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DOE BER SCIDAC

NASA Vector winds
NASA Physical Oceanography

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

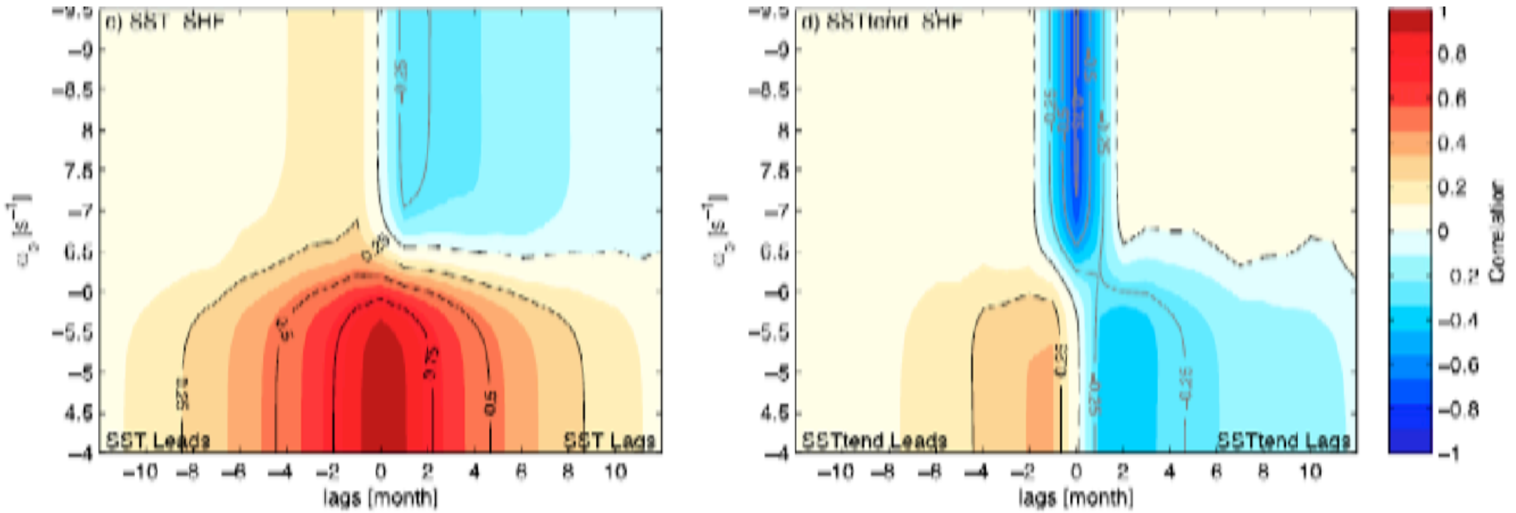
$$\frac{dT_a}{dt} = \alpha(T_o - T_a) - \gamma_a T_a + N_a, \quad \text{and} \tag{1}$$

$$\frac{dT_o}{dt} = \beta(T_a - T_o) - \gamma_o T_o + N_o, \tag{2}$$

where T_a is the near-surface atmospheric temperature, T_o is the SST, (α, β) are exchange coefficients normalized by the respective heat capacities of the atmosphere and ocean with $\beta \ll \alpha$, (γ_a, γ_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



