The Gulf Stream signature on SST: observations and impact on the North Atlantic storm-track

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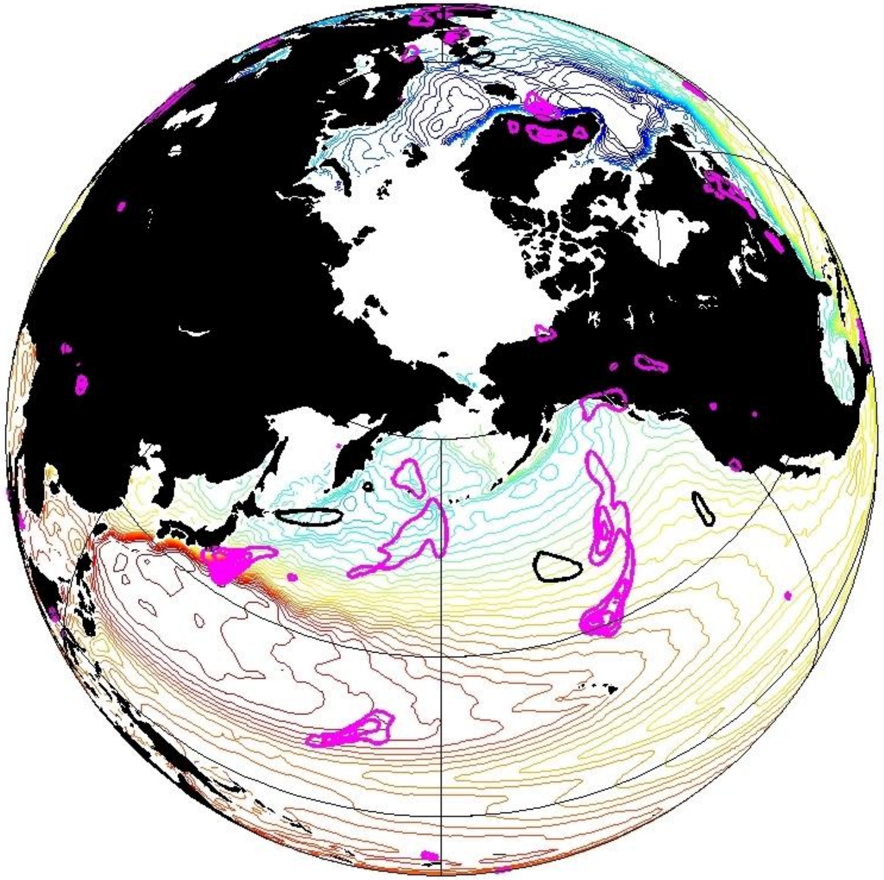
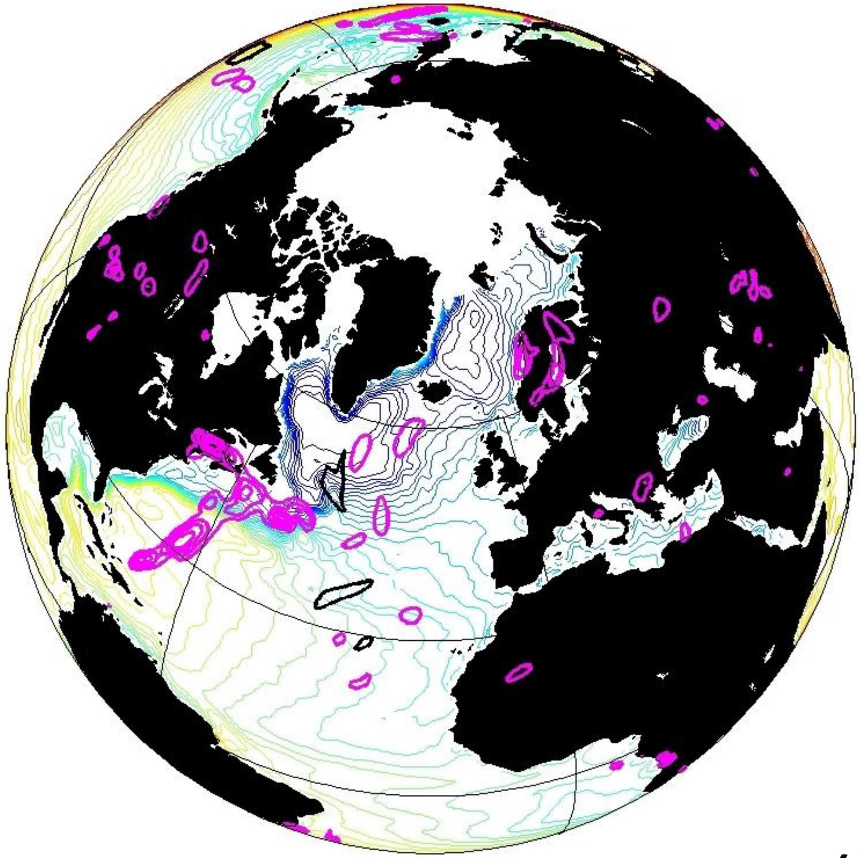
Motivation: the matching of spatial scales between oceanic western boundary currents & atmospheric fronts



Mean Ocean Dynamic Topography

Data from Maximenko et al. (2002) with CI = 5cm



—— ω(500mb)>0.5 Pa/s

—— ω(500mb)<-0.5 Pa/s

Data from ERAint at 12 UTC on a random DJF day

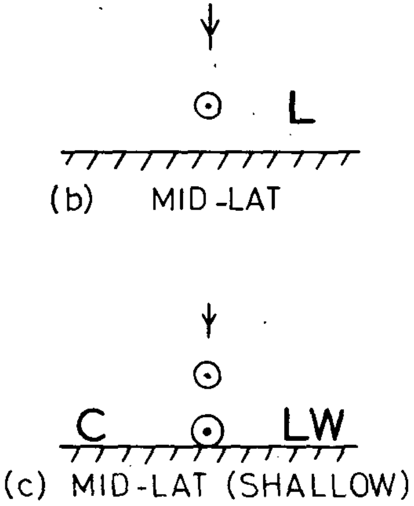
Outline

- Two mechanisms of oceanic forcing at the 10-100km scale
- Open questions
- Conclusions

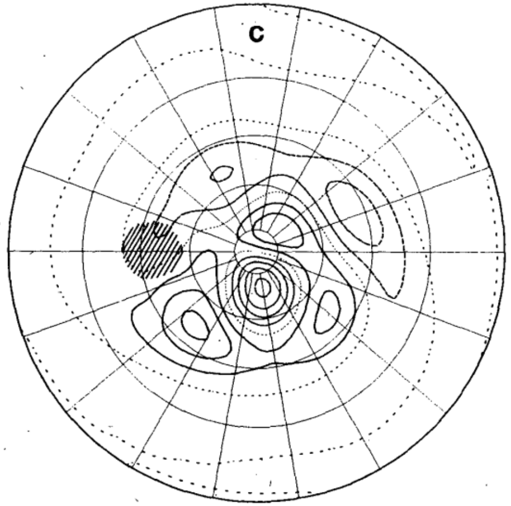
SST forcing of the extra-tropical storm track

- Low res AGCM (>100km): shallow heating, weak frontal circulations, weak diabatic effects, quasi-geostrophic dynamics

- High res AGCM (<100km): vigorous frontal circulations and diabatic effects, non quasi-geostrophic dynamics

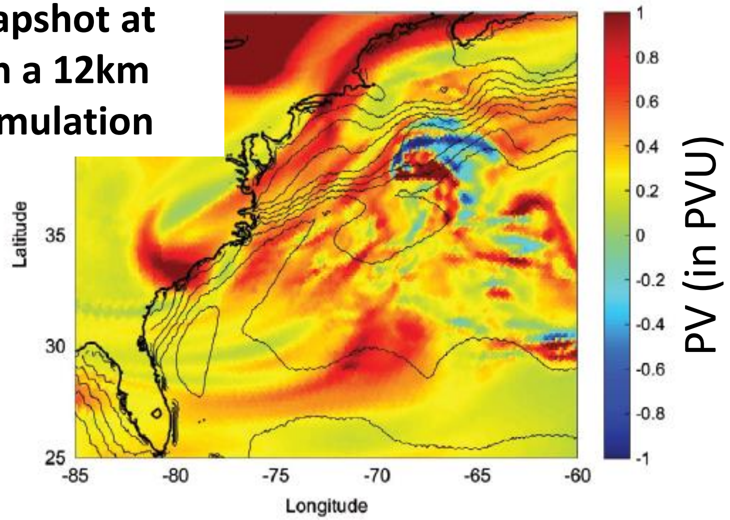


Z300 in response to a heat source at 45N



Hoskins & Karoly (1981)

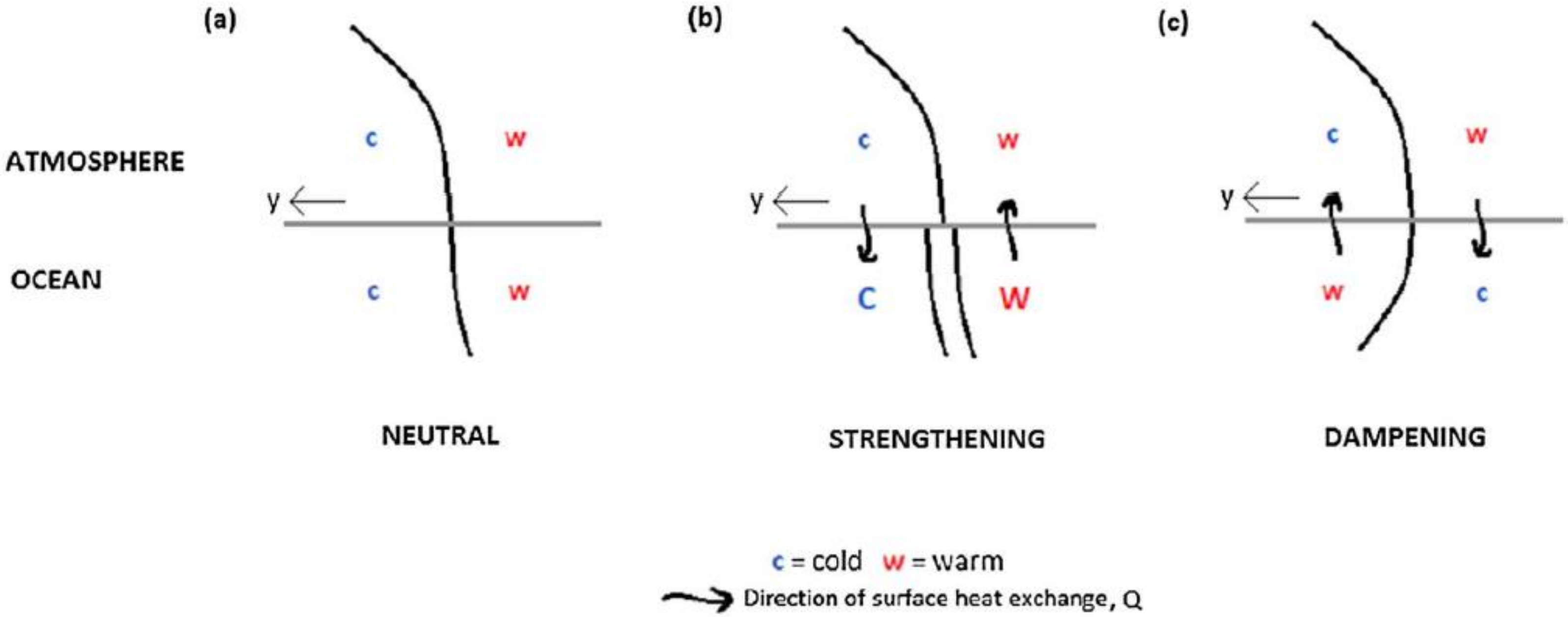
PV snapshot at 5km in a 12km UM simulation



Sheldon et al (2017)

1. Thermal damping and strengthening (TDS)

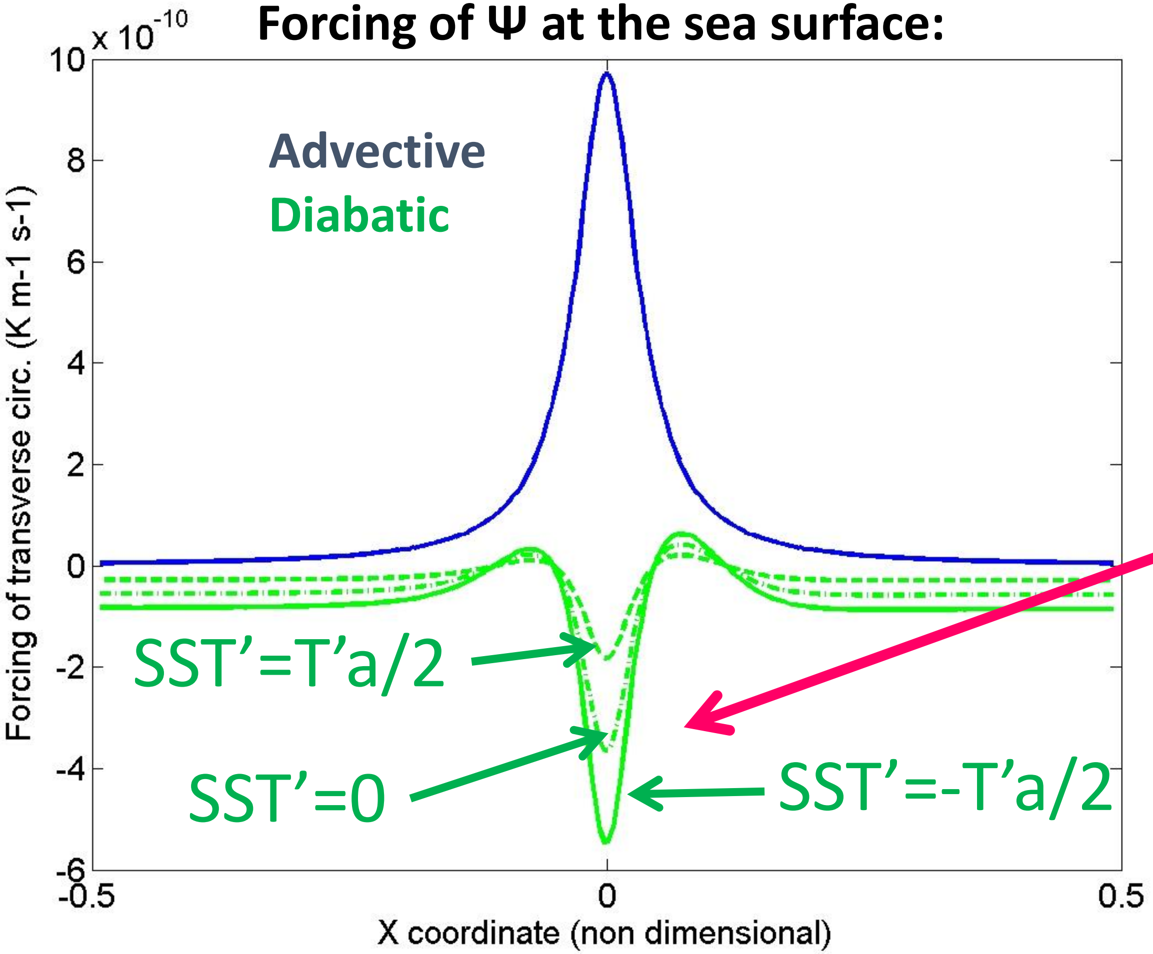
- Simple modulation of the surface turbulent heat fluxes by the relative orientation of oceanic and atmospheric fronts



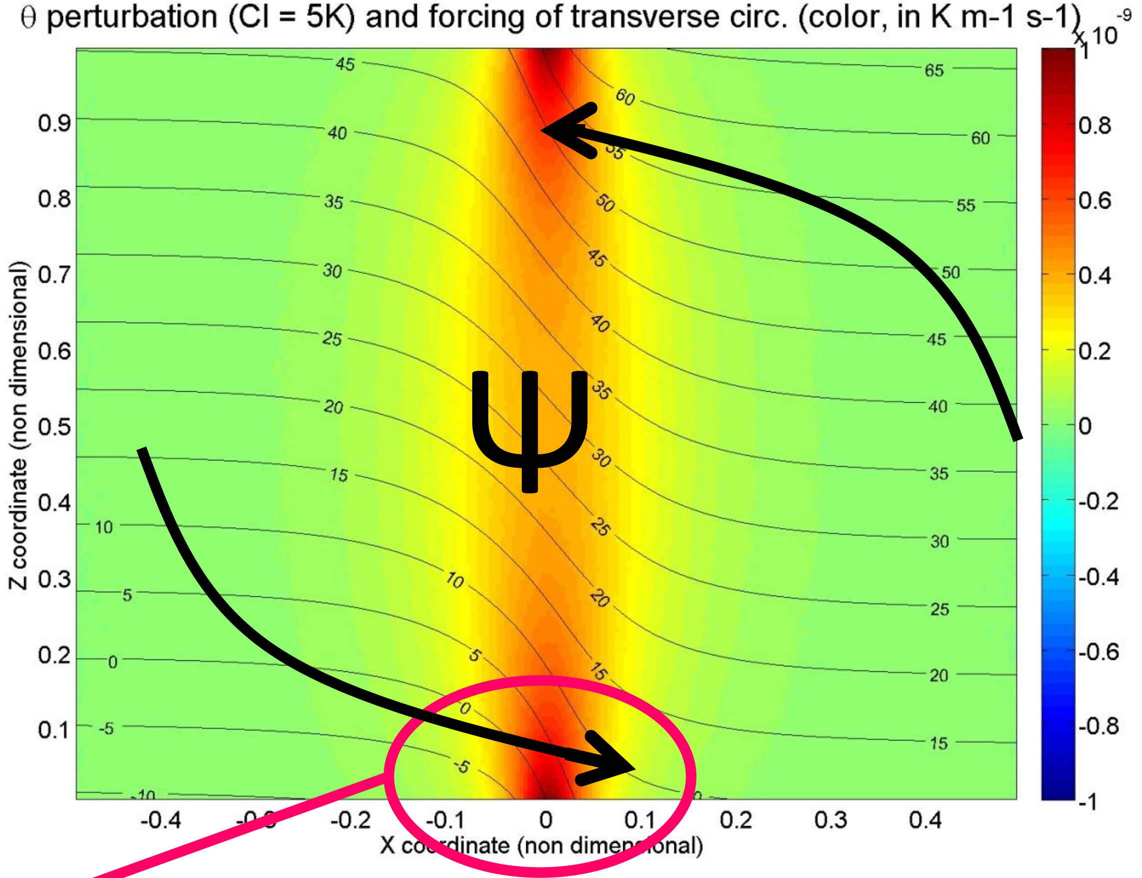
(…or "climatological ocean")

TDS in the Hoskins-Bretherton model (1972)

Forcing of Ψ at the sea surface:



θ perturbation (CI = 5K) and forcing of transverse circ. (color, in K m-1 s-1)



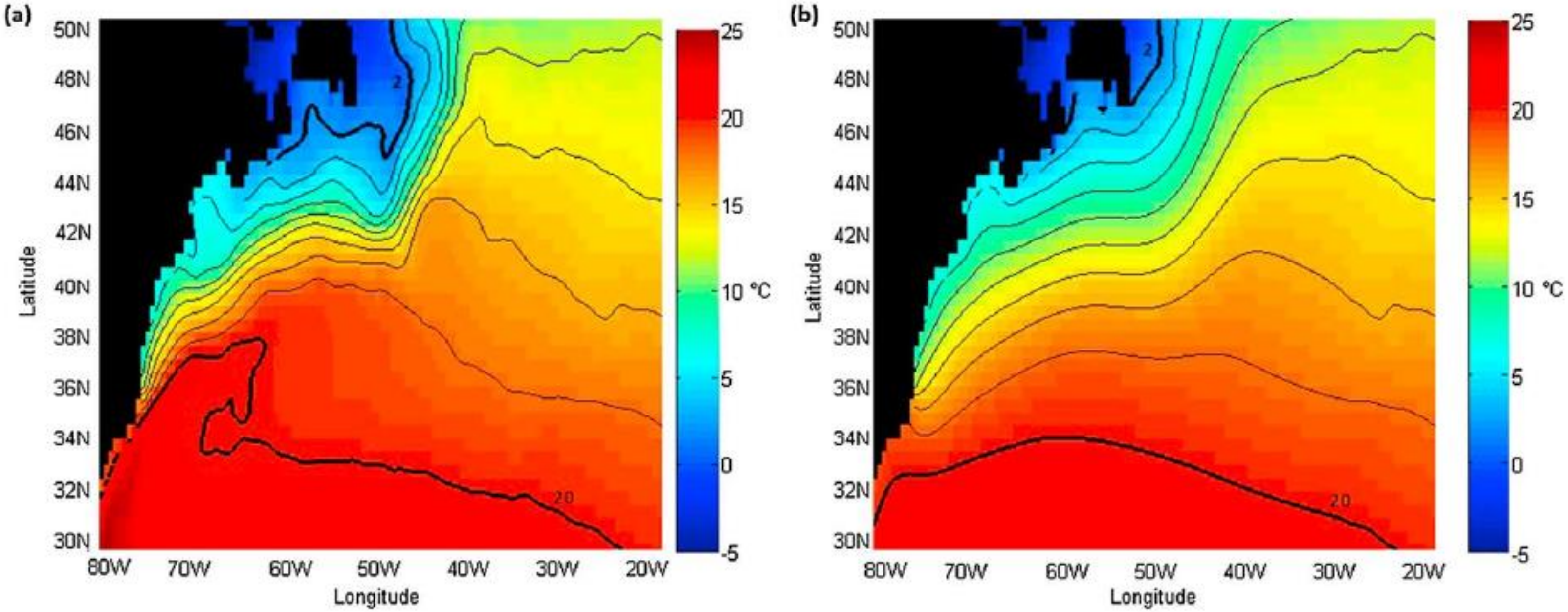
A significant modulation of the transverse circulation is caused by diabatic effects

TDS in a realistic model (Parfitt et al, 2016)

- Prescribed SSTs with the Japanese AFES model (T239, L48) over 1981-2000
- One control (CNTL) experiment with realistic SSTs
- One perturbed (SMTH) experiment with spatially smoothed SSTs

20-yr mean wintertime SST

CNTL



SMTH

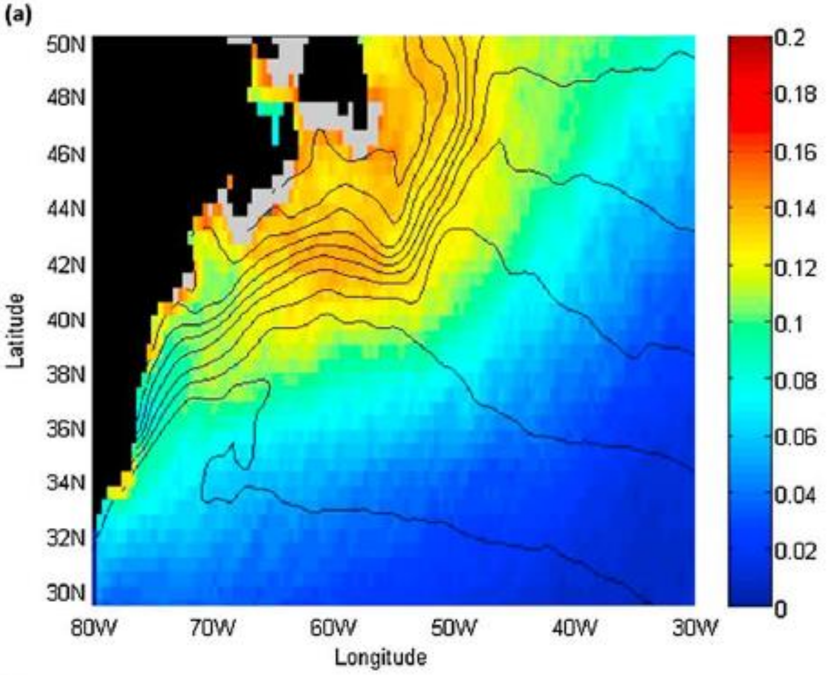
Identification of fronts

(Parfitt et al., 2017)

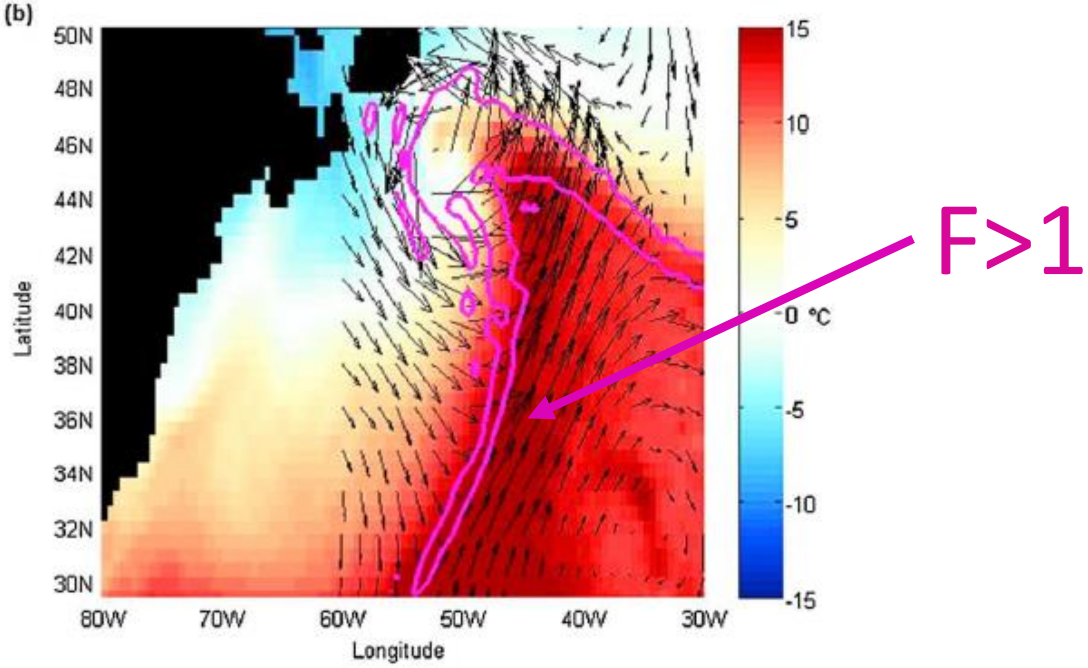
$$F = \frac{\varsigma \nabla T}{f(40N)(\frac{1K}{100km})}$$

