A Review of the Gulf Stream and Associated Impacts on Weather and Climate from the Modeling Perspective

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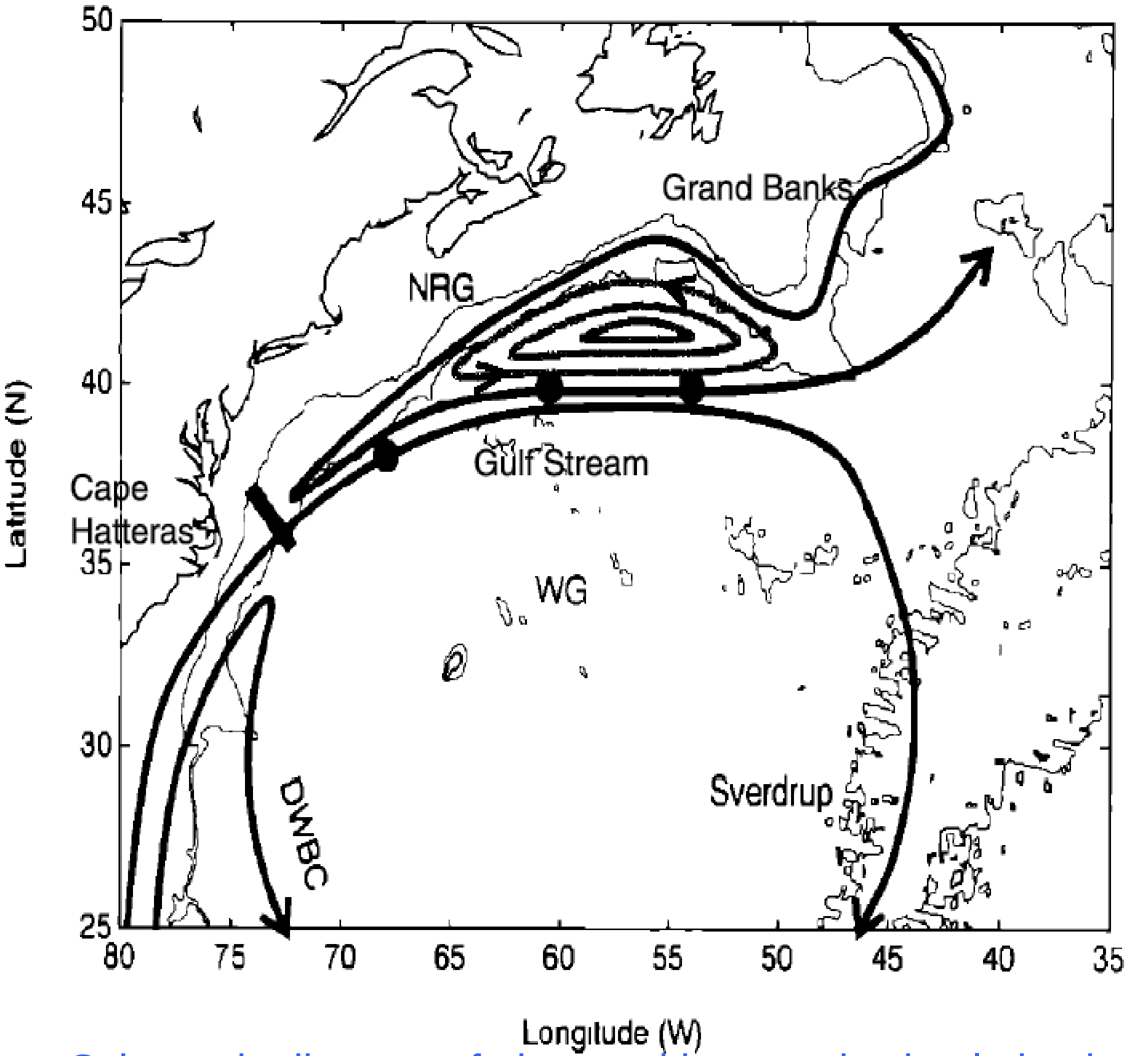
"Whither the Gulf Stream Workshop"

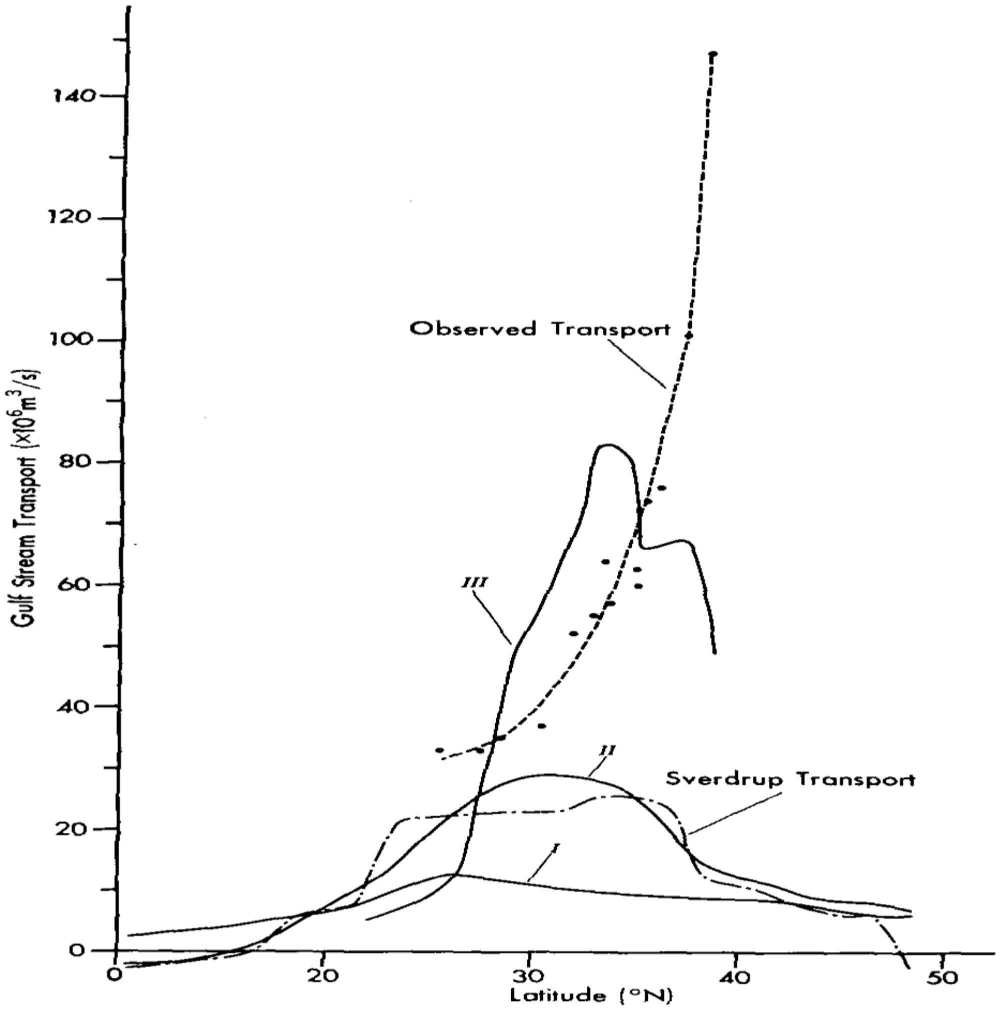
June 15, 2022

Introduction of the Gulf Stream Characteristics



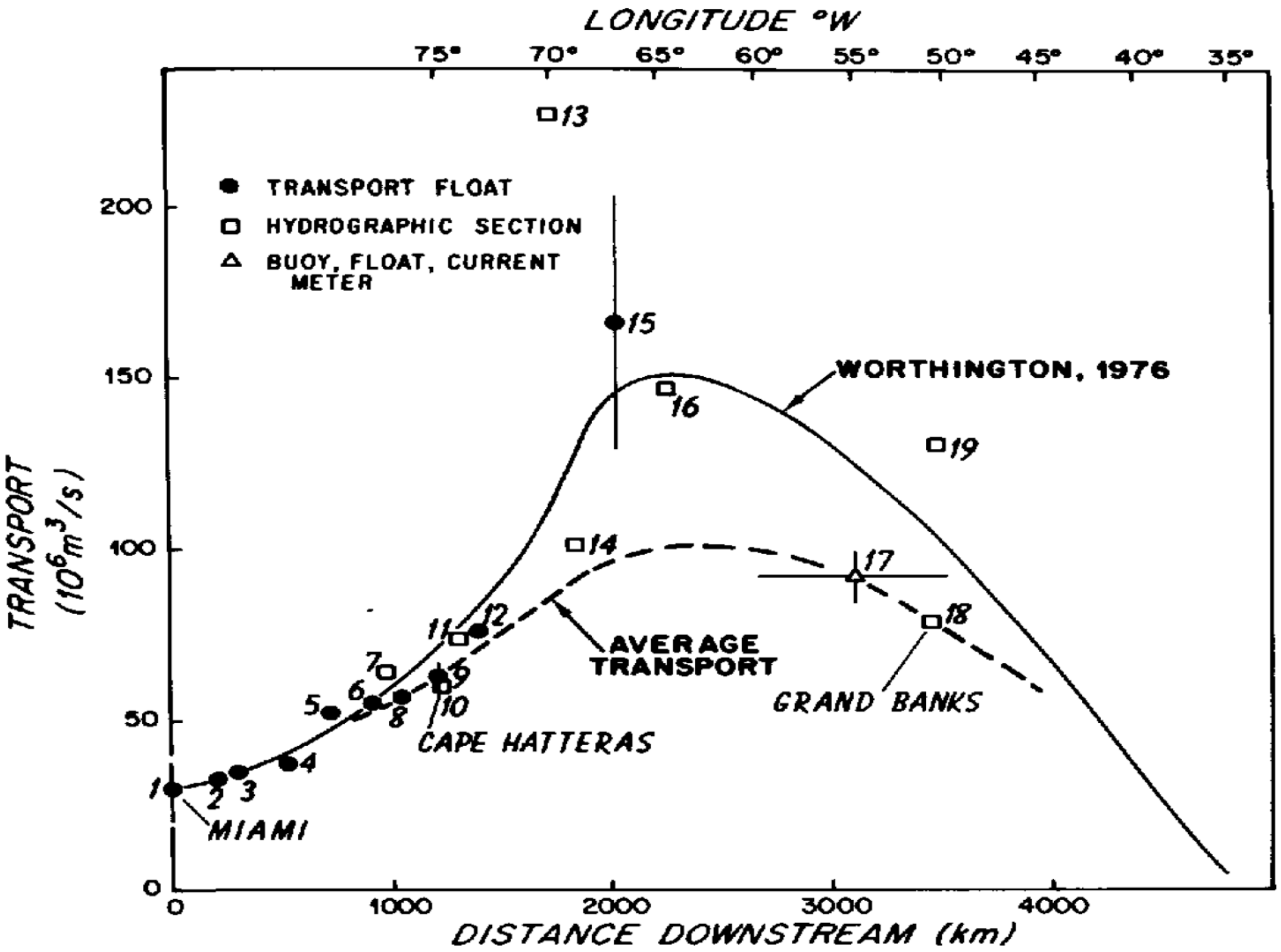
Schematic diagram of observed barotropic circulation in the western North Atlantic adapted from Hogg (1992)

The Gulf Stream separates at Cape Hatteras, where it intersects the deep western boundary current (DWBC)

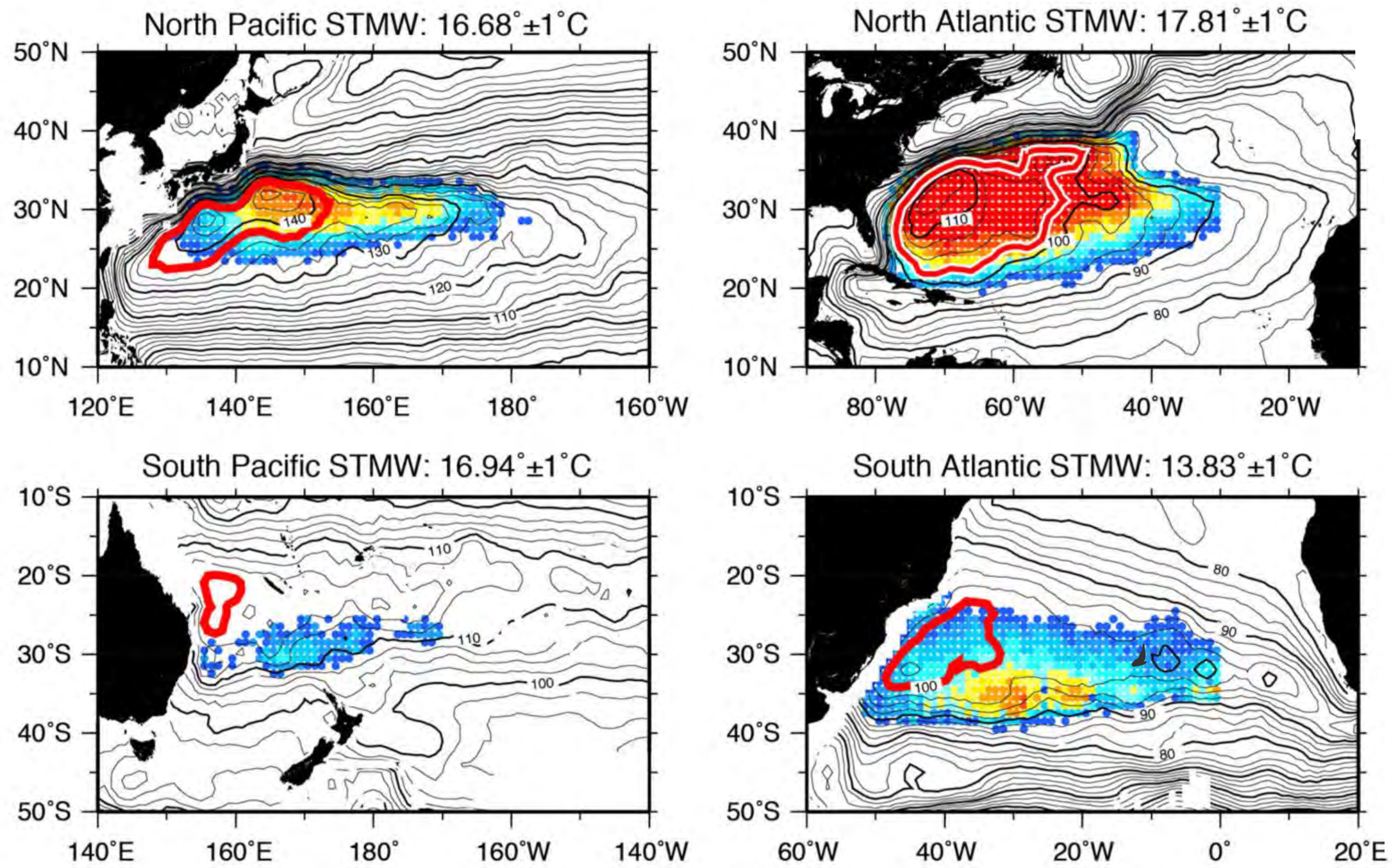


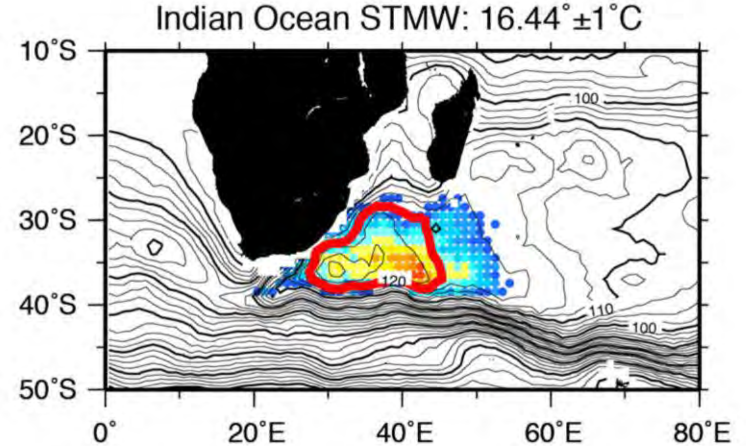
The Gulf Stream transport is much larger than that estimated from the wind-driven transport (Holland and Hirschman, 1972)

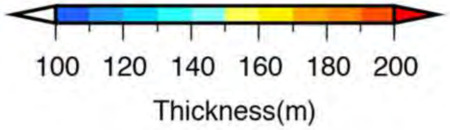
Introduction of the Gulf Stream Characteristics

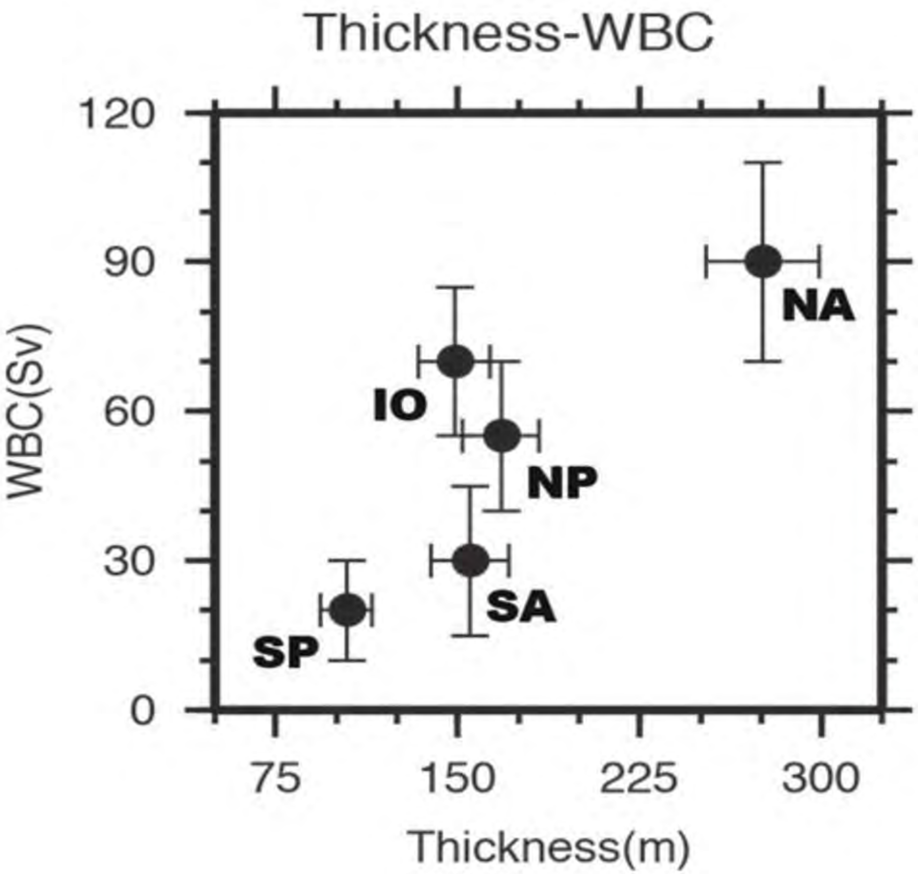


The observed mean Gulf Stream transport increases from ~30Sv at the Florida Straits to ~93Sv south of the Grand Banks; the observed synoptic Gulf Stream transport can reach ~150 Sv south of the Grand Banks (Richardson, 1985)









The largest WBC transport of the Gulf Stream is closely related to the existence of the AMOC in the Atlantic basin

