Mechanisms for boundary layer wind response to the Gulf Stream in a regional atmospheric model

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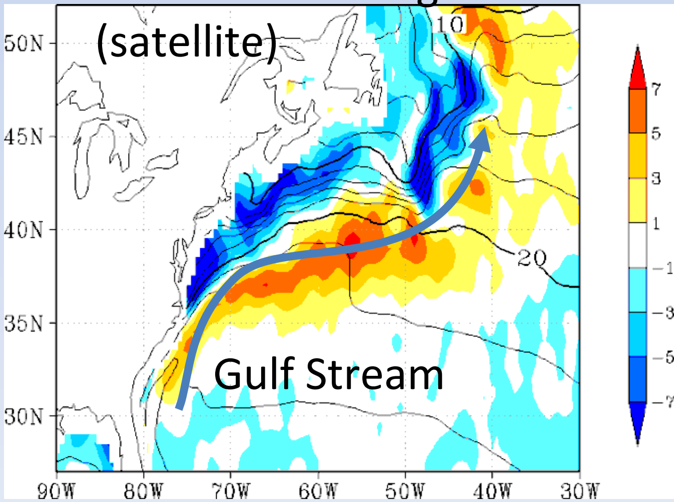
10-m wind convergence



1. INTRODUCTION

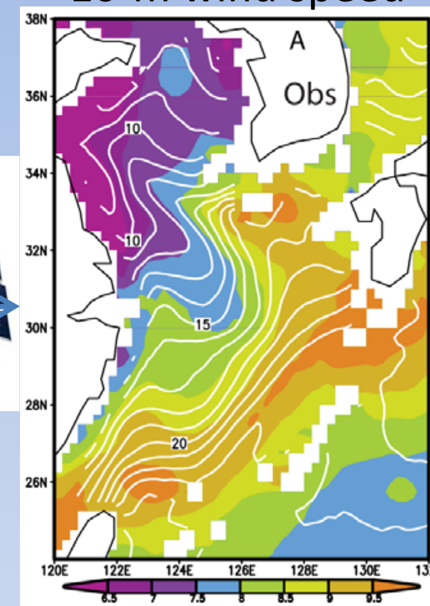
Air-sea interaction over cool ocean

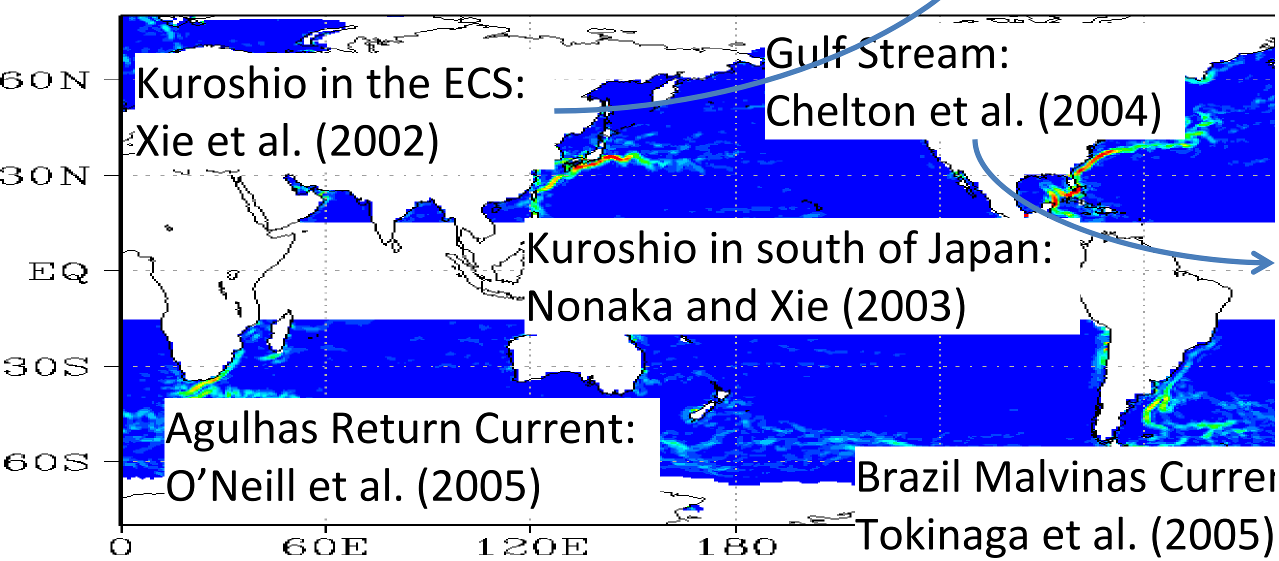
- **Low resolution** studies (before early ’00s)
  - Basin scale long-time averaged SST is negative correlated with surface wind speed
  - Cool ocean was thought to be passive for atmosphere.

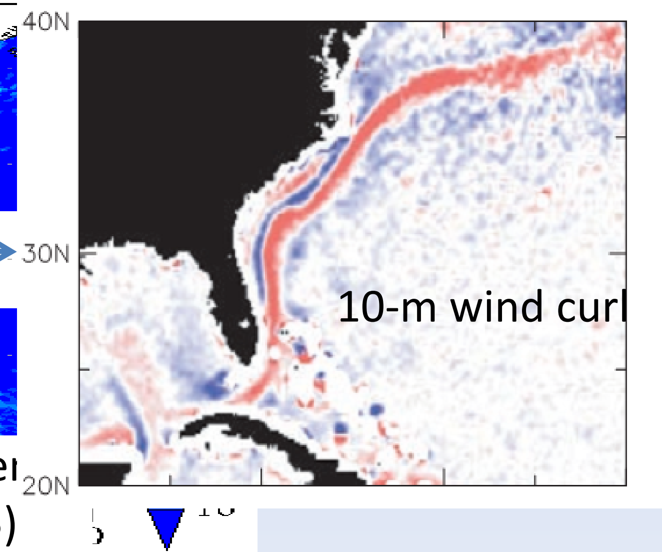
Air-sea interaction over cool ocean

- **Low resolution** studies (before early ’00s)
  - Basin scale long-time averaged SST is negative correlated with surface wind speed
    - ➢ Cool ocean was thought to be passive for atmosphere.
- **High resolution** studies (after early ’00s)
  - Surface winds exhibit narrow structures anchored on oceanic currents.
    - ➢ Cool ocean can be active for atmosphere.

