Mesoscale Coupled Ocean-Atmosphere Interaction

Dudley B. Chelton
Oregon State University

Outline:

- Introduction

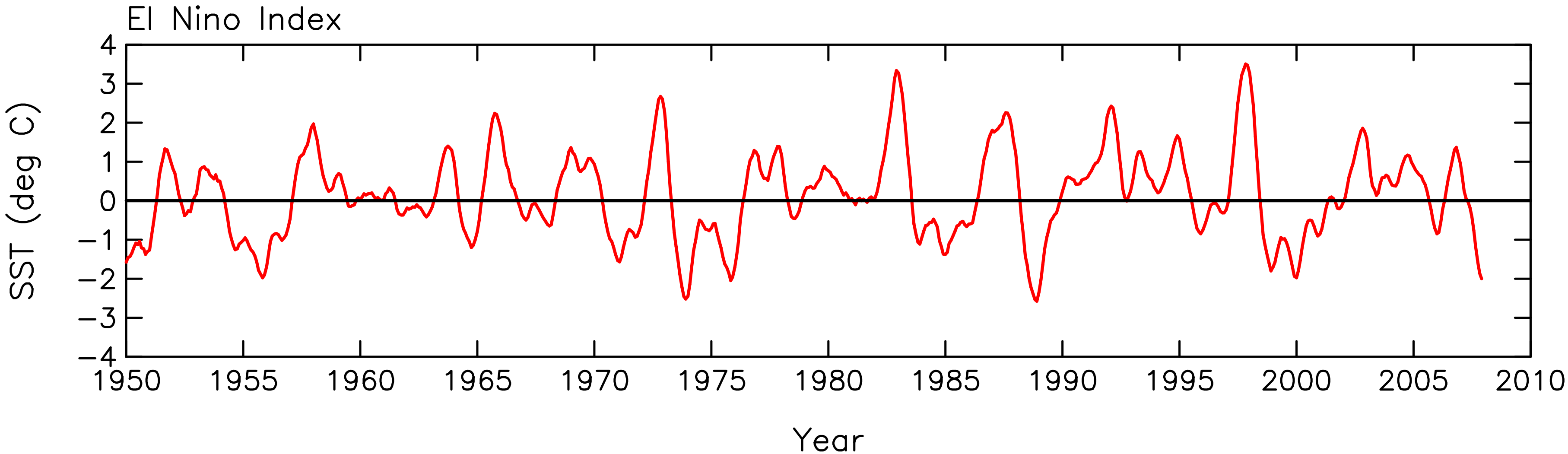
  The climate data record challenge: sustained satellite observations of the key variables of interest (surface winds, SST and SSH)

- Brief summary of SST influence on surface winds
  - *SST influence on surface winds from QuikSCAT, ECMWF operational, ECMWF Reanalysis, NCEP operational and NCEP Reanalysis*
  - *SST influence on wind stress curl*

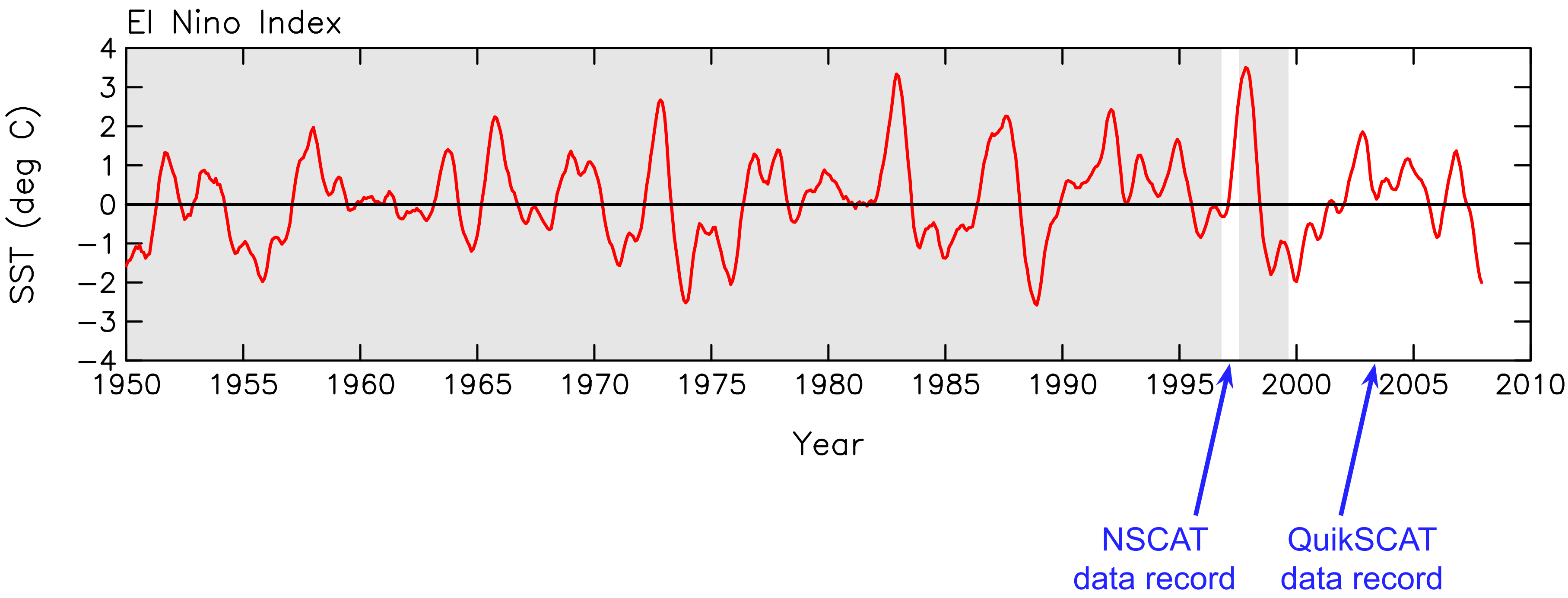
- Brief summary of the feedback effects on the ocean circulation

  Four examples:
  - *Effects on tropical instability waves*
  - *Effects on baroclinic instability (Spall, 2007)*
  - *Effects on basin-scale ocean circulation (Hogg et al., 2009)*
  - *Effects on eastern boundary current systems (Jin et al, 2009)*

