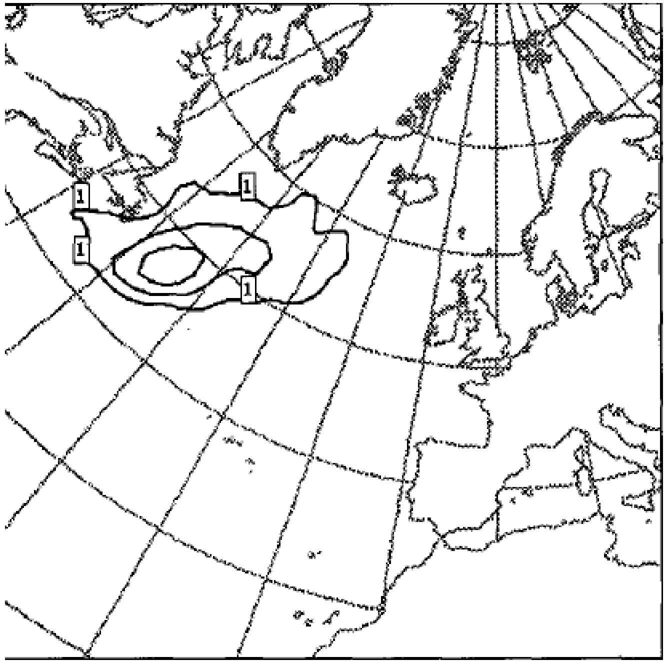
The Gulf Stream, the Jet Stream…and the "Quantum Café"

Brian Greene's Quantum Café: https://www.youtube.com/watch?v=t2CGXRcVFwE

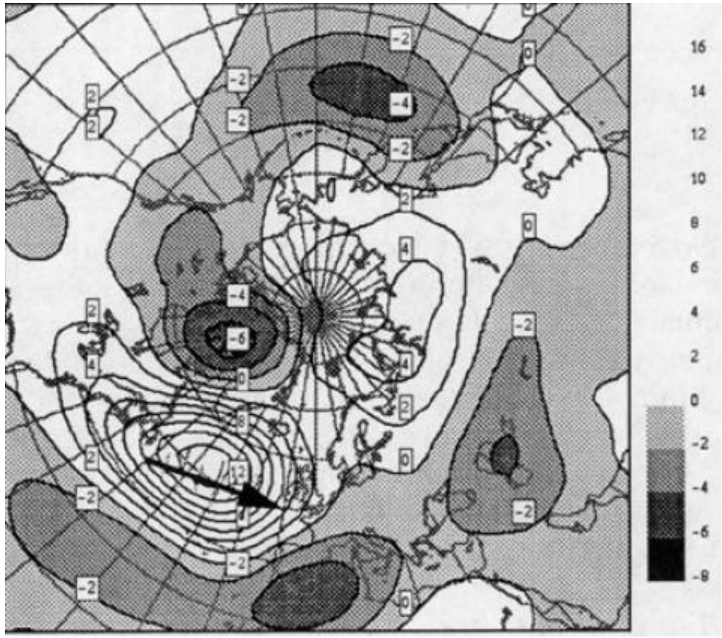
Peng et al. (1995)

Consider this

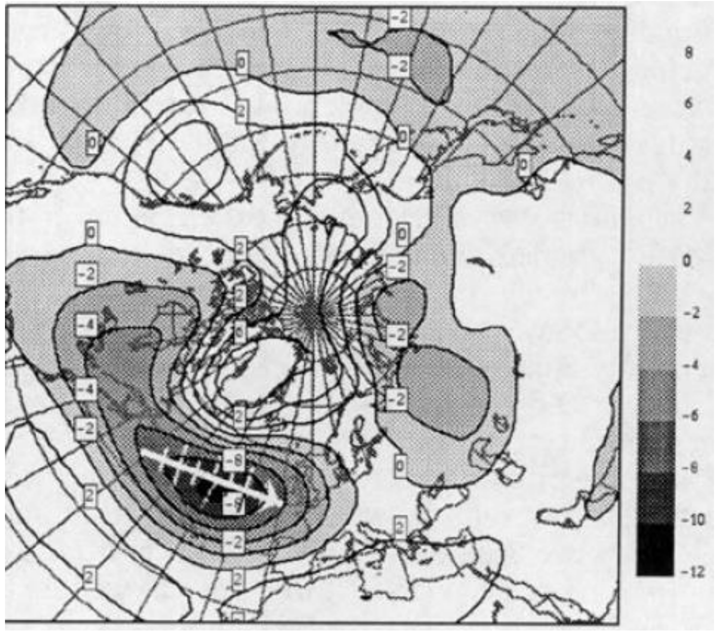
Imposed SST anomaly (max = +3.5K)



Z500 response (ci=2dam=20m)



November/December: high pressure



January/February: low pressure

- Same SST anomaly prescribed in November and January produce completely different responses in the same model (T42, L21)

…these (and many other perplexing results) lead to asking:

Q1 Is the forcing of changes in the atmospheric Jet Stream by ocean currents such as the Gulf Stream fundamentally a "case-by-case" problem in which details matter?

Q2 Or are there processes within the coupled ocean-atmosphere system which are missing in the current modelling framework and which, if they were present, would lead to a more linear state of affair?

Outline:

- A comparison of “observed” and simulated response of the Jet Stream to SST changes in the Gulf Stream region

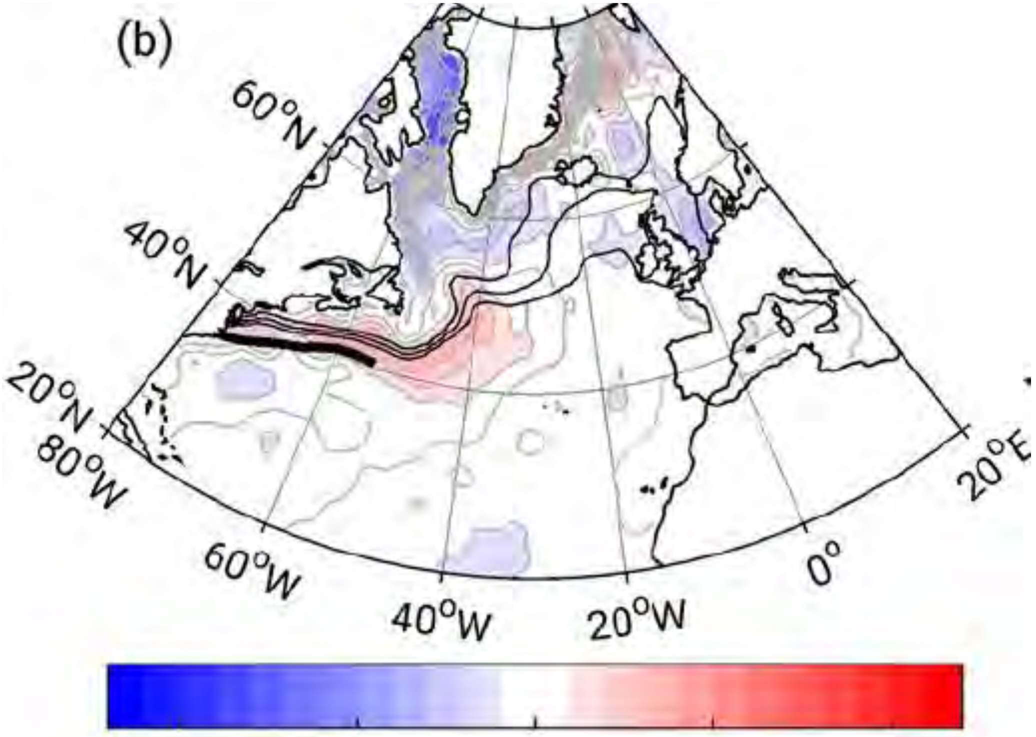
- The root cause of the “Quantum café” behaviour

- Oceanic and atmospheric “noise” (mesoscale)

Focus here on wintertime, upper level circulation and weekly to yr-to-yr timescales

1. A comparison of “observed” and simulated response to SST anomalies near the Gulf Stream

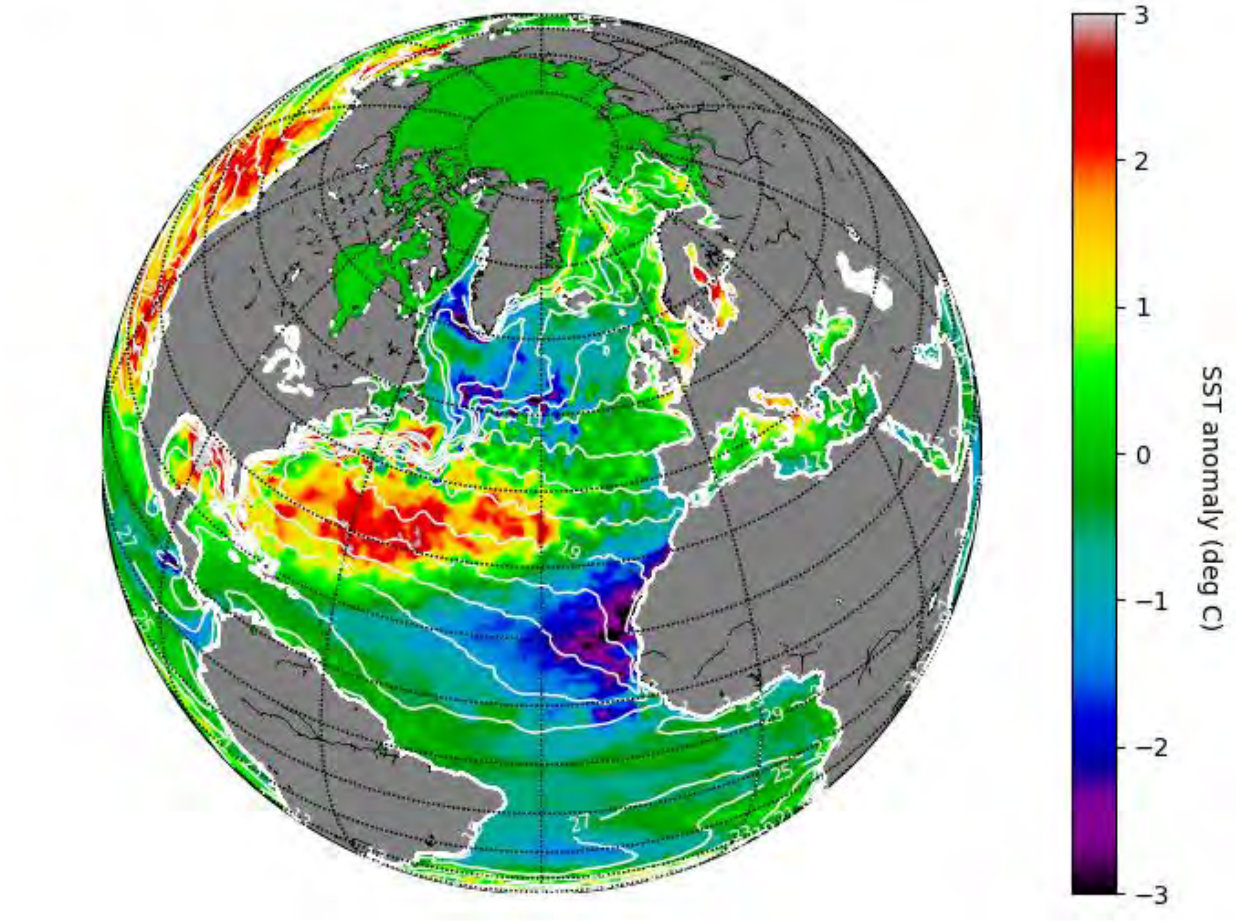
Well identified SST fluctuations near the Gulf Stream



Kwon & Joyce (2013)

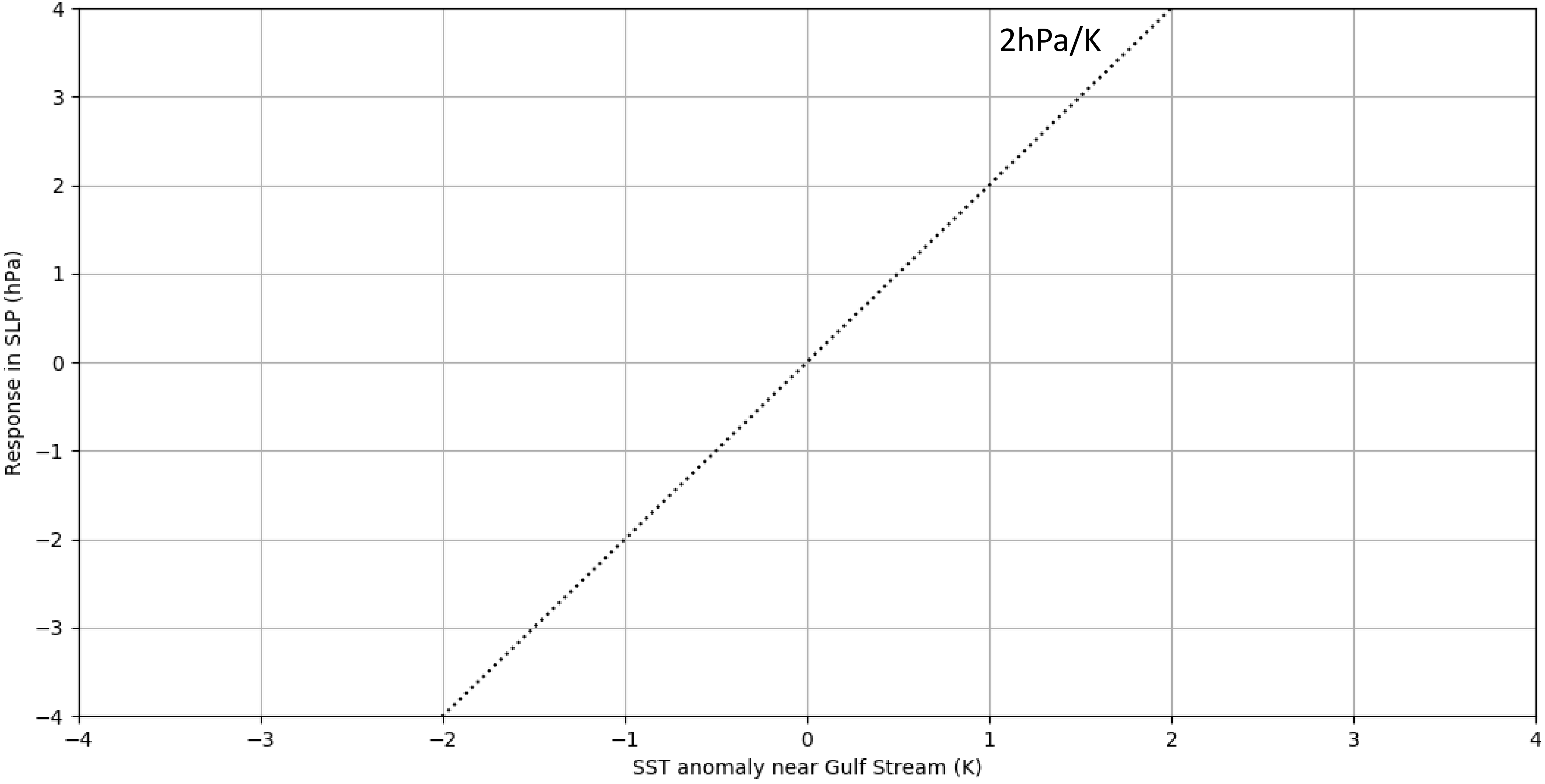
Gulf Stream shift

(JFM SST one year after GS shift index)