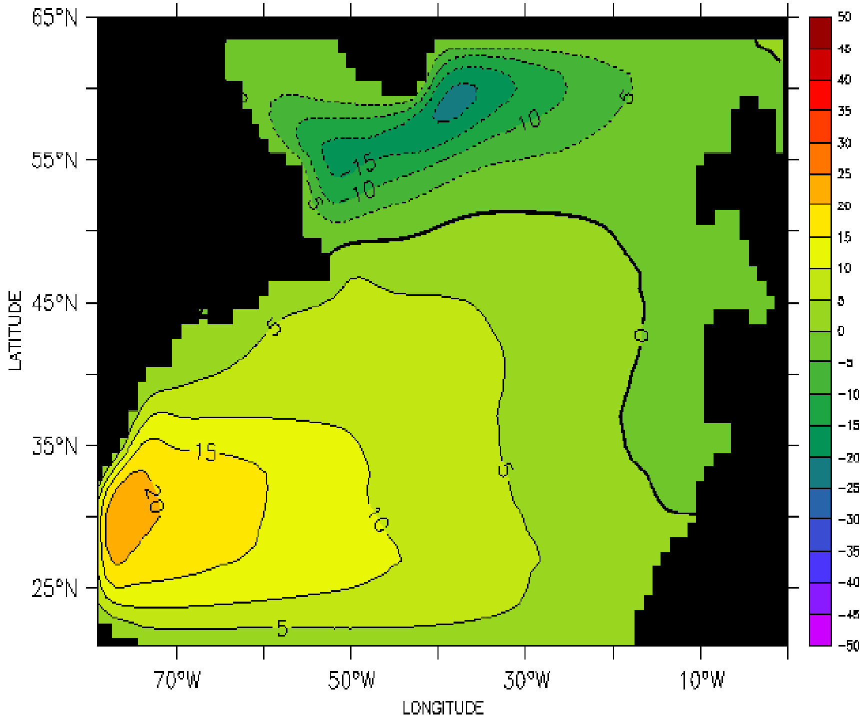
The North Atlantic hosts the thickest Subtropical Mode Water (STMW) in the world Ocean, which is related to the fact that the Gulf Stream has the largest WBC transport (Tsubouchi et al. 2016)

Mechanism of the Gulf Stream Separation

Barotropic Streamfunction

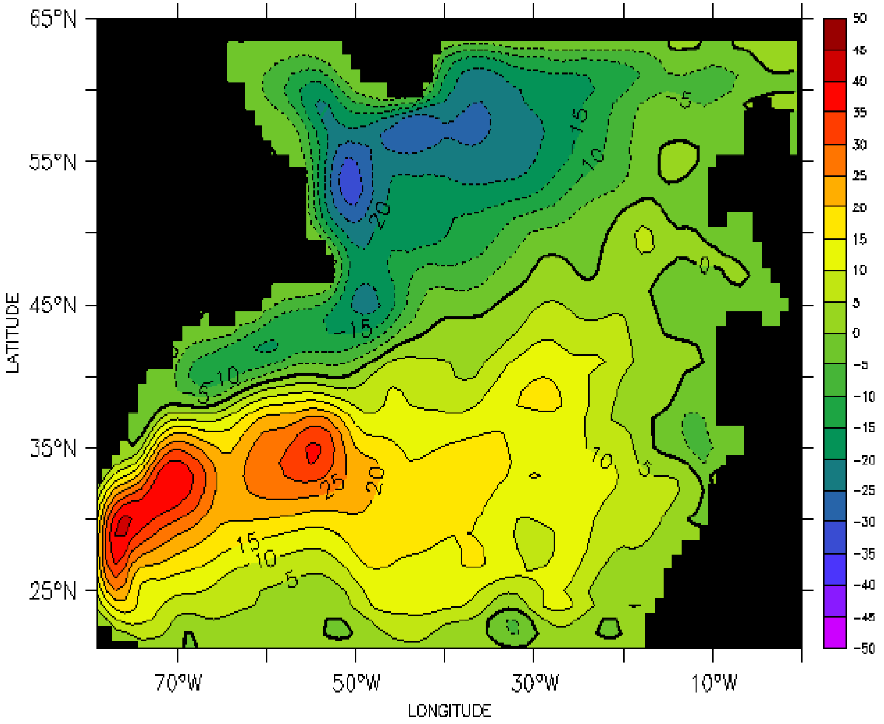
Wind stress curl $\nabla \times \boldsymbol{\tau} \neq 0$

$\boldsymbol{W_B = 0}$



Wind stress curl $\nabla \times \boldsymbol{\tau} \neq 0$

$\boldsymbol{W_B \neq 0}$ (GFDL diagnostic calculation)

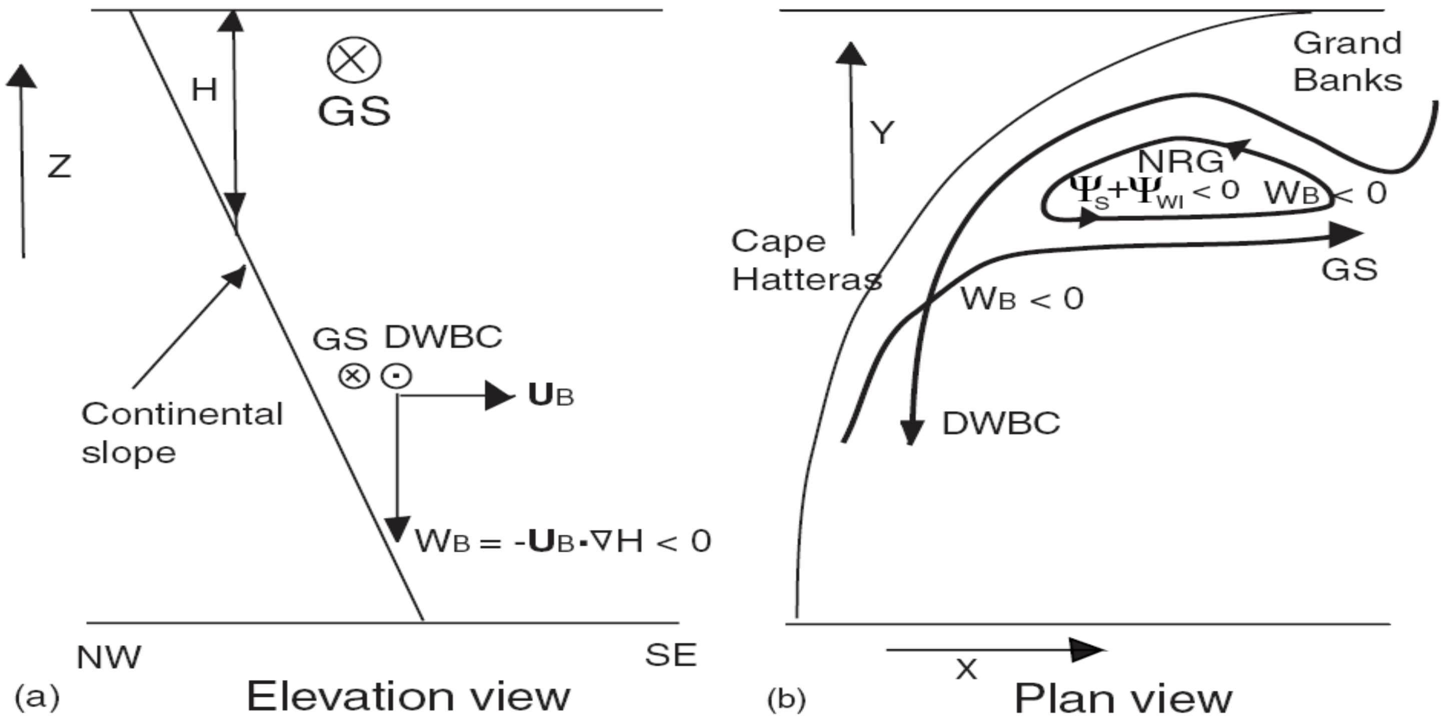


Zhang and Vallis, 2007

- For a pure wind-driven gyre circulation without any role of the AMOC, the Gulf Stream will move along the North American east coast as a western boundary current (WBC) without a separation, and there is no northern recirculation gyre (NRG) as observed

- If the effect of the bottom vertical velocity ($\boldsymbol{W_B}$) induced by the interaction of the deep AMOC branch with bottom topography is included, the Gulf Stream separates from the US east coast near Cape Hatteras, a cyclonic NRG appears north of the Gulf Stream, and the Gulf Stream transport is much stronger

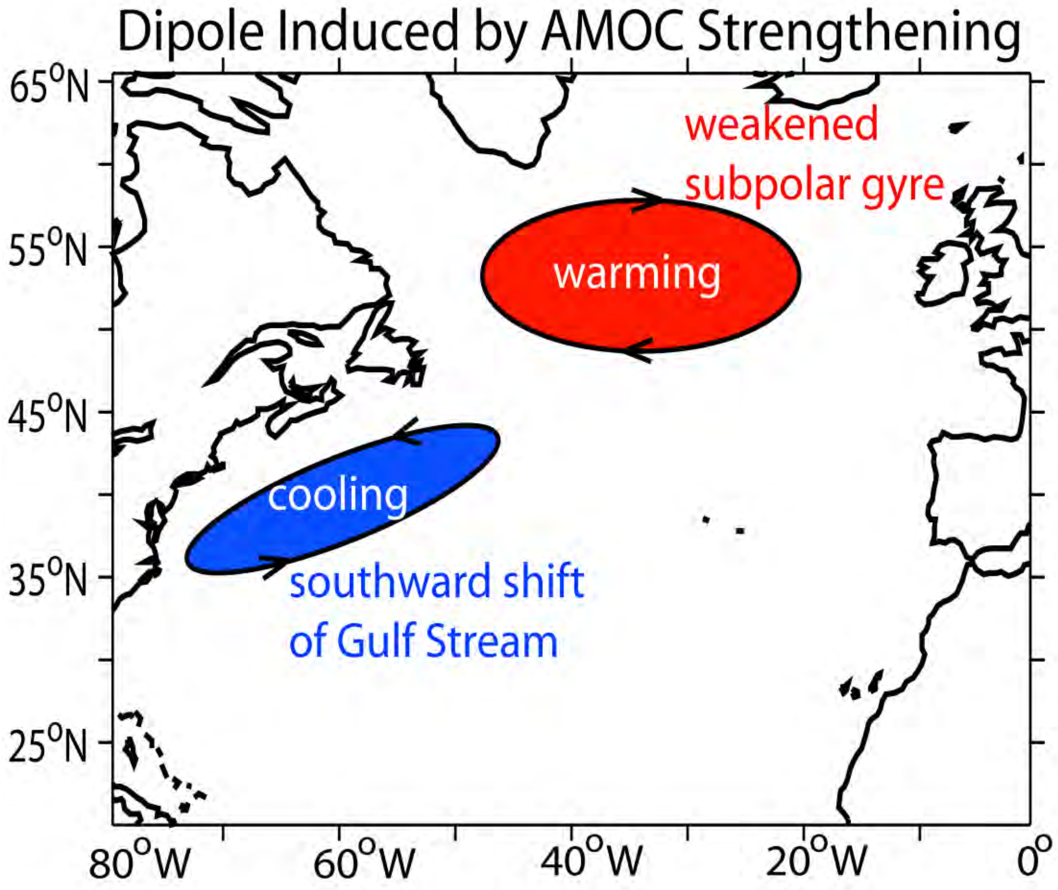
Mechanism of the Gulf Stream Separation

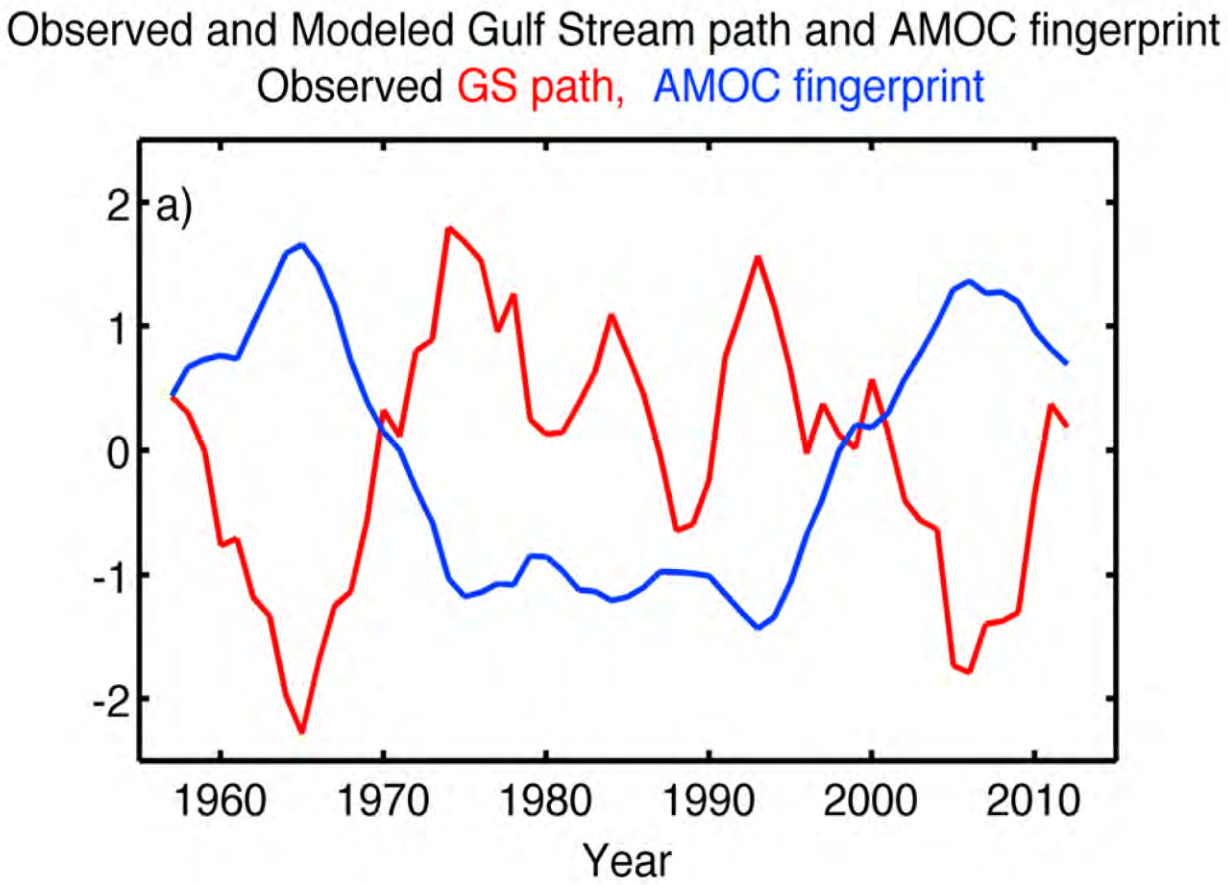


Zhang and Vallis, 2007

When the deep western boundary current (DWBC) associated with the AMOC moves downslope, it induces a negative bottom vertical velocity (W_B<0) and thus a positive bottom vortex stretching (- f_0 W_B>0), resulting in the cyclonic northern recirculation gyre (NRG) and the separation of the Gulf Stream (GS) path from the US east coast

Anti-correlated Multidecadal Variability between the Gulf Stream path and the AMOC

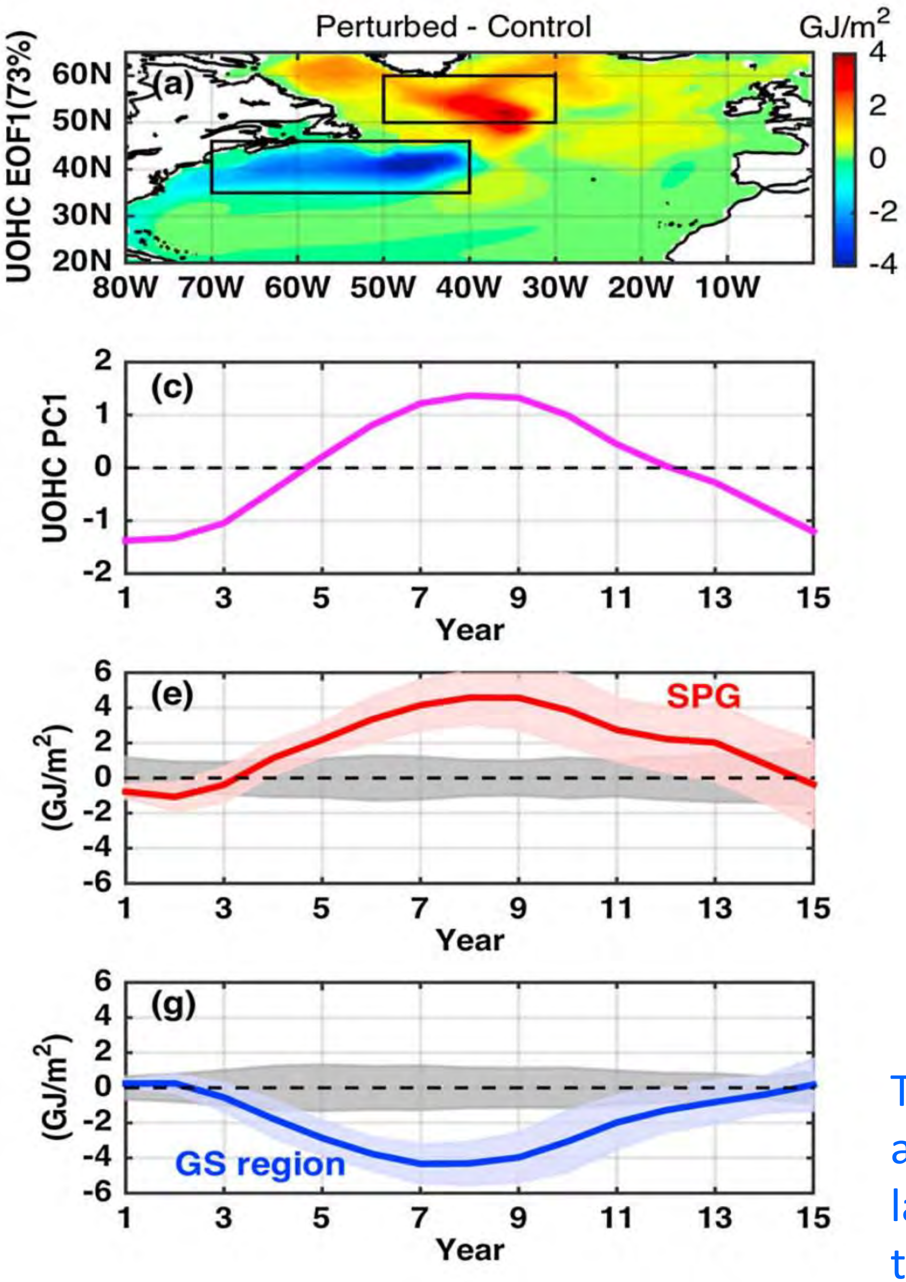




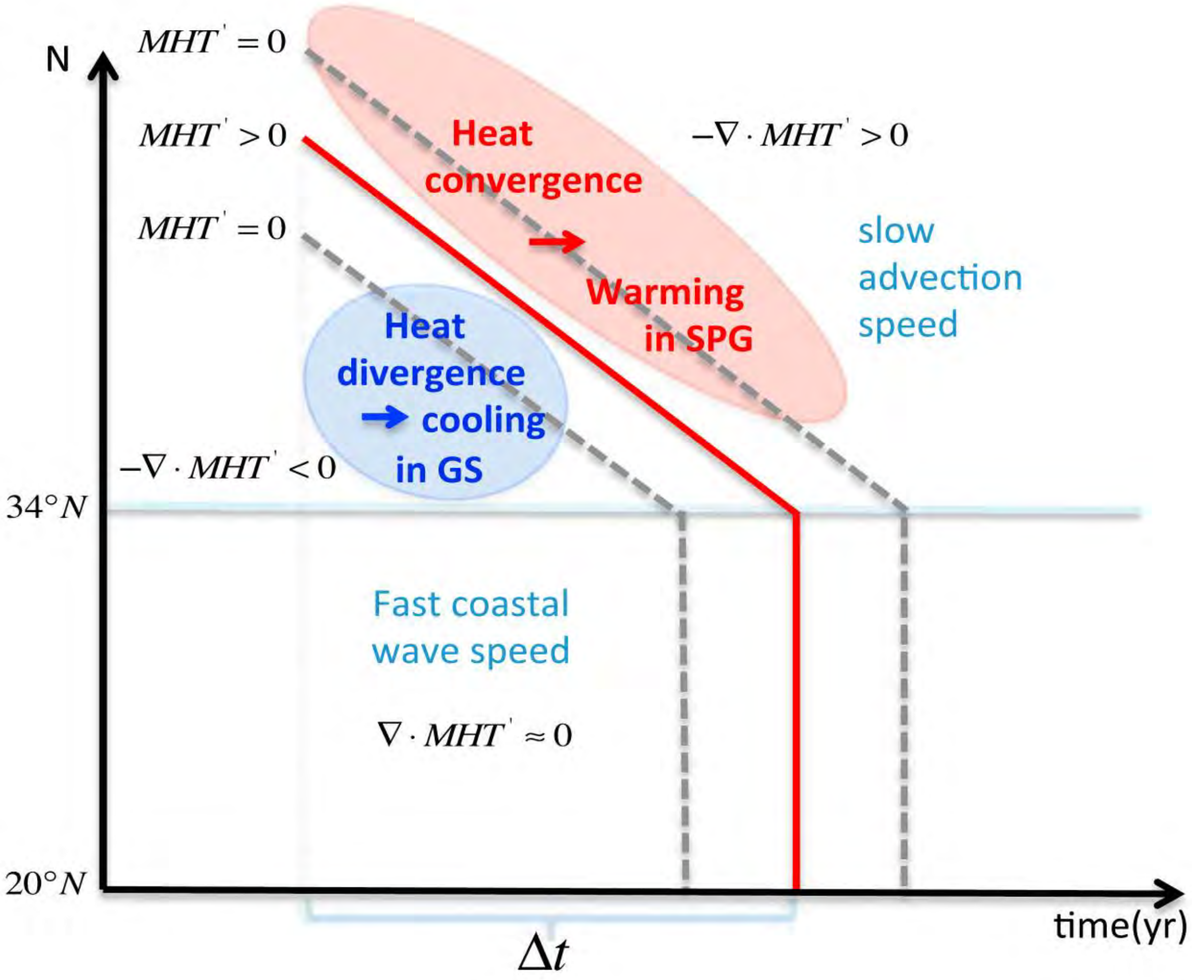
Zhang, 2008; Joyce and Zhang, 2010; Sanchez-Franks and Zhang, 2015