- Uses a combination of thermodynamic and dynamic quantity at 925hPa

Climatology: frequency of gridboxes with F>1 (=frontal frequency) in CNTL

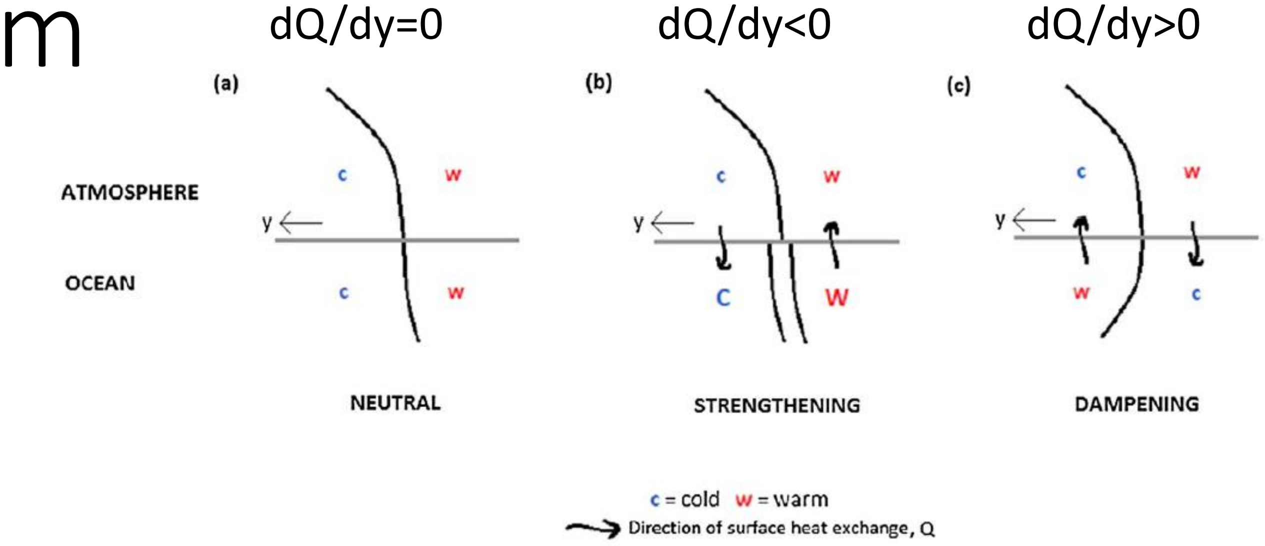


Snapshot: temperature and winds at 925 hPa on a given day



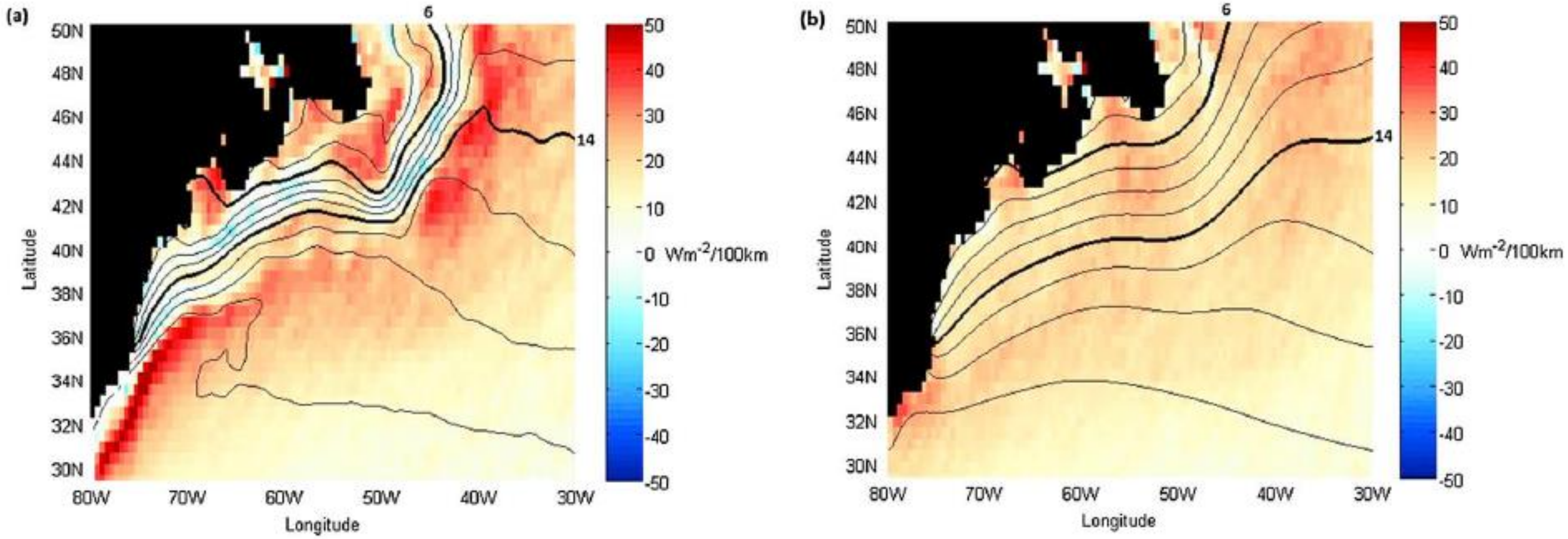
Test of the TDS mechanism

- Key variable: gradient of surface sensible heat flux Q across atmospheric fronts



Wintertime mean dQ/dy

CNTL

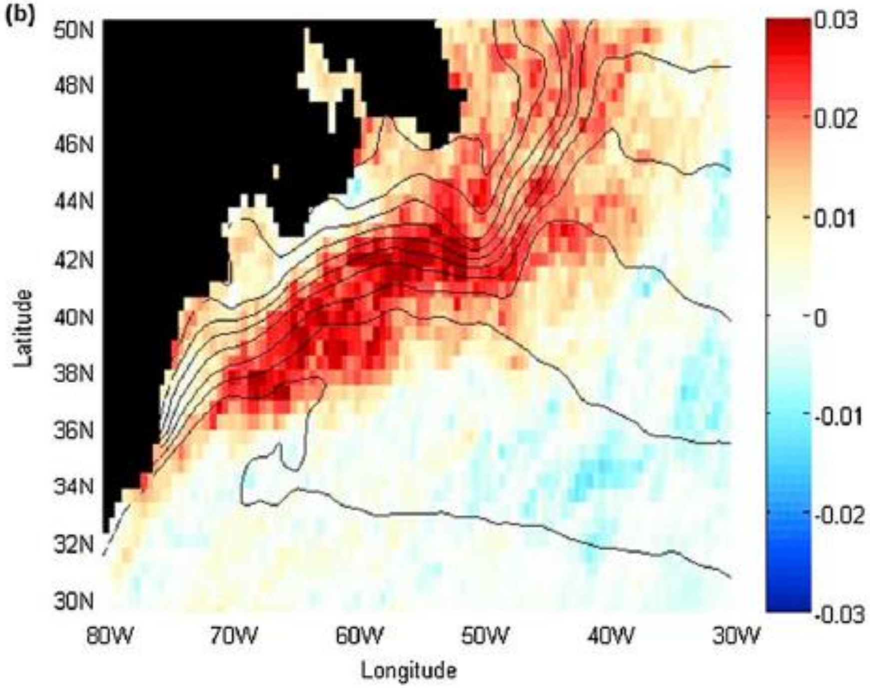


SMTH

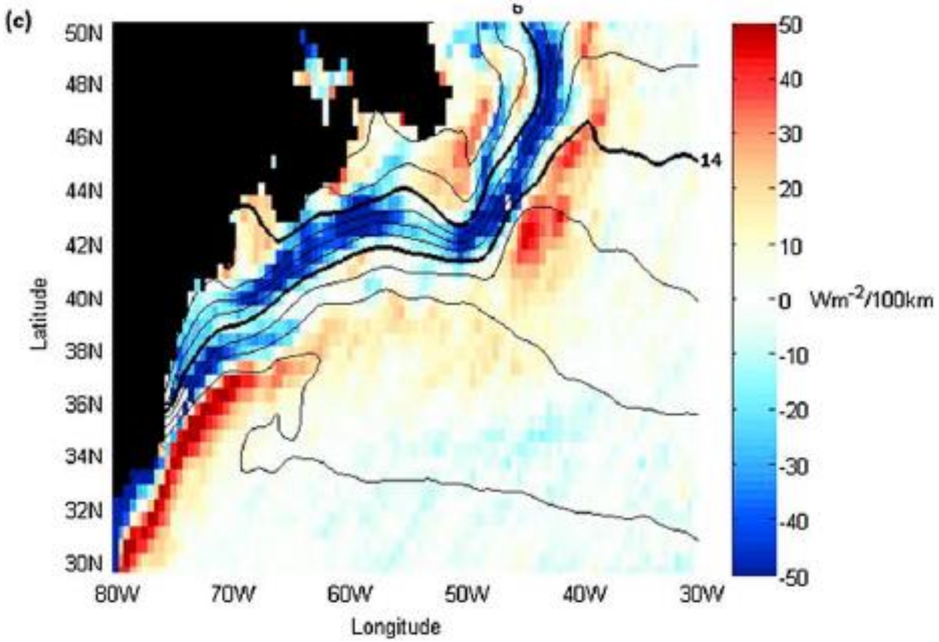
Test of the TDS mechanism

- The prediction is that fronts will strengthen in CNTL as they cross the Gulf Stream, and then will be more damped compared to SMTH.

Frontal frequency (CNTL-SMTH)

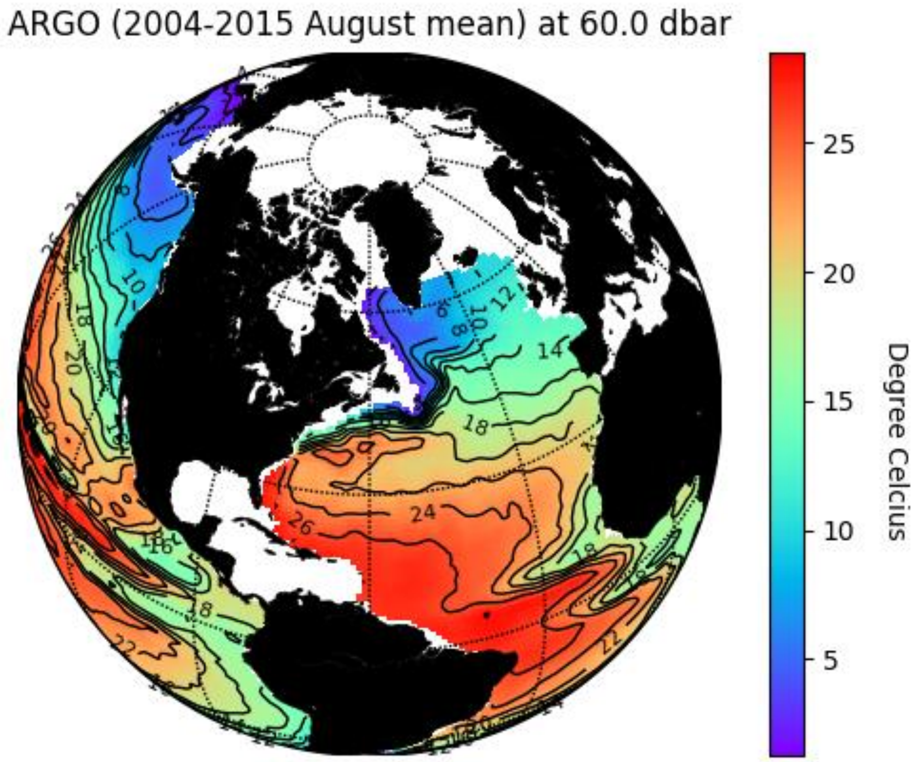


dQ/dy (CNTL-SMTH)

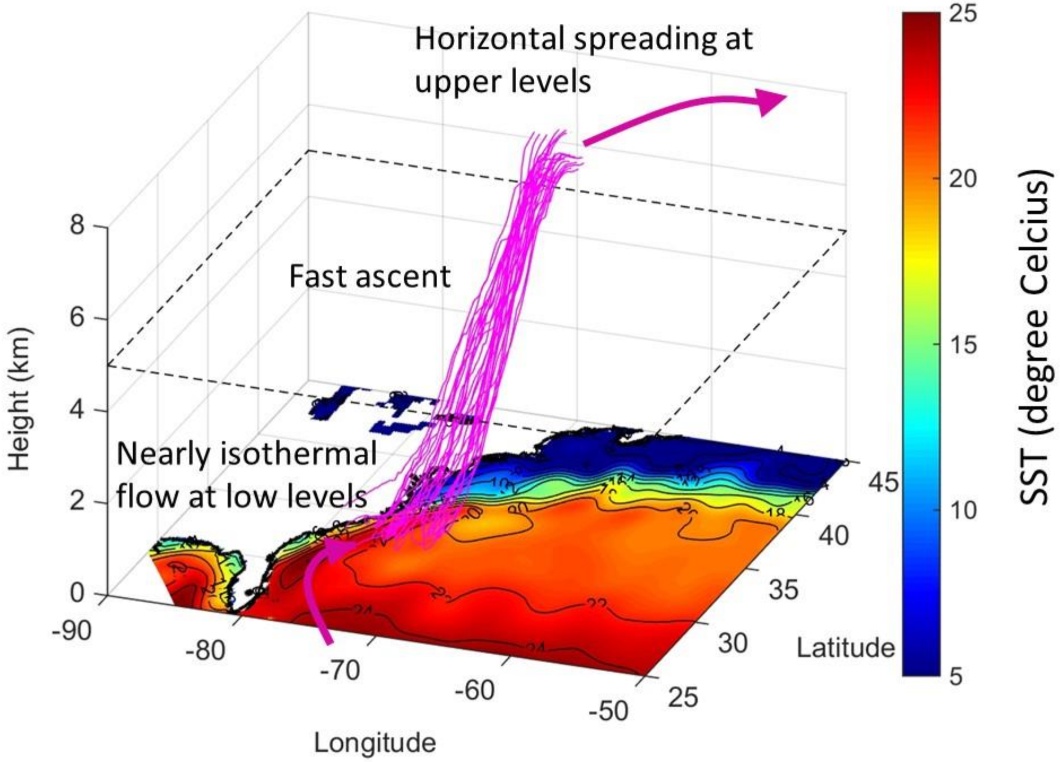


✓

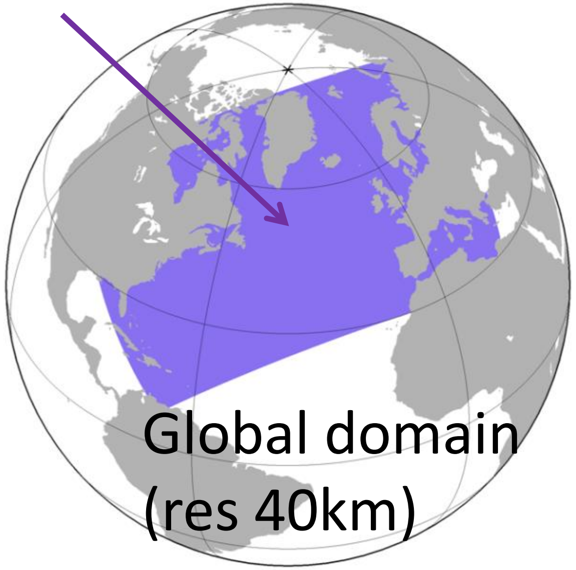
2. The “warm path” (Sheldon et al., 2017)



ARGO (2004-2015 August mean) at 60.0 dbar



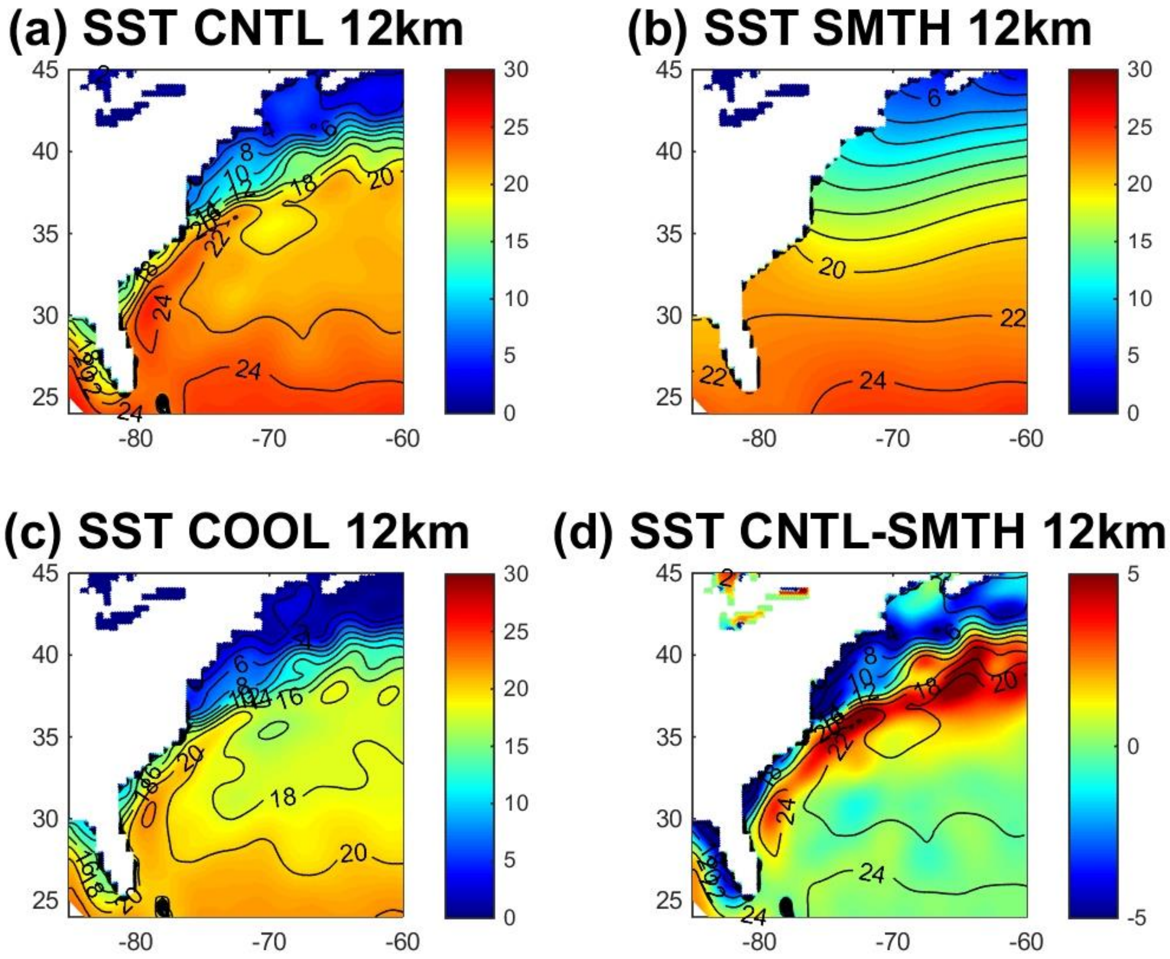
Simulations with the Met Office Unified Model



North Atl. domain
(res 12km)

Global domain
(res 40km)

- Nested grid over North Atlantic
- One event: cyclone crossing the Gulf Stream on Jan 14 2004
- Different SST configurations



(a) SST CNTL 12km

(b) SST SMTH 12km

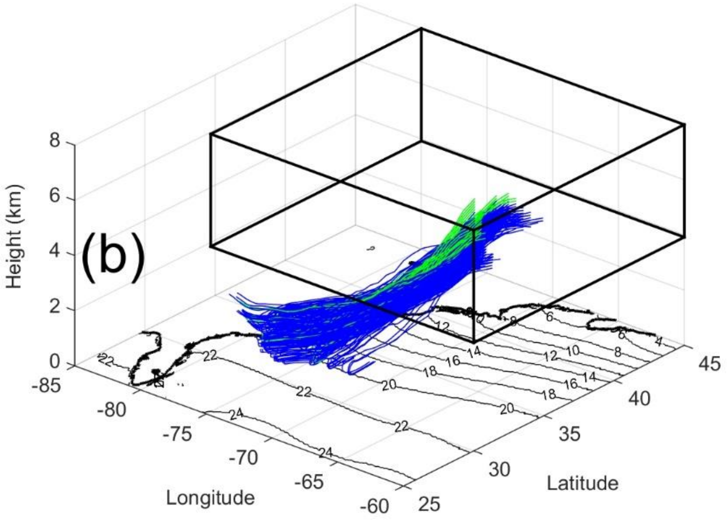
(c) SST COOL 12km

(d) SST CNTL-SMTH 12km

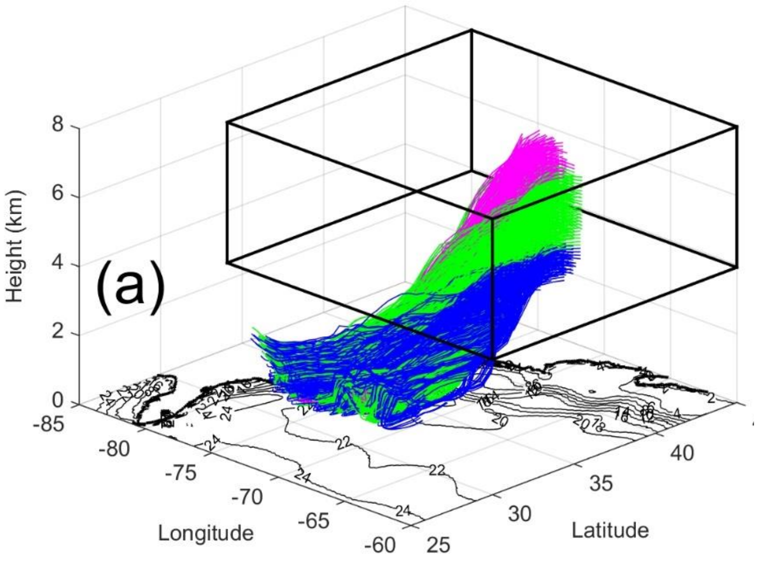
Back trajectories (from t=24h) originating from low levels

Initial release volume

SMTH



CNTL

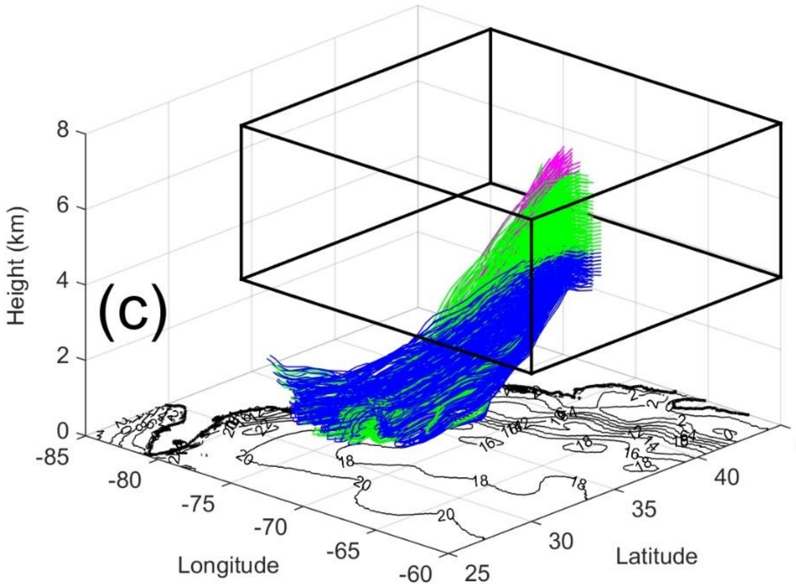


zi>7km

5km< zi < 7km

zi<5km

COOL



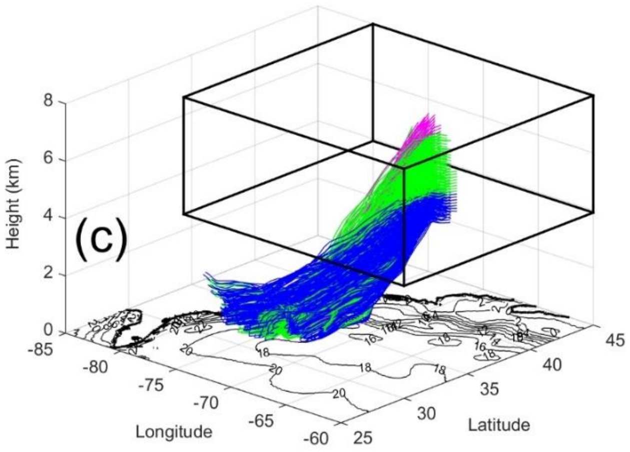
Analysis of trajectories

- The bottom/top heavy feeding of the ascent from low levels is primarily set by the SST gradient
- The overall amount of feeding of the ascent from low level is sensitive to the absolute value of the SST

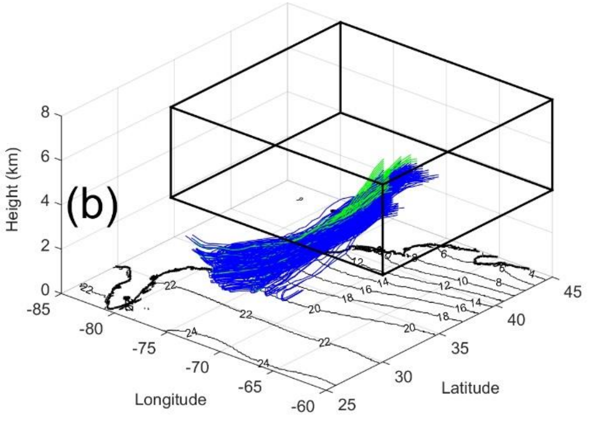
Number of back trajectories

Experiment	12 km
CNTL	
(all)	1178
$(z_o \geq 7\text{km})$	167
$(5\text{ km} \leq z_o < 7\text{km})$	613
$(z_o < 5\text{km})$	398
$(z_o \geq 5\text{km})/(z_o < 5\text{km})$	1.95
SMTH	
(all)	275
$(z_o \geq 7\text{km})$	0
$(5\text{ km} \leq z_o < 7\text{km})$	27
$(z_o < 5\text{km})$	248
$(z_o \geq 5\text{km})/(z_o < 5\text{km})$	0.1
COOL	
(all)	625
$(z_o \geq 7\text{km})$	29
$(5\text{ km} \leq z_o < 7\text{km})$	306
$(z_o < 5\text{km})$	290
$(z_o \geq 5\text{km})/(z_o < 5\text{km})$	1.15

