Dynamics and impacts of

Eddy-driven air-sea interaction
in the California Current System

Hyodae Seo (WHOI)
Art Miller, Joel Norris (SIO)

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http://earthobservatory.nasa.gov
O-A interaction on coastal upwelling
Broad-scale vs eddy-scale
SST vs surface current

SeaWiFS surface chlorophyll concentration
http://earthobservatory.nasa.gov
Eddy-driven air-sea interaction: wind and wind stress

$$\tau = \rho_a C_D (W - U) |W - U|$$

10m wind

$$W = W_b + W_{SST}$$

Eddy composites in the Southern Oceans

SST

Wind speed

Correlation bet’n highpass filtered SST & W

Frenger et al. 2013
Eddy-driven air-sea interactions: Ekman pumping velocity

$$\tau = \rho_a C_D (W - U) \lvert W - U \rvert$$

Consider an idealized anticyclonic warm-core eddy in the Southern Ocean (Chelton 2013)

SST and SSH

Dipole Ekman pumping

Ekman pumping anomaly in quadrature with SSH → northward propagation of a warm-core anticyclonic eddy
Eddy-driven air-sea interactions: under-stress

$$\tau = \rho_a C_D (W - U) |W - U|$$

surface current

$$U = U_b + U_e$$

Wb

WSS

\( W = W_b + W_{SST} \)

10m wind

T\( e - \tau \)

Downwelling

Upwelling

U\( e - \tau \)

Affect the propagation

Reduce the eddy-amplitude
Previous studies: Jin et al. (2009)

**SST-wind coupling effect in an idealized ocean model**

- SST-wind coupling weakens the alongshore wind stress, *baroclinic instability* and EKE.
- No distinction between the effects of background-scale and eddy-scale SSTs
U-τ coupling effect also damps the EKE in an OGCM

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

Previous studies: Eden and Dietze (2009)

- Again, no separation between background and small-scale currents.
Goal

Examine effect of *eddy-driven* air-sea interaction through SST and surface current on energetics of the CCS and Ekman pumping
Numerical modeling study of eddy-wind interaction:
High-res. O-A coupled model with separation of the spatial scale of O-A coupling

**Scripps Coupled Ocean Atmosphere Regional (SCOAR) Model**
*Seo et al. (2007; 2014, J. Climate); http://hseo.whoi.edu/scoar/

- Surface meteorology
  - (U10, V10, SLP, T2, Q2, Qsw, Qiw, Pr)

- Surface forcing
  - (τx, τy, Qnet, Pr, Qsw)

**Model Coupler**

- WRF or RSM
- SST & Surface current
- ROMS

- Online 2-D smoothing (3°×3° or 1.5°×1.5°)

- WRF-ROMS at 7 km resolutions represents the small-scale eddies and their interaction with the atmosphere
- Driven by NCEP-FNL and SODA
- A 2D online smoothing to suppress the small-scale coupling; the large-scale coupling is preserved
- Features up to 300 or 150km are considered small-scale (eddy or meso-scale)
Experiments

\[ \tau = \rho_a C_D (W-U)|W-U| \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \tau ) formulation includes</th>
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<tbody>
<tr>
<td><strong>CTL</strong></td>
<td>( T_b ) ( T_e ) ( U_b ) ( U_e )</td>
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<tr>
<td><strong>noT_e</strong></td>
<td>( T_b ) ( U_b ) ( U_e )</td>
</tr>
<tr>
<td><strong>noU_e</strong></td>
<td>( T_b ) ( T_e ) ( U_b )</td>
</tr>
<tr>
<td><strong>noT_eU_e</strong></td>
<td>( T_b ) ( U_b )</td>
</tr>
<tr>
<td><strong>noU_{tot}</strong></td>
<td>( T_b ) ( T_e )</td>
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</table>

6-yr simulations: 2005-2010

**CTL-noT_e**: effect of \( T_e \)
**CTL-noU_e**: effect of \( U_e \)
Simulated summertime climatology:
SST, wind stress, and latent heat flux

2005-2010 JJAS
SODA SST, QuikSCAT wind stress and OAFLUX LH
Summertime eddy kinetic energy

- $T_e - \tau$ has no impact on EKE
- $U_e - \tau$ reduces the EKE substantially
- $U_{tot} - \tau$ reduces the EKE only slightly more (additional 10%)

- The EKE reduction by under-stress occur largely on eddy-scales

$T_e - \tau$ coupling

- Affect the propagation

$U_e - \tau$ coupling

- Affect the magnitude

$\tau$ refers to the wind stress curl associated with eddy-related processes.

Changes in wind speed and cloud fraction alter solar radiation, surface temperature, and turbulent mixing of the marine atmospheric boundary layer.

The eddy kinetic energy (EKE) decreases by about 25% in the kinetic energy of sea surface currents (Fig. 1).

The eddy's temperature patterns alter surface winds, while its eddy kinetic energy modifies the curl of the wind stress.

The signs of the wind-stress curl are pronounced in the eddy interior and along the boundary layer, where eddies are typically observed.

The eddy's surface temperature and height anomalies are collocated, as is its eddy kinetic energy.

The mesoscale eddies are influenced by their immediate surroundings; the eddies are an aggregation of mesoscale structures.

The eddies affect the propagation of their immediate surroundings; the eddies influence the surface winds.

The eddies are an aggregation of mesoscale structures, influencing the surface winds.

