The Influence of Oceanic Mesoscale Eddies on Surface Stress

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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
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 **positively** 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)

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)

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

\[ \nabla \times \mathbf{u}, \nabla \times \tau > 0 \quad \text{COOL} \]

\[ \nabla \cdot \mathbf{u}, \nabla \cdot \tau > 0 \quad \text{WARM} \]

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

Note that divergence response is consistently stronger than curl response.
A regional example: The California Current System

September 2004

\( \tau \) and SST

\[ 0.2 \text{ N m}^{-2} \]

C.I.=0.03 N m\(^2\), Heavy contour = 0.12 N m\(^2\)

\( \nabla \times \tau \)

5 N m\(^{-2}\) per 10\(^4\) km

= 45 cm d\(^{-1}\) upwelling at 40\(^\circ\)N

\( \nabla \cdot \tau \)

\( ^\circ \text{C/100 km} \)
A regional example: The California Current System

September 2004

C.I.=0.03 N m$^{-2}$, Heavy contour = 0.12 N m$^{-2}$

C.I.=0.5$^\circ$ C/100 km

5 N m$^{-2}$ per 10$^4$ km = 45 cm d$^{-1}$ upwelling at 40$^\circ$N
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

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Meridional Profiles of Wind Forcing

Empirical SST-induced changes in the atmospheric wind stress:

\[
\left( a\tau^x, a\tau^y \right) = C_D \left( 1 + \alpha \Delta T \right) |a u_m| \left( a u_m, a v_m \right),
\]

\[
\Delta T = o T_m - a T_m
\]

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 \( o \tau = (o \rho / a \rho) a \tau \) is

\[
W_{Ek} = \frac{1}{f} \int_0^\infty \left( o \tau^y - o \tau^x \right),
\]
Small-Scale, SST-Induced Perturbations of Ekman-Pumping Velocity, $w_{\text{Ekman}}$

Mean SST Field

Mean $w_{\text{Ekman}}$

Standard Deviation of $w_{\text{Ekman}}$

Hogg et al. (2009, J. Phys. Oceanogr.)
Sensitivity of Upper-Layer Streamfunction to the Coupling Coefficient, $\alpha$

$\alpha = 0$

$\alpha = 0.05$

$\alpha = 0.10$

$\alpha = 0.15$

Maximum Zonal Velocity of Jet for $\alpha = 0, 0.05, 0.10$ and $0.15$

Hogg et al. (2009, J. Phys. Oceanogr.)
SST–Wind Interaction in Coastal Upwelling: Oceanic Simulation with Empirical Coupling

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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.
Figure 5: Cross-shore sections of $T$ and $v$ [cm s$^{-1}$], averaged alongshore and between days 40-80: (left) uncoupled, (middle) coupled, and (right) their difference.

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

28 Aug 1996

There are 2495 eddies in this map (http://cioss.coas.oregonstate.edu/eddies/)
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 \((\Delta x, \Delta y)\) 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 Lifetimes ≥16 Weeks During the 7.5 Years of Overlap of the Four Satellite Datasets

1 June 2002 - 30 November 2009

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Mesoscale eddy influence on SST and wind speed
Global Composite Averages of SST in Eddy-Centric Coordinates

Regions of Southward $\nabla T$

Clockwise Rotating

Counterclockwise Rotating

Normalized Distance from Eddy Centroid
Global Composite Averages of SST in Eddy-Centric Coordinates

Schematic of Horizontal Advection

Regions of Southward ∇T

Clockwise Rotating

Counterclockwise Rotating

Normalized Distance from Eddy Centroid
Global Composite Averages of SST in Eddy-Centric Coordinates

Regions of Northward VT

Clockwise Rotating

Counterclockwise Rotating

Regions of Southward VT

Clockwise Rotating

Counterclockwise Rotating

Normalized Distance from Eddy Centroid

Normalized Distance from Eddy Centroid

Contour Interval is 0.05°C
Global Composite Averages of Wind Speed in Eddy-Centric Coordinates

Regions of Northward VT

Clockwise Rotating

Counterclockwise Rotating

Regions of Southward VT

Clockwise Rotating

Counterclockwise Rotating

Normalized Distance from Eddy Centroid

Contour Interval is 0.025 ms\(^{-1}\)
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

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- 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.
Figure 5: Cross-shore sections of $T$ and $v$ [cm s$^{-1}$], averaged alongshore and between days 40-80: (left) uncoupled, (middle) coupled, and (right) their difference.

Temporal Evolution of the Eddy Field

Sea-Surface Temperature, Day 60

Area-Averaged KE

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

Figure 9: Surface vorticity $\zeta(x, y)$ (normalized by $f$) on day 160: (a) uncoupled and (b) coupled simulations.

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

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 mesoscale 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 anticyclone with 10 cm amplitude and 90 km radius in 7 ms\(^{-1}\) westerly winds at 30°N

The surface stress is determined from the relative wind:

\[ \vec{u}_{rel} = \vec{u}_a - \vec{u}_o \]

\[ \nabla \times \vec{u}_{rel} \approx -\nabla \times \vec{u}_o \]

\[ \vec{\tau} = \rho_a C_D |\vec{u}_{rel}| \vec{u}_{rel} \]

\[ W_E = \frac{1}{\rho_o f} \nabla \times \vec{\tau} \]
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

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

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


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....)*