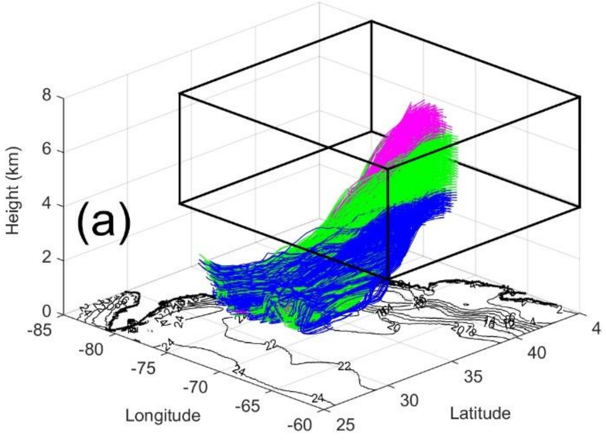
COOL



SMTH



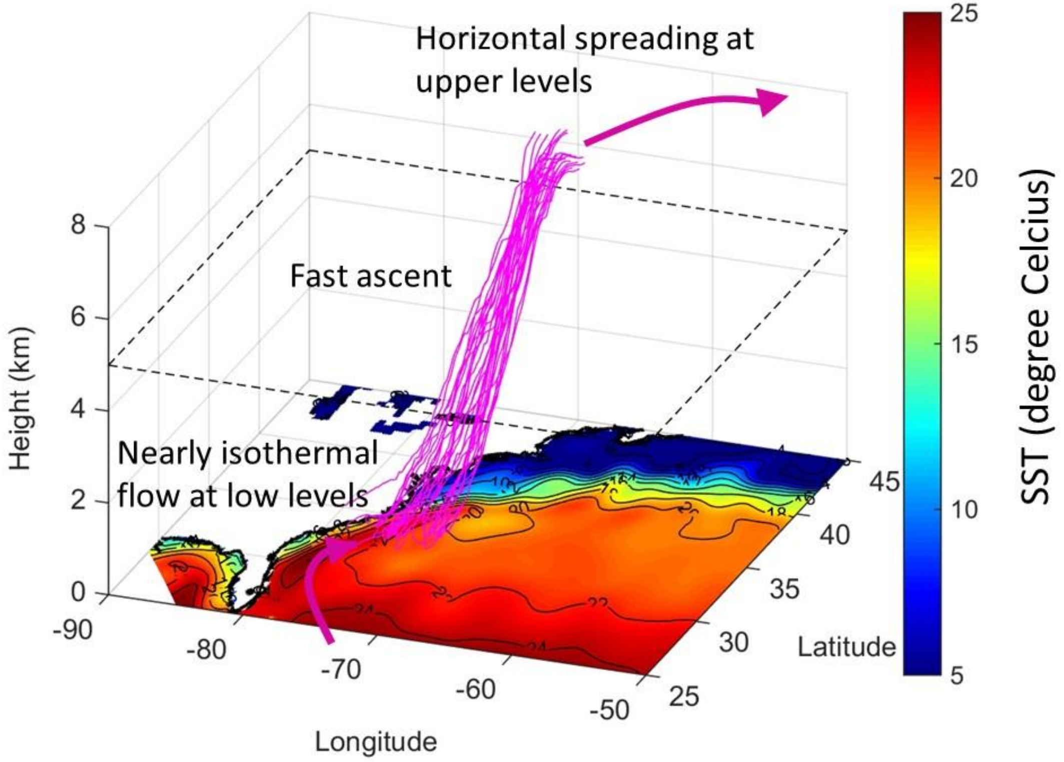
CNTL



Thermodynamic mechanism

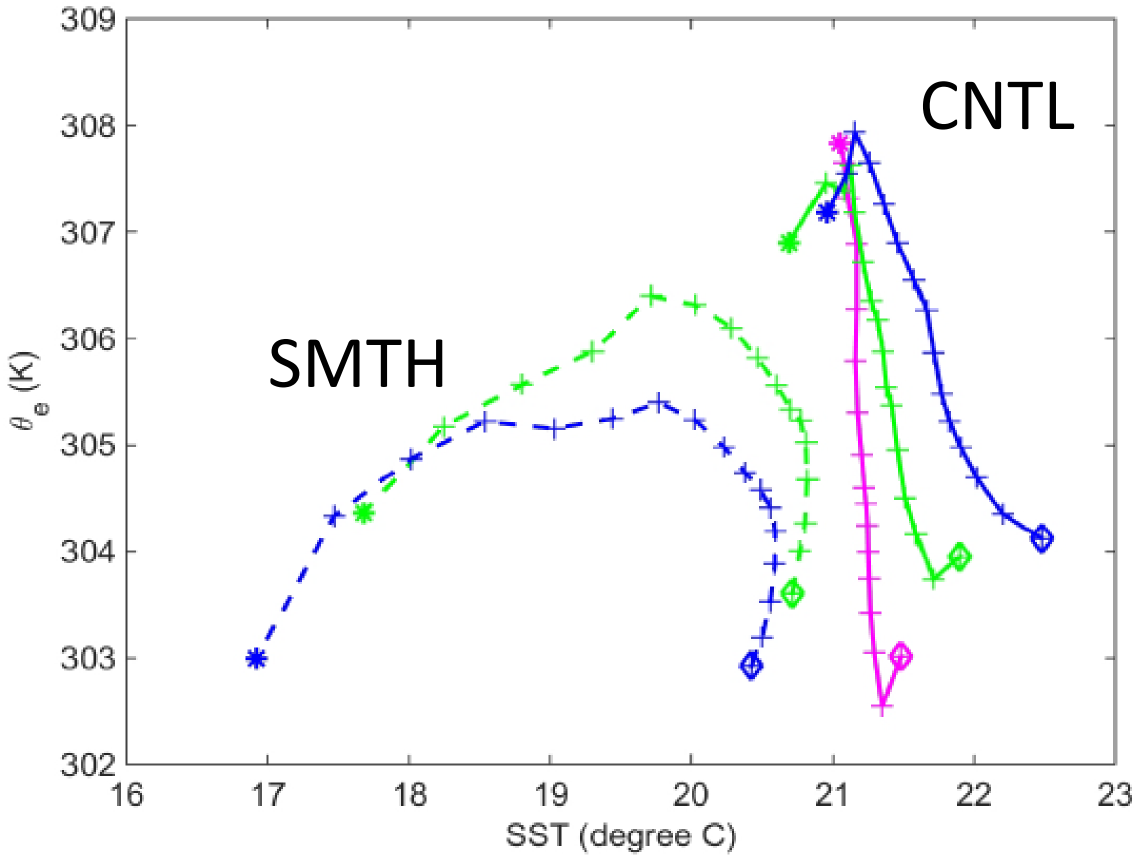
zi>7km | 5km< zi < 7km | zi<5km

- Warm SSTs along the Gulf Stream maintain high θe of air parcels


Horizontal spreading at upper levels

Fast ascent

Nearly isothermal flow at low levels


CNTL

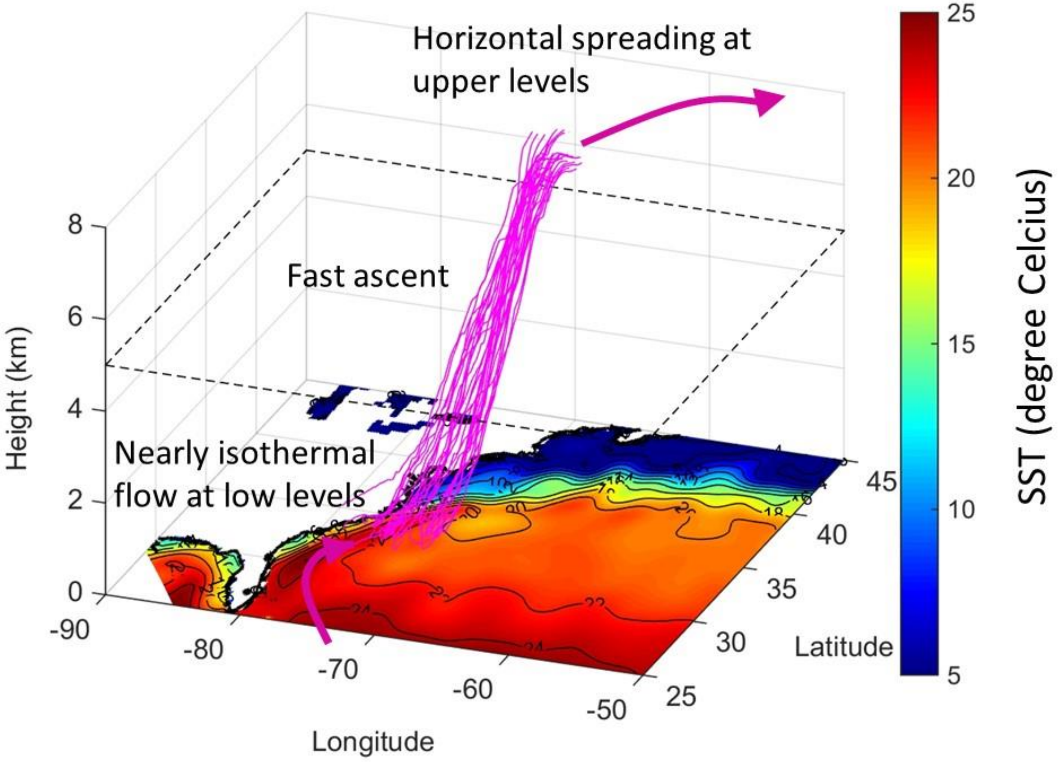
SMTH

NB: Plotted in magenta are the trajectories (zi≥7km) in CNTL(12km)

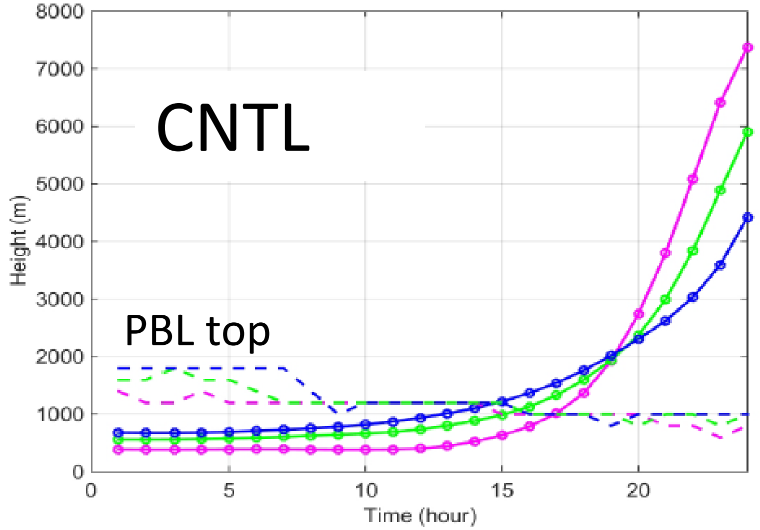
Thermodynamic mechanism

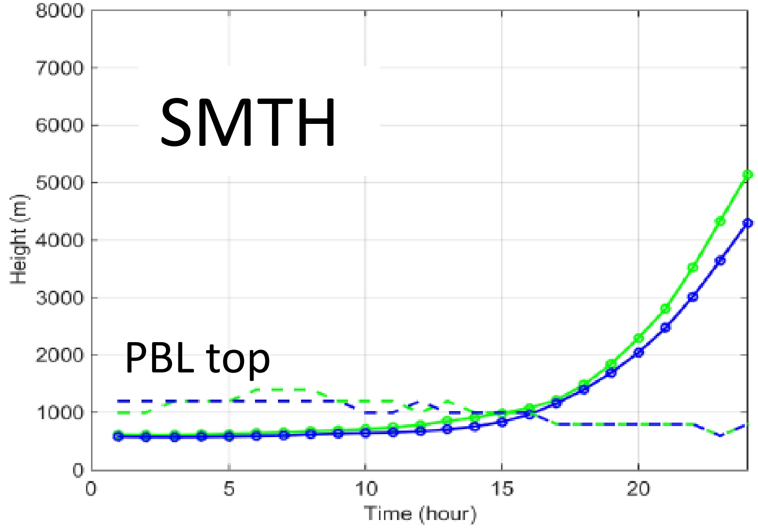
zi>7km | 5km< zi < 7km | zi<5km

- Proximity to PBL top reduces the θe air of air parcels via entrainment



NB: Plotted in magenta are the trajectories (zi≥7km) in CNTL(12km)



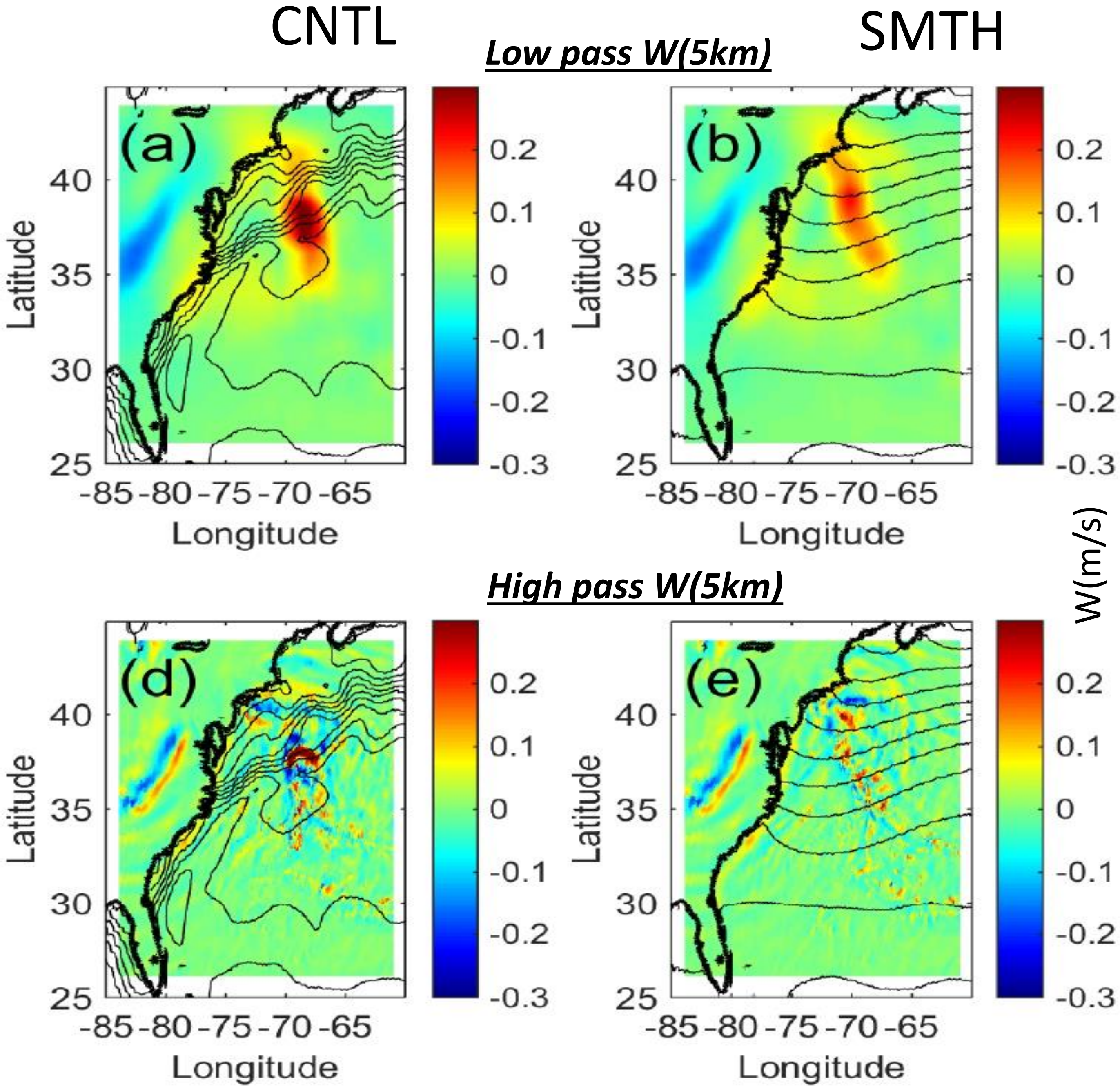


Dynamical mechanism

- SST gradient to the North of the Gulf Stream warm tongue reinforces and even destabilizes the vertical motion of the cyclone

- Updrafts/downdrafts are spread along the front in SMTH but more concentrated and vigorous in CNTL

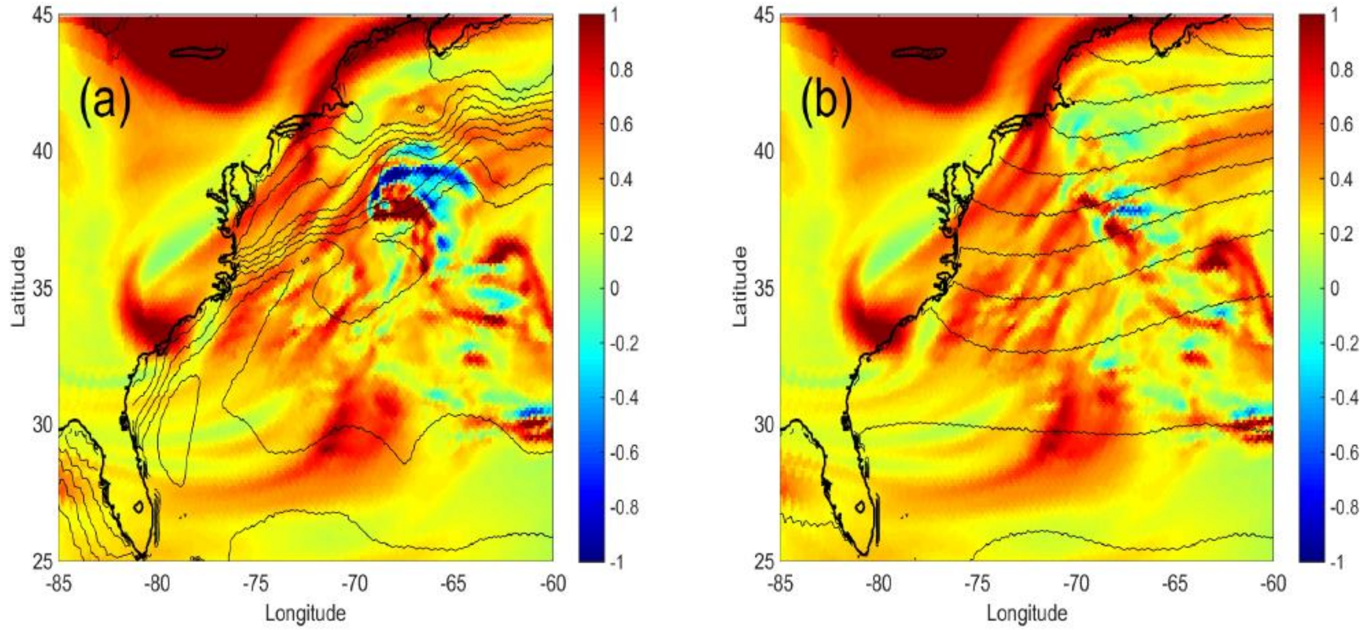
- The low pass motion is also stronger and more concentrated in CNTL compared to SMTH



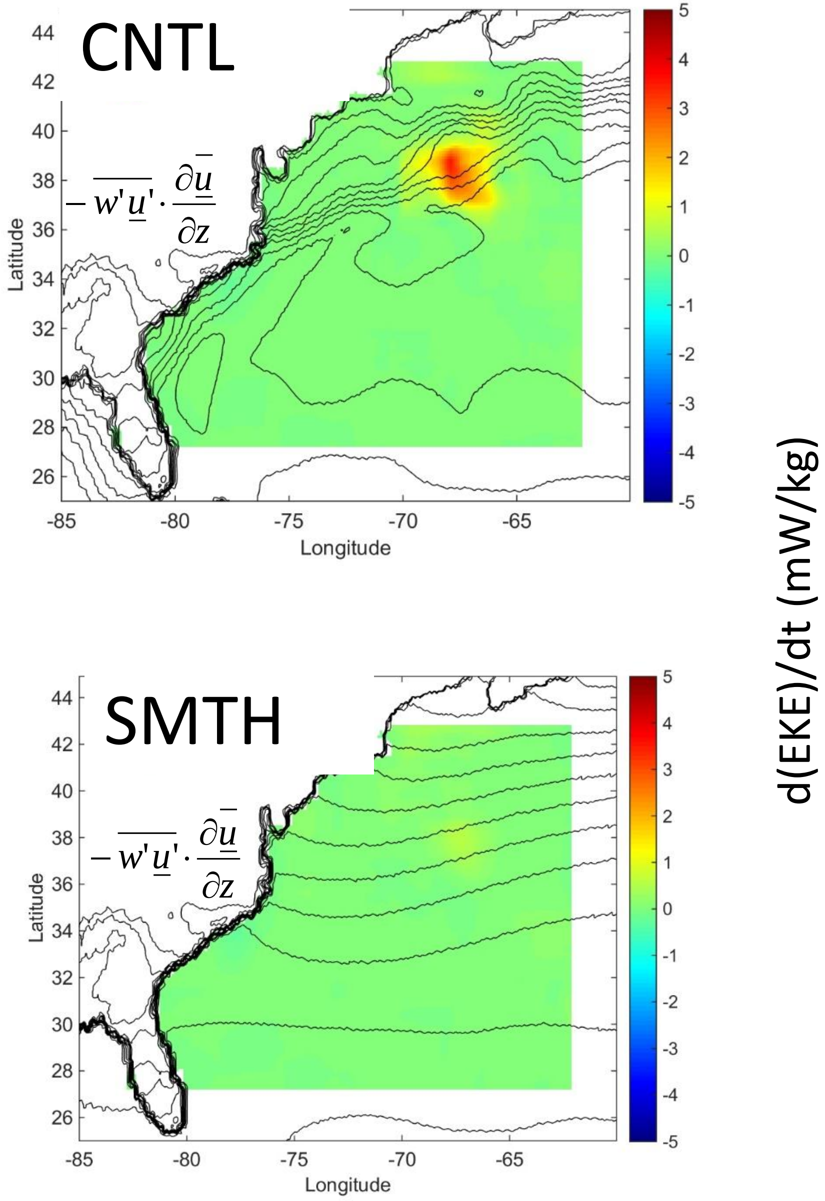
Dynamical mechanism

- Diagnostics indicate a form of shear instability is at play

CNTL **_Ertel PV (5km)_** SMTH



Growth of perturbations’ KE due to instability at 5km

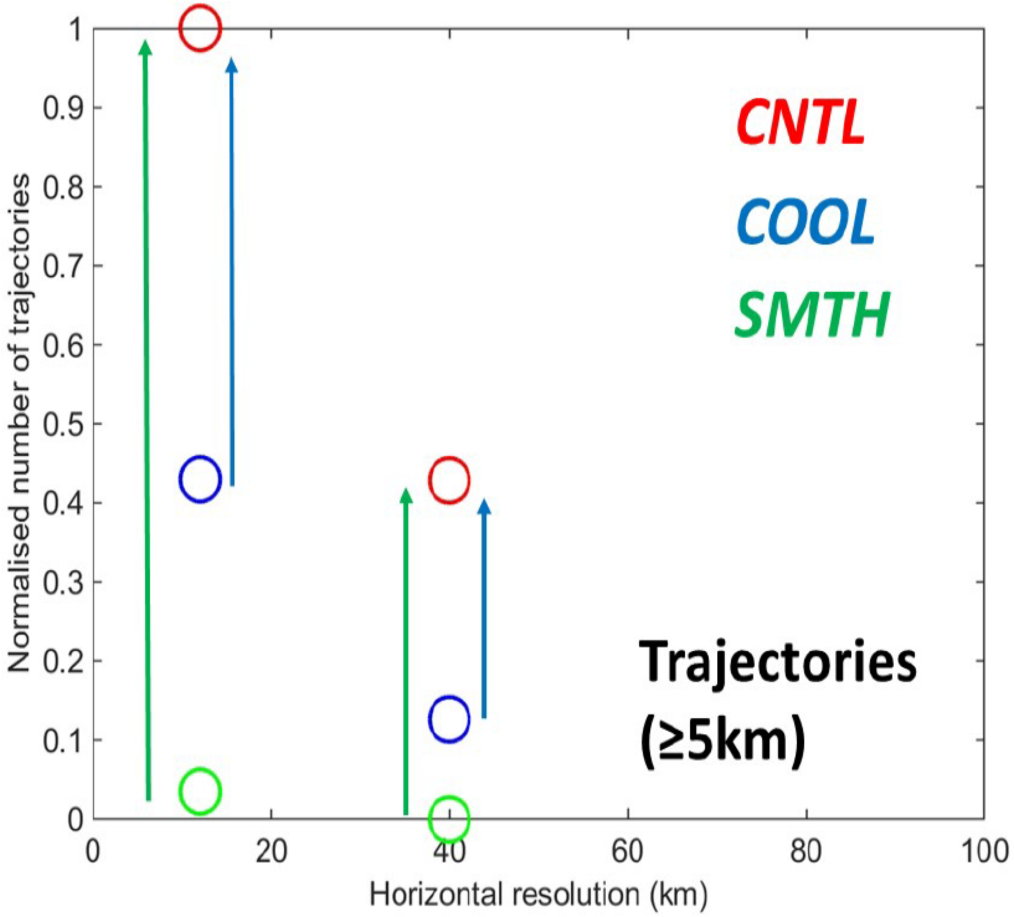


3.Open questions, issues with the previous mechanisms or their validation

Issue 1: which horizontal resolution is sufficient?

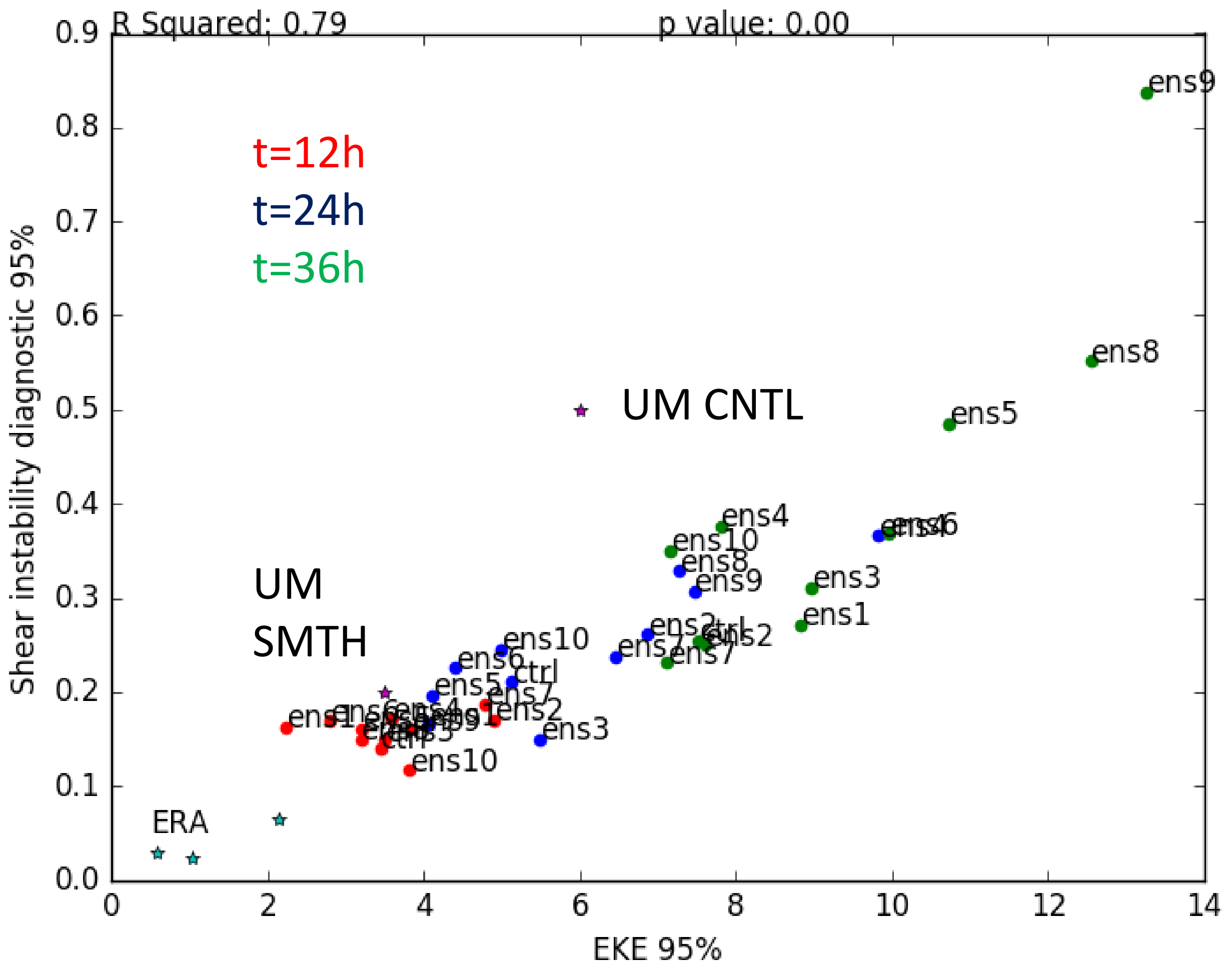
- Systematic decrease in the number of trajectories feeding the ascent from low levels when going from 12km to 40km with the UM

- Upper level oceanic forcing scales approximately with horizontal resolution (0.4/1~1/2.5, 0.3/0.6~1/2)



Issue 2: stochastic or deterministic?

