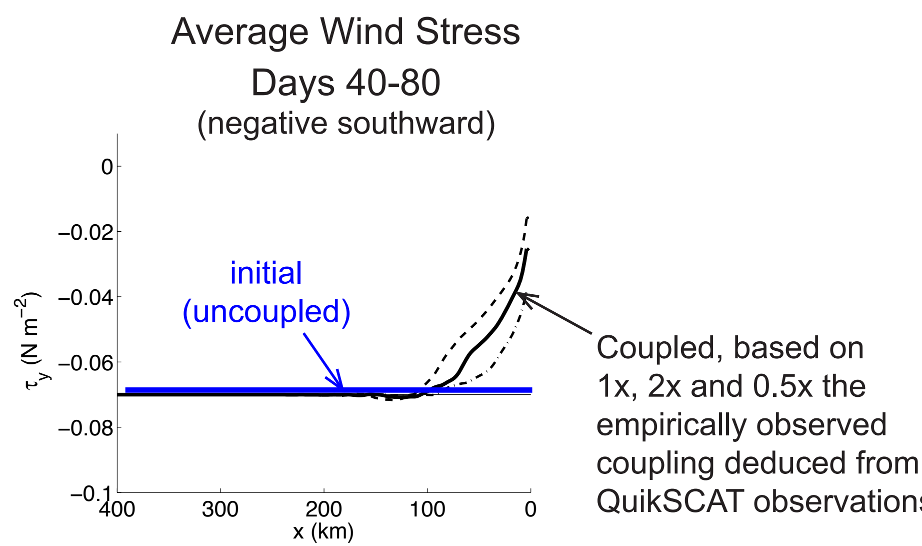
XIN JIN, CHANGMING DONG, JAISON KURIAN, AND JAMES C. MCWILLIAMS
Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, California

DUDLEY B. CHELTON
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

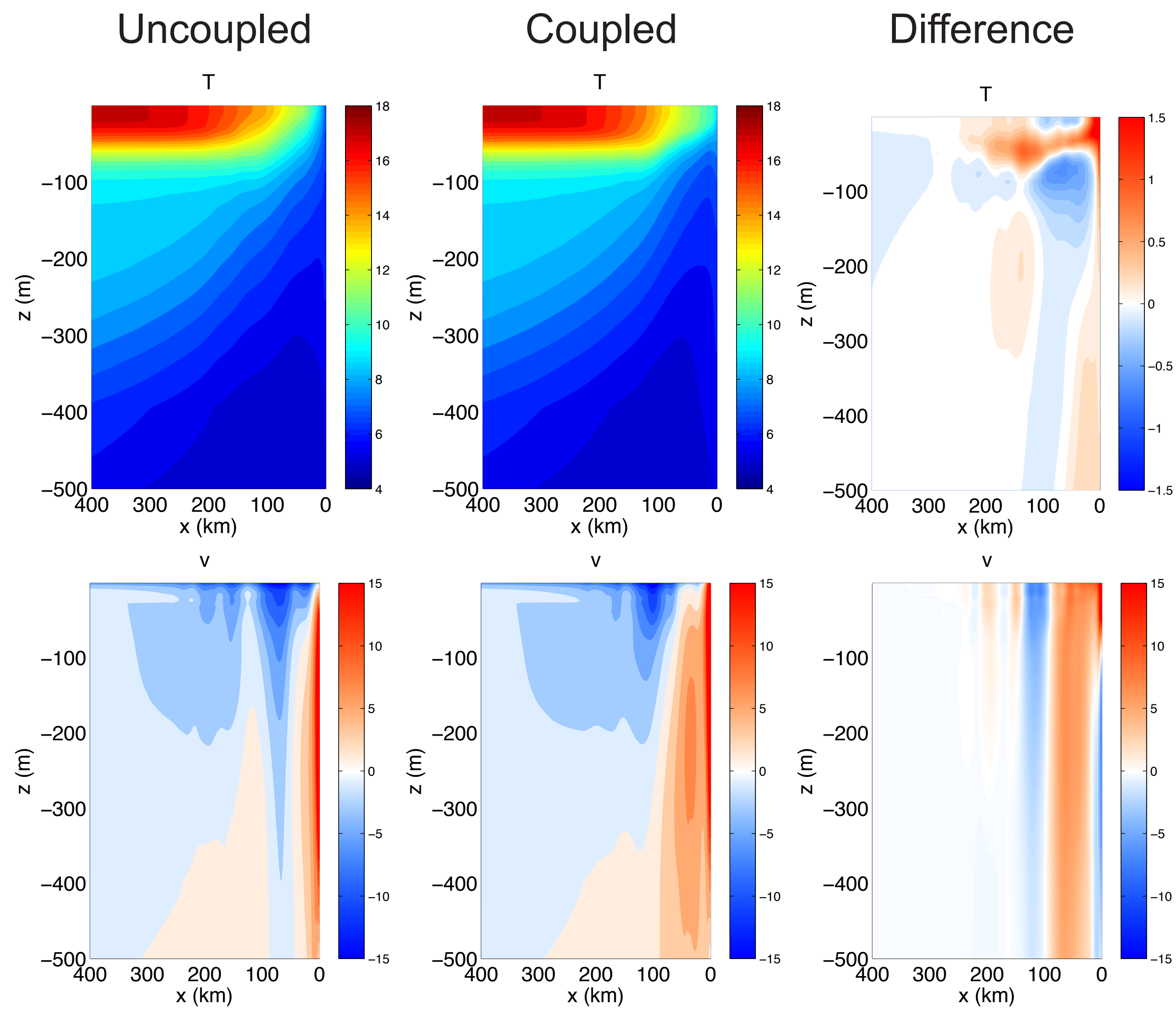
ZHIJIN LI
NASA Jet Propulsion Laboratory, Pasadena, California