The meridional shifts of the Gulf Stream path are anticorrelated with the AMOC strength at multidecadal timescales

Decadal Predictability of the Temperature Anomalies along the Gulf Stream Path

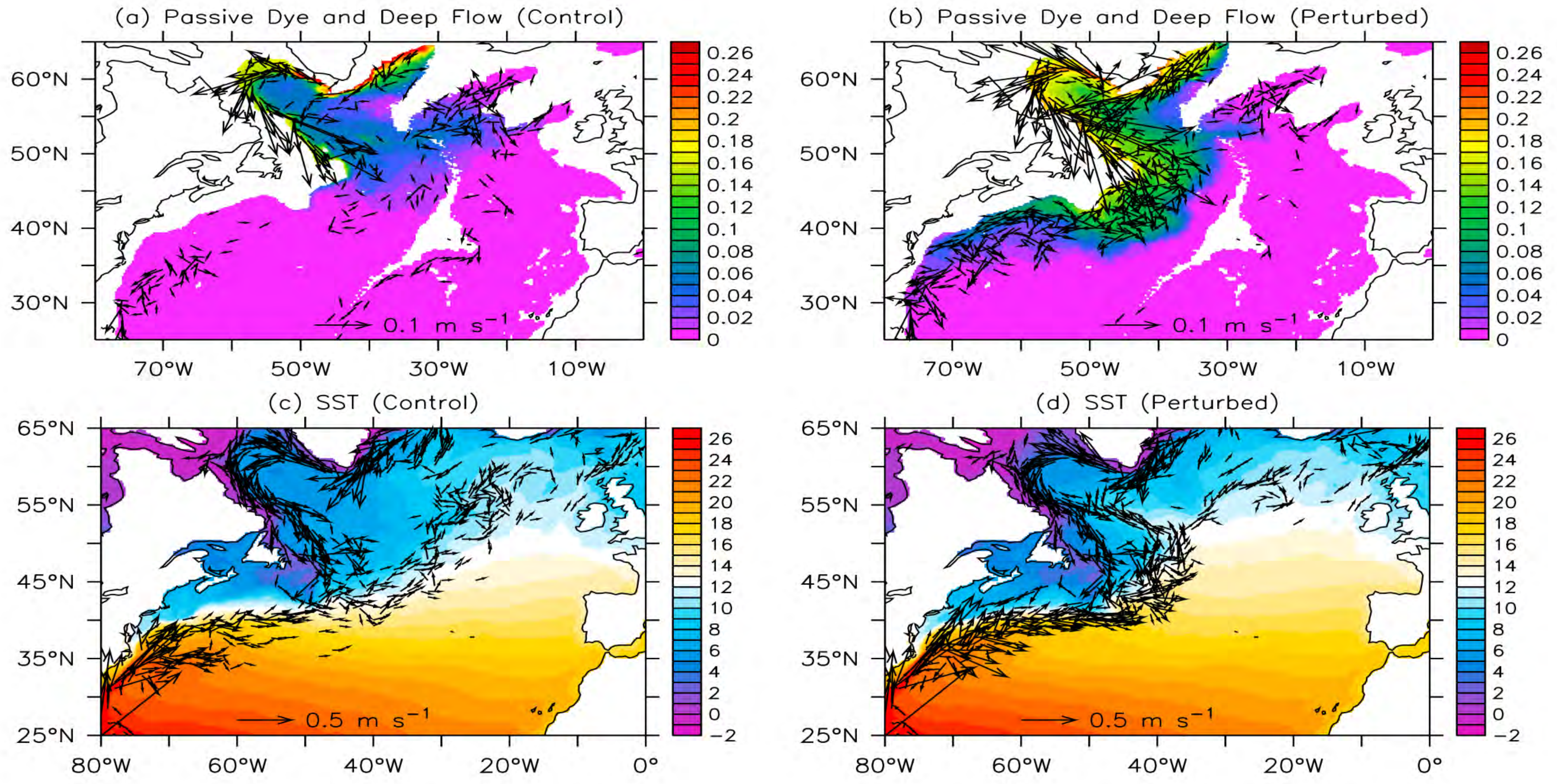


GFDL CM2.1



The southward propagation of the anomalies of the AMOC and associated meridional heat transport (MHT) from the northern high latitudes can lead to temperature anomalies along the Gulf Stream path that are predictable at the decadal timescale (Zhang and Zhang, 2015)

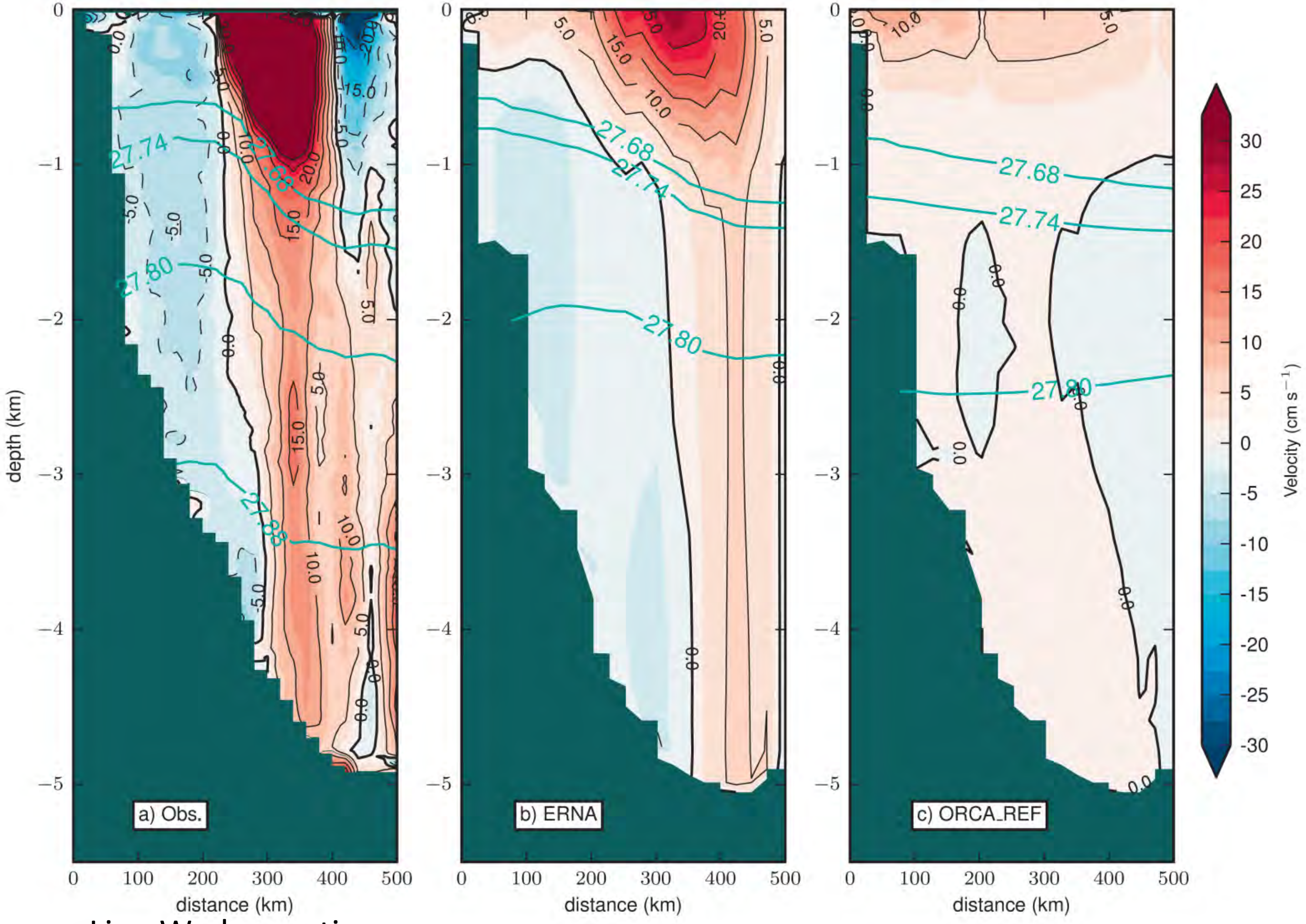
Impact of the AMOC on Modeling Biases of the Gulf Stream Path



Zhang et al 2011 (GFDL CM2.5, 1/4^{o} ocean resolution)

A more realistic (stronger/deeper) AMOC/DWBC can lead to more realistic Gulf Stream and North Atlantic Current pathways, stronger Gulf Stream transport, and larger SST contrast across the Gulf Stream path

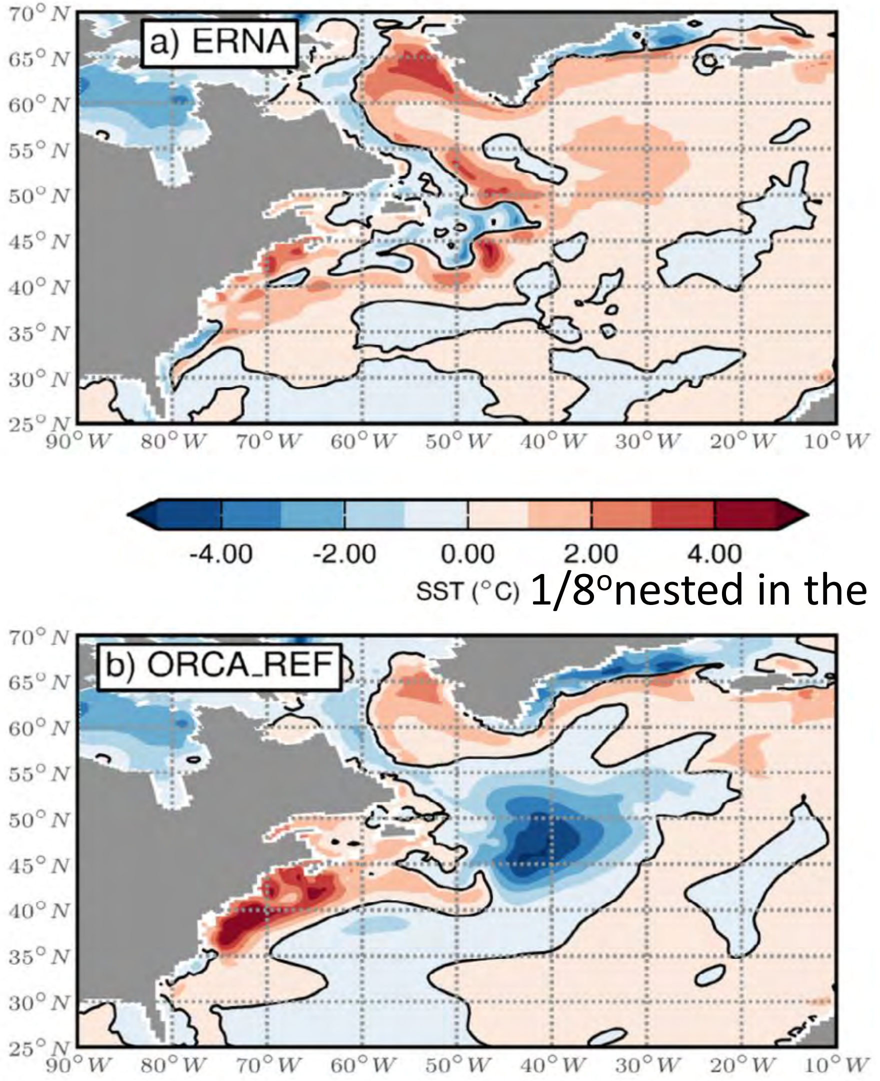
Modeling Biases of the Gulf Stream Path



Line W observations (Toole et al. 2011)

1/8° nested in the NA

1/2°

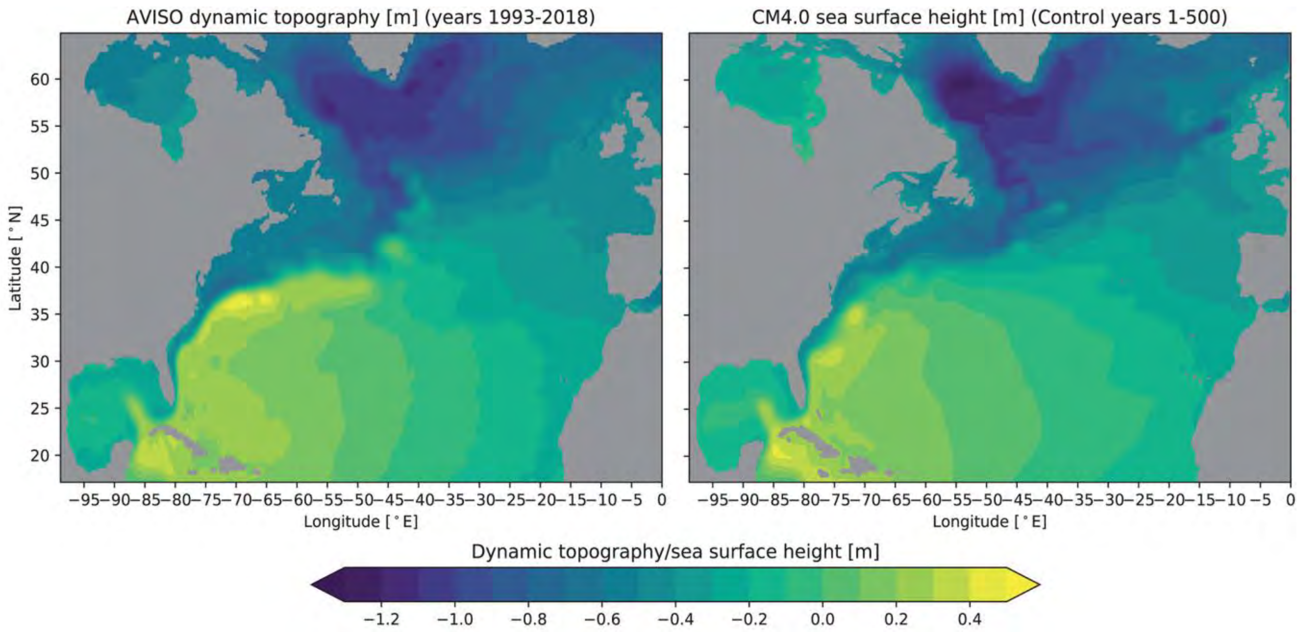


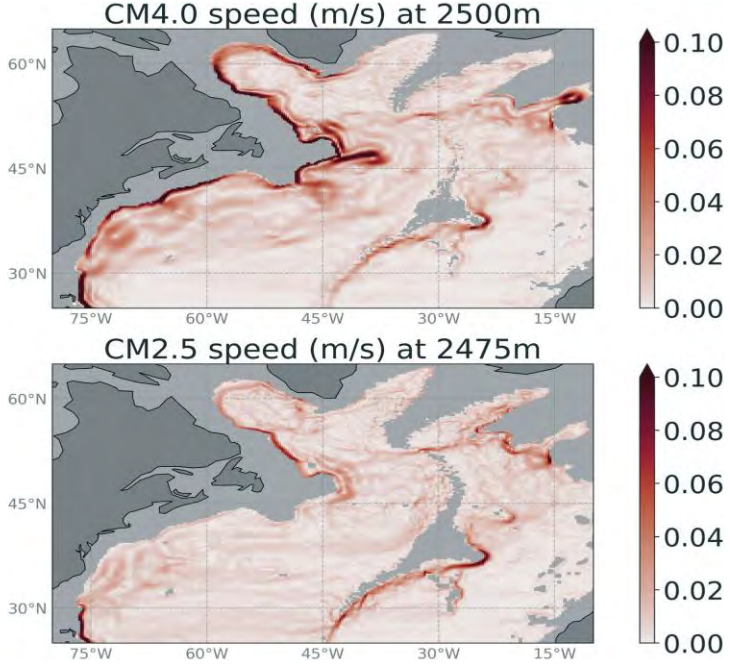
1/8°nested in the NA

1/2°

The Gulf Stream separation/pathway can be improved by increasing the ocean model (NEMO) resolution from 1/2° to 1/8°, which simulates a stronger DWBC. The SST biases are much smaller with the improved Gulf Stream separation and North Atlantic current pathway (Talandier et al. 2014)

