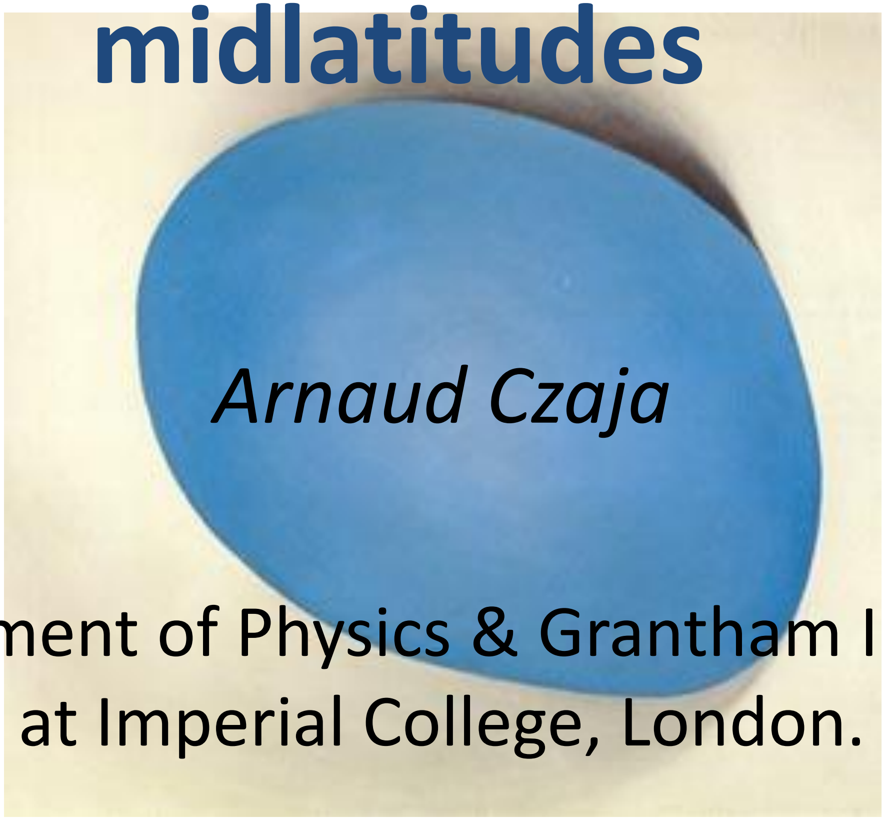
Ocean-Atmosphere coupling in midlatitudes



Arnaud Czaja

Department of Physics & Grantham Institute
at Imperial College, London.

Thanks to the students of the Physics Department, Brian Hoskins & Raymond Hide for inspiring discussions on this topic!

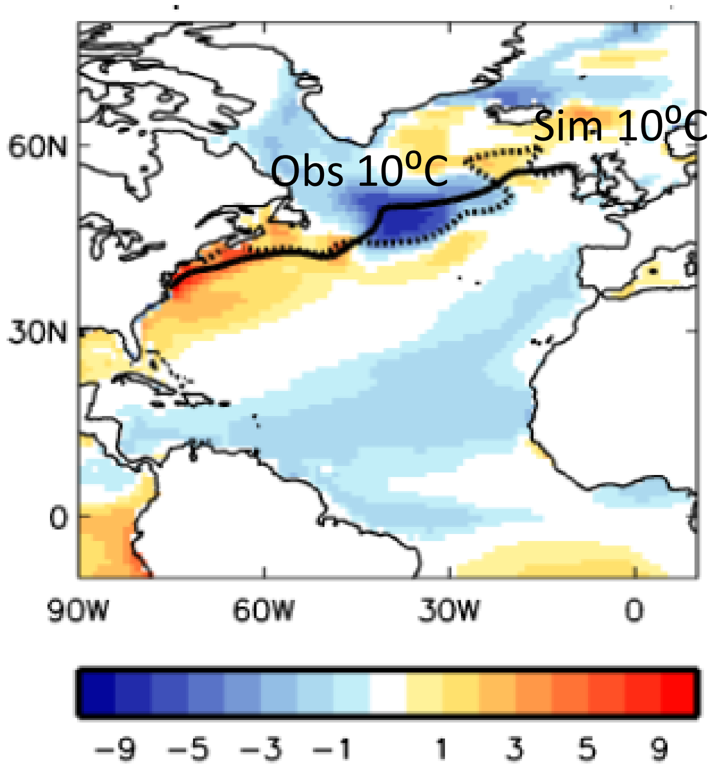
Outline

- Motivation: some recent model results
- Key physics: does ocean – atmosphere coupling invigorate or damp the storm track?
- “Frontal” ocean-atmosphere coupling

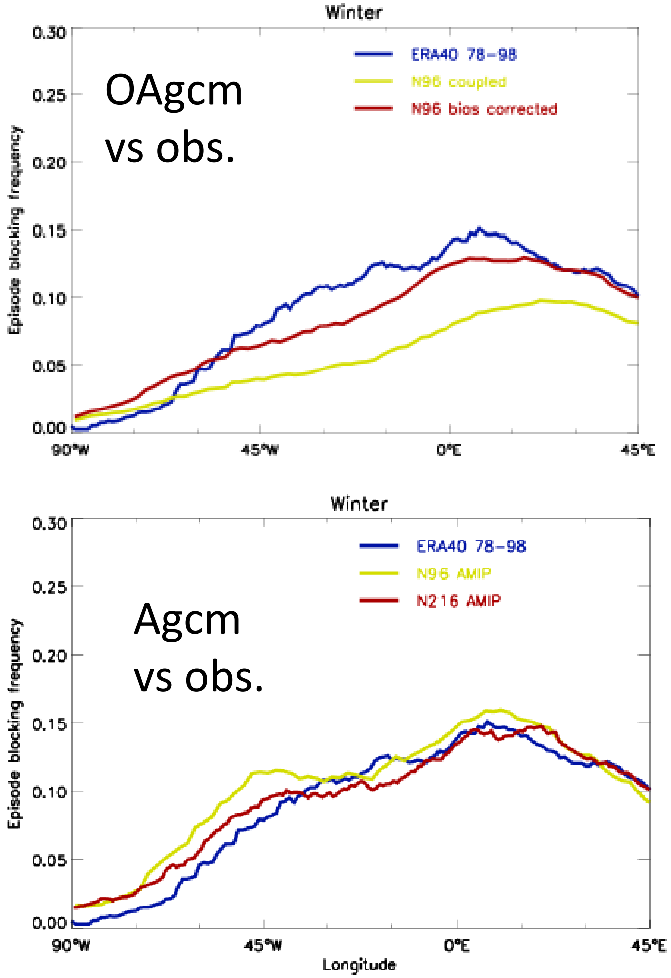
Part 1 –Recent (exciting) model results...

Improved blocking frequency as a result of better Atlantic SST simulation

SST bias in HadGEM3 (N96)

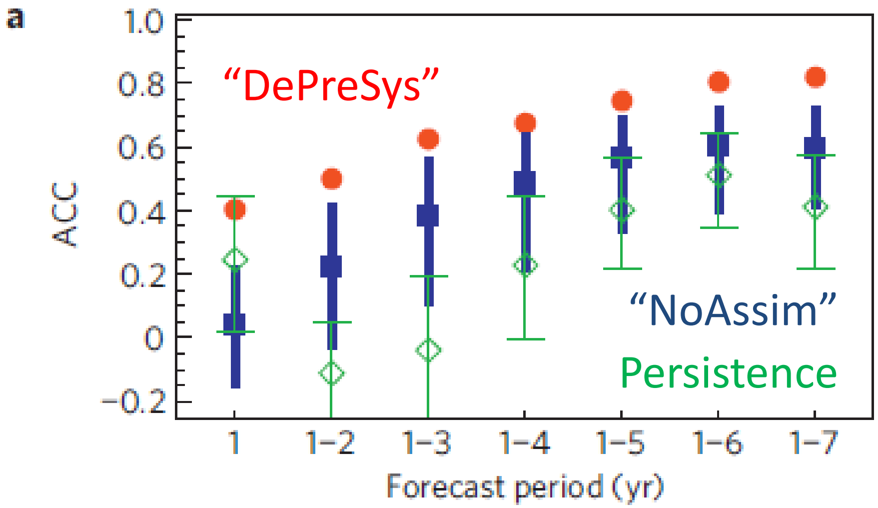


European blocking index

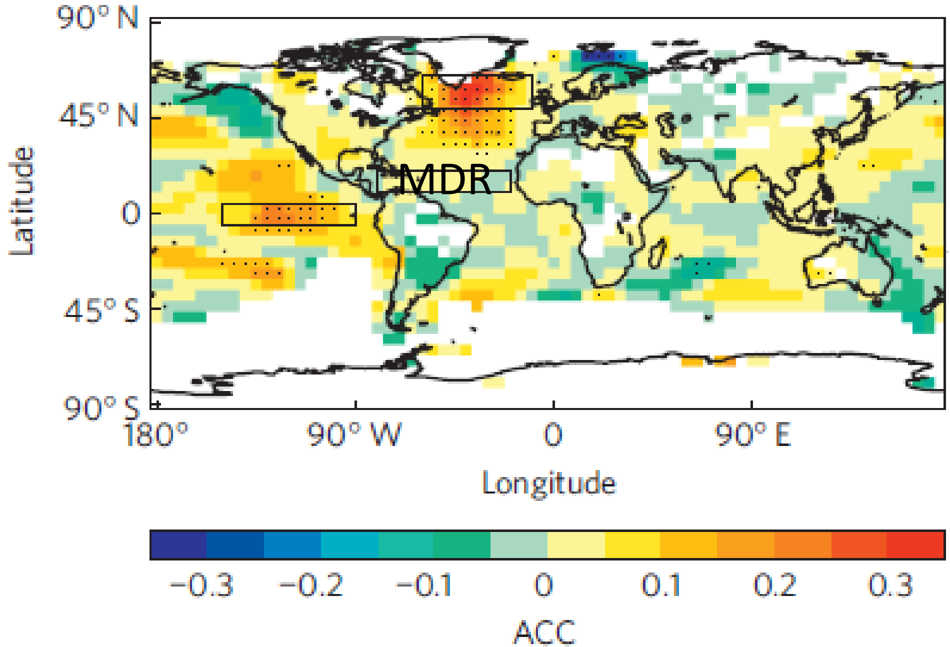


Scaife et al. (2010)