A "25-Cent" Empirical Coupled Model:

- *Based on:*
  - *the ROMS model of an idealized eastern boundary current system with a straight coastline.*
  - *QuikSCAT-based empirical coupling coefficients for the feedback on the ocean.*
- *The winds are modified at each time step to conform to the empirical coupled relations among SST gradients, wind direction, and the local curl and divergence of the wind stress.*
- *This leads to an evolving modified wind obtained by inverting the diagnosed curl and divergence fields, while maintaining the original wind values on the open-ocean boundary.*

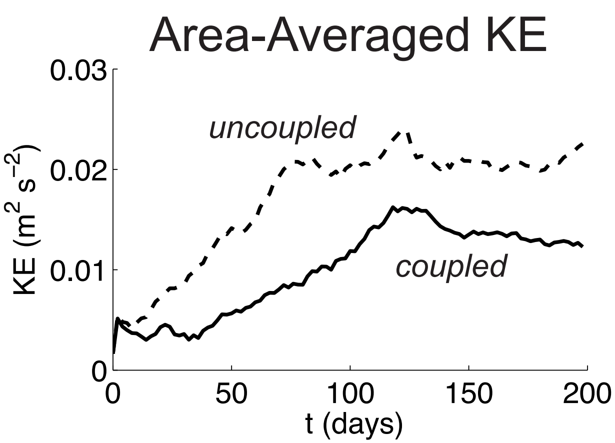


Temperature and Alongshore Velocity

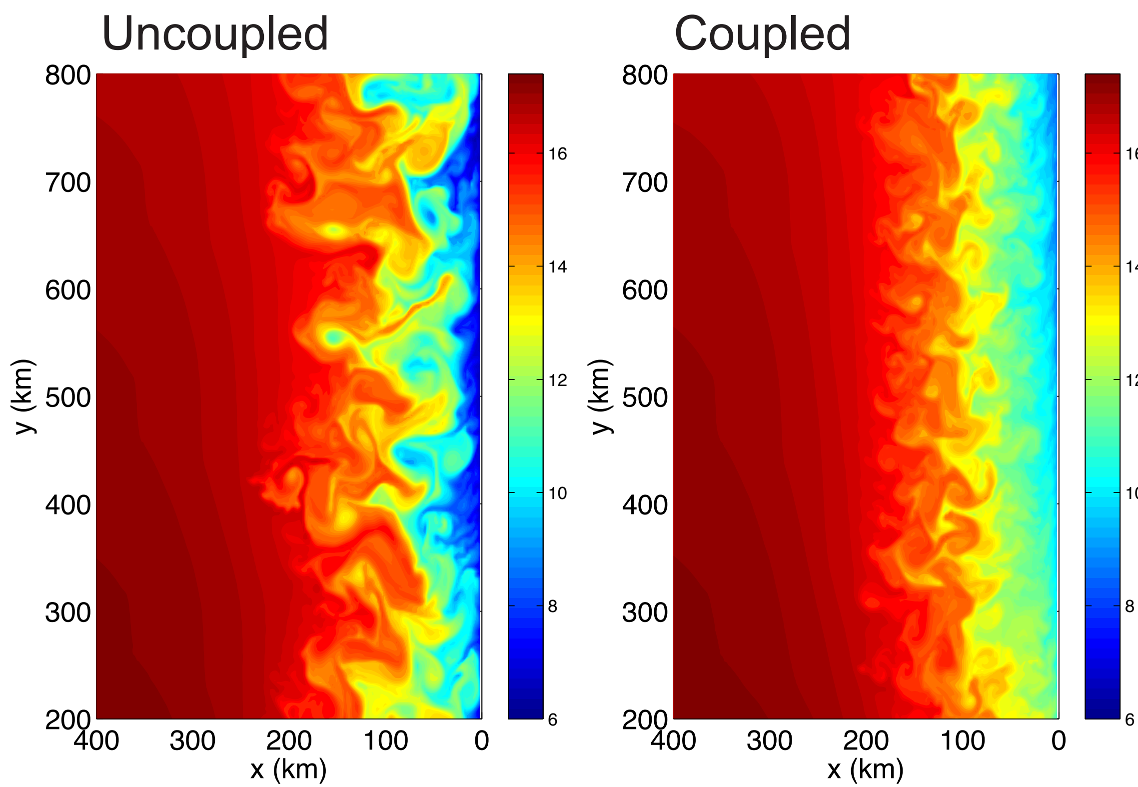


Jin et al. (2009, J. Phys. Oceanogr.)