- Compare the UM simulation (12km) with ECMWF hindcasts (“control”+10 members, 0.2 deg)
- The large spread of the shear instability diagnostic suggests that a statistical approach is needed

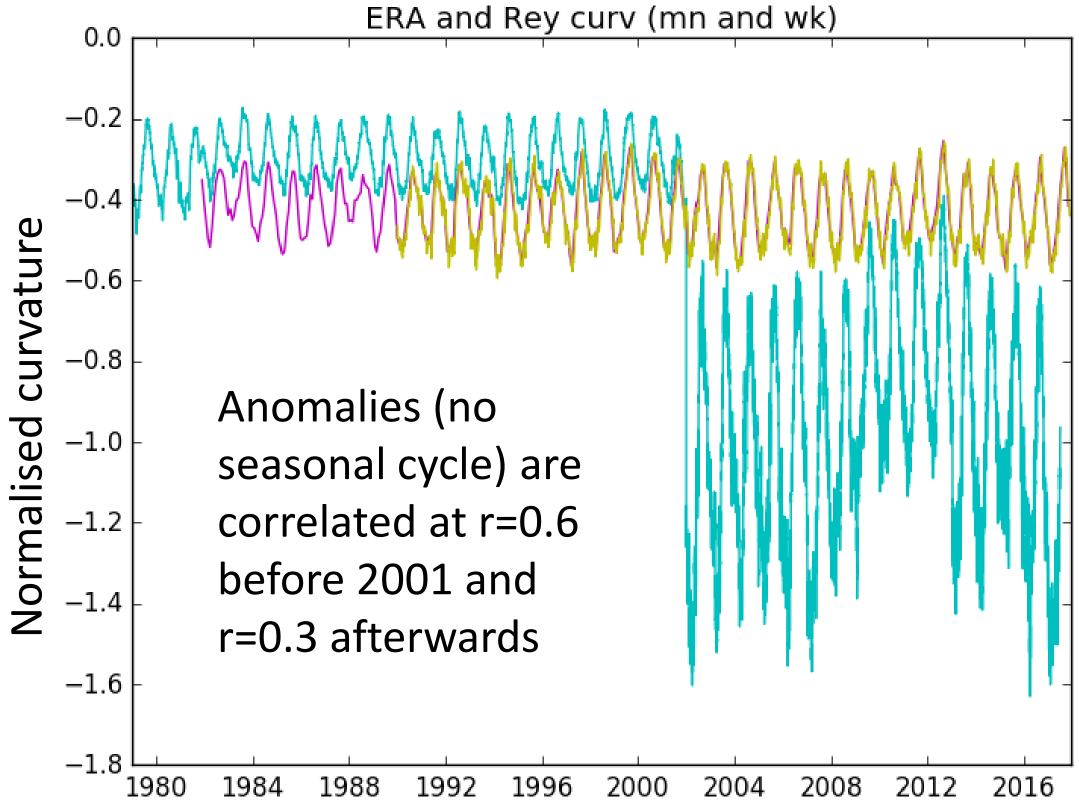


From Alison Cobb’s PhD at Imperial

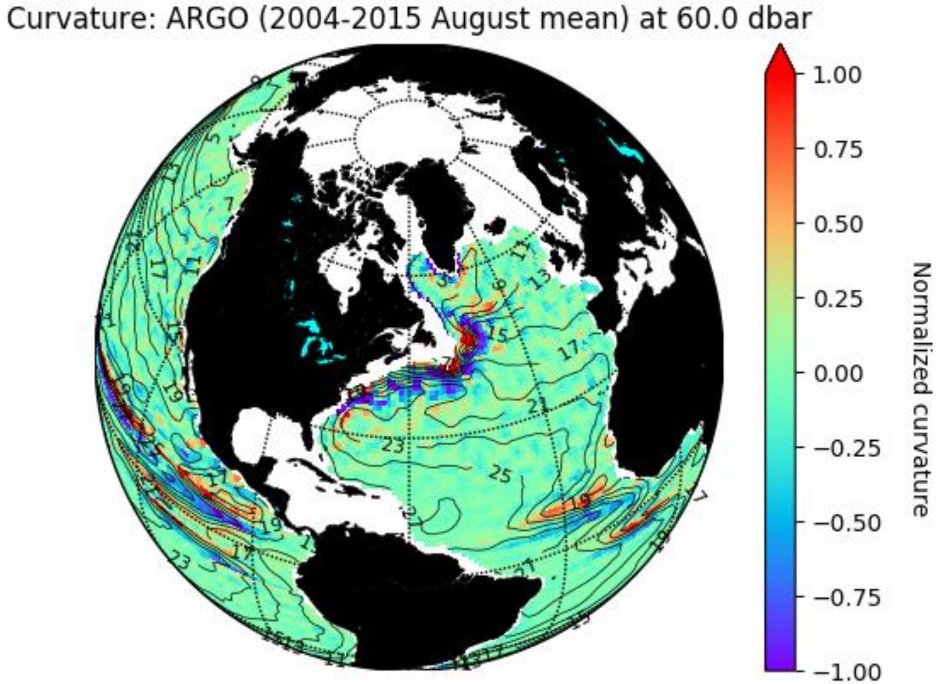
Issue 3: SST datasets…

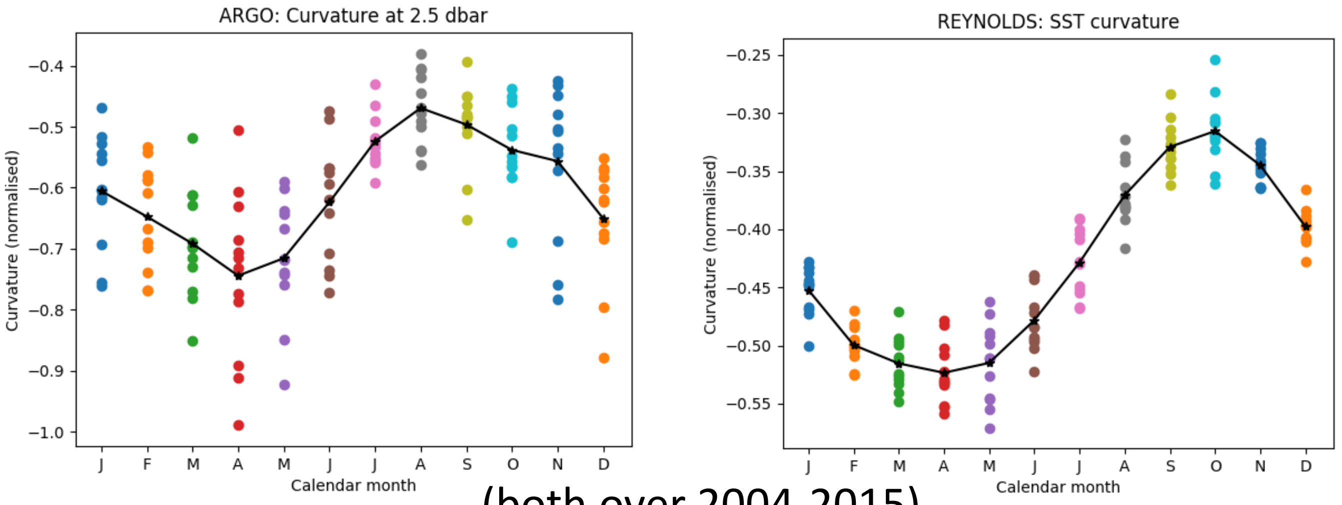
Isolate the warm tongue using the horizontal Laplacian of temperature

(NB: all curves normalised by the same value)


ERA and Rey curv (mn and wk)

Anomalies (no seasonal cycle) are correlated at r=0.6 before 2001 and r=0.3 afterwards


Curvature: ARGO (2004-2015 August mean) at 60.0 dbar


ARGO: Curvature at 2.5 dbar

REYNOLDS: SST curvature

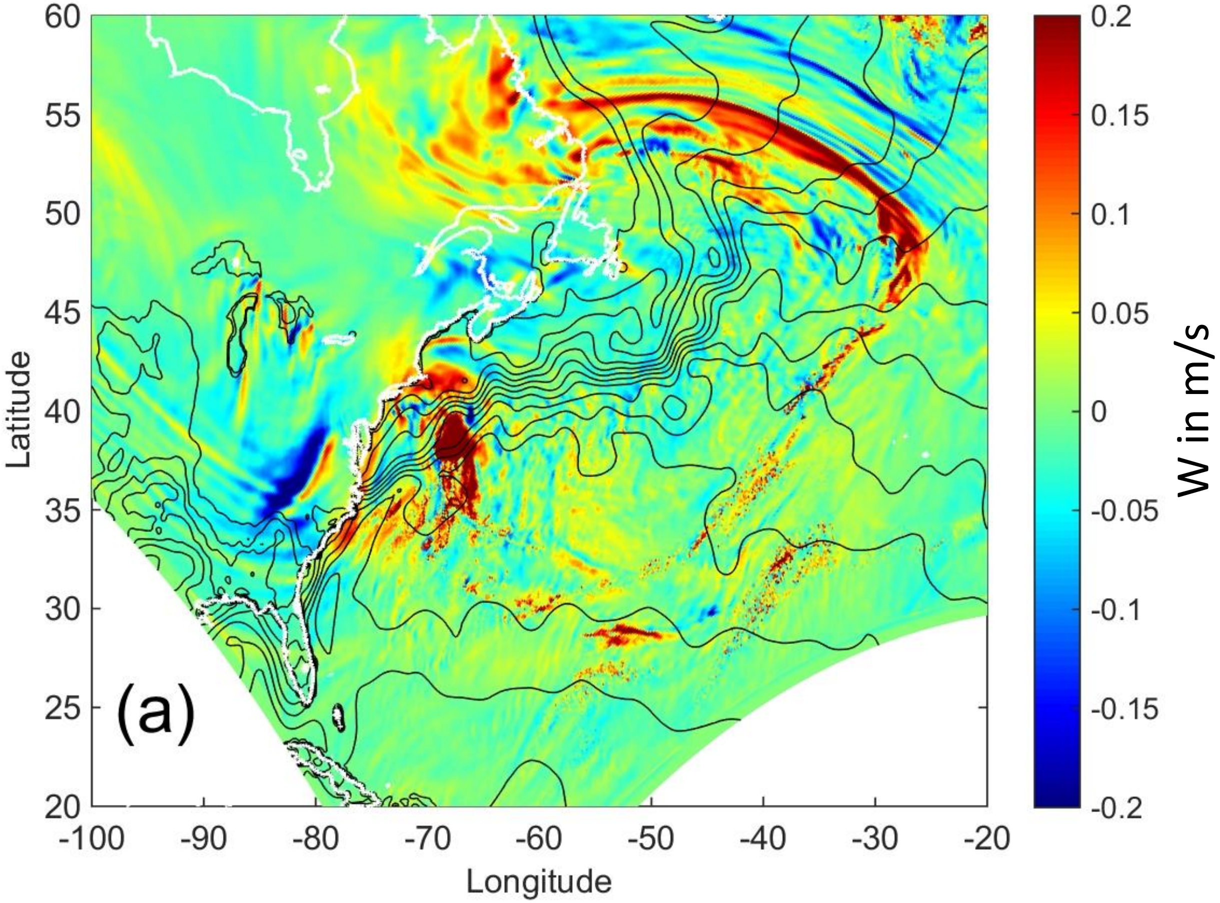
(both over 2004-2015)

Conclusions

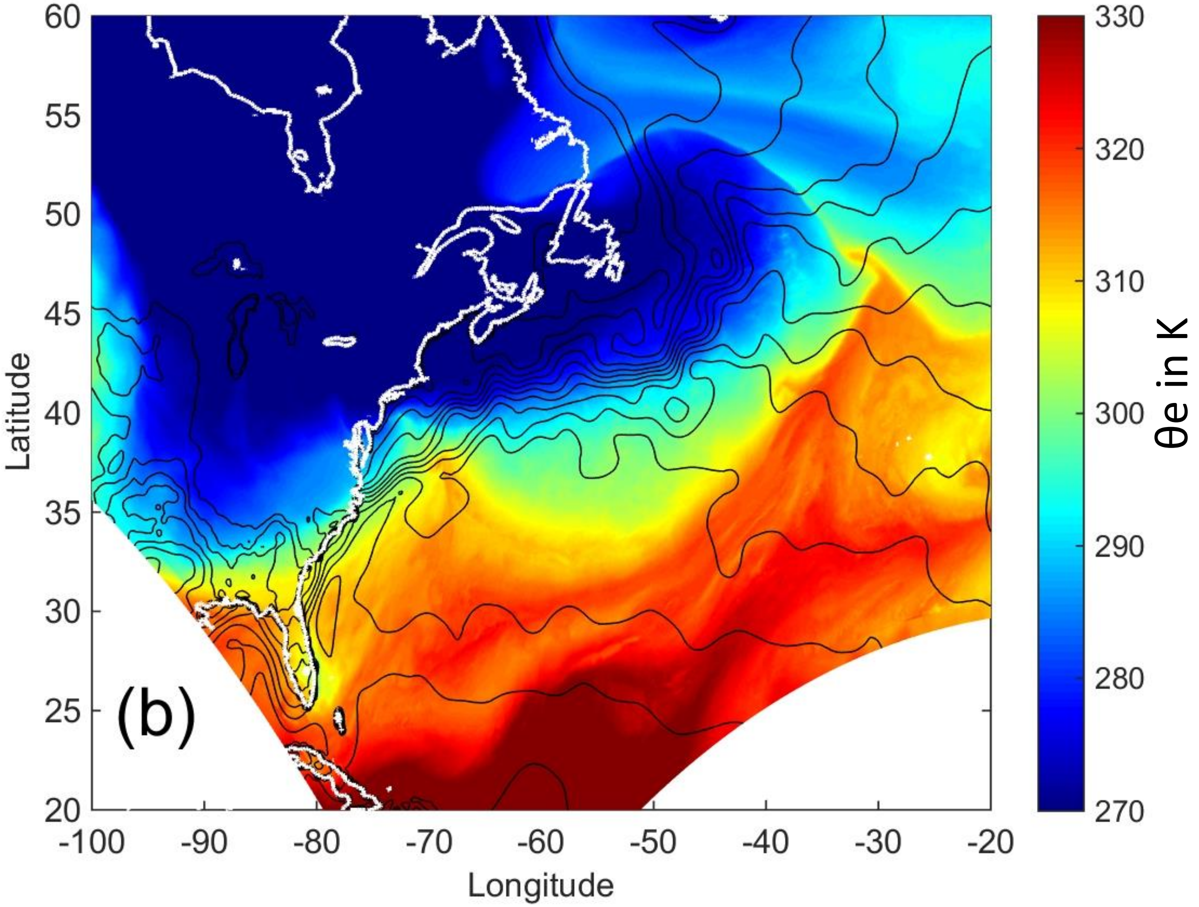
- There is a clear impact of the Gulf Stream (i.e., warm tongue & SST gradient) on the frontal circulation of cyclones
- As spatial resolution increases, new mechanisms by which the Gulf Stream affects cyclones emerge (e.g., TDS at 60km, shear instability at 25km)
- The cumulative effect of these “high res” air-sea interactions on the storm-track (e.g., NAO) is unknown

Extras

Synoptic situation at t=24h



Upward velocity at 5km



Equiv. pot. temp (K) at 500m

3. Remote, large scale impact of Gulf Stream air-sea interactions

- Is the mechanism occurring frequently?

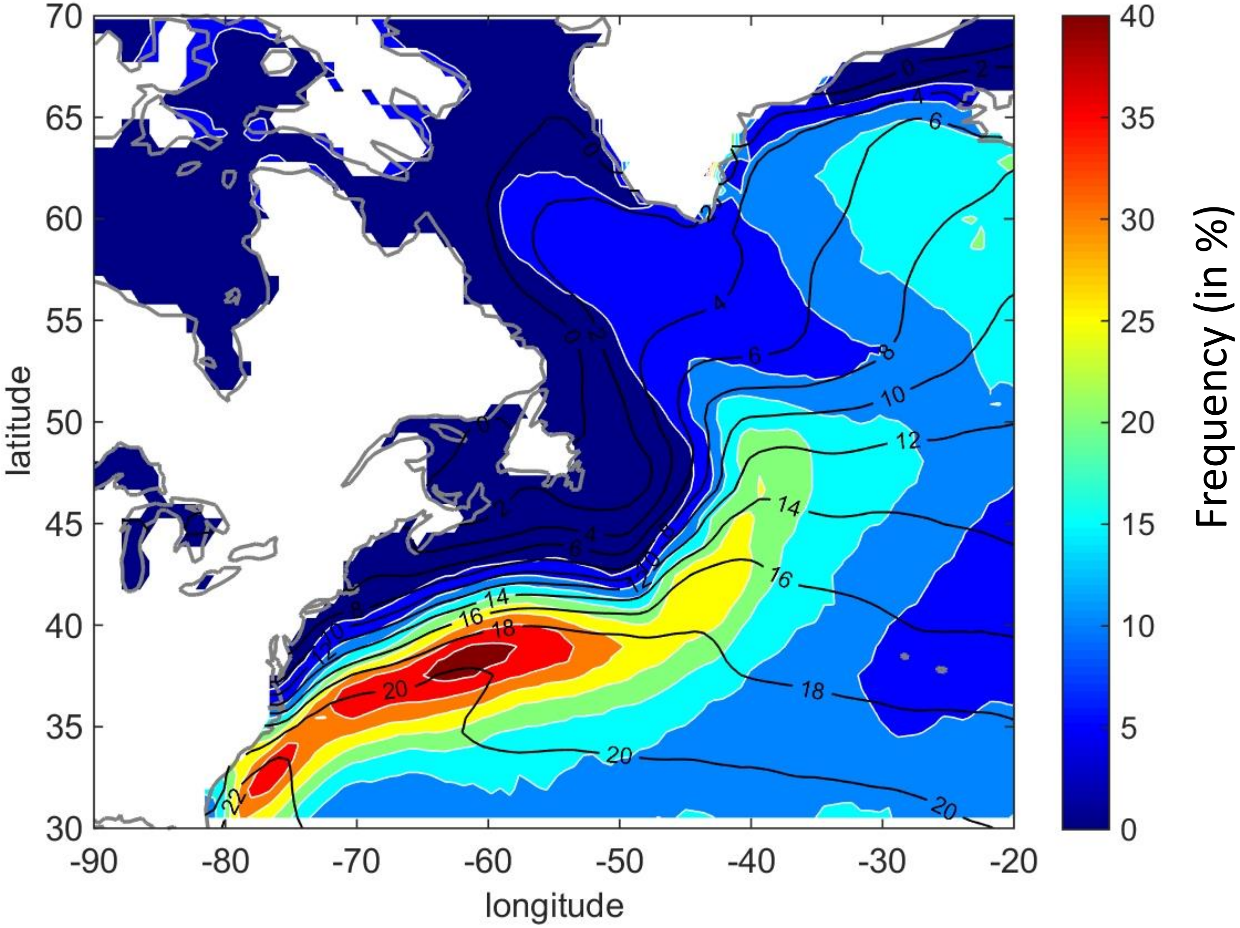
- Does it have an impact beyond the direct vicinity of the Gulf Stream?

The “warm path” in ERA-interim data

(DJF, 1979-2012)

- Follow semi-geostrophic framework of Shutts (1990) to define ascending trajectories from a given low level location
- Measure the θe difference from low level to the tropopause along the “trajectory” to estimate the magnitude of the ascent
- Map shows enhanced frequency of occurrence of Δθe < 0 (strong ascent) along the Gulf Stream warm tongue consistent with UM results

Fraction of wintertime days with Δθe<0

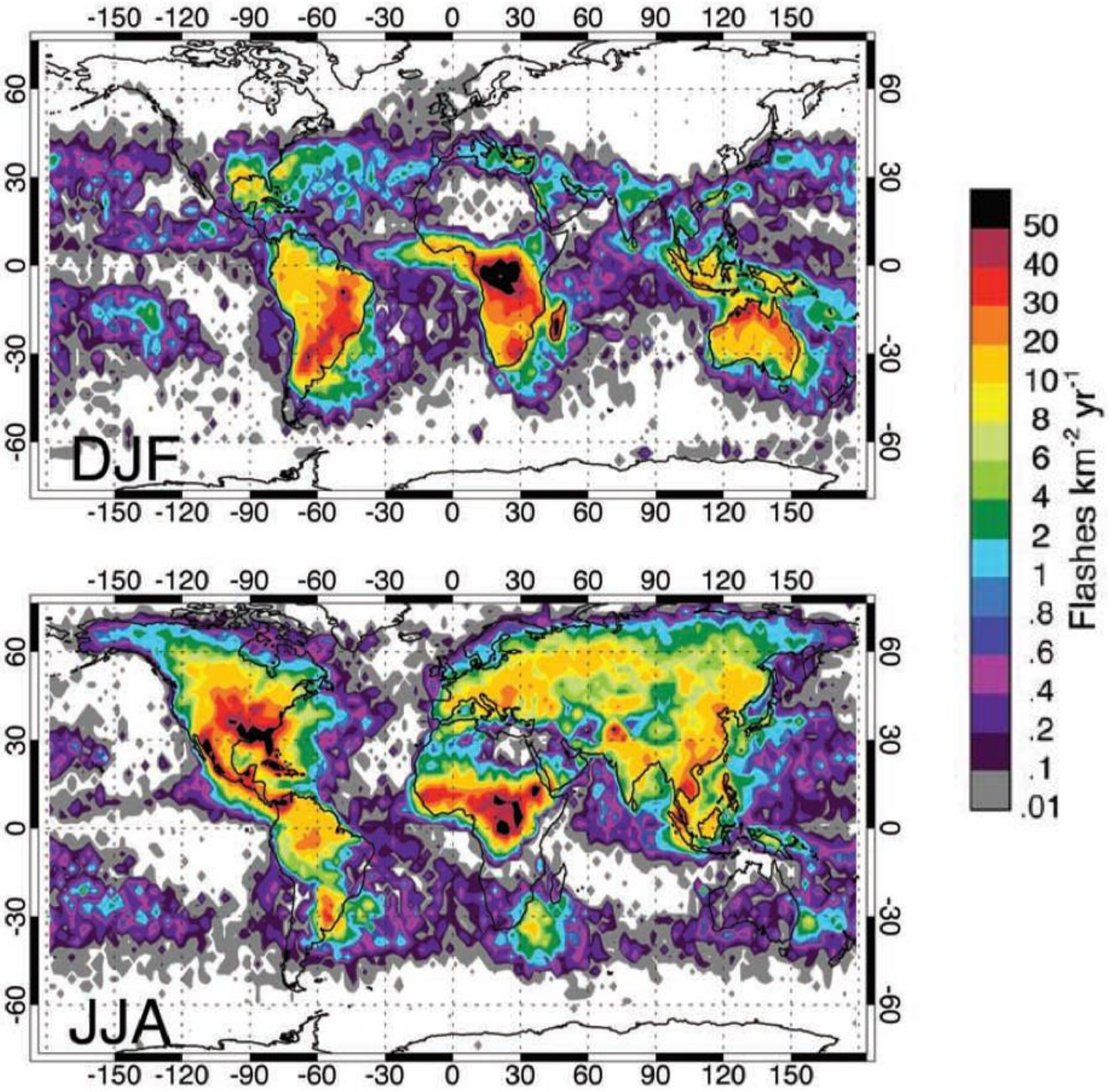


NB low level condition assumed is Ta = SST, RH = 80%

Interpretation of lightening strikes' observations

* The Gulf Stream features prominently as the place with highest frequency of lightning over the oceans

*Presence of strong ascent in cyclones could be instrumental in setting this feature (de Boer et al., 2013)



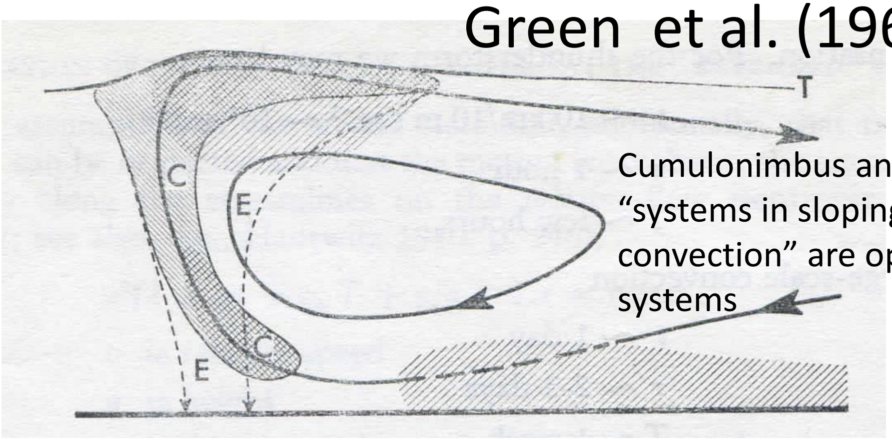
Christian et al., 2003

Cumulative effect of the warm path: forcing of the Jet Stream

- Upward and downward motions in cyclones do not cancel out (Green et al., 1966; Emanuel, 1985).
- The synoptic waves thus contribute directly to the time mean upward motion
- → Direct vorticity forcing at upper levels induced by the Gulf Stream warm tongue
- → non local and more robust impact than shallow thermal forcing from low levels

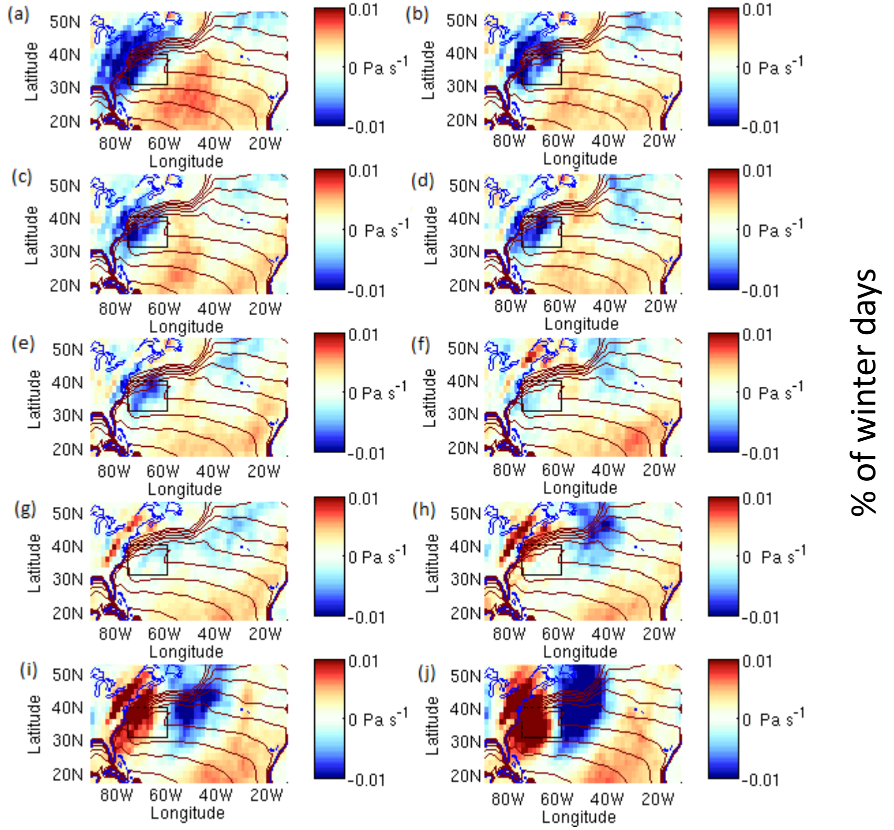
Parfitt & Czaja, QJRMS (2015)

Green et al. (1966)



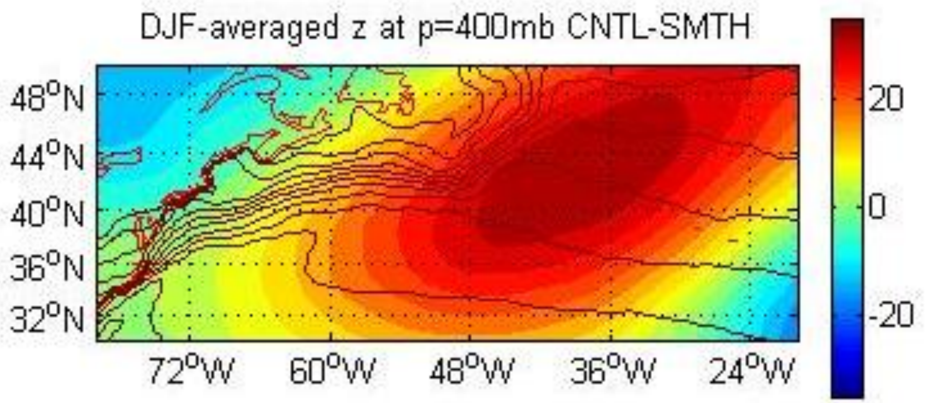
Cumulonimbus and "systems in sloping convection" are open systems

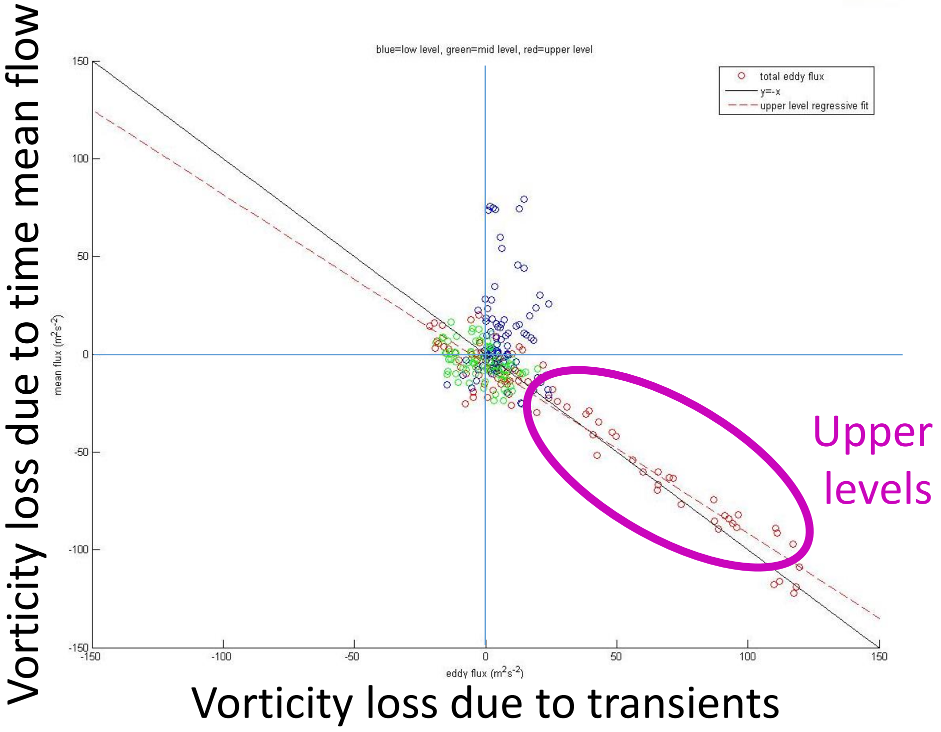
Decomposition of ω at 500hPa



Gulf Stream forcing and model biases

- Analysis of the AFES simulations (Minobe et al., 2008) with realistic (CNTL) and smoothed (SMTH) SSTs
- The time mean upper level flow is deflected north eastward (more tilted jet) in the CNTL experiment
- This is driven by changes in the divergent circulations and their associated vorticity transport

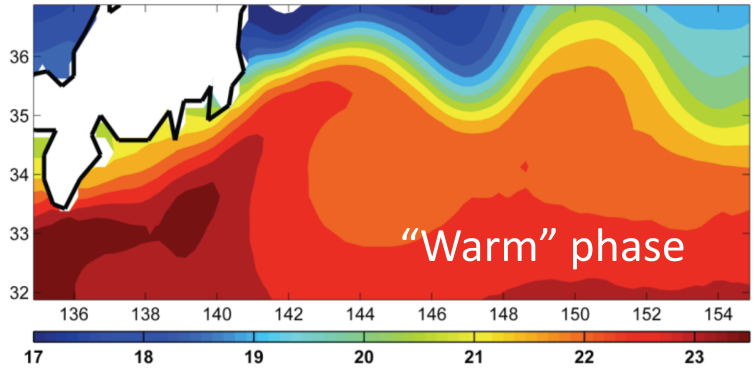


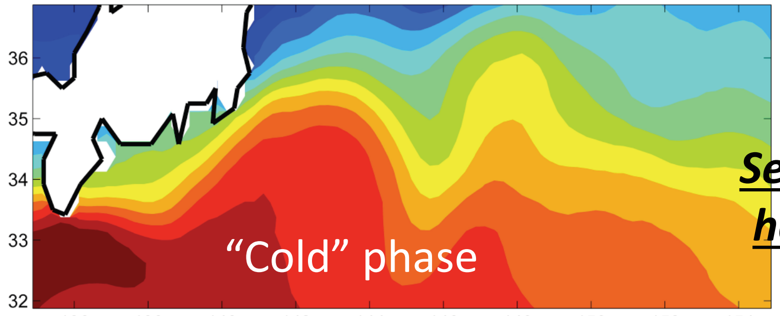


Kuroshio's impact on blocking (O'Reilly & Czaja, 2014)