Some surprising predictive skill on decadal timescales



Skill of multi-yr prediction of Tropical Atlantic storm frequency

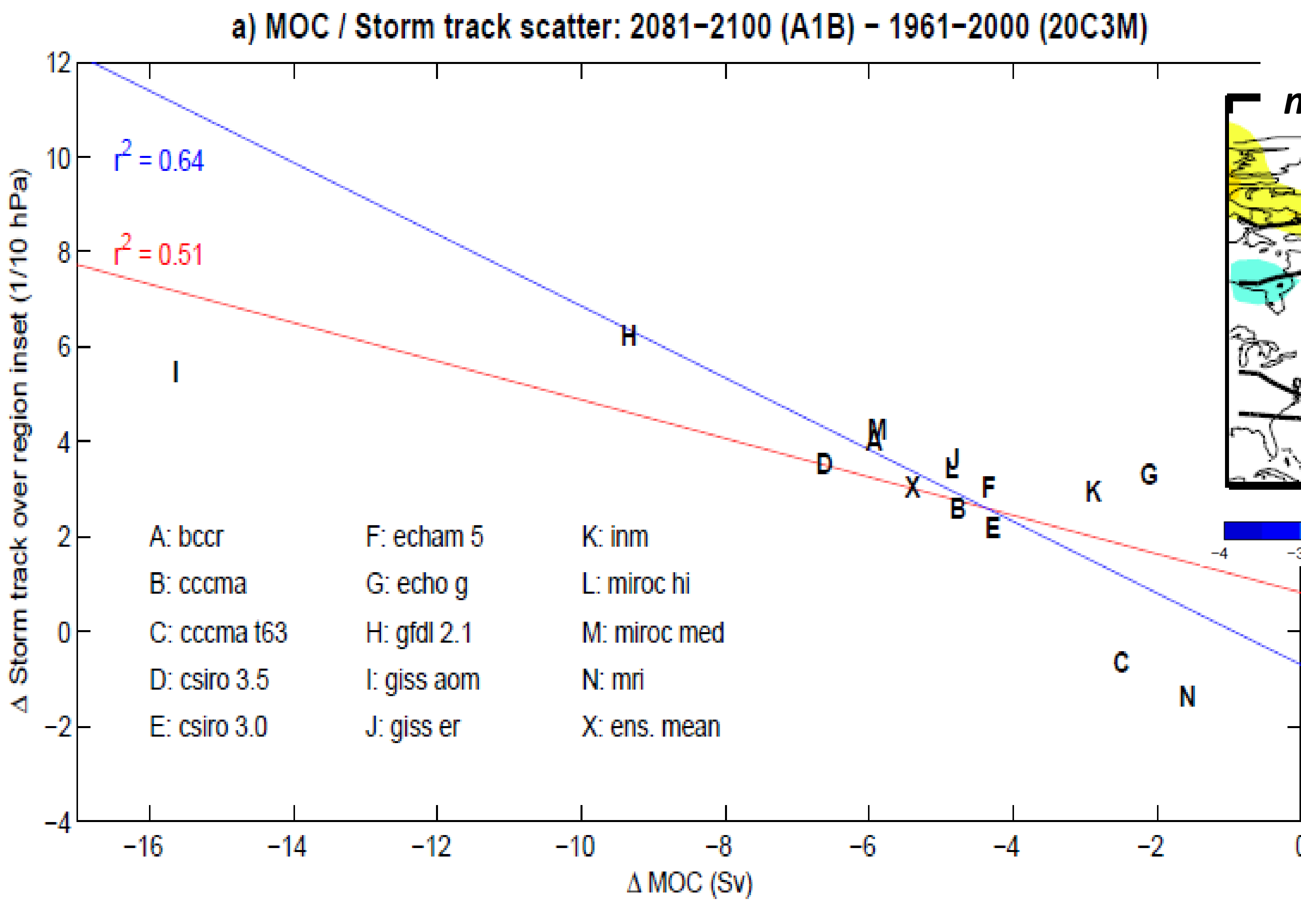


Change in cor(Ts-obs,Ts-pred) when using observed dynamical as opposed to random initialization

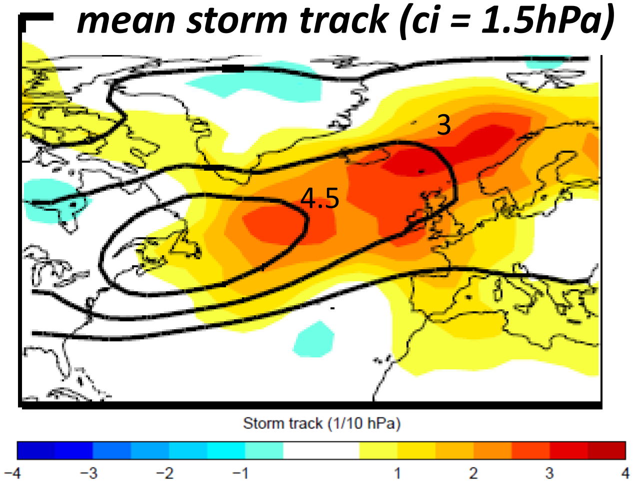
Smith et al. (2010)

--see also Dunstone et al. (2011)

Impact of ocean circulation on storm-tracks: IPCC AR4 model results



Storm track regressed on MOC reduction (color) & mean storm track (ci = 1.5hPa)



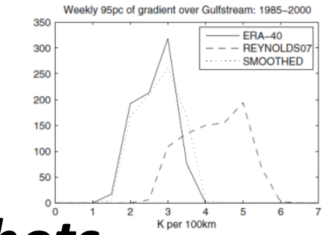
- Spread in Atlantic storm-track is caused in part by spread in MOC changes

Woollings et a. (2011)

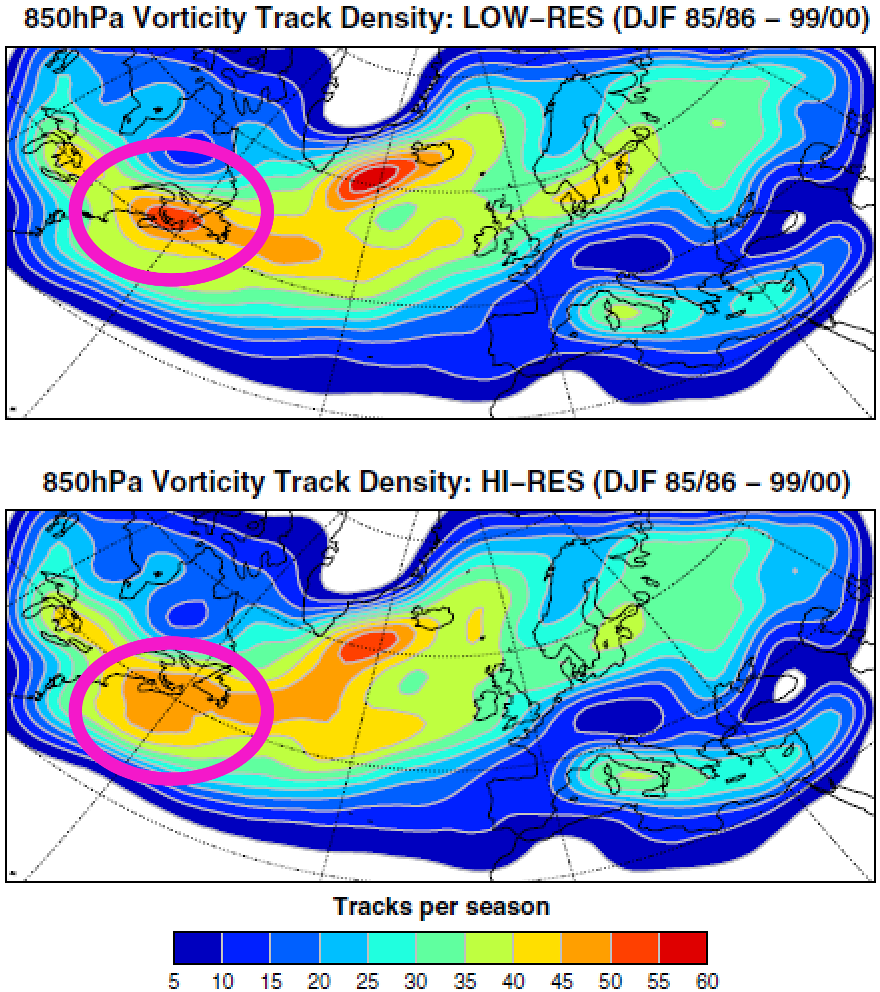
- The previous results do not rely on high resolution AOGCMs.

- As longer (multi-decadal) simulations and ensemble of simulations (even multi-model ensemble) become available, the impact of the ocean circulation on the atmosphere becomes more apparent in midlatitudes.