Temporal Evolution of the Eddy Field



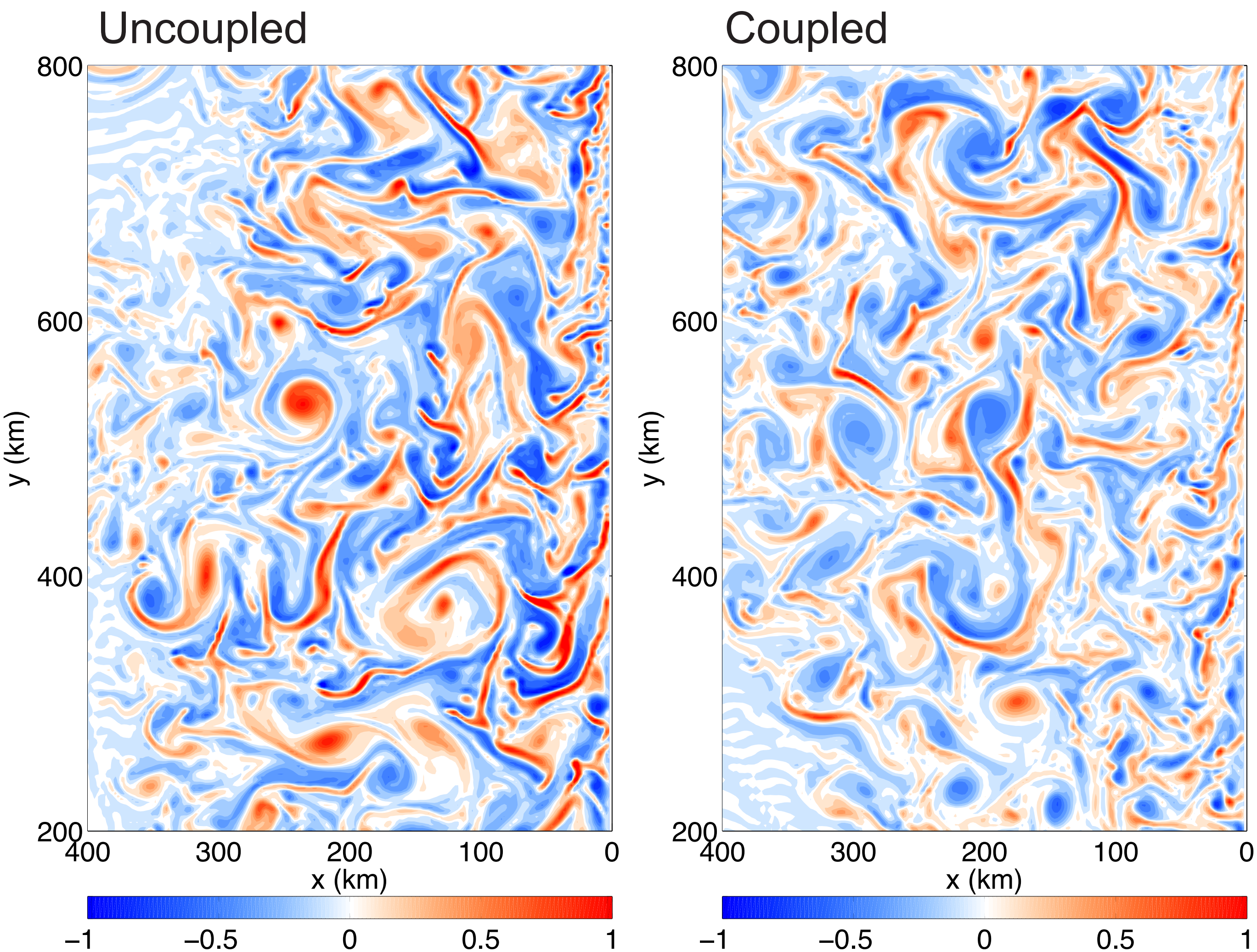
Sea-Surface Temperature, Day 60



Note the weaker cross-shore gradient of SST and the weaker eddy kinetic energy in the coupled model run.

Jin et al. (2009, J. Phys. Oceanogr.)