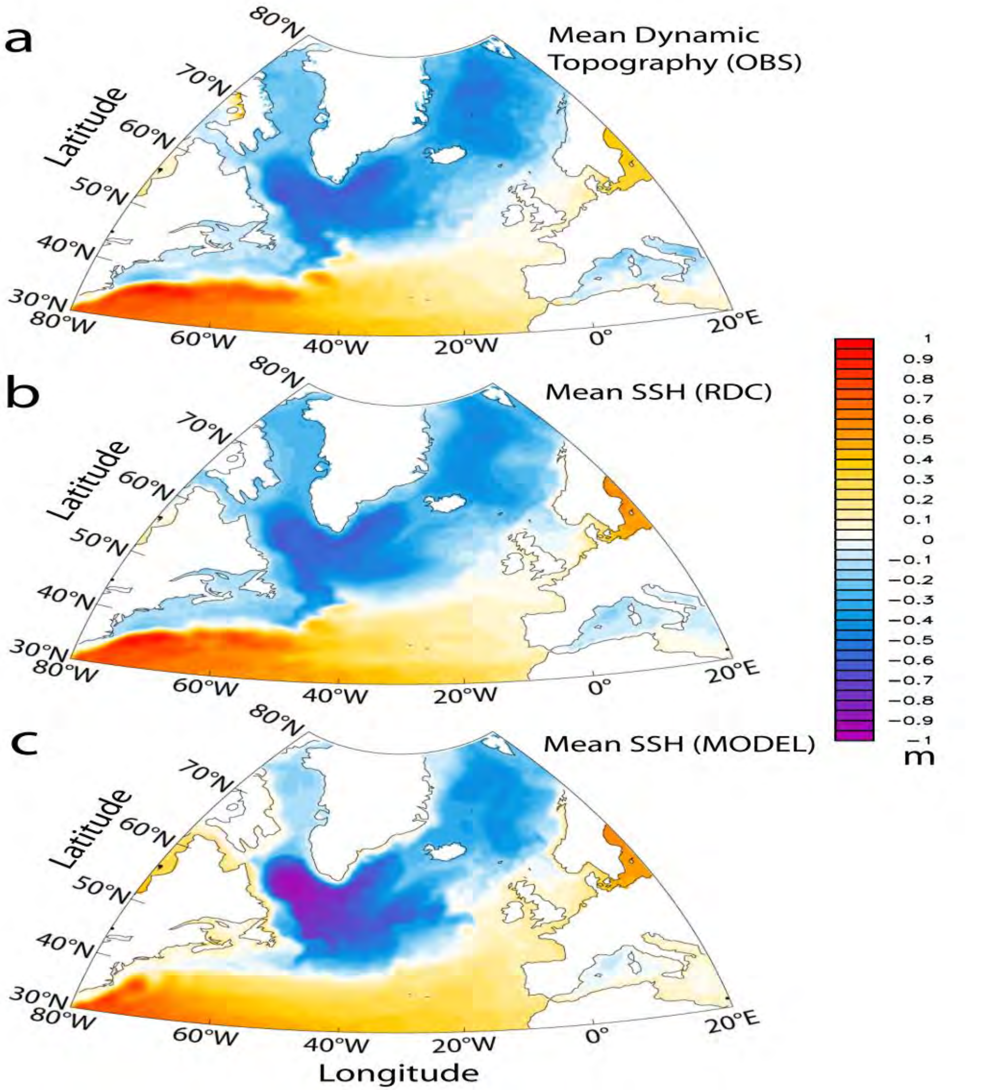
Modeling Biases of the Gulf Stream Path





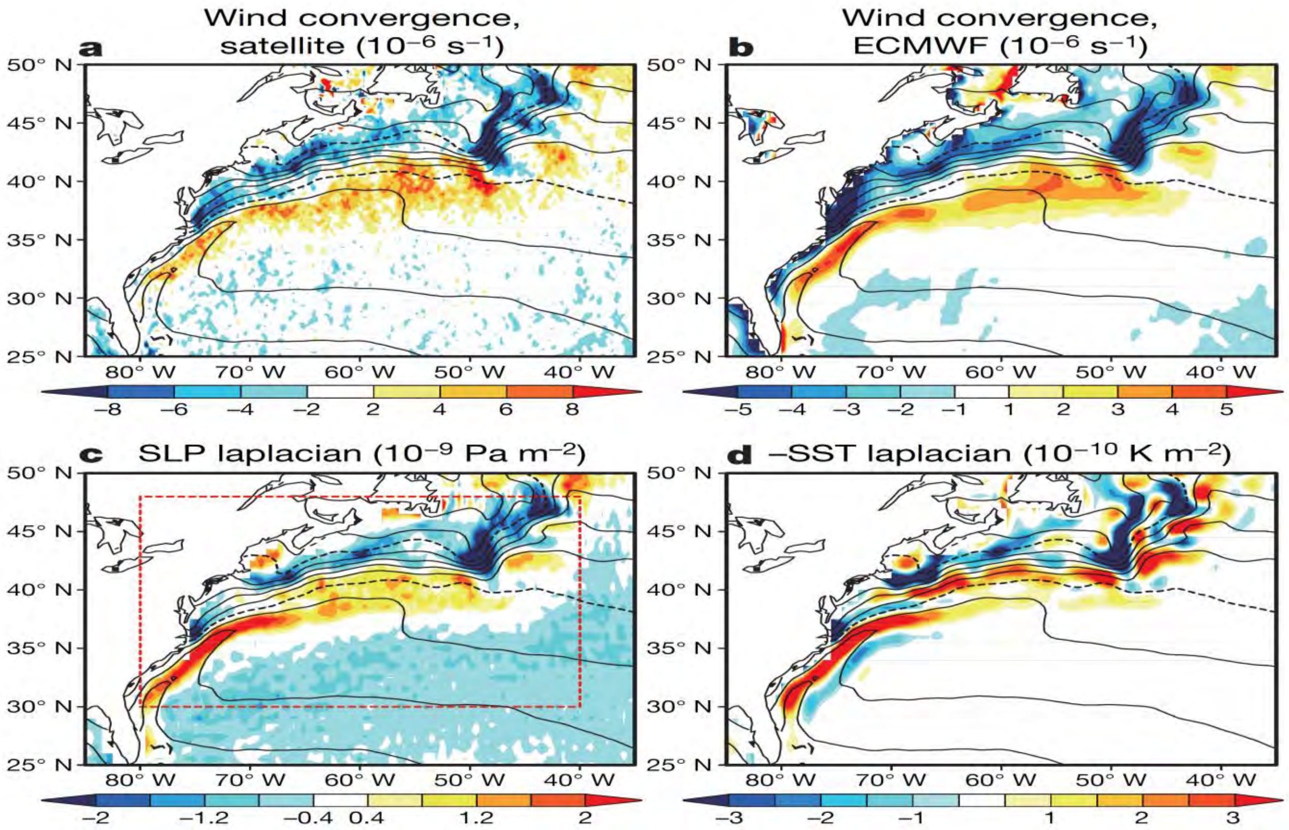
Model biases of the Gulf Stream separation are not just due to lower ocean model resolutions

With the same 1/4° ocean resolution, the latest GFDL coupled model CM4 (with the improved momentum advection scheme and hybrid vertical coordinate) has a much stronger DWBC and thus an improved Gulf Stream separation compared to CM2.5 (Held et al. 2019)



When CM2.5 temperature/salinity are restored to the observed hydrographic data through the robust diagnostic calculation (RDC), there is a realistic Gulf Stream separation comparable to that revealed from satellite observations (Zhang and Thomas, 2021)

Impacts of the Gulf Stream on Weather and Climate



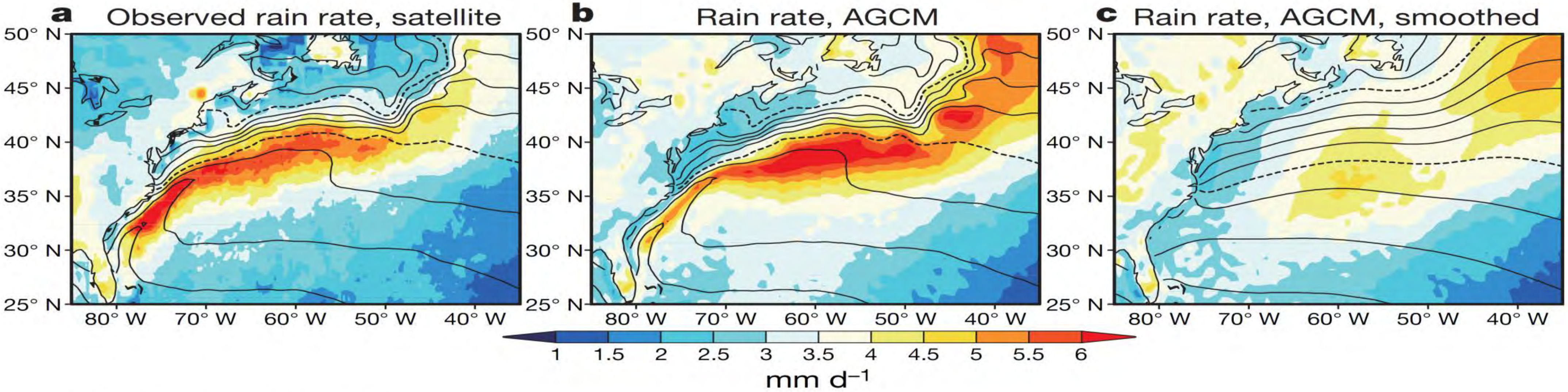
The observed climatological mean surface wind convergence, SLP laplacian, and SST Laplacian over the Gulf Stream front supports a local linkage among them (Minobe et al. 2008), consistent with the marine atmospheric boundary layer (MABL) model (Lindzen and Nigam, 1987)

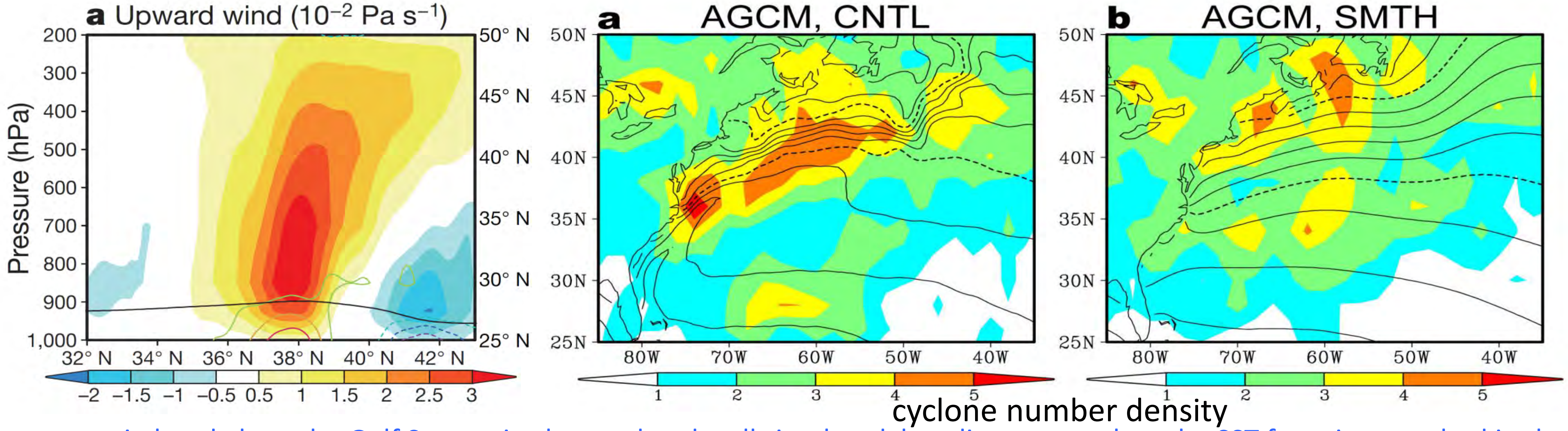
TABLE 1. Annual and seasonal correlation coefficients for 10-m wind convergence ($-\nabla \cdot \mathbf{V}_{SFC}$), ∇^2SLP, and $-\nabla^2$SST based on the monthly data of CNTL (SMTH) over the North Atlantic Ocean within 30°–48°N, 80°–40°W.

Season	$-\nabla \cdot \mathbf{V}_{SFC}$ and ∇^2SLP	∇^2SLP and $-\nabla^2$SST	$-\nabla \cdot \mathbf{V}_{SFC}$ and $-\nabla^2$SST
MAM	0.71 (0.55)	0.44 (−0.05)	0.25 (−0.05)
JJA	0.66 (0.62)	0.42 (−0.02)	0.31 (0.06)
SON	0.67 (0.62)	0.41 (0.03)	0.28 (0.08)
DJF	0.68 (0.49)	0.46 (−0.13)	0.22 (−0.05)
ANN	0.69 (0.55)	0.44 (−0.07)	0.25 (−0.01)

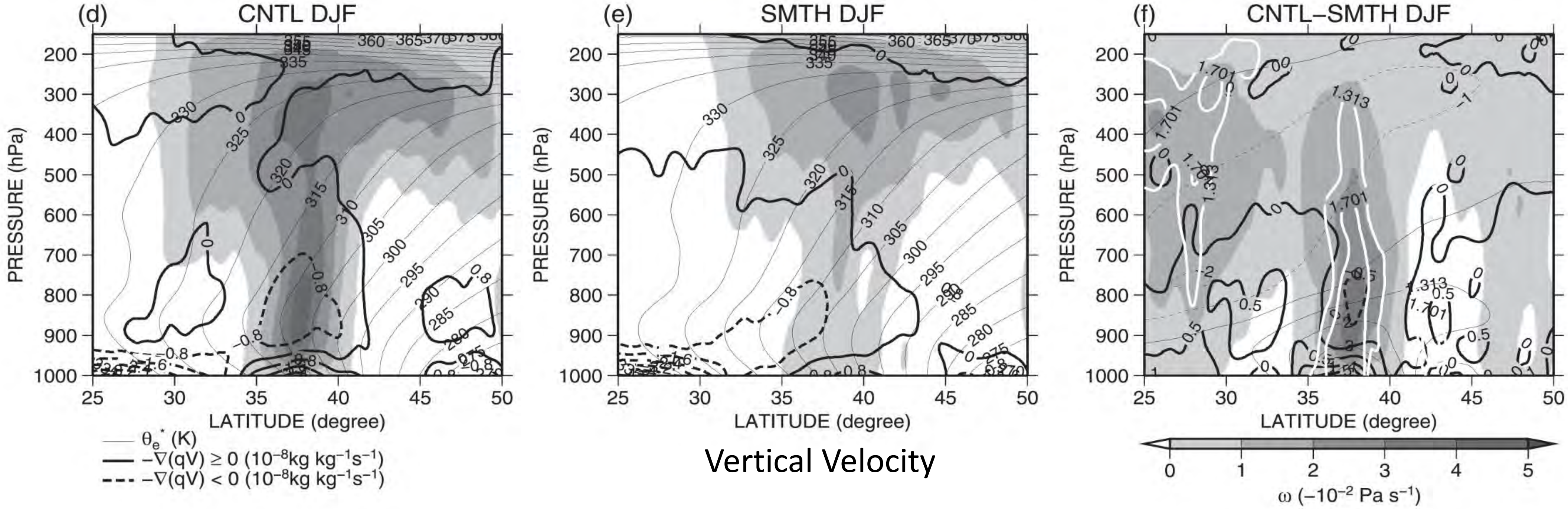
A follow-up study shows that the AGCM (AFES2) simulated correlations of surface wind convergence with SST Laplacian is much weaker than with SLP Lapacian, especially when the SST front is smoothed (Kuwano-Yoshida et al. 2010)

“Influence of the Gulf Stream on the troposphere” - Minobe et al. 2008



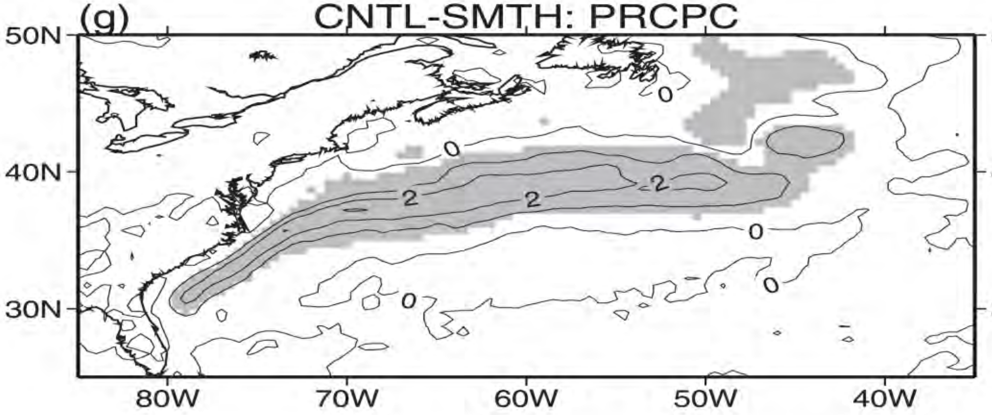


- A narrow rain band along the Gulf Stream is observed and well simulated, but disappears when the SST front is smoothed in the AGCM
- The simulated extra-tropical cyclone number density over the Gulf Stream path is reduced with the smoothed SST front
- The observed upward motion over the open-ocean Gulf Stream pathway (after the separation) is proposed as an indicator that the local Gulf Stream front affects the entire troposphere