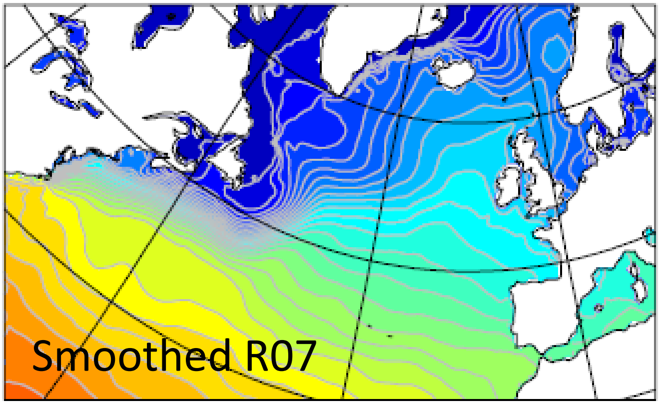
Improved representation of storm tracks as Δx(SST) increases

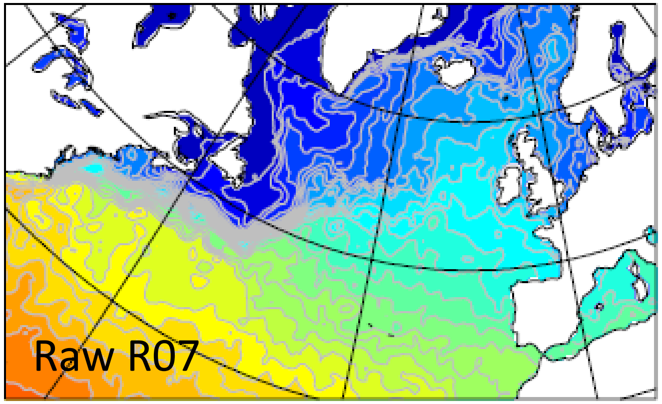


AGCM (50km, L19) forced at boundaries



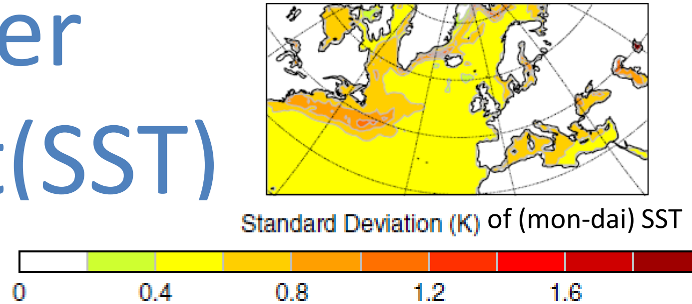
SST snapshots





Woollings et al. (2009)

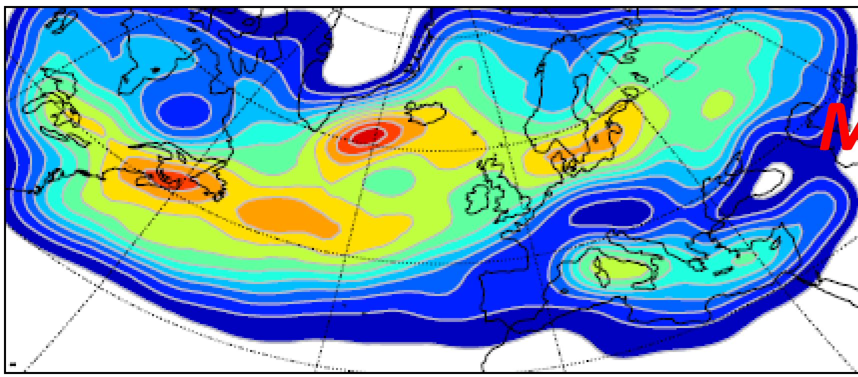
Downstream impact over Europe when increasing Δt(SST)



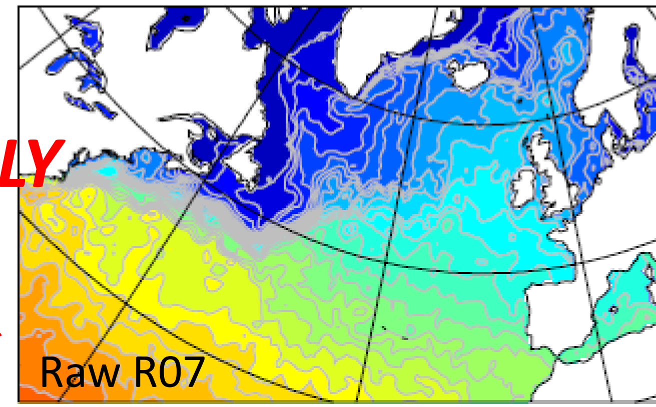
AGCM (50km, L19) forced at boundaries

SST snapshot

850hPa Vorticity Track Density: MONTHLY (DJF 85/86 – 99/00)

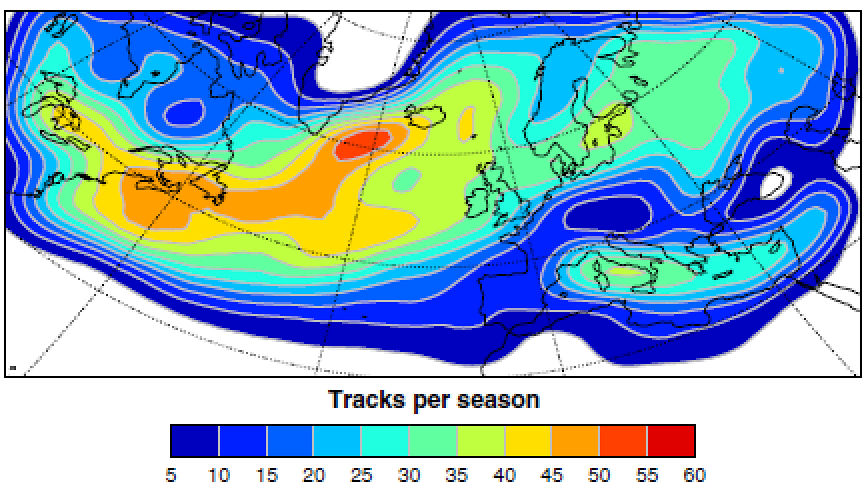


MONTHLY

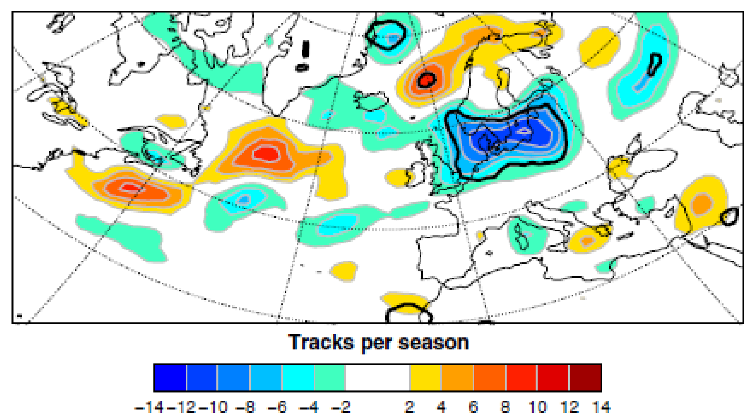


DAILY

850hPa Vorticity Track Density: DAILY (DJF 85/86 – 99/00)



DAILY – MONTHLY



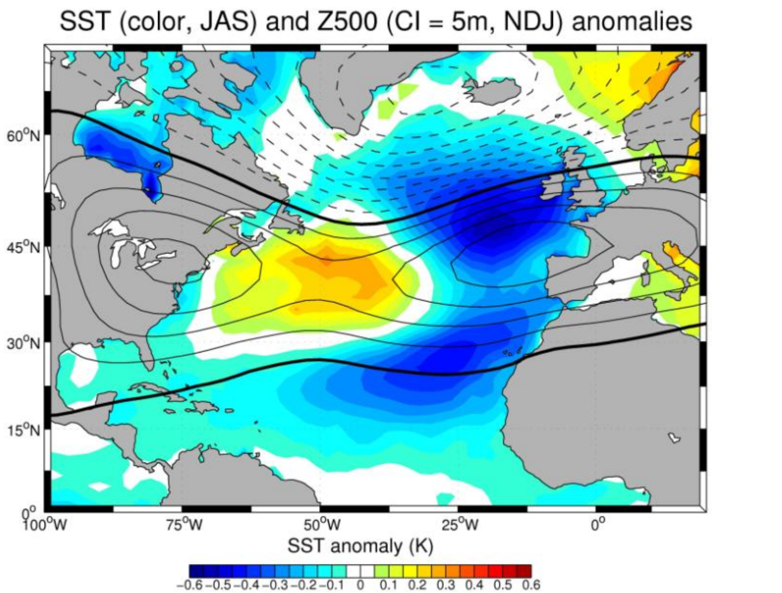
Woollings et al. (2009)

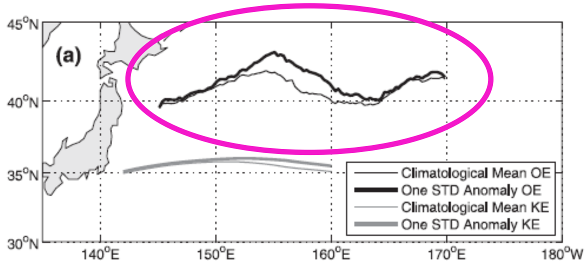
Oceanic impact on the atmosphere in reanalysis datasets