Surface Vorticity (Normalized by f) on Day 160



In the coupled simulation, cyclonic eddies (red) are weakened and there is a much greater abundance of anticyclonic eddies (blue).

Jin et al. (2009, J. Phys. Oceanogr.)

Conclusions of the Jin et al. (2009) study:

- *The cold upwelled water at the coast causes the nearshore winds to diminish, generating a nearshore positive wind stress curl that:*

  - weakens the equatorward surface current.

  - strengthens the poleward undercurrent.

  - weakens the alongshore SST front.

  - slows the development of baroclinic instability and weakens the mesocale eddy field.

  - reduces the eddy kinetic energy by about 25%.

- *The coupling preferentially disrupts the coherent evolution of cyclonic eddies because they have stronger SST signatures due to ageostrophic effects.*

  - this increases the relative abundance of anticyclonic eddies.

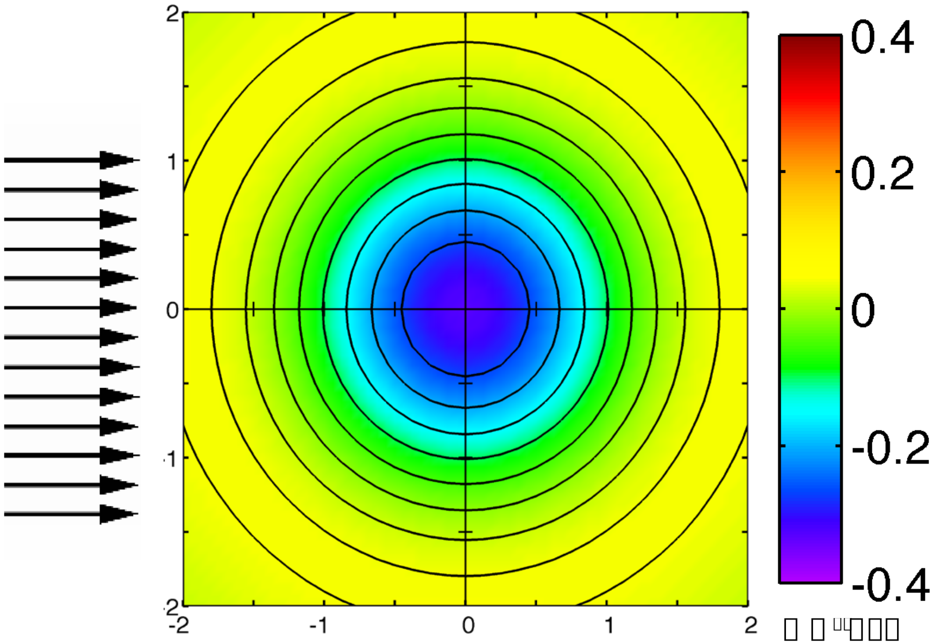
- *Overall conclusion: All of the salient large-scale and mesoscale features of eastern boundary current systems are altered by this 2-way ocean-atmosphere coupling.*

Eddy-induced surface current influence on Ekman pumping

Ekman Pumping from Eddy Surface Currents

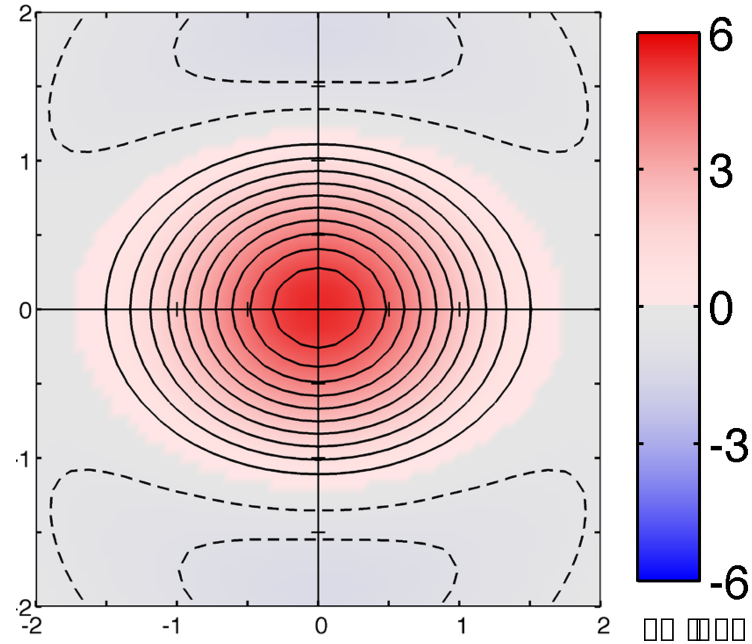
For an idealized Gaussian <u>anticyclone</u> with 10 cm amplitude and 90 km radius in 7 ms^{-1} <u>westerly</u> winds at 30°N

