Air-Sea interaction over ocean fronts and eddies

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Updated with new studies from 2008-present
A motivation: Strong wind frequency
Sampe and Xie, 2007. Mapping high sea winds from space’, BAMS.
Liu, Tang and Xie 2008. Wind power distribution over the ocean. GRL.

QuikSCAT scatterometer data
Overview

• Early work, proposed mechanisms
• Case studies:
  – 1. Equatorial Front
  – 2. Gulf Stream
  – Satellite data, Field experiments and modelling
• Broader Impacts:
  – Feedback on ocean
  – Storm Track response
  – Climate response
  – Modelling issues
(1) Role of pressure gradients

- Lindzen and Nigam (1987) noted that air temperature anomalies were proportional to SST anomalies throughout the boundary layer in the tropics.
- Ideal gas law and hydrostatic balance then implies that pressure gradients are negatively correlated with SST gradients.
- Winds driven by pressure gradients lead to surface convergence and convection.

\[
\frac{\partial p}{\partial z} = -\rho g
\]

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<thead>
<tr>
<th>Warm Air</th>
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<td>High pressure</td>
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<td>Warm SST</td>
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<th>Cold Air</th>
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<td>Low pressure</td>
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<td>Cold SST</td>
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Near equator – Coriolis term dropped

Lindzen-Nigam schematic

Warm SST

Max $\nabla\text{SST} \nabla P$

Front

Cold SST

$Lindzen$ and $Nigam$ boundary layer model

$V$ momentum balance: Integrate over boundary layer

balance between Coriolis, pressure, drag:

$f\rho U = -\frac{1}{h} \int \frac{\partial p}{\partial y} dz - \frac{1}{h} \rho Cd.vV$: near equator $0 \sim -\int \frac{\partial p}{\partial y} dz - \rho Cd.vV$

Linearise $\Rightarrow 0 = -\int \frac{\partial p}{\partial y} dz - \delta v$ so $v = -\frac{1}{\varepsilon} \int \frac{\partial p}{\partial y} dz$

Assume $\nabla p' \propto -\nabla\text{SST}'$ \ thus $v \propto \frac{1}{\varepsilon} \frac{\partial\text{SST}}{\partial y}$
However...

- Wallace et al (JCLI, 1989) noted that strongest meridional winds are NOT observed at the SST front: instead there is wind divergence at the front.
- Confirmed by Chelton et al JCLI, 2001 using satellite scatterometer data.
(2) Role of vertical mixing

- Wallace et al, Hayes et al (JCLI, 1989) proposed that changes of near-surface stability across an SST front modify the wind profile.

- Air flowing from cold to warm water

- [Diagram showing wind or $\theta$ over warm SST and wind or $\theta$ over cold water]

\[ \frac{\partial U}{\partial t} = -\frac{1}{\rho_0} \frac{\partial}{\partial z} u'w' \]
Case 1. Equatorial Pacific

• Cold tongue/warm pool complex, ITCZ, cross-equatorial winds

• Data from Eastern Pacific Investigation of Climate Processes (EPIC)
Model vs Eastern Pacific Investigation of Climate Processes (EPIC) data

Potential Temperature Profiles
Mean of 8 days on which EPIC NCAR C130 flights were run along 95W.
Model vs Eastern Pacific Investigation of Climate Processes (EPIC) data

Meridional Wind profiles

Dashed: cold tongue
Dots: north of front

Mean of 8 days on which EPIC NCAR C130 flights were run along 95W.
So far all agrees with momentum mixing hypothesis.

• However...
95° W: relationship of SST gradients to pressure gradients

Because of thermal advection, air temperature gradient is broader and more downstream than SST gradient...consequently pressure gradient is located downstream, at around 3-4 N.

A simple thermal advection/surface heating balance model confirmed this mechanism (Small et al 2005).
Meridional velocity also peaks at this latitude suggesting that here

\[ v \approx -\frac{1}{\varepsilon} \int \frac{\partial p}{\partial y} dz \]
Wind response to Equatorial Front (2)

What is the atmospheric response to transients (ocean mesoscale eddies)?

Tropical Instability Waves:
• Affect clouds (Deser et al 1993)
• Affect heat budget of cold tongue through horizontal advection and vertical mixing - Jochum and Murtugudde 2006, Menkes, Vialard et al 2006, Moum et al. 2009)
• Affect biology (Yoder et al)
• Coupled processes and feedbacks on ocean(Seo et al 2007, Small et al 2009)
• Affect mean climate (Jochum et al 2005, Seo et al 2006) ...and climate variability (Jochum, Deser and Philips 2007)

Tropical Instability Waves

OBSERVATIONS.

2 month record of SST, neutral 10 m winds, from TMI and QuiKSCAT, filtered and regressed onto SST.

Hashizume et al 2001, JGR

MODEL.

Regional atmospheric model simulation.

Response to daily evolving, realistic SST.

Small et al 2003, JCL.
Surface winds are driven by the pressure

Small et al 2003, JCLI.