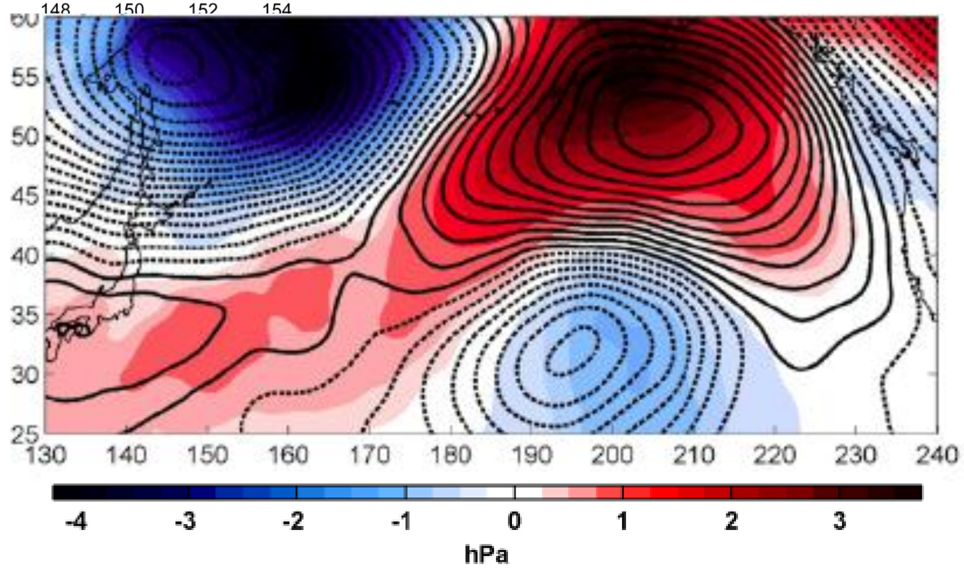
- Warm state of the Kuroshio is associated with more frequent Alaskan blocking

SST composites (deg C)

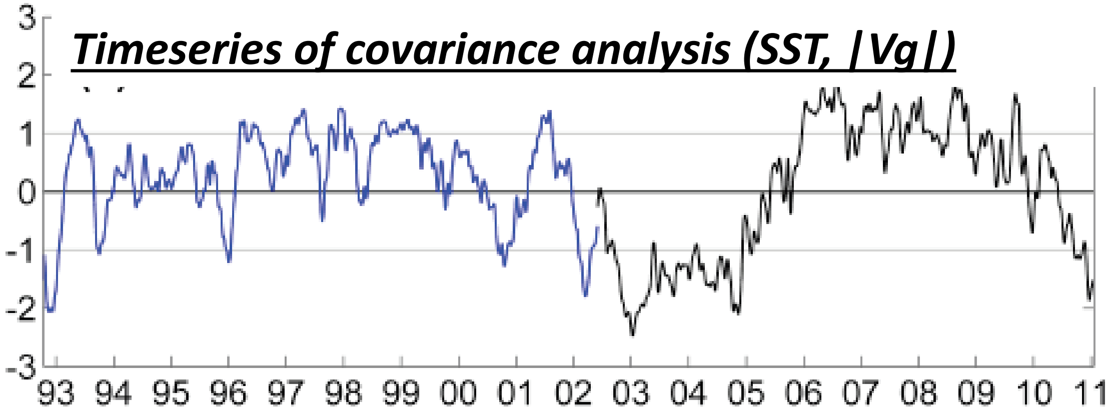




Sea level pressure (color) and 500mb height field (CI=4m) in MAM during warm phase



Timeseries of covariance analysis (SST, |Vg|)



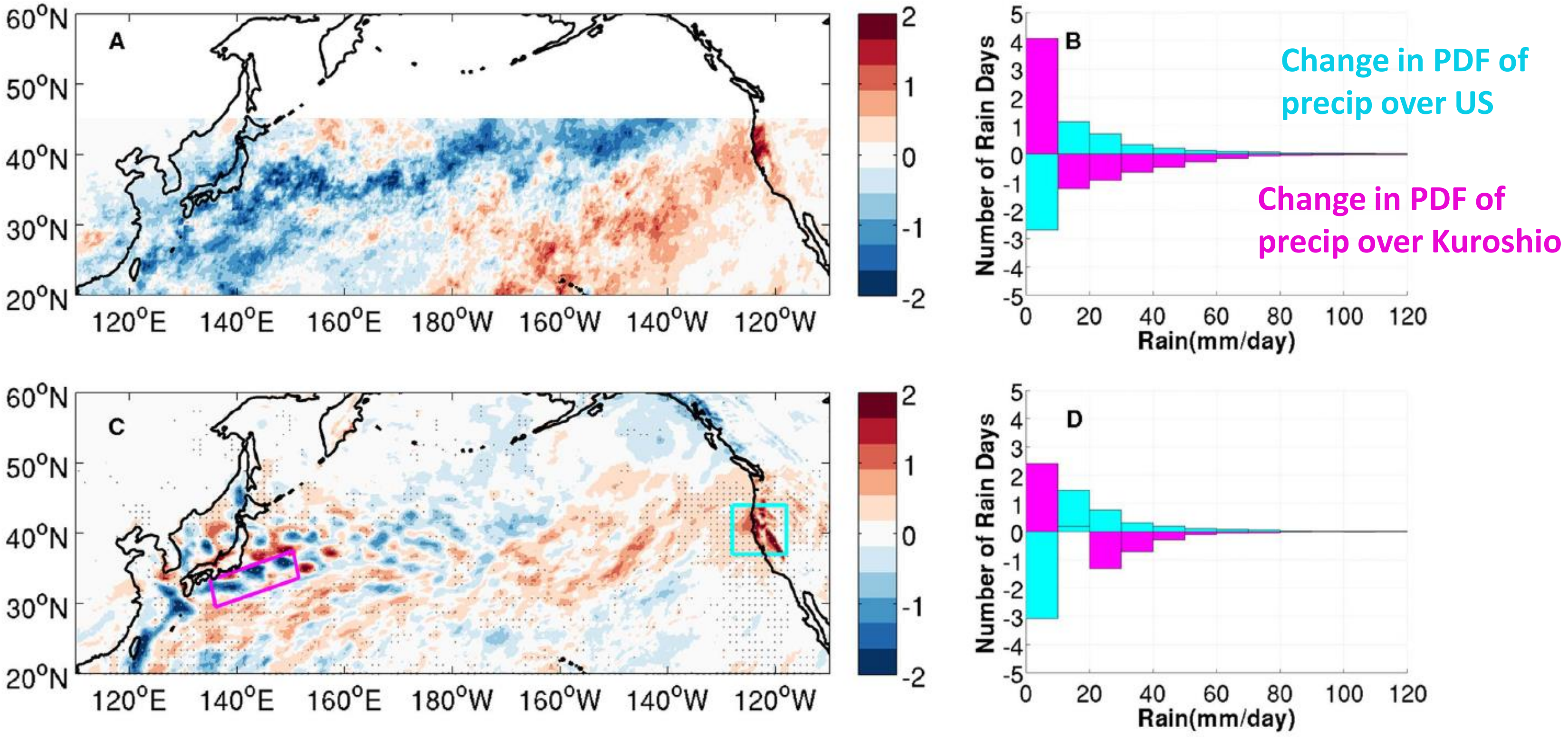
Impact of meso-scale ocean eddies on atmospheric precipitation and circulation

- 10 member ensemble, CNTL and SMTH SST experiments (ONDJFM 2007-08)
- WRF at 27km, 30L resolution over an entire North Pacific sector
- US rainfall influenced by the presence of mesoscale eddies

Ma et al. (2015)

Precipitation anomalies (mm/day)

Observations (TRMM): five "eddy rich – eddy poor" Kuroshio NDJFMs



Model: CNTL-SMTH SST runs in NDJFM

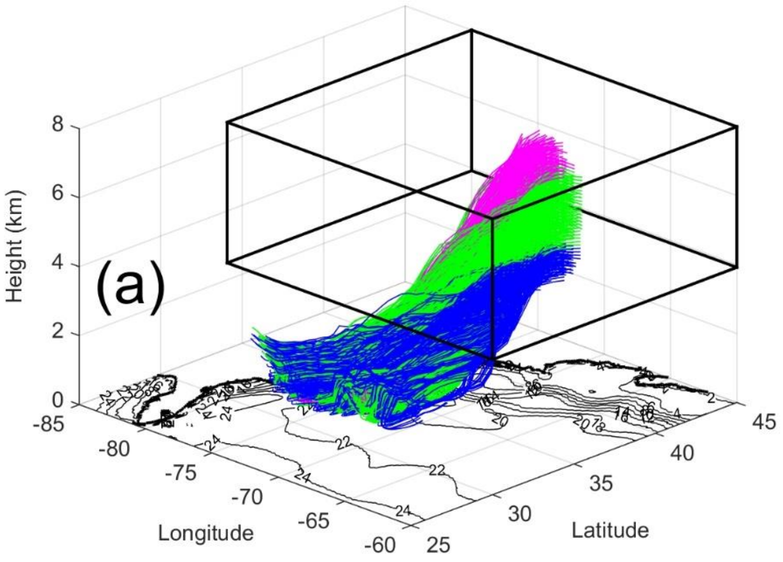
Summary

- There is evidence for an impact of air-sea interactions on 10-100km scale on the vertical motion of cyclones crossing the Gulf Stream
- Both thermodynamical and dynamical mechanisms are involved and require a horizontal resolution finer than 40km
- The impact of this mechanism on low frequency variability is suggested but it needs to be investigated more fully: (i) assess the occurrence of the mechanism in operational forecasts over many cyclones (ii) empirically estimate its remote impact through compositing or other methods

Extras

Back trajectories originating from low levels *(12km)*

CNTL



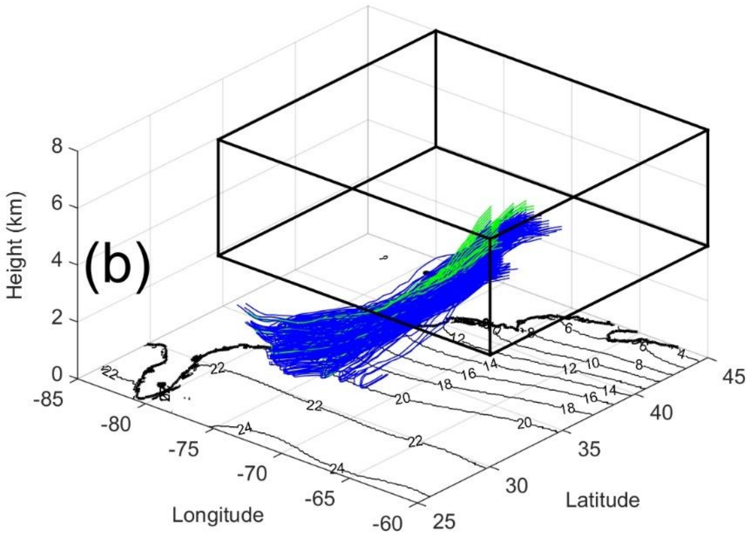
zi>7km

5km< zi < 7km

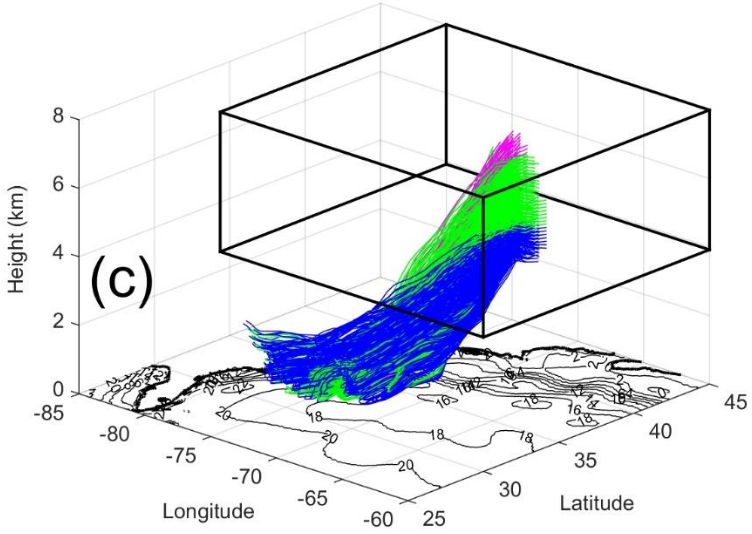
zi<5km

SMTH

Initial release volume



COOL



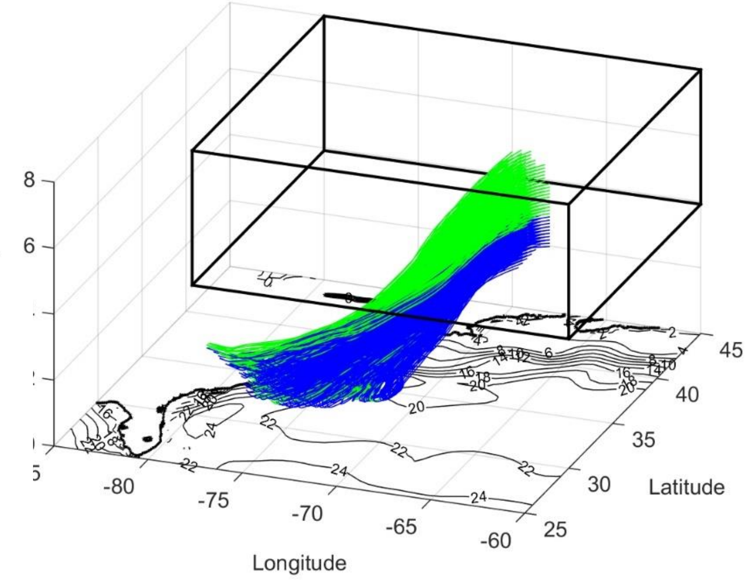
Back trajectories originating from low levels *(40km)*

zi>7km

5km< zi < 7km

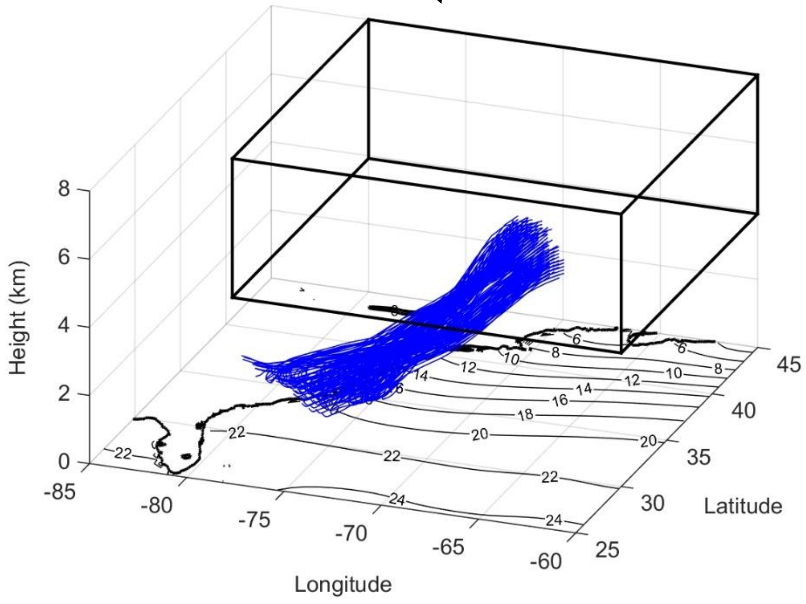
zi<5km

CNTL

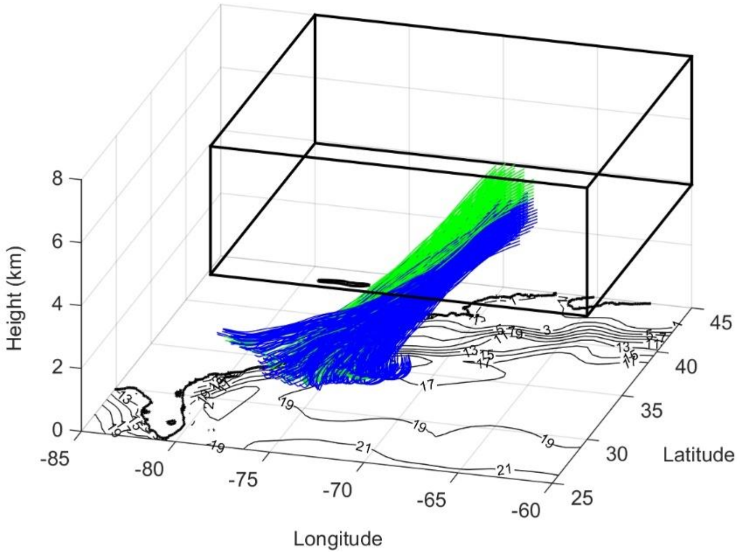


SMTH

Initial release volume

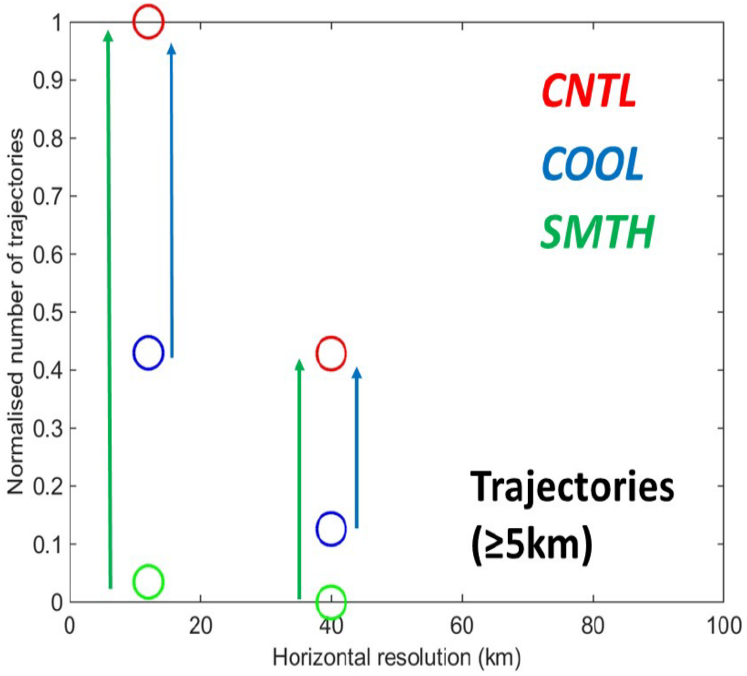


COOL



The warm path: impact of resolution (12km vs 40km

- Systematic decrease in the number of trajectories feeding the ascent from low levels
- Upper level oceanic forcing scales approximately with horizontal resolution (0.4/1~1/2.5, 0.3/0.6~1/2)



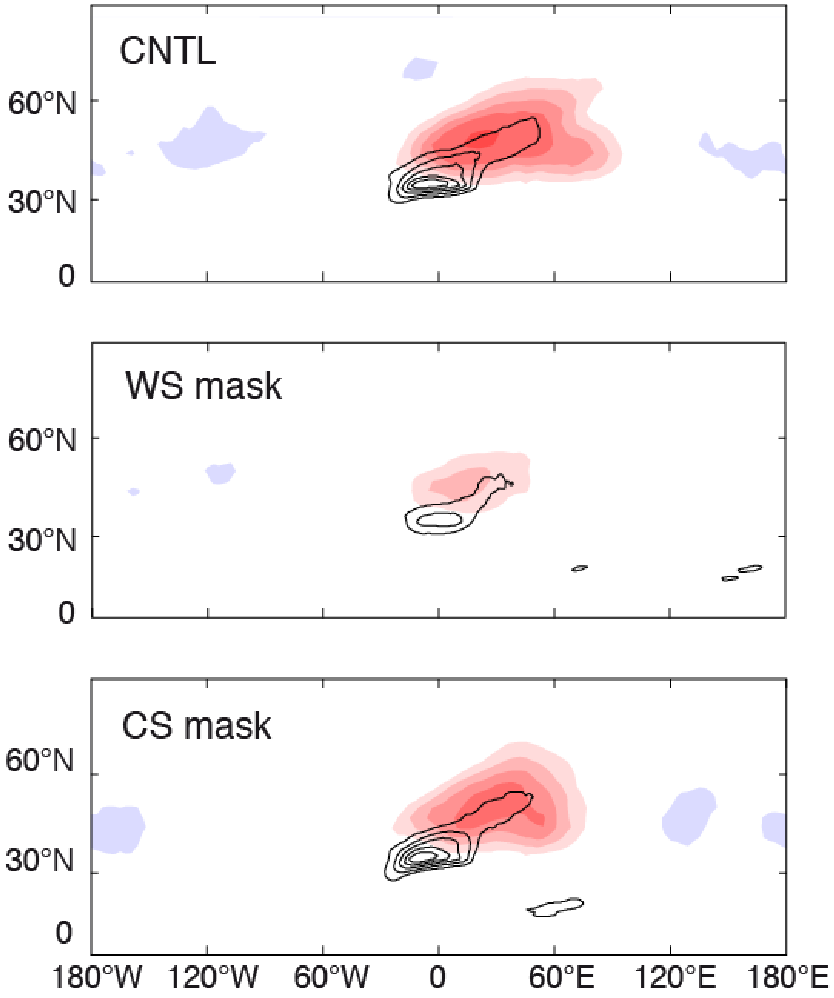
Number of back trajectories

Experiment	12 km	40 km	ratio (40km/12km)
CNTL			
(all)	1178	734	0.62
($z_o \geq$ 7km)	167	0	0
(5 km $\leq z_o <$ 7km)	613	334	0.54
($z_o <$ 5km)	398	400	1
($z_o \geq$ 5km)/($z_o <$ 5km)	1.95	0.83	0.42
SMTH			
(all)	275	148	0.53
($z_o \geq$ 7km)	0	0	0
(5 km $\leq z_o <$ 7km)	27	0	0
($z_o <$ 5km)	248	148	0.6
($z_o \geq$ 5km)/($z_o <$ 5km)	0.1	0	0
COOL			
(all)	625	394	0.63
($z_o \geq$ 7km)	29	0	0
(5 km $\leq z_o <$ 7km)	306	98	0.32
($z_o <$ 5km)	290	296	1.02
($z_o \geq$ 5km)/($z_o <$ 5km)	1.15	0.33	0.28

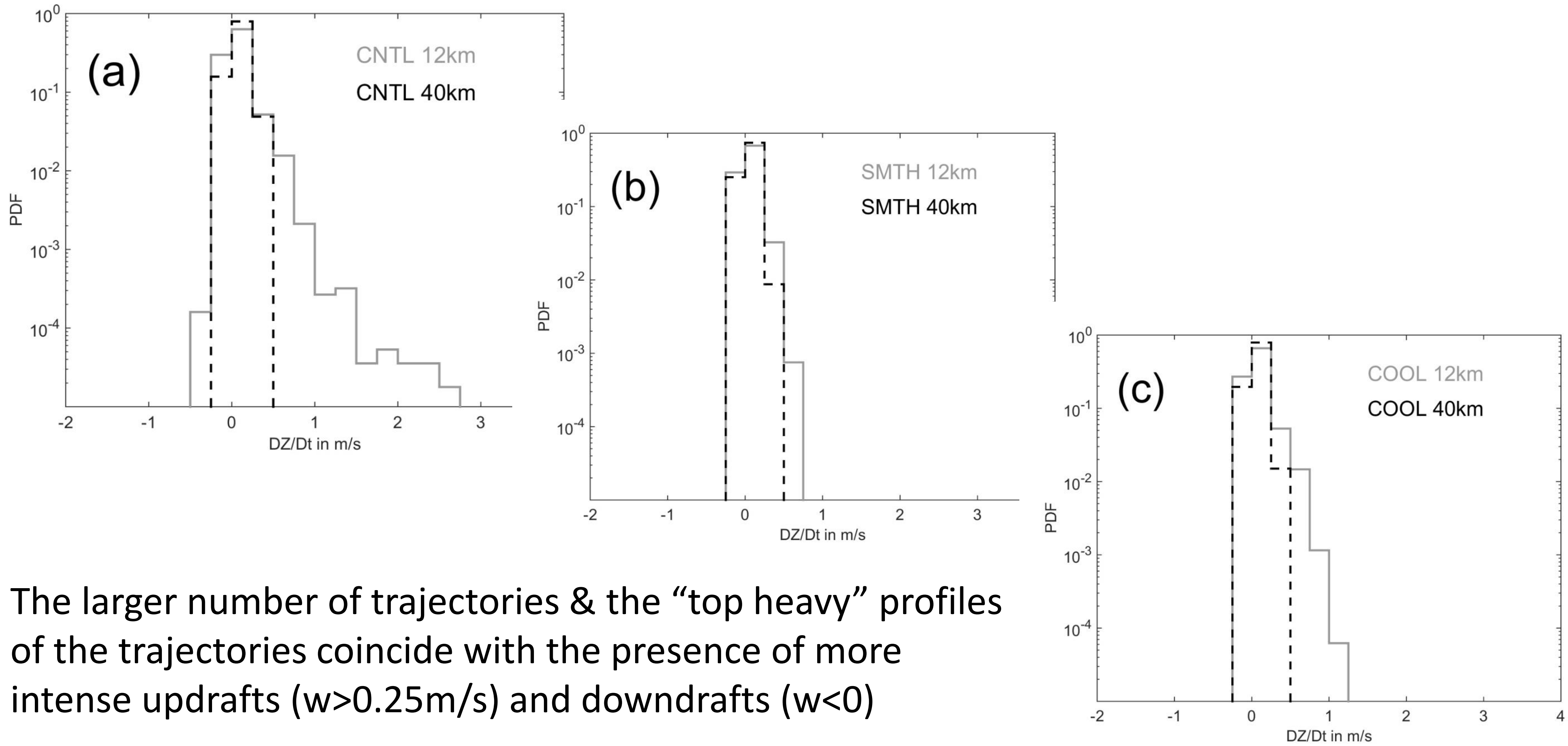
Cold and warm paths in AGCMs: model “surgery”

- Aquaplanet simulations with the MITgcm (grey radiation, simplified convection scheme) at low resolution (~2.8 deg)
- Response of the storm-track to a localized SST gradient (CNTL-SMTH) where the atm. sees either CS only, WS only, or both.
- The cold sector is the primary forcing agent at this resolution

EKE at 300hPa (ci=0.2 SI) & EXPT-SMTH (color)