An Example Climate Data Record

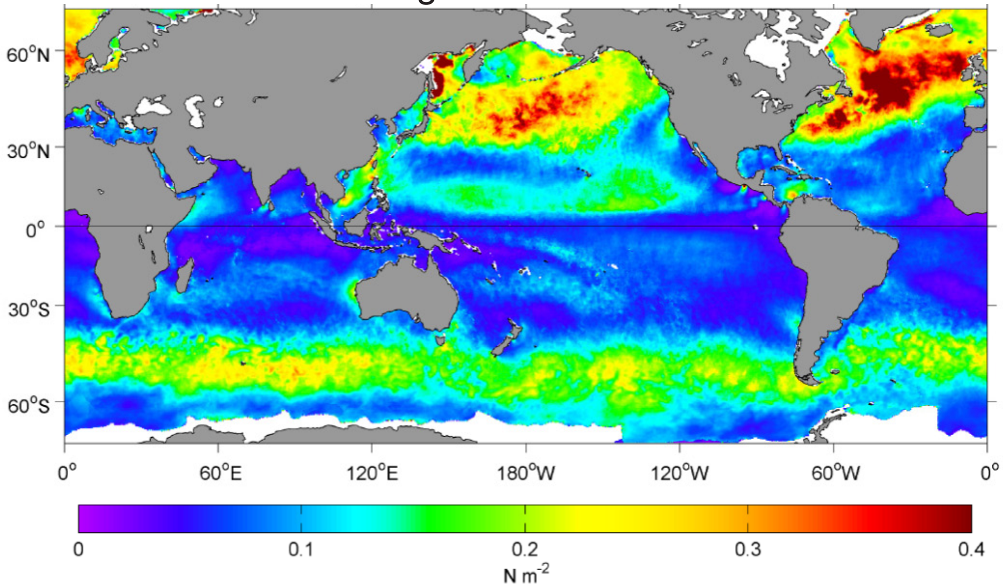


An Example Climate Data Record

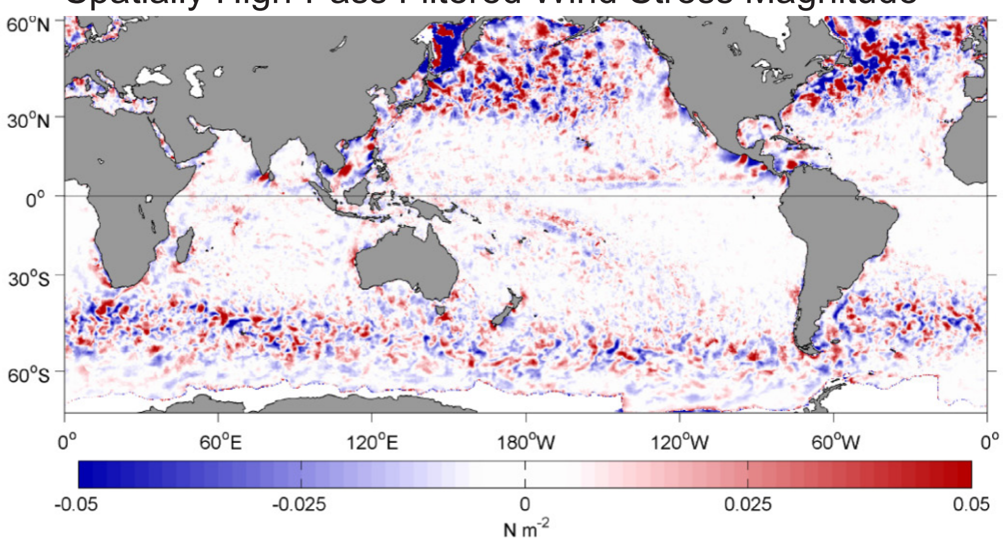


QuikSCAT Wind Stress Magnitude, January 2007

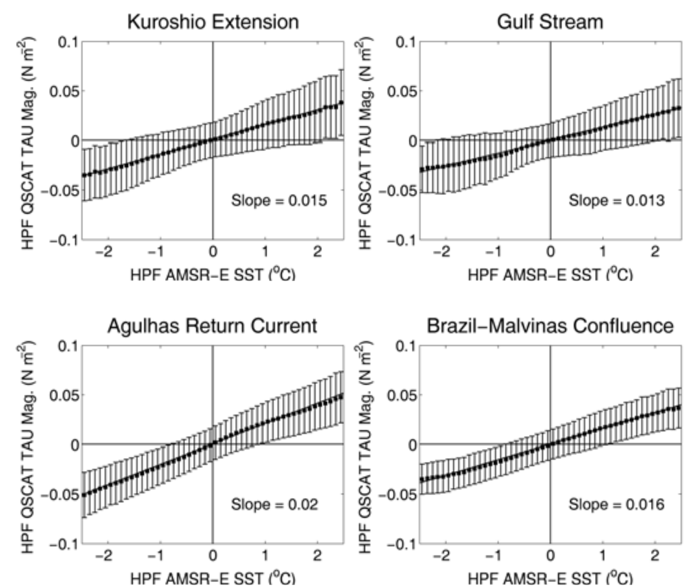
Total Wind Stress Magnitude



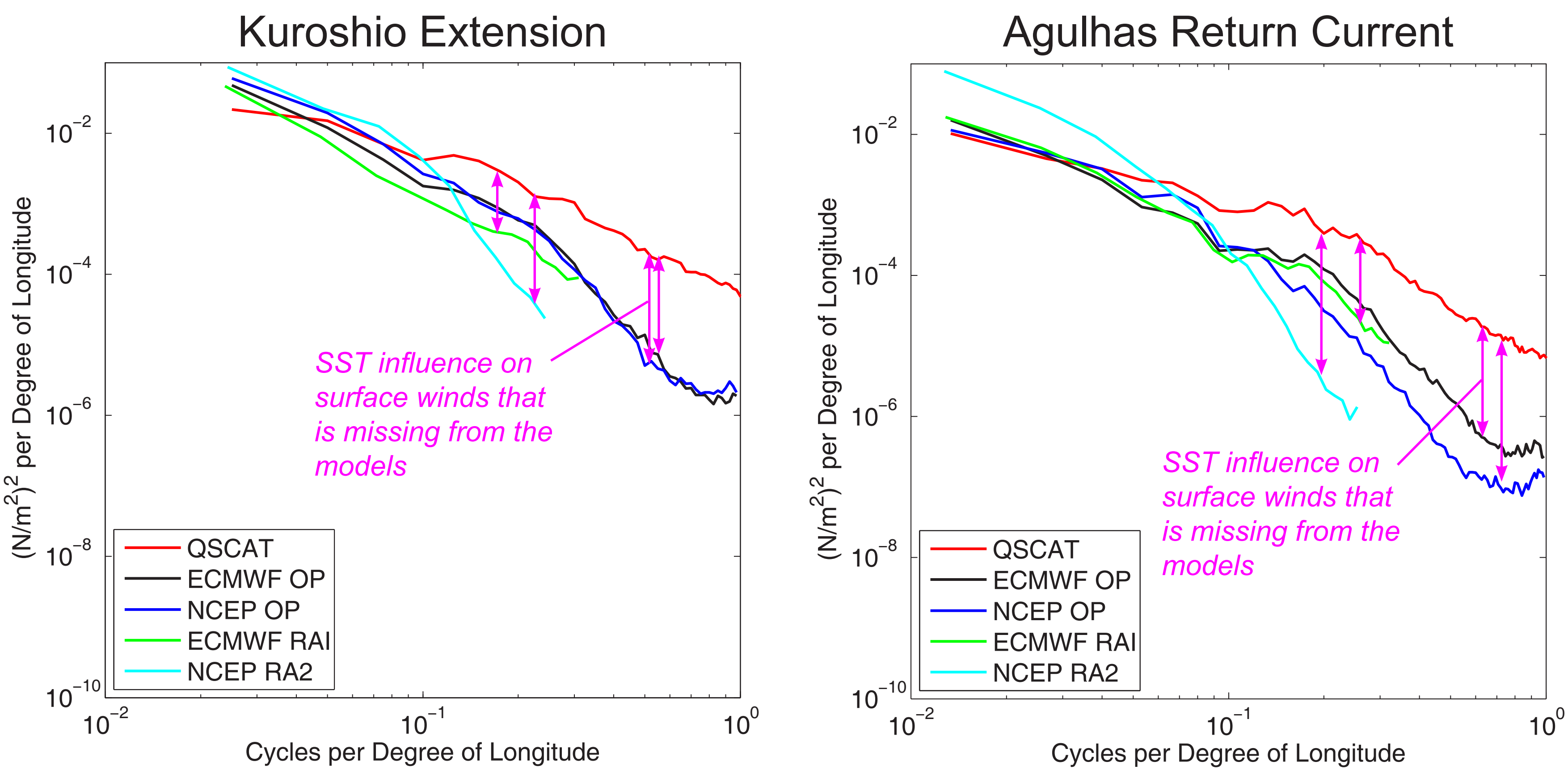
Spatially High-Pass Filtered Wind Stress Magnitude