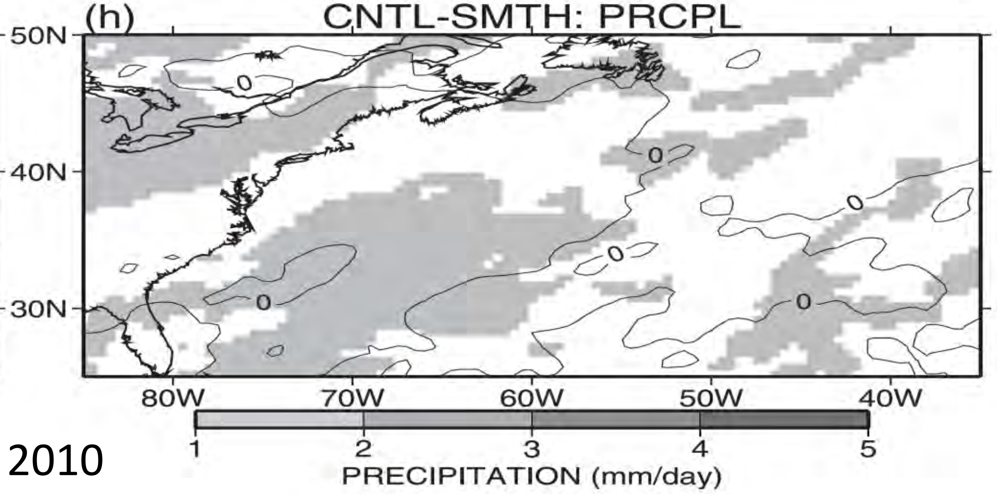


Vertical Velocity

Difference in Convective Precipitation



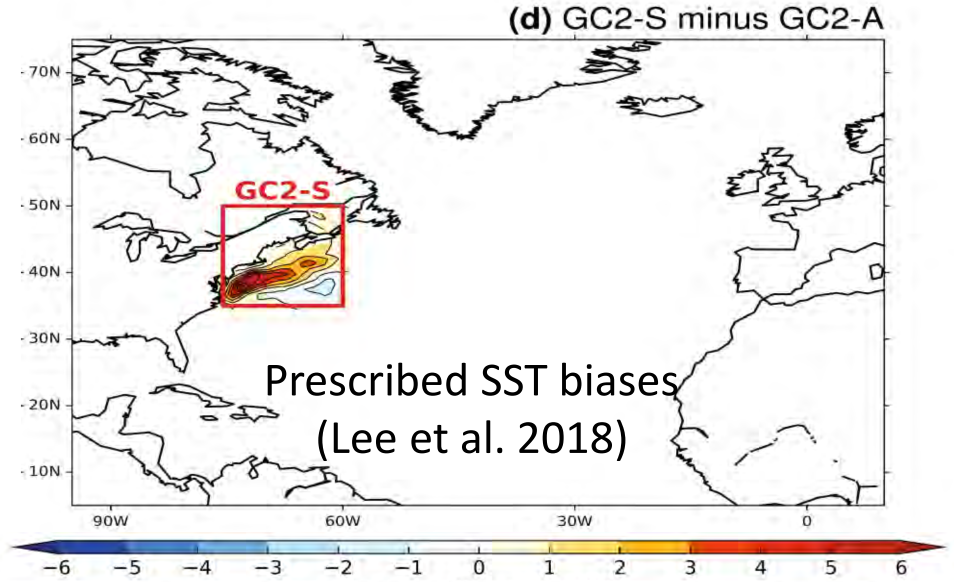
Difference in Large-scale Precipitation

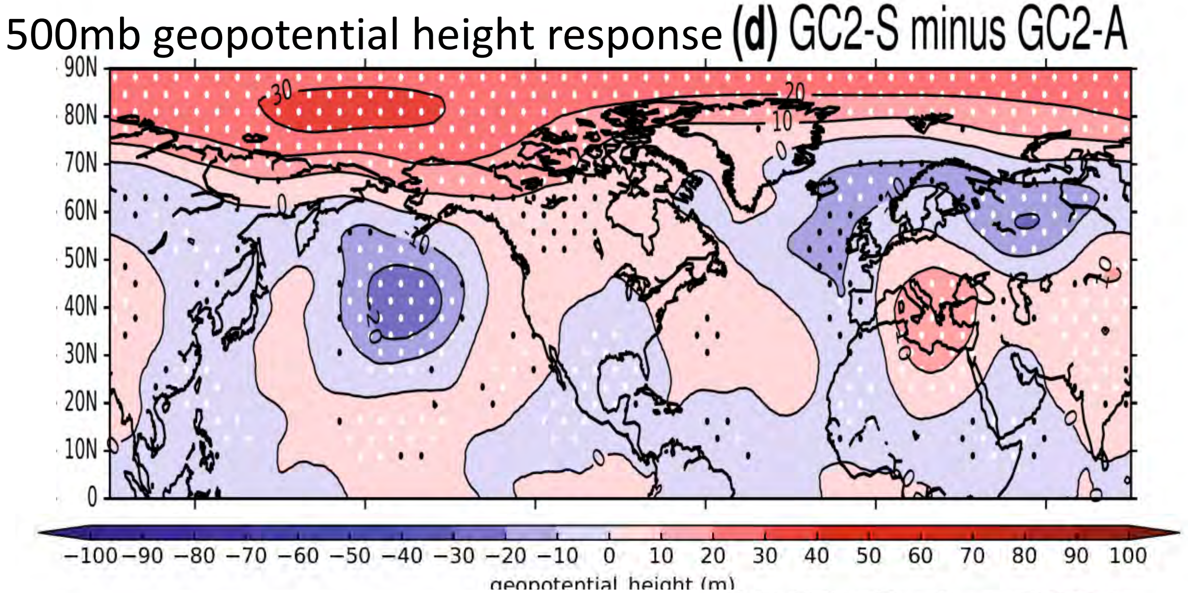


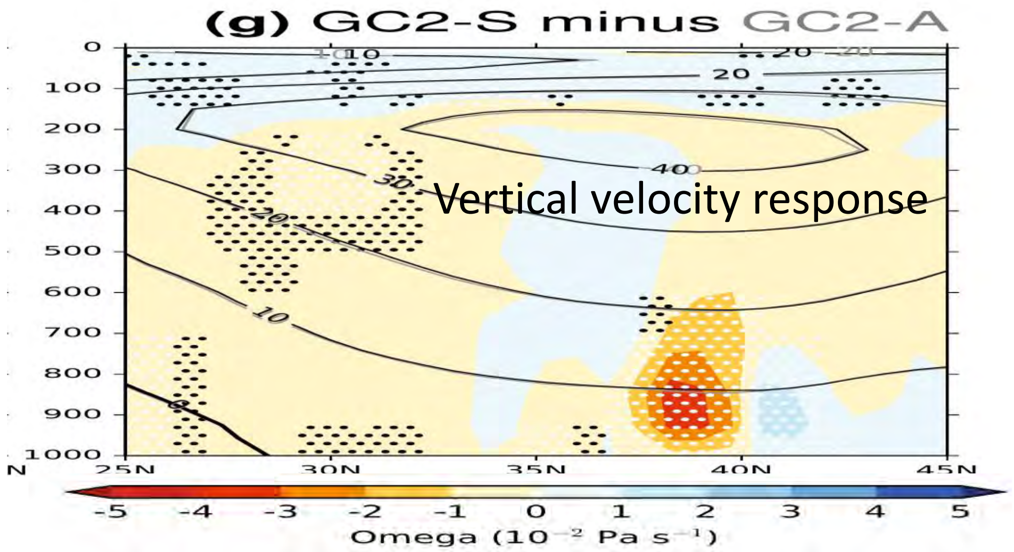
Kuwano-Yoshida et al. 2010

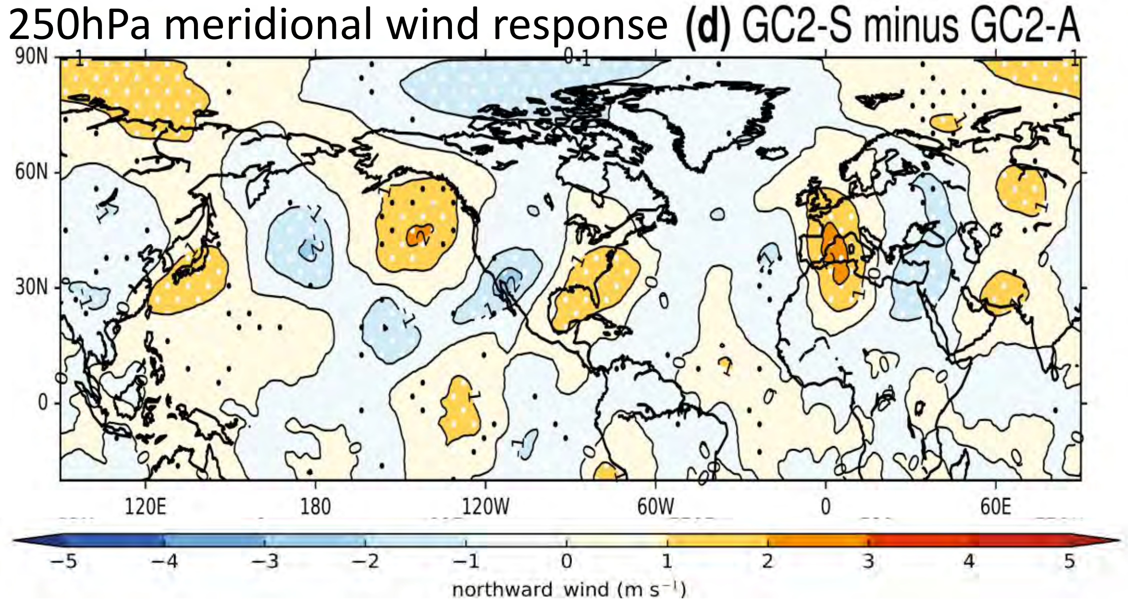
- The simulated impact of the open-ocean Gulf Stream pathway (after the separation) in winter is limited to the lower troposphere
- The simulated annual mean impact is mainly on convective precipitation, and there is not much impact on large-scale precipitation

Simulated Atmospheric Response to the Warm Gulf Stream SST Biases



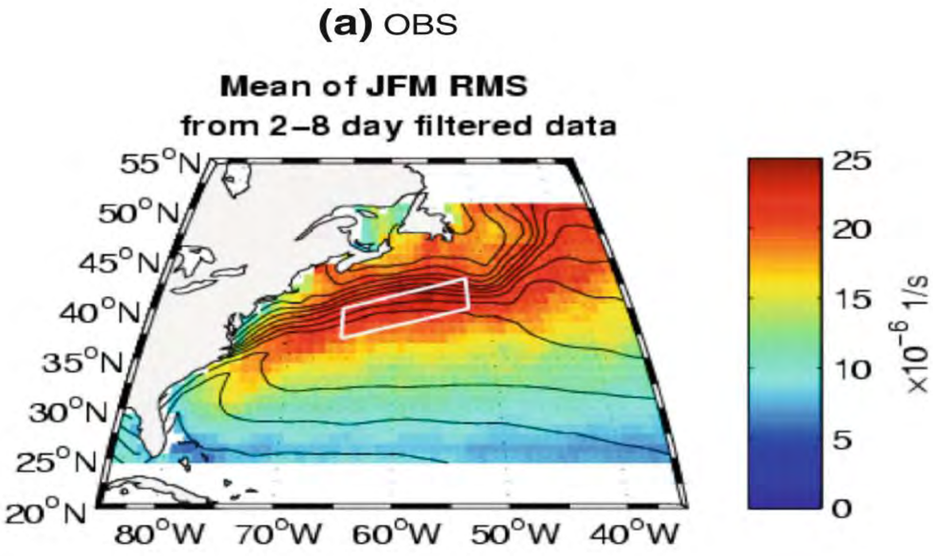




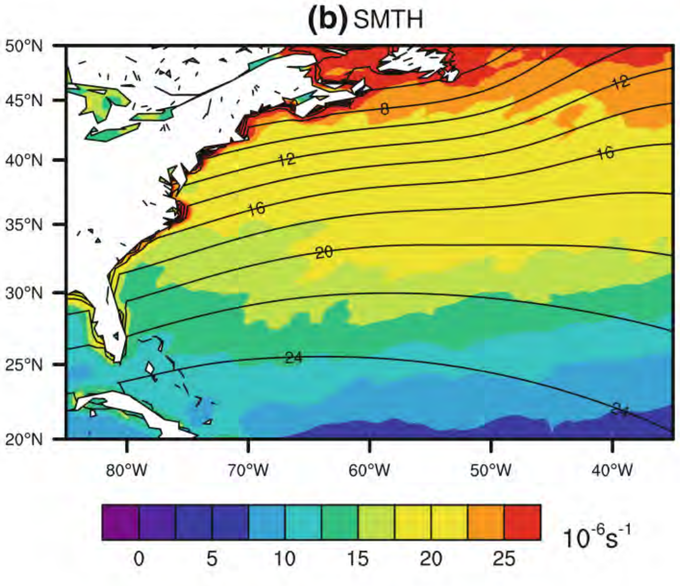


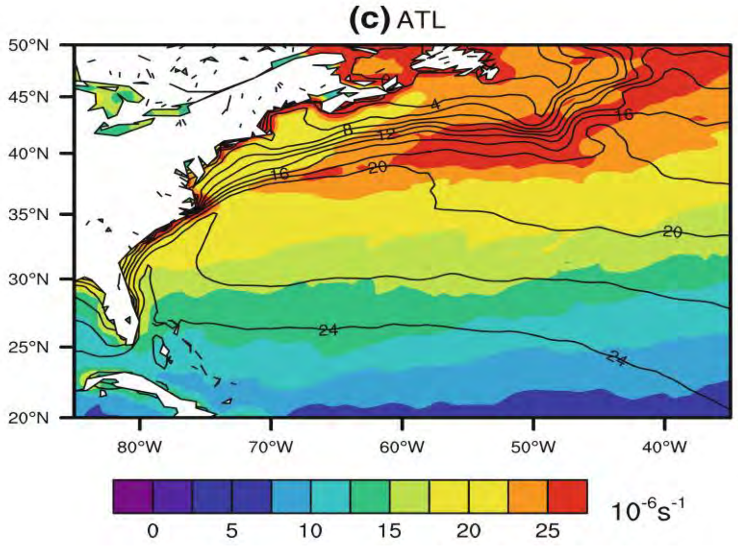
- The simulated response of the vertical velocity over the Gulf Stream path is shallow, mainly in the lower troposphere
- The simulated stationary Rossby wave response is more zonal and can be seen over eastern Asia and the Pacific, different from the less zonal response obtained through the barotropic wave model forced over the Gulf Stream bias region (Lee et al. 2018)

Gulf Stream SST Gradient and Storm Track

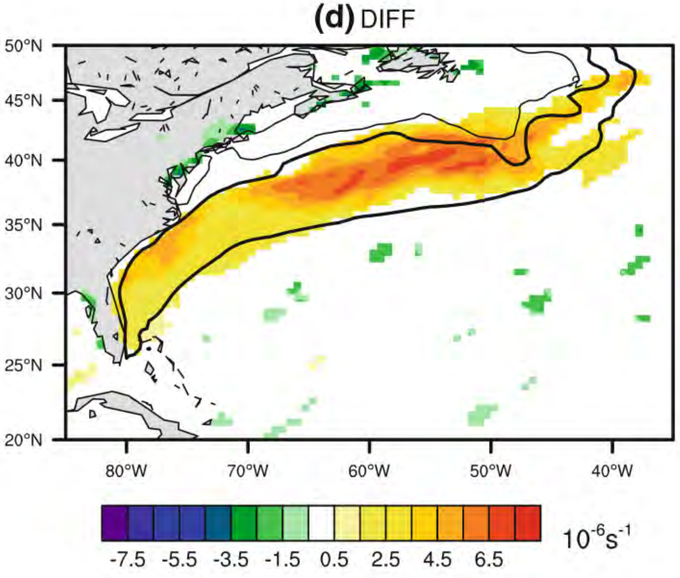


The observed NA winter storm track is centered along the Gulf Stream path (Joyce et al. 2009)

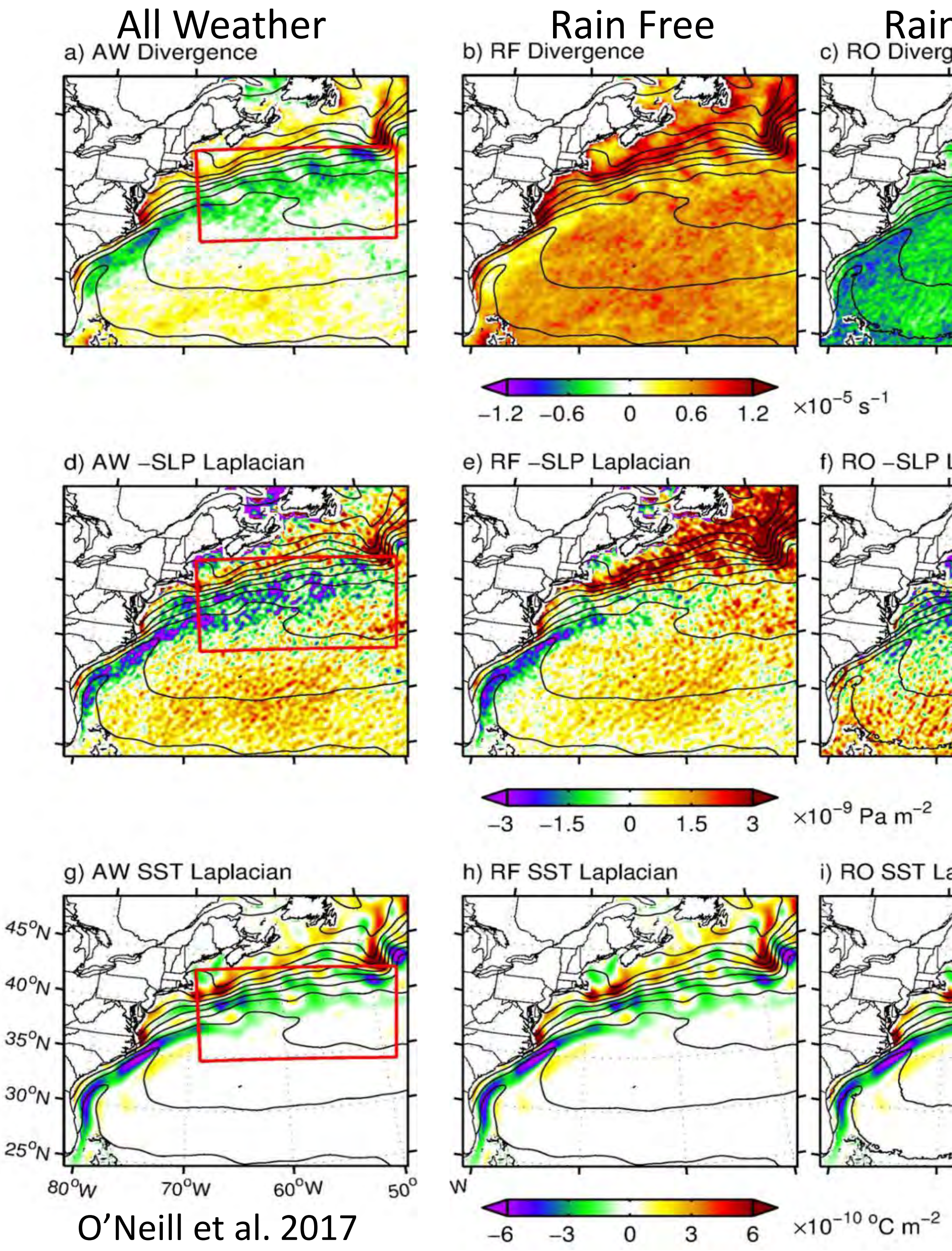




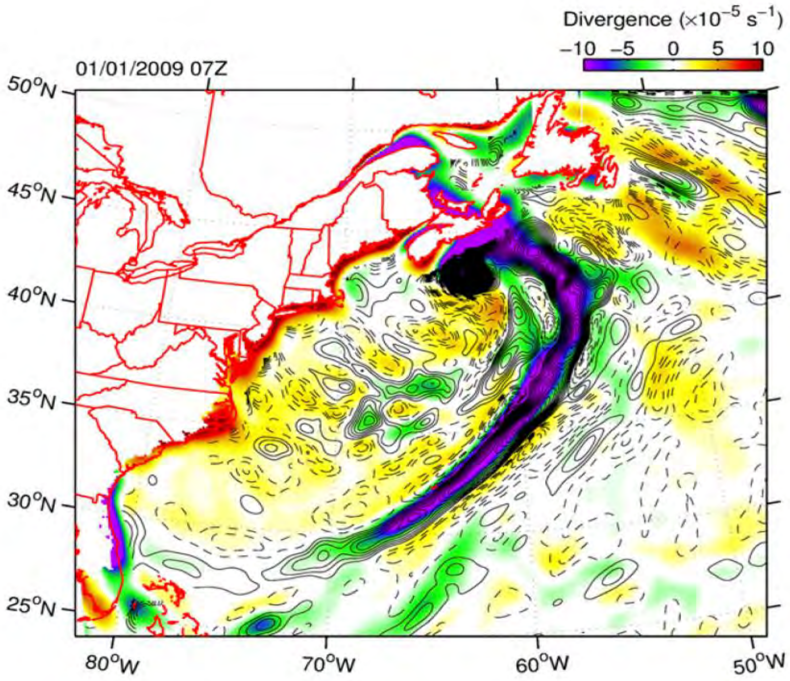
Small et al. 2014



AGCM (NCAR CAM4) simulations show that SST gradients across the Gulf Stream strength the storm track (Small et al. 2014)



O'Neill et al. 2017

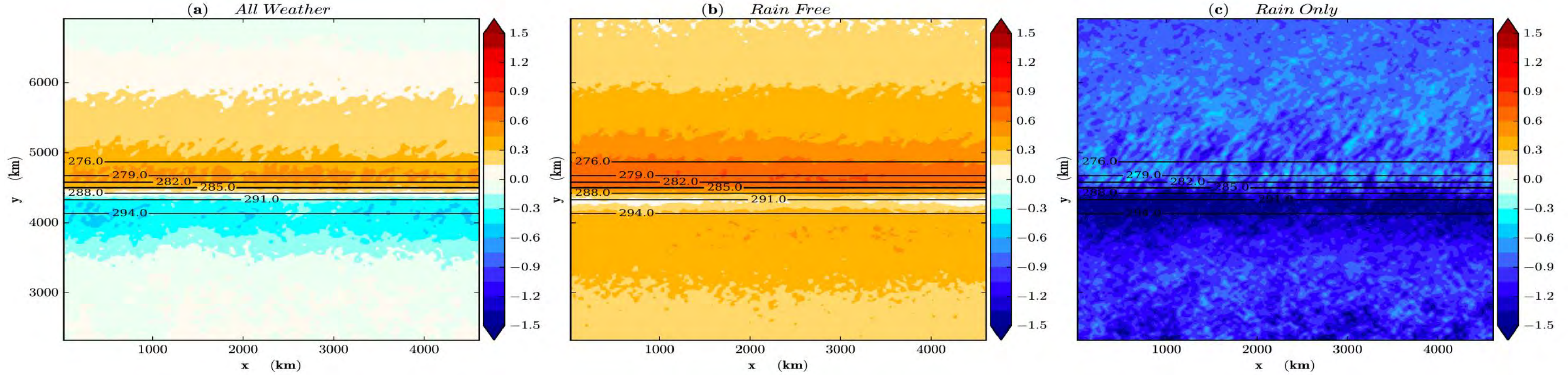


Snapshot of COAMPS simulated surface wind convergence during a storm, which is associated with SLP Laplacian, but not with SST Laplacian