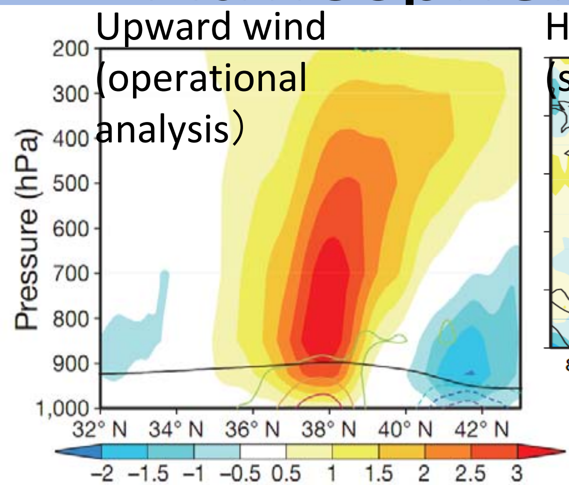
10-m wind speed

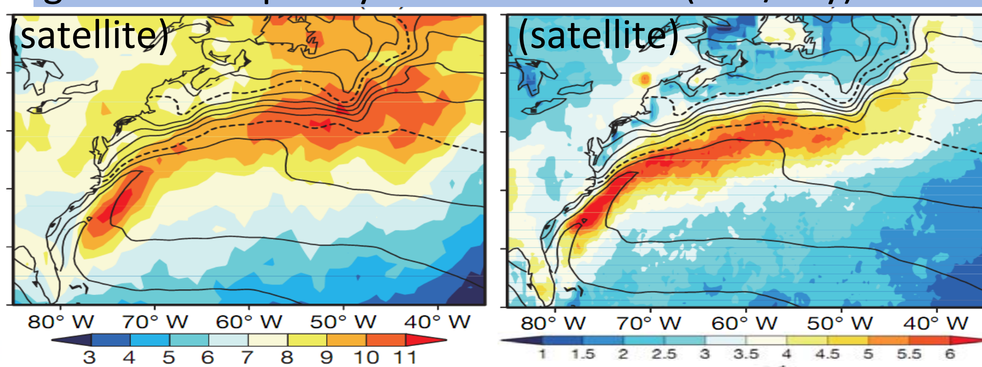






Atmospheric response to the Gulf Stream



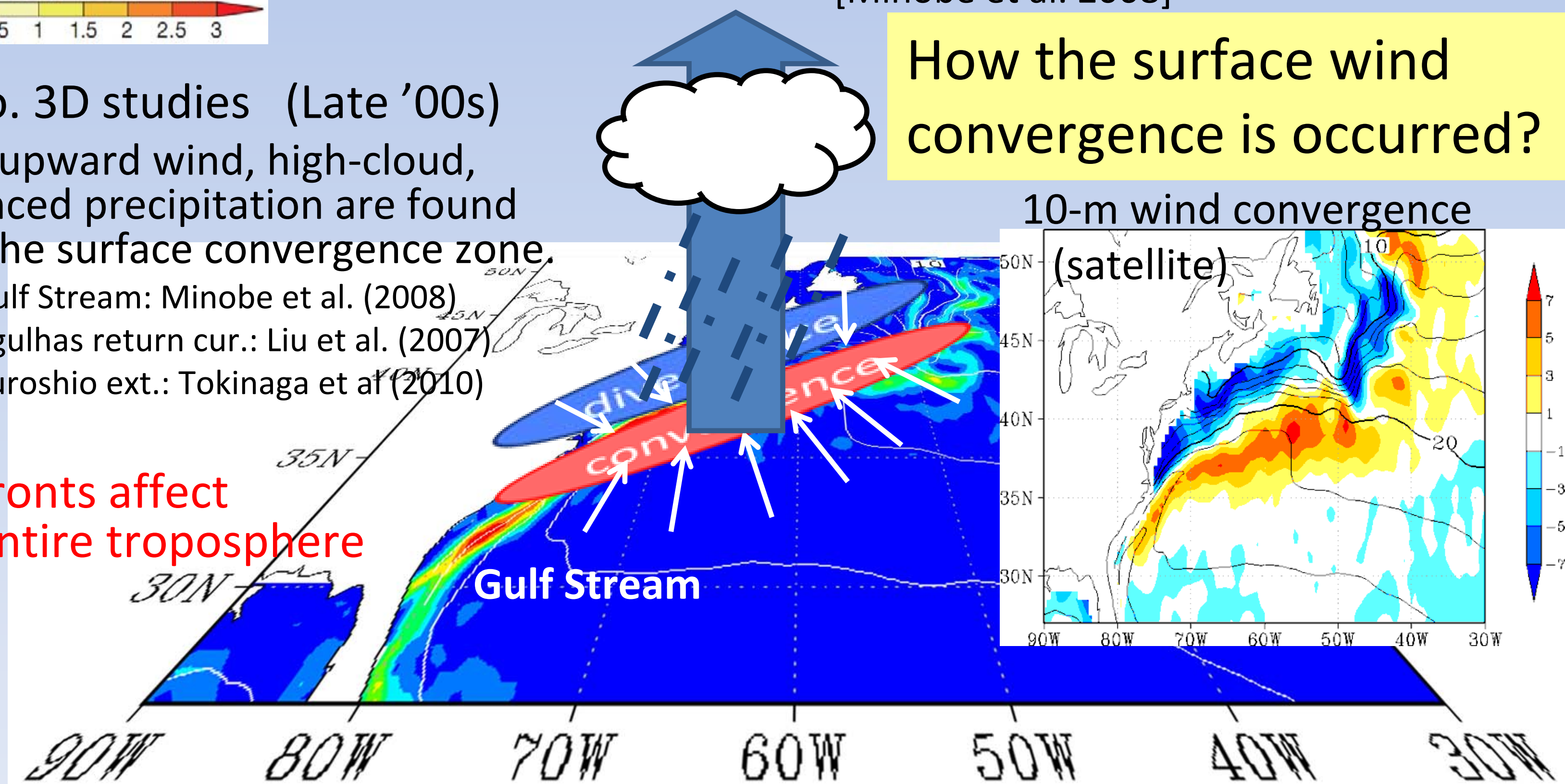


[Minobe et al. 2008]

How the surface wind convergence is occurred?

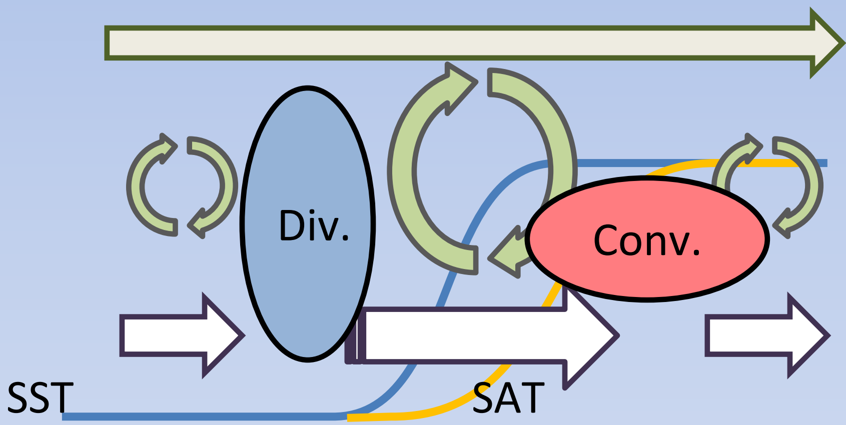
- High-reso. 3D studies (Late '00s)
  - Deep upward wind, high-cloud, enhanced precipitation are found over the surface convergence zone.
    - Gulf Stream: Minobe et al. (2008)
    - Agulhas return cur.: Liu et al. (2007)
    - Kuroshio ext.: Tokinaga et al (2010)