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

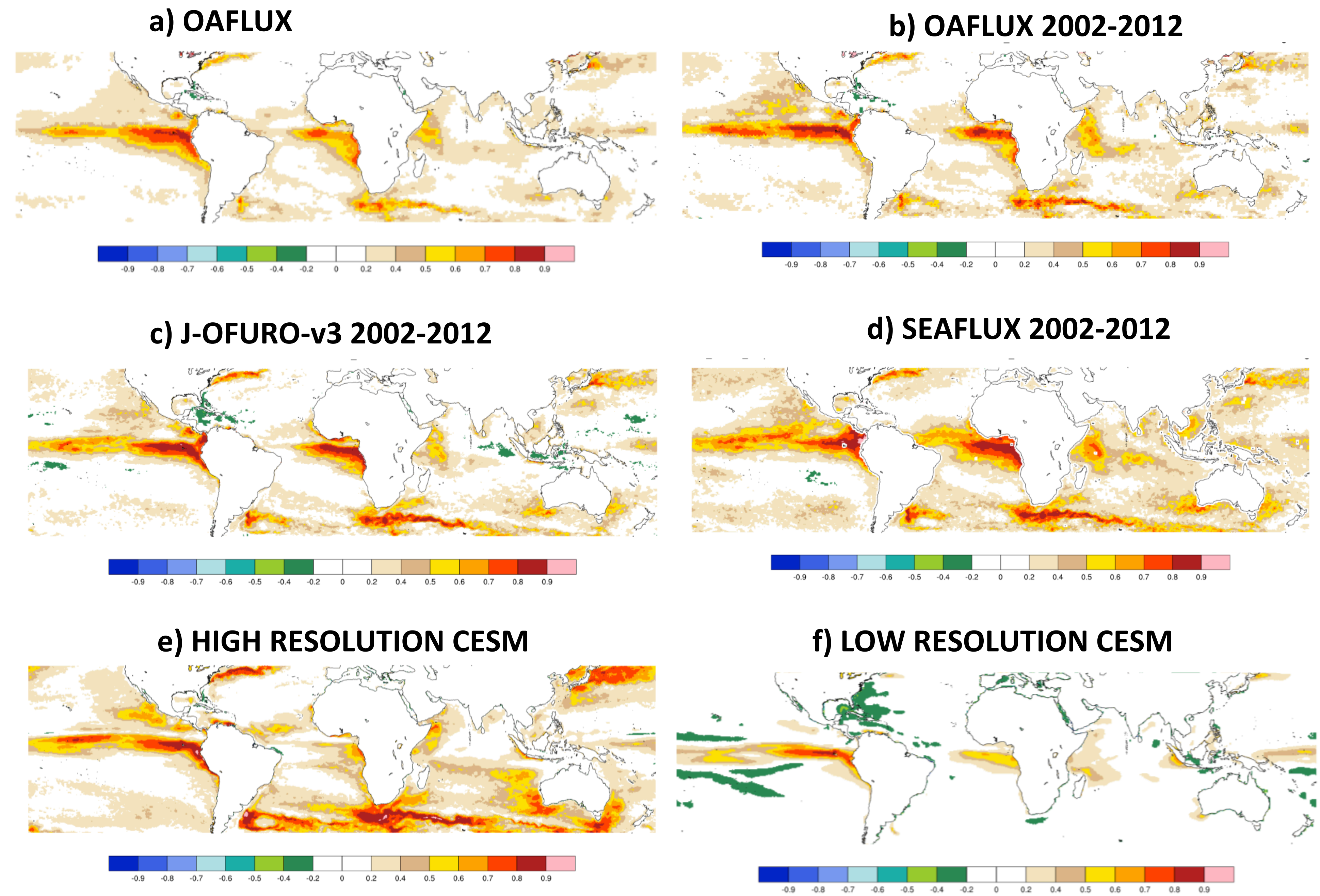
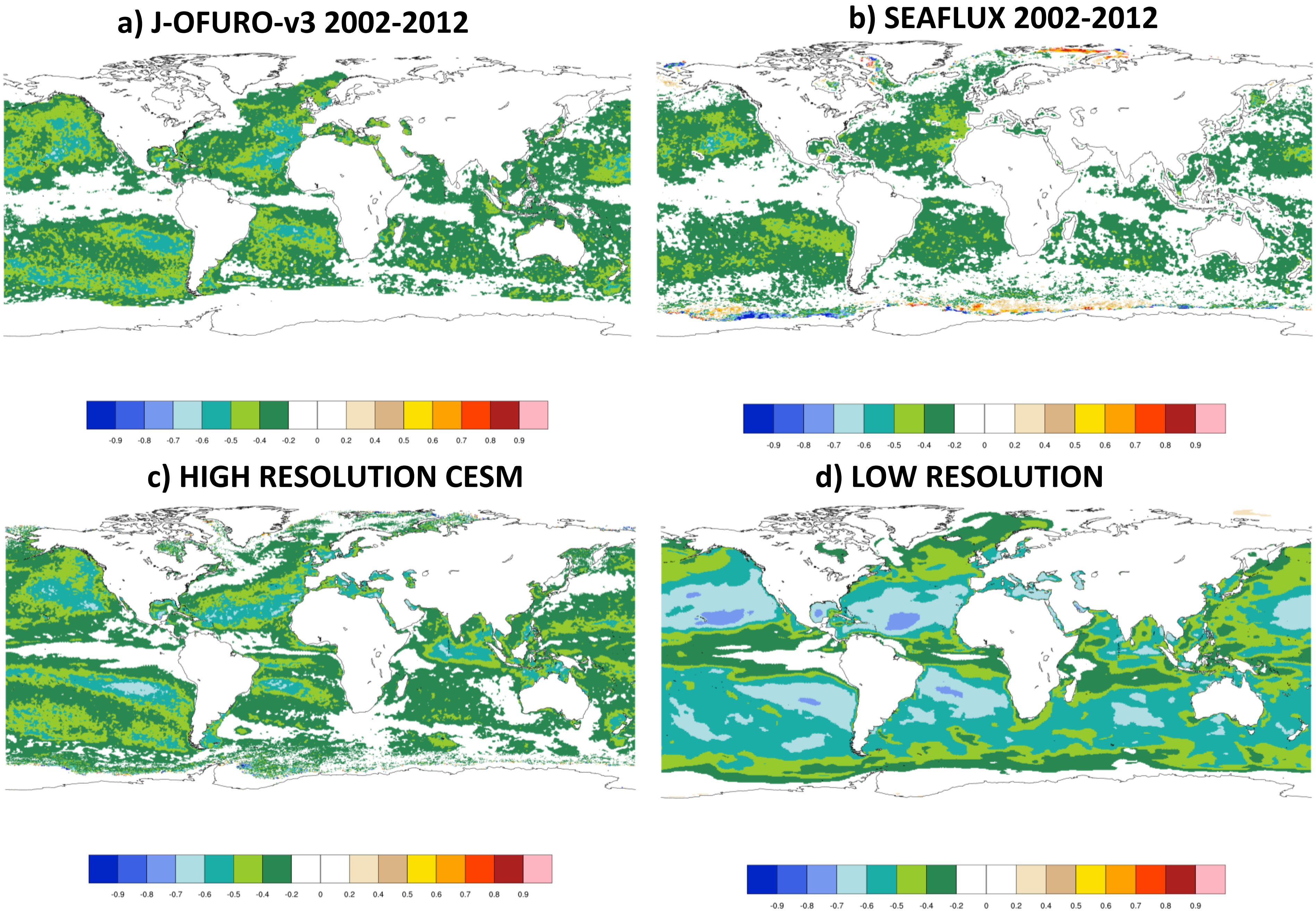
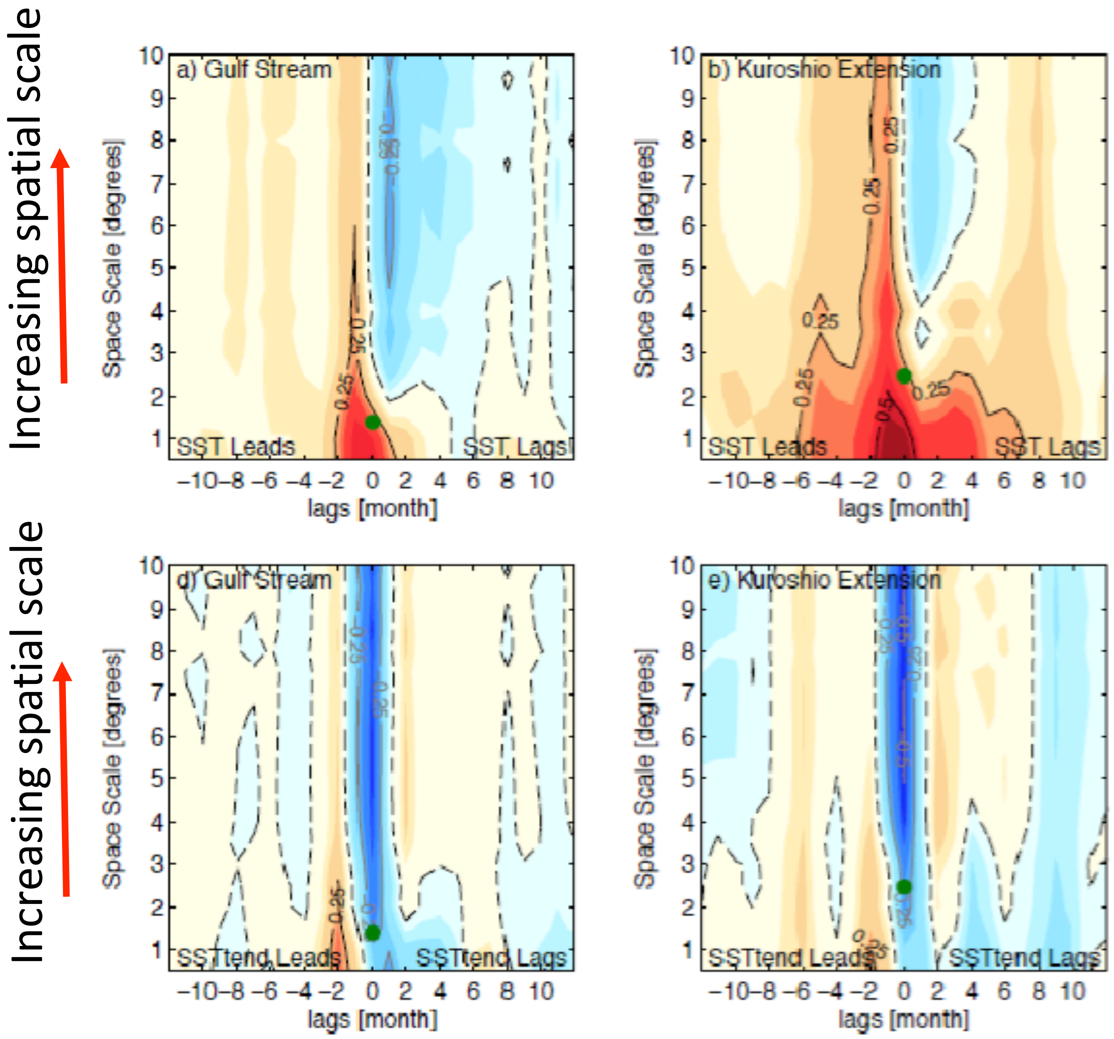
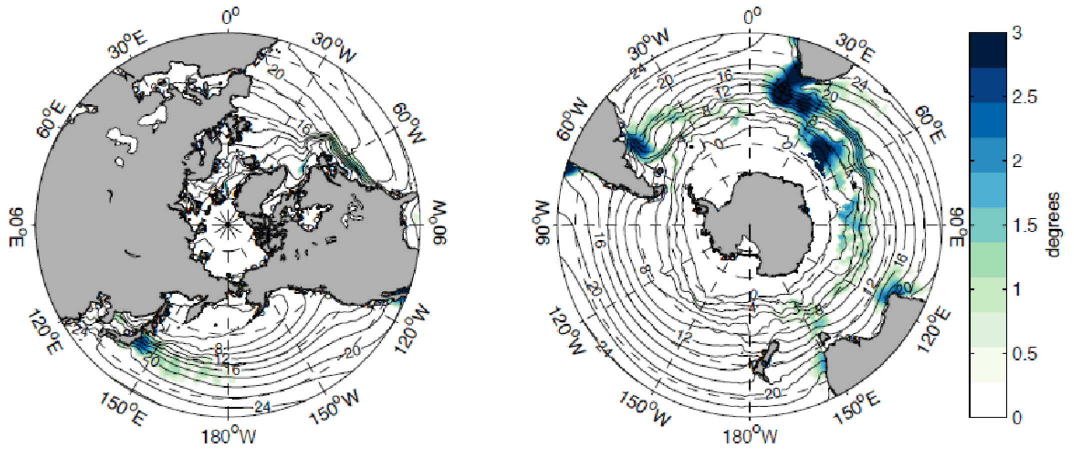


Fig. 5. Monthly: SST tendency -LHFLX correlations



Scale dependence in OAFLUX data





576 FIG. 11. Transition length scale (L_c) at monthly time scales (color contours). Black contours are the climato-
577 logical mean SST.

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

Boundary Layer Model (1)

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

$$+fU = -P_y + [\tau^y(Z) - \tau^y(0)]/Z + A^y, \quad (2b)$$

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

Takatama et al. 2011, 2015

Under approximation of no advection (A terms=0), negligible stress at height Z (tau(Z)=0)
We can derive

$$-(u_x + v_y)\rho_0 = (p_{xx} + p_{yy})\varepsilon/(\varepsilon^2 + f^2).$$

Lindzen and Nigam 1987, Minobe et al 2008

Convergence ~ -Laplacian(SLP)

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

… so that e.g. p’ ~ -SST’

Convergence’ ~ -Laplacian(SST’)

Boundary Layer Model (2)

Linear response to a weak SST front

Linearised about background Ekman spiral

Also includes back-pressure effect

1^{st} order (linear) response

$$\vec{u}^{(0)} \cdot \nabla \Theta^{(1)} = \gamma \left(T^{(1)} - \Theta^{(1)} \right) + A_h \nabla^2 \Theta^{(1)}$$

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

air-sea temperature differences modulates vertical eddy viscosity

$$\vec{F} = \nabla \underbrace{\int_s^1 \Theta^{(1)} ds'}_{\text{pressure gradient mechanism}} + \partial_s \left(\underbrace{\delta^{(1)} \left. \frac{\partial E}{\partial \delta} \right|_{\delta^{(0)}} \partial_s \vec{u}^{(0)}}_{\text{vertical mixing mechanism}} \right)$$

$$\underbrace{\vec{u}^{(0)} \cdot \nabla \vec{u}^{(1)} + w^{\star(1)} \partial_s \vec{u}^{(0)}}_{\text{advection}} + \underbrace{\hat{e_3} \times \vec{u}^{(1)}}_{\text{Coriolis}} + \underbrace{\nabla h^{(1)}}_{\text{back pressure}} - \partial_s \underbrace{E^{(0)} \partial_s \vec{u}^{(1)}}_{\text{background mixing}} = \vec{F}$$

$$\vec{u}^{(0)} \cdot \nabla h^{(1)} + \nabla \cdot \vec{u}^{(1)} + \partial_s w^{\star(1)} = 0$$

Schneider and Qiu 2015

Schneider and Qiu, 2015, *J. Atmos. Sci.*, in press.

nondimensionalized by Rossby radius of deformation, boundary layer height, inversion strength etc.