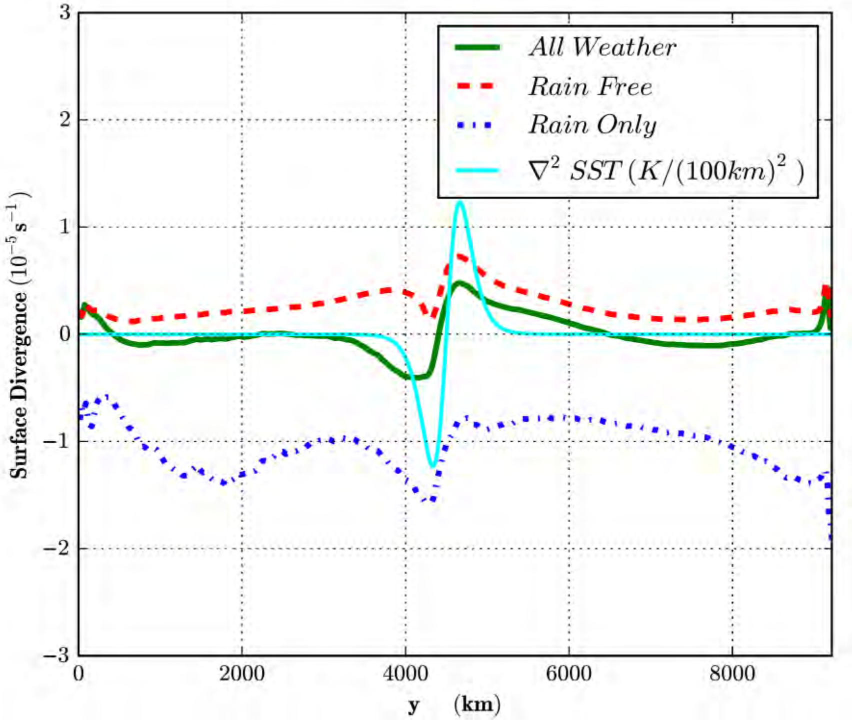
- The simulated all-weather mean surface convergence over the Gulf Stream path is a residue of the divergence over rain-free days plus the convergence over the extreme rare rain-only days
- The linkage with SST Laplacian does not hold instantaneously, suggesting an important role of synoptic storms in causing the instantaneous surface wind convergence and SLP Laplacian

(O'Neill et al. 2017)

Surface Divergence



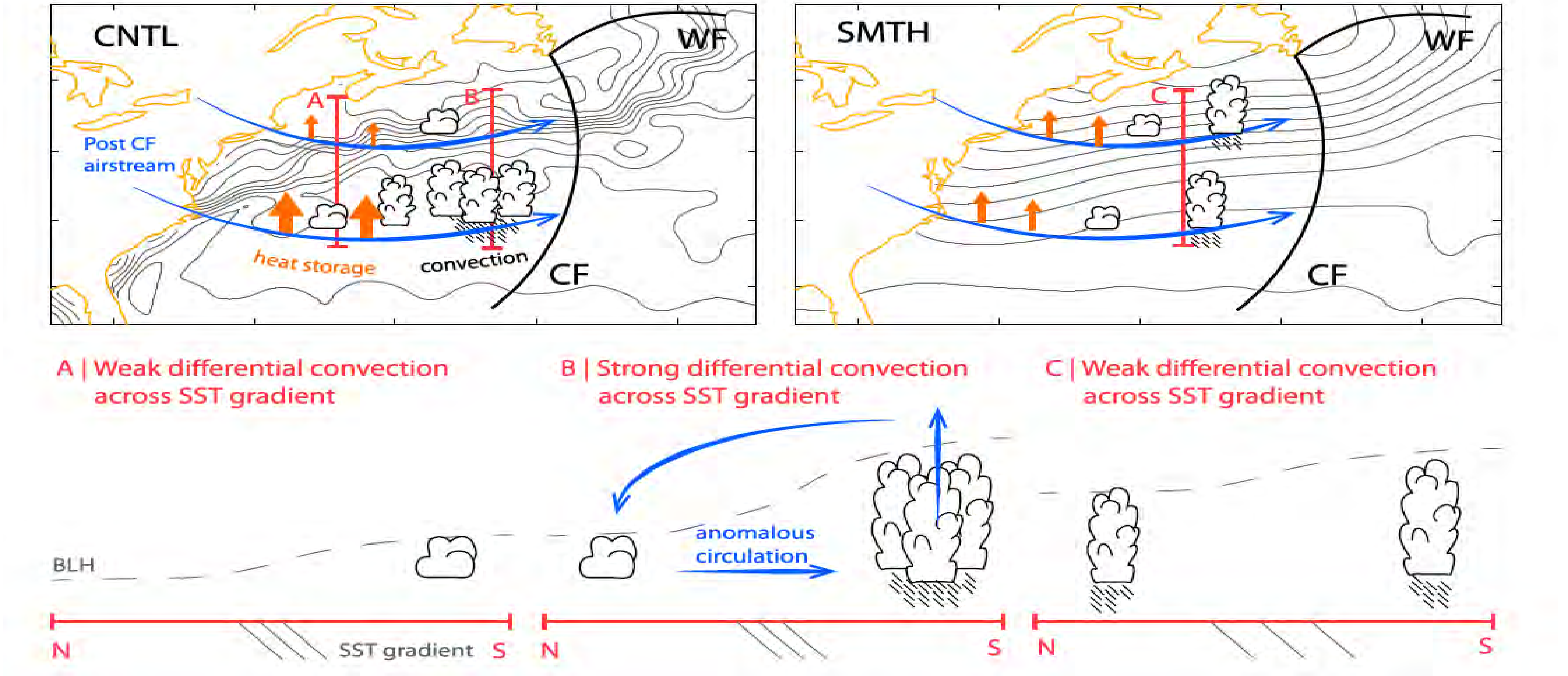
Zonal Averaged Surface Divergence



Idealized WRF simulations forced by a prescribed zonally symmetric SST front show similar results: divergent for rain free, convergent for rain only due to synoptic storms, but the zonal averages show the imprints of the MABL associated with the SST front (Plougonven et al. 2018)

"The community is still searching for a robust diagnostic, uncontaminated by storm-track variability, that demonstrates the coupled air–sea response in western boundary currents."

- O'Neill et al. 2018

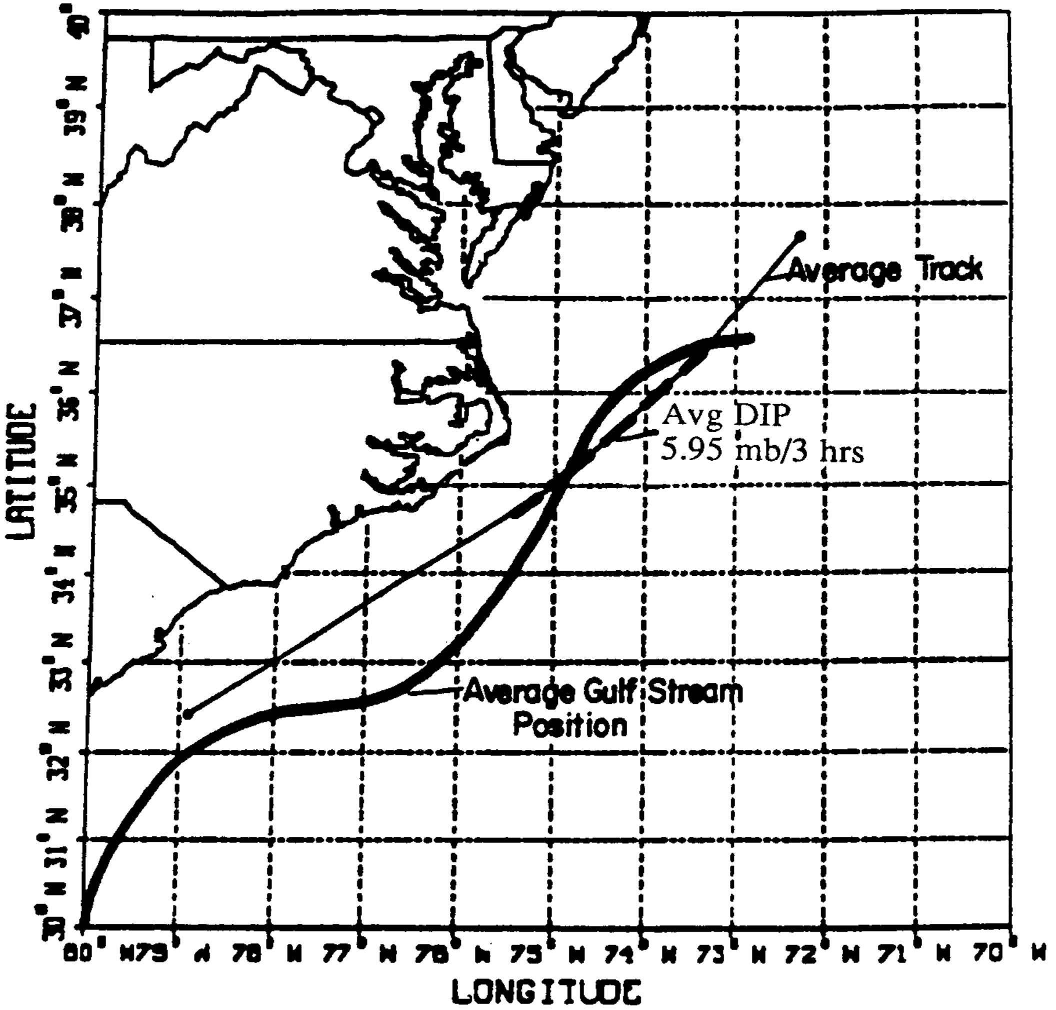


Vannière et al. 2017

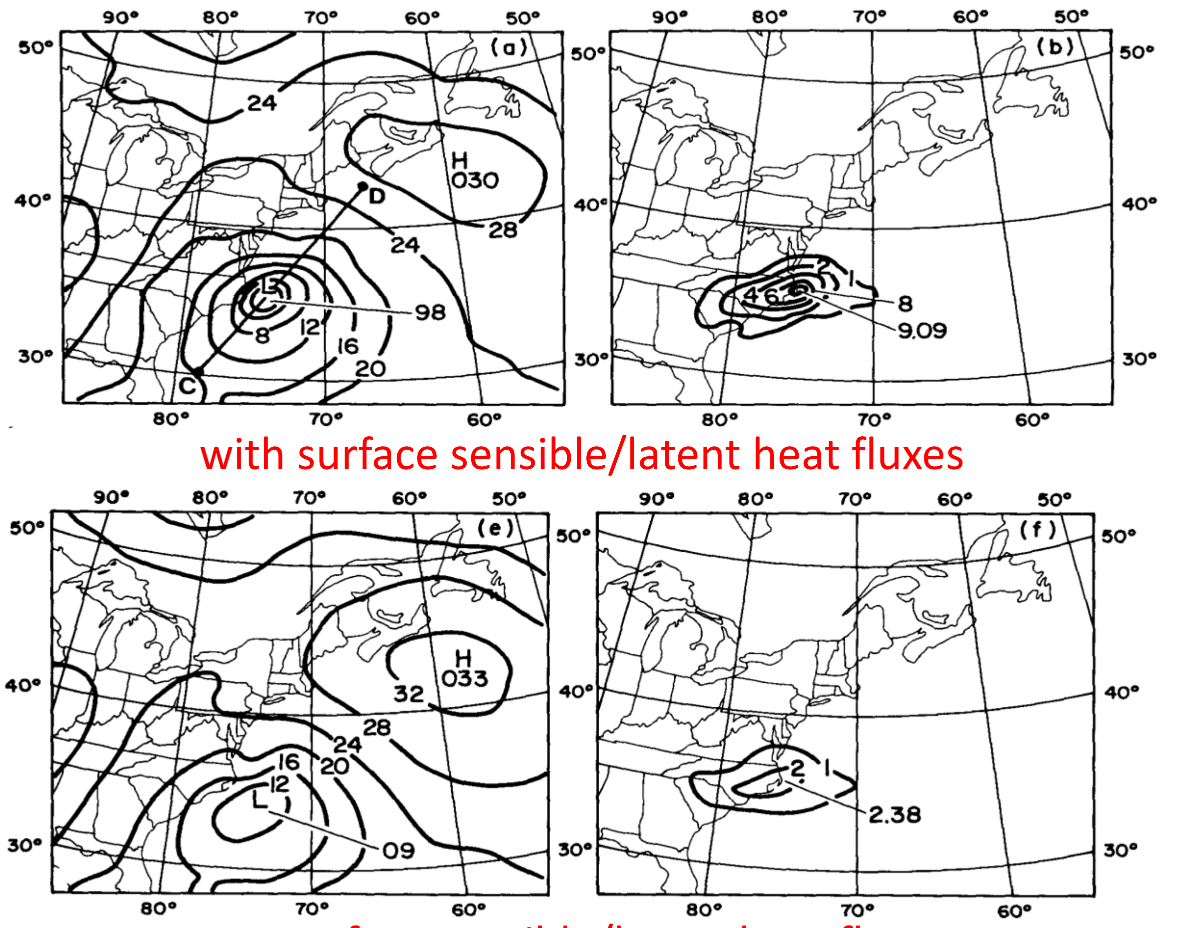
- AGCM (MetUM) simulations of a single extra-tropical cyclone with realistic or smoothed SST front suggests that the precipitation response to the SST gradient across the open-ocean Gulf Stream pathway is dominated by convective precipitation in the cold sector of the storm
- The differential convection sets a pressure anomaly over the boundary layer that drives surface wind convergence

Impacts of the Gulf Stream on Winter Bomb Storms

The Gulf Stream is a key development region for winter bomb storms in the North Atlantic (Sanders and Gyakum, 1980)



NCAR/PSU Simulated SLP and 12-h accumulated precipitation



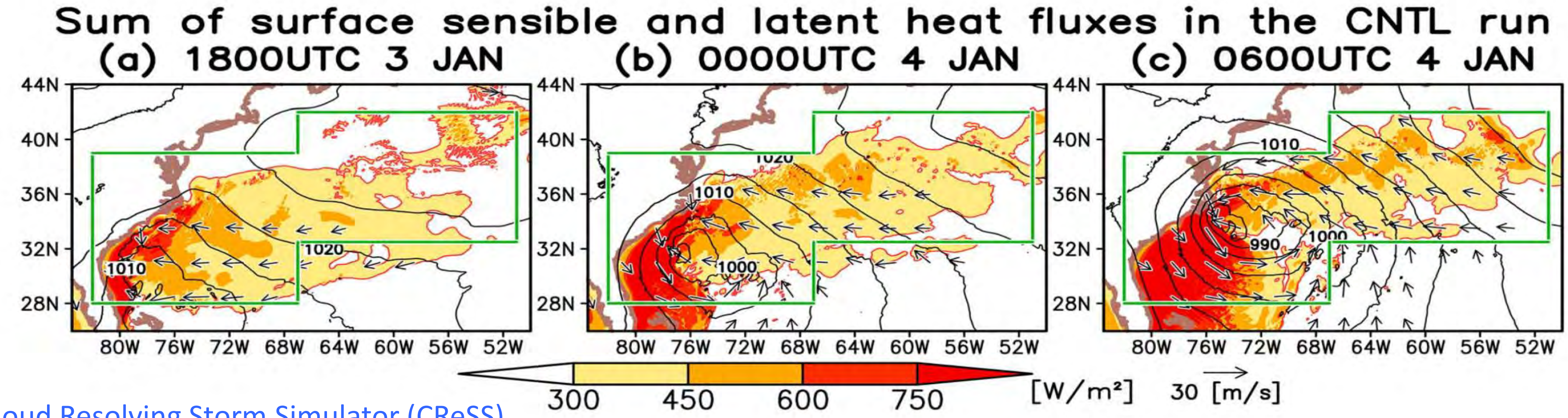
with surface sensible/latent heat fluxes

no surface sensible/latent heat fluxes

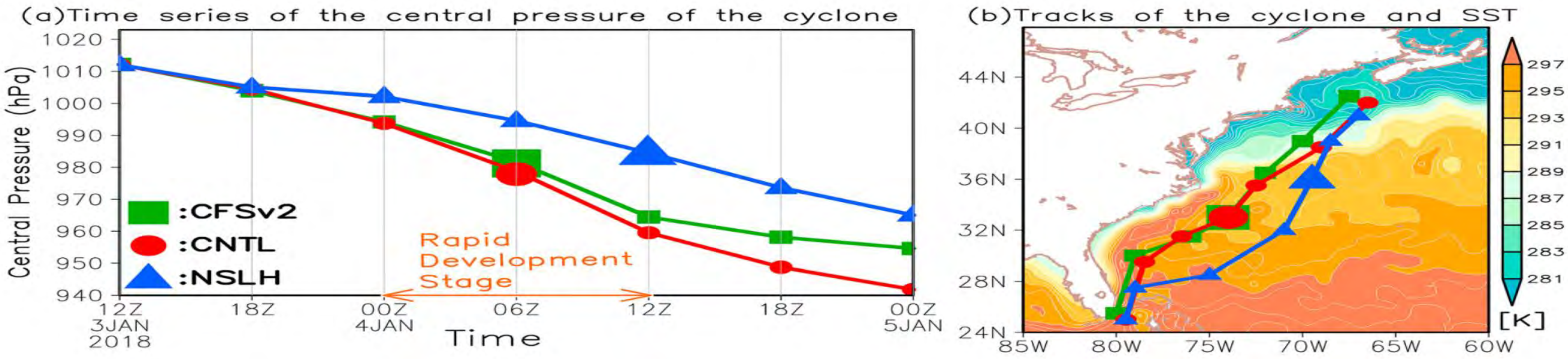
Storm intensification rates are related to the distance of the Gulf Stream from the coast, especially near the Gulf Stream separation point around Cape Hatteras (Cione et al. 1993)

Surface sensible/latent heat fluxes released over the Gulf Stream off the US east coast are important for the early development and rapid intensifications of explosive winter storms (Kuo et al. 1991)

Significant Impacts of Heat Supply from the Gulf Stream on a "Superbomb" Cyclone – Hirata et al. 2019



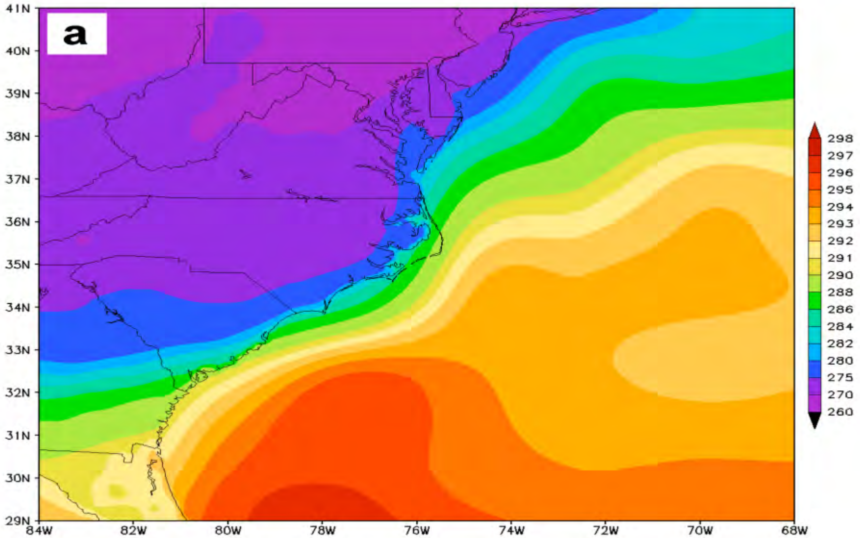
1/50° Cloud Resolving Storm Simulator (CReSS)