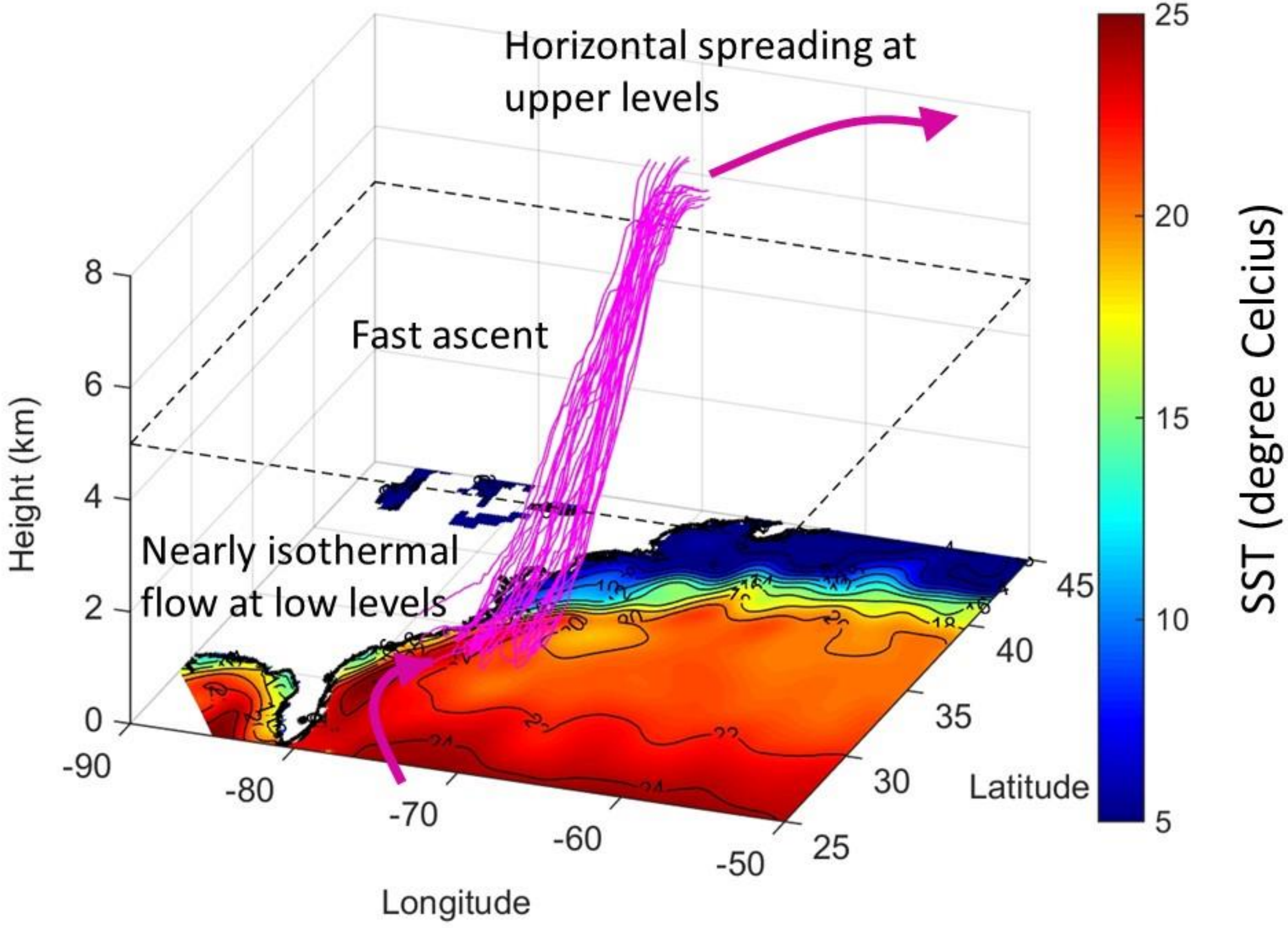
PDFs of Lagrangian upward velocity



The larger number of trajectories & the "top heavy" profiles of the trajectories coincide with the presence of more intense updrafts (w>0.25m/s) and downdrafts (w<0)

Summary: the “warm path”

- Warm SSTs along the Gulf Stream maintain high θe of air parcels
- The large SST gradients to the north reinforce the direct transverse circulation at the cold front embedded in the cyclone



NB: Plotted in magenta are the trajectories (zi≥7km) in CNTL(12km)

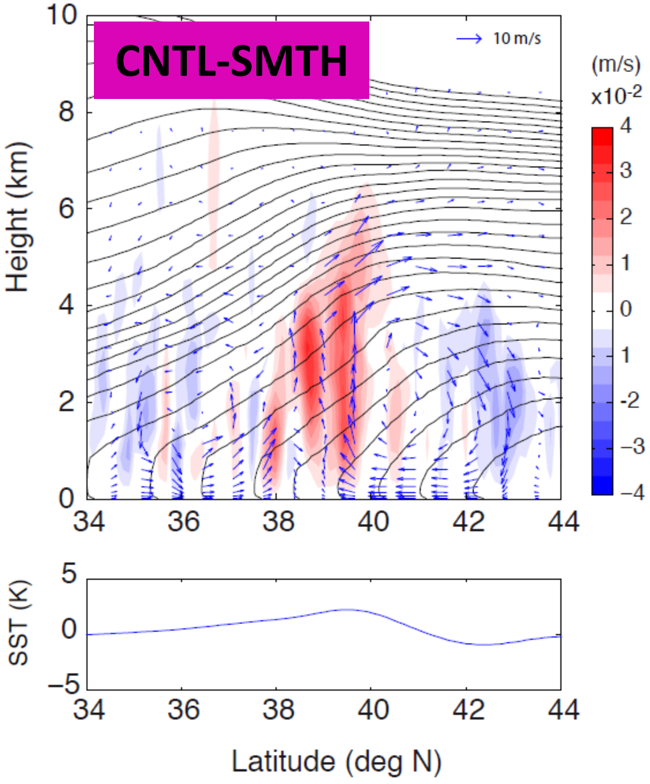
The cold path: air-sea interactions in the cold sector

(Vannière et al., J. Clim., 2016)

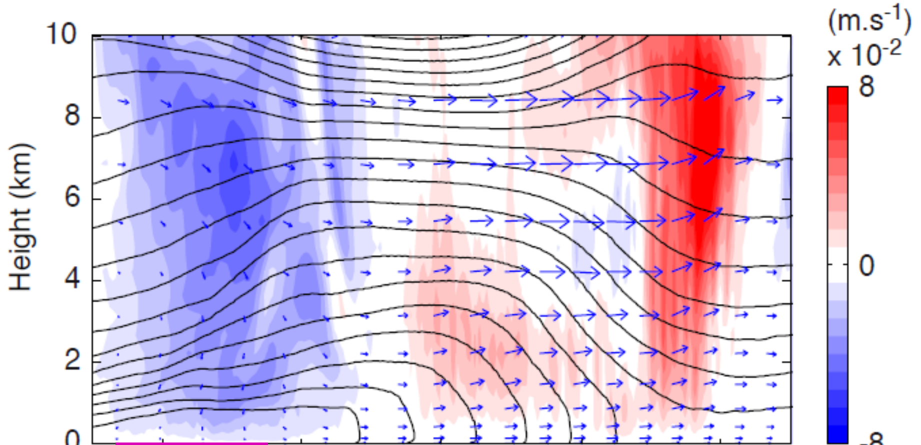
- Shallower & stronger air-sea interactions compared to the warm sector

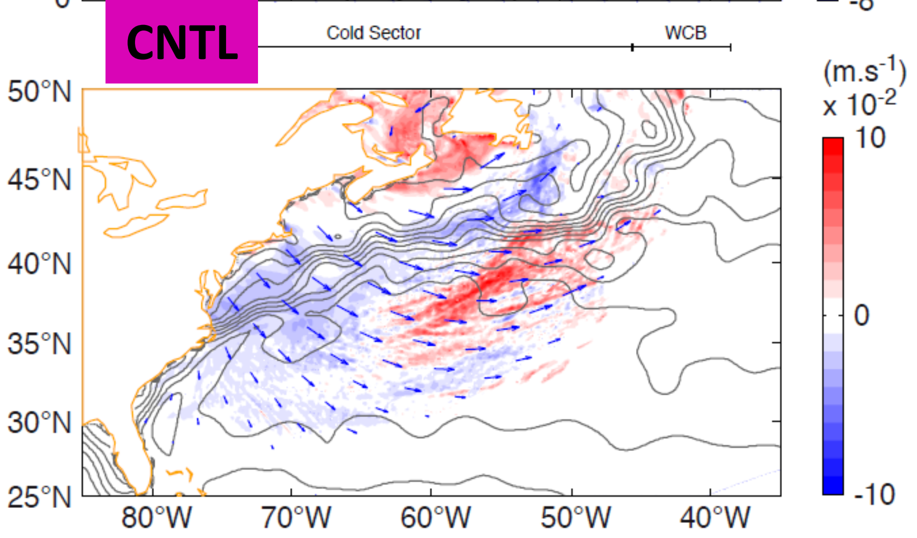
- CNTL – SMTH indicates that the Gulf Stream warm tongue generates an asymmetry in the cold sector divergent circulation

Upward wind (color), wind vectors and θ averaged over 65W-45W



Upward wind (color) and wind vectors at 36N





Upward wind at 700m (color) and wind vectors at 10m in the cold sector

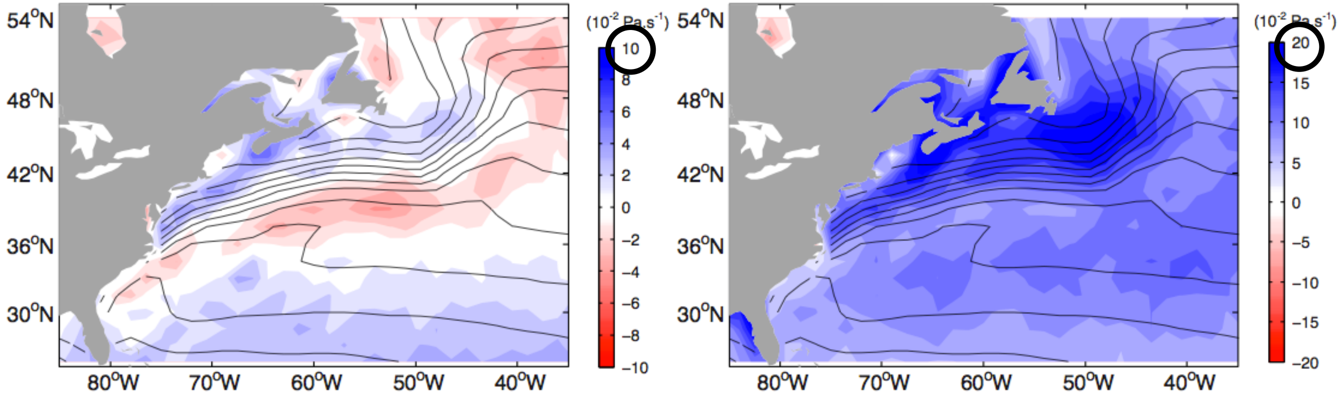
NB: data is averaged over the 3rd day of simulation

Scaling the results “up” to the climatology

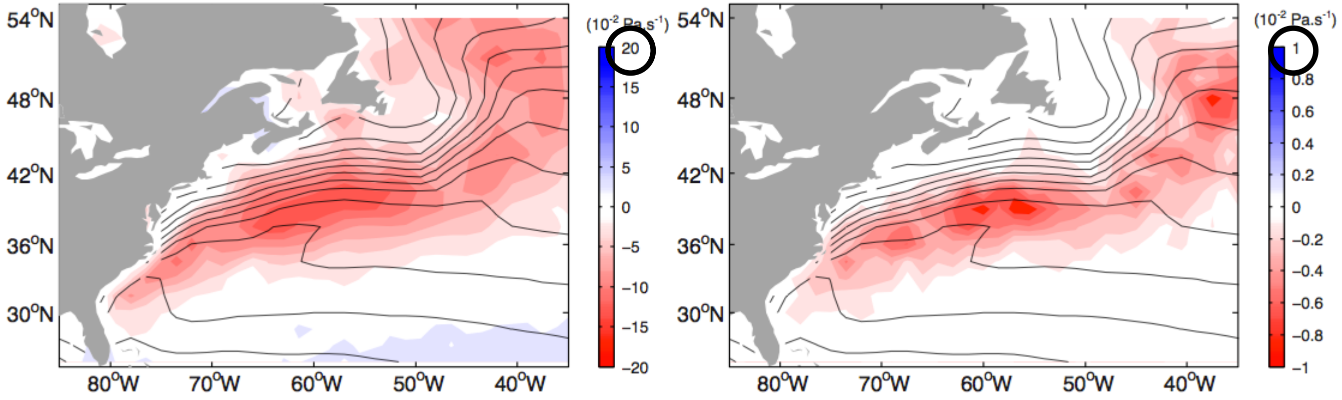
Contribution of warm and cold sectors to climatological features (ERAint, DJF 1979-2012)

- Ascent along the Gulf Stream is primarily set by the cumulative effect of the warm sectors (with a ~20% contribution from the “cold sector cell” to the CS+WS ascent)
- The anchoring of precipitation and ascent reported in several studies (e.g., Minobe et al., 2008; Kirtman et al., 2012) is not causal

(a) Time mean vertical wind at 700mb (b) Vertical wind in CS at 700mb



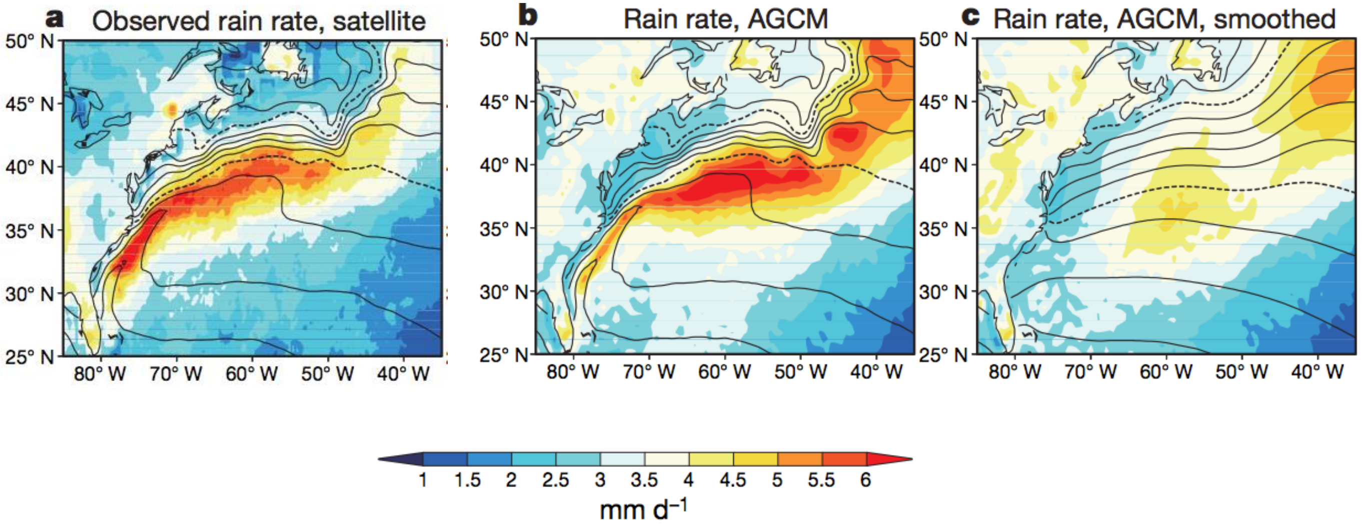
(c) Vertical wind in WS at 700mb (d) Contribution of CS if CV > 5mm



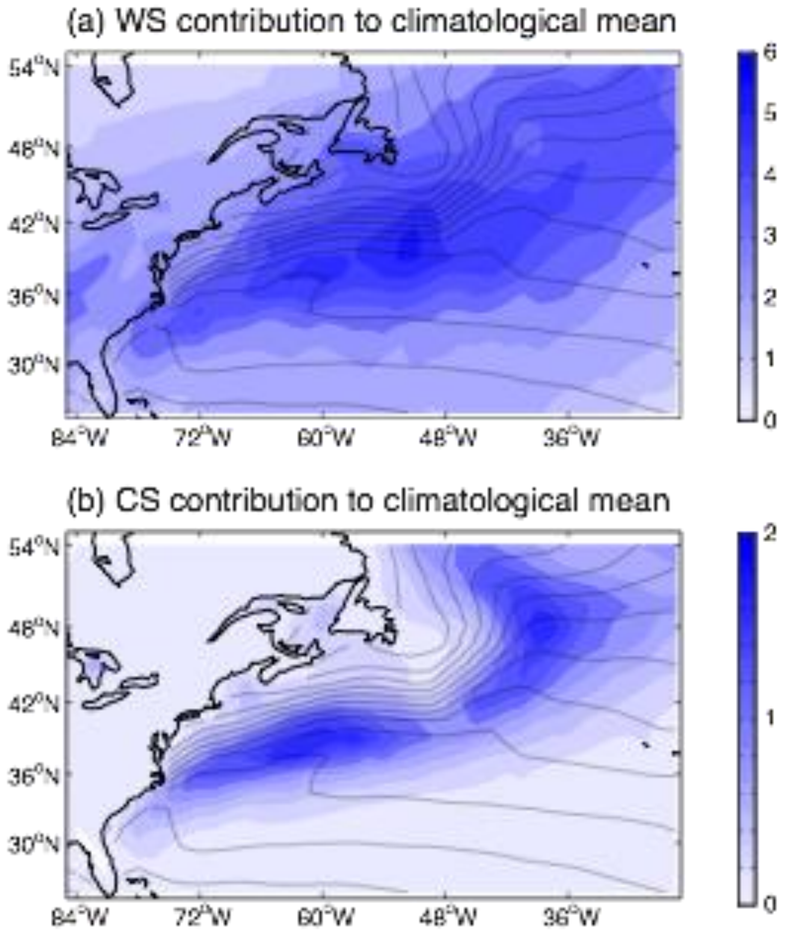
Vannière et al. (2016), in prep.

Contribution of warm and cold sectors to climatological features (ERAint, DJF 1979-2012)

- The anchoring of precipitation reported in several studies (e.g., Minobe et al., 2008; Kirtman et al., 2012) reflects primarily air-sea interactions in the cold sector of midlatitudes' storms

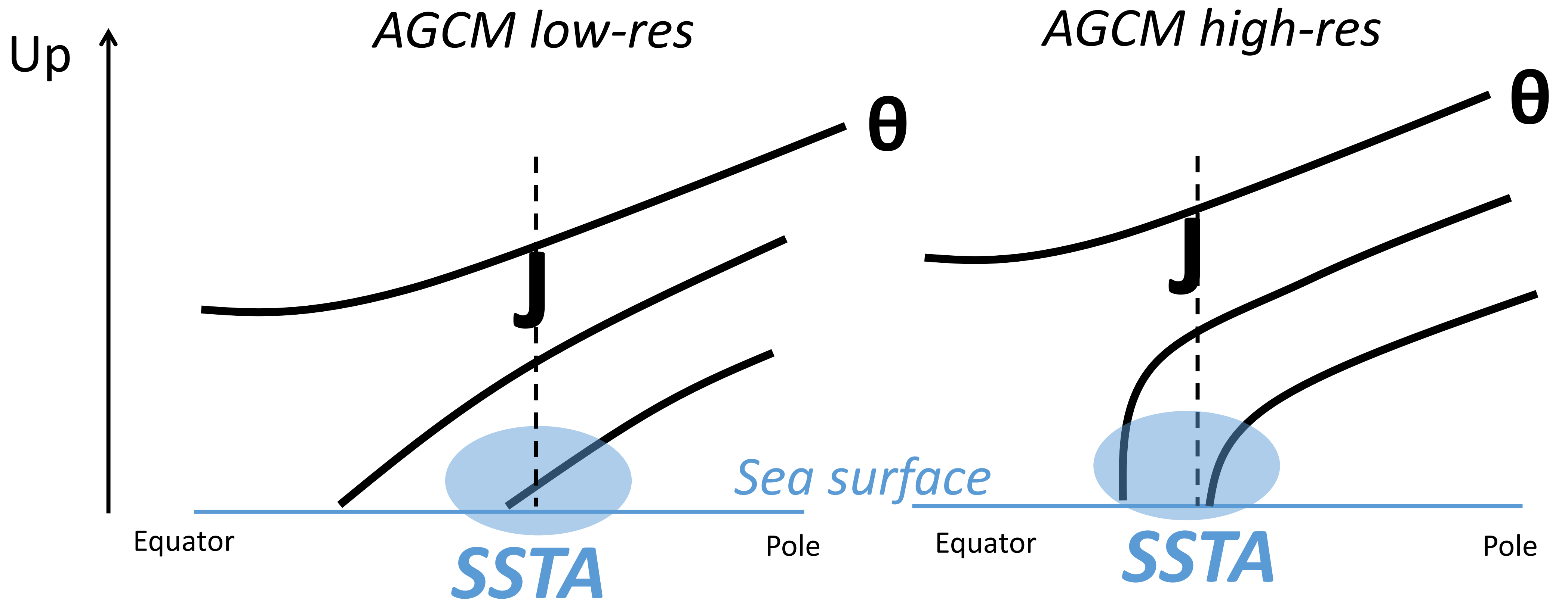


Minobe et al. (2008)



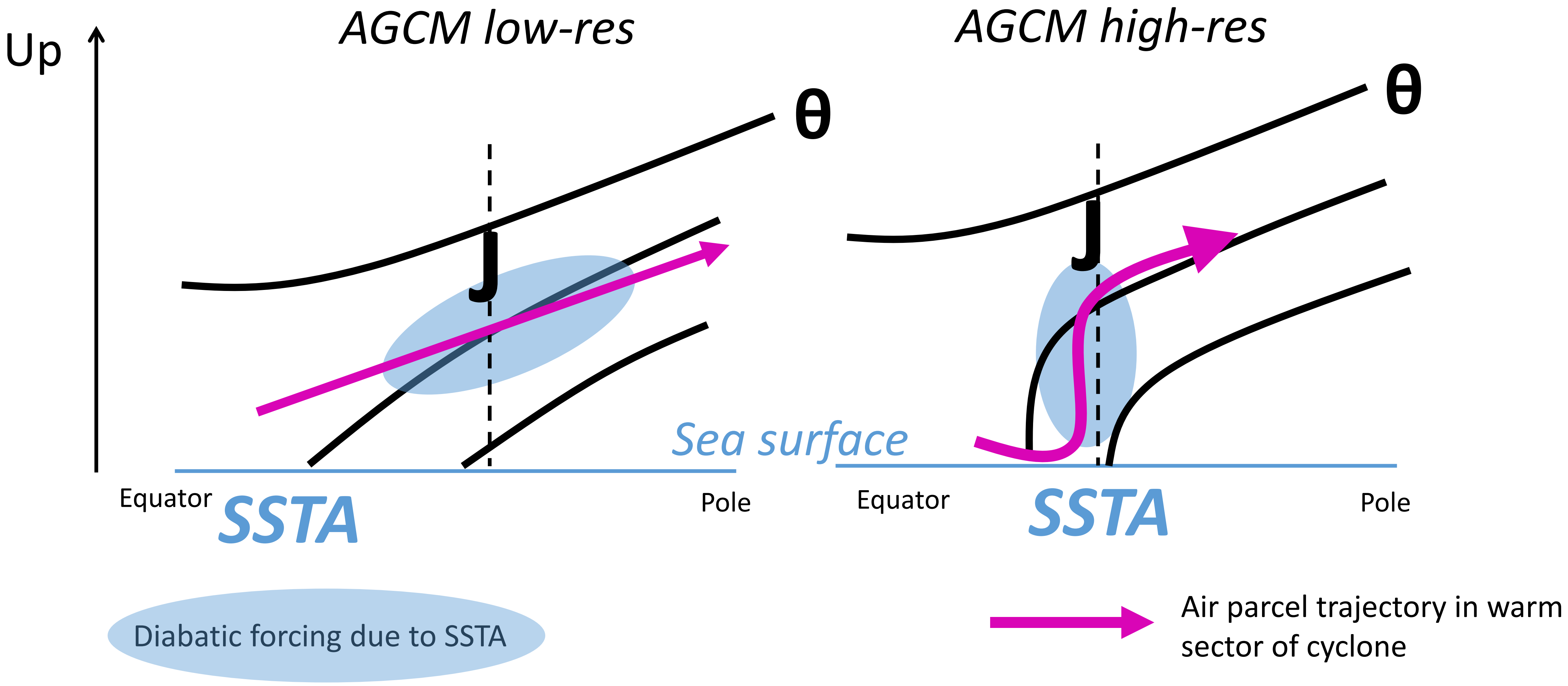
Vannière et al. (2016), in prep.

Old paradigm: cold sectors & ocean-atmosphere coupling

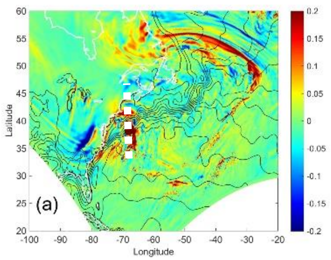


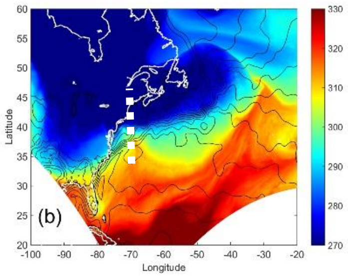
Diabatic forcing due to SSTA

New paradigm: warm sectors & ocean-atmosphere coupling

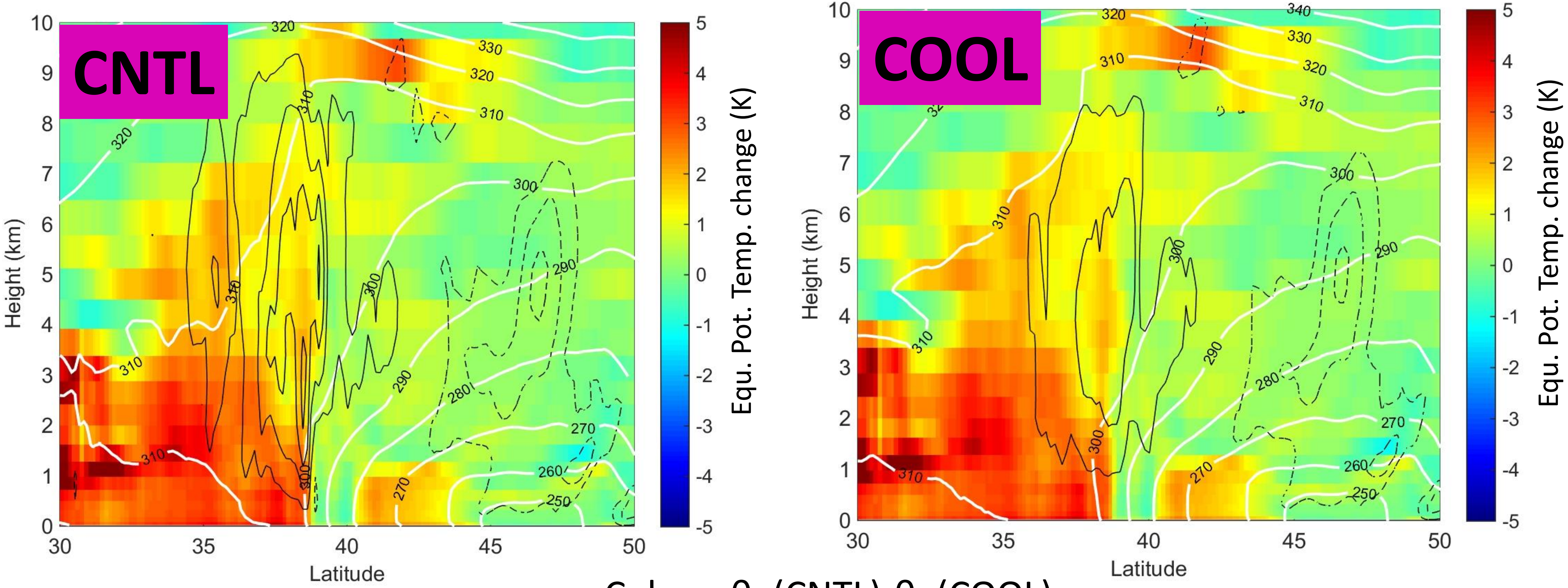


North-South sections





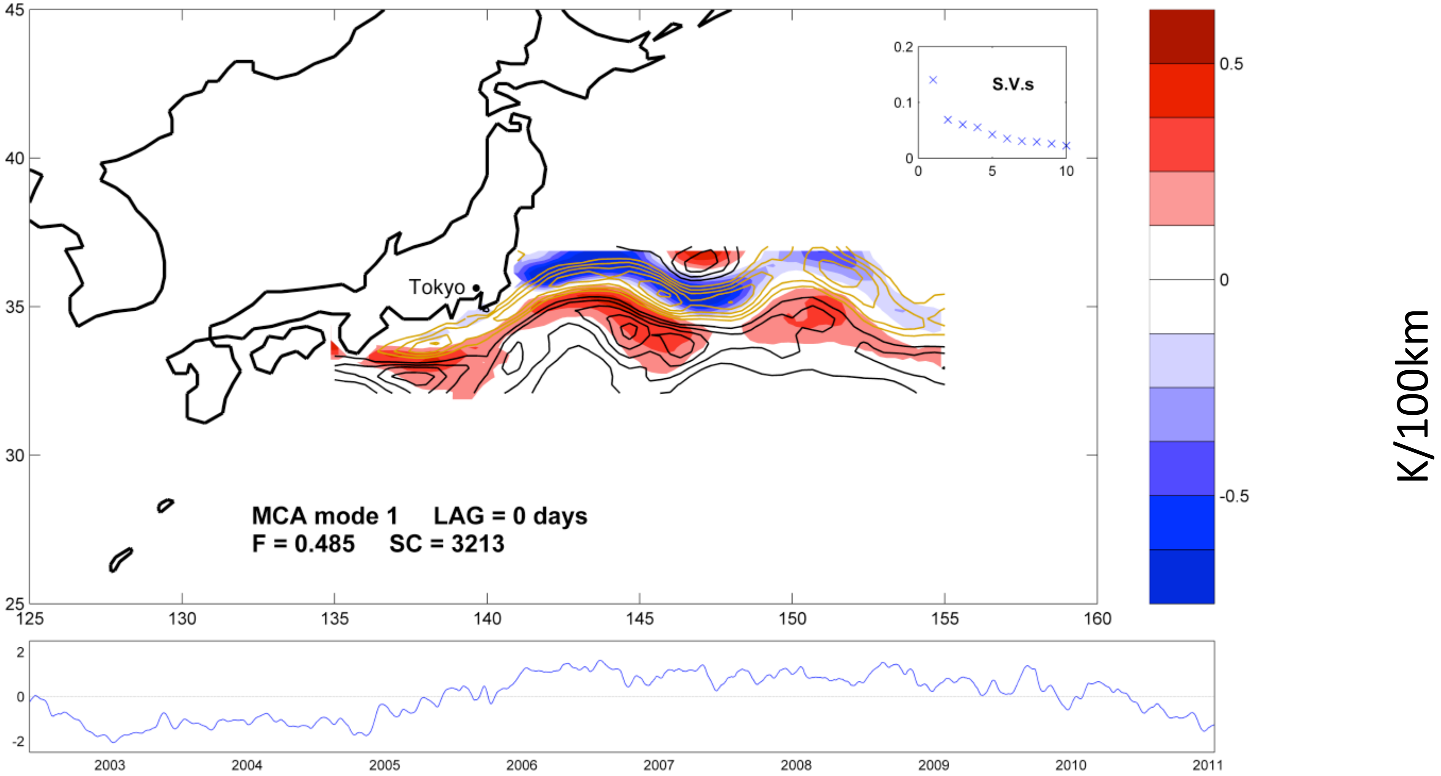
Vertical velocity (black, ci=0.1ms/ & 0.025m/s) and θe (white, ci=10K)



