Ocean mesoscale, surface heat fluxes and surface convergence

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Thanks to Shang-Ping Xie, Meghan Cronin, Dudley Chelton for early inspiration
And to many others for discussions and results

Apologies in advance: I may not mention your favorite paper – too many papers to mention all!
Outline

• 1. Surface turbulent heat flux response to eddies

• 2. Models for response of atmosphere boundary layer to SST fronts and eddies

• 3. Surface convergence over western boundary currents

• 4. Some discussion points

• I will not cover remote atmosphere response to boundary currents and eddies
  • Claude Frankignoul and Mike Alexander wrote a review on this for a paper I have been leading for last 5 years .... Not yet finished/published...

• Nor will I cover feedback to ocean (see Ma et al. 2016 and others)

• Also not cover Lagrangian tracking/compositing of eddies
  • E.g. Frenger et al., Ma et al., Gaube et al.
Part 1. Mesoscale SST and surface heat flux

• Will focus on turbulent heat flux
  • Main contributor to heat flux response to SST
  • Dominated in turn by latent heat flux

• Use various observed heat fluxes products and CESM model simulations
Stochastic model of air-sea interaction
Frankignoul, Hasselmann 1977
Barsugli and Battisti 1998
Wu et al. 2006
Smirnov et al 2014
Zhang et al 2017
Bishop et al. 2017

\[
\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a, \quad \text{and} \\
\frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o + N_o,
\]

where \(T_a\) is the near-surface atmospheric temperature, \(T_o\) is the SST, \((\alpha, \beta)\) are exchange coefficients normalized by the respective heat capacities of the atmosphere and ocean with \(\beta \ll \alpha\), \((\gamma_a, \gamma_o)\) are radiative damping coefficients, and \((N_a, N_o)\) represent stochastic forcing arising from weather or turbulent eddies in the atmosphere and ocean, respectively.

From
Bishop et al 2017

Increasing ocean noise

Correlation between SST and surface heat flux. Positive heat flux out of ocean.

Correlation between SST tendency and surface heat flux.
Fig. 4. Monthly: SST-LHFLX correlations

a) OAFLUX

b) OAFLUX 2002-2012

c) J-OFURO-v3 2002-2012

d) SEAFLUX 2002-2012

e) HIGH RESOLUTION CESM

f) LOW RESOLUTION CESM
Fig. 5. Monthly: SST tendency - LHFLX correlations

a) J-OFURO-v3 2002-2012

b) SEAFLUX 2002-2012

c) HIGH RESOLUTION CESM

d) LOW RESOLUTION
Scale dependence in OAFLUX data

From Bishop et al 2017
Part 2. Models of wind response to fronts

• Lindzen Nigam 1987  Pressure adjustment mechanism/ Ekman-balanced-mass-adjustment
• Hayes et al 1989, Wallace et al 1989  Vertical mixing mechanism
• Feliks et al 2004, 2007  Pressure adjustment mechanism boundary layer+ QG free trop.
• Takatama et al 2011, 2015  Combined model
• Schneider and Qiu 2015  Combined model
• Gemmrich, Monahan, this conference  Stochastic model
Under approximation of no advection (A terms=0), negligible stress at height $Z$ ($\tau(Z)=0$)

We can derive

$$
-fV = -P_x + \frac{\tau^x(Z) - \tau^x(0)}{Z} + A^x \quad \text{and} \quad (2a)
$$

$$
+ fU = -P_y + \frac{\tau^y(Z) - \tau^y(0)}{Z} + A^y, \quad (2b)
$$

$$
\frac{\tau^x(0)}{Z} = \varepsilon U \quad \text{and} \quad \frac{\tau^y(0)}{Z} = \varepsilon V. \quad (3)
$$

Underlying assumption that air temperature, moisture anomalies follow underlying SST anomalies

... so that e.g. $p' \sim -\text{SST}'$

Convergence $\sim -\text{Laplacian(SLP)}$

Lindzen and Nigam 1987, Minobe et al 2008
Linear response to a weak SST front

Linearised about background Ekman spiral

Also includes back-pressure effect

Boundary Layer Model (2)