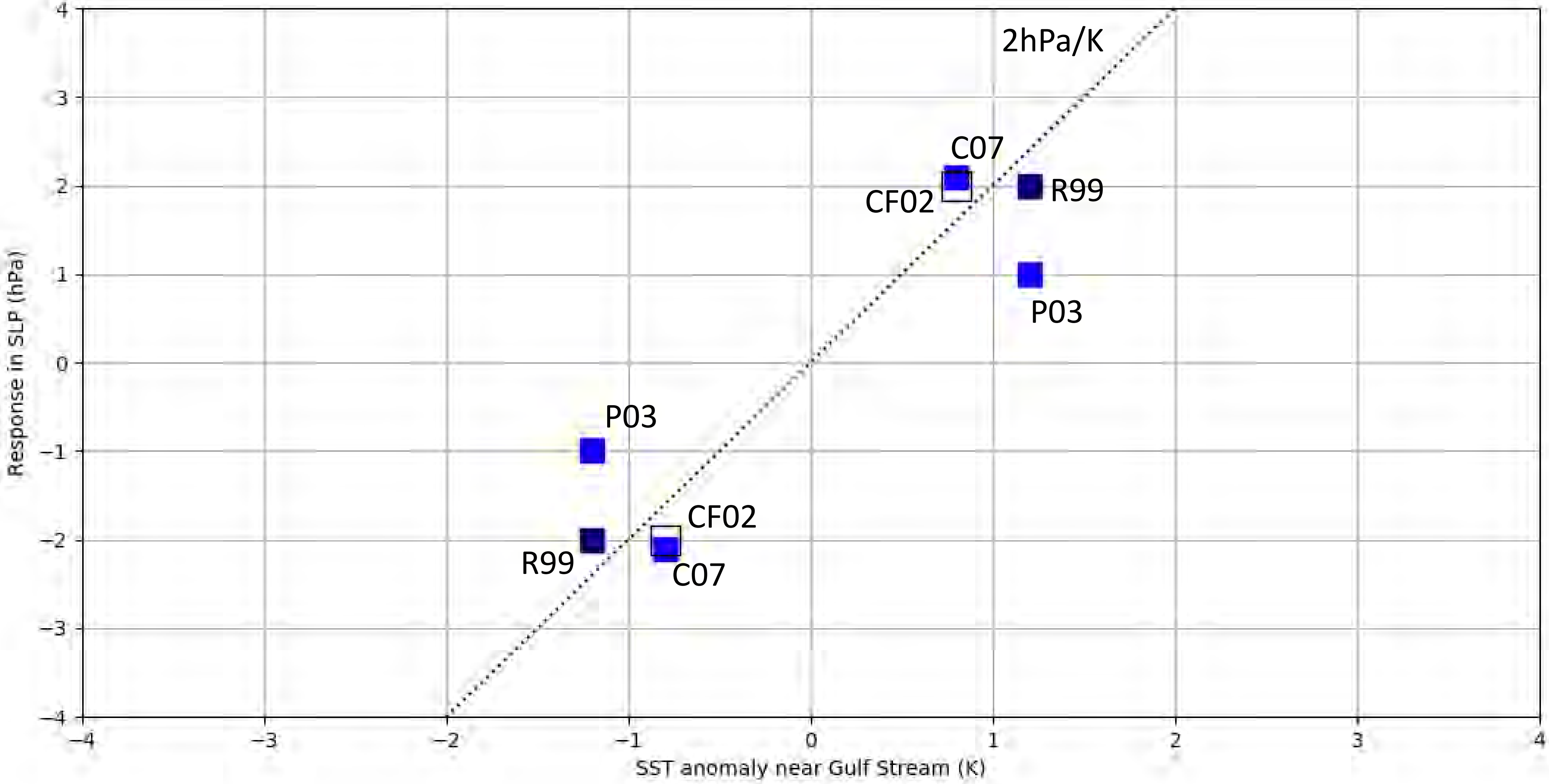
SST tripole

(JFM 2015 - JFM 2010 using NOAA-Reynolds SST)



Positive SLP signs refer to a (+) NAO-like response for warmer than usual conditions near the Gulf Stream

Squares: SST tripole



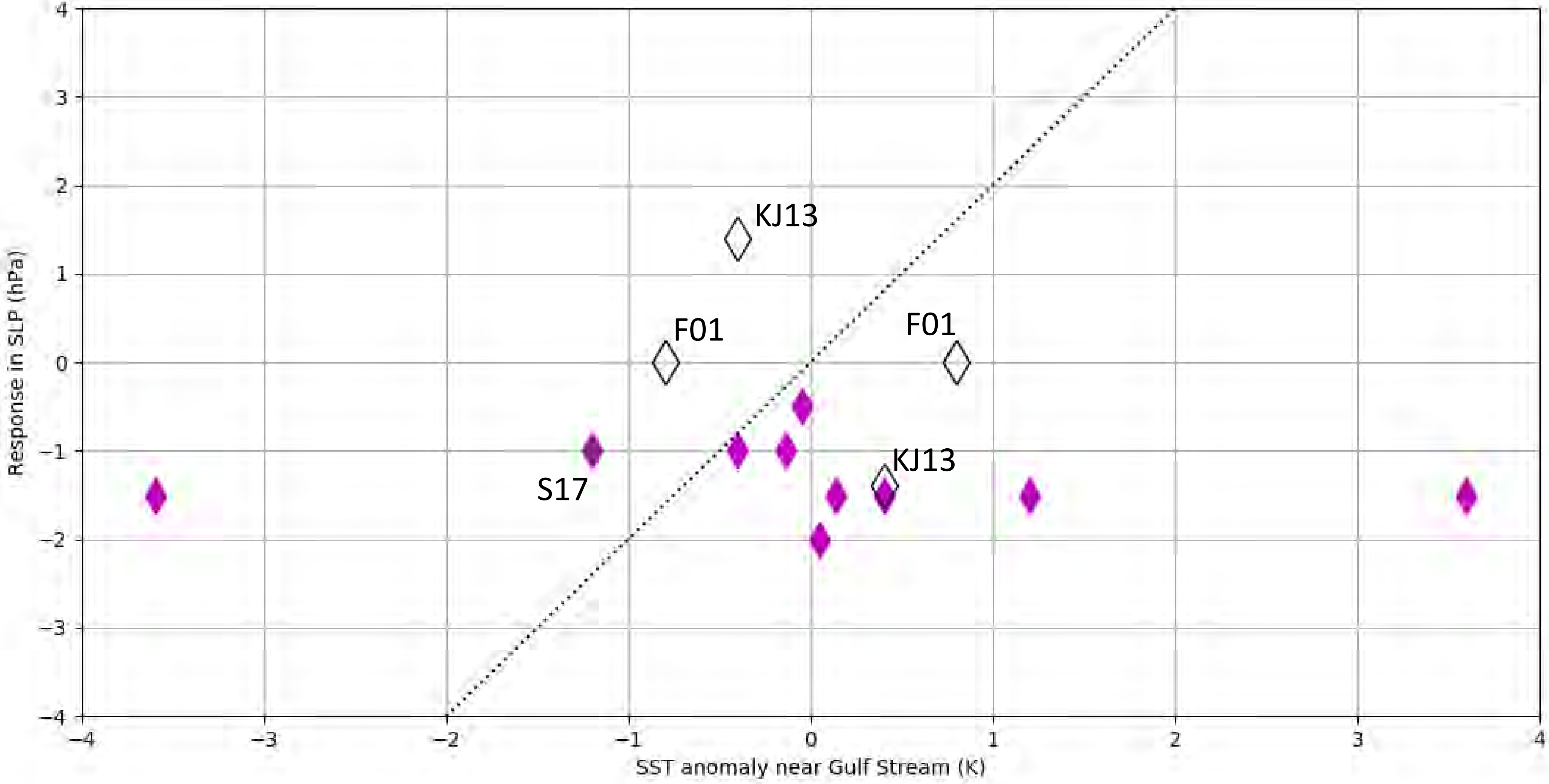
350km

250km

“Obs” in black open symbol: Czaja & Frankignoul (2002)

AGCMs in color: Rodwell et al. (1999); Peng et al. (2003); Cassou et al. (2007)

Diamonds: Gulf Stream shift

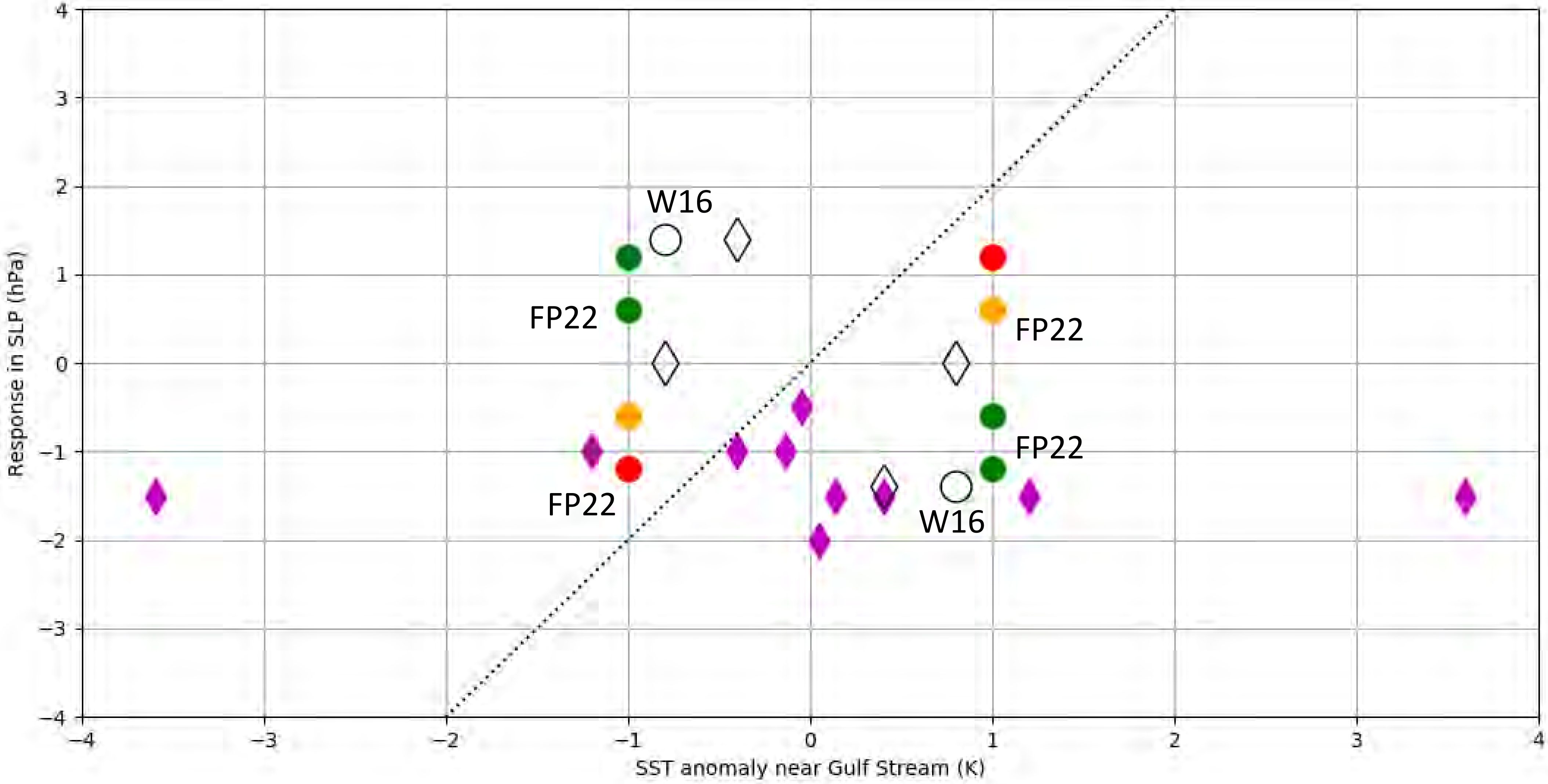


"Obs" in black open symbol: Frankignoul et al. (2001); Kwon & Joyce (2013)

AGCMs in color: Seo et al. (2017)

40km

Circles: SST gradients



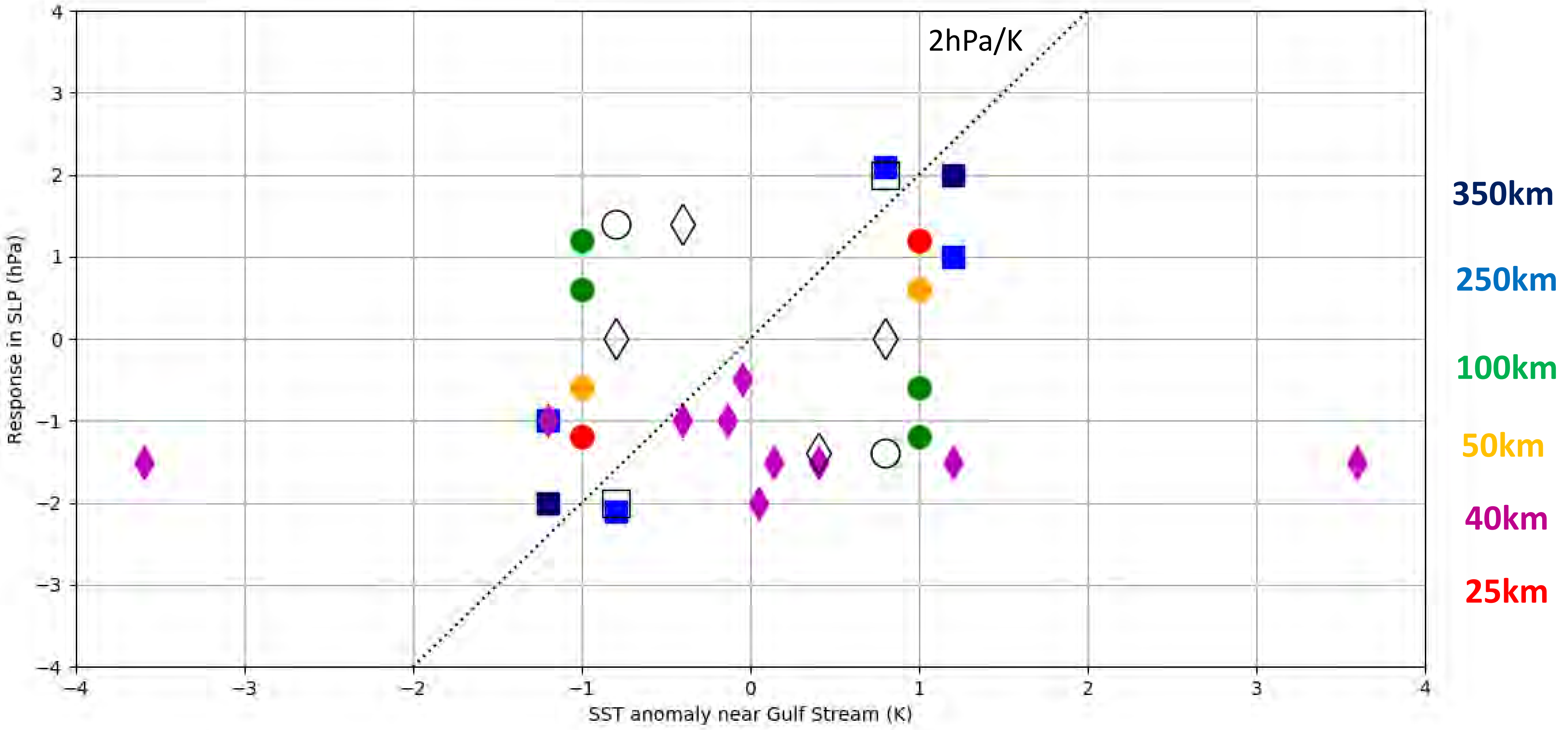
"Obs" in black open symbol: Frankignoul et al. (2001); Kwon & Joyce (2013); Wills et al. (2016)