Boundary Layer Model (2)

Linear response to a weak SST front

Linearised about background Ekman spiral

Also includes back-pressure effect

Ist order (linear) response

$$\vec{u}^{(0)} \cdot \nabla\Theta^{(1)} - \gamma\left(T^{(1)} - \Theta^{(1)}\right) + A_h \nabla^2 \Theta^{(1)}$$

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

air-sea temperature differences modulates vertical eddy viscosity

$$\vec{F} = \nabla \underbrace{\int_s^1 \Theta^{(1)} ds'}_{\text{pressure gradient mechanism}} + \partial_s \left(\underbrace{\delta^{(1)} \frac{\partial E}{\partial \delta}\bigg|_{\delta^{(0)}} \partial_s \vec{u}^{(0)}}_{\text{vertical mixing mechanism}} \right)$$

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Schneider and Qiu, 2015, *J. Atmos. Sci.*, in press

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

References	Main conclusions
Lindzen and Nigam (1987), Feliks et al. (2004, 2007, 2011)	Lindzen-Nigam introduce response of convergence to laplacian(SST) in the Tropics. Feliks et al. develop coupled boundary layer/QG model where Laplacian(SST) forces convergence and vertical motion impacting free troposphere, for mid-latitudes
Minobe et al. 2008, 2010, Kuwano-Yoshida et al. 2010	Gulf Stream anchors surface convergence, deep ascent and precipitation. Surface convergence governed by pressure adjustment to SST field. Seasonally, deeper motion in summer than in winter.
Joyce et al 2009, Booth et al 2010, 2017, Woollings et al 2010, Small et al. 2014.	Near-surface storm track co-located with Gulf Stream. Nakamura 2004 – baroclinicity set by ocean?
Parfitt et al 2016	Atmospheric fronts tend to co-align and strengthen with SST front
Czaja and Blunt 2011, Sheldon et al. 2017 2013	The troposphere above the western boundary currents is frequently well mixed, up to 20% of the time in winter. Enhanced ascent in warm conveyor belt.
Brachet et al 2012	Deep circulation cell generated over Gulf Stream in long term mean in idealized model experiments. Long-term convergence governed by pressure adjustment to SST field (boundary layer process), short-term convergence governed by synoptic storms.
Takatama et al. 2011, 2015	Separated out effect of pressure gradient and vertical mixing in diagnostic approach: analyzed divergence and curl
Vanniere et al 2017	In cold sector of storms, during cold-air-outbreaks, heat and moisture from ocean is imprinted in the atmosphere boundary layer, giving rise to a Lindzen-Nigam type of response of surface convergence and precipitation to boundary layer pressure.
Parfitt and Czaja 2015 O'Neill et al. 2015, 2017	Long-term mean surface convergence and vertical motion over Gulf Stream in observations governed by synoptic storm activity, due to maximum of surface storm track along Gulf Stream. Found that on majority of days (i.e. the median) there is surface divergence over the Gulf Stream, contrary to expectation of pressure adjustment to SST. A few large amplitude storm events give rise to the time-mean convergence and vertical motion.

Table 1. Examples of literature on surface convergence response to Gulf Stream.

LOTS OF PAPERS!!!!

Pressure adjustment mechanism

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**

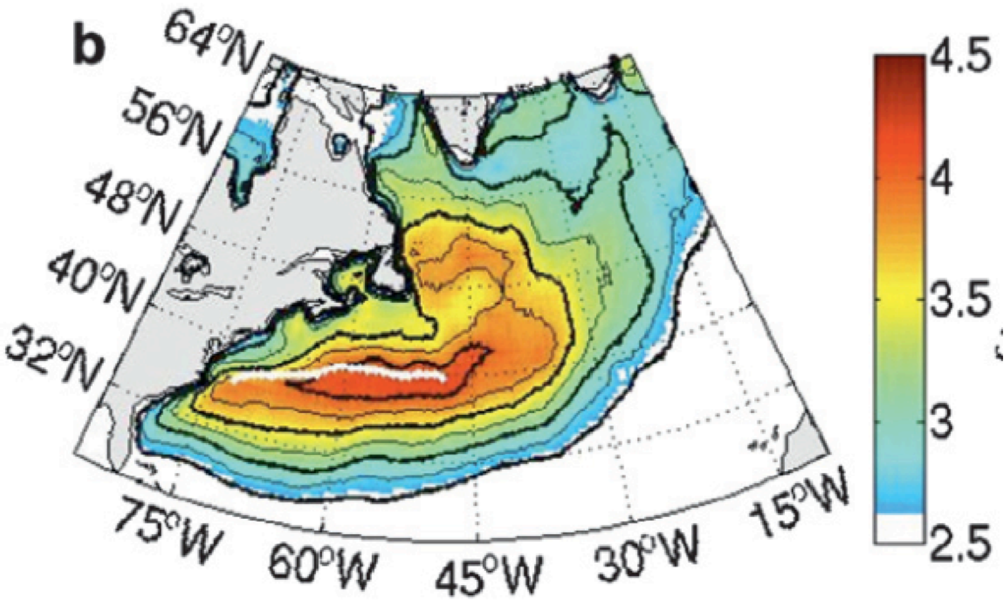
Decomposed convergence and curl in terms of pressure/vertical mixing

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

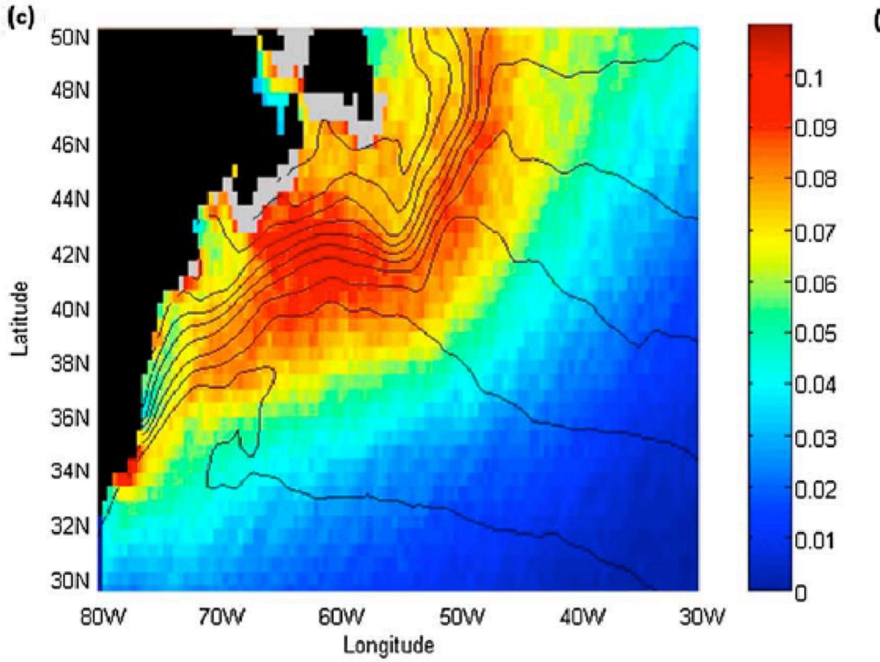
Surface convergence over Gulf Stream mainly due to some extreme storms. Highly skewed distribution. Median is weak divergence, not convergence.