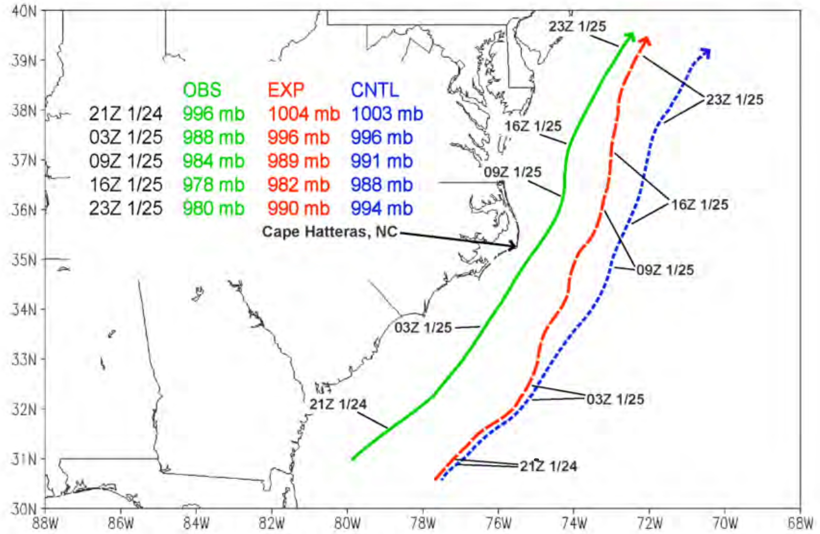


The surface sensible/latent heat fluxes released along the Gulf Stream front plays a crucial role in the rapid intensification of the "superbomb" cyclone on Jan. 4, 2018. The experiment without surface sensible/latent heat fluxes (NSLH) fails to predict the track and intensity of the storm

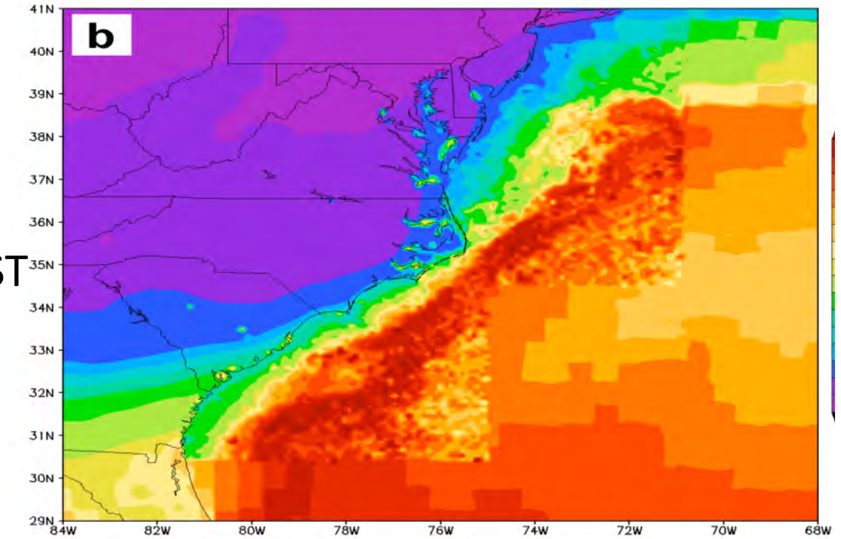
The need of high resolution SST data over the Gulf Stream region for accurate storm predictions

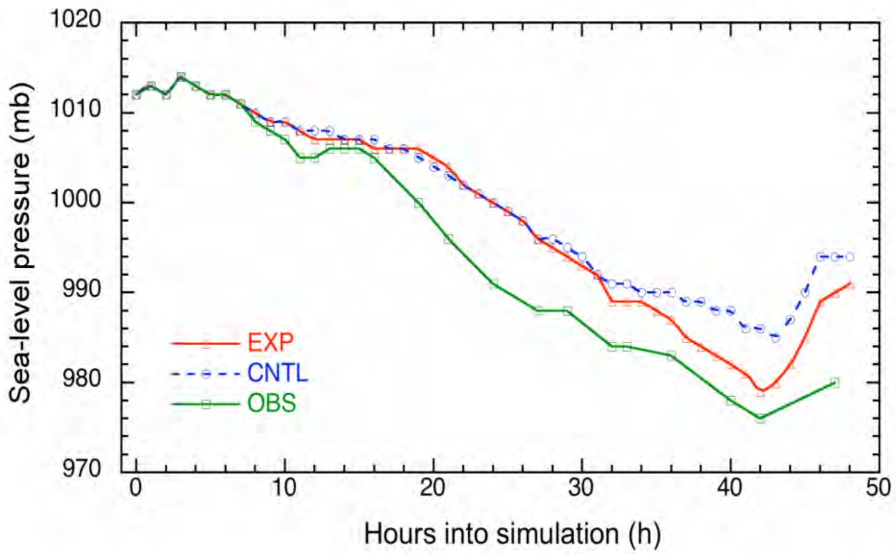
CNTL
NCEP 2.5° SST





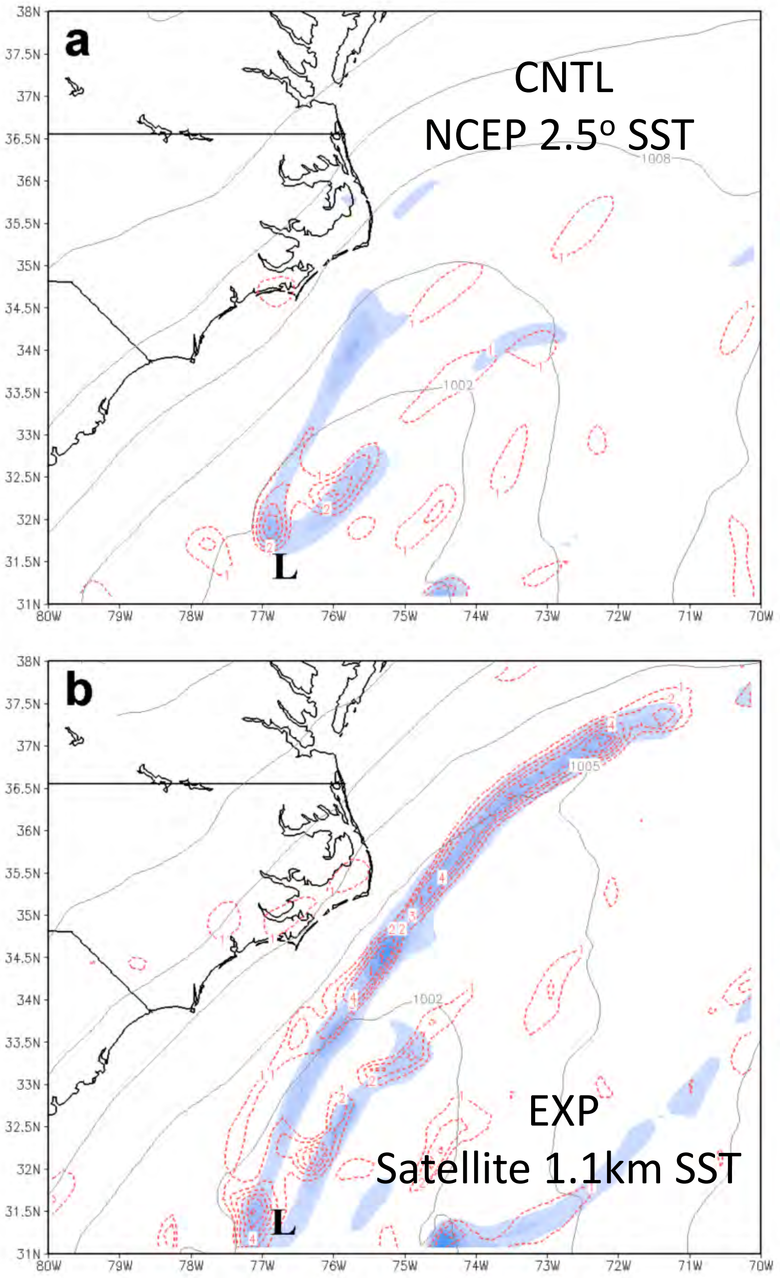
EXP
Satellite 1.1km SST



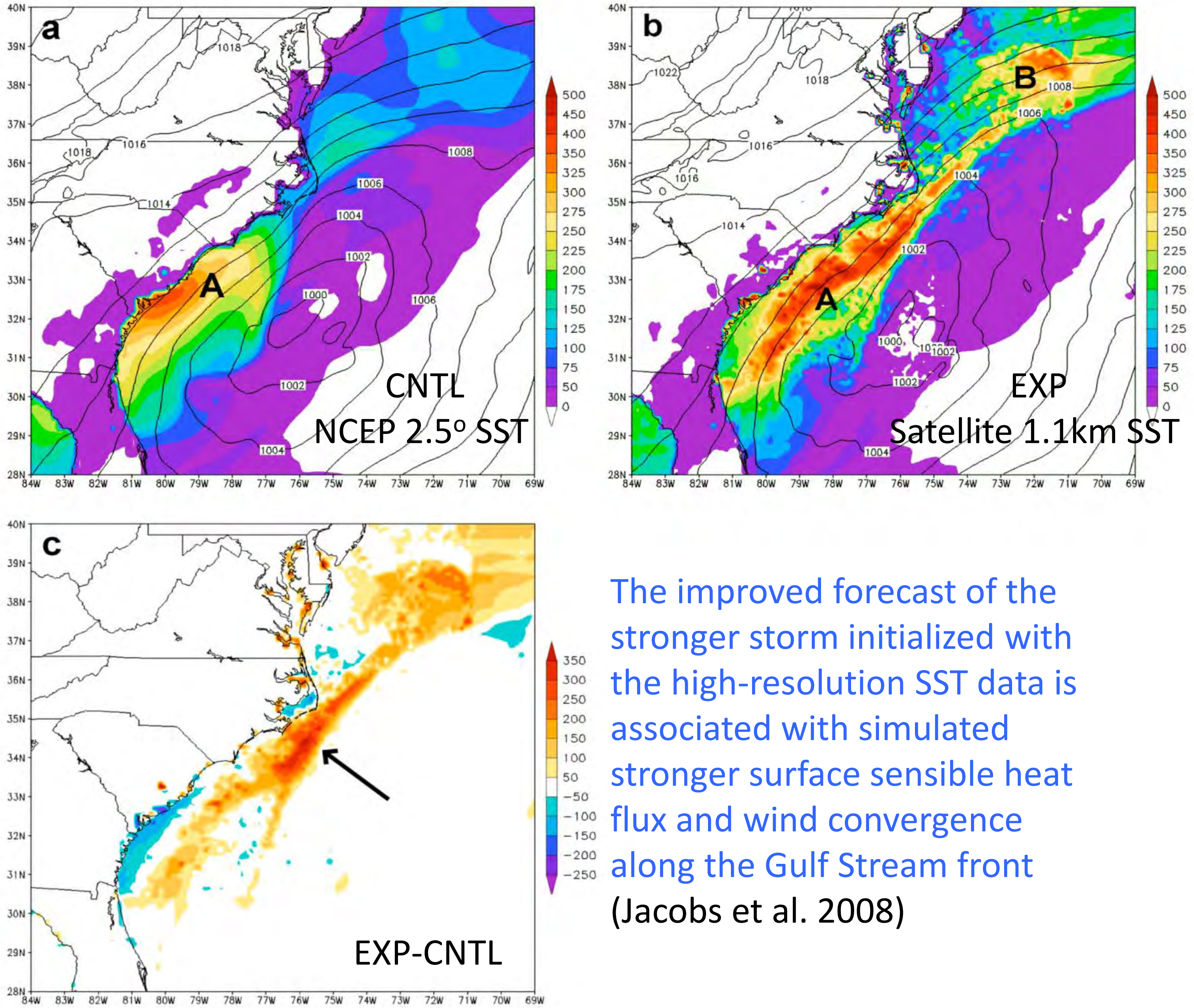


High-resolution initial SST data, which reveal a much larger SST gradient and warm-core filaments over the Gulf Stream, improve model (NCAR/PSU MM5) forecasts of the track and intensity of the US east coast winter storm of Jan. 24-25 2000 (Jacobs et al. 2008)

Surface Convergence

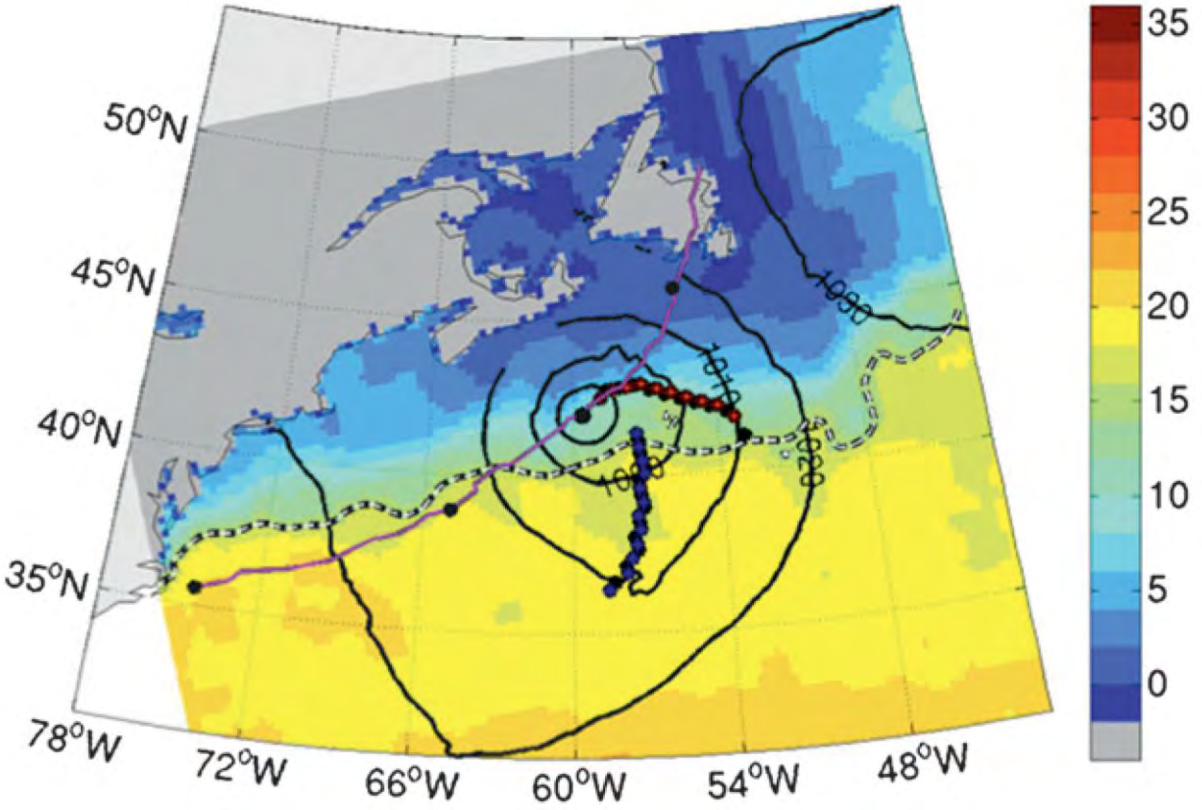


Surface Sensible Heat Flux and SLP

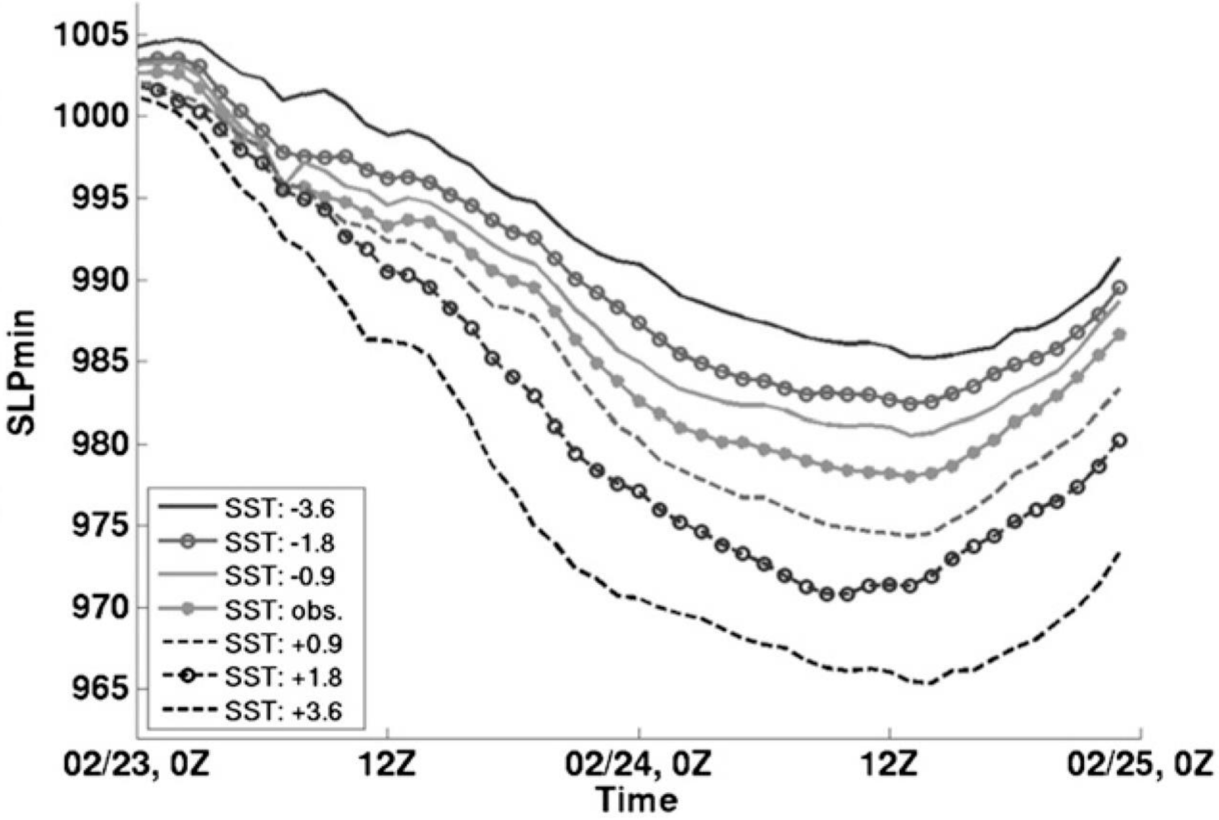


The improved forecast of the stronger storm initialized with the high-resolution SST data is associated with simulated stronger surface sensible heat flux and wind convergence along the Gulf Stream front (Jacobs et al. 2008)

Importance of the Gulf Stream SST at the Storm Developed Stage



WRF simulated track and SLP of the Feb2001 storm overlapped with the observed SST

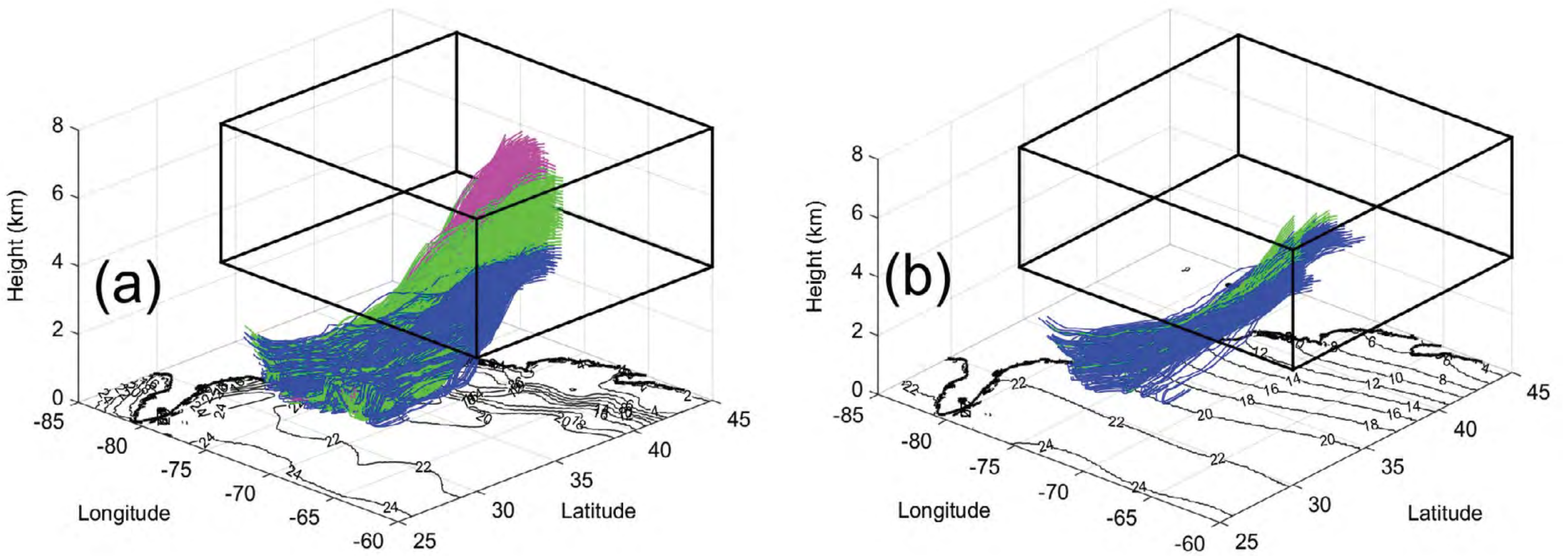


Time evolution of the simulated Feb2001 storm strength (SLP minimum) forced with different SST perturbations