SSH and Geostrophic Vorticity



contour interval 1 cm

Surface Current-Induced Ekman Pumping



contour interval 0.5 cm day^{-1}

The surface stress is determined from the relative wind:

$$\vec{u}_{\mathrm{rel}} = \vec{u}_{\mathrm{a}} - \vec{u}_{\mathrm{o}}$$

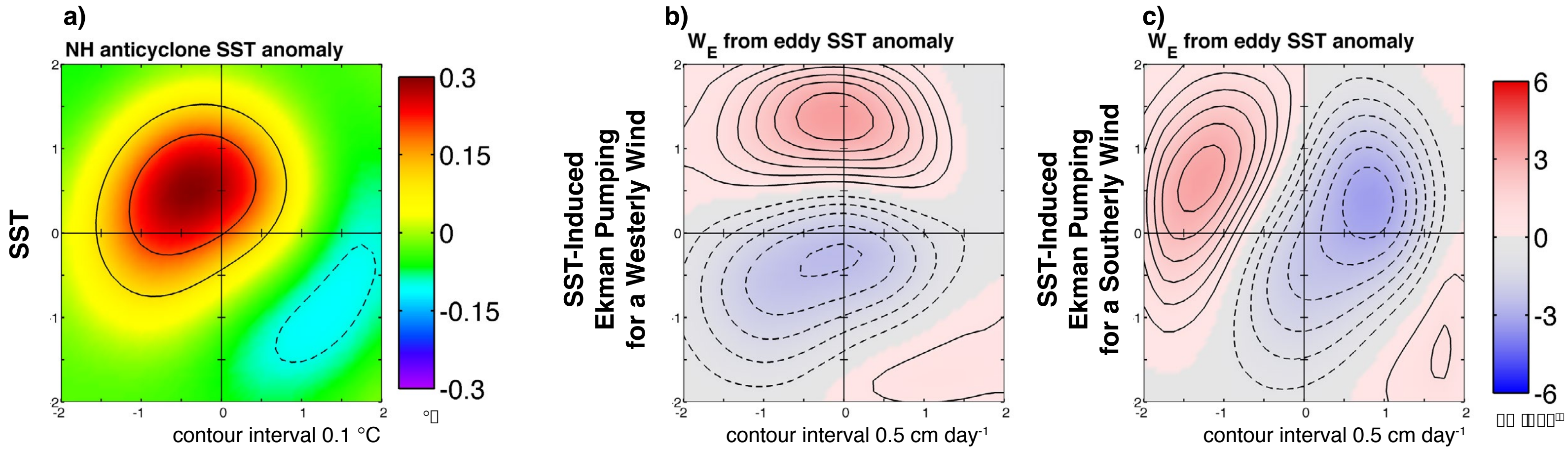
$$\nabla \times \vec{u}_{\mathrm{rel}} \approx -\nabla \times \vec{u}_{\mathrm{o}}$$

$$\vec{\tau} = \rho_{\mathrm{a}} C_D |\vec{u}_{\mathrm{rel}}| \vec{u}_{\mathrm{rel}}$$

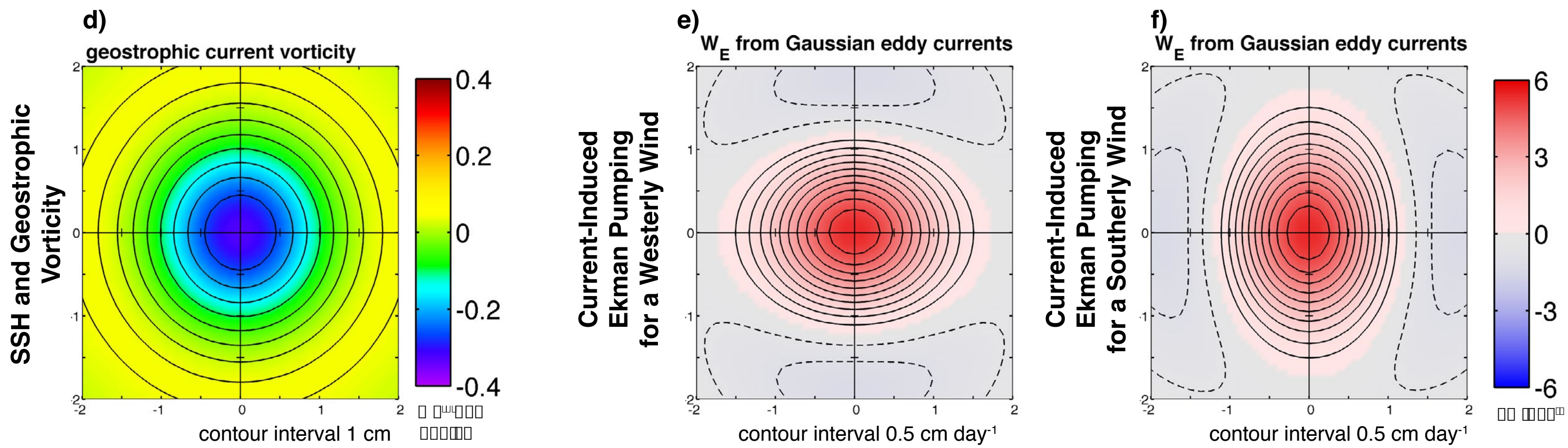
$$W_E = \frac{1}{\rho_{\mathrm{o}} f} \nabla \times \vec{\tau}$$