Storm Tracks and Atmosphere Fronts

Surface Storm Track



Cold front frequency

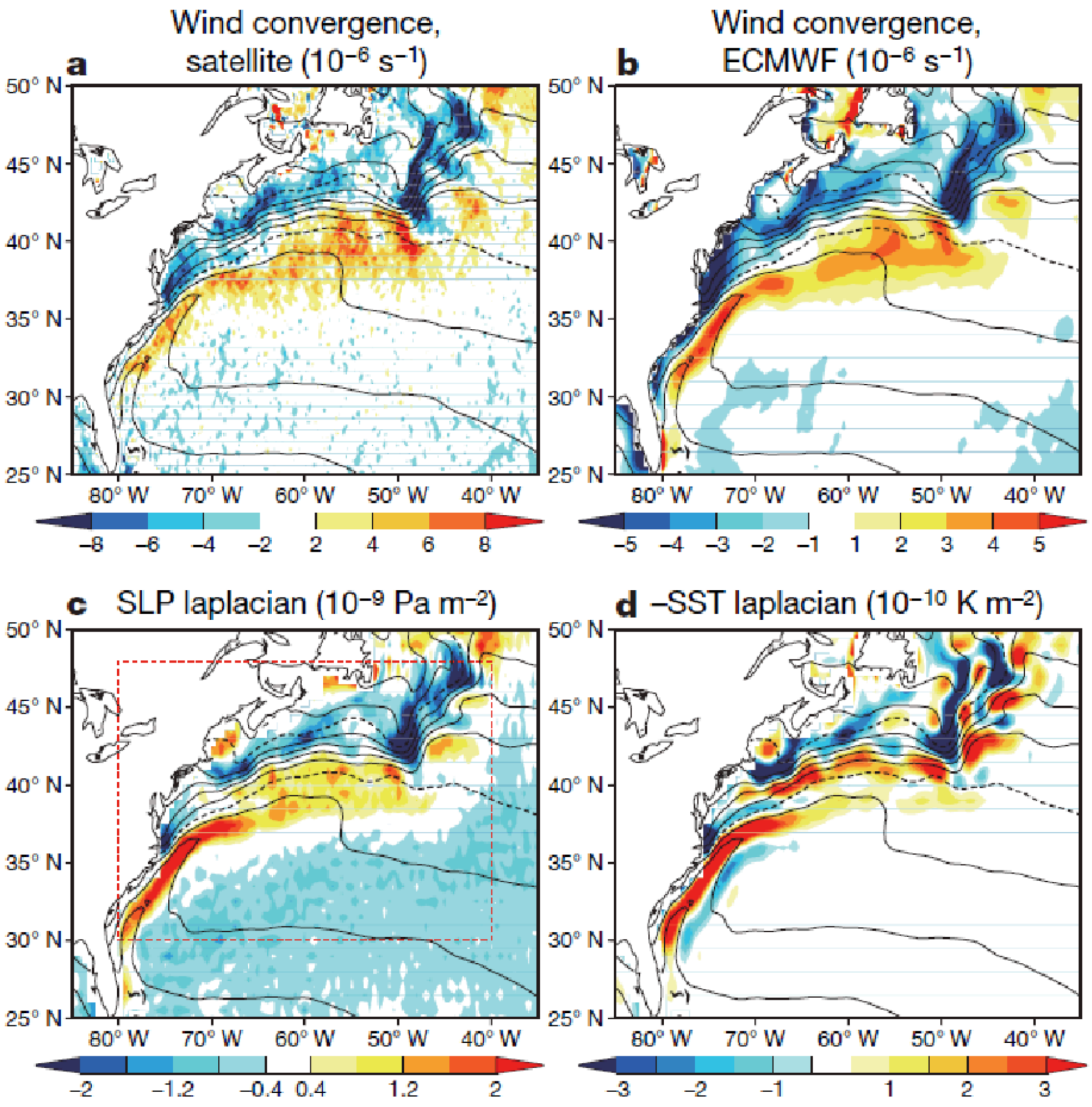


From Booth et al 2010
Surface storm track defined as band-pass filtered meridional wind standard deviation.White line if Gulf Stream mean position
Proposed mechanisms include 1) SST front setting atmosphere baroclinicity 2) vertical mixing of momentum 3) enhanced surface latent heat flux over fronts …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…

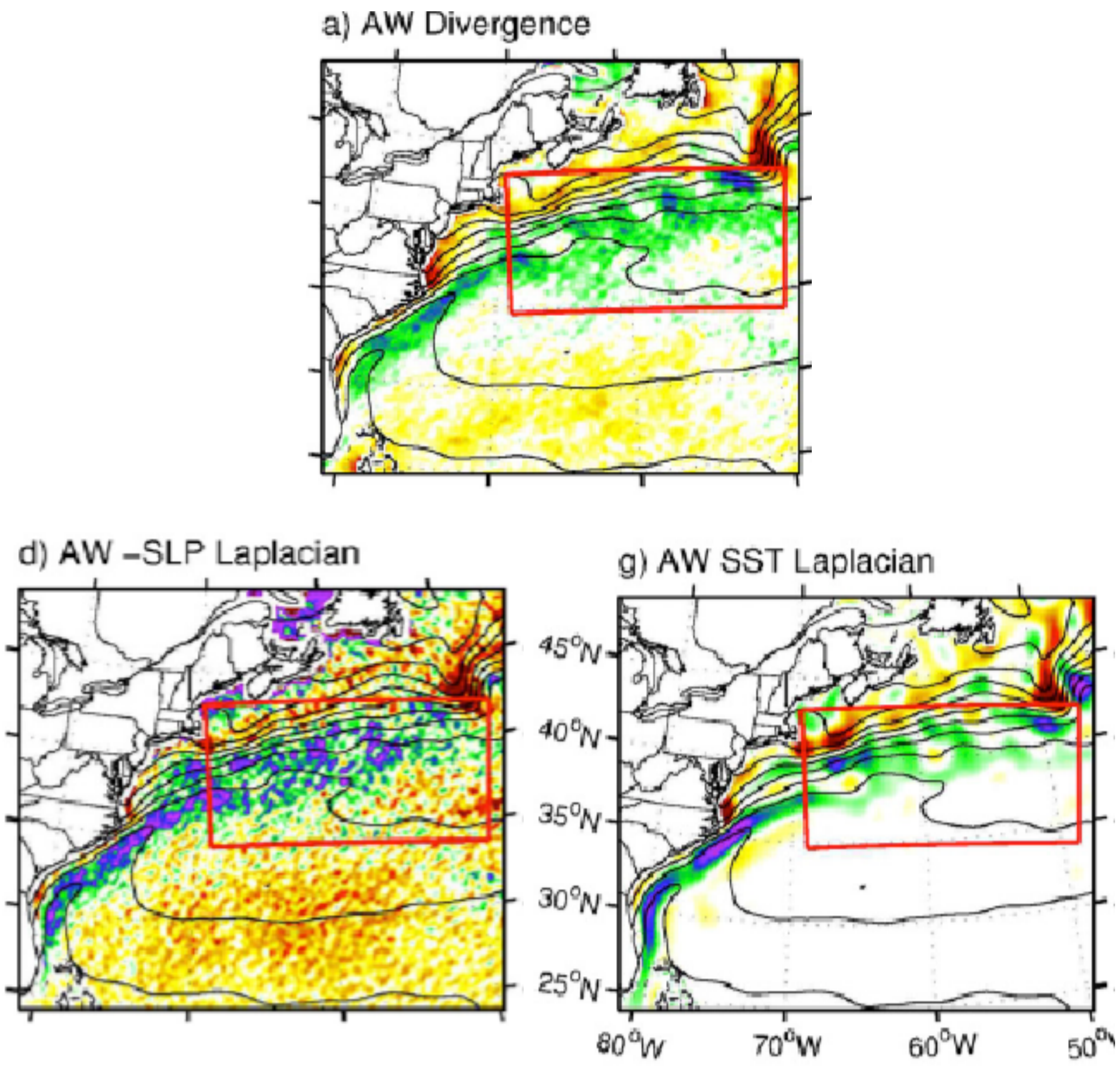
From Parfitt et al. 2016. Atmosphere cold front frequency (as a fraction) in a control high resolution model.

"Thermal damping and strengthening"

Long-term mean properties – surface convergence etc.



Minobe et al 2008.

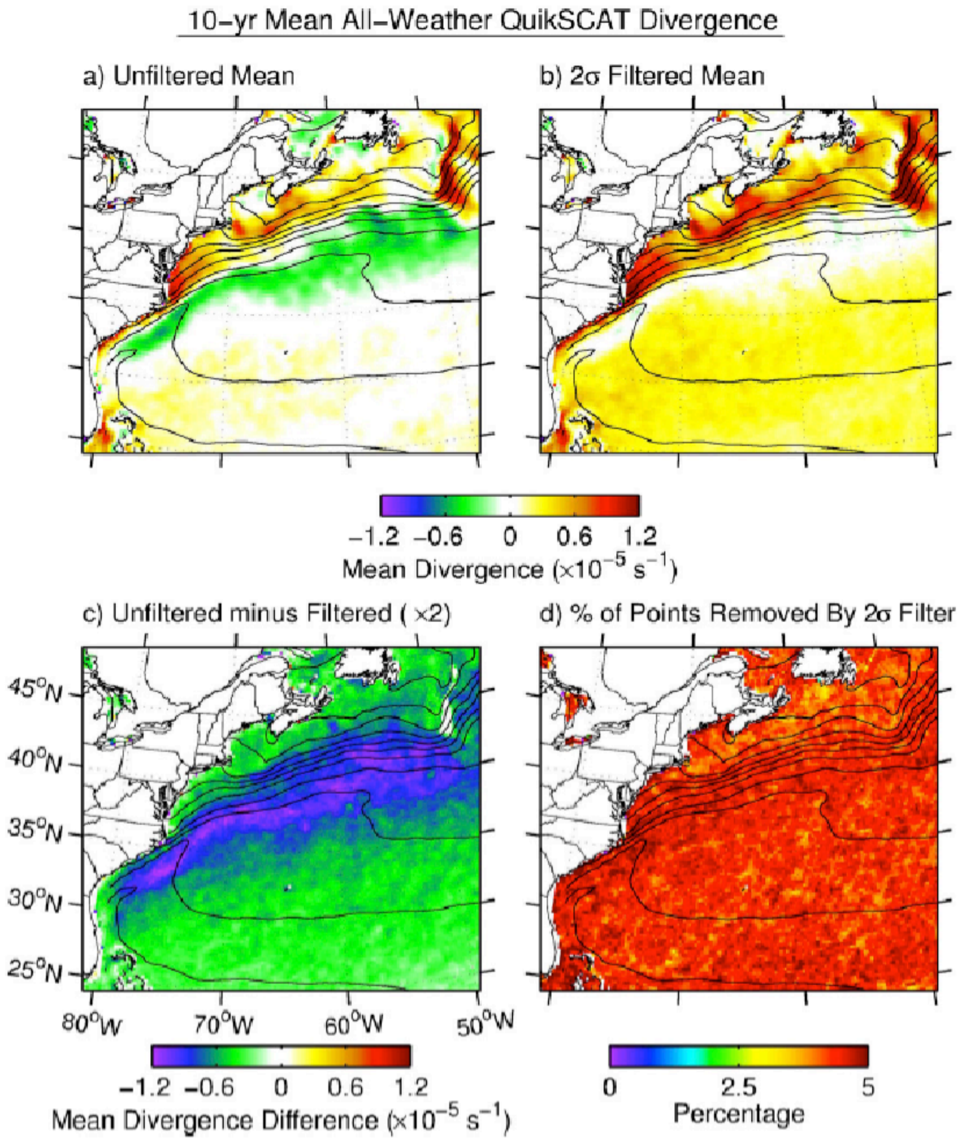


Note: sign convention opposite to Minobe et al 2008.