- In the North Atlantic

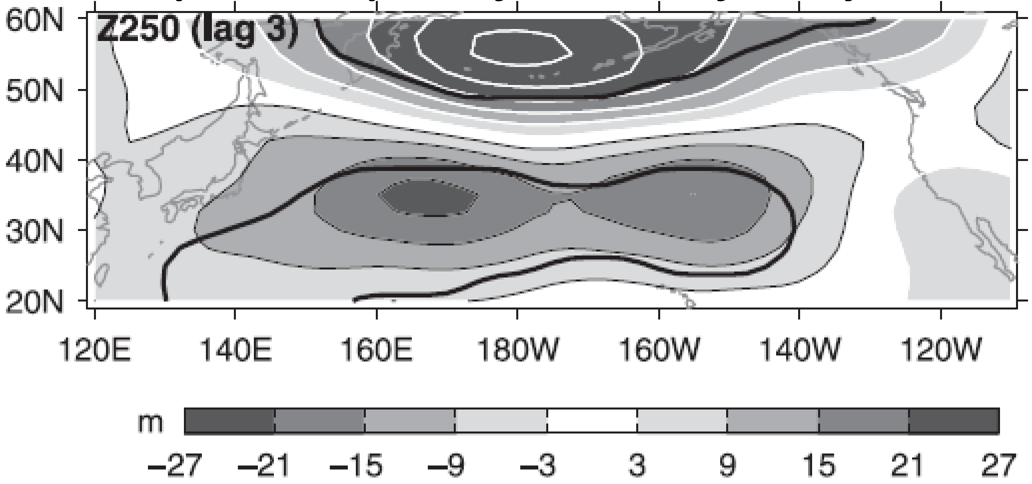
- ...and the North Pacific

Czaja & Frankignoul (2002)





Atmospheric response for a 1σ shift in Oyashio index



Frankignoul et al. (2011)

Part 2 --Key physics: does ocean-atmosphere coupling strengthen or damp the storm track?

- Counter intuition is key in midlatitudes!
- Anchoring of the storm track
- Thermal damping of weather waves

NB: Ocean circulation or large scale seasonal SST anomaly

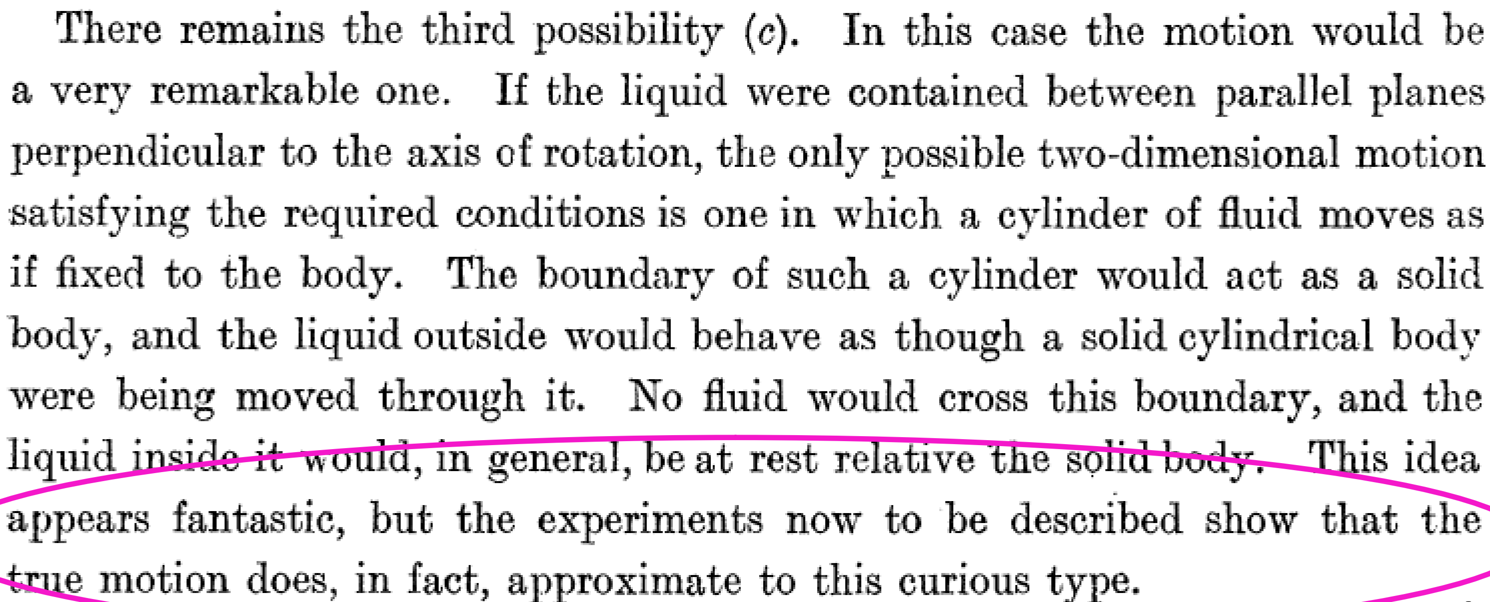
Counter intuition in midlatitudes…

- *“Something is interesting when you find that it does not agree with your intuition”*
  Prospective Imperial UG student.

- The extra-tropical oceans/atmosphere have their own “double slit experiment” (the strange effects of rotation)

Counter intuition in midlatitudes...

- ***Taylor columns***: a fast rotating fluid like the atmosphere can be efficiently steered from below.


There remains the third possibility (*c*). In this case the motion would be a very remarkable one. If the liquid were contained between parallel planes perpendicular to the axis of rotation, the only possible two-dimensional motion satisfying the required conditions is one in which a cylinder of fluid moves as if fixed to the body. The boundary of such a cylinder would act as a solid body, and the liquid outside would behave as though a solid cylindrical body were being moved through it. No fluid would cross this boundary, and the liquid inside it would, in general, be at rest relative the solid body. This idea appears fantastic, but the experiments now to be described show that the true motion does, in fact, approximate to this curious type.

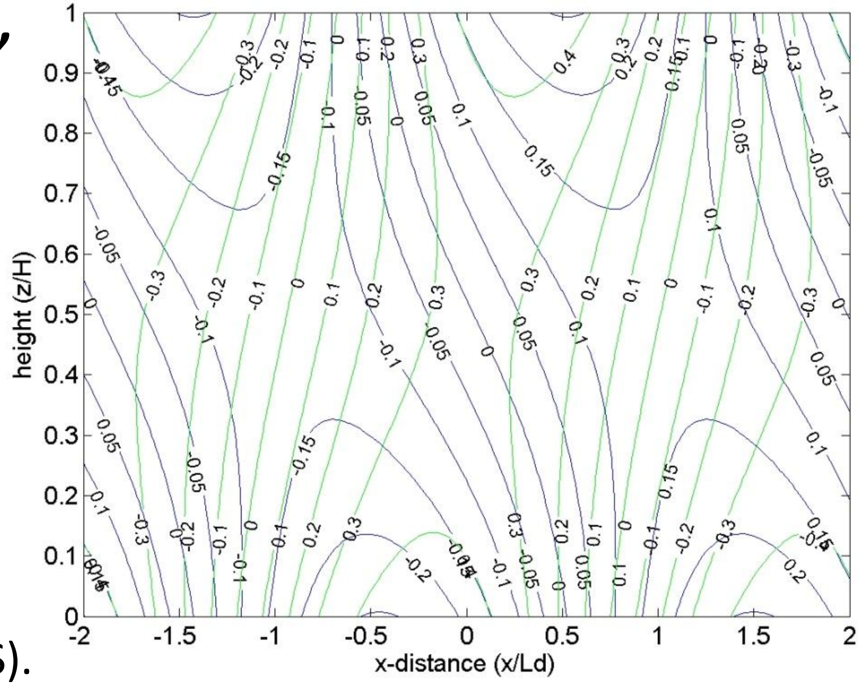
Taylor (1923)

Counter intuition in midlatitudes...

- *Steering from boundaries is not limited to Taylor columns but is at the heart of "weather waves"*

Perturbation pressure & temperature for the most unstable Eady mode

Tropopause



Earth's surface

$$\psi \equiv \tan^{-1}(v/u),$$

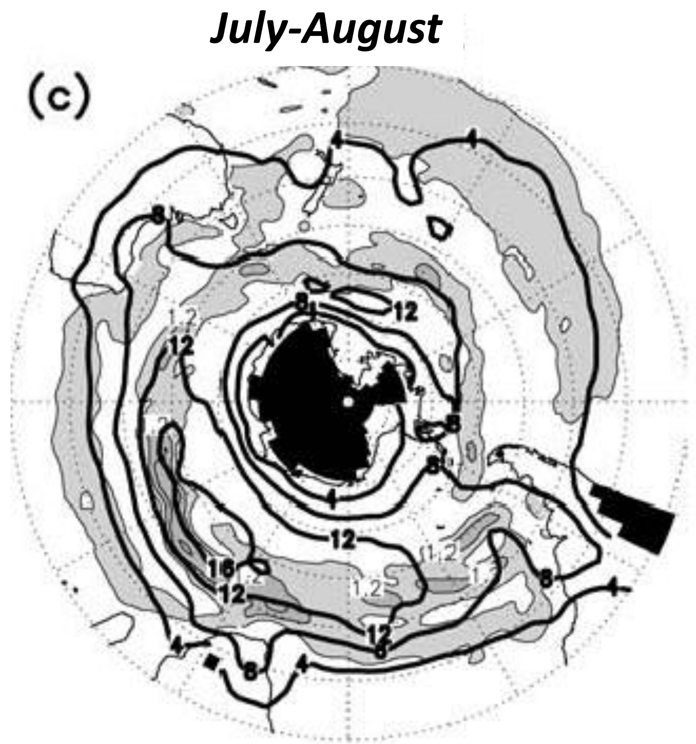
$$\sigma \equiv 1/S\,\overline{\partial\psi/\partial s}, \quad \approx 1$$

Distance along the direction of the axis of rotation (max value=S).