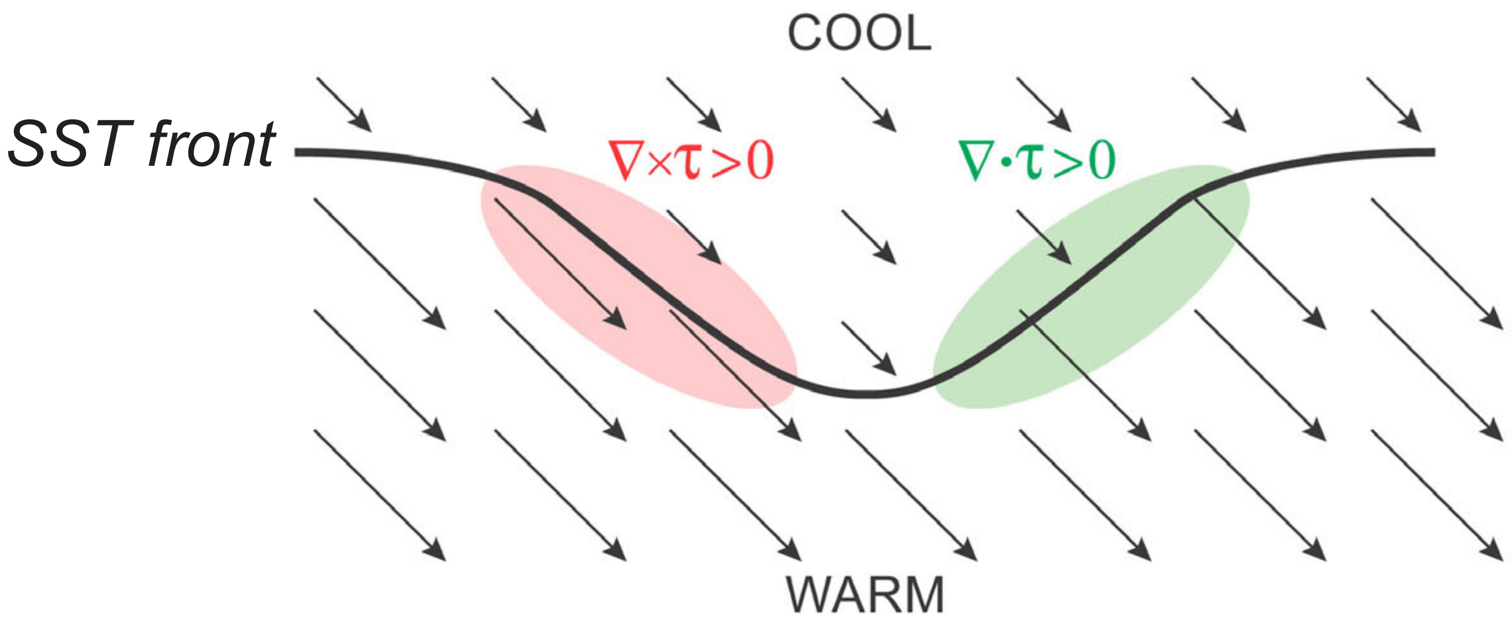
Linear Relations Between Wind Stress Magnitude and SST



Zonal Wavenumber Spectra of Wind Stress Magnitude
January 2001 - 2008



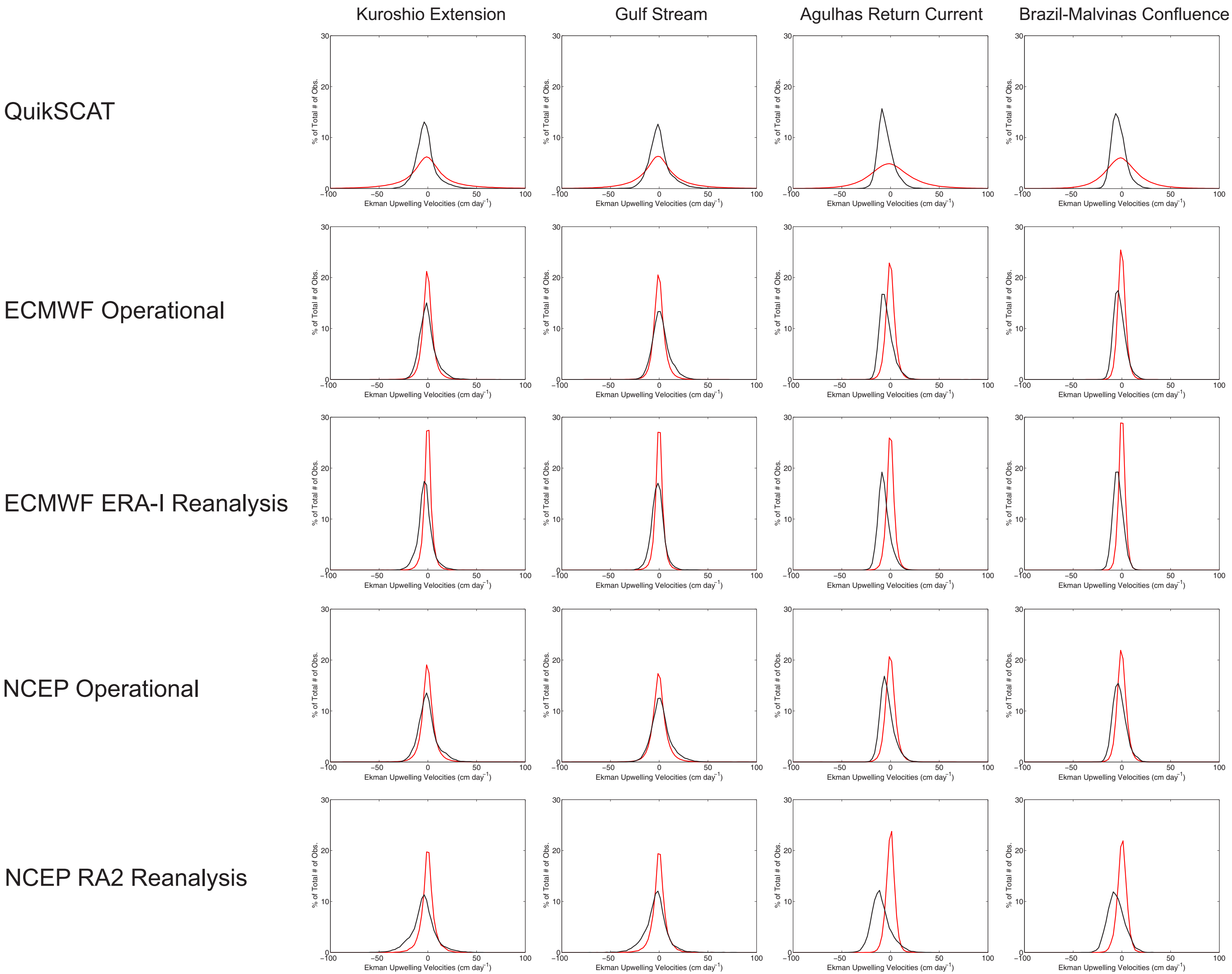
SST Effects on the Curl and Divergence of Surface Wind Stress



Wind vorticity and wind stress curl associated with crosswind SST gradients

Wind and wind stress divergence associated with downwind SST gradients

Distributions of ***Large-Scale*** and ***Small-Scale*** Ekman Upwelling Velocites



Published Studies of Feedback Effects on Ocean Circulation

Pezzi, L. P., J. Vialard, K. J. Richard, C. Menkes, and D. Anderson, 2004: Influence of ocean-atmosphere coupling on the properties of tropical instability waves. *Geophys. Res. Lett.*, **31**, L16306, doi:10.1029/2004GL019995.