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?

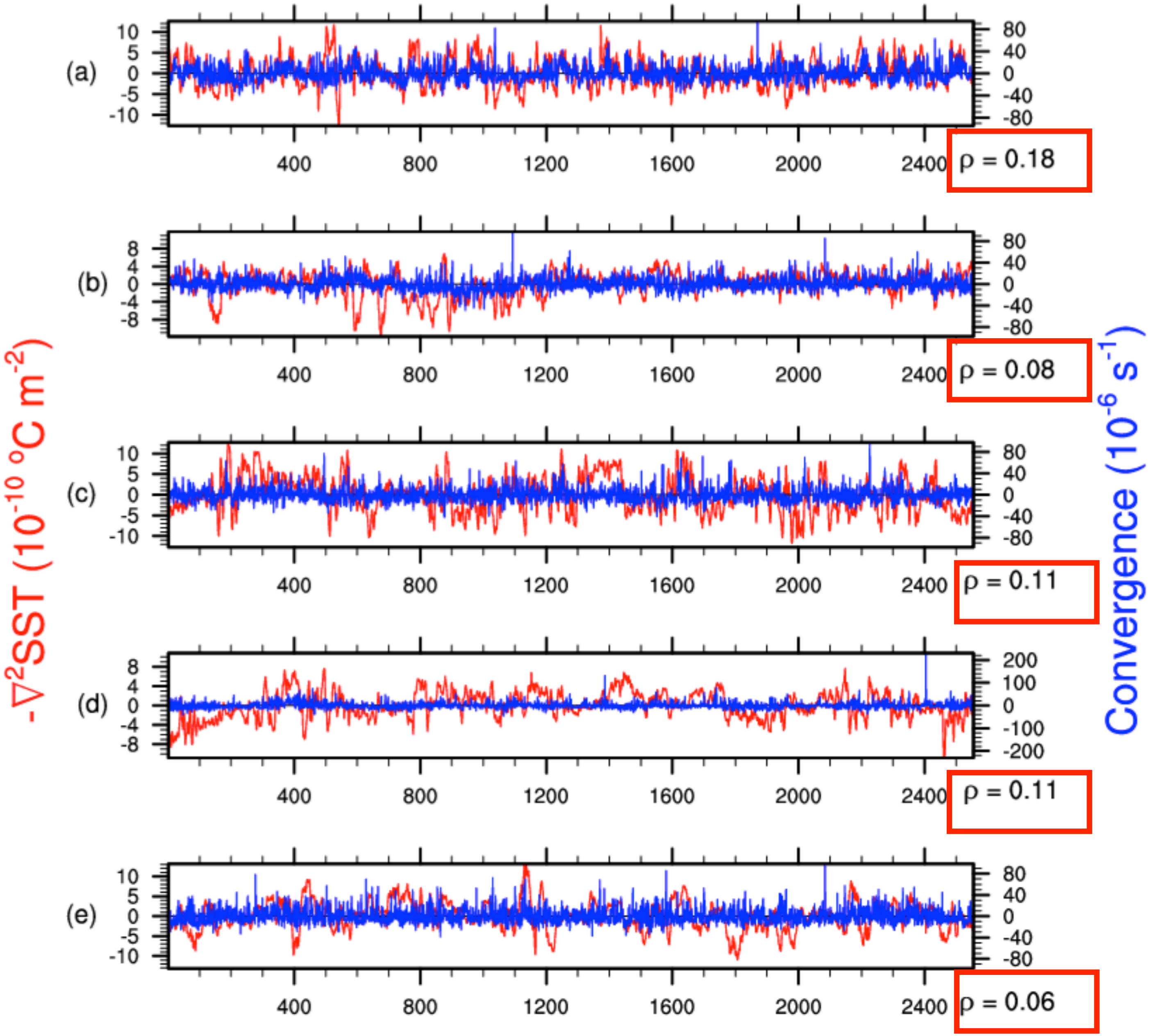
$$\nabla^2 P_{SL} = a\zeta_{850} - b\nabla^2 T_{BL}. \qquad (3)$$

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) ζ_{850}, the relative vorticity at 850 hPa; and (iii) the Laplacian of the boundary-layer temperature

Feliks et al. 2004, 2007, Brachet et al. 2012

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?

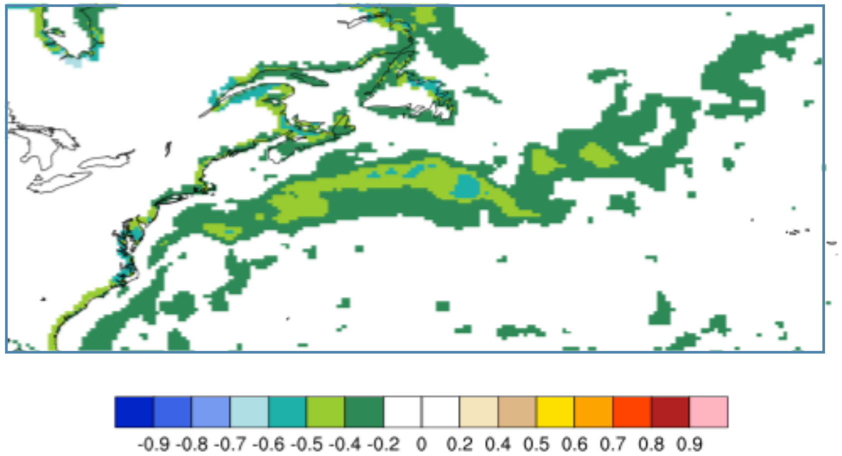
- Assume daily variability of surface convergence driven by synoptic storms and atmosphere fronts
- So look at longer timescales
  - Monthly to interannual to 5 year
- Investigate relationship between SST, Tair(2m), sea level pressure, and convergence at bottom model level
  - Standard correlation/covariance 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

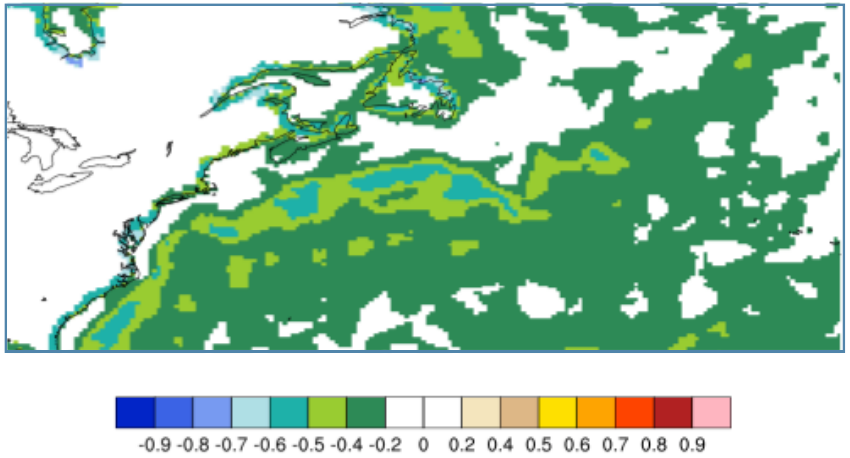
- In following panels:
- Negative correlations are consistent with SST/Tair forcing boundary layer response
- Except for correlation of Lap(sea level pressure) and Convergence
    - Positive correlations consistent with SLP forcing convergence