➢ SST fronts affect the entire troposphere

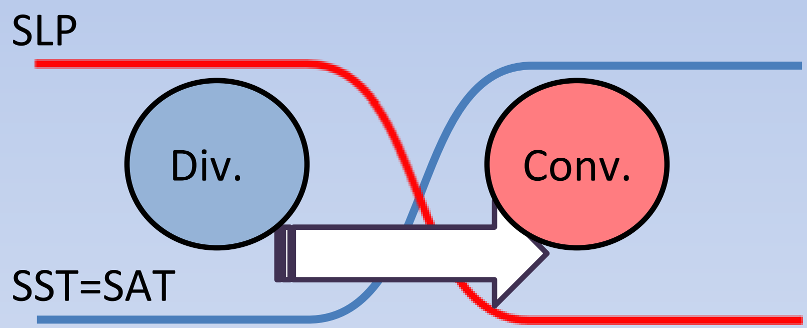


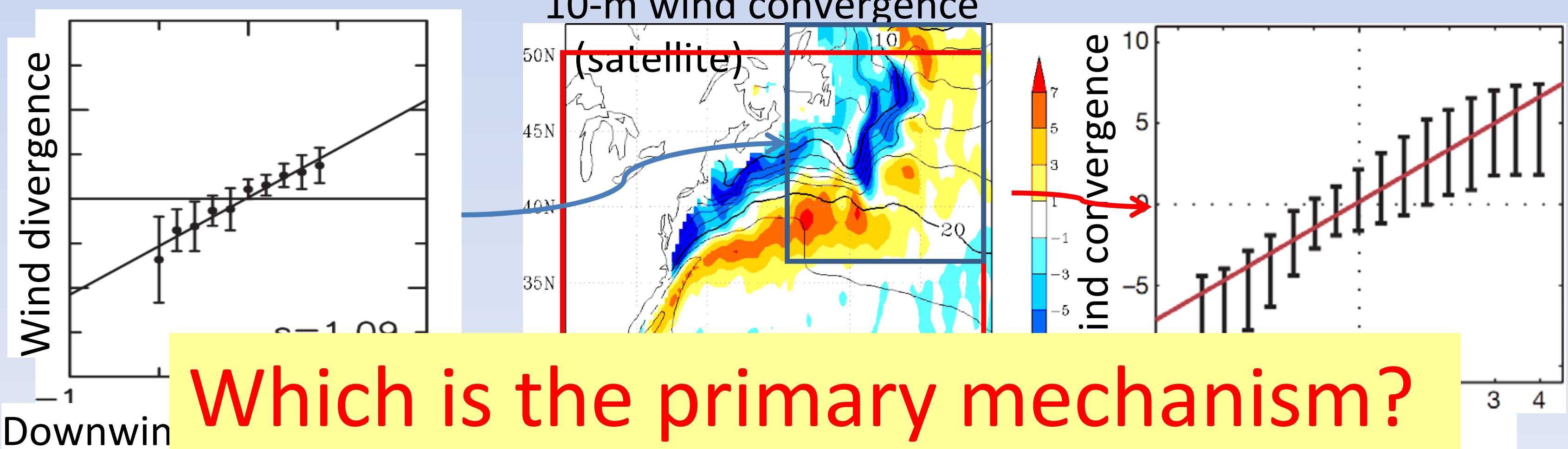
Mechanisms of wind response to SST fronts

Downward momentum mixing mechanism
(Wallace et al. 1989)



Pressure adjustment mechanism
(Lindzen and Nigam 1987)





Chelton et al. (2004, Science)

Minobe et al. (2008, Nature)

Which is the primary mechanism?

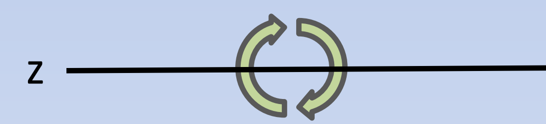
2. MODEL AND METHOD

Momentum budget analysis

- Conventional diagnostics:
  momentum budget at a certain height
  - **Tropics**: Small et al. (2003); **The gulf Stream**: Wai and Stage (1989), Song et al. (2006); **Southern ocean**: O'Neill et al. (2010); **Idealized front**: Spall et al. (2007), Skyllingstad et al. (1989)

$$\cancel{\frac{\partial \vec{u}}{\partial t}} = -f\vec{k}\times\vec{u} \quad -\vec{u}\nabla\cdot\vec{u} \quad -\frac{1}{\rho}\nabla p \quad +\frac{\partial \vec{\tau}}{\partial z}$$

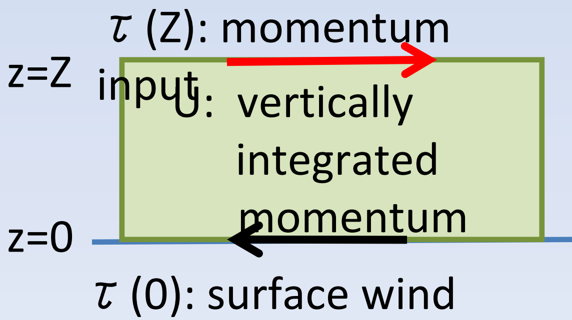
Coriolis | Horizontal advection | Pressure gradient | Vertical mixing



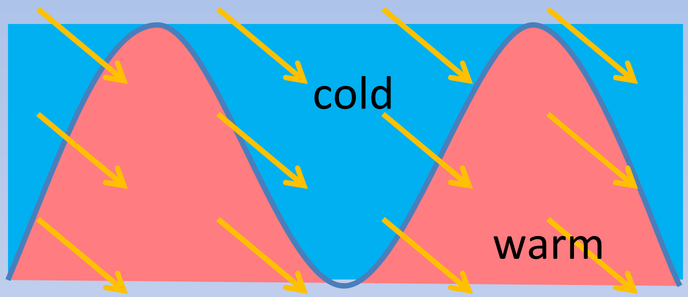
- Our new diagnostics:
  momentum budget of a vertically integrated air column

$$\cancel{\frac{\partial \vec{U}}{\partial t}} = -f\vec{k}\times\vec{U} \quad +\vec{A} \quad -\nabla P \quad +\vec{\tau}(Z)-\vec{\tau}(0)$$

Horizontal advection



In the case of pure downward momentum mixing mechanism



(Hayes et al. 1989)

Upper level wind

$$u_2 = \mathrm{const}$$

Surface wind

$$u_1 = \frac{c}{\varepsilon} u_2$$

Momentum input/output in Surface layer

$$\tau(Z) = c(\mathrm{SST}) u_2$$

$$\tau(0) = \varepsilon u_1$$

Dumping time scale due to surface stress

Steady state

$$\vec{\tau}(Z) - \vec{\tau}(0) = 0$$

Our new diagnostics show contribution of the downward momentum mixing.

$$u_1 = \frac{1}{\varepsilon} \vec{\tau}(Z)$$

The conventional diagnostics show only balance, cannot show the contribution.

$$\frac{\partial}{\partial z} \vec{\tau} = 0$$

… and the pressure adjustment mechanism

$$-\nabla P \quad + \vec{\tau}(Z) \quad - \vec{\tau}(0) = 0$$

Our diagnostics 1 10 -11 Downward momentum input is the primary forcing.

Conventional diagnostics

$$\frac{\partial}{\partial z}\vec{\tau}$$

Must balance with other forcing -1

The net vertical friction term always work as dumping.

Diagnostics for convergence

- Our basic equation:

$$0 = -f\vec{k} \times \vec{U} + \vec{A} - \nabla P + \vec{\tau}(Z) - \vec{\tau}(0)$$

Where is the pressure adjustment contribution?

$$-\nabla \cdot \vec{U} = -\frac{1}{f} \nabla \times (\vec{A} + \vec{\tau}(Z) - \vec{\tau}(0))$$

  - Pressure adjustment mechanism should cause convergence through surface stress.

- Considering that $\vec{\tau}(0)$ is linear sum of each forcing,

$\vec{\tau}(0) =$ forcing due to the downward momentum mixing mechanism
+ forcing due to the pressure adjustment mechanism
+ forcing due to horizontal advection
+ forcing due to …

- $\vec{\tau}(0)$ can be treated as $\vec{\tau}(0) = \varepsilon \vec{U}$

$$0 = -f\vec{k} \times \vec{U} + \vec{A} - \nabla P + \vec{\tau}(Z) - \varepsilon \vec{U}$$

This is only an assumption in our diagnostics.

Diagnostics for convergence

- Diagnostic equation for convergence is:

$$-U_x - V_x =$$

$M_1=[\varepsilon/(\varepsilon^2+f^2)]_x+[-f/(\varepsilon^2+f^2)]_y$

$M_2=[f/(\varepsilon^2+f^2)]_x+[\varepsilon/(\varepsilon^2+f^2)]_y$

The most important

Downward momentum mixing

$$-\frac{\varepsilon}{\varepsilon^2+f^2}\nabla\bullet\vec{\tau}(Z)-\frac{f}{\varepsilon^2+f^2}\nabla\times\vec{\tau}(Z) \quad -M_1\tau^x(Z)-M_2\tau^y(Z)$$