Color = θe(CNTL)-θe(COOL)

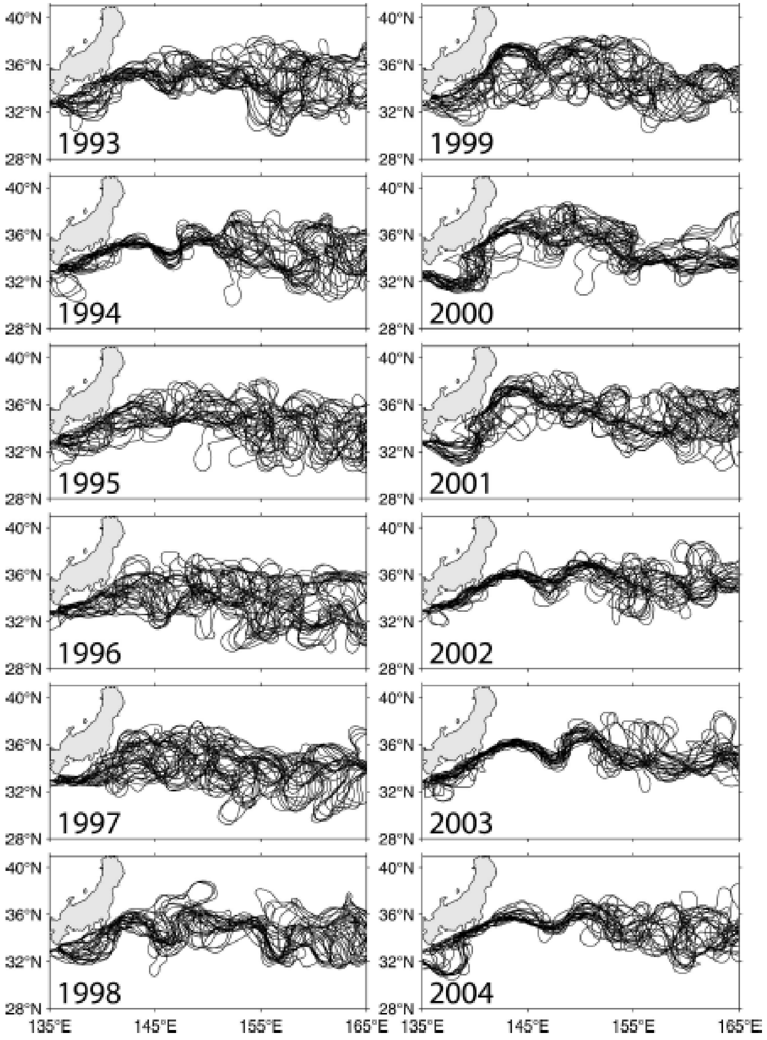
Variability of "western boundary currents" (e.g., Gulf Stream, Kuroshio) from satellite altimetry

MCA between geostrophic current (ci=5cm/s) and grad SST (color)



Chris O'Reilly's PhD thesis (2014)

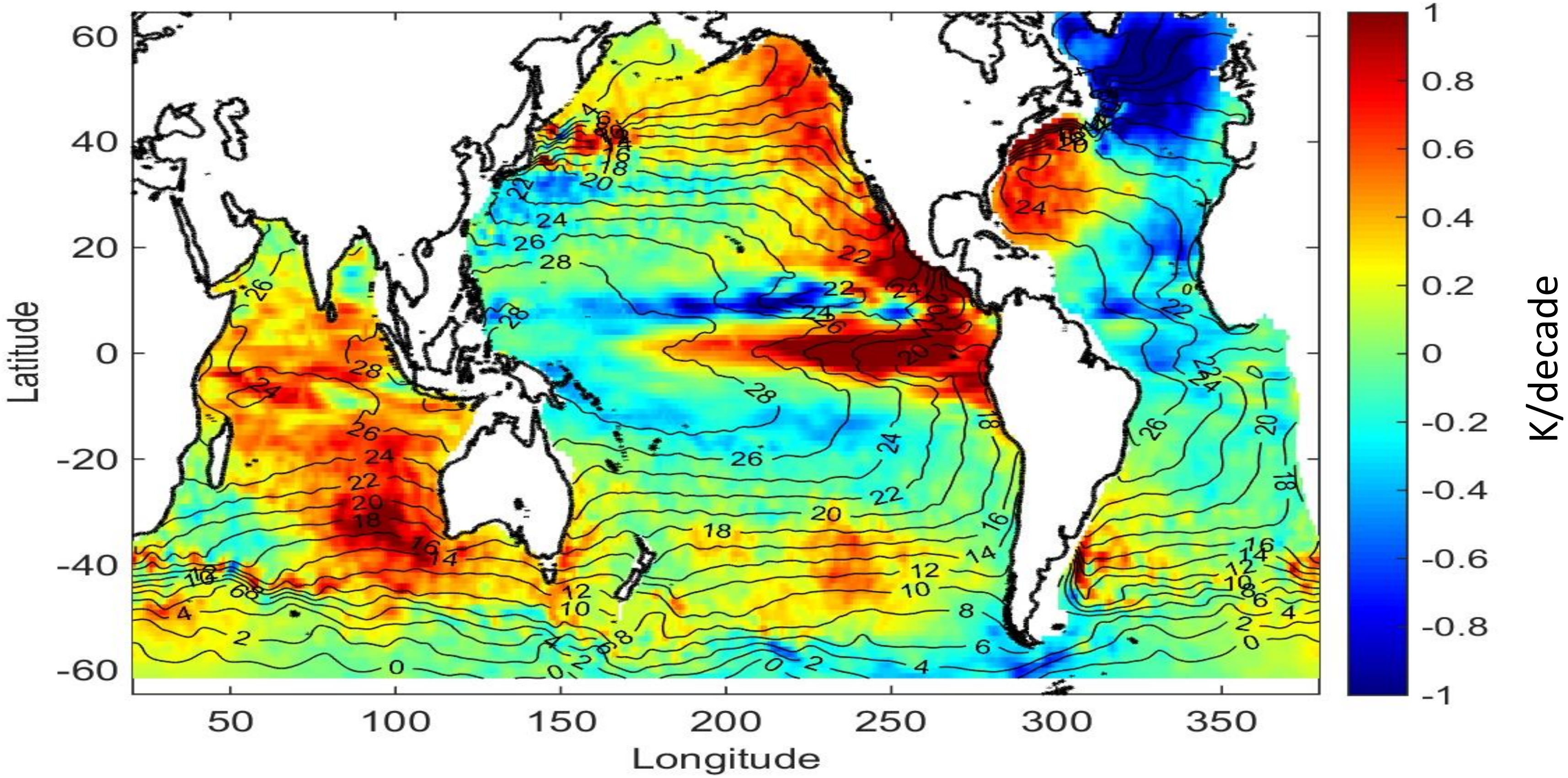
SSH-170cm plotted every 14 days



Qiu and Chen (1995)

Observed changes in ocean heat content from Argo floats (2004-2015)

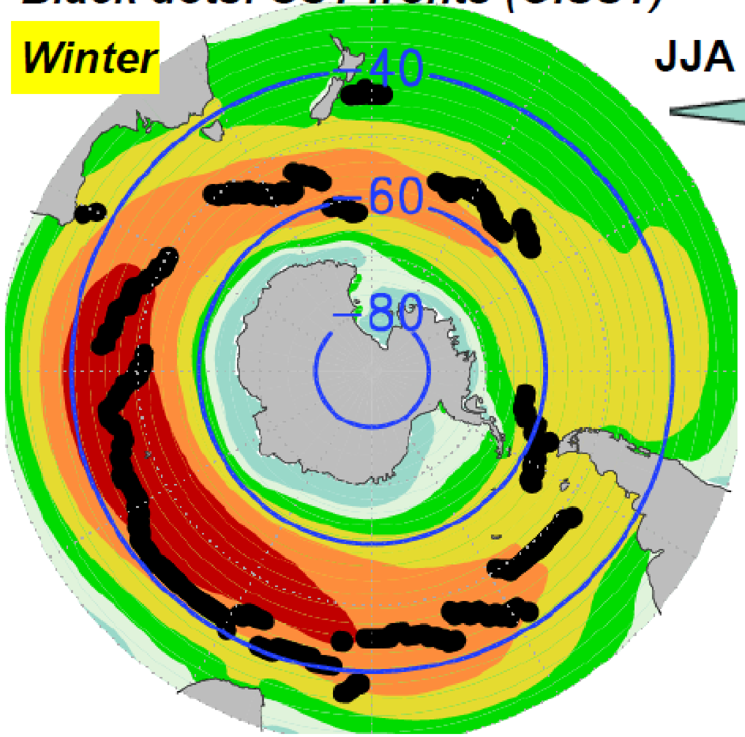
Upper ocean (0-100m) heat content trend



Global average ~0.5 W/m² driving sea level rise ~1mm/yr…
but also changes in global weather patterns?

Coupling of storm-track & SST fronts (Nakamura & Shimpo, 2004; Nakamura et al., 2008)

Black dots: SST fronts (OISST)



JJA climatology of 925hpPa westerlies (U925)

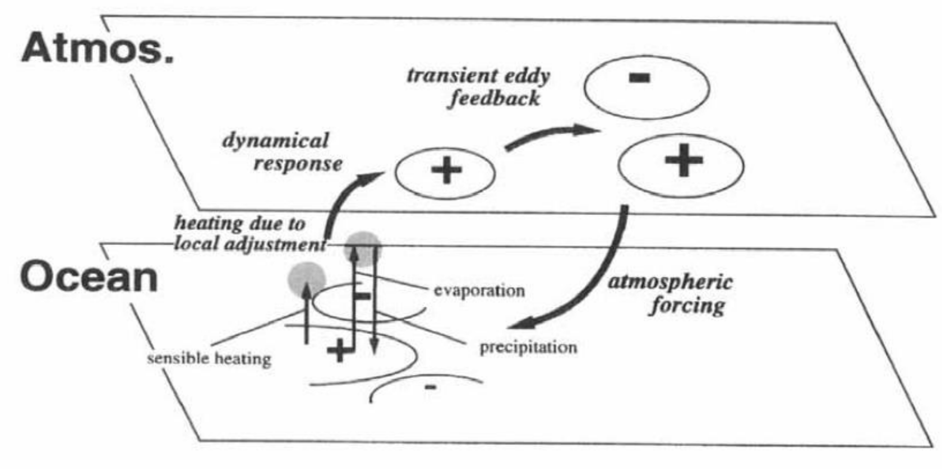
ERA-Interim (1979-2011)

- ***Overall latitudinal correspondence*** *between SST fronts and U925 axis*
- ***SST front*** can efficiently maintain a surface baroclinic zone against eddy heat transport, which is necessary for recurrent cyclone development and thereby the formation of a stormtrack and eddy-driven polar front jet (**PFJ**).

- Feedback loop between ACC - SST fronts – surface winds

Robustness of the response of AGCMs to extra-tropical SST anomalies

- ***Cold path (SSTA →cold sector)***: shallow thermal forcing, no direct impact on upper level vorticity, strong dependence on mean state (and hence on AGCMs)



Watanabe & Kimoto (2000)

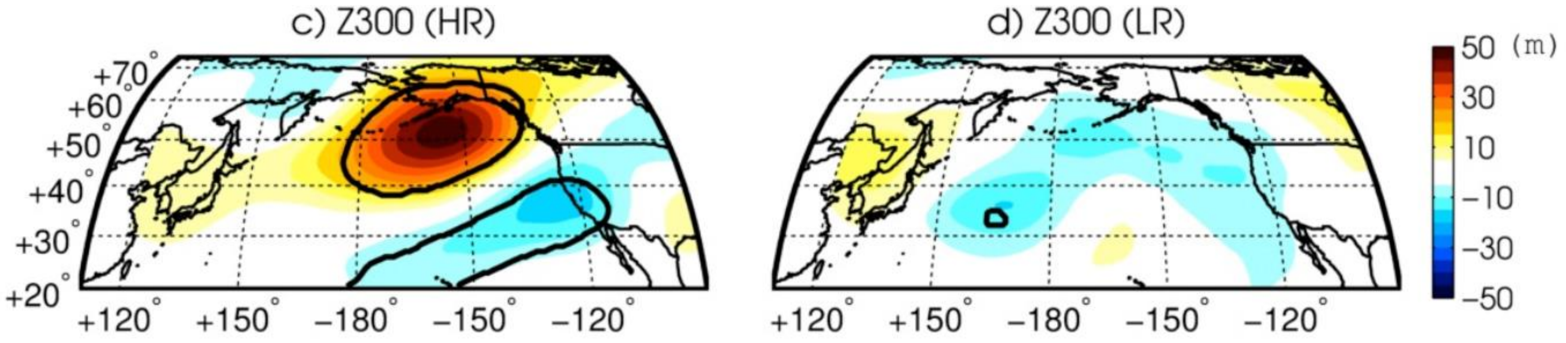
PV equation: F = vorticity forcing   Q = thermal forcing

$$\bar{u}\partial_x[\nabla_H^2\psi' + f^2/N^2\partial_{zz}^2\psi'] + v'[\beta + f\partial_z(\bar{\theta}_y/\bar{\theta}_z)] = F + f\partial_z(Q/\bar{\theta}_z)$$

Robustness of the response of AGCMs to extra-tropical SST anomalies

- ***Warm path (SSTA → warm sector):*** deep vorticity and thermal forcing, direct impact on upper level vorticity, robust response

Upper level response to a warm SST anomaly centred on the Oyashio front



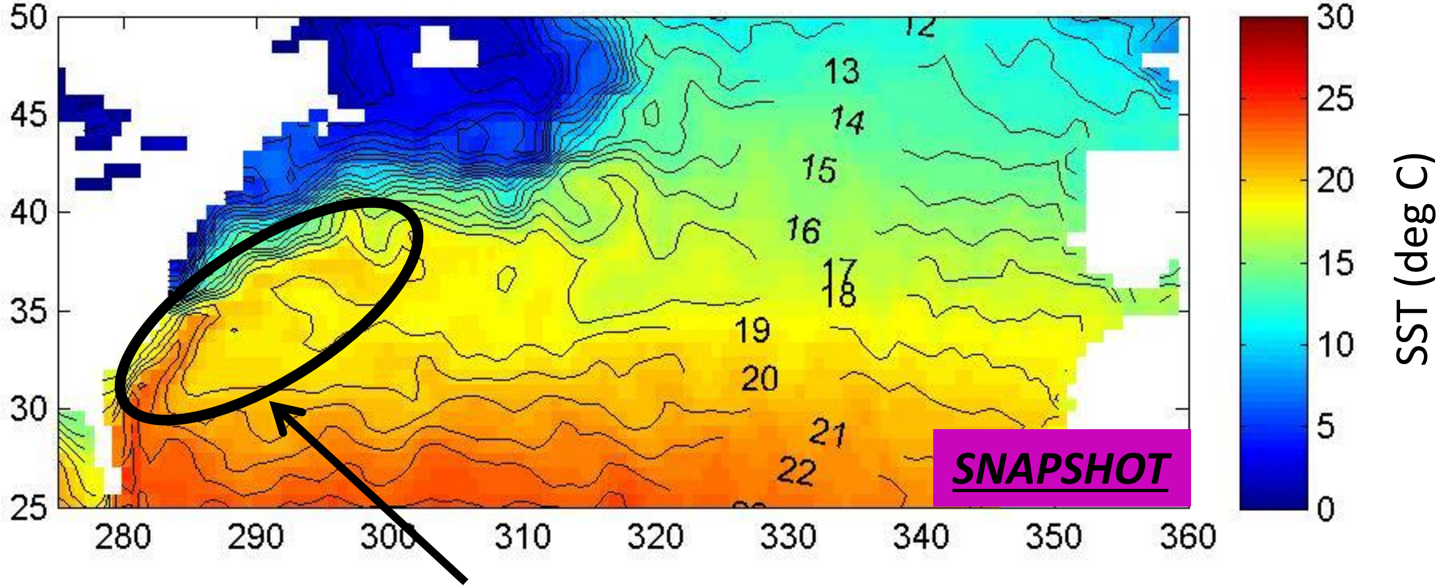
HR=0.25deg AGCM

LR=1deg AGCM

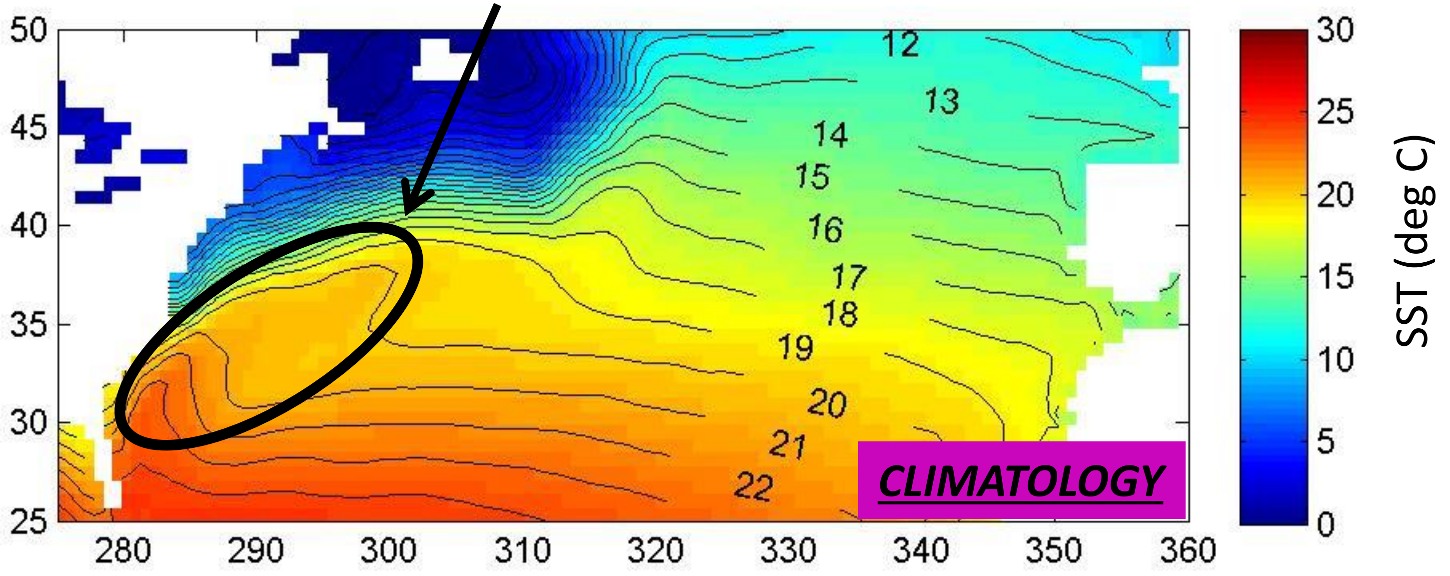
Smirnov et al. (2015)

PV equation: F = vorticity forcing   Q = thermal forcing

$$\bar{u}\partial_x[\nabla_H^2\psi' + f^2/N^2\partial_{zz}^2\psi'] + v'[\beta + f\partial_z(\bar{\theta}_y/\bar{\theta}_z)] = F + f\partial_z(Q/\bar{\theta}_z)$$



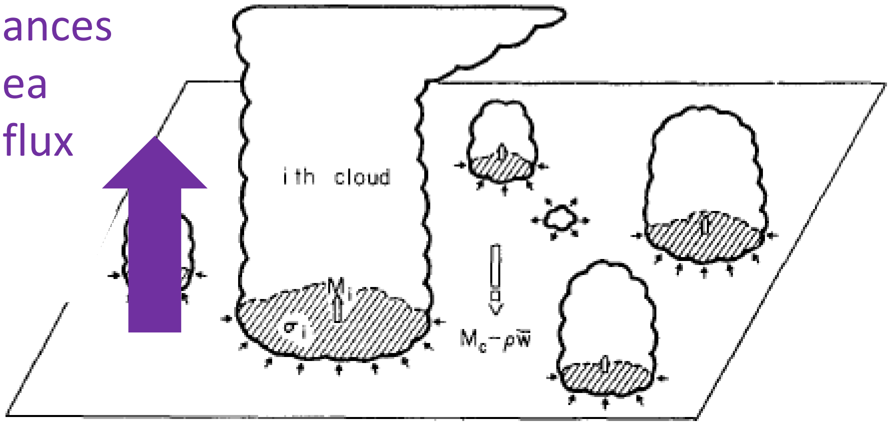
Gulf Stream “warm tongue”



NB: ERA-interim data (DJF 1979-2012)

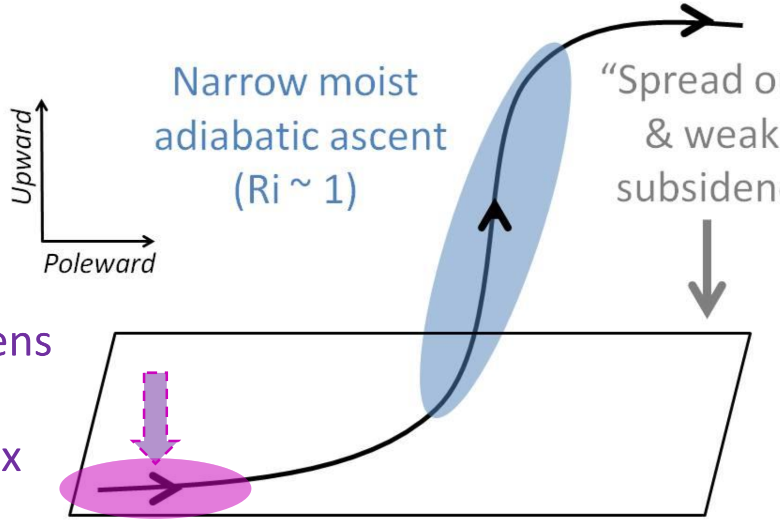
Working hypothesis: two different physics

- ***“Cold path” (=GS→cold sector)***: large turbulent surface heat fluxes generate CAPE & shallow convection; “dry physics”.



GS enhances air-sea heat flux

- ***“Warm path”(=GS→warm sector)***: Weak air-sea heat fluxes; deep, slanted and moist adiabatic ascent.



Narrow moist adiabatic ascent (Ri ~ 1)

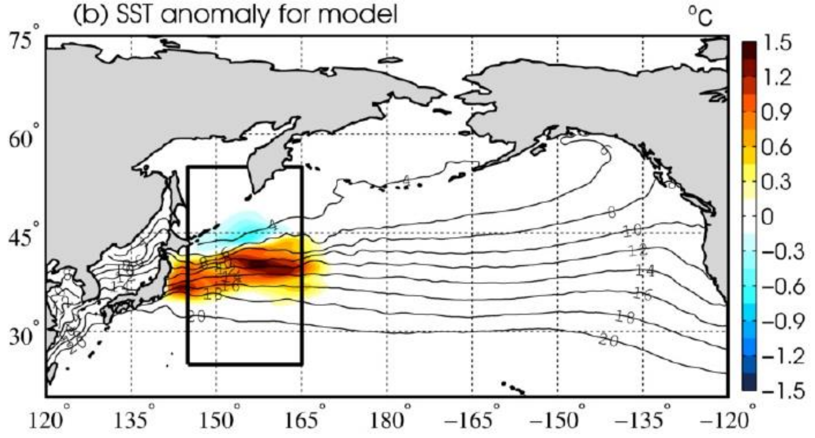
“Spread out” & weak subsidence

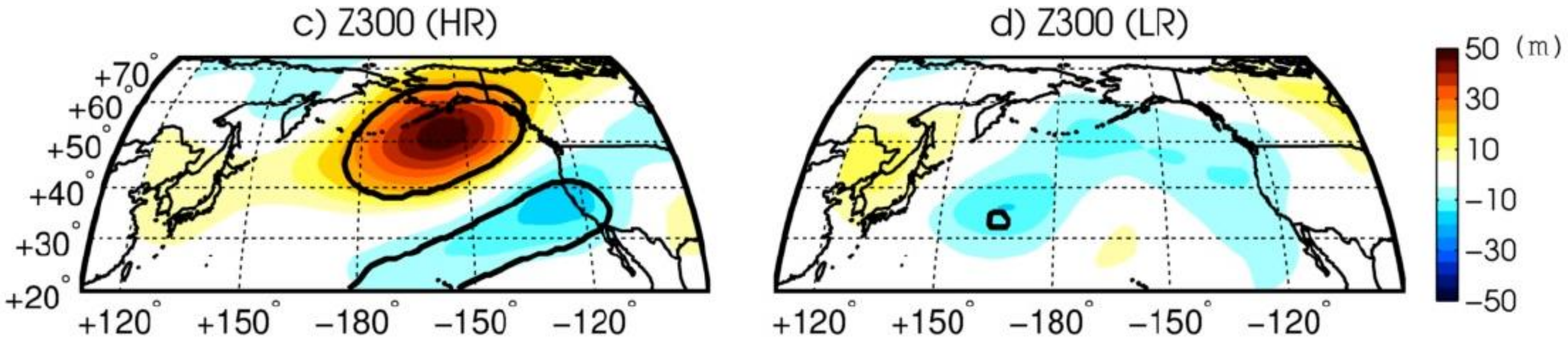
GS weakens air-sea heat flux

Nearly thermally adjusted air & water

Impact of resolution for the atmospheric response to extra-tropical SST anomalies

- CAM5, 30L, 0.25 deg (="high res") vs 1deg (="low res") forced by the same SST anomaly
- 25 members, NDJFM season
- Robust remote response at 300hPa in high-res but not in low-res





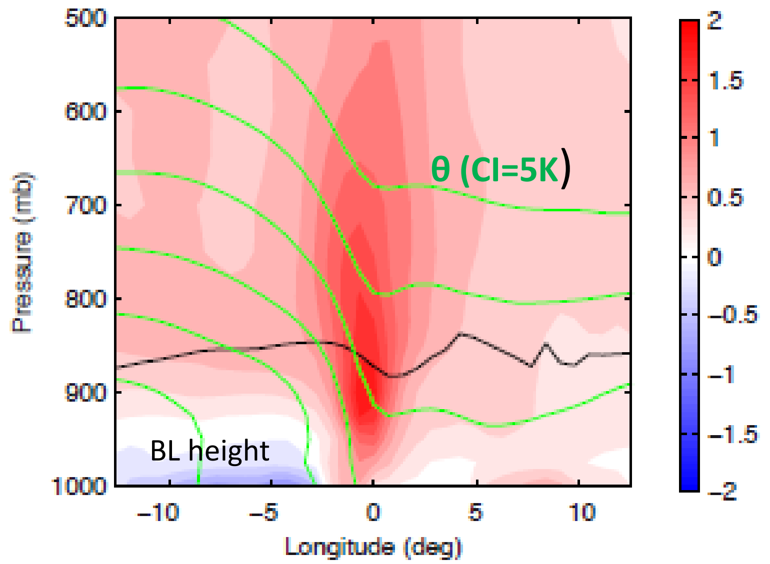
Smirnov et al. (2015)

A “cold sector mask” based on low level potential vorticity (PV)