Observations from TAO moorings (Cronin et al 2003, JCLI) confirmed the downstream pressure response.
An analysis of wind response to SST in oceanic eddies: 40°S to 40°N

Cross-spectral analysis reveals a consistent relationship between SST and wind speed in the Atlantic, Pacific and Indian Oceans.

Based on an analysis of QuikSCAT neutral 10 m winds and TRMM TMI SST.

Small et al 2005b (JGRO)

See also Chelton et al 2001 JCLI, 2004 Sci..

Xie 2004 BAMS

Wind speed response in m/s/K

Phase difference between wind speed and SST
Positive correlation between SST and wind speed on ocean mesoscales

Small et al 2008: “A review of air-sea interaction over ocean fronts and eddies.” Dynamics of Atmospheres and Oceans. Contains descriptions of all proposed mechanism of atmospheric response, and coupled effects. These processes are now seen in coupled models e.g. Bryan et al., CCSM, thus confirming observations...
Case 2. Gulf Stream

• Important supplier of heat to atmosphere – Trenberth and Caron 2001, Wunsch 2005

• Helps warm Europe and downstream regions? (but see Seagur et al 2002, and Rhines and Hakkinen 2008)

• Part of Meridional Overturning Circulation – may reduce in future climate change (e.g. Dai et al 2005, Hurrell et al. 2006)?

• Important to storm tracks -diabatic heating at ocean fronts help maintain atmospheric storm tracks (Hoskins and Valdes 1990, Nakamura et al 2008) and annular modes (Nakamura et al 2008).
  • A number of numerical modeling studies suggest that smoothing out the SST gradients in western boundary currents leads to much reduced storm track activity (Minobe et al 2008, Taguchi et al 2009)

• Effect on individual storms, bombs (Sanders 1986) —e.g. Cione et al 1993, Jacobs et al 2005 relate storm growth to temperature contrast from coast to Gulf Stream north wall (surface Baroclinicity).
Annual mean Mean heat fluxes

From Yu and Weller 2007 – WHOI analysed flux datasets.
Roughness changes across Gulf Stream

Deep motion over Gulf Stream

From Minobe et al., 2008. Relationship of surface wind convergence, surface pressure, deep vertical motion and the Gulf Stream front. Ascent linked to Laplacian of sea level pressure (Lindzen-Nigam type model).
Areas of Deep convection in mid-latitudes

Accordingly, we classify a grid point on a given daily map as potentially unstable to deep (surface to tropopause) moist convection if, at that grid point

\[ S_{tp} - s_0 < 0 \]

where specific entropy of moist air \( s \)

- Fraction of days (in percent) for which the criterion \( s_{tp} - s_o < 0 \) is met poleward of 20° for (a) the Northern winter of 2003–2004 and (b) the Southern hemisphere winter of 2004. The calculation was not carried out over continent (black) and sea-ice (fraction of days set to zero) covered grid points. This figure is available in colour online at wileyonlinelibrary.com/journal/qj
Separation of mechanisms:

- Different mechanisms at different background wind speeds (Spall et al. 2007)
- Momentum budgets (O’Neill et al., Takatama et al. 2011)
- Mean flow vs synoptic variability (Liu, Xie, pers. comm. 2012)
Boundary layer changes across ocean front

From Small et al. 2008 and based on Spall et al. 2007.
Broader Impacts

• Feedback on ocean
• Response of storm tracks
• Climate response
Feedback onto the ocean

- SST gradients lead to gradients in surface stress which impact the ocean
- Over cool upwelling regions (e.g. Cal. Curr. System) stress is reduced. This may reduce upwelling (Perlin et al., Jin et al. 2009).
- Impact of ocean surface currents on stress have bigger impact on Ekman pumping (Chelton et al.)
- Changes in wind stress curl affect local Ekman pumping (Chelton et al. 2007) and may also affect gyre circulations (Hogg et al.).
Wind stress, its divergence and curl, over Tropical Instability Waves.
From Chelton et al. 2001

A schematic representation of how varying SSTs near a strong front influence wind stress, and how these wind stress variations might generate divergences and curls. Vectors of surface wind stress are shown.
From Maloney and Chelton 2006
Ekman pumping anomalies due to action of current on surface stress

$$w_E = \frac{1}{\rho_0} \nabla x \frac{\tau}{f}$$

Let’s analyse the component of stress $\tau'$ which is due to current.

$$w_E' = \frac{1}{\rho_0} \nabla x \frac{\tau'}{f}$$

$$w_E' \approx \frac{\rho_a}{\rho_0} C_D U_{10} \frac{3 \xi}{2 f_0}$$  Dewar and Flierl 1987.

Figure 8. Ekman pumping (color, $10^{-6}$ ms$^{-1}$cm$^{-1}$) and SSHA (contours), both regressed onto SSHA at 120°W, 4.5°N.

a) using observations of sea surface height anomalies (SSHA) from altimeters and stress derived from 10 m neutral wind from QuiKSCAT.

b) Fully coupled model.

c) as b) but with estimated Ekman pumping derived from Exp. 1 vorticity (contours, $10^{-6}$ ms$^{-1}$cm$^{-1}$).