AGCMs in color: Seo et al. (2017); Famooss Paolini et al. (2022)

50km **100km**

25km **40km**

Circles: SST gradients / Diamonds: Gulf Stream shift / Squares: SST tripole



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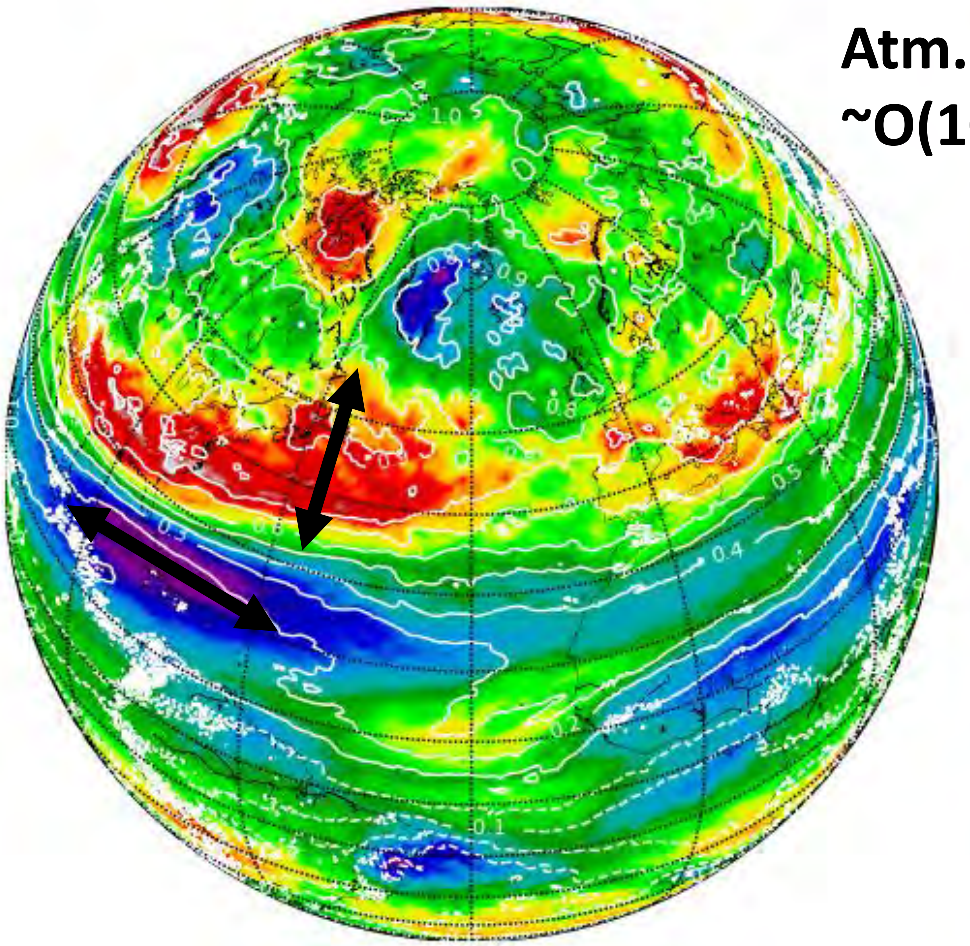
AGCMs in color: Rodwell et al. (1999), Peng et al. (2003); Cassou et al. (2007); Seo et al. (2017); Famooss Paolini et al. (2022)

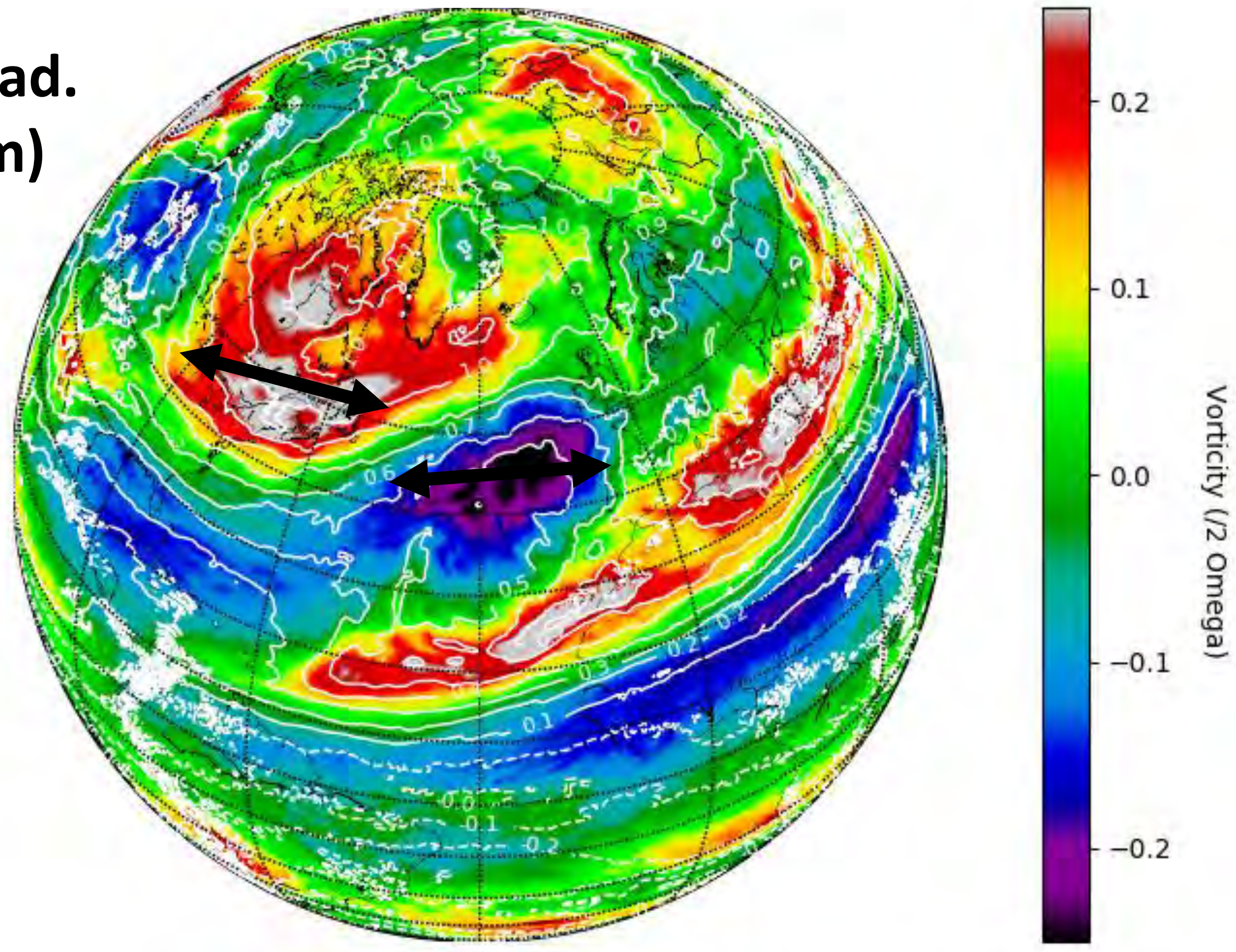
2. The root cause of the “Quantum café” behaviour

ERA5: 300hPa vorticity in Jan-Feb-Mar (white contours ζ+f, color ζ)

Atm. def. rad.
~O(1000km)

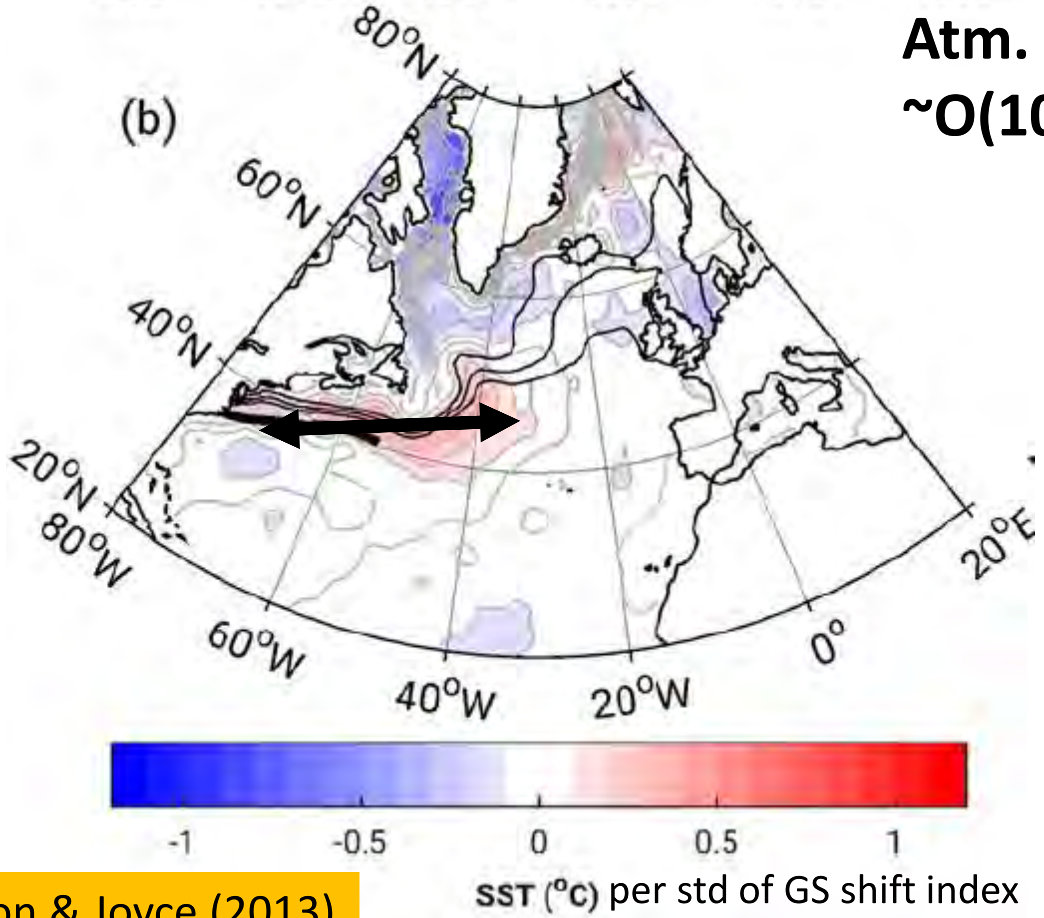


2010 (NAO = -1.11-1.98-0.88)



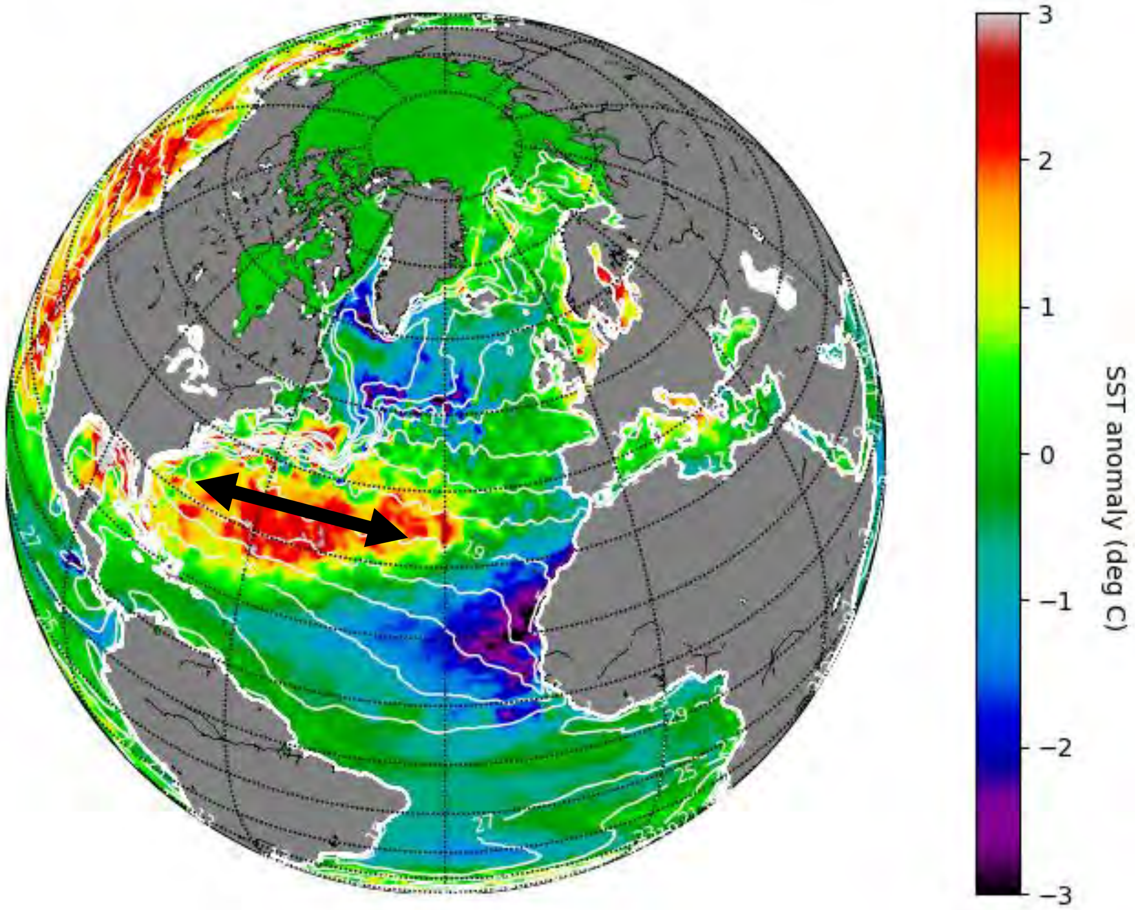
2015 (NAO = +1.79+1.32+1.45)

Well identified SST fluctuations near the Gulf Stream



Kwon & Joyce (2013)

Atm. def. rad.
~O(1000km)



Gulf Stream shift

(JFM SST one year after GS shift index)

SST tripole

(JFM 2015 - JFM 2010 using NOAA-Reynolds SST)

A useful framework: linear storm-track model

- Decay and dissipation of Jet Stream meanders approximately balance generation of these meanders by noise

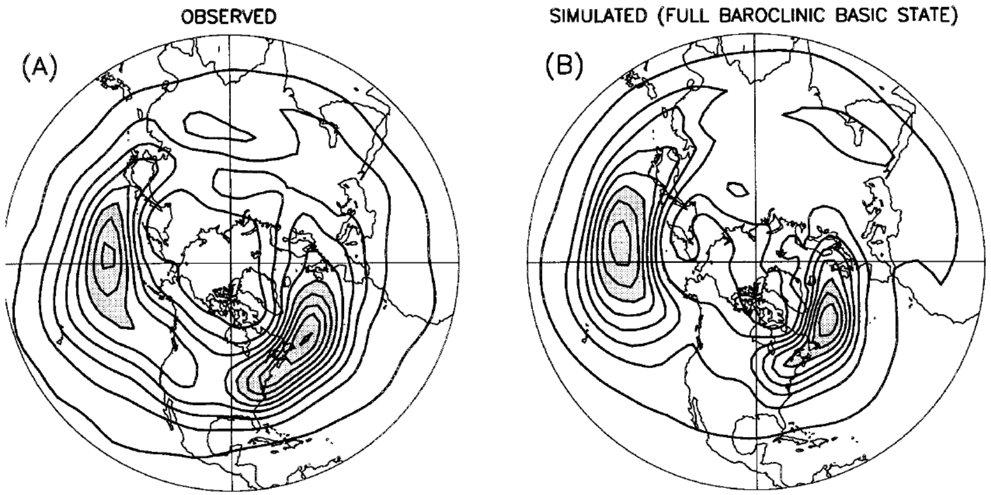
Input: stochastic forcing

$$(L + D)C_o + C_o(L^T + D^T) + F = 0$$

Output: Eddy covariance matrix

Input: linear dynamics + damping operators

Whitaker and Sardeshmukh (1999)
Peng and Whitaker (1999)