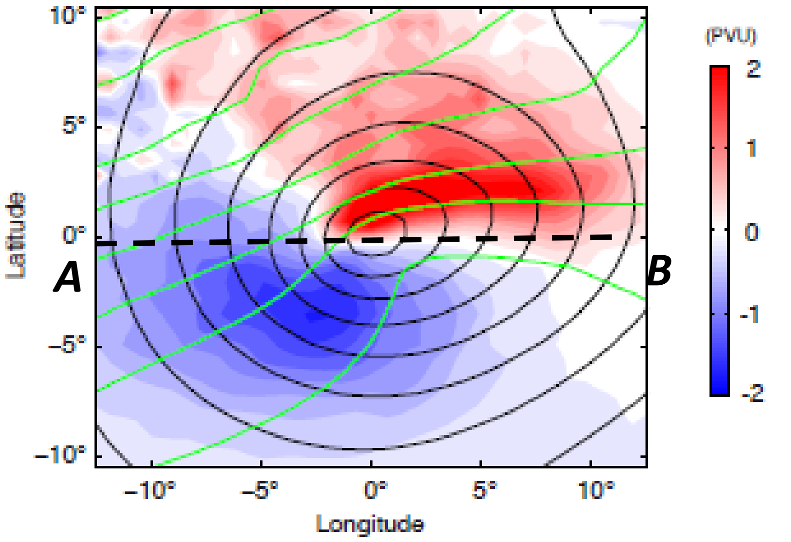
- ERAinterim data (DJF, 1979-2012)
- The cold sector of extra-tropical cyclones is well singled out by the presence of PV<0 below 900hPa
- This mask can be used to isolate the contribution of cold sectors to the climatology

Vanniere et al. QJRMS, 2015

PV section across A-B

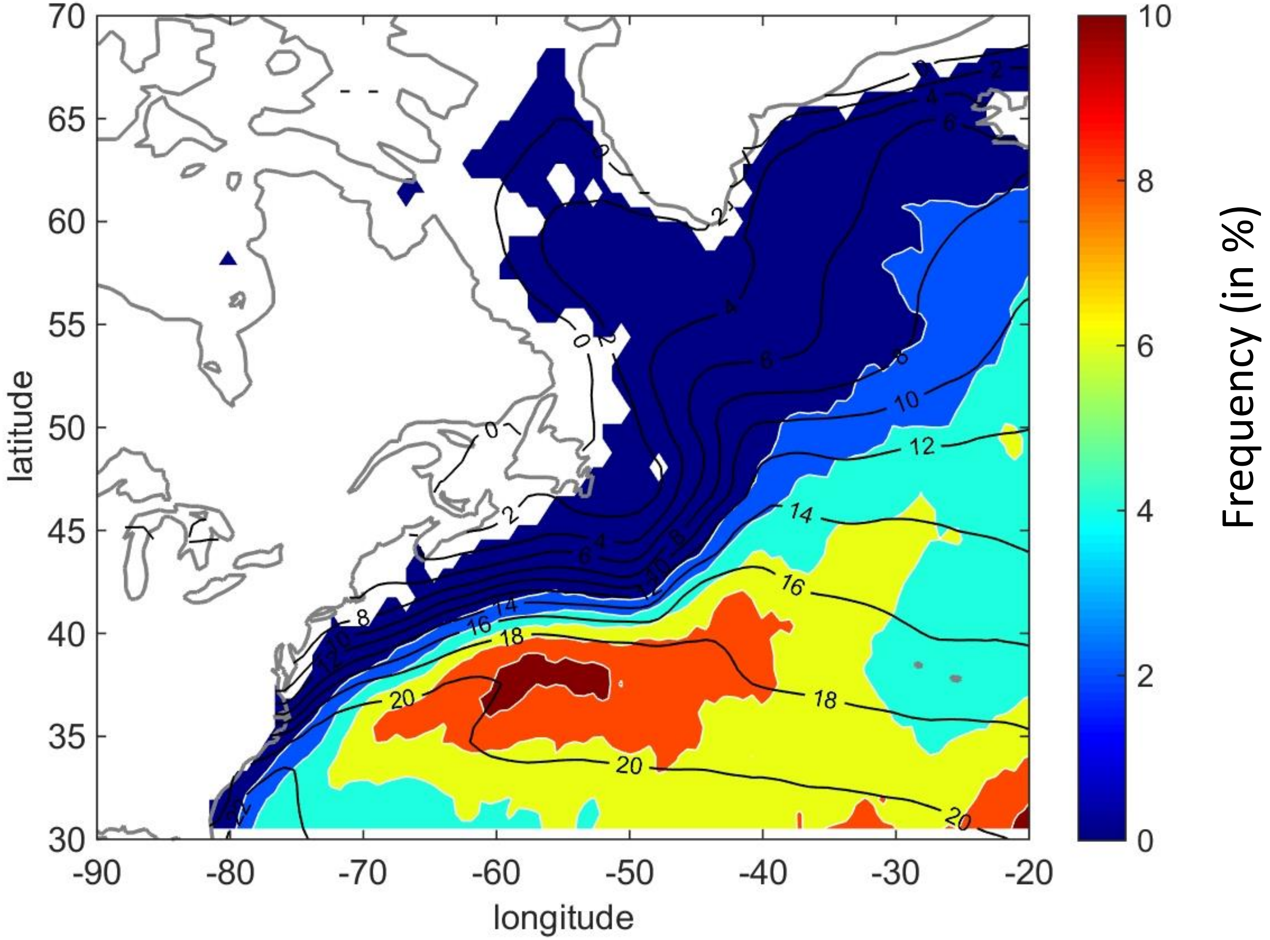


Composite PV at the surface



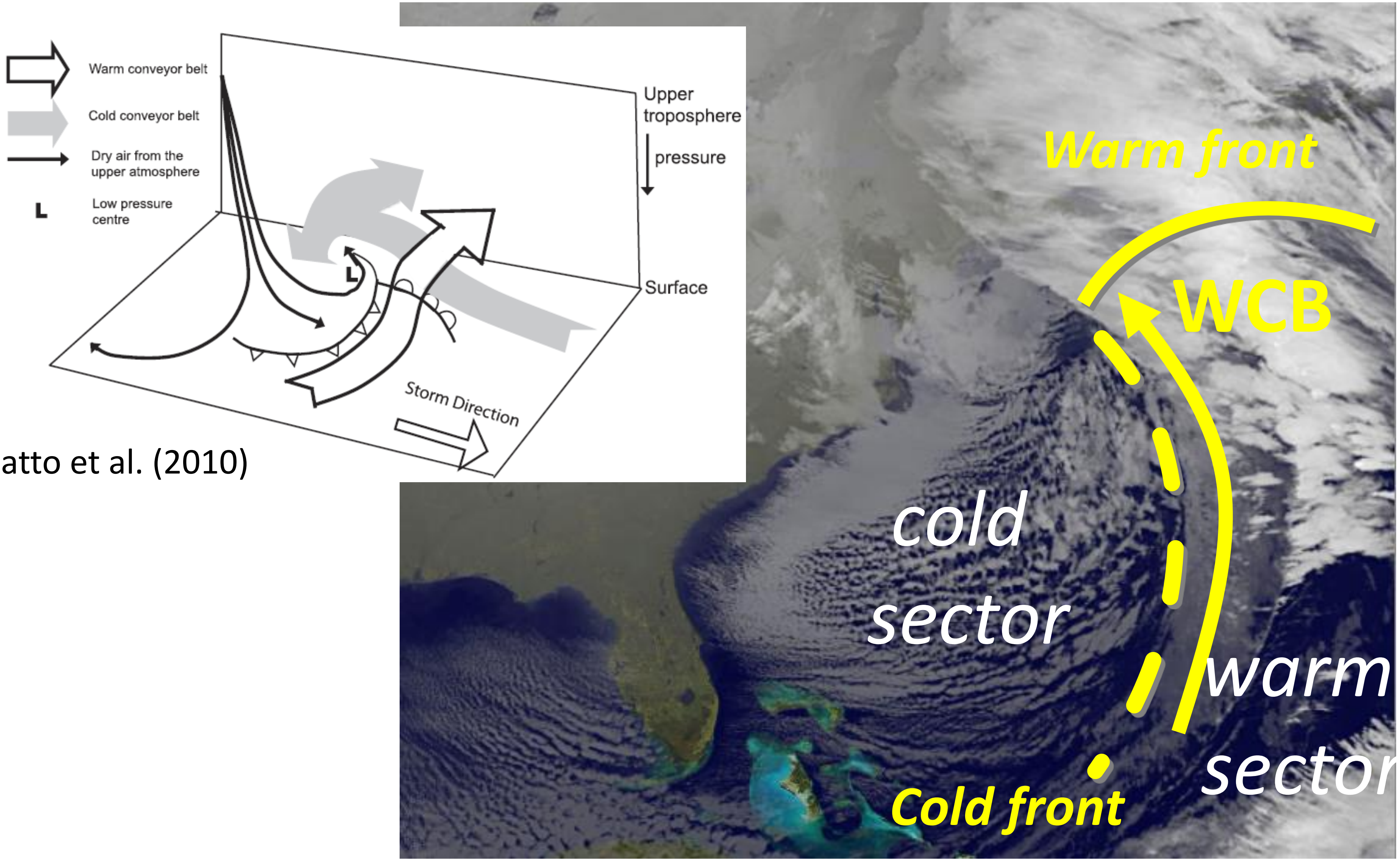
Semi-geostrophic analysis of ERA-interim data

- Follow semi-geostrophic framework of Shutts (1990) to define filaments originating from a given low level location
- Measure the θe difference from low level to the tropopause to estimate the buoyancy contrast across the filament
- Map shows enhanced frequency of occurrence of Δθe < 0 along the Gulf Stream warm tongue


Fraction of wintertime days with Δθe<0

NB low level condition assumed is actual state at 950hPa

Warm and cold sectors

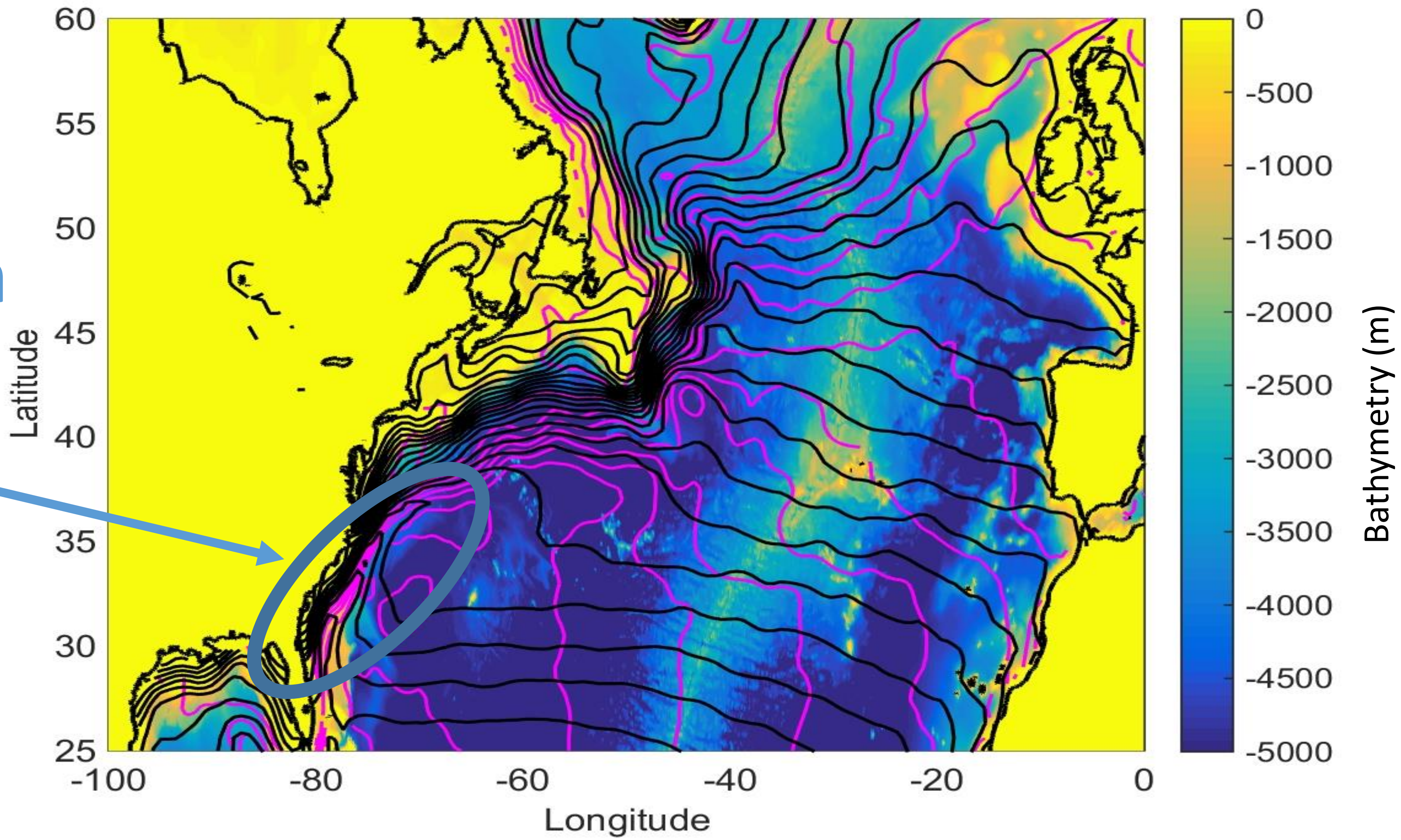


Catto et al. (2010)

Infrared image (GOES satellite, 13 December 2010)

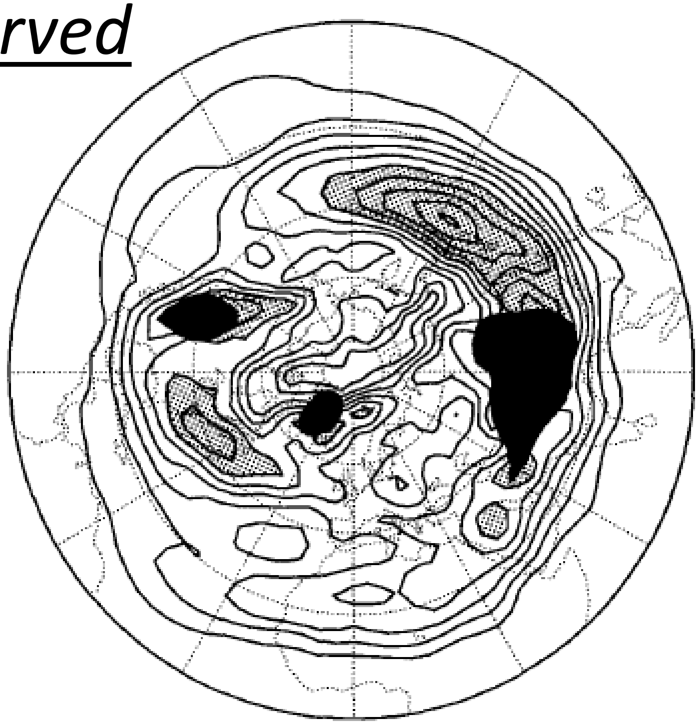
Sea surface ***temperature*** (DJF/2002-2012, black, CI = 1K from ERAint)
& ***dyn. ocean topography*** (YR/1992-2002, magenta, CI = 10cm, Maximenko et al, 2009)

The Gulf Stream
“warm tongue”



Coupling of storm tracks and western boundary currents (Hoskins & Valdes, 1990)

Observed



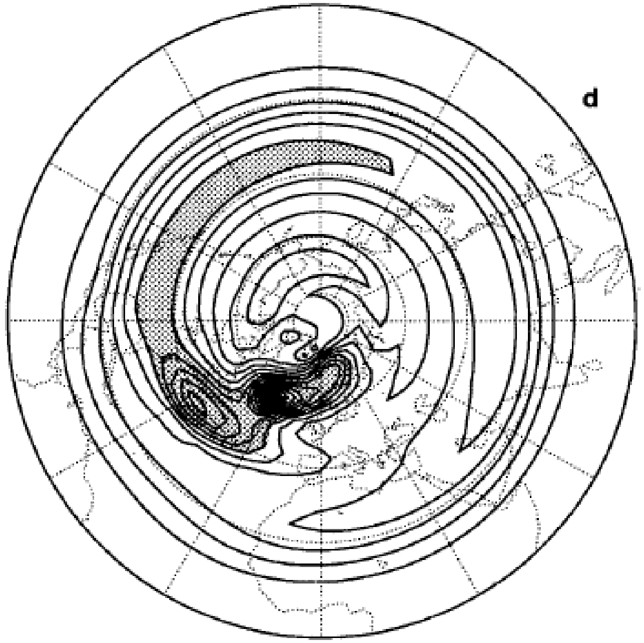
Eady growth rate at 780mb in winter

(CI = 0.1 day-1)

$$\sigma_{Eady} \propto f_o/\sqrt{R_i}$$

$$\text{with } R_i \equiv \frac{N^2}{|v_z|^2}$$

Response to North Atlantic diabatic heating

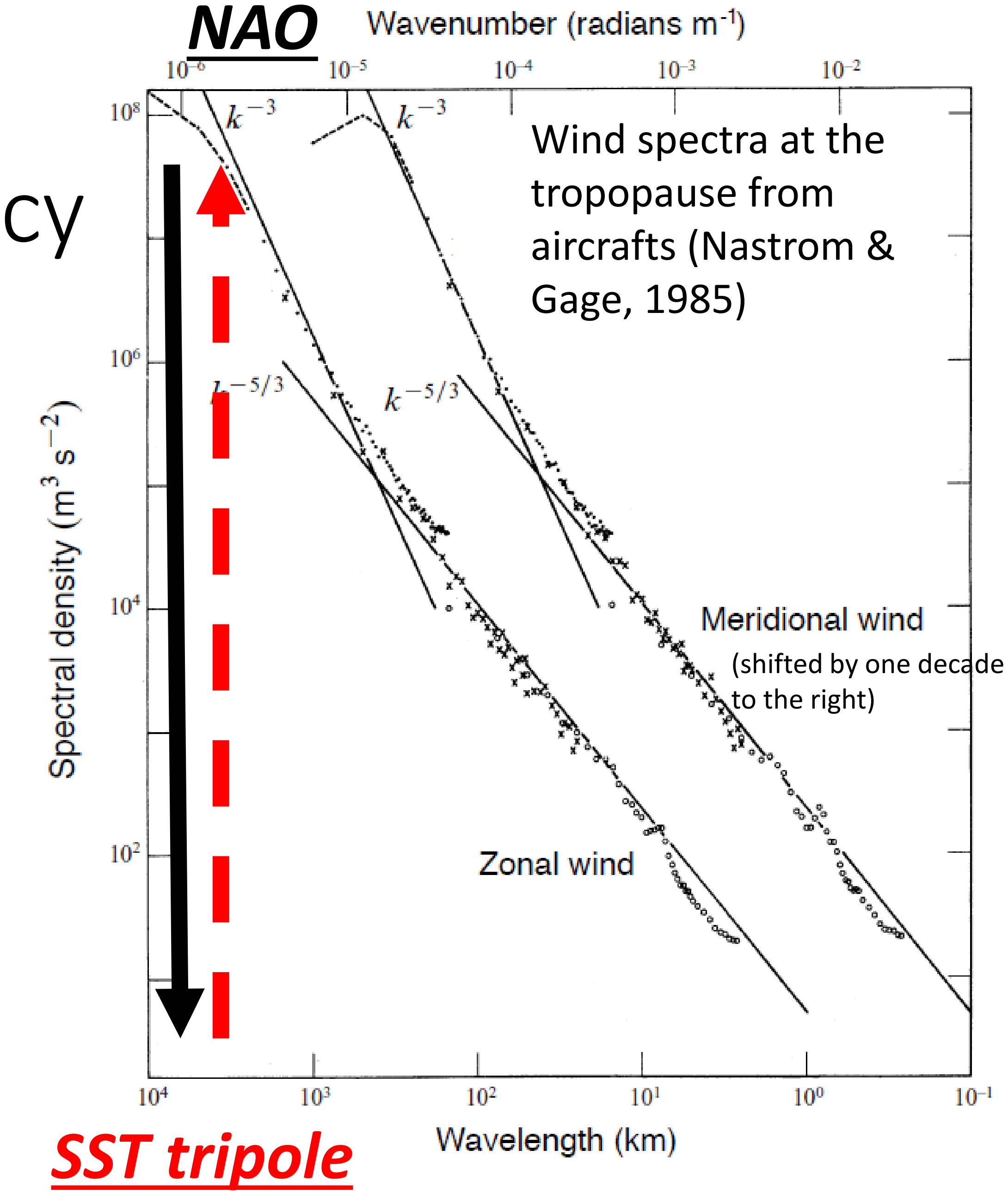


- Feedback loop between western boundary currents – SST – storm track

Key question: impact of North Atlantic SST on the low-frequency variability of the atmosphere

- Work up to the late 2000s has focused on the direct impact at low wavenumber, where the inverse cascade of energy in the atmosphere has been established (e.g., Boer and Sheperd, 1983)

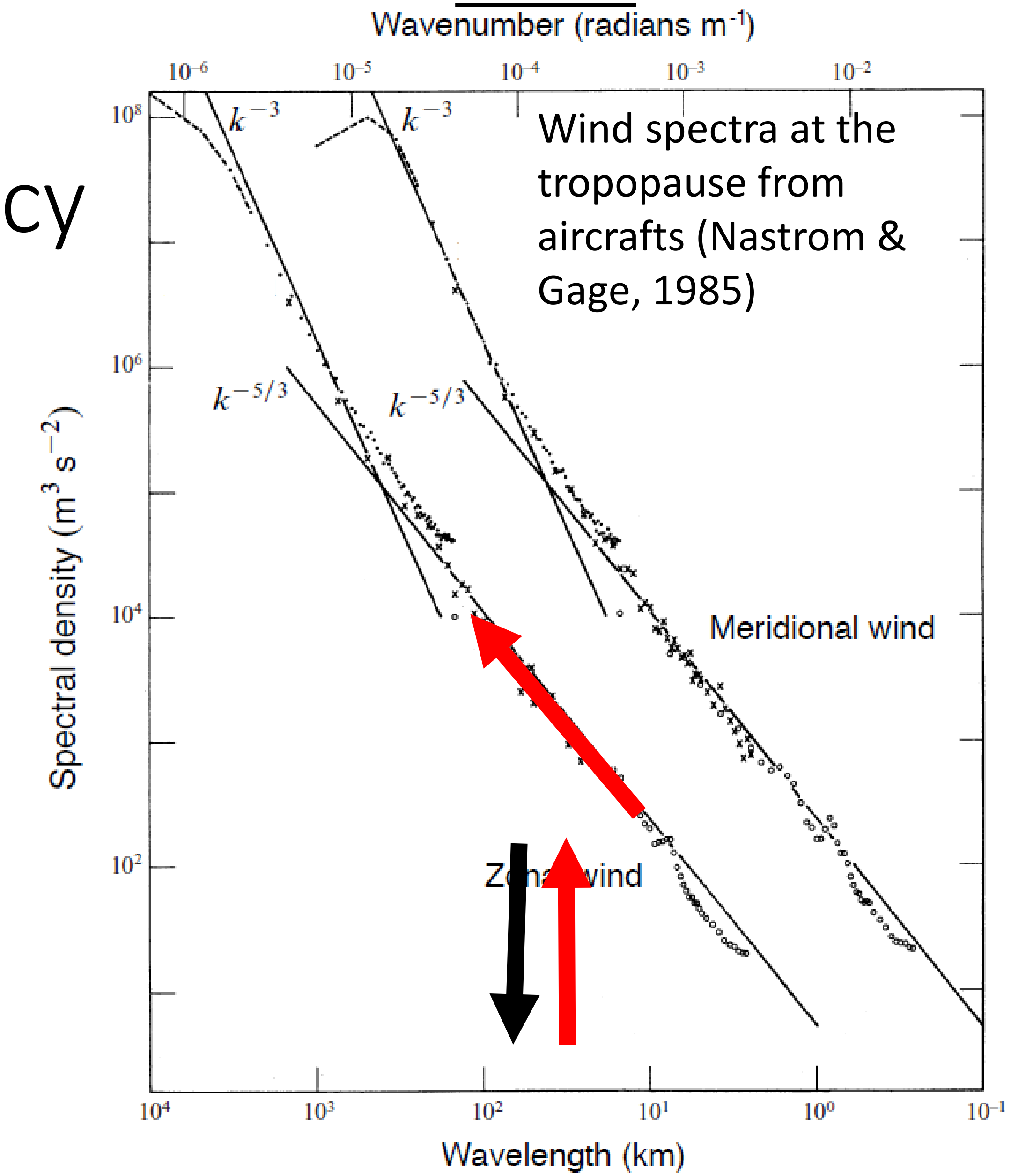
- Interaction is primarily A→O


Wind spectra at the tropopause from aircrafts (Nastrom & Gage, 1985)

Key question: impact of North Atlantic SST on the low-frequency variability of the atmosphere

- Modelling results suggest an impact of Gulf Stream SSTs on the frontal circulation of cyclones and the cyclones themselves (k-5/3 range)
- Interaction is certainly O→A & likely to be A→0 as well

Fronts

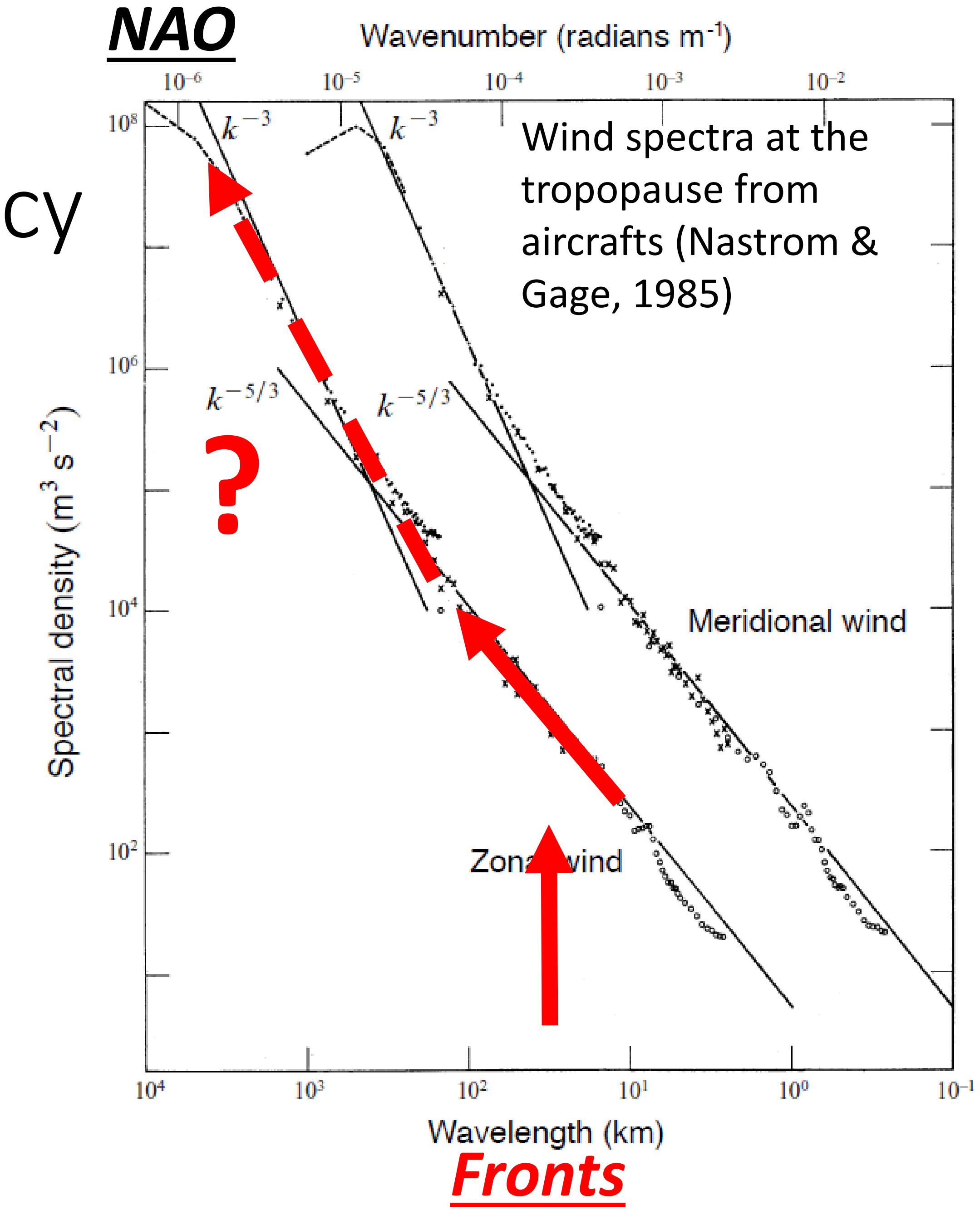


Wind spectra at the tropopause from aircrafts (Nastrom & Gage, 1985)

Fronts

Key question: impact of North Atlantic SST on the low-frequency variability of the atmosphere

- How far is the impact of air-sea interactions in the k-5/3 range extend to large scale?



Wind spectra at the tropopause from aircrafts (Nastrom & Gage, 1985)