Eddy-Induced Ekman Pumping for an Idealized Anticyclone

From SST influence on Surface Winds at 30°N
for an Eddy-Induced SST Anomaly of 0.3°C and a Wind Speed of 7 m/s

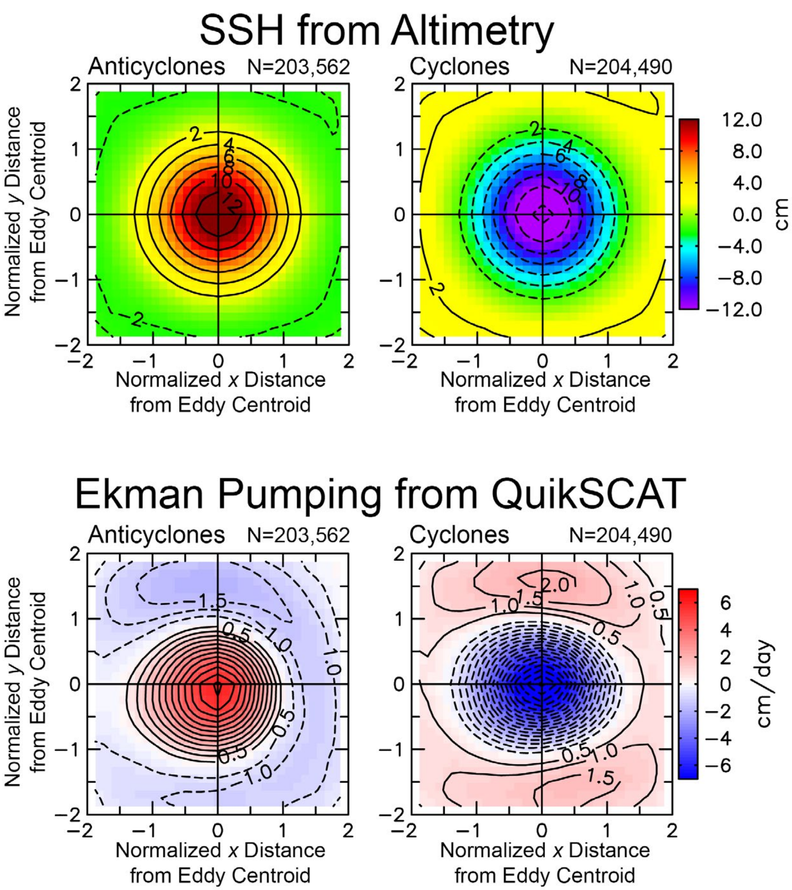


From Surface Current Effects on Surface Stress at 30°N
for an Eddy with 10 cm Amplitude and 90 km Radius and a Wind Speed of 7 m/s



QuikSCAT validation of the dominance of surface current effects over SST effects on Ekman pumping inferred from idealized eddies

Global composite averages of SSH and the total eddy Ekman pumping measured by QuikSCAT

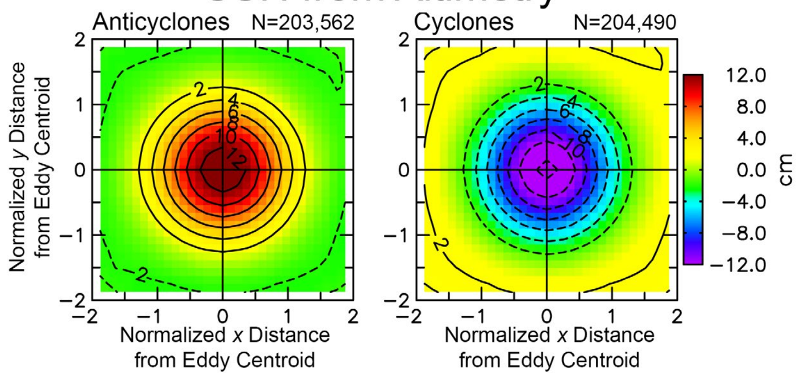


The monopole structures of eddy-induced Ekman pumping indicates the dominance of surface current effects.