400 hPa eddy (1-8 day) Ψ variance. Heat and vorticity fluxes are also well captured *in the long term mean. This is a 2-layer dry QG model!*

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A useful framework: linear storm-track model

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Input: stochastic forcing

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Whitaker and Sardeshmukh (1999)
Peng and Whitaker (1999)

Gulf Stream's role:

L: favors transient growth in certain locations (Hoskins and Valdes, 1990; Nakamura et al., 2004)

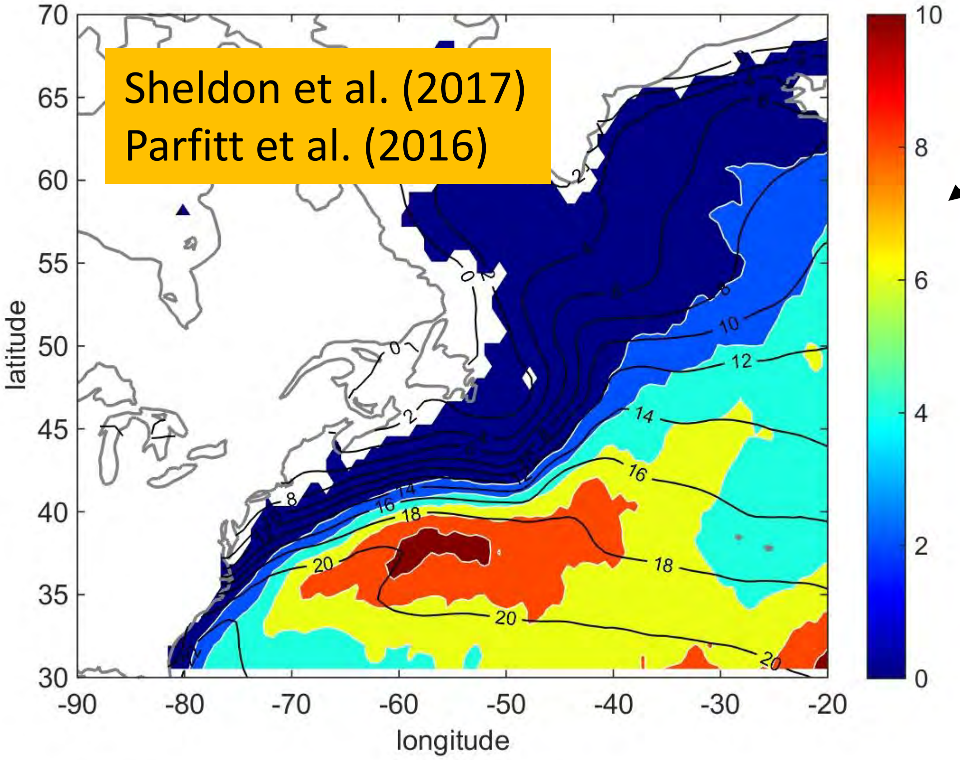
D: provides major source of damping (Hall and Sardeshmukh, 1999; Czaja, 2012)

F: organises mesoscale activity (Minobe et al., 2008)

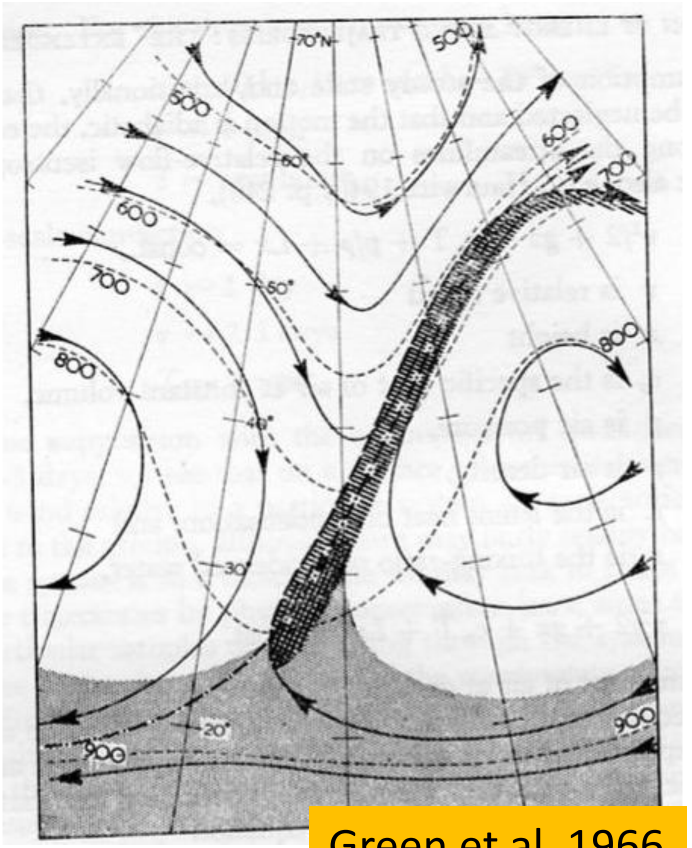
3. Oceanic and atmospheric “noise” (mesoscale)

Atmospheric noise & the Gulf Stream

- Weather systems are open systems: the strong ascent along the cold and warm fronts is not locally balanced by subsidence within the system



Fraction of wintertime days with θe(tropopause)-θe(950hPa) <0



Green et al. 1966

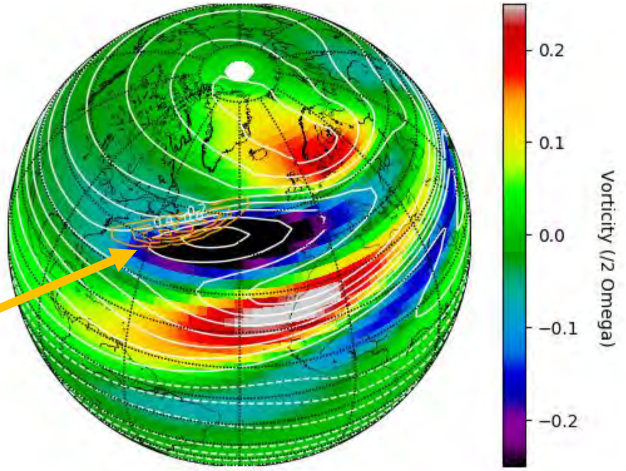
- The process is stochastic in time, including a time mean value, but with a well defined structure in space

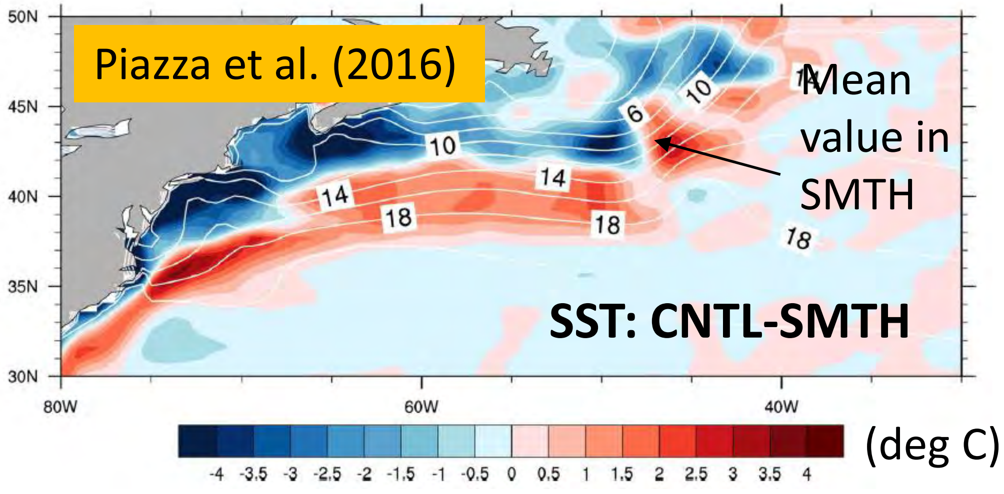
$$(L+D)C_o + C_o(L^T + D^T) + F = 0$$

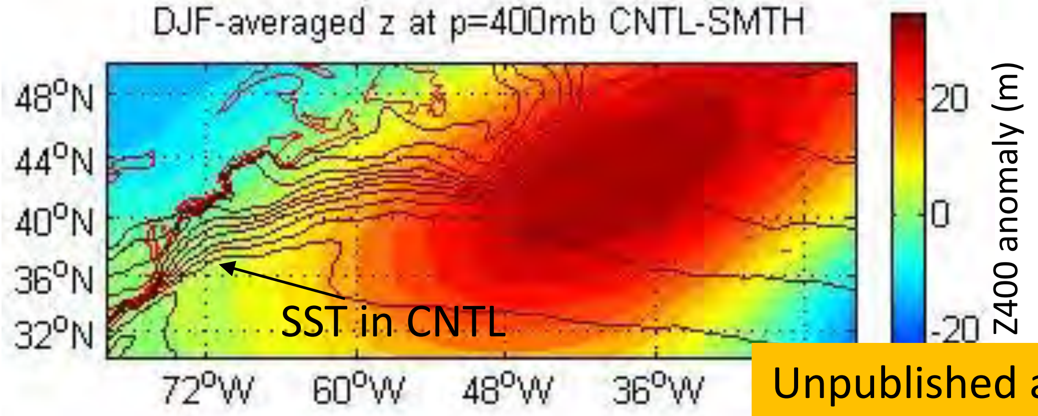
Evidence of **F** in SMTH/CNTL SST experiments

Upper level vorticity response to a line source in a linear barotropic model (f+ζ in contours, ζ in color)

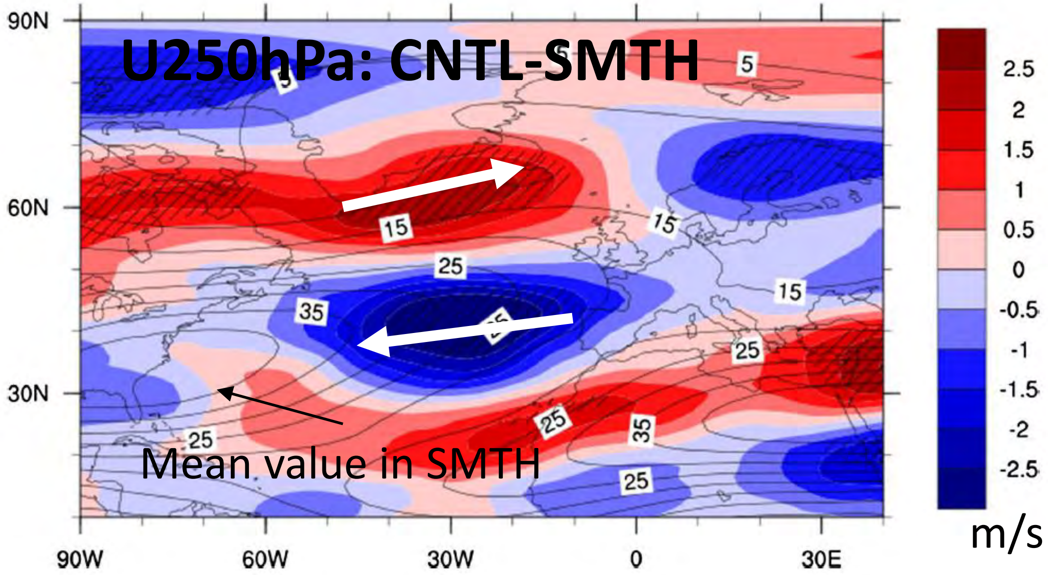
Anticyclonic vorticity source
(20 degree tilt, 10-day damping)







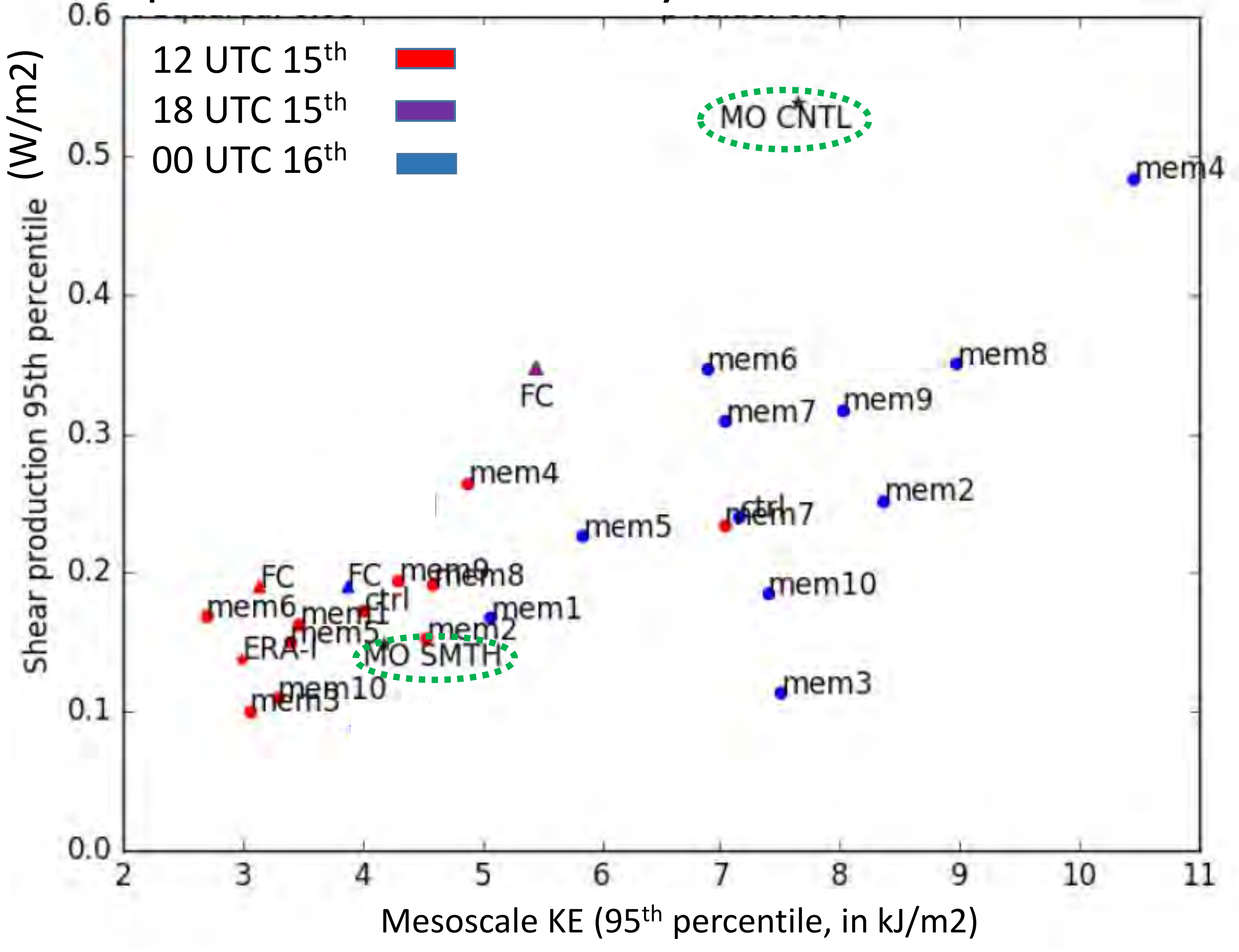
Unpublished analysis of Minobe et al. (2008)