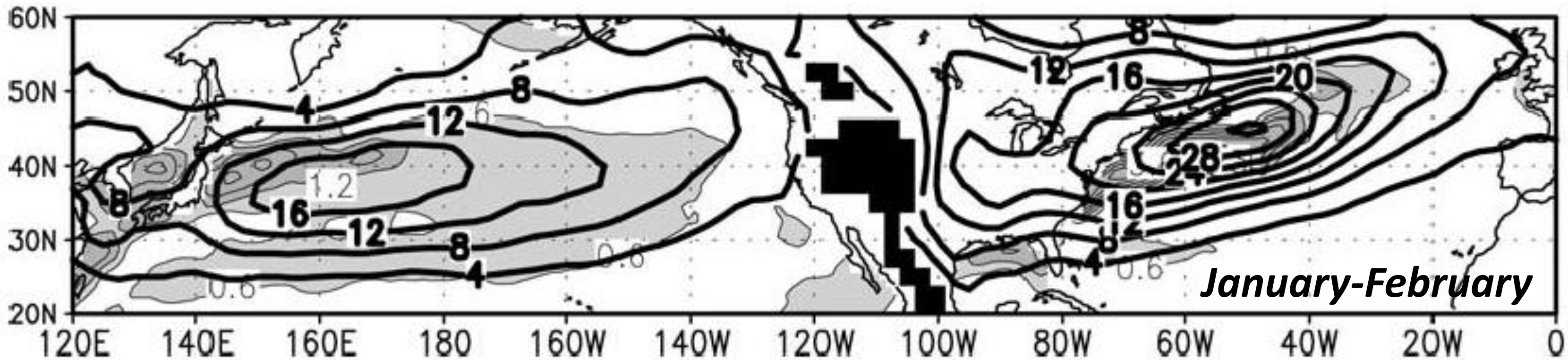
Hide (1971)

O/A coupling and the atmospheric storm track

- Acknowledging the intriguing role played by surface boundaries in midlatitudes, focus on the effect of the ocean on the atmospheric storm track



V'T' at 850mb *(in K m/s)* ***and dSST/dy*** *(in K/110km)*



NB: Based on NCEP reanalysis data.

Nakamura et al. (2004)

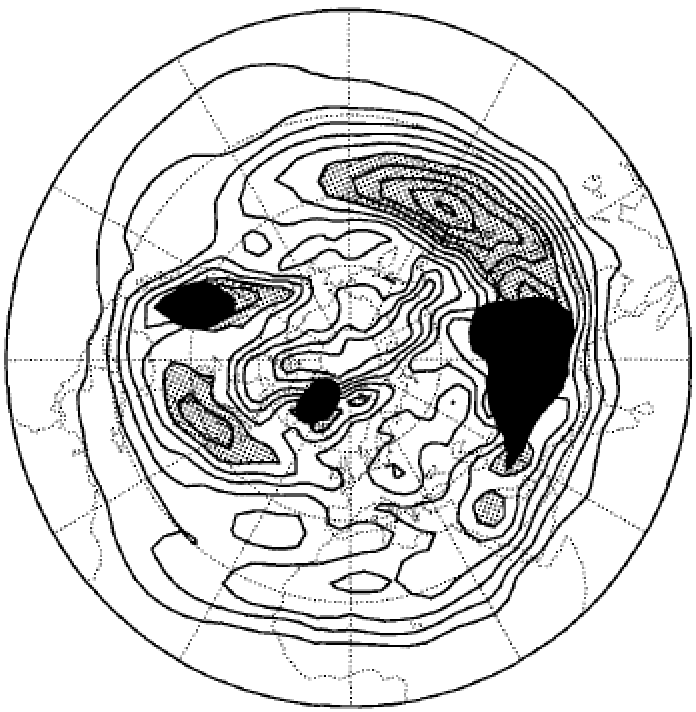
Anchoring of the storm track

- Assuming that low level air temperatures reflect somehow SST changes, warmer SSTs and / or larger SST gradients will enhance the low level Eady growth rate and hence (possibly) "anchor" the storm track.

$$\sigma_{Eady} \propto f_o/\sqrt{R_i} \quad \text{with } R_i \equiv \frac{N^2}{|v_z|^2}$$

Seminal study: Hoskins-Valdes (1990)

Midlatitude storm tracks are “anchored” over western boundary currents which they drive → self-sustaining.



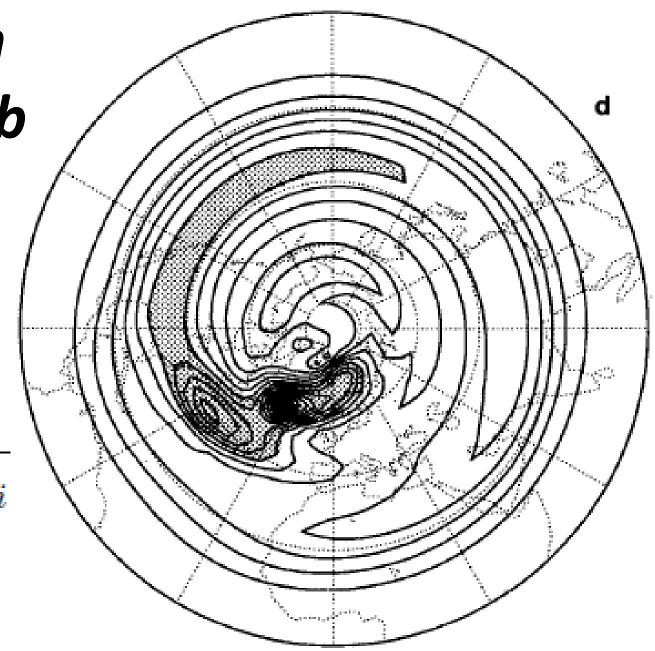
Observed

Eady growth rate at 780mb in winter

(CI = 0.1 day-1)

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

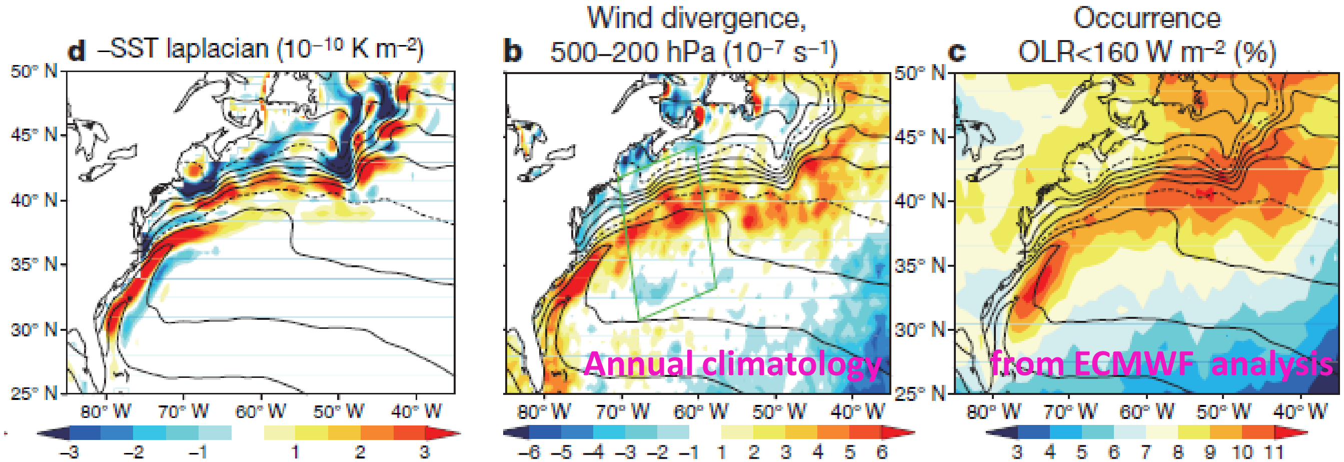
$$\text{with } R_i \equiv \frac{N^2}{|v_z|^2}$$



Response to North Atlantic diabatic heating

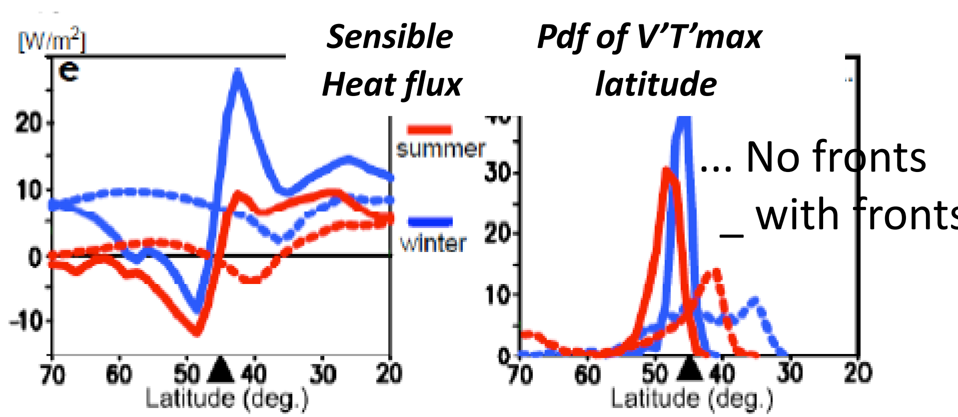
A recent revival of the Hoskins-Valdes ideas

- SST fronts "anchor" precipitation/convection over the Gulf Stream.