Pressure adjustment

$$+\frac{\varepsilon}{\varepsilon^2+f^2}\nabla^2 P \quad +M_1P_x+M_2P_y$$

Horizontal advection

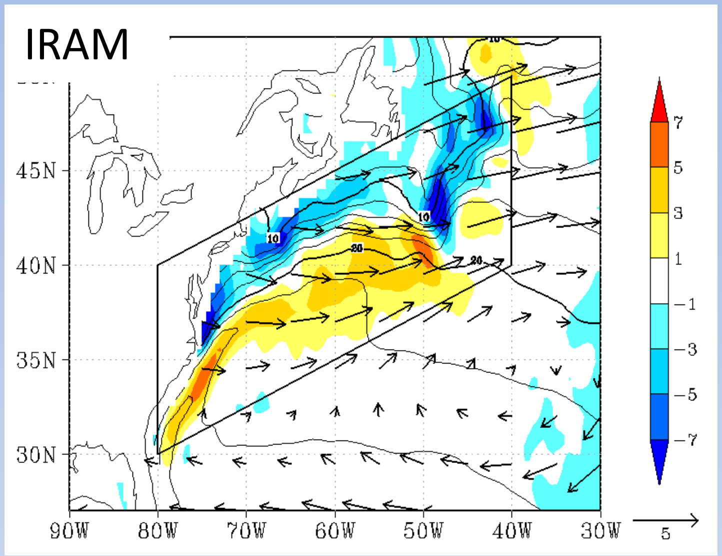
$$-\frac{\varepsilon}{\varepsilon^2+f^2}\nabla\bullet\vec{A}-\frac{f}{\varepsilon^2+f^2}\nabla\times\vec{A} \quad -M_1A^x-M_2A^y \quad .$$

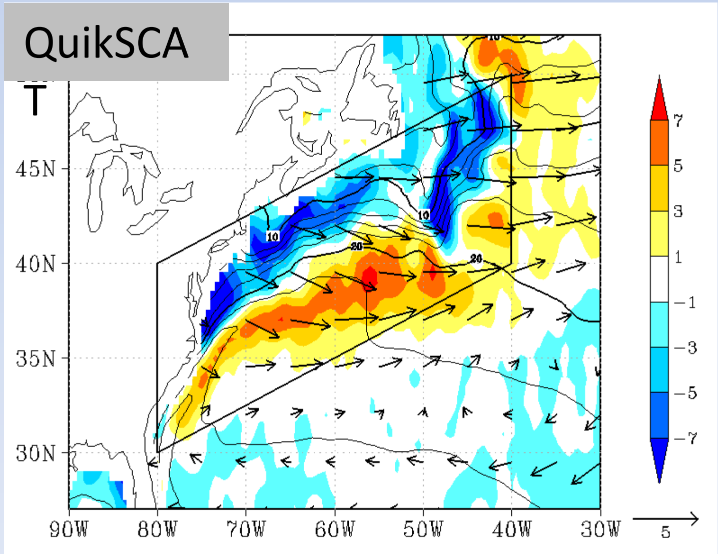
Experimental design

- Model: IPRC Regional Climate Model (Wang 2002)
- Domain:
  - 100°W-20°W
  - 5°N-65°N
- Resolution
  - Horizontal: 0.5°
  - Vertical: 28 σ layers
- Period: 5 years (Dec. 2001- Nov. 2006)
- Boundary condition
  - Lateral: NCEP reanalysis 1 (6hourly, 2.5°)
  - SST: NCEP Real Time Global SST (daily, 0.5°)

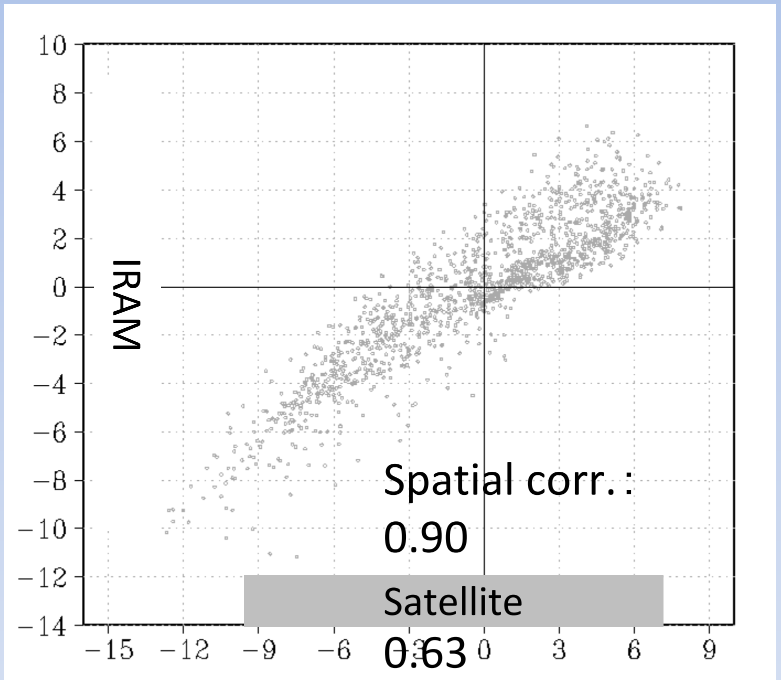
3. RESULT

Reproducibility of the 10-m wind conv.



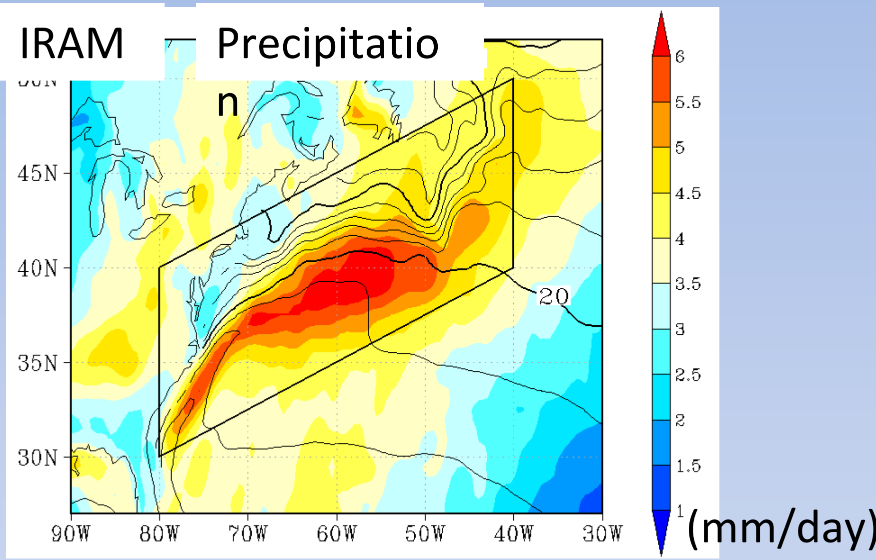


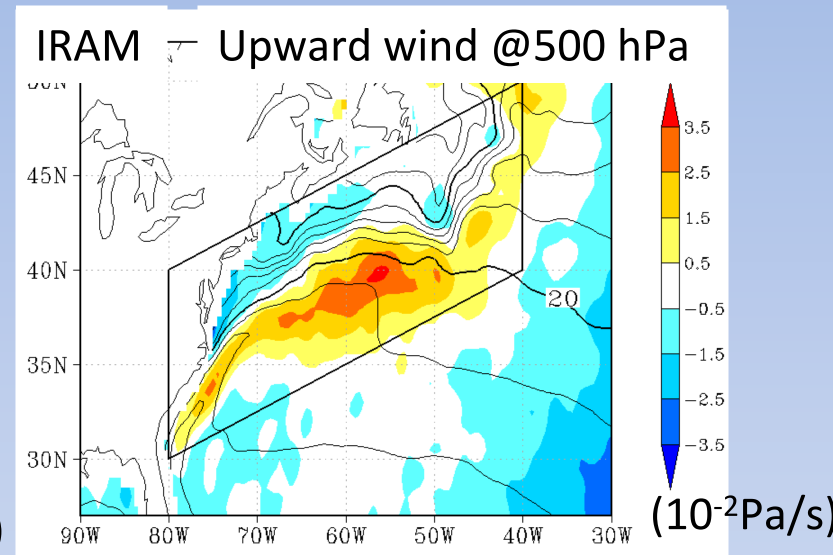
Annual climatology of 10-m wind convergence (color), SST contour, wind vector