Seo, H., M. Jochum, R. Murtugudde, A. J. Miller, and J. O. Roads, 2007: Feedback of tropical instability-wave-induced atmospheric variability onto the ocean. *J. Climate*, **20**, 5842-5855.

Spall, M. A., 2007: Effect of sea surface temperature-wind stress coupling on baroclinic instability in the ocean. *J. Phys. Oceanogr.*, **37**, 1092-1097.

Hogg, A. McC., W. K. Dewar, P. Berloff, S. Kravstov, and D. K. Hutchinson, 2009: The effects of mesoscale ocean-atmosphere coupling on the large-scale ocean circulation. *J. Climate*, in press.

Jin, X., C. Dong, J. Kurian, J. C. McWilliams, D. B. Chelton, and Z. Li, 2009: SST-wind interaction in coastal upwelling: Oceanic simulation with empirical coupling. *J. Phys. Oceanogr.*, in press.

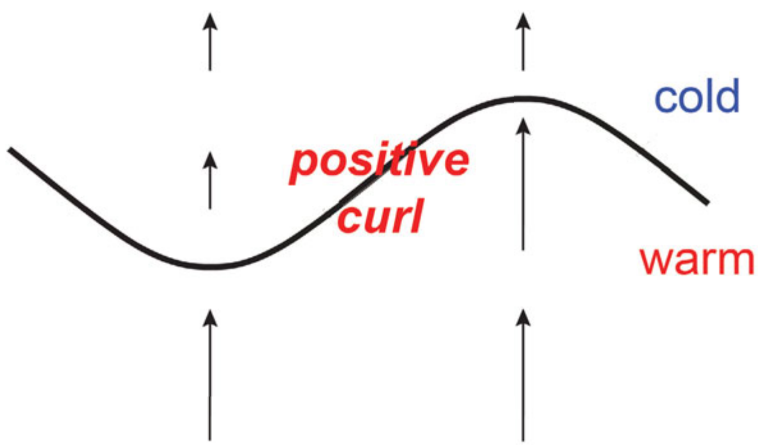
Note: The coupling in all of these studies except Seo et al. (2007) is empirical, deduced from QuikSCAT observations.

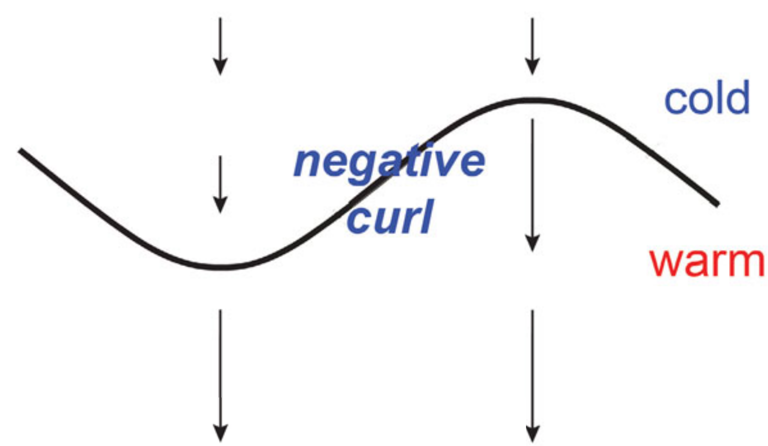
APRIL 2007 JOURNAL OF PHYSICAL OCEANOGRAPHY VOLUME 37

Effect of Sea Surface Temperature–Wind Stress Coupling on Baroclinic Instability in the Ocean

MICHAEL A. SPALL

Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts





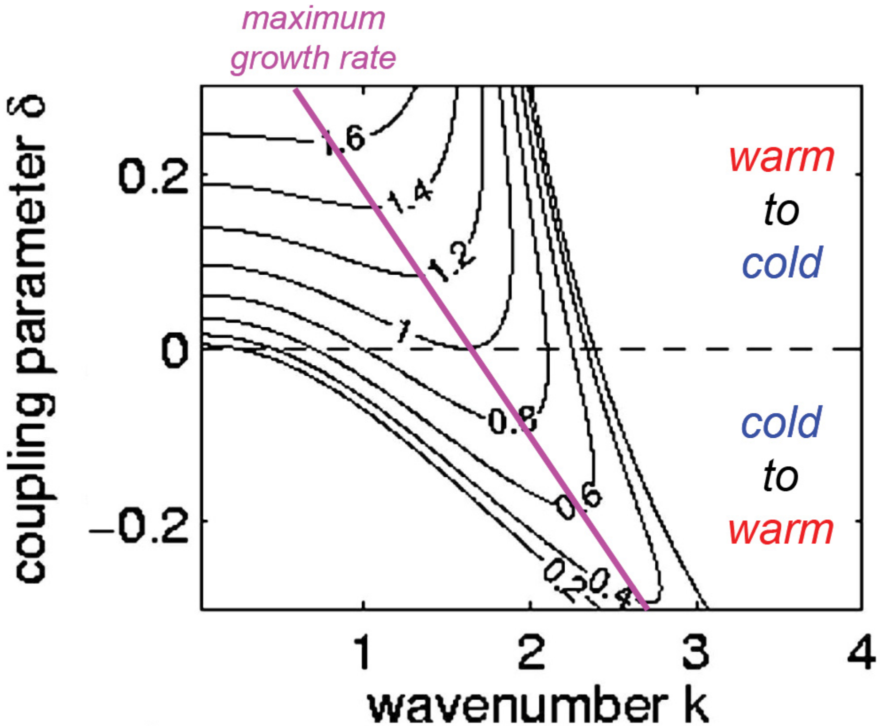
SST-induced positive wind stress curl generates upwelling and **cyclonic vorticity** that pushes the wave crest poleward and the trough equatorward

=> positive feedback that enhances the growth rate of an instability

SST-induced negative wind stress curl generates downwelling and **anticyclonic vorticity** that pushes the wave crest equatorward and the trough poleward

=> negative feedback that reduces the growth rate of an instability

Normalized Growth Rate



$$\delta = \gamma N^2/\alpha g f U$$

$\gamma =$ wind stress curl coupling coefficient

$$\rho = \rho_0 - \alpha T$$

FIG. 2. Theoretical growth rate from (13), normalized by the maximum growth rate for the uncoupled Eady problem, as a function of wavenumber k and coupling parameter δ.

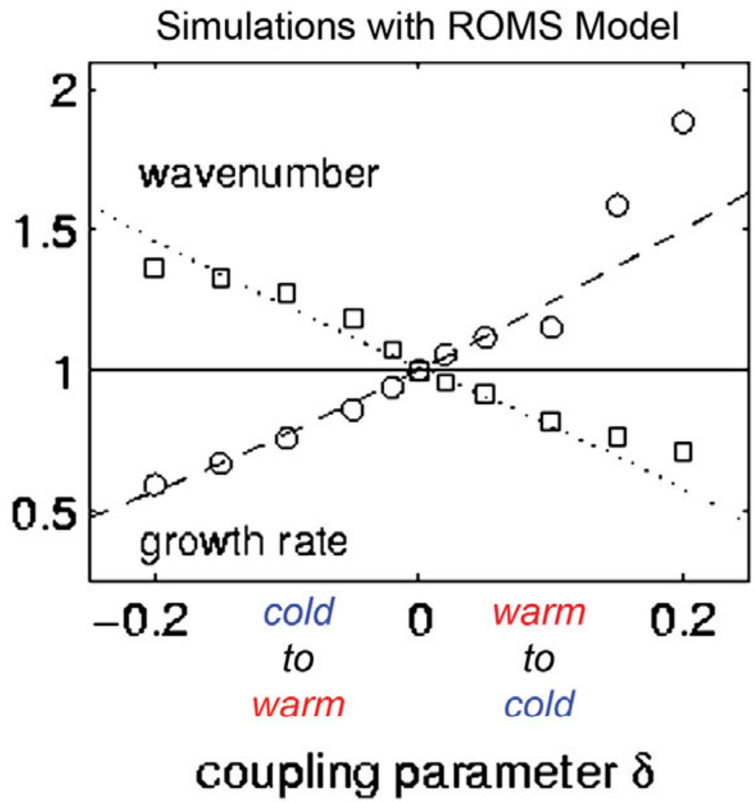


FIG. 3. Growth rate (circles) and wavenumber (squares) of growing wave from the numerical model as a function of the coupling parameter δ. Predictions from the linear theory are given by the dashed and dotted lines. All quantities are normalized by their value for the uncoupled Eady problem.