Minobe et al. (2008, 2010)

- SST fronts "maintain" low level atmospheric baroclinicity through surface heat fluxes.



Nakamura et al. (2008)

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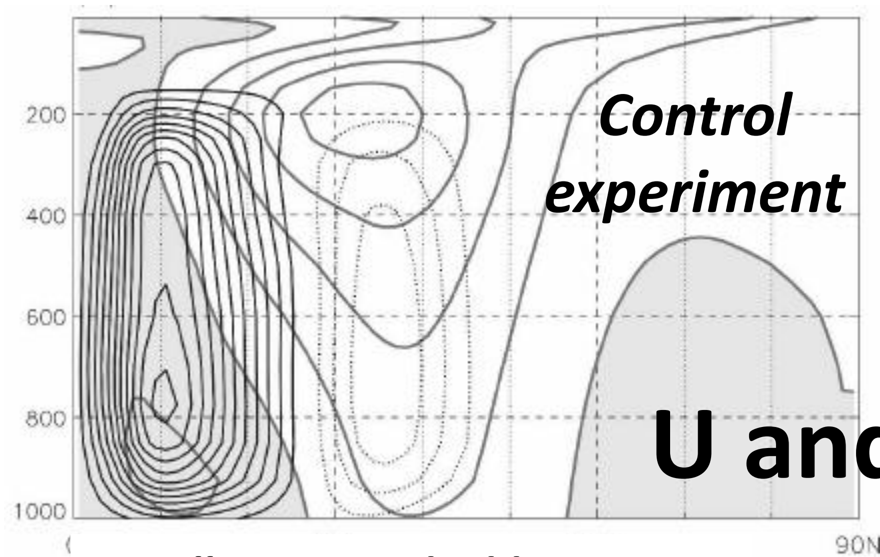
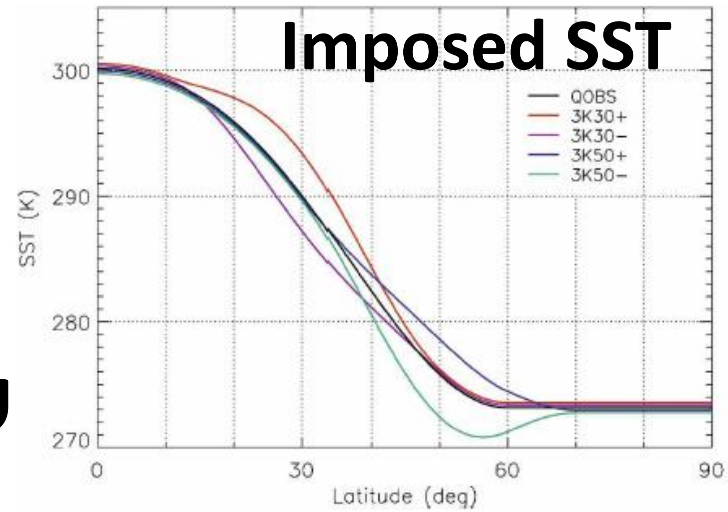
$$\sigma_{Eady} \propto f_o/\sqrt{R_i} \quad \text{with } R_i \equiv \frac{N^2}{|v_z|^2}$$

NB: But how deep must the SST impact on air temperature be?

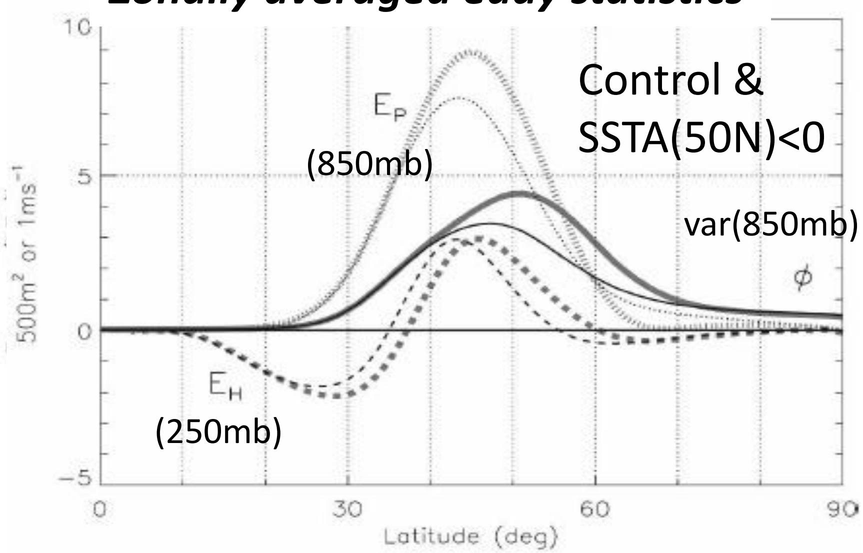
SST influence in stable boundary layer conditions (aquaplanet) –Brayshaw et al. (2008)



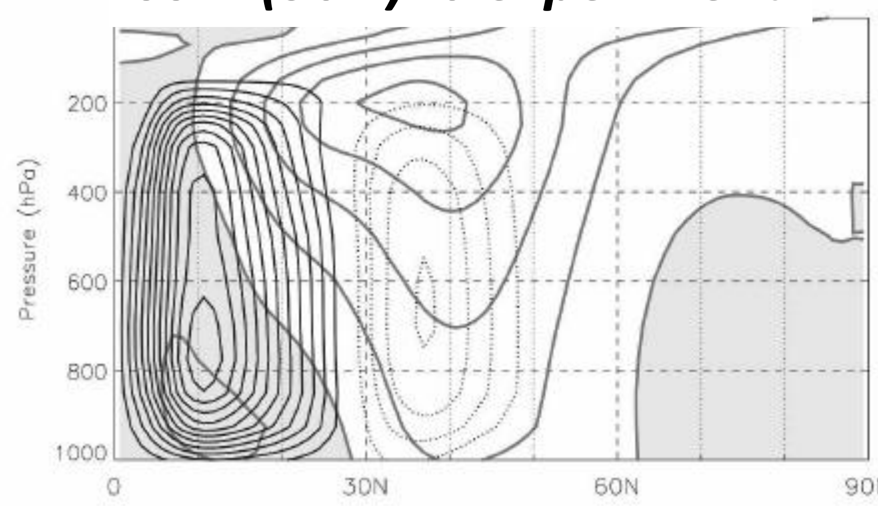


U and Ψ

Zonally averaged eddy statistics



SSTA(50N)<0 experiment



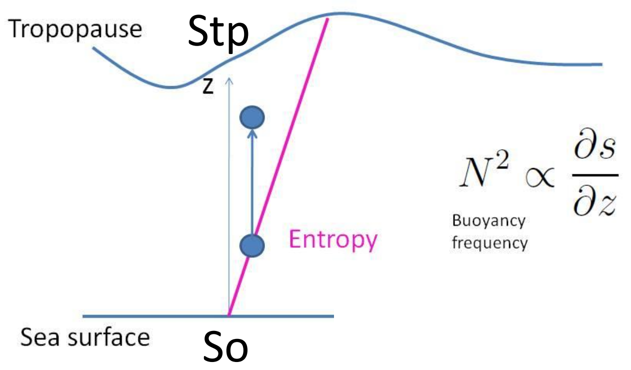
- The previous result makes the case that SST changes do not necessarily need to be conveyed by deep unstable boundary layers to affect the whole troposphere.

- Rotation effects make the extra-tropical atmosphere sensitive to surface boundaries (e.g., Taylor columns, the Eady baroclinic instability problem, etc)

- Intuition based on non rotating fluid (and maybe the Tropics) might be misleading.

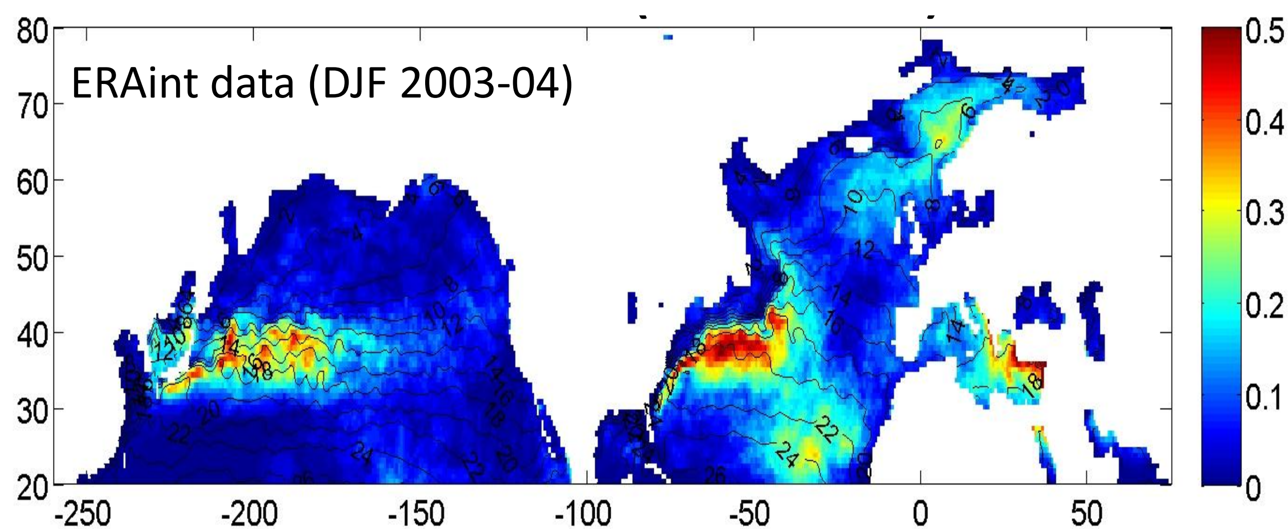
SST influence in unstable boundary layer conditions (e.g., Gulf Stream)