Results: North Atlantic

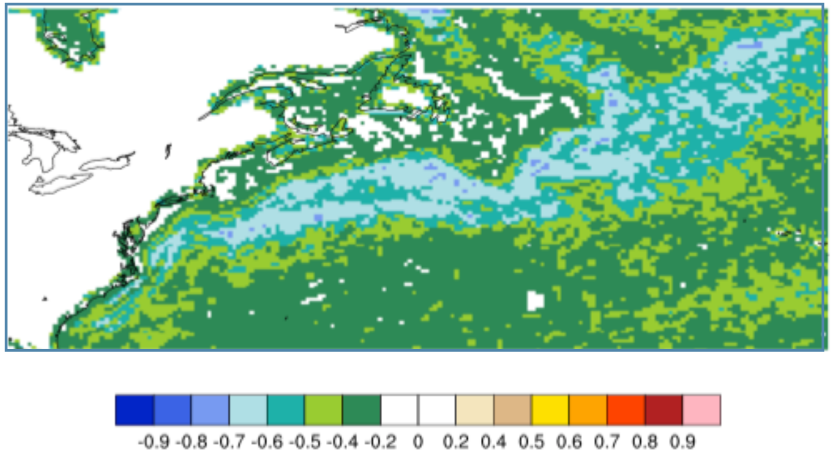
Correlation, SST and sea level pressure



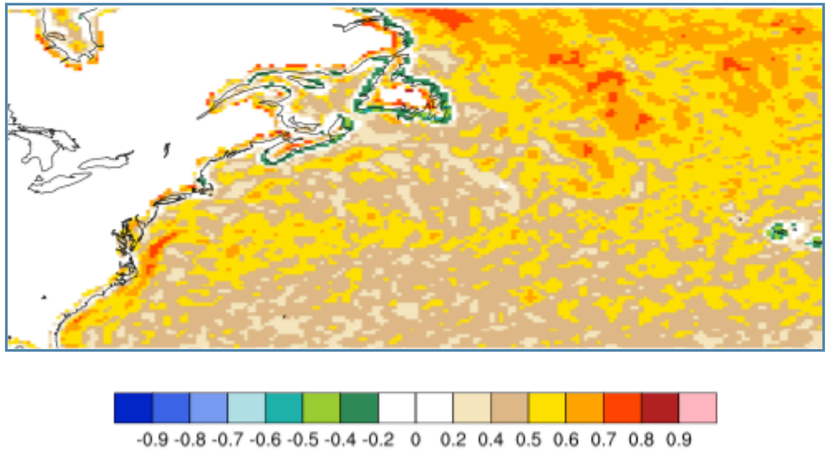
Correlation, T(air) and sea level pressure



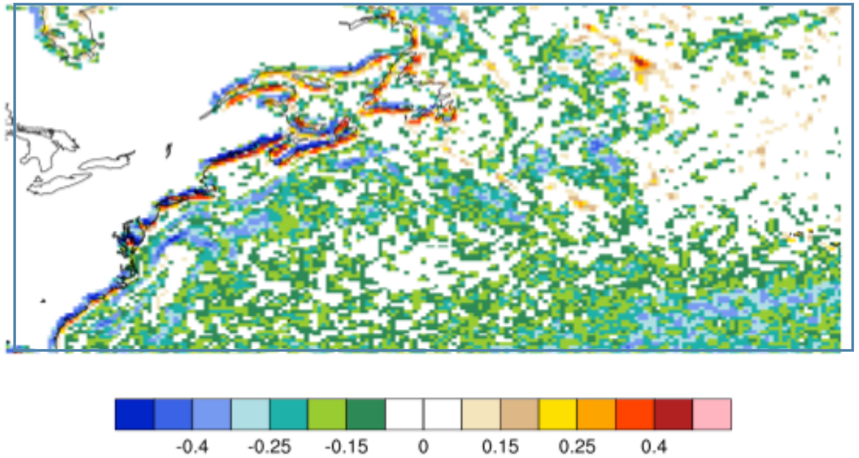
Correlation, Lap(T(air)) and Lap(SLP)



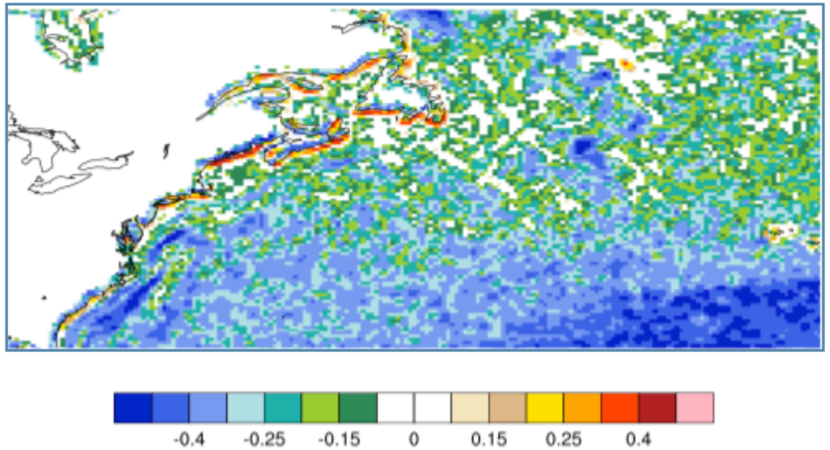
Correlation, Convergence and Lap(SLP)



Correlation, Lap(SST) and Convergence



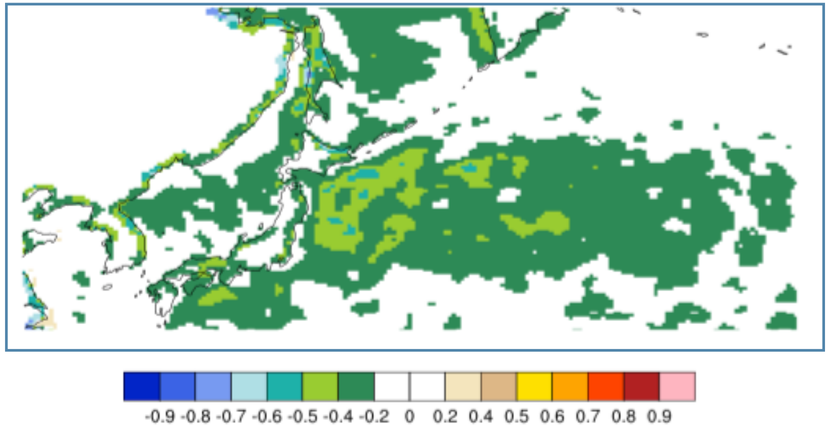
Correlation, Lap(T(air)) and Convergence



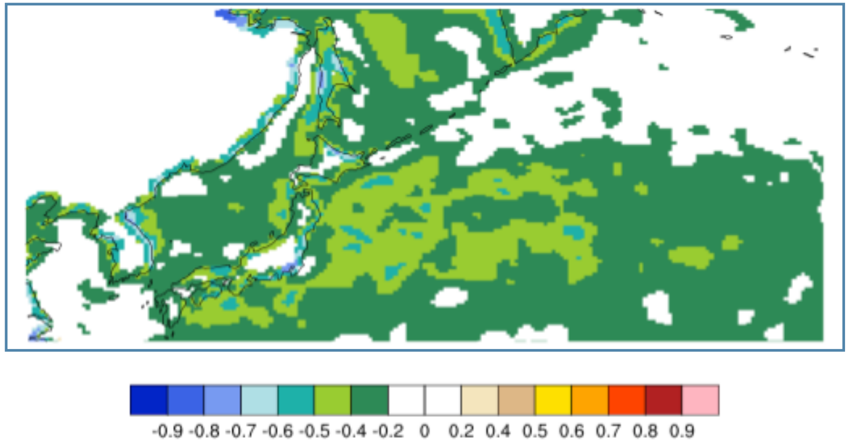
Note reduced color bars in last two panels

Results: North Pacific

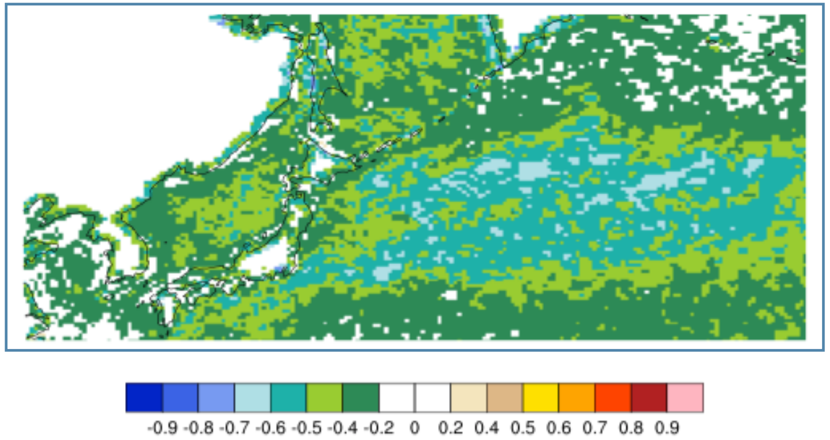
Correlation, SST and sea level pressure



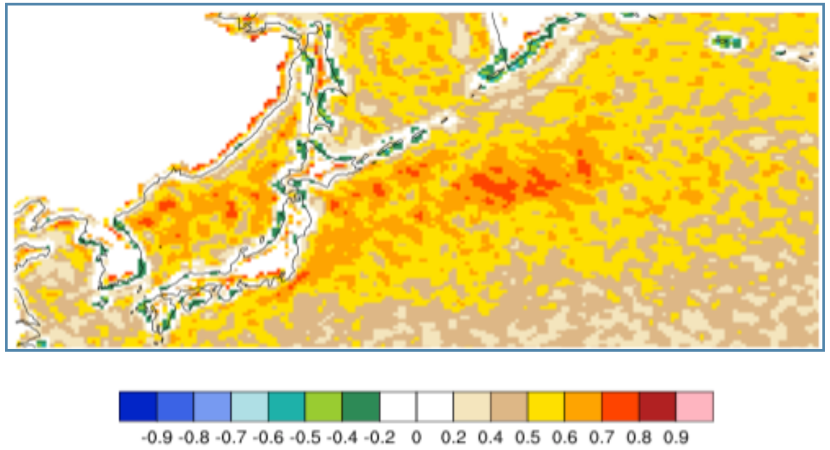
Correlation, T(air) and sea level pressure