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

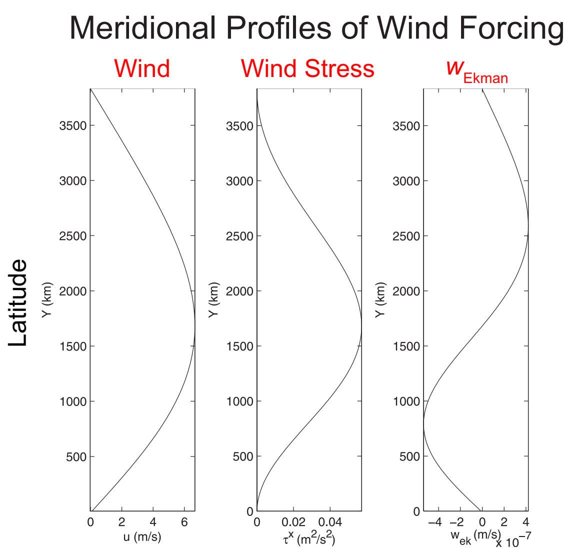
ANDREW MCC. HOGG
Australian National University, Canberra, Australian Capital Territory, Australia

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



Empirical SST-induced changes in the wind stress:

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

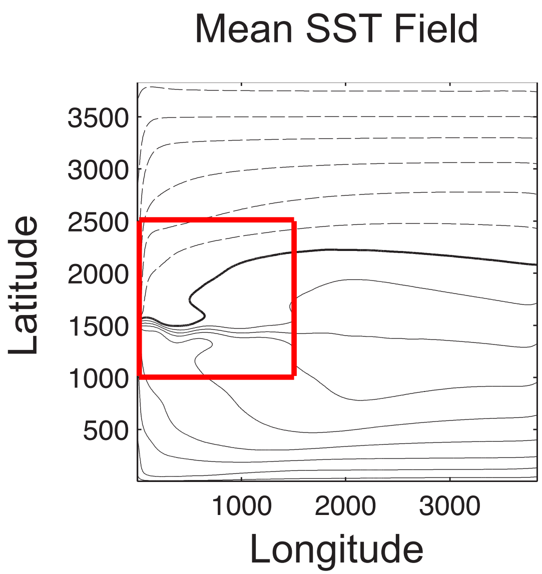
coupling coefficient chosen to match coupling deduced from QuikSCAT observations

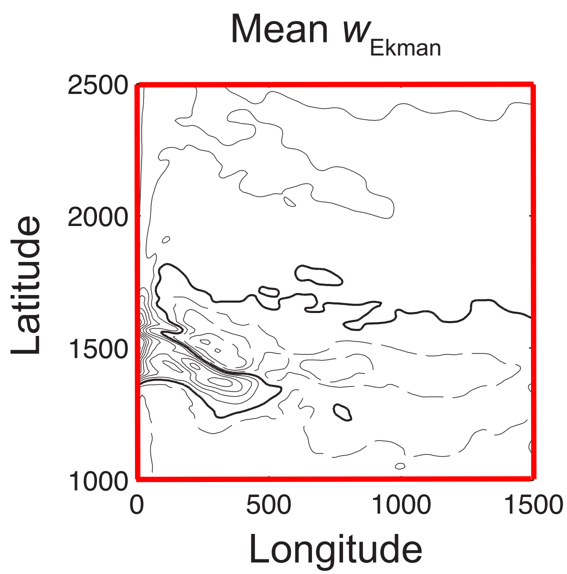
$$\Delta T = {}^oT_m - {}^aT_m$$

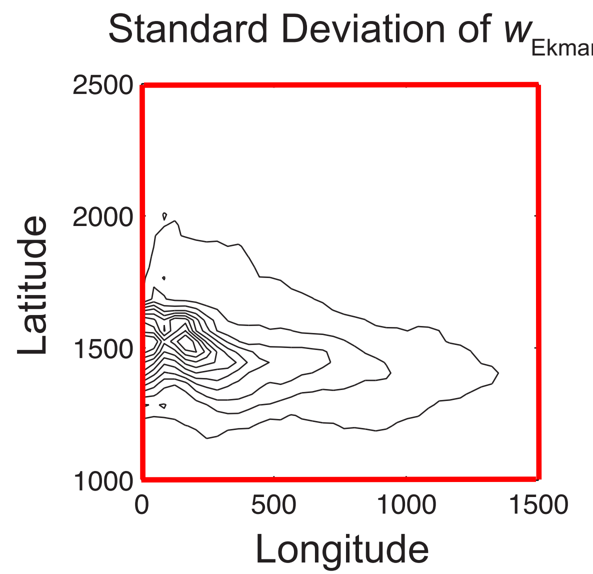
Ekman-pumping velocity:

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

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

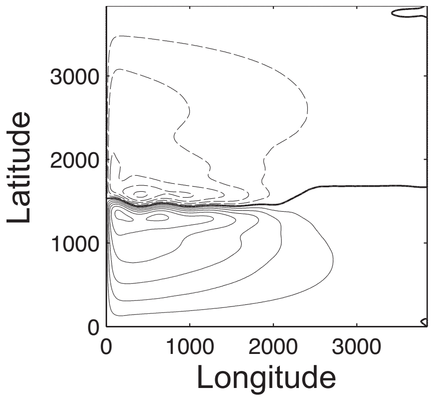




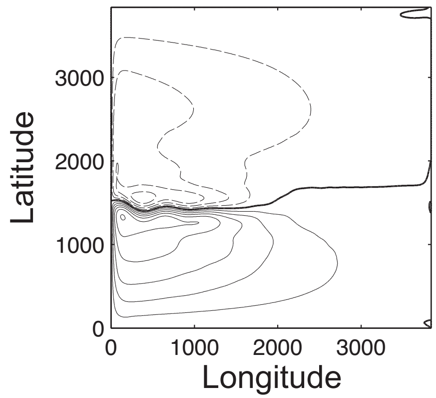


Sensitivity of Upper-Layer Streamfunction to the Coupling Coefficient, α

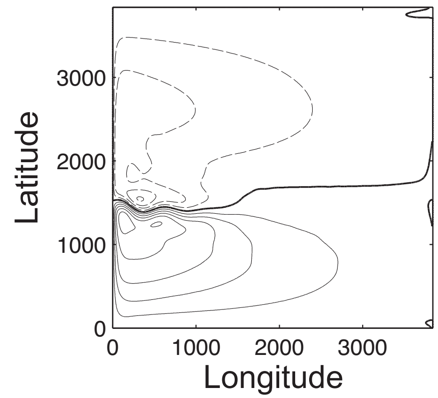
$\alpha = 0$



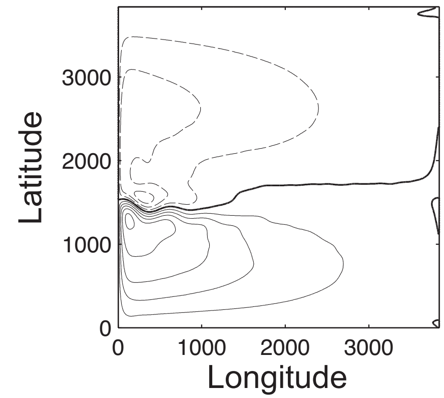
$\alpha = 0.05$



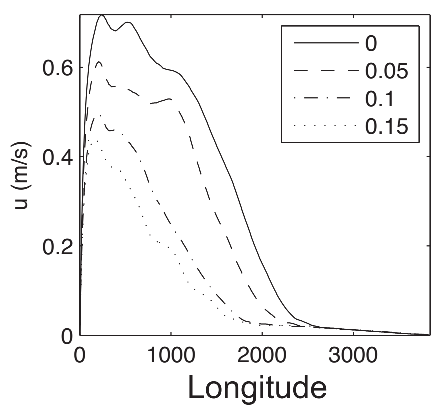
$\alpha = 0.10$



$\alpha = 0.15$



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



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

- *Small-scale forcing along mid-latitude jets is critically important.*
- *The midlatitude jet is destabilized by SST-induced small-scale forcing near the point where the jet separates from the western boundary.*
- *This reduces the eastward transport of the jet, thus decreasing the strength of the gyre circulation by 30-40%.*
- *The mechanism appears to differ from that proposed by Spall (2007). Hogg et al. (2009) propose that the destabilization is due to SST-induced Ekman pumping shifting the jet to the south.*
- *Overall conclusion: The feedback effects of this 2-way ocean-atmosphere coupling can produce large-scale effects on the ocean circulation.*

IN PRESS, 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

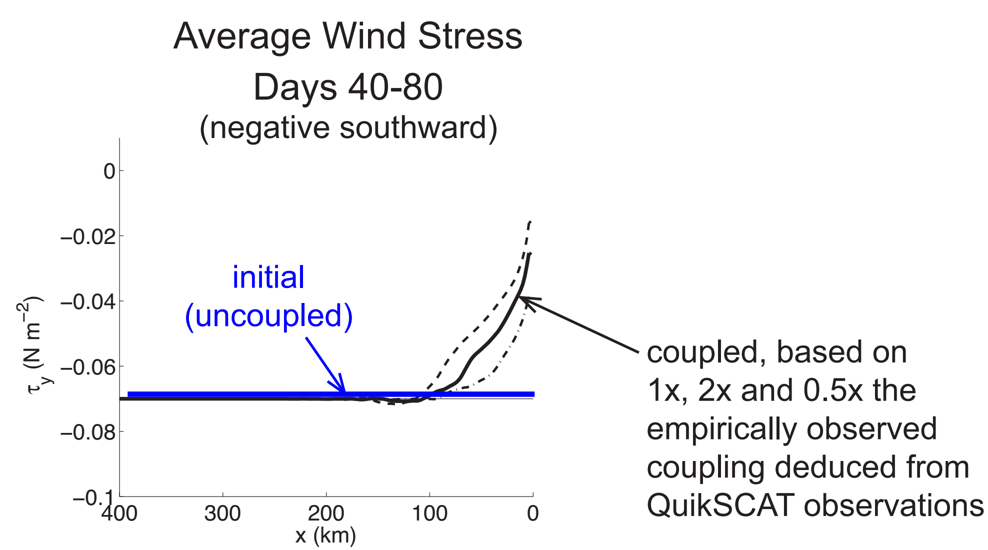
Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, California

DUDLEY B. CHELTON

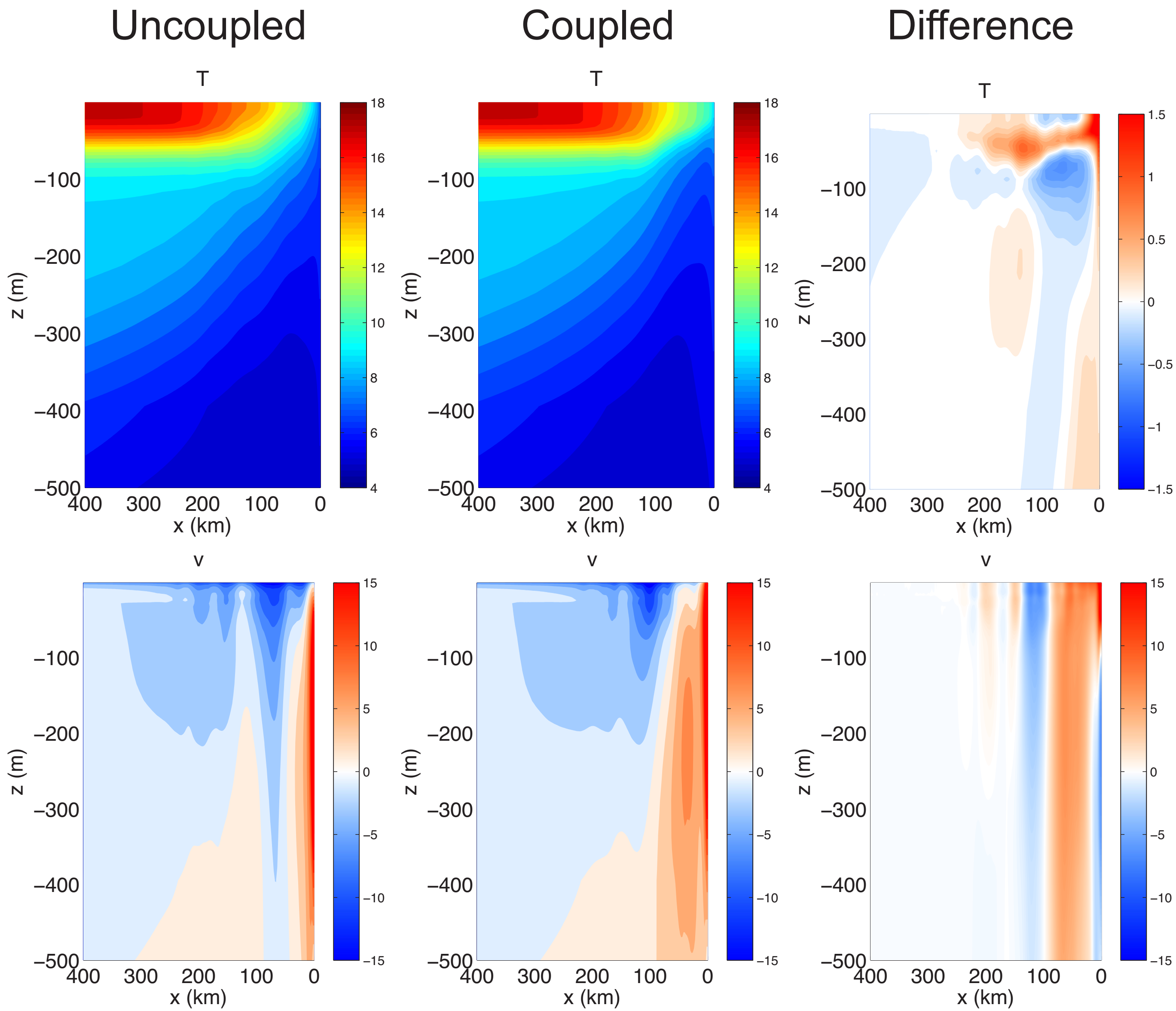
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon