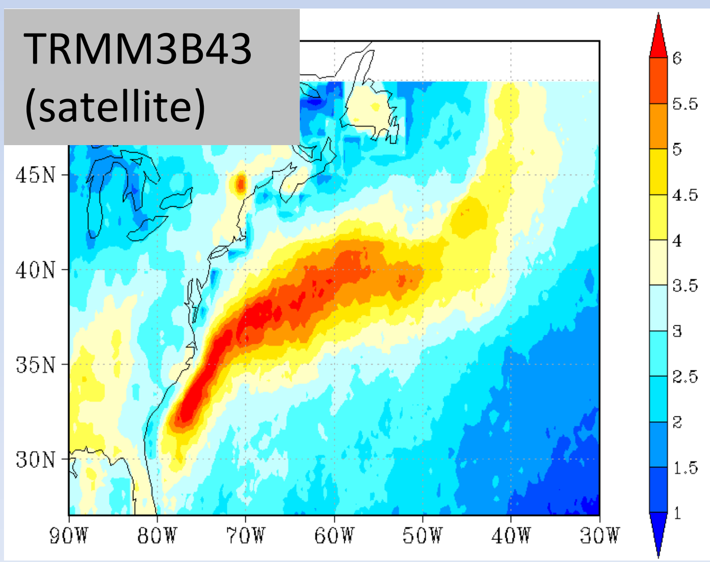


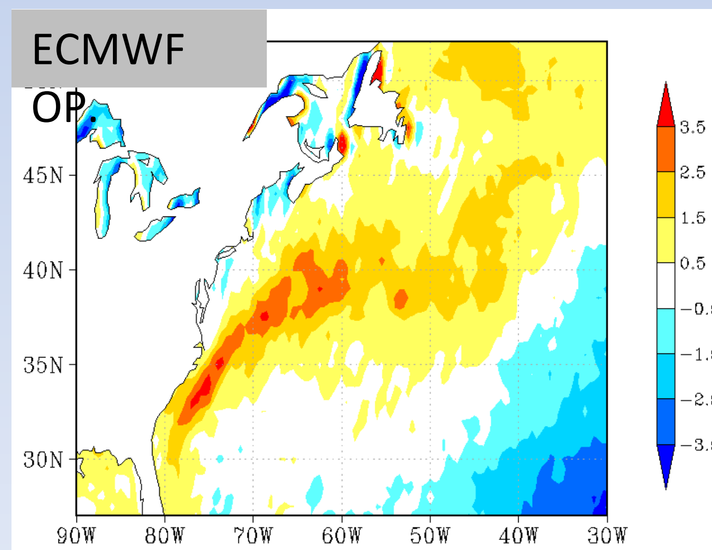
Spatial pattern is successfully captured by the model.