- The organisation of mesoscale activity in AGCMs(dx~50km) leads to anticyclonic upper level circulation downstream of the Gulf Stream

Evidence of **F** in operational forecast ensembles

Spread of ECMWF forecasts after cyclone cross the Gulf Stream



Models:

-ECMWF forecast (FC) dx=40km

-ECMWF hindcast (ctrl+10 members) dx=18km

-MO (CNTL & SMTH) dx=12km

A. Cobb PhD's thesis at Imperial College

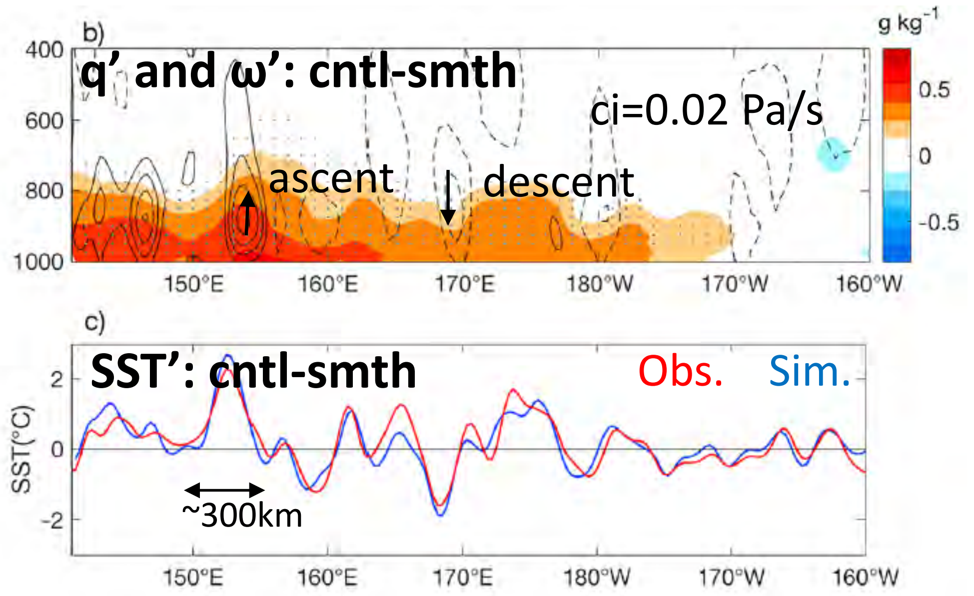
Oceanic noise & the Jet Stream

- Export of heat and moisture at the top of the marine boundary layer through w’,q’,T’ correlation on the scale of the oceanic eddy field (Small et al., 2008; Ma et al., 2015, 2017)

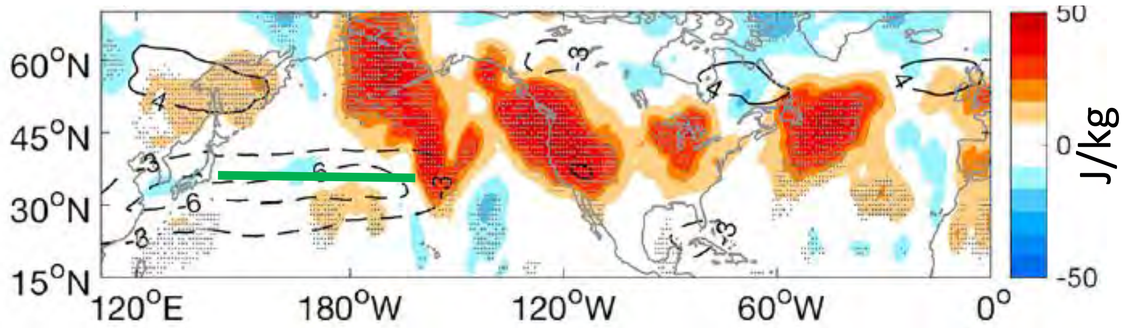
- The moistier and warmer environment favours baroclinic growth of weather systems in AGCM(dx~25km)+slab ocean

$$(L + D)C_o + C_o(L^T + D^T) + F = 0$$

Sections along the green line in bottom panel



U300 (ci=3m/s) & EKE300 (cntl)-EKE300(smth) in color



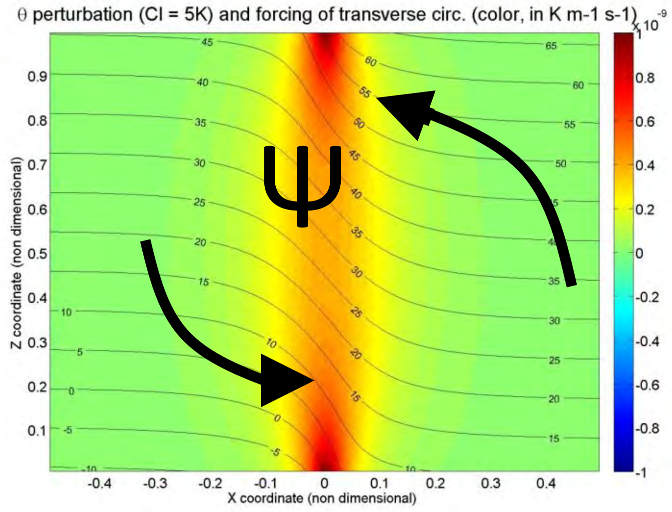
Jia et al. 2020

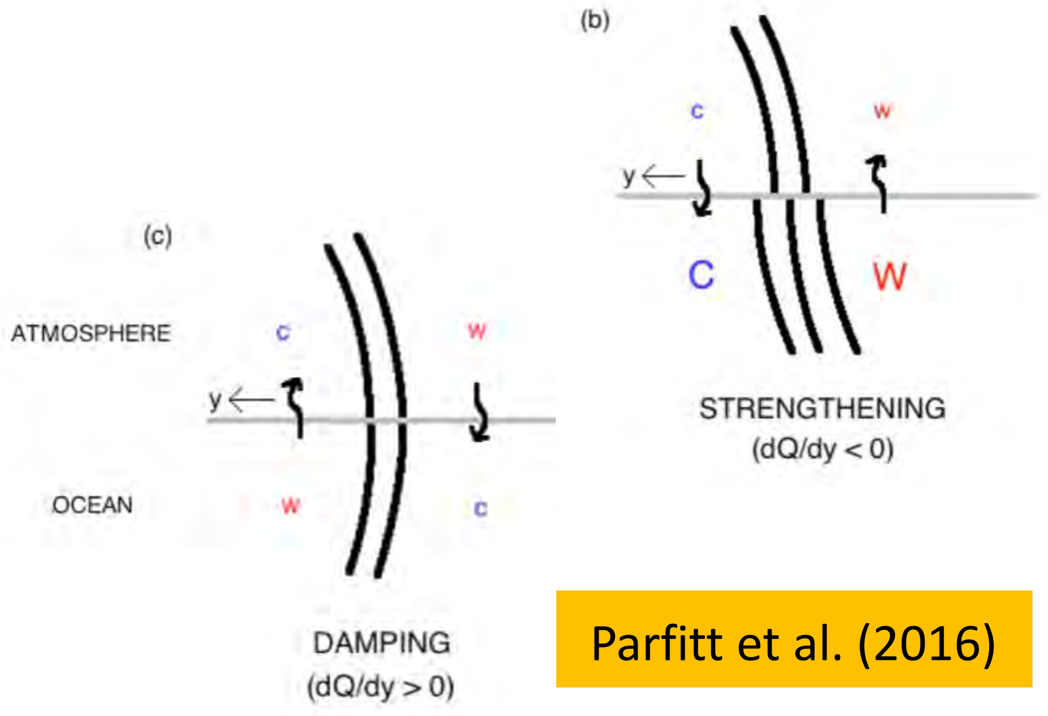
The coupling of oceanic and atmospheric mesoscale circulations

- Fronts develop as singularities in theoretical models (Hoskins and Bretheron, 1972)

- Is it a coincidence that the lengthscale of atmospheric and oceanic mesoscales are comparable?

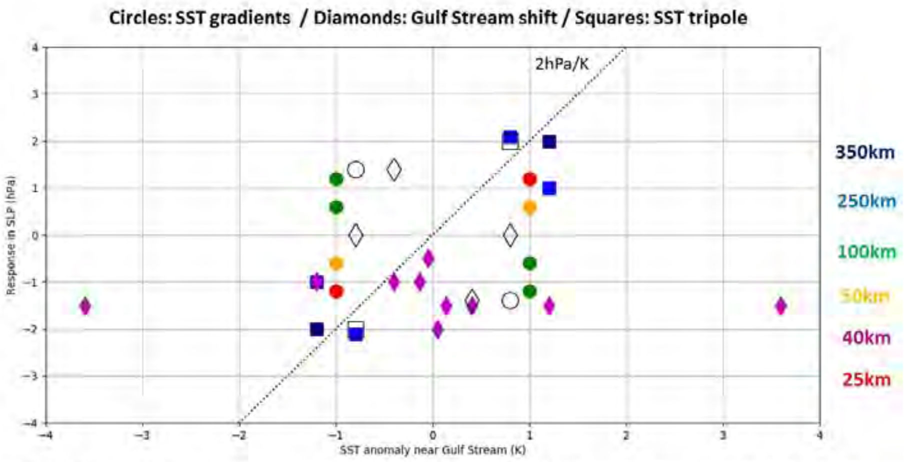
$$L_a = \frac{U_a}{f} \sim \frac{N_o H_o}{f} = L_o \approx 100km$$





Parfitt et al. (2016)

Summary: the Gulf Stream, the Jet Stream and … the "Quantum café"



"Obs" in black open symbol: Czaja and Frankignoul (2002); Frankignoul et al. (2001); Kwon & Joyce (2013); Wills et al. (2016)

AGCMs in color: Rodwell et al. (1999), Peng et al. (2003); Cassou et al. (2007); Seo et al. (2017); Famooss Paolini et al. (2022)

- Details matter when it comes to the forcing of the Jet Stream by the Gulf Stream.
- In the framework of linear storm track modelling, this sensitivity reflects the impact the Gulf Stream has on the background flow (**L**)
- There might be a more robust forcing associated with the organisation of (atm.) mesoscale activity by the Gulf Stream in AOGCMs of O(10km) resolution (**F**), but this process is stochastic in nature

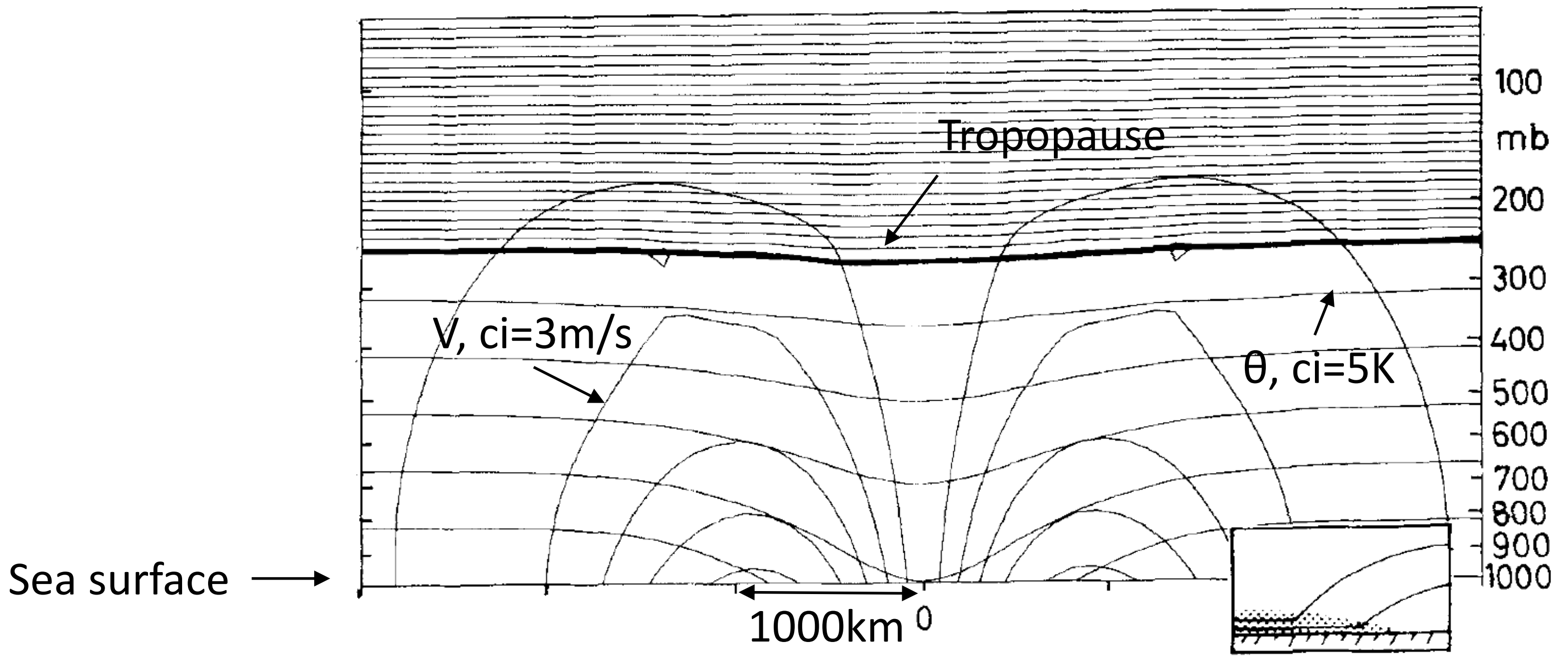
$$(L + D)C_o + C_o(L^T + D^T) + F = 0$$

Outstanding questions

- What are the emerging mechanisms of Gulf Stream forcing of the Jet Stream in HR models which are not present in LR models?
- Can we develop a parameterisation of these mechanisms in order to sample the natural variability of the Gulf Stream and run ensemble of long coupled simulations A(~100km) / O(~10km)?
- …

extras

The root cause of “Quantum café behaviour”: quasi geostrophic (QG) dynamics --1

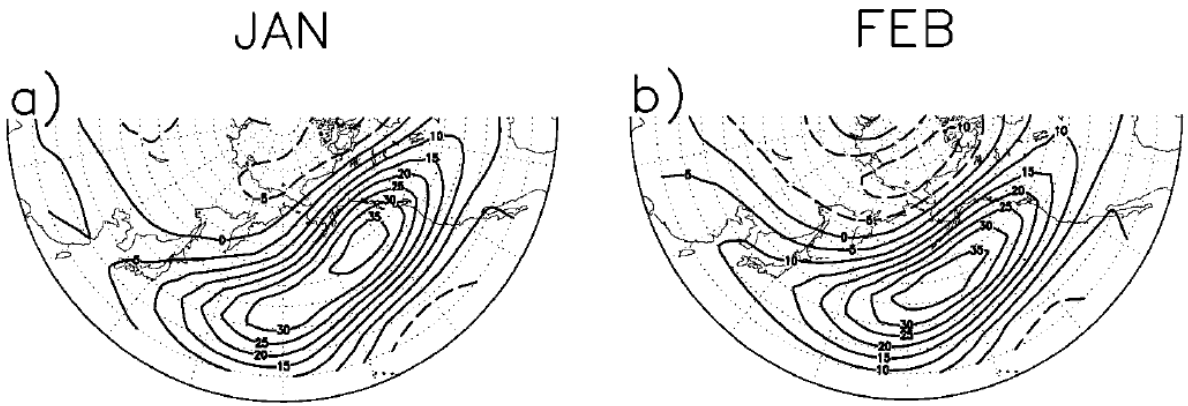


Cyclonic circulation generated by a circular warm surface temperature anomaly of +10K (Hoskins et al., 1985)