ZHIJIN LI

NASA Jet Propulsion Laboratory, Pasadena, California

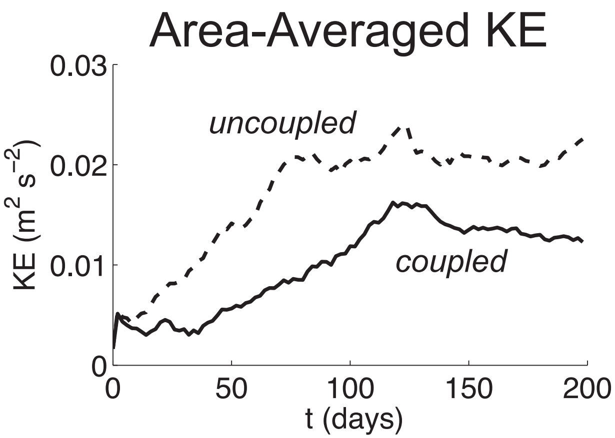


Temperature and Alongshore Velocity

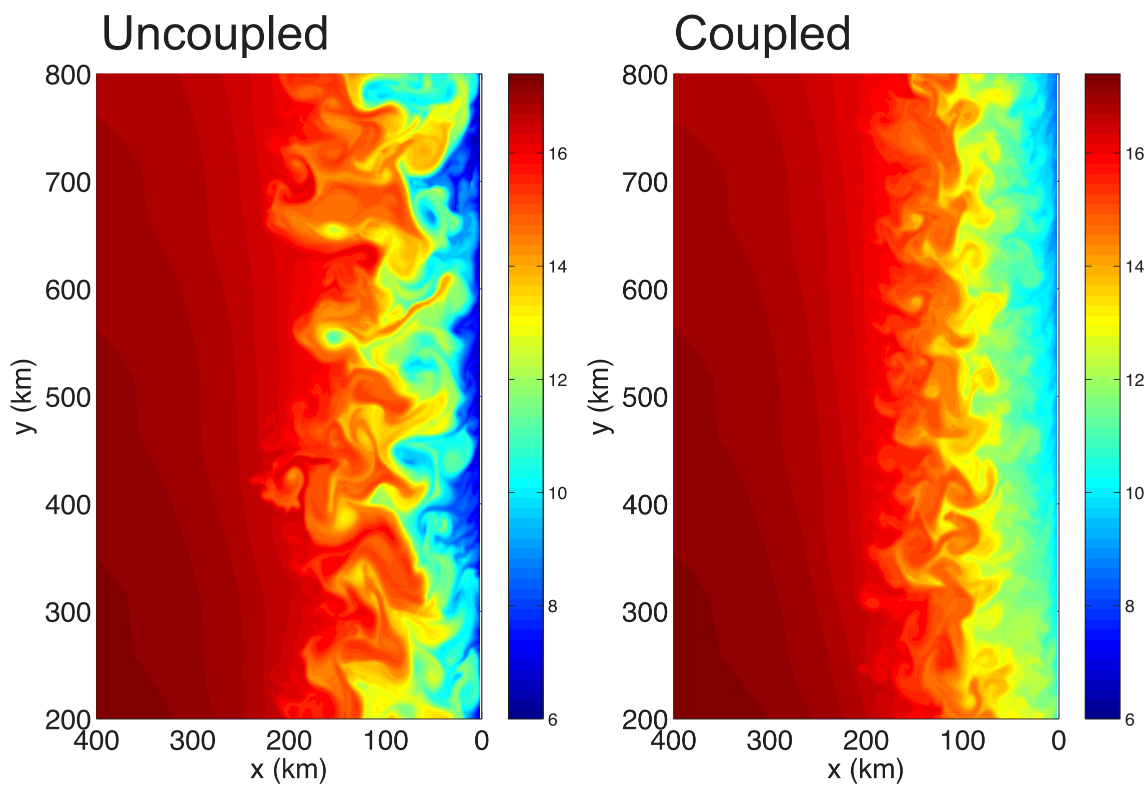


Jin et al. (2009, J. Phys. Oc., in press)

Temporal Evolution of the Eddy Field



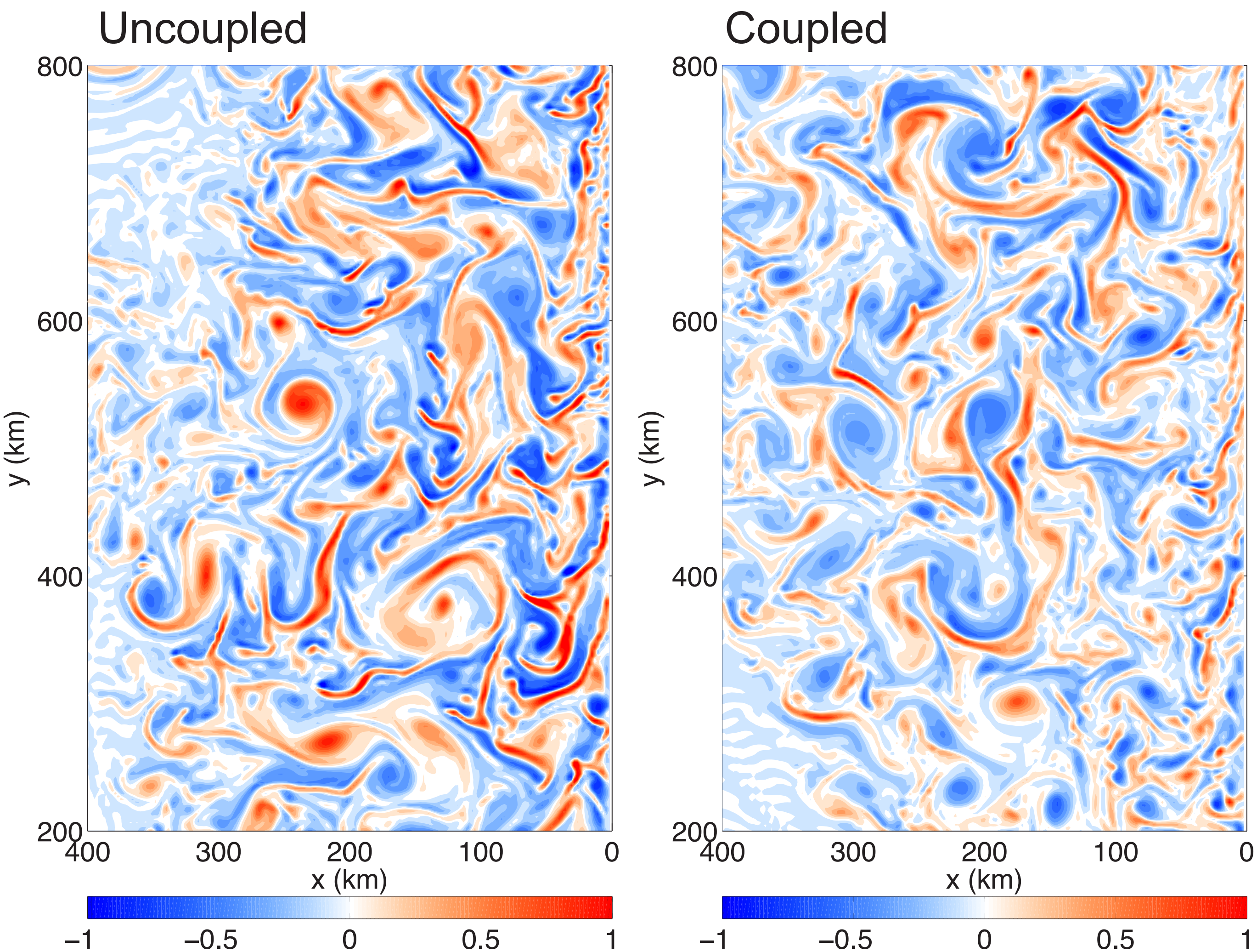
Sea-Surface Temperature, Day 60



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. Oc., in press)

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. Oc., in press)

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.*
- *The coupling over oceanic eddies preferentially weakens cyclonic eddies, thus increasing the abundance of anticyclonic eddies.*
- *Overall conclusion: All of the salient features of eastern boundary current systems are altered by this 2-way ocean-atmosphere coupling.*

GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L16306, doi:10.1029/2004GL019995, 2004

Influence of ocean-atmosphere coupling on the properties of tropical instability waves

Luciano P. Pezzi
Centro de Previsão de Tempo e Estudios Climaticos (INPE), Cachoeira Paulista, Brazil

Jérôme Vialard
Laboratoire d'Océanographie Dynamique et de Climatologie, Institut de Recherche Pour le Développement, Paris, France

Kelvin J. Richards
International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii, USA

Christophe Menkes
Laboratoire d'Océanographie Dynamique et de Climatologie, Institut de Recherche Pour le Développement, Paris, France

David Anderson
European Centre for Medium-Range Weather Forecasts, Reading, UK

Empirical SST-induced changes in the wind stress based on QuikSCAT observations:

$$\vec{\tau} = \vec{\tau_0} + \begin{pmatrix} \alpha\left(SST - \overline{SST}\right) \\ \beta\left(SST - \overline{SST}\right) \end{pmatrix}$$

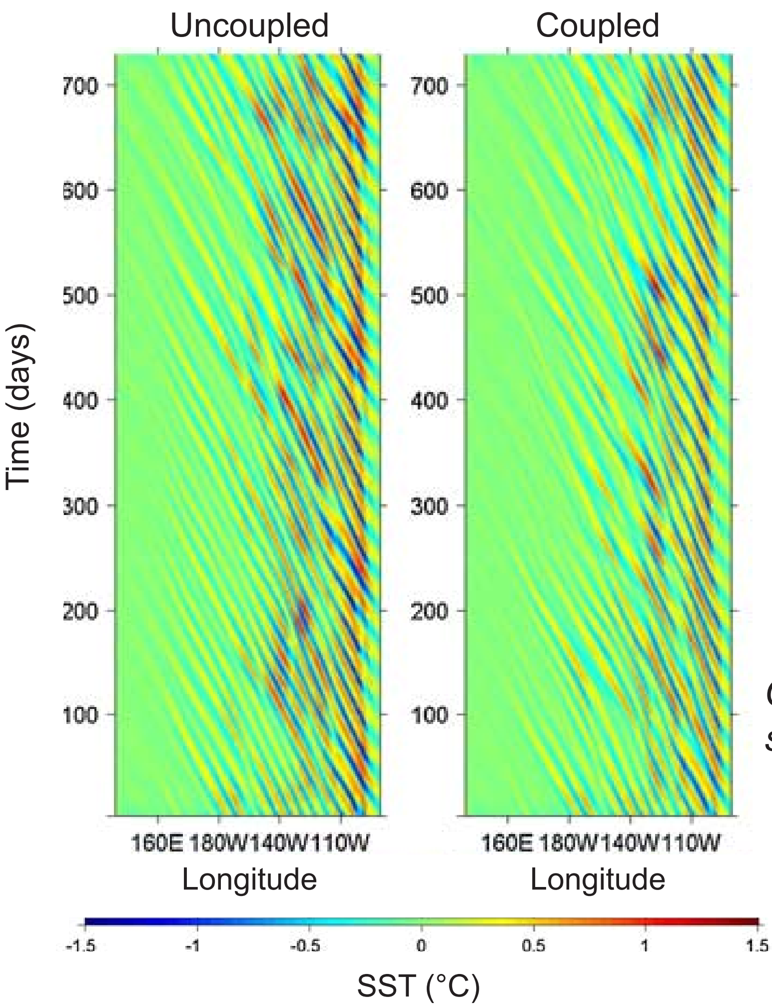
SST = model instantaneous SST

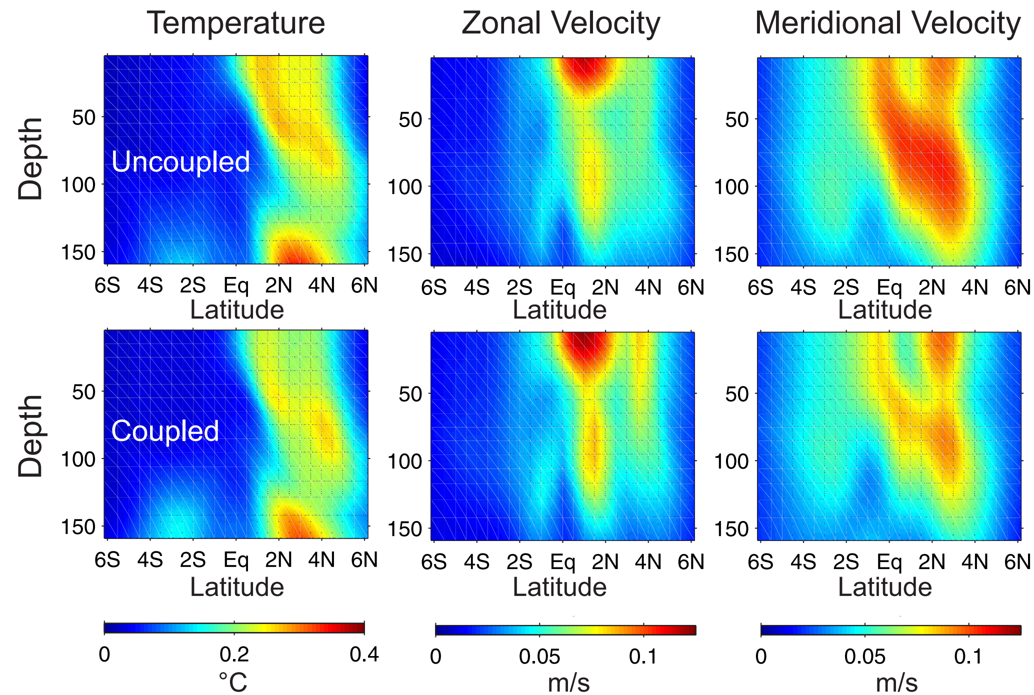
$\overline{SST}$ = model time-averaged SST

α = - 0.02 = coupling coefficient for τ_x

β = - 0.008 = coupling coefficient for τ_y

Feedback Effects of TIW SST-Induced Perturbations of Surface Wind Stress on SST and Upper-Ocean Temperature and Velocity





Conclusions of the Pezzi et al. (2004) and Seo et al. (2007) studies:

- *The 2-way coupling results in a negative feedback on TIWs that:*
  - *reduces the temperature and meridional variability associated with TIWs.*
  - *increases the zonal velocity variability associated with TIWs.*
  - *damps the growth rate of TIWs.*
  - *decreases the meridional fluxes of heat and momentum, thereby altering the mean state in a manner that decreases SST in the equatorial cold tongue and strengthens the Equatorial Undercurrent.*
- *Overall conclusion: The feedback effects of this 2-way ocean-atmosphere coupling are modest (about 10%), but significant.*

Conclusions

- The ocean and atmosphere are a 2-way coupled system on scales of ~100-1000 km.
- The SST influence on surface winds is only marginally present in the wind fields generally used to force global ocean models (e.g., the operational ECMWF and NCEP winds, or worse yet, and more commonly, their reanalysis counterparts).
- The importance of this ocean influence on the atmosphere, and its feedback effects on the ocean, are only beginning to be investigated from the "short" 10-year QuikSCAT dataset.
- The studies that have been conducted to date show that the feedback effects from the O(1) perturbations of the wind stress curl field significantly alter the mesoscale and large-scale ocean circulation.
- Recent studies have shown that this coupling between SST and surface winds also extends deep into the troposphere (not shown here).
- *What are the climate impacts?*
  Sustained scatterometer and microwave SST observations with resolution and accuracy at last as good as QuikSCAT and AMSR are required to understand the implications for short-term and longer-term climate variability.