Reproducibility of the tropospheric response



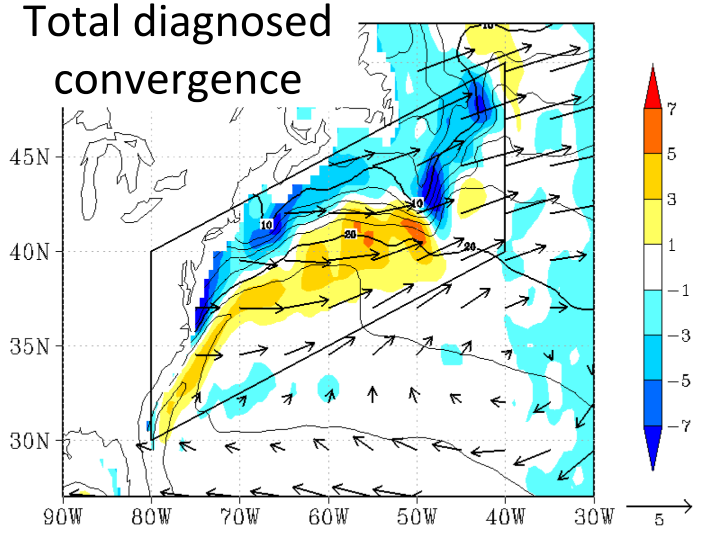




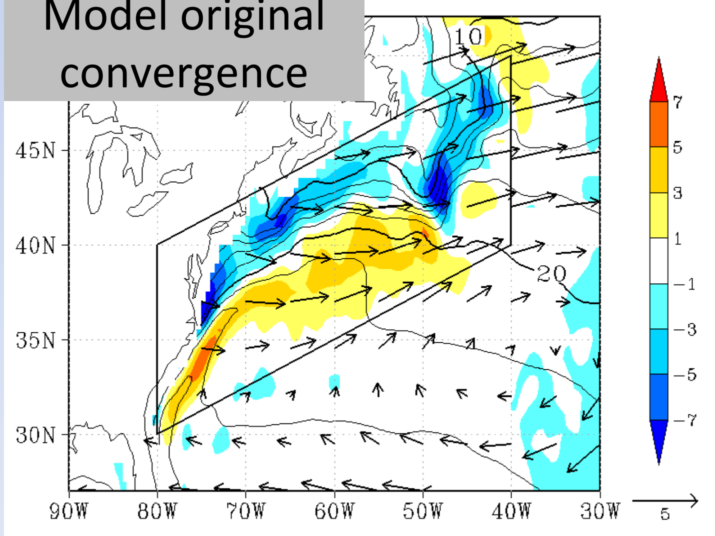


Validation of the diagnostics

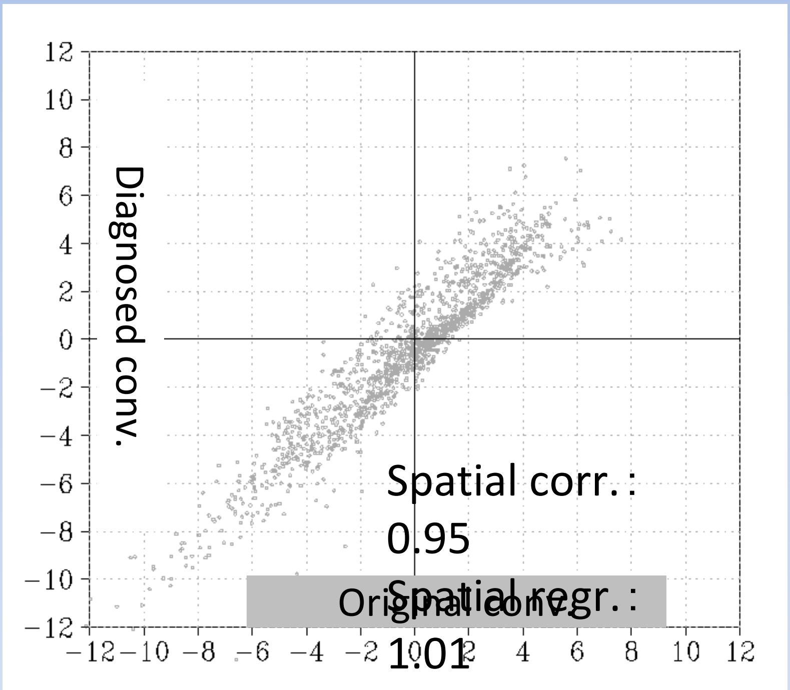
Total diagnosed convergence



Model original convergence



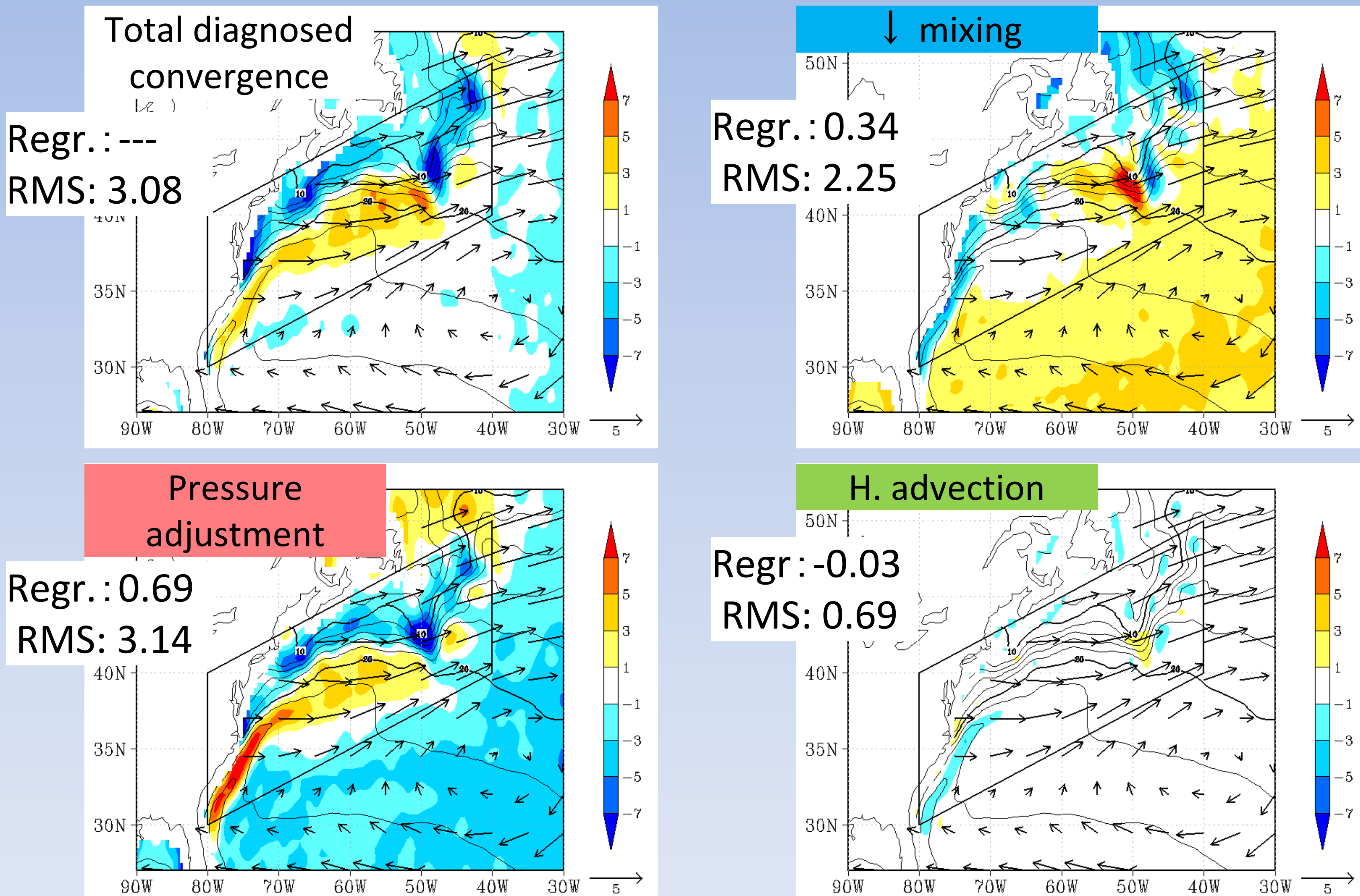
Annual climatology of
vertically averaged momentum convergence



This ascertains the validity of the assumption.

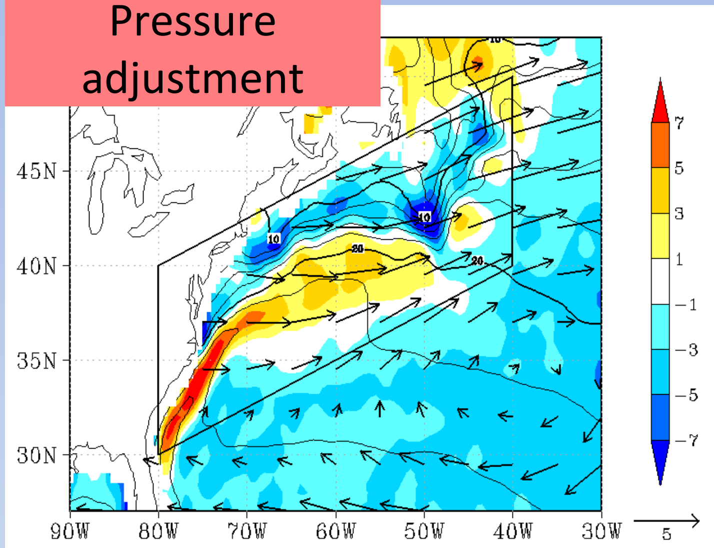
The surface winds are well represented by the vertically averaged momentum

Contribution of each mechanism



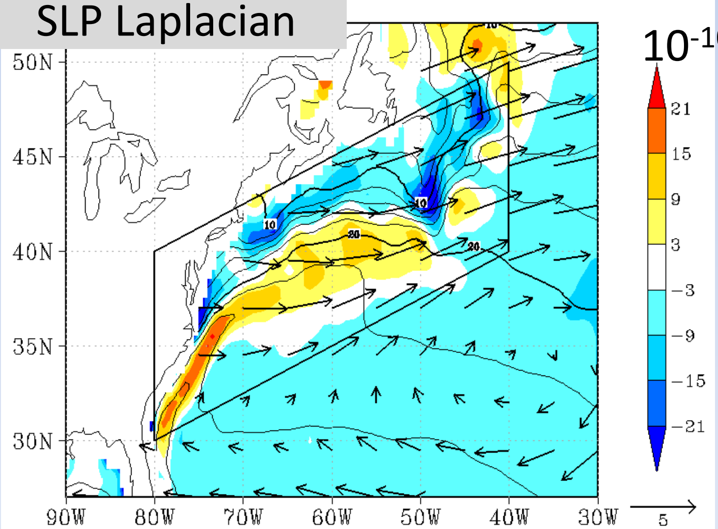
Spatial pattern of the pressure adjustment mechanism

Pressure adjustment

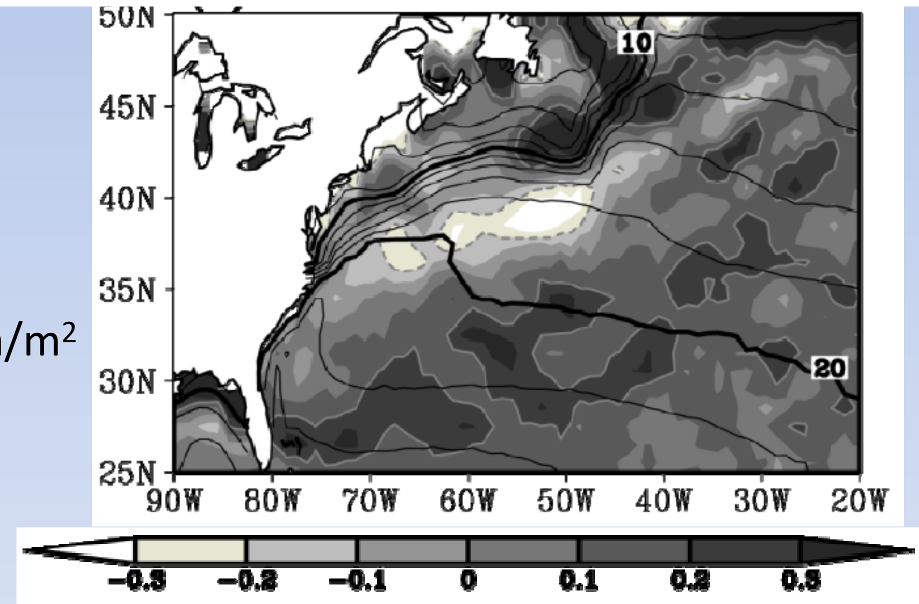


SLP Laplacian

10^{-10} Pa/m^2



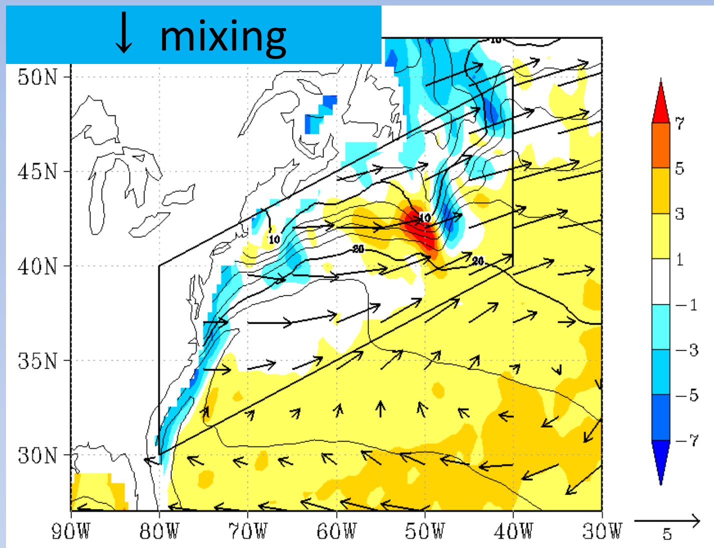
High-pass filtered ICOADS climatological SLP