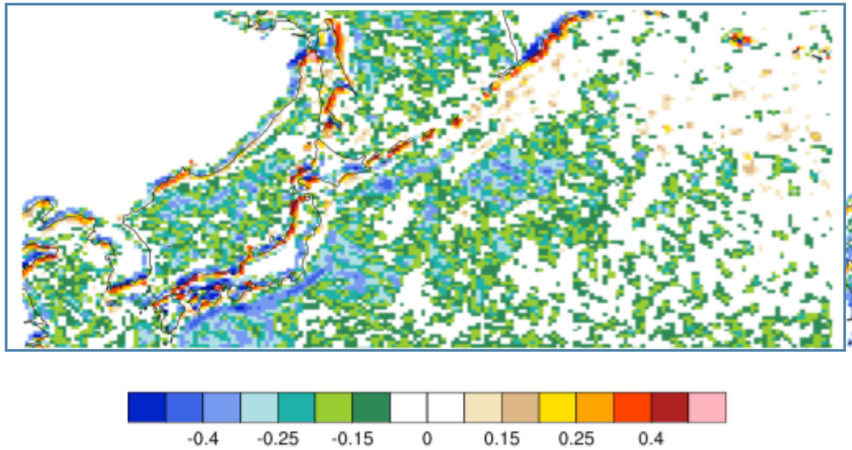
Correlation, Lap(T(air)) and Lap(SLP)



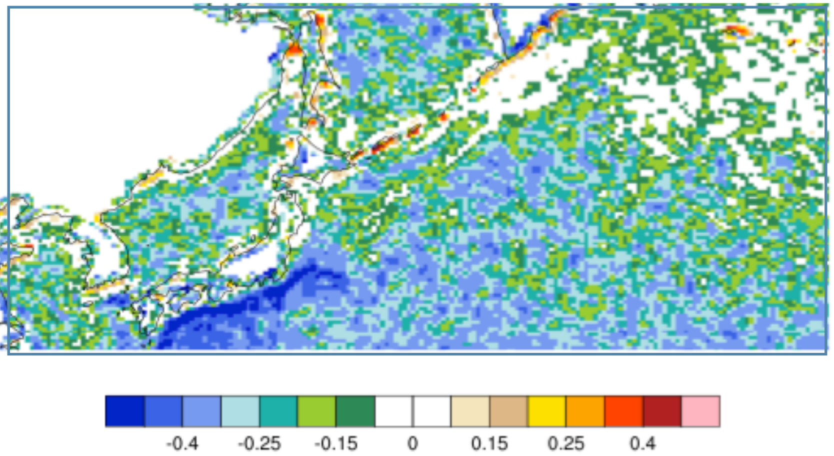
Correlation, Convergence and Lap(SLP)



Correlation, Lap(SST) and Convergence



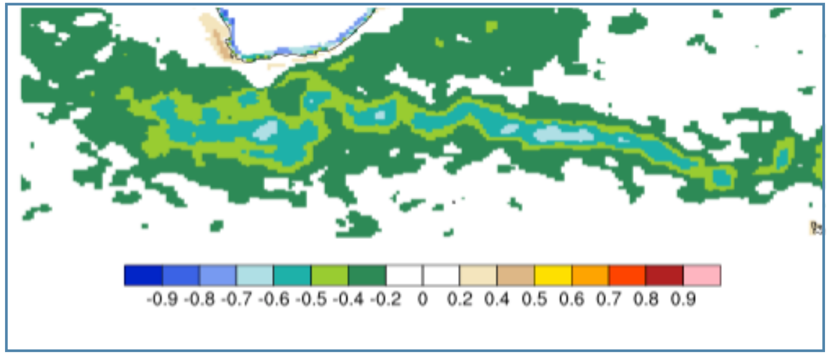
Correlation, Lap(T(air)) and Convergence



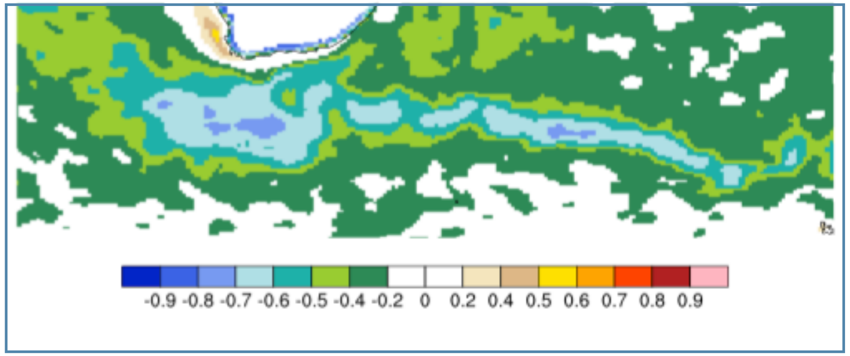
Note reduced color bars in last two panels

Results: Agulhas return Current

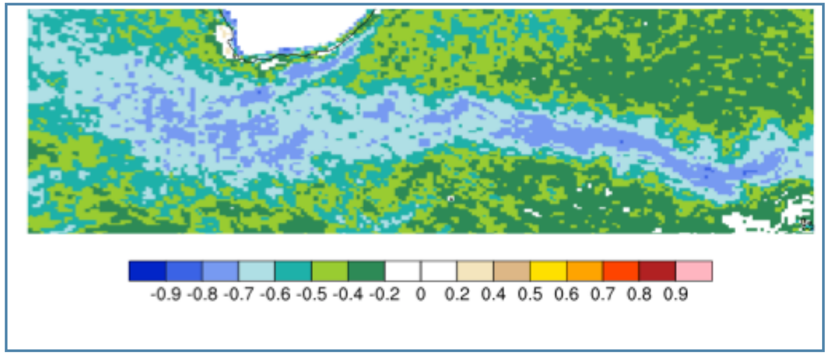
Correlation, SST and sea level pressure



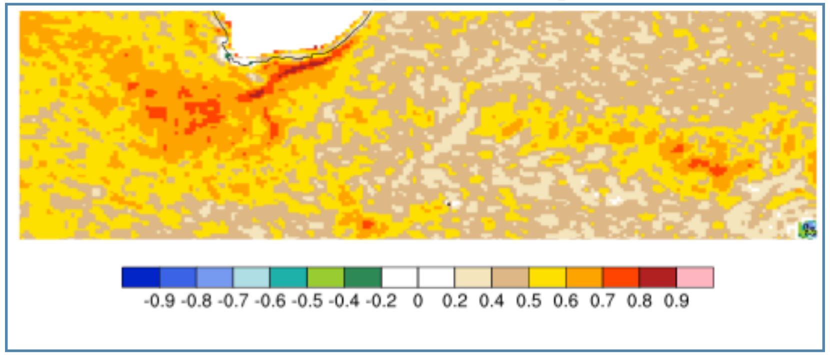
Correlation, T(air) and sea level pressure



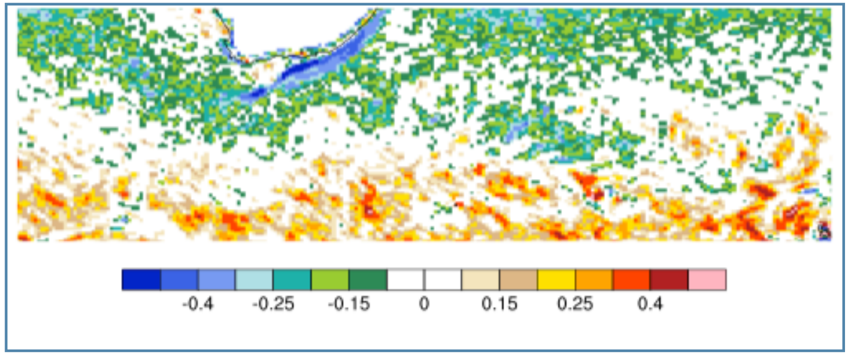
Correlation, Lap(T(air)) and Lap(SLP)



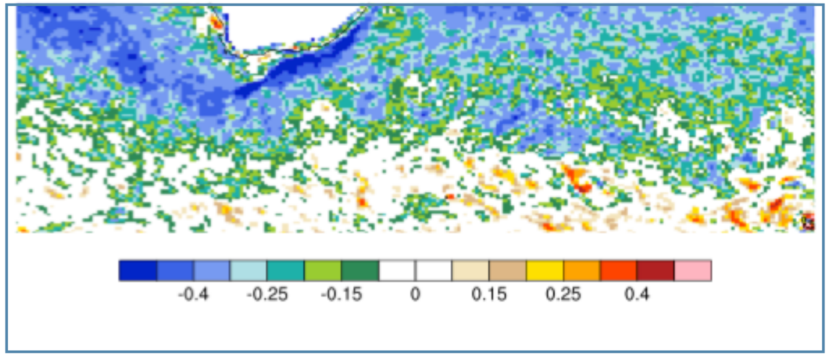
Correlation, Convergence and Lap(SLP)