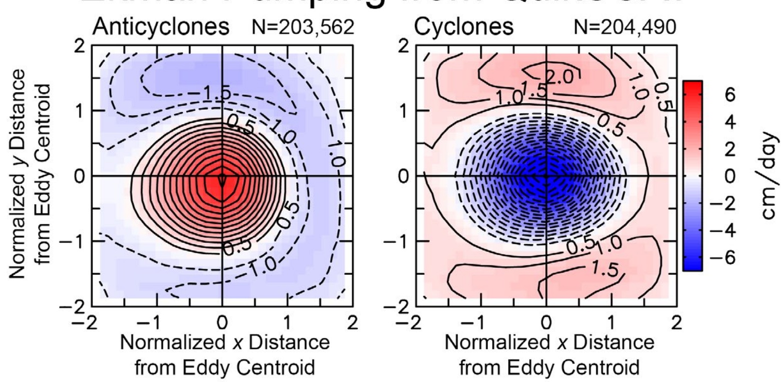
QuikSCAT validation of the dominance of surface current effects over SST effects on Ekman pumping inferred from idealized eddies

Global composite averages of SSH and the total eddy Ekman pumping measured by QuikSCAT

SSH from Altimetry



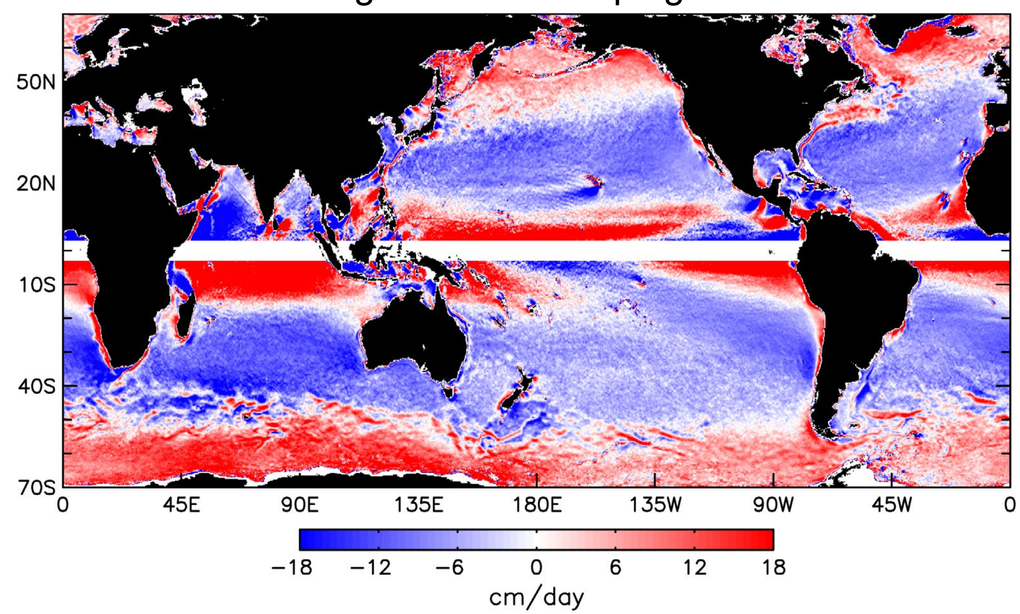
Ekman Pumping from QuikSCAT



The monopole structures of eddy-induced Ekman pumping indicates the dominance of surface current effects.

The magnitudes of eddy-induced Ekman pumping are at least half as large as the Ekman pumping from the large-scale wind field.

10-Year Average Ekman Pumping from QuikSCAT



The 1/e attenuation time scale of this Ekman pumping is about 1 year

Recent models that adjust the surface stress for surface current effects

Eden, C., and H. Dietze, 2009: Effects of mesoscale eddy/wind interactions on biological new production and eddy kinetic energy. *J. Geophys. Res.*, **114**, doi: 10.1029/2008JC005129.