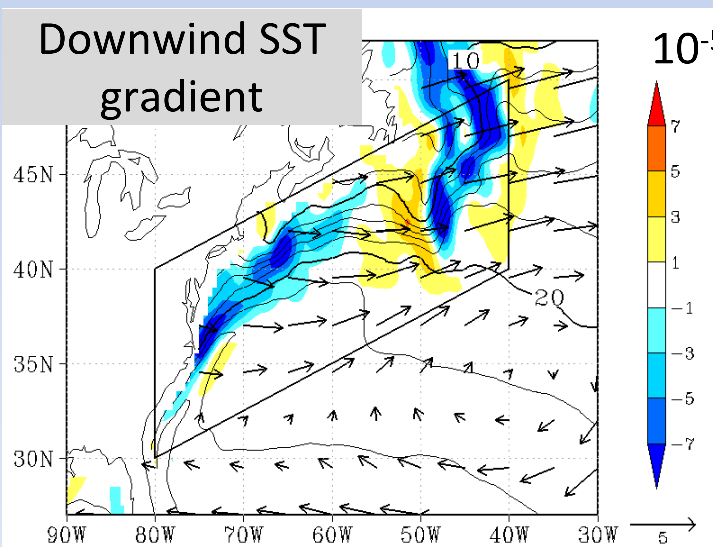


Minobe et al. [2010]

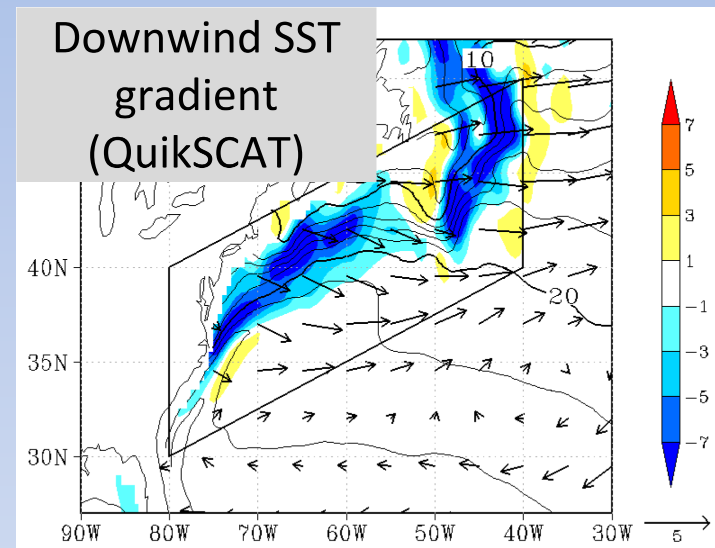
Spatial pattern of the pressure adjustment mechanism is explained by SLP Laplacian,

Spatial pattern of the downward momentum mixing mechanism



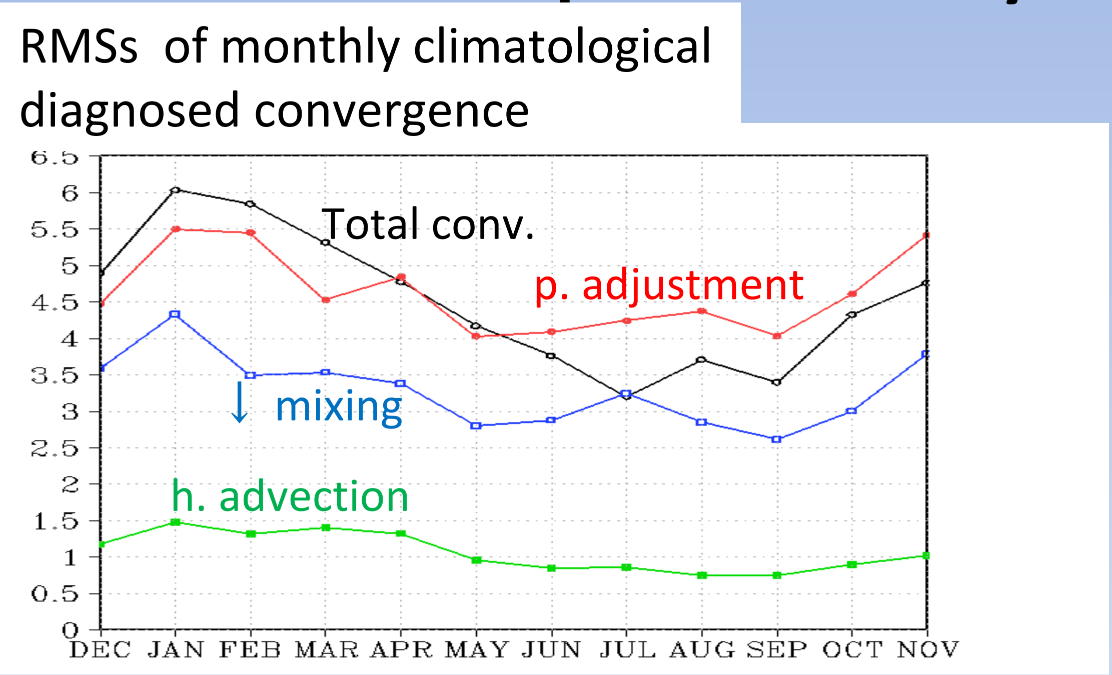


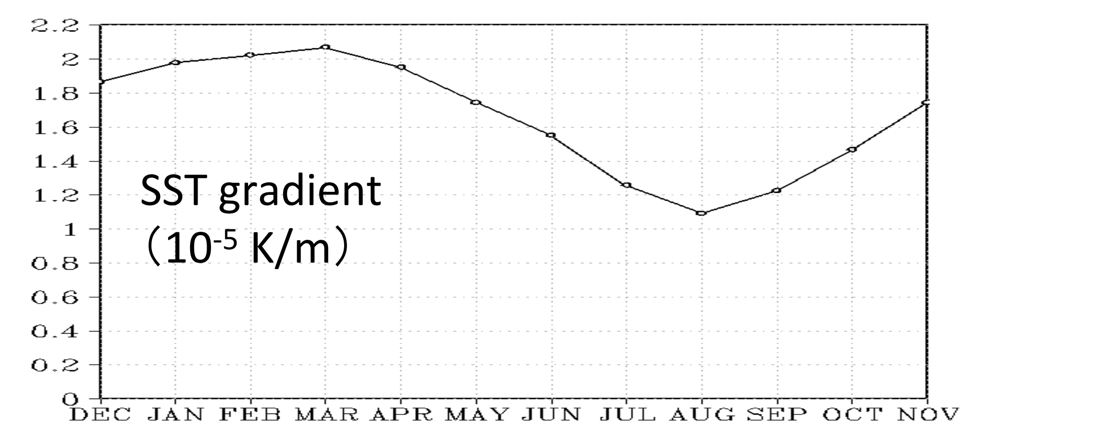
10^{-5} K/m/s



Spatial pattern of the downward momentum mixing mechanism is explained by downwind SST gradient.