From Small et al. (2009)
Storm tracks and ocean fronts

• In midlatitudes, atmospheric synoptic eddies pass along well-defined “storm tracks”.

• Ocean fronts can induce air temperature gradients above, and stability
  – Affects the “Eady Growth rate” or baroclinicity

• Near surface, changes in stability across ocean fronts may alter structure of storm track
Surface Storm Track (Booth)

(a) The free-tropospheric storm track, defined as the standard deviation of the bandpass-filtered meridional winds at 850 hPa. Colors and contours show the same data, with 0.5 (thick lines) and 0.25 m s$^{-1}$ (thin lines) contour intervals. (b) The surface storm track, defined as the standard deviation of the bandpass-filtered meridional winds at 10 m, with colors and contours as in (a). (c) Wintertime mean for air–sea instability (SST minus SAT) of the atmospheric boundary layer. Color and contours show the same data, with contour interval of 1°C. The blue and magenta boxes indicate the locations where the time correlations are calculated (see text). (d) Estimate of the surface storm track as defined in the text (dark gray shading) and surface storm track [contours; same data as shown in (b)]. The mean path of the Gulf Stream, derived from altimetry data, is shown in white in (b),(c), and (d).
Free tropospheric storm track

• Literature unresolved as to what effect ocean fronts has on real storm tracks:
  – Ocean fronts essential to eddy variability associated with polar front jet (Nakamura et al. 2008)
  – Self-maintenance, eddies and mean jet, no role of ocean (Robinson 2006)

• Let’s show two contrasting viewpoints
From Wilson et al. 2009. Storm tracks in four very different realisations of the FORTE model: (a) control state with mountains and ocean dynamics; (c) with mountains and without ocean dynamics. The storm tracks are shown by the square root of the high-pass filtered eddy kinetic energy density (shaded, metres per second) at 250mbar, over ten winters.
Aquaplanet Model

From Nakumura, Sampe et al. 2008, Sampe et al. 2010. Meridional profiles of the mean states of (a) SST, b) SST gradient, c) longitudinal variance of 250-hPa meridional wind fluctuations (m^2/s^2) associated with subweekly disturbances. Control (CTL, realistic SST) and No Front (NF, heavily smoothed SST) experiments shown. Dashed lines – no front experiment.
Climate Impacts

• Shifts in ocean currents lead to SST anomalies and to heating anomalies in atmosphere
  – Shallow and deep

• Linear response to heating (e.g. Hoskins and Karoly 1981, Palmer and Sun 1985)
  – Tropical vs mid-latitude

• Non-linear, eddy response (e.g. Peng et al. papers, see Kushnir et al. 2002)
  – Eddy fluxes affect the mean circulation
  – Eddy effect on annular modes (Lorenz and Hartmann 2001)
Climate Impacts of Oyashio, Kuroshio Extension shifts

Estimated response in geopotential height at (top) 250 hPa, (middle) SLP, and (bottom) Ekman pumping to a unit value of the OEI (typical northward displacement), assuming $d = 2$ months, based on lag 3. White (gray) contours are for negative (positive) values. The dark contours indicate 10% significance.

Estimated response to a unit value of the KEI, based on a lag of 2 seasons, assuming $d = 1$ season. White (gray) contours are for negative (positive) values. The thick continuous line indicates the 10% significance level.

Typical latitudinal profiles of 250-hPa $[U]$ (m/s) for the positive (solid) and negative (dashed) phases of the annular mode for the (a) winter and (b) summer hemispheres in the CTL experiment. (c) and (d): As in Figures 4a and 4b, respectively, but for the NF experiment. Based on the composites for 17~29 events in which the mode index (PC1) exceeds its 3 standard deviations in magnitude. Circles denote $[U]$ anomalies significant at the 95% confidence level.

Lag-correlation (color shaded) and regression coefficients (contoured) of January anomalies of (a) SST, (b) SLP, and (c) Z250 with the November SAFZ-SST index. The index is based on the ICOADS data, while SST anomalies in (a) are based on HadISST data. SLP and Z250 are based on the NCEP–NCAR reanalysis. (d)–(f) As in (a)–(c), but for February. The contour intervals for the regression coefficients are shown at the lower-right corner of each with units of K K$^{-1}$, hPa K$^{-1}$, and m K$^{-1}$ for SST, SLP, and Z250, respectively.

Modelling Issues

• Most reanalyses and models underestimate coupling between ocean SST and overlying stress, even when high-resolution SST is used (Maloney and Chelton 2006).

• This may underestimate the impact on the deeper atmosphere, & remote teleconnections

• Problem may lie with the boundary layer schemes (Song et al. 2009), vertical/horizontal resolution, or with representation of the background state.

• Investigations by e.g. NCAR, OSU.
• Chelton, D. B., and S.-P. Xie 201. 0Coupled ocean-atmosphere interaction at oceanic mesoscale. Oceanography, 23, 52-69.