The simulated storm strength at the developed stage increases with the SST perturbations over the Gulf Stream region. The surface fluxes under the storm warm sector have a dominant role through their regulation of the heat and moisture in the air that enters the warm conveyor belt (WCB) (Booth et al. 2012)

Control exp with observed SST front

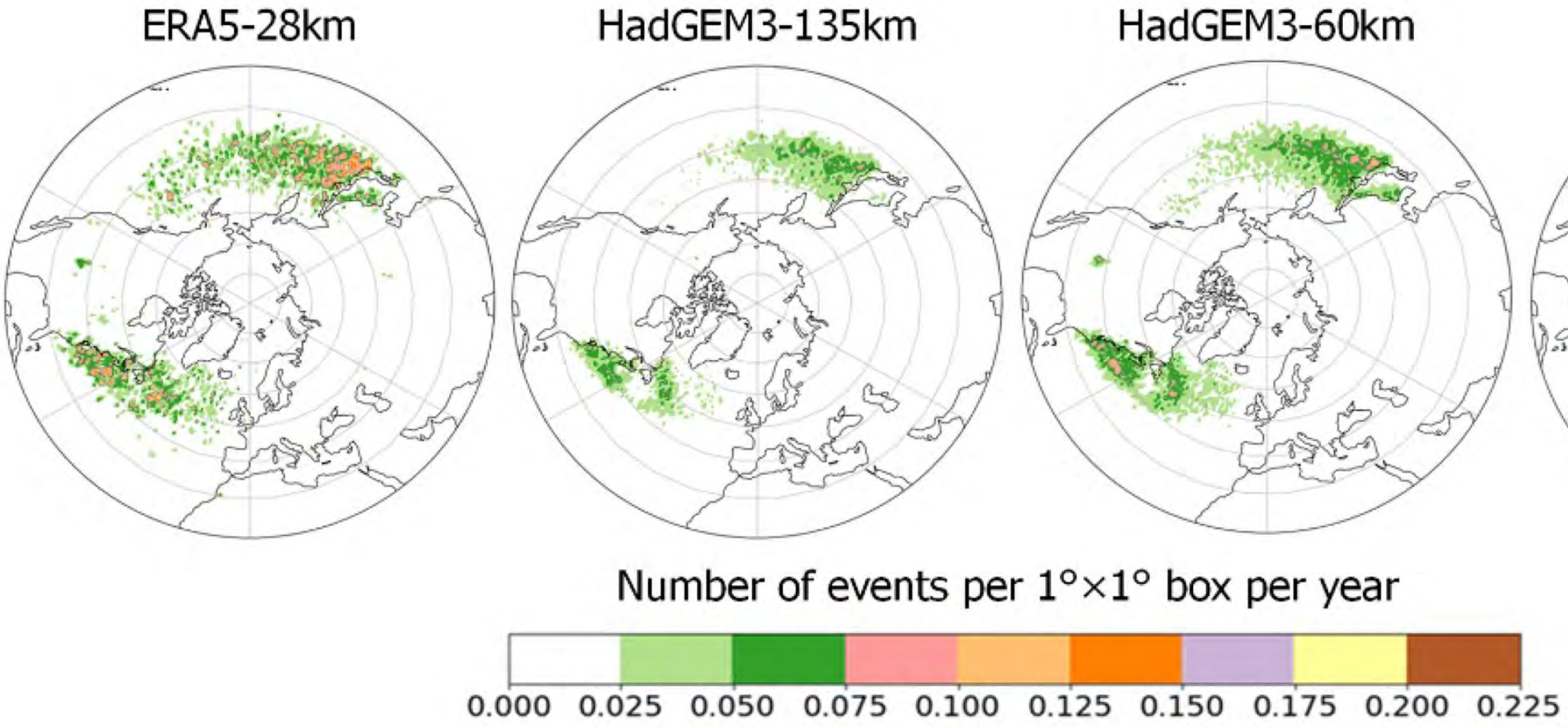
Exp with smoothed SST front



Back trajectories from MetUM simulated core ascending motion at t=24h, originating from low levels over the ocean at t=0h

The SST gradient over the Gulf Stream region is important for the simulated enhanced ascending motion associated with the warm conveyor belt (WCB) in cyclones, an effect not well represented in coarse resolution AGCMs (Sheldon et al. 2017)

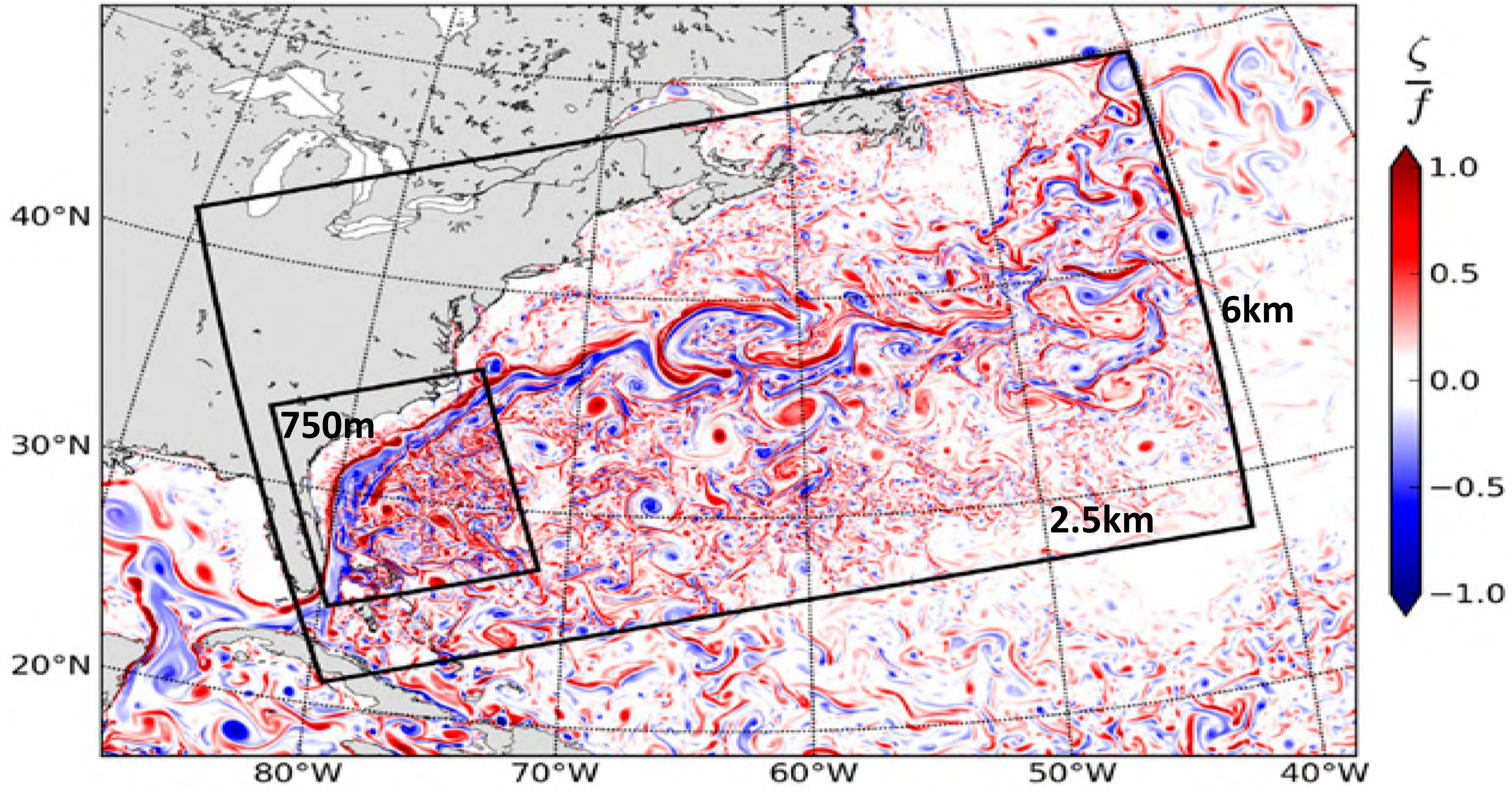
Impacts of Horizontal Resolutions of AGCMs on Simulated Bomb Cyclones



bomb cyclone density

Higher horizontal resolution in AGCMs substantially increases densities of simulated bomb cyclones near the WBC regions, and the averaged horizontal size of the simulated bomb cyclones are reduced, suggesting the importance of high atmospheric resolution in simulating extreme extratropical cyclone events (Gao et al. 2020)

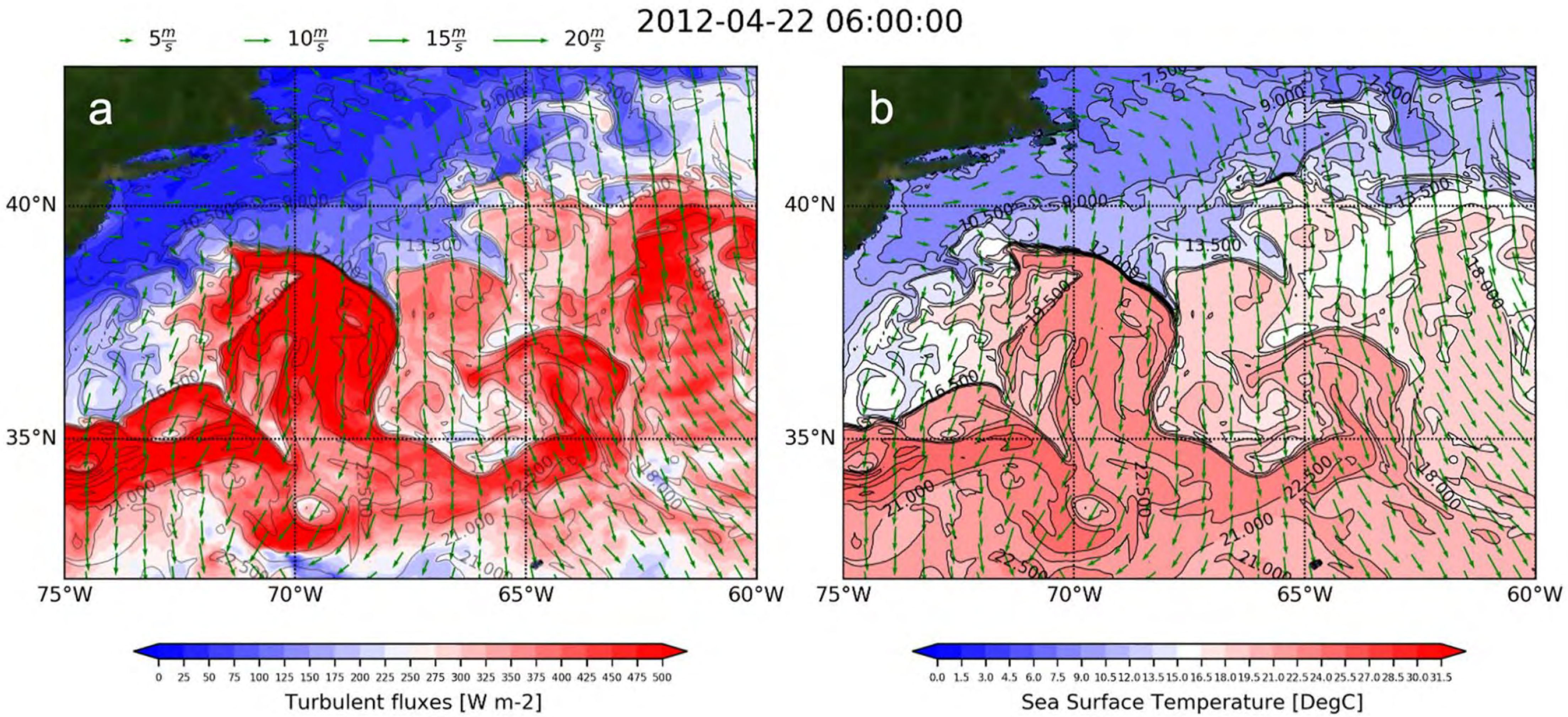
Ocean Mesoscale/Submesoscale in the Gulf Stream Region



Snapshot of surface relative vorticity ζ divided by Coriolis parameter f in the Gulf Stream region at the end of winter, simulated by ROMS with nested grids

The Gulf Stream is characterized by meanders and eddies. Ocean model simulations with refined grid resolutions exhibit increased and more realistic amount of submesoscale activity (Gula et al. 2015)

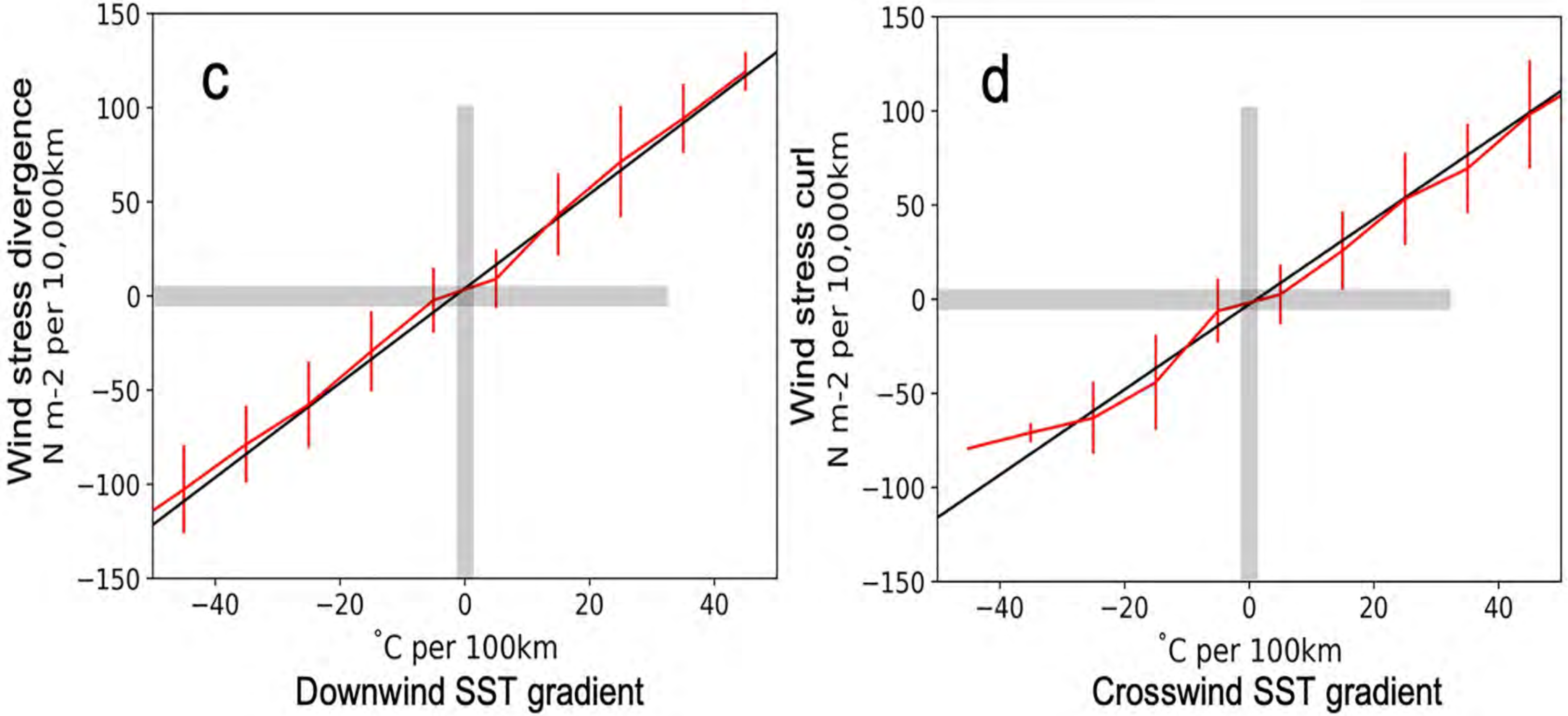
Air-Sea Interactions at the Ocean Mesoscale/Submesoscale in the Gulf Stream Region



Snapshot of simulated surface winds, turbulent heat fluxes, and SST in the Gulf Stream region from a global high-resolution coupled model GEOS-MITgcm (3km ocean, 6km atmosphere)

The simulated mesoscale eddies are bordered by sharp submesoscale SST fronts, and huge amount of surface turbulent heat fluxes are released over warm mesoscale SSTs during cold air outbreaks events (Strobach et al. 2022)

Wind Stress Curl and Divergence in Response to Submesoscale SST Fronts in the Gulf Stream Region



Binned scatter plots at high background wind conditions from the global high-resolution coupled model GEOS-MITgcm (3km ocean, 6km atmosphere) simulations

Strobach et al. 2022

The relationship between surface wind stress divergence/curl and SST gradients in the high wind speed regime is consistent with previous studies (Chelton et al. 2001, 2004; O'Neill et al. 2003), and the magnitudes of wind stress divergence/curl are much larger in response to the sharp submesoscale SST fronts in the Gulf Stream region

Summary and Challenging Issues

- The Gulf Stream separation/pathway and associated recirculation gyres/transport is closely linked to the AMOC
- Climate models need to simulate realistic AMOC-associated deep flow near the western boundary to achieve a realistic Gulf Stream separation/pathway, Gulf Stream transport, and associated strong SST gradient
- The temperature anomalies along the open-ocean Gulf Stream pathway are predictable on decadal timescales with initialized AMOC anomalies at northern high latitudes
- The impact of the open-ocean Gulf Stream pathway (after the separation) is limited to the lower troposphere in winter and is mainly on convective precipitation
- The upward motion at the upper troposphere across the Gulf Stream pathway is likely induced by synoptic storms from a remote origin, not forced directly by the open-ocean Gulf Stream pathway (after the separation)
- The Gulf Stream may affect the upper troposphere indirectly through its impacts on synoptic extratropical cyclones
- The Gulf Stream is important for the early development and rapid intensifications of the US east coast winter bomb cyclones (provides pre-conditions through the sensible/latent heat and moisture release), and also affects the storm at the developed stage through the latent heat/moisture release into the storm warm conveyor belt (WCB)

- The simulated zonal structure of the stationary Rossby wave response to the Gulf Stream SST bias is not well understood, inconsistent with the response from the linear barotropic wave model

- The linkage between surface wind convergence/SLP Laplacian and SST Laplacian does not hold instantaneously. Creative diagnostics are needed to clearly separate the impacts of the Gulf Stream marine atmospheric boundary layer (MABL) and the impacts of the synoptic storms on atmosphere circulation

- What causes the climatological mean surface wind convergence/SLP Laplacian along the Gulf Stream front? Could it be forced by the vertical convection related to turbulent heat/moisture release along the Gulf Stream pathway?

- High resolutions are needed for both atmosphere models and Gulf Stream front conditions for accurate predictions/simulations of US east coast winter bomb cyclones

- The air-sea interactions associated with mesoscale/submesoscale activity over the Gulf Stream region need to be resolved and assessed using high resolution coupled models