- Any surface temperature anomaly on the scale of the atm. deformation radius will affect the whole troposphere because of the dynamical nature of boundaries in QG dynamics (in this sense Gulf Stream effects reaching the tropopause are not surprising)

The root cause of “Quantum café behaviour”: quasi geostrophic (QG) dynamics --2

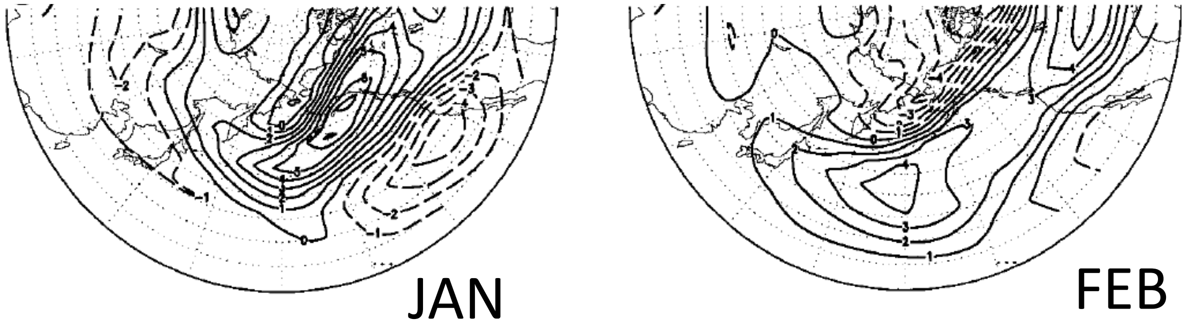
- At upper level, this perturbation leads to *sensitive* changes in storm track statistics



Initial upper level (Z250) perturbation induced by a North Pacific SST anomaly

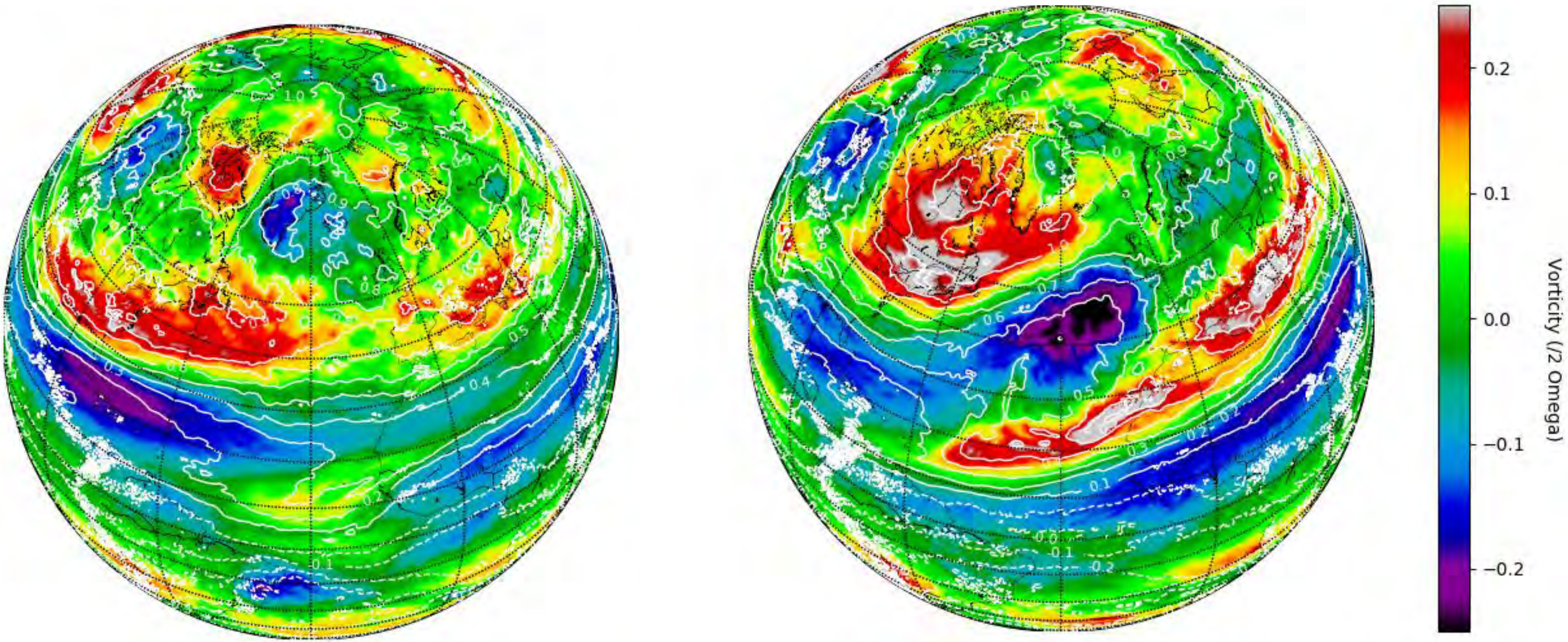
Induced change in eddy statistics predicted by a linear “storm-track” QG model

(Z tendency due to band-pass eddies)



Peng and Whitaker (1999)

ERA5: 300hPa vorticity in Jan-Feb-Mar (white contours ζ+f, color ζ)

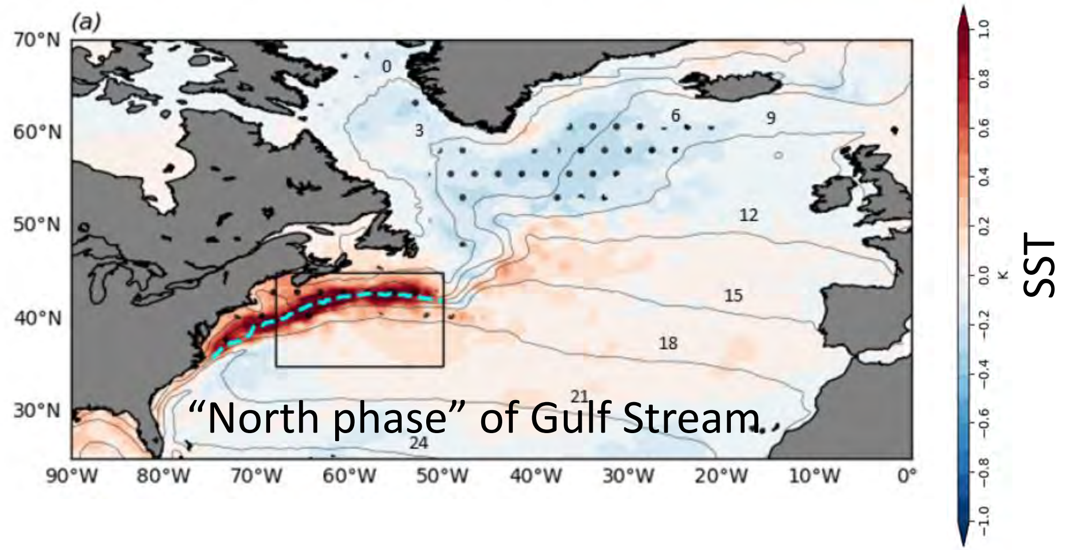


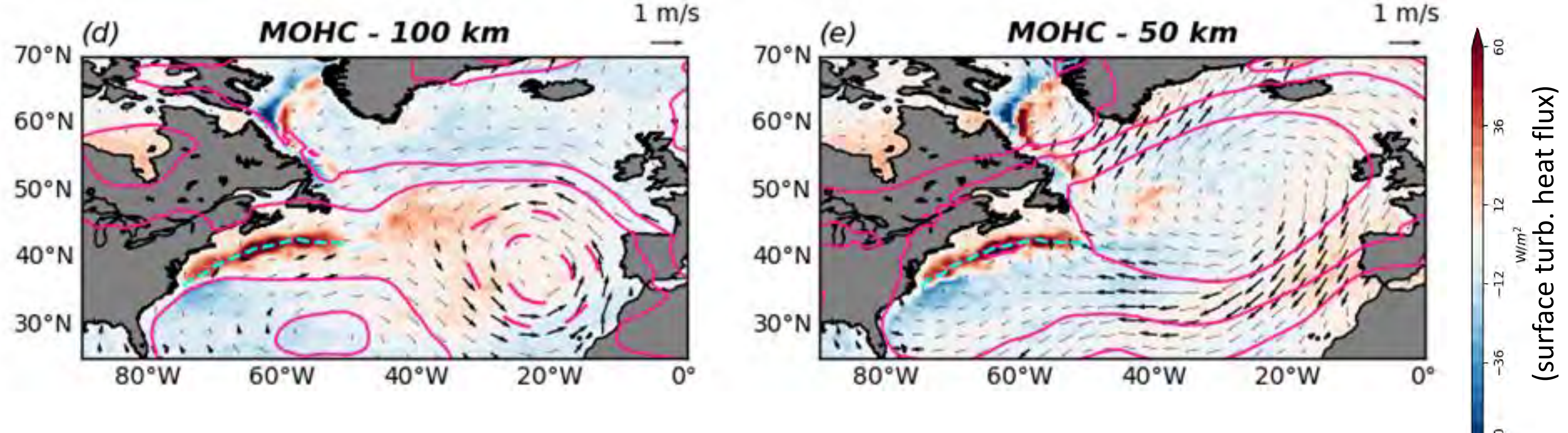
2010 (NAO = -1.11-1.98-0.88)

2015 (NAO = +1.79+1.32+1.45)

…or this

- Prescribed phases of the Gulf Stream lead to completely different ensemble mean response in AGCMs with only a factor 2 change in dx

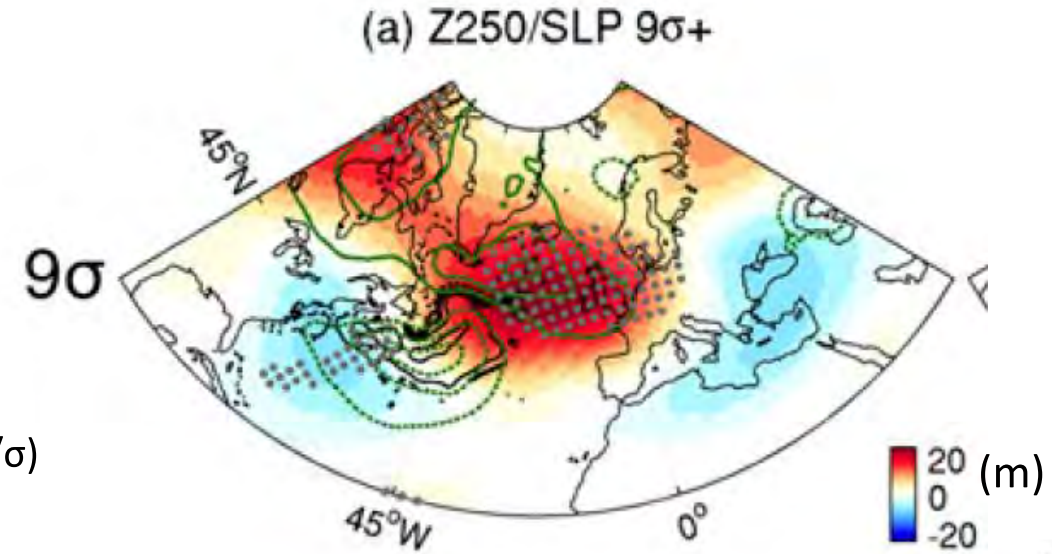




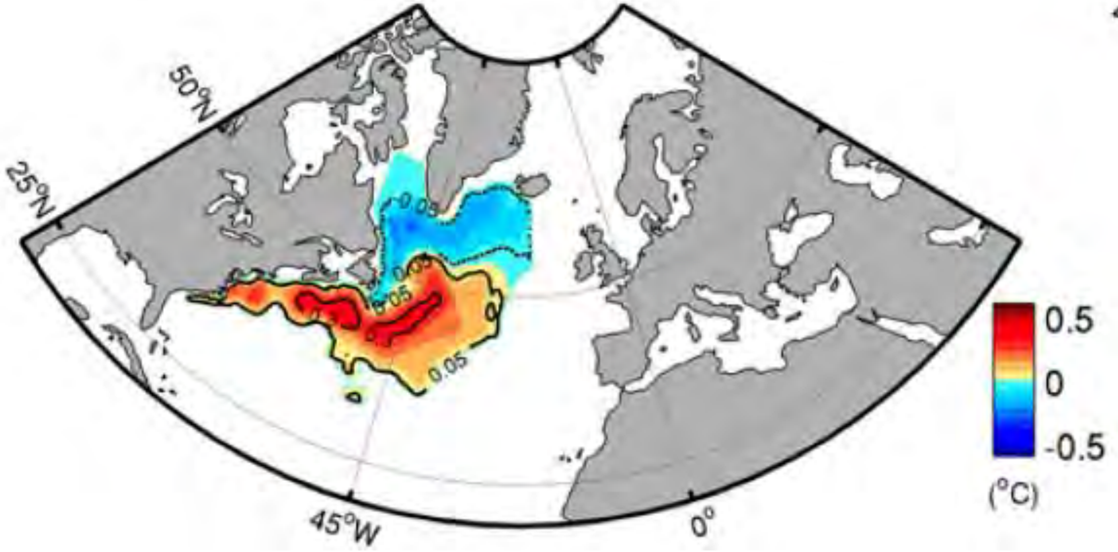
Famooss Paolini et al. (2022)

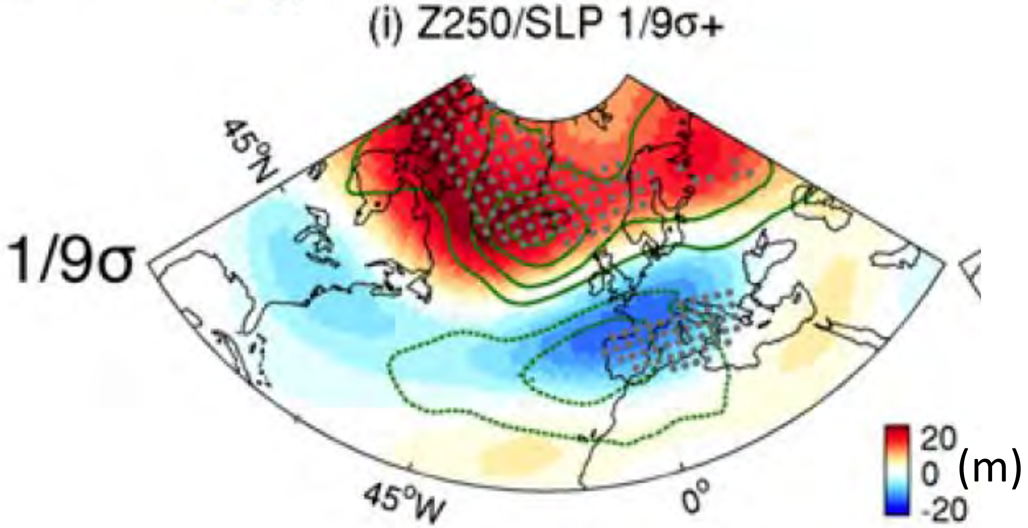
SLP with ci = -1.2, -0.6, -0.3, 0.3, 0.6, 1.2 hPa and surface winds (arrows)

Or this…



Imposed SST anomaly (max = +0.4K/σ)