1st order (linear) response

\[ \bar{u}^{(0)} \cdot \nabla \Theta^{(1)} = \gamma (T^{(1)} - \Theta^{(1)}) + A_h \nabla^2 \Theta^{(1)} \]

\[ \delta^{(1)} = T^{(1)} - \Theta^{(1)} \]

\[ \bar{F} = \nabla \int_s^{(1)} \Theta^{(1)} ds' + \partial_s \left( \begin{array}{c}
\delta^{(1)} \frac{\partial E}{\partial \delta} \\
\partial_s \bar{u}^{(0)}
\end{array} \right) \]

\[ \begin{align*}
\bar{u}^{(0)} \cdot \nabla \bar{u}^{(1)} + w^*(1) \partial_s \bar{u}^{(0)} - \partial_s \bar{h}^{(1)} - \partial_s w^*(1) &= \bar{F} \\
\nabla h^{(1)} - \partial_s E^{(0)} \partial_s \bar{u}^{(1)} &= \bar{F} \\
\n\bar{u}^{(0)} \cdot \nabla h^{(1)} + \nabla \cdot \bar{u}^{(1)} + \partial_s w^*(1) &= 0
\end{align*} \]

Schneider and Qiu 2015

nondimensionalized by Rossby radius of deformation, boundary layer height, inversion strength etc.
Linear response to a weak SST front

Linearised about background Ekman spiral

Also includes back-pressure effect

Boundary Layer Model (2)

1\textsuperscript{st} order (linear) response

\[ \vec{\eta}(0) \cdot \nabla \Theta^{(1)} - \gamma (T^{(1)} - \Theta^{(1)}) + A_s \nabla^2 \Theta^{(1)} \]

\[ \delta^{(1)} = T^{(1)} - \Theta^{(1)} \]

Surface convergence (\& vertical motion) has a component due to:
1. Laplacian (surface air temperature)
2. Downwind surface air temperature gradient

Gradients in surface air temperature driven by gradients in SST
Part 3. Low level Convergence over mesoscale features and western boundary currents

• I will focus on Gulf Stream mean state and variability
• This includes eddies but is not exclusively focused on eddies (sorry)

• Next slide: sequence of papers related to convergence over the Gulf Stream
Surface convergence and deep precipitation over Gulf Stream - Pressure adjustment mechanism?

Storm tracks co-located with Gulf Stream – at least in boundary layer

Atmospheric fronts modified by Gulf Stream

Warm conveyor belt modified by Gulf Stream (unstable lower trop.)

Surface convergence over Gulf Stream - Pressure adjustment mechanism + synoptic storms

Decomposed convergence and curl in terms of pressure/vertical mixing

Surface convergence in cold sector of storm over Gulf Stream - Pressure adjustment mechanism including moisture

Surface convergence over Gulf Stream mainly due to some extreme storms. Highly skewed distribution. Median is weak divergence, not convergence.
Storm Tracks and Atmosphere Fronts

Surface storm track defined as band-pass filtered meridional wind standard deviation. White line if Gulf Stream mean position.

Proposed mechanisms include 1) SST front setting atmosphere baroclinicity 2) vertical mixing of momentum 3) enhanced surface latent heat flux over fronts...e.g. Nakamura 2004 Booth et al 2010, 2017 Joyce and Kwon 2009 Small et al 2014

See also Ogawa-san presentation this week: mean sensible heat flux governed by meridional wind variance...

From Parfitt et al. 2016. Atmosphere cold front frequency (as a fraction) in a control high resolution model.

“Thermal damping and strengthening”
Long-term mean properties – surface convergence etc.

Note: sign convention opposite to Minobe et al 2008.
O’Neill et al. 2017, JCLIM. Results from COAMPS simulations, 1-year mean.
• So everyone is in agreement then – pressure adjustment mechanism drives convergence over the Gulf Stream

  • Keep listening...
Look what happens when you remove the most extreme storms, which occur in only about 5% of data.

Also, median conditions are surface divergence

The field of Laplacian of SST is similar on all days – but convergence only occurs on a small amount of days
Is there an “anchoring” effect?

O’Neill et al. 2017, JCLIM. QuiKSCAT data.
What’s going on then?

\[ \nabla^2 P_{SL} = a \zeta_{850} - b \nabla^2 T_{BL}. \]


We will be mainly interested in the three key variables that appear in this equation: (i) the Laplacian of \( P_{SL} \), the sea level pressure (SLP); (ii) \( \zeta_{850} \), the relative vorticity at 850 hPa; and (iii) the Laplacian of the boundary-layer temperature.