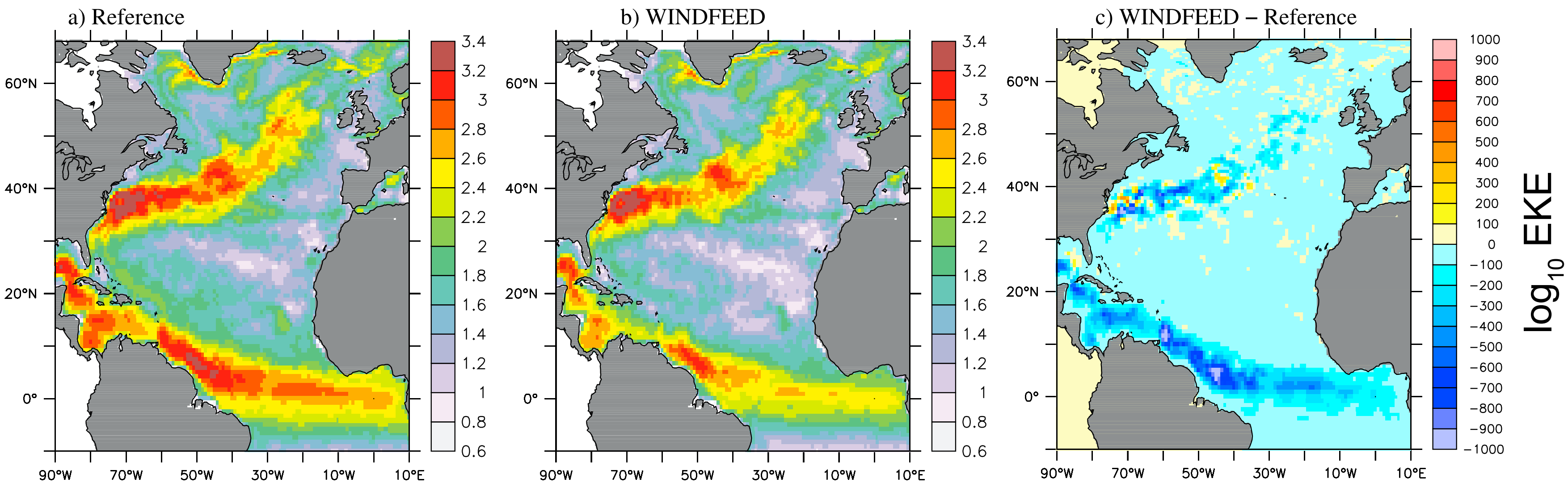
Hutchinson, D.K., A.M. Hogg, & J.R. Blundell, 2011: Southern Ocean response to relative wind stress forcing. *J. Phys. Oceanogr.*, **40**, 326-339.

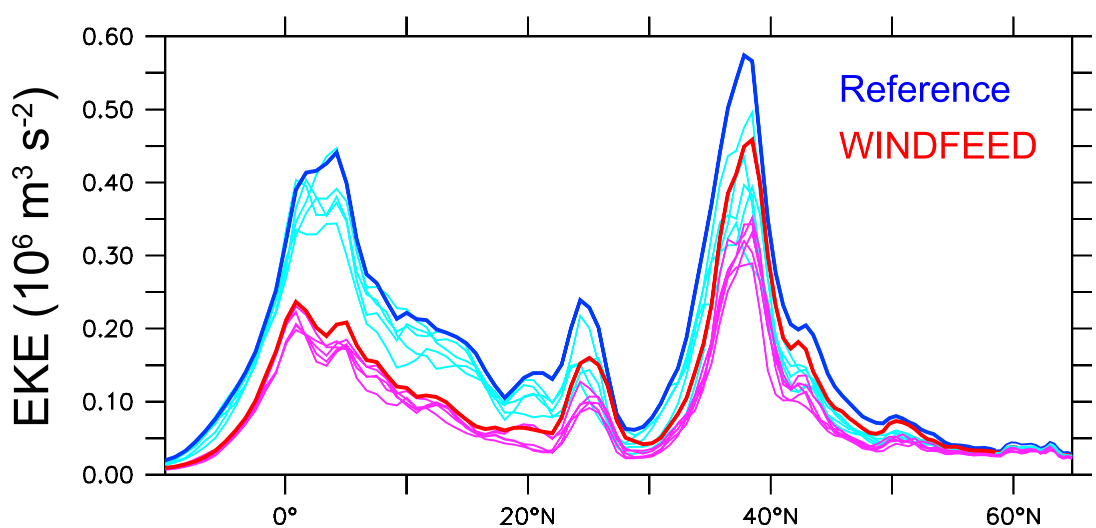
Anderson, L., D. McGillicuddy, M. Maltrud, I. Lima & S. Doney, 2011: Impact of eddy–wind interaction on eddy demographics and phytoplankton community structure in a model of the North Atlantic Ocean. *Dyn. Atmos. Oceans*, doi:10.1016/j.dynatmoce.2011.01.003.

McClean, J.L., & 14 other authors, 2011: A prototype two-decade fully-coupled fine-resolution CCSM simulation. *Ocean Modelling*, **39**, 10-30.

Eddy Kinetic Energy With and Without Surface Current Effects on the Surface Stress Field

Eden et al. (2009), J. Geophys. Res.





Light blue and purple lines are individual years 2001-2005

Conclusions

- Air-sea interaction over SST frontal regions significantly alters the large-scale and mesoscale ocean circulation.

- This air-sea interaction that has been studied extensively over SST frontal regions also occurs over mesoscale eddies.

  - Spatial variability of the eddy-induced SST perturbations generates Ekman pumping associated primarily with crosswind SST gradients.

- Eddy-induced Ekman pumping also occurs from the effects of eddy surface currents on the surface stress field.

  - In most regions of the world ocean, this surface current effect is stronger than the SST/air-sea interaction influence on Ekman pumping.

- Eddy-induced Ekman pumping dramatically alters the mesoscale eddy field.

  - It likely also alters the large-scale circulation through eddy-mean flow interactions. (This is work in progress....)