Stability to vertical displacements:
vertical entropy gradient



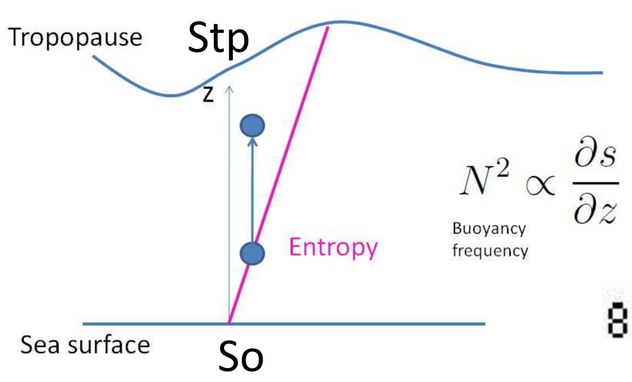
Fraction of wintertime days with (S_{tp}-S_o < 0) in color & time mean SST

Czaja and Blunt (2011)

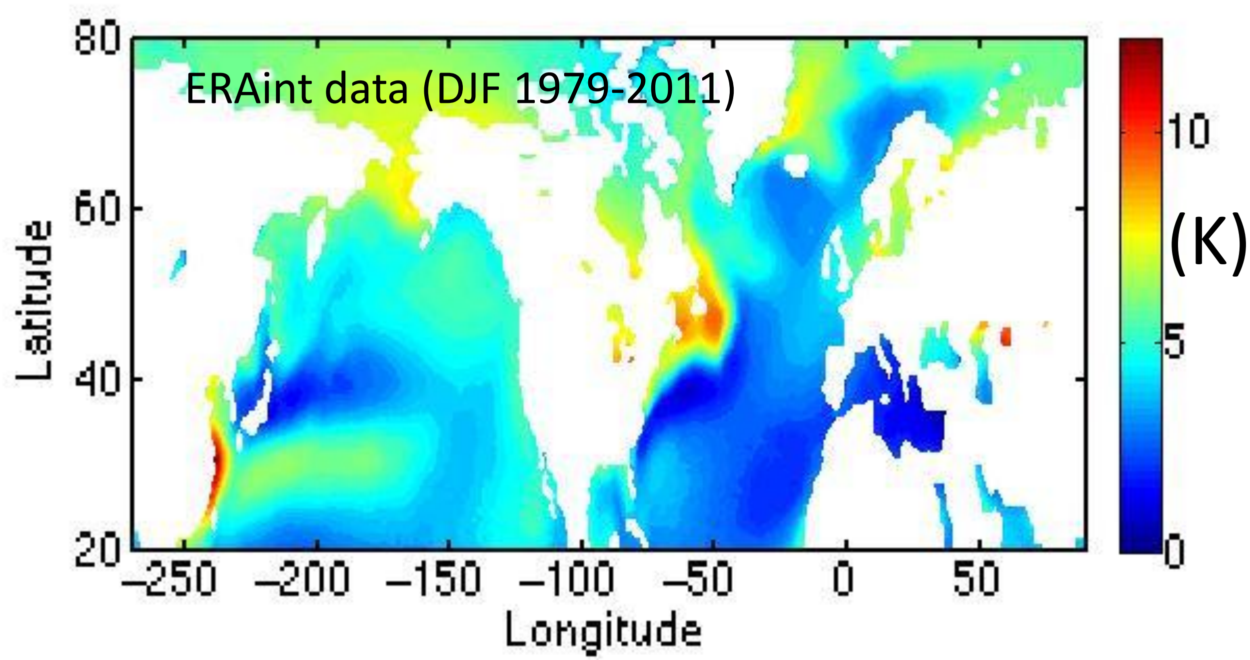


SST influence in unstable boundary layer conditions (e.g., Gulf Stream)

Stability to vertical displacements: vertical entropy gradient



SST change required to alter the mean wintertime stability $\overline{(\text{Stp-So})}$ by 50%



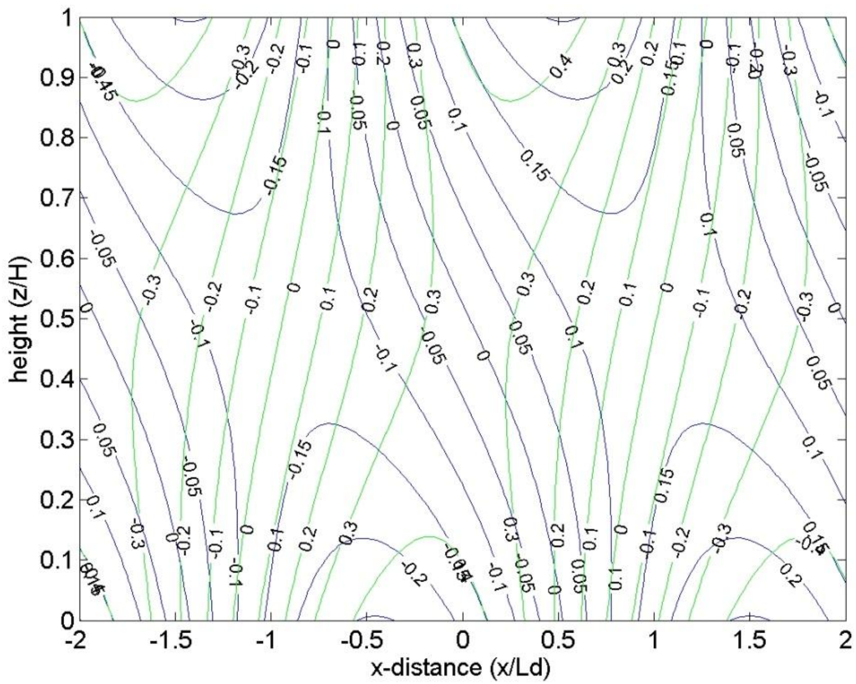
Sheldon and Czaja (2012)

Thermal damping of the storm track

- *Baroclinic growth arises as an unstable interaction between upper and lower level "boundary waves"*
- *If the lower boundary wave is damped, this interaction is made less efficient*
- *The large heat capacity of the ocean drives low level damping through air-sea heat fluxes*

Perturbation pressure & temperature for the most unstable Eady mode

Tropopause



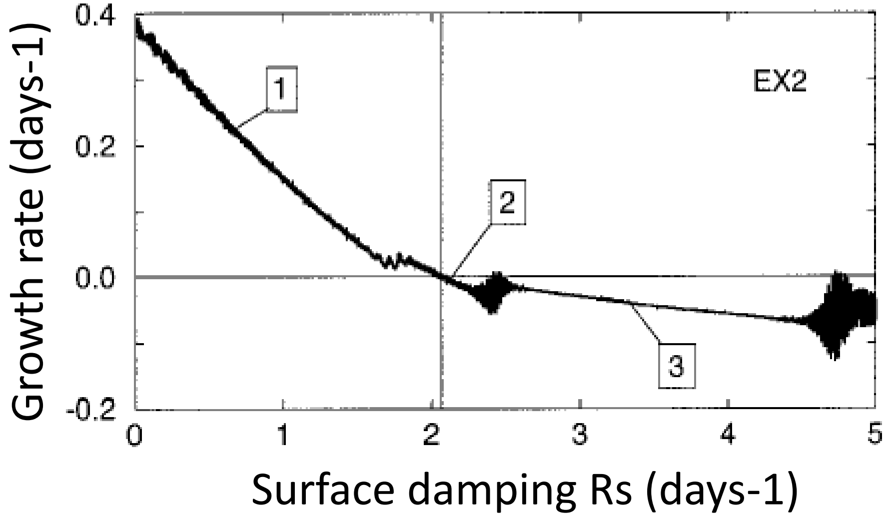
Ocean's surface

(Hoskins, ~1978)

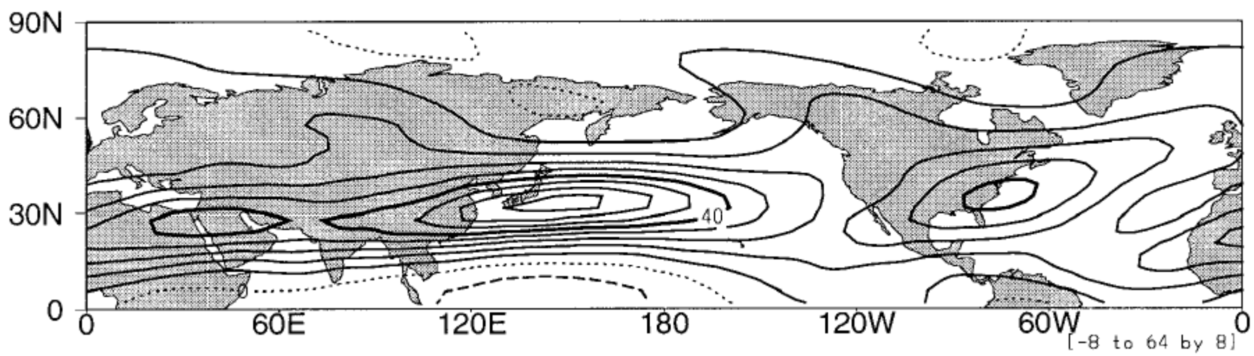
Thermal damping of the storm track

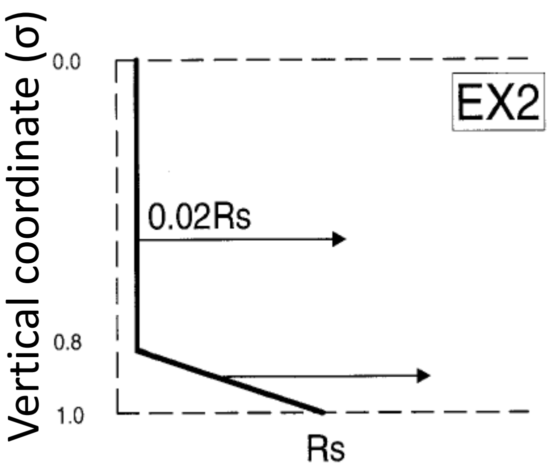
- Linear calculations suggest indeed that the storm-track is sensitive to the magnitude of surface thermal damping
- Storms' wavelength and period increase with surface damping