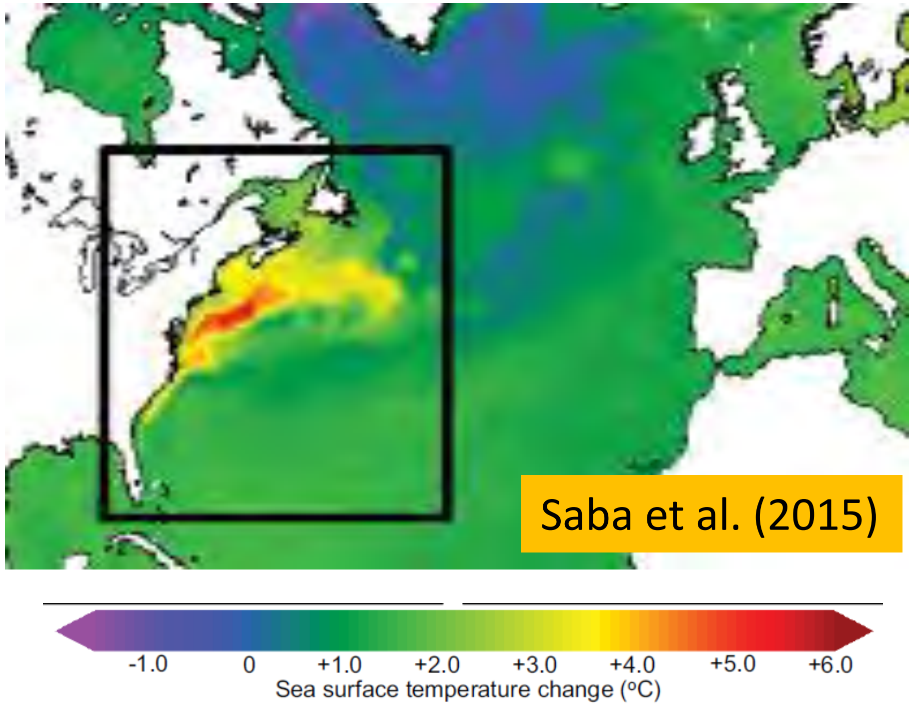




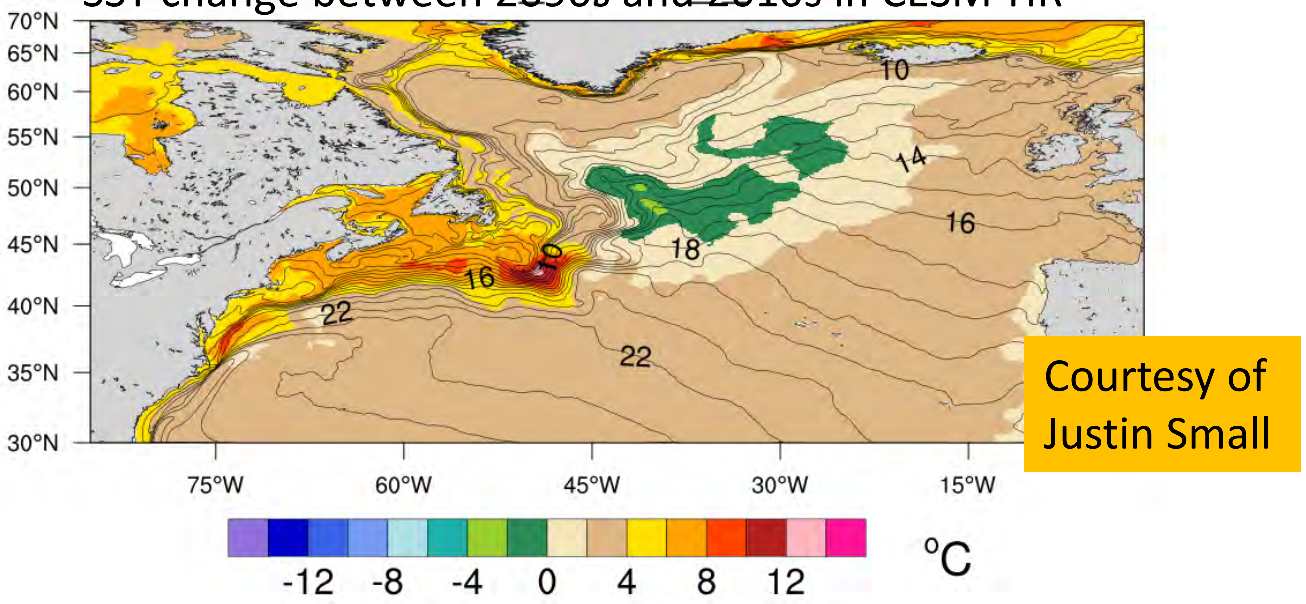
- WRF model (40km, L28) produces same Z250 amplitude of response to an SST anomaly of 3.6K and 0.04K amplitude

Well identified SST fluctuations near the Gulf Stream?

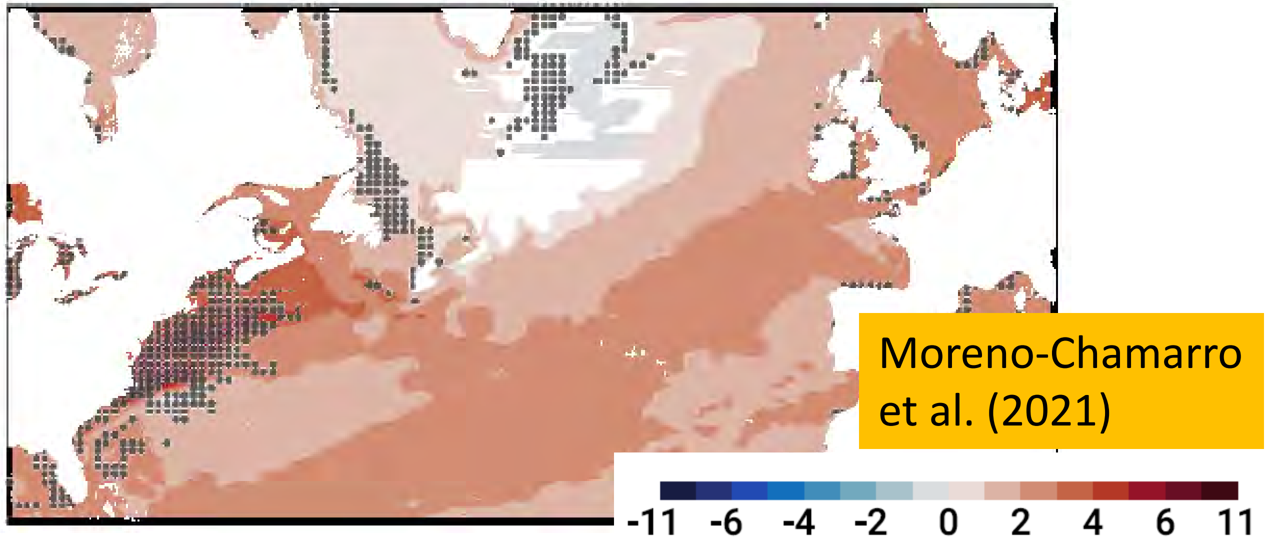
SST change at CO2 doubling in GFDL-HR (0.5deg A/0.1deg O)



SST change between 2090s and 2010s in CESM-HR



Change in SST between 2030-2050 and 1960-1980 in HadGEM3-HH (50km A/10km O)

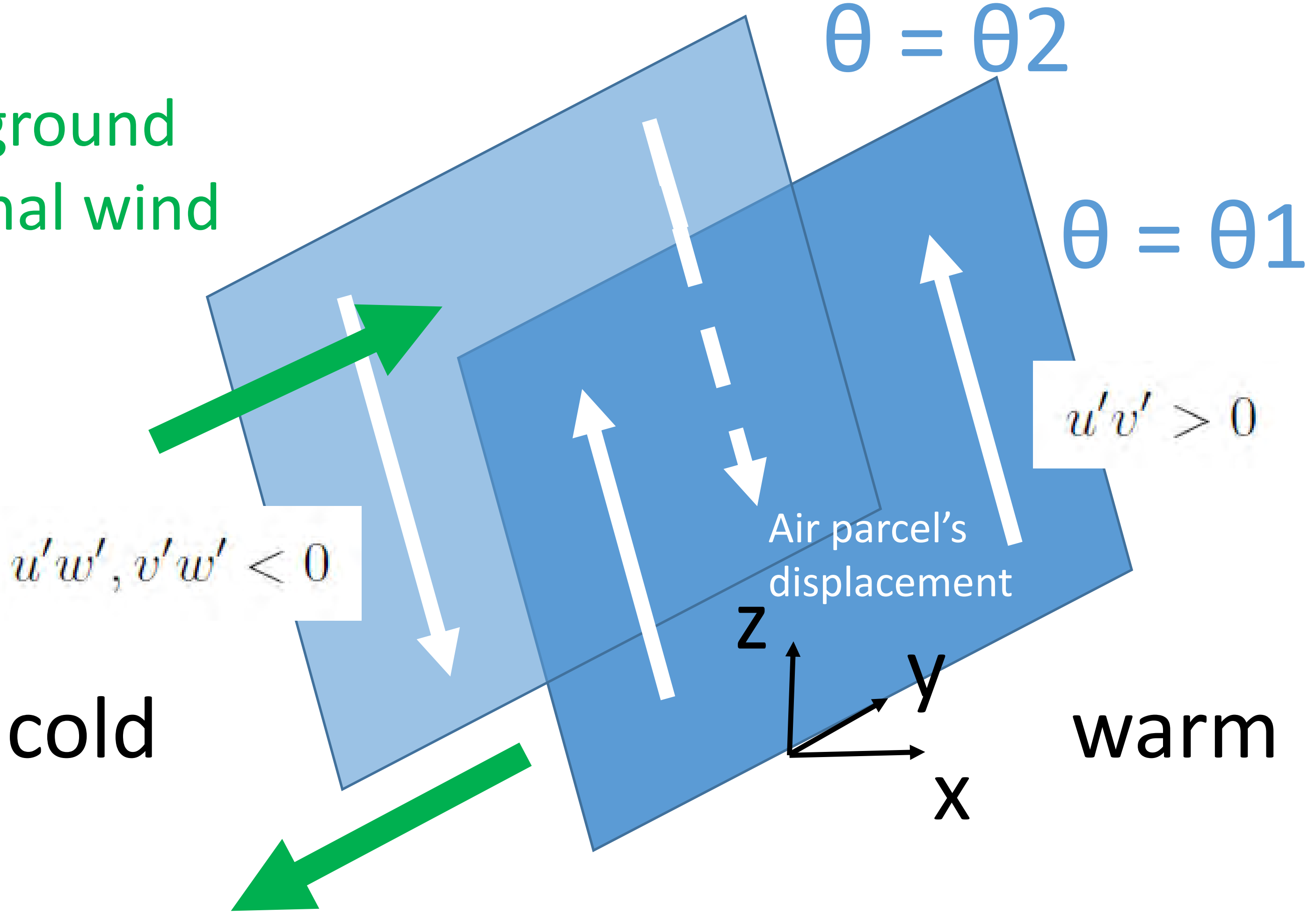


Slantwise stability

- The simplest form of unstable displacement (Ri ~1) of air parcels to slantwise displacement is sliding motion along isentropes (θ'=0):

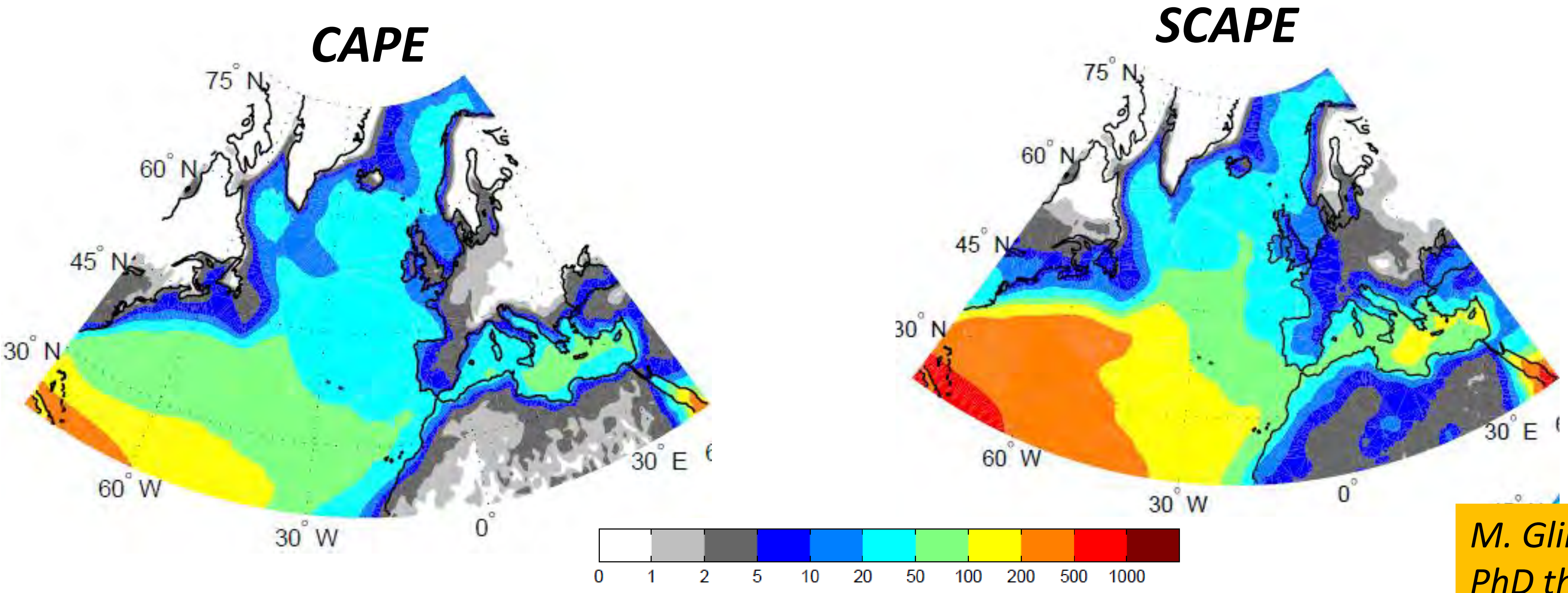
$$\frac{\partial u'}{\partial t} - f_o v' = 0$$
$$\frac{\partial v'}{\partial t} + \zeta_\theta u' = 0$$

$$\boxed{\frac{1}{2}\frac{\partial}{\partial t}(u'^2 + v'^2) = -w'v'v_{o,z}}$$



Organisation of mesoscale activity by the Gulf Stream

- No localisation of the climatology over the Gulf Stream in standard metrics



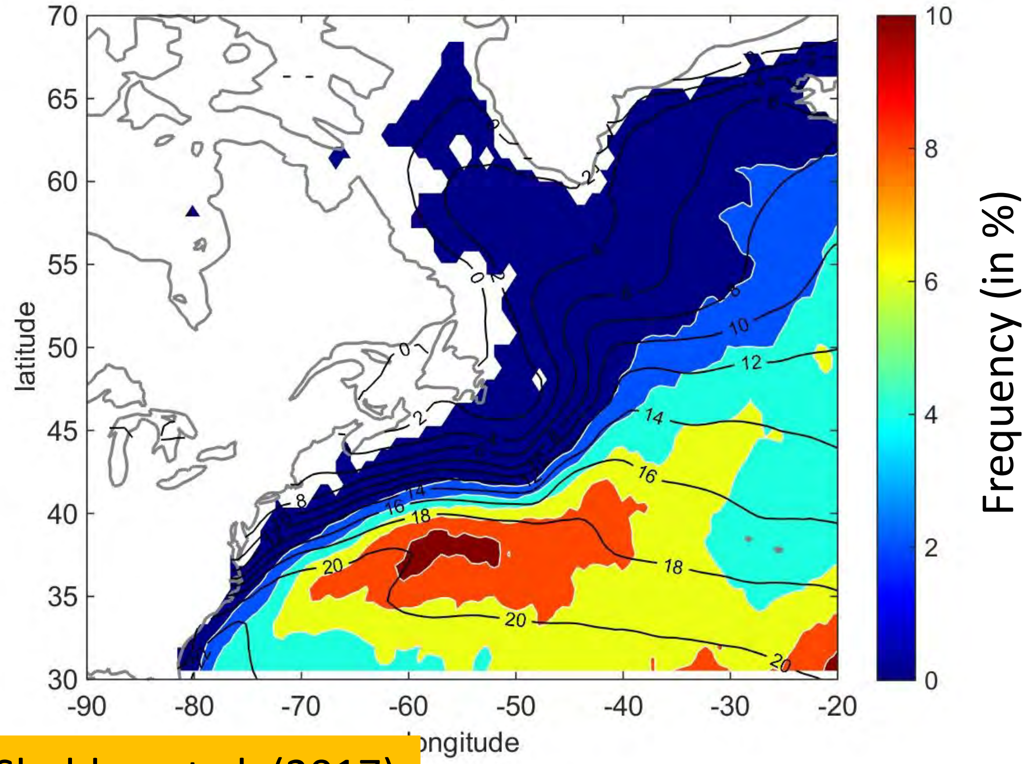
DJF mean CAPE or SCAPE (J/kg)