Seasonal dependeincy



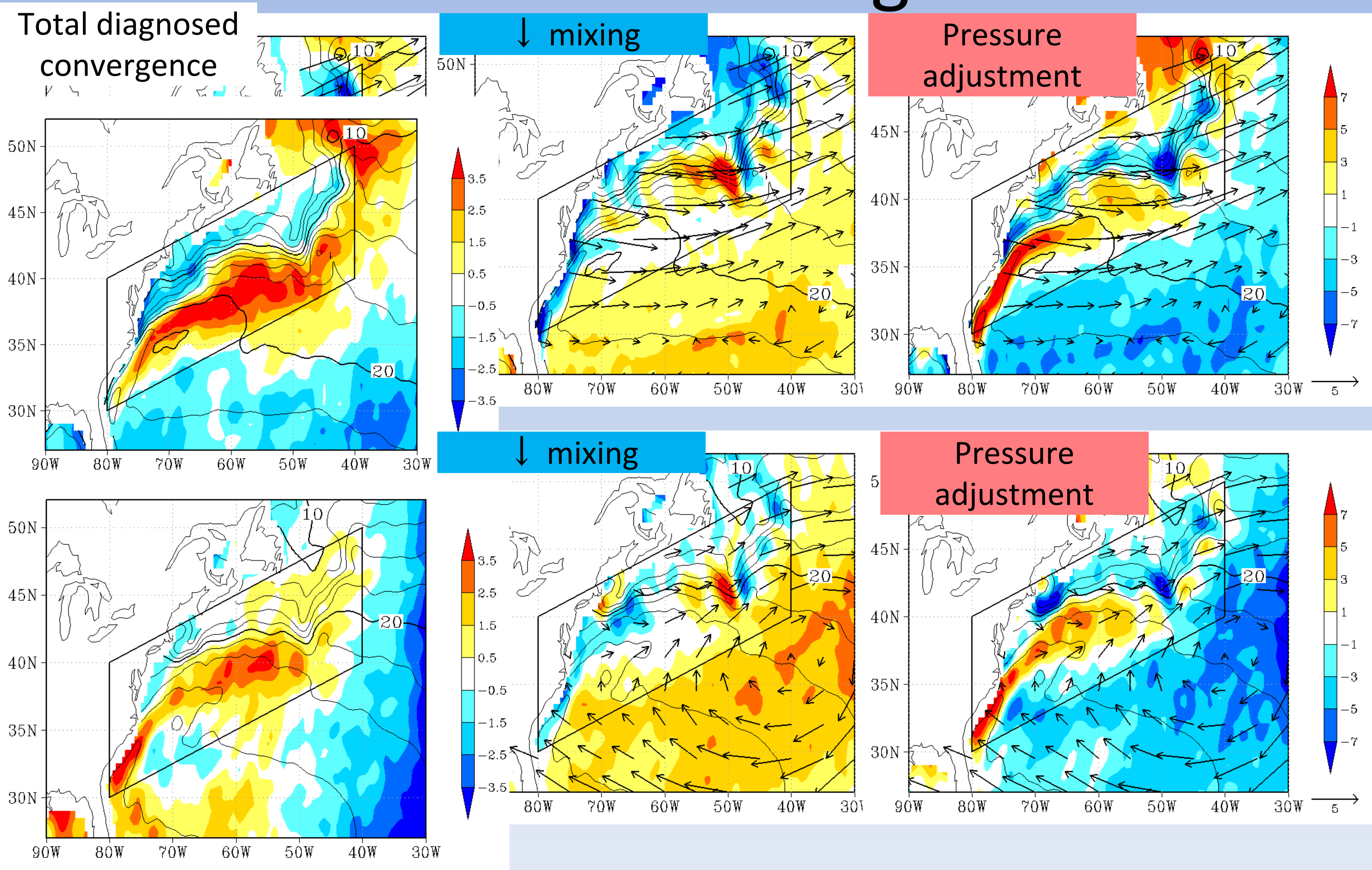


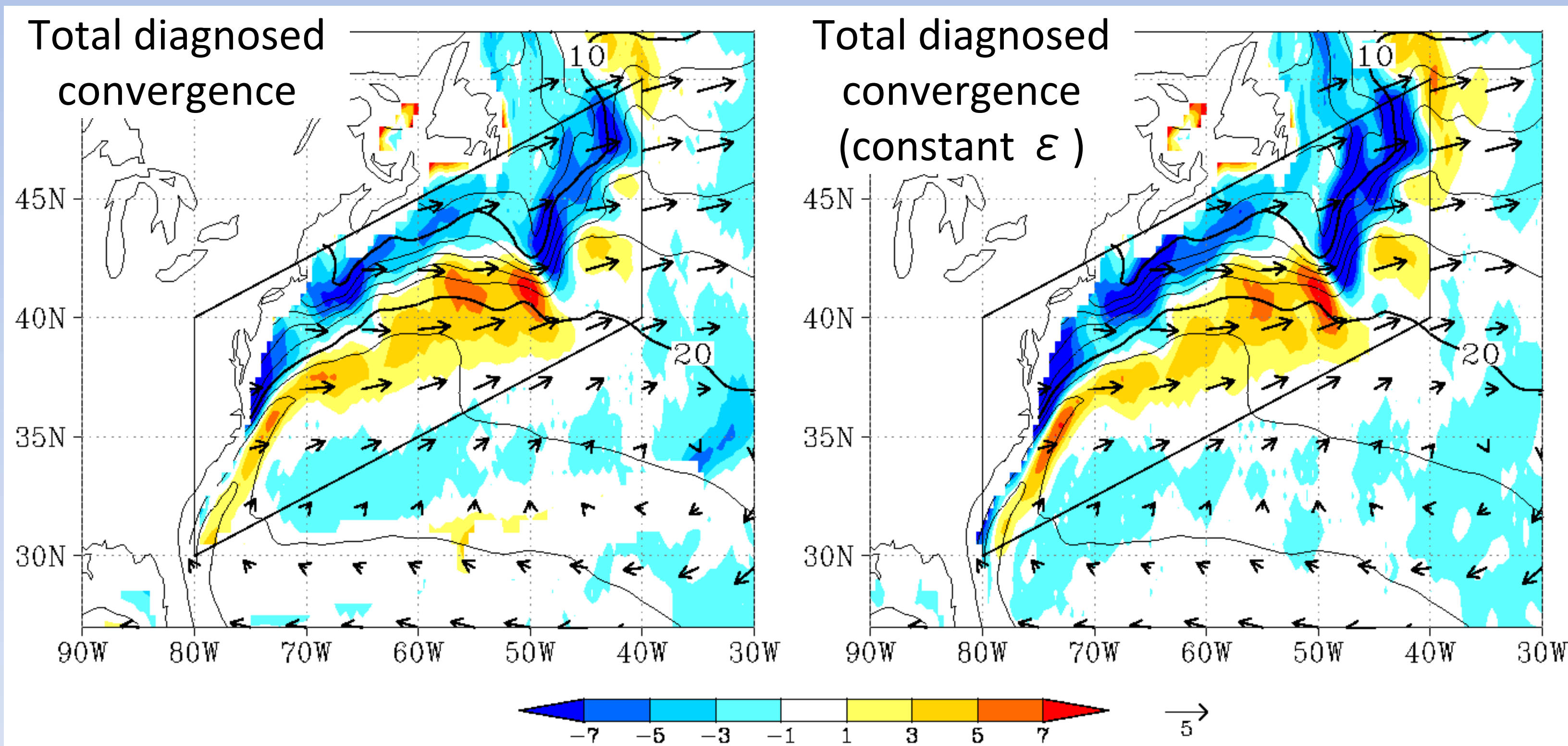
4. SUMMARY

Summary

- We apply new diagnostics for 5 years integration of IPRC regional climate model.
- The dominant (~70%) pressure adjustment mechanism and the secondary (~30%) downward momentum mixing mechanism coexist for the surface wind divergence/convergence over the Gulf Stream.
- The contributions of these mechanisms are qualitatively explained:
  - the SLP Laplacian for the pressure adjustment mechanism,
  - the downwind SST gradient for the downward momentum mixing mechanism.

Seasonal changes





Spatial corr.:
0.95
Spatial regr.:
1.01

Spatial corr.:
0.94
Spatial regr.:
1.11

$\varepsilon = 1.96 \times 10^{-4}$ /s