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

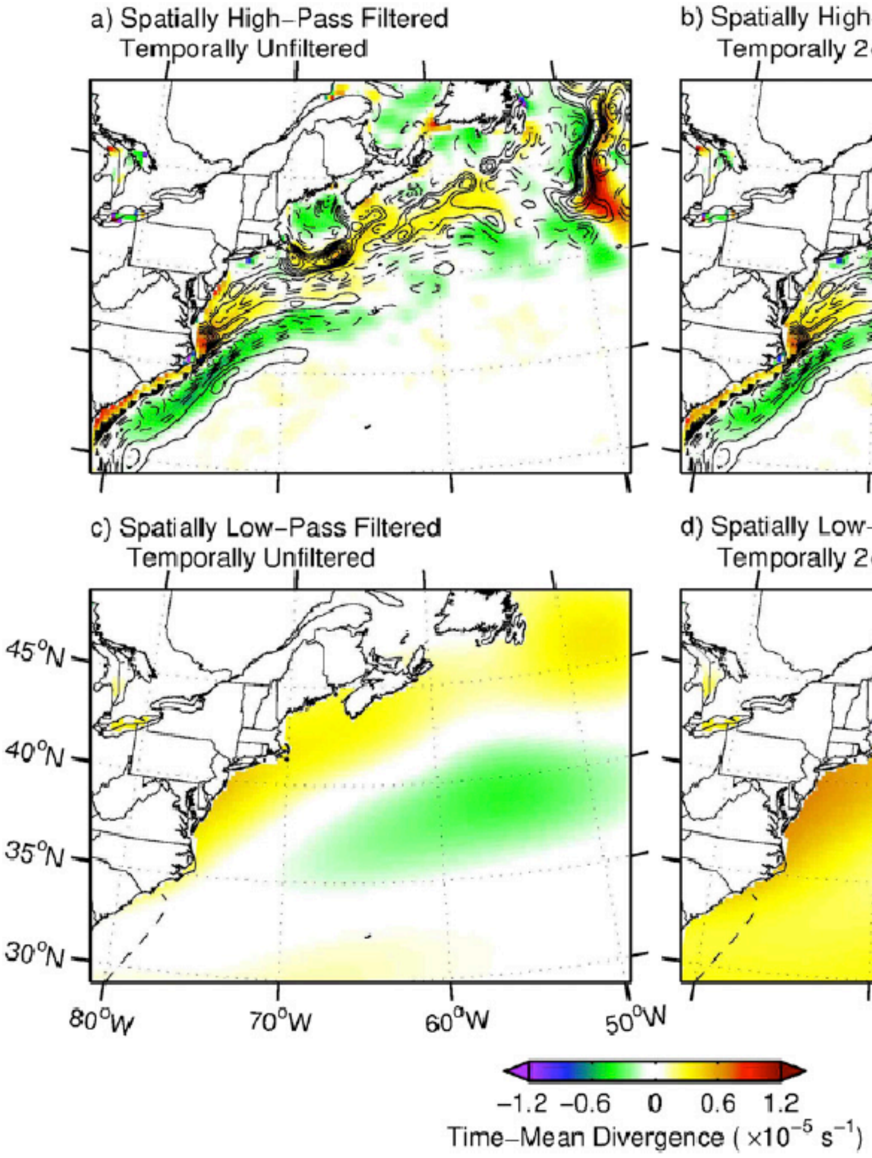


FIG. 11. Maps of the 10-yr time-mean QuikSCAT divergence (colors) and Reynolds SST Laplacian (contours). Each map differs in the spatial and temporal filtering applied to the divergence and SST Laplacian as follows: (a) temporally unfiltered and spatially high-pass filtered, (b) temporally 2σ extreme-value filtered and spatially high-pass filtered, (c) temporally unfiltered and spatially low-pass filtered, and (d) temporally 2σ extreme-value filtered and spatially low-pass filtered. The spatial high (low)-pass filter attenuates spatial variability with wavelengths longer (shorter) than 1000 km. For the SST Laplacian contours, the contour interval is $1 \times 10^{-10}\,°\mathrm{C\,m^{-2}}$, positive contours are solid and negative dashed, and the zero contour has been omitted for clarity.

O'Neill et al. 2017, JCLIM. QuiKSCAT data.

$-\varepsilon/(\varepsilon^2 + f^2) \times \nabla^2 P$ & LML Conv. ($10^{-5}\ s^{-1}$)
ne120, 30 levels, 0.25° Daily SST, annual using 7 years
(f.e11.b16.F2000C5.ne120_025.bob_011)

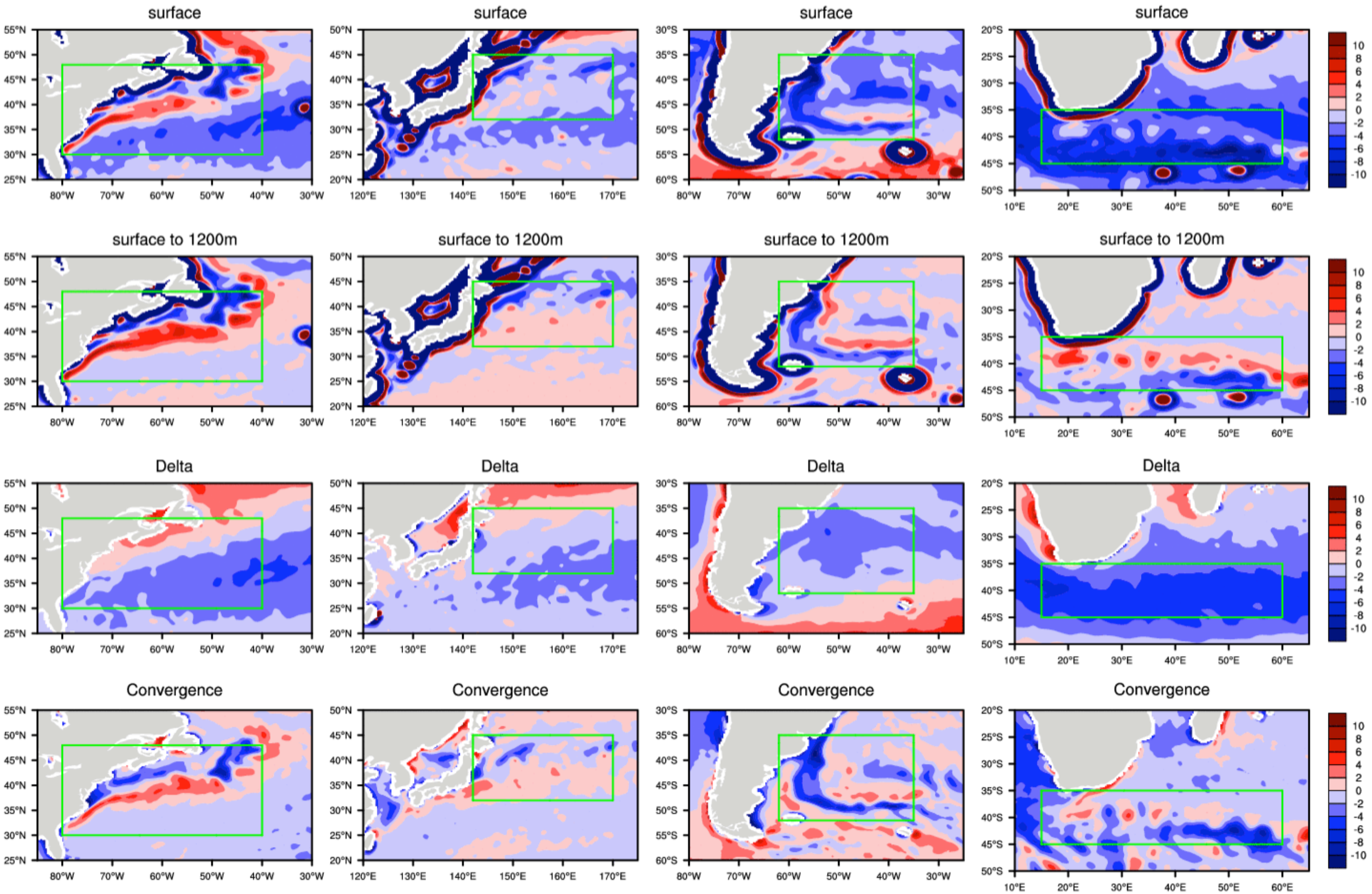
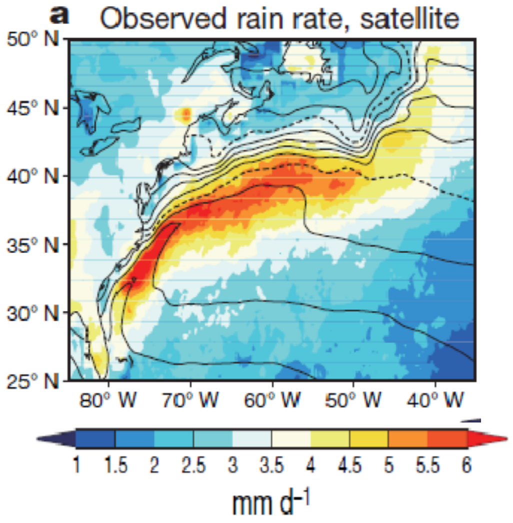


Fig.4. The estimated surface convergence response to Laplacian of: top: surface pressure second row: boundary layer pressure increment, third row: deep pressure. Final row: full model surface convergence. Courtesy Bob Tomas. See also Minobe/Takatama/Terray.

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