M. Glinton's PhD thesis at Reading Uni

Organisation of mesoscale activity by the Gulf Stream

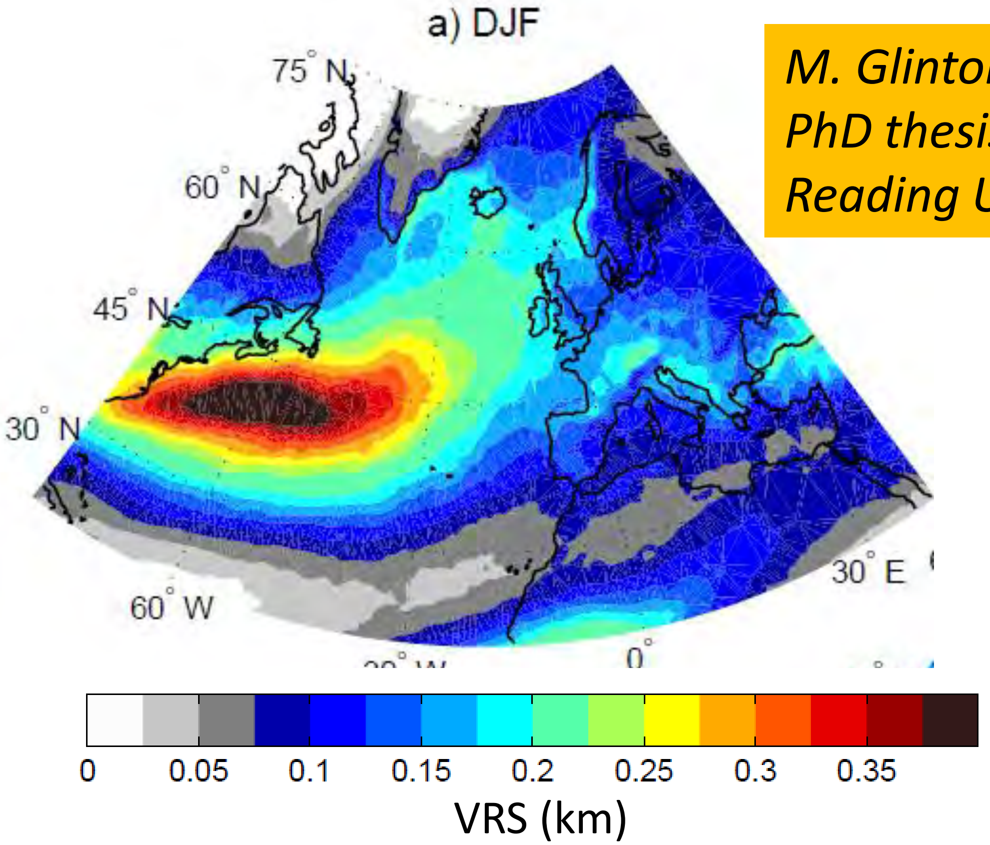
- Very different situation when a measure of the depth of the instability is included

Fraction of wintertime days with θe(tropopause)- θe(950hPa) <0



Sheldon et al. (2017)

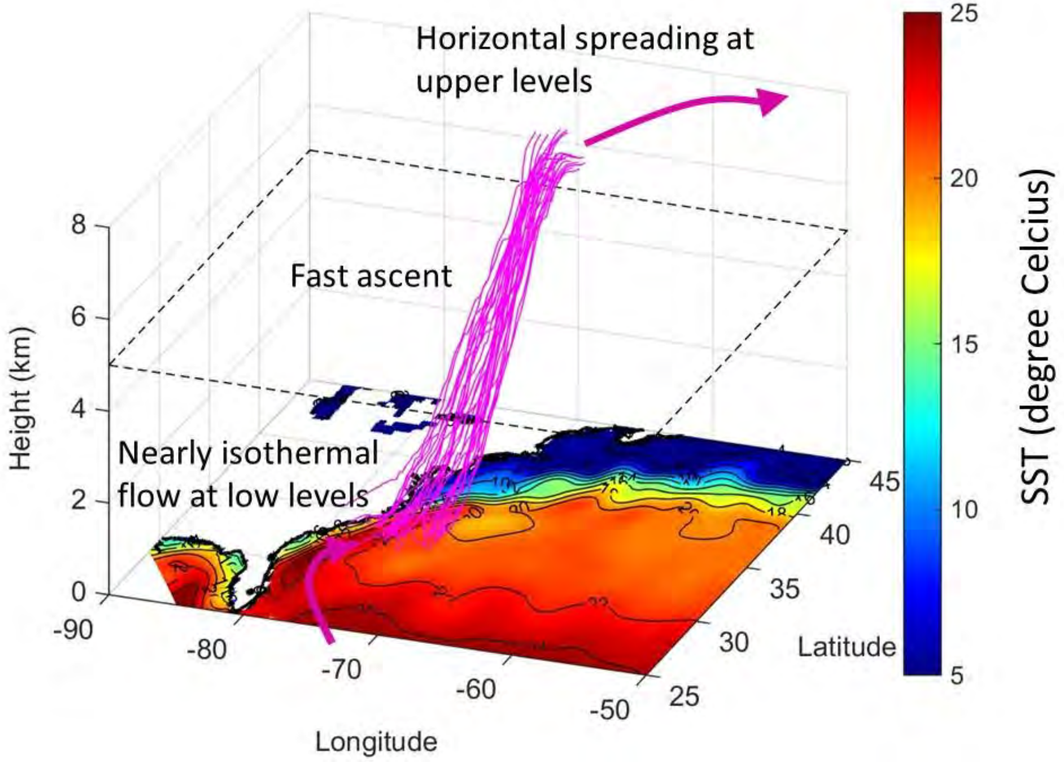
DJF mean vertical extent of realisable slantwise instability



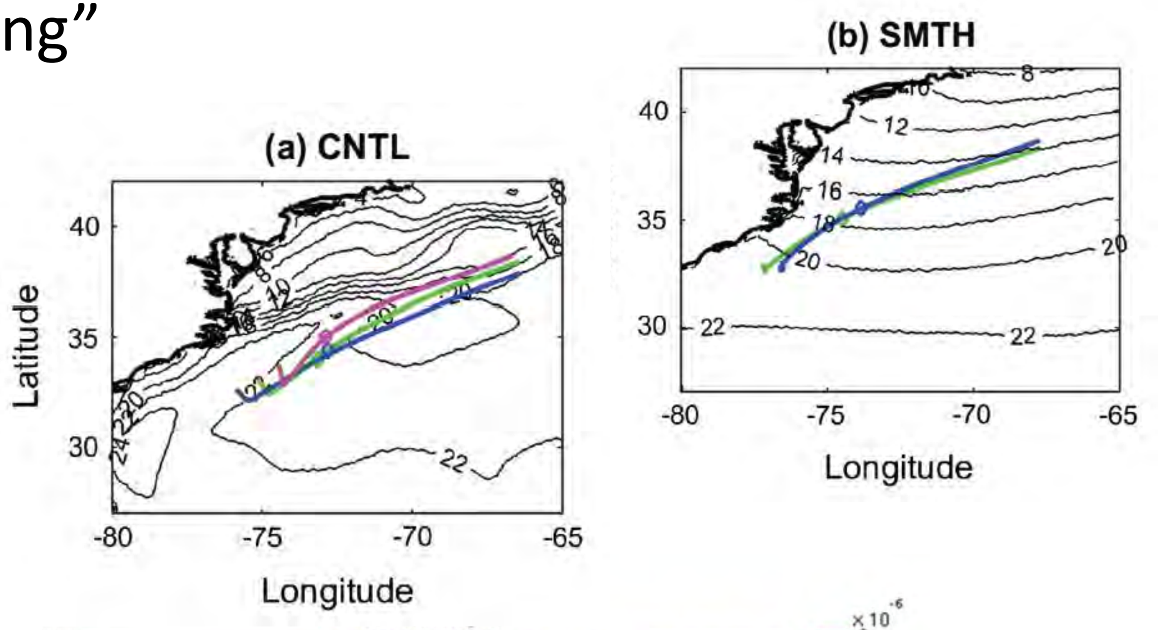
M. Glinton's PhD thesis at Reading Uni

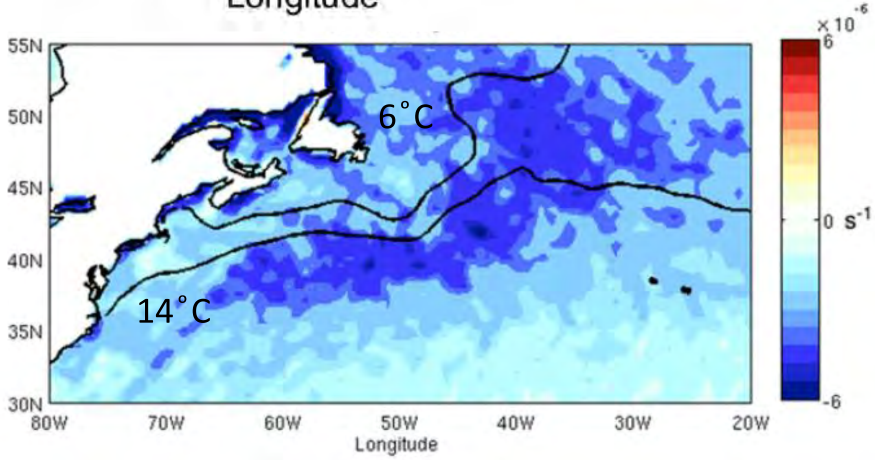
The "warm path"

- Warm SSTs along the Gulf Stream maintain high θe of air parcels ascending in the warm conveyor belt of cyclones
- This is a mechanism relying on weak surface heat fluxes and "moist isentropic gliding"



Trajectories reaching above 7km in CNTL run with dx=12km. None exist in SMTH at this resolution, nor in CNTL with dx=40km.

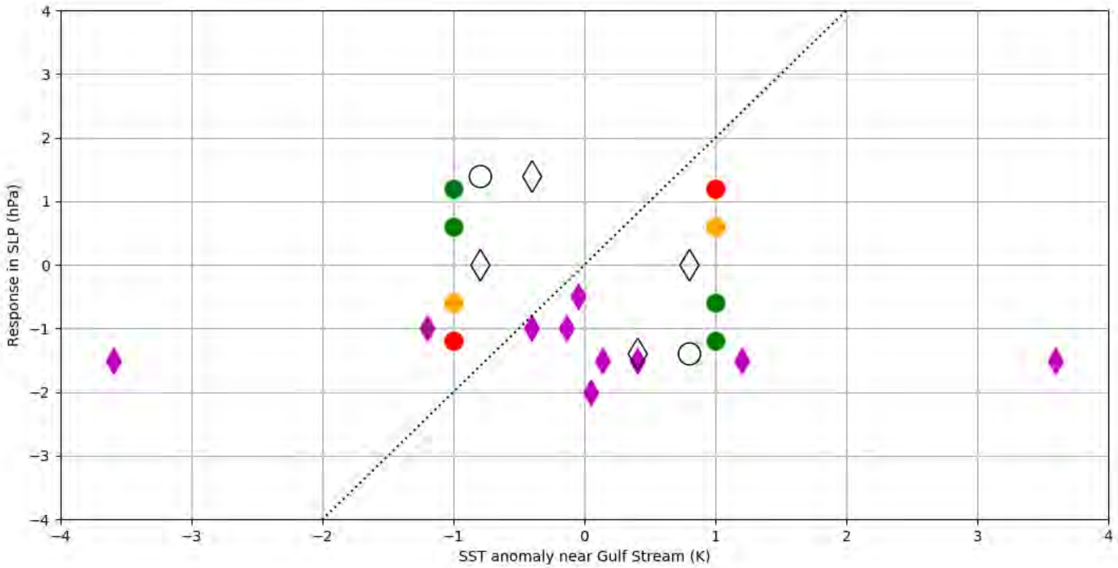




900 hPa divergence explained by frontal ascent (Southern EDJ regime)

Sheldon et al. (2017) & Parfitt and Kwon (2020)

Interpretation of the scatterplots: Gulf Stream shift

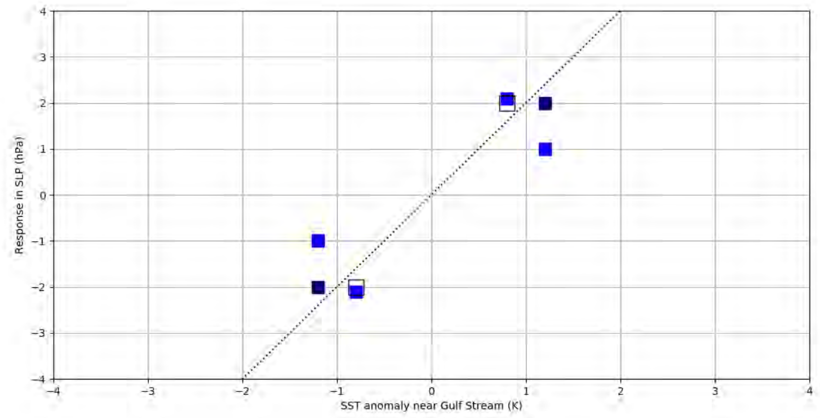


- The spread in AGCMs reflect (i) transient growth of weather systems and/or (iii) the organisation of “noise” by the Gulf Stream

$$(L + D)C_o + C_o(L^T + D^T) + F = 0$$

Interpretation of the scatterplots: SST tripole

- The SST tripole is driven by the NAO and approximately coincides with its free troposphere temperature anomaly



→eddy statistics are not altered by the presence of the tripole* (the NAO exists in the first place because it is sustained by eddy statistics –Barsugli and Battisti, 1998; Peng and Robinson, 2001) + low noise in low-res AGCMs

→ robust response in low-res AGCMs

$$(L \cancel{+} D)C_o + C_o(L^T \cancel{+} D^T) + \cancel{F} = 0$$

*what alters the eddy statistics is the interior diabatic heating which is minimised when SST anomalies have had time to develop (warm air over warm water)

Beware of pattern thinking!