AVISO

no$T_e$

no$U_e$

no$T_e U_e$

no$U_{tot}$

117 cm$^2$/s$^2$ (-1%)

166 cm$^2$/s$^2$ (+42%)

161 cm$^2$/s$^2$ (+38%)

179 cm$^2$/s$^2$ (+53%)

CTL: $T_e$ & $U_e$

$U_{tot}$

$116$ cm$^2$/s$^2$

$161$ cm$^2$/s$^2$

$179$ cm$^2$/s$^2$
Weakened EKE with $U_e - \tau$:
EKE budget and Ekman pumping
Eddy energetics

\[ \text{BT} = -\left( u'u'U_x + u'v'U_y + u'w'U_z + \overline{v'u'V_x} + \overline{v'v'V_y} + \overline{v'w'V_z} \right), \] 

\[ \text{BC} = -\frac{g}{\rho_0} \overline{\rho'w'}, \] 

\[ P = \frac{1}{\rho_0} \left( u'\tau'_x + v'\tau'_y \right). \]

Wind work if positive, eddy drag if negative
Across-shore distribution of EKE budget terms

- **Baroclinic conversion**
  - Only a small reduction in noUe → cannot explain the higher EKE

- **Eddy-wind interaction**
  - 24% increase in noUe → over the eddy-rich coastal zone (up to ~300 km)
  - $U_e - \tau$ reduces the wind work
Ue-τ coupling increases the eddy drag and reduces the momentum input

- In noUe, 30% weaker eddy drag
- In noUe 7-10% stronger wind work

Changes in absolute magnitude are comparable
Eddy-driven Ekman pumping velocity

\[ W_{tot} = \frac{1}{\rho_o} \nabla \times \left( \frac{\tau}{(f + \zeta)} \right) \]

\[ \approx \frac{\nabla \times \tau_{SST}}{\rho_0(f + \zeta)} - \frac{1}{\rho_0(f + \zeta)^2} \left( \tilde{\tau}_y \frac{\partial \zeta}{\partial x} - \tilde{\tau}_x \frac{\partial \zeta}{\partial y} \right) + \frac{\nabla \times \tilde{\tau}}{\rho_0(f + \zeta)} + \frac{\beta \tau^x}{\rho_0(f + \zeta)^2} \]

\( W_{SST} \)
SST induced Ekman pumping
Chelton et al. (2001)

\( W_\zeta \)
Surface vorticity gradient-induced nonlinear Ekman pumping

\( W_{LIN} \)
Curl-induced linear Ekman pumping

\( W_\beta \)
\( \beta \) Ekman pumping (negligible)
Estimating eddy SST-driven Ekman pumping velocity

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

OBS based on QuikSCAT wind stress and TRMM SST

\[
\omega = \nabla \times \nabla \times \tau - \frac{\rho_o}{\rho} f \frac{\partial \psi}{\partial x} + \nabla \frac{\partial \zeta}{\partial t} \approx \alpha_c \nabla \frac{\partial \psi}{\partial x} + \nabla \frac{\partial \zeta}{\partial t}
\]

JAS 2005-2009
Estimated Ekman pumping velocities

Based on AVISO SSH & QuikSCAT wind stress

JAS 2005-2009

m/day
Estimated Ekman pumping velocities

**W**<sub>SST</sub>  **W**<sub>ζ</sub>  **W**<sub>LIN</sub>  **W**<sub>tot</sub>

**noT<sub>e</sub>**

**noU<sub>e**

m/day

JAS 2005-2009
Inferred feedback to eddy activity through $W_\zeta$

Total Ekman pumping velocity difference

**Figure 1**

<table>
<thead>
<tr>
<th>CTL-noU_e $W_{TOT}$ &amp; $\zeta$</th>
<th>CTL-noU_e $W_{TOT}$ vs $\zeta$</th>
<th>Downwelling over cyclonic vorticity anomaly</th>
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<td>$\downarrow$ U_e-τ weakens the amplitude of the eddies</td>
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**JAS 2005-2010**
Inferred Feedback to eddy activities through $W_{\text{SST}}$
Total Ekman pumping velocity difference

Ekman pumping acting on the maximum SST gradients → If anything, it influences the geostrophic current in which eddies are embedded
Summary and Discussion

A significant role of eddy-driven air-sea interaction through surface current in the energetics of the CCS and the Ekman pumping velocity

- The weakened EKE due to reduced wind momentum input and enhanced eddy drag (nearly of equal importance).

- Eddies modify Ekman vertical velocities
  - $W_\zeta$ suppresses the eddy activity
  - $W_{SST}$ may influences the eddy propagation
    - Eddy-centric analysis to examine the changes in propagation characteristics of the eddies (e.g., Gaube et al. 2015; Renault et al. 2016)

- Would the eddy-wind interactions affect the atmosphere beyond the boundary layer?
Rectified changes in SST and rainfall

- SST anomalies are driven by the changes in offshore temperature advection in the mixed layer.

- Small (3-7%) change in rainfall, but it does reflect the local SST anomaly.
Ongoing work: Arabian Sea circulation system and the Findlater Jet

- EKE (Somali Current)
- $\zeta/f$
- total Ekman pumping
- Moisture transport by the Findlater Jet

**OBS vs. CTL vs. noUtot**

- 47% weaker flow fields
- Weaker Great Whirl anticyclone
- Stronger cyclonic forcing over the GW
- Some intensification and shift in the FJ moisture transport
Planned work: WBCs and the midlatitude storm track

WBC downstream influence on the weather system development
Thanks!
hseo@whoi.edu