Convergence driven by sea level pressure Laplacian has components due to upper vorticity (e.g. from storms) and also due to boundary layer temperature.
Daily timeseries at points in WBCs
Lap(SST)-surface Convergence relationship

Timeseries of Lap(SST) and surface convergence from daily data

From 7 years of daily data of CAM/CESM. Correlations (in red boxes) are very low.
Can we detect any influence of Lap(SST) on variability of surface convergence?

• Assume daily variability of surface convergence driven by synoptic storms and atmosphere fronts

• So look at longer timescales
  • Monthly to interannual to 5 year

• Investigate relationship between SST, Tair(2m), sea level pressure, and convergence at bottom model level
  • Standard correlation/covariance analysis at each point
  • More sophisticated methods should be used!
  • Data is high pass box-car filtered to show 10deg. Scale or less

• I use 40 years of monthly data from high-resolution coupled CESM.
  • As it is a coupled model it has a not perfect Gulf Stream separation, but does not greatly affect the following results
Sign convention

• In following panels:

• Negative correlations are consistent with SST/Tair forcing boundary layer response

• Except for correlation of Lap(sea level pressure) and Convergence
  • Positive correlations consistent with SLP forcing convergence
Results: North Atlantic

Correlation, SST and sea level pressure

Correlation, T(air) and sea level pressure

Correlation, Lap(T(air)) and Lap(SLP)

Correlation, Convergence and Lap(SLP)

Correlation, Lap(SST) and Convergence

Correlation, Lap(T(air)) and Convergence

Note reduced color bars in last two panels
Results: North Pacific

Correlation, SST and sea level pressure

Correlation, T(air) and sea level pressure

Correlation, Lap(T(air)) and Lap(SLP)

Correlation, Convergence and Lap(SLP)

Correlation, Lap(SST) and Convergence

Correlation, Lap(T(air)) and Convergence

Note reduced color bars in last two panels
Results: Agulhas return Current

Correlation, SST and sea level pressure

Correlation, T(air) and sea level pressure

Correlation, Lap(T(air)) and Lap(SLP)

Correlation, Convergence and Lap(SLP)

Correlation, Lap(SST) and Convergence

Correlation, Lap(T(air)) and Convergence

Note reduced color bars in last two panels
Summary of monthly+ analysis of lap(Ta) and surface convergence

• Tropics
  • high correlation
  • low covariance

• Western boundary currents, sharp fronts
  • High correlations in narrow regions ,
  • high covariance

• Broad eddying region (i.e. region of large ocean EKE)
  • High covariance
  • Weak correlation

• Time-scale dependence
  • Correlations get stronger for longer timescales (e.g. interannual)
  • But statistical significance less as sample size shorter
Let’s return to time-mean convergence
O’Neill et al. 2017, JCLIM. QuiKSCAT data.
Fig. 4. The estimated surface convergence response to Laplacian of: top: surface pressure second row: boundary layer pressure increment, third row: deep pressure. Final row: full model surface convergence. Courtesy Bob Tomas. See also Minobe/Takatama/Terray.
Three Discussion Slides
Discussion slide: What drives deep response to Gulf Stream

• Boundary layer processes **directly** drive deep response?
  • Feliks et al. 2004, 2007
  • Minobe et al 2008
• Synoptic Storms?
• Extreme storms?
• Atmospheric Fronts?
• boundary layer modifies storm track (**indirect** effect)?
  • Air-sea heat fluxes at fronts dictating baroclinicity (Nakamura 2004, Small et al 2014)
  • Vertical motion from boundary layer? (Feliks et al)
  • Atmosphere fronts affected by surface heat fluxes (Parfitt et al.)
Discussion slide: Scale dependence and coupling coefficients

• O’Neill et al illustrate scale-dependence of SST-wind coupling
• Schneider et al analyse scale-dependence

• Coupling coefficients
  • Traditional SST-wind speed etc coefficients (Chelton et al., O’Neill et al.)
  • Or more sophisticated wavenumber approach (Schneider and Qiu) with background wind and wind speed dependence?
What ocean scales affect the atmosphere

And what atmosphere grid scale is needed?

See also Bryan et al 2010