Modal growth vs surface damping



Background state: 500mb zonal wind



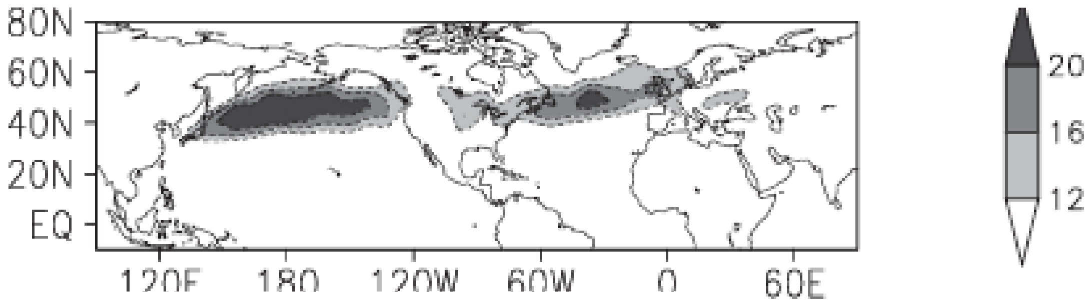


Hall & Sardeshmukh (1998)

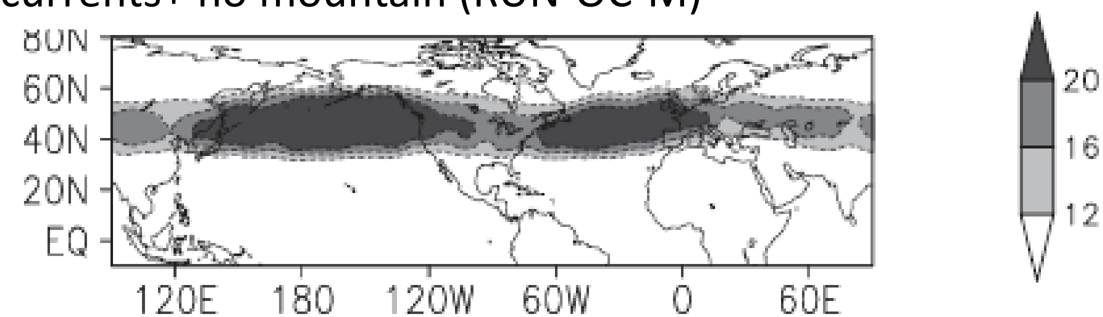
Thermal damping of the storm track

V'T' at 750mb

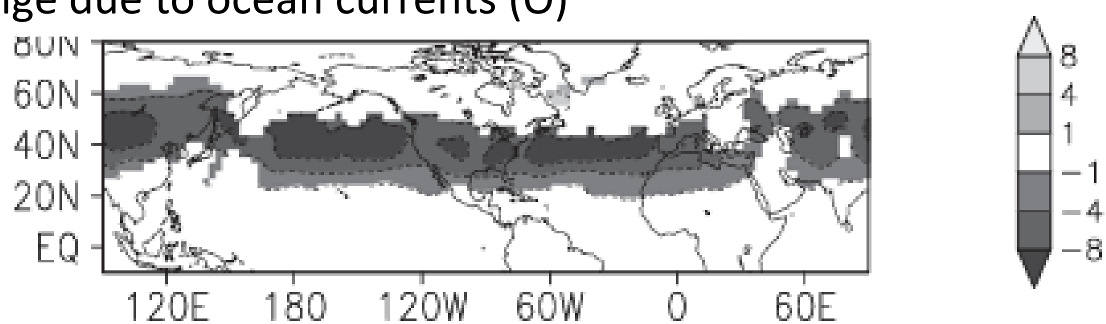
Currents+Mountain (RUN+OC+M)



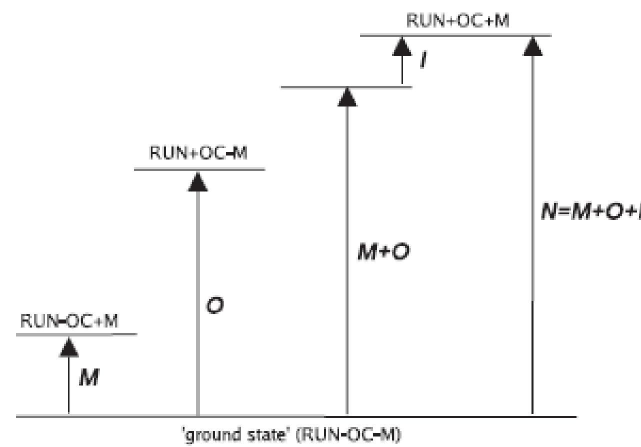
No currents+ no mountain (RUN-OC-M)



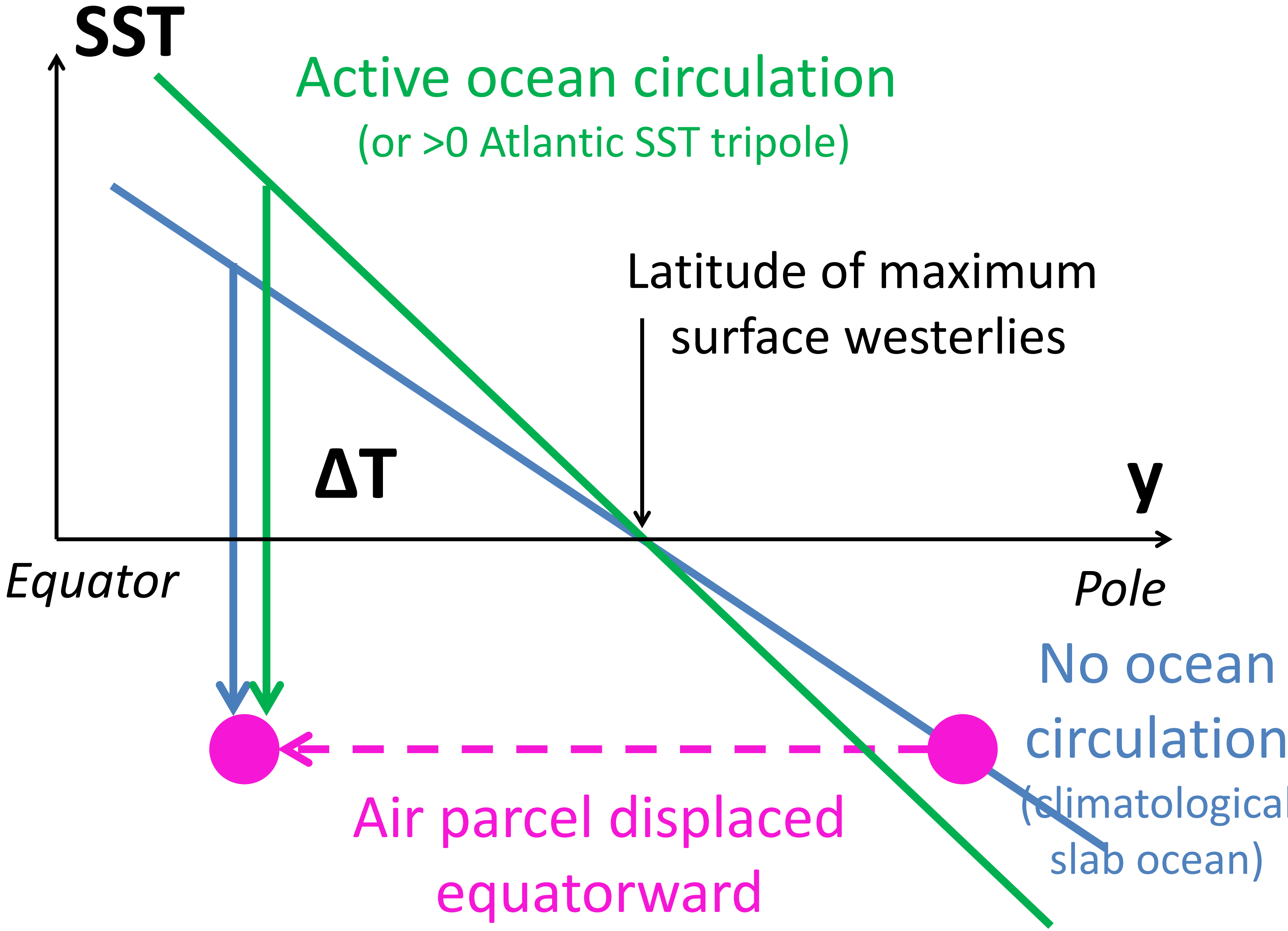
Change due to ocean currents (O)



Coupled model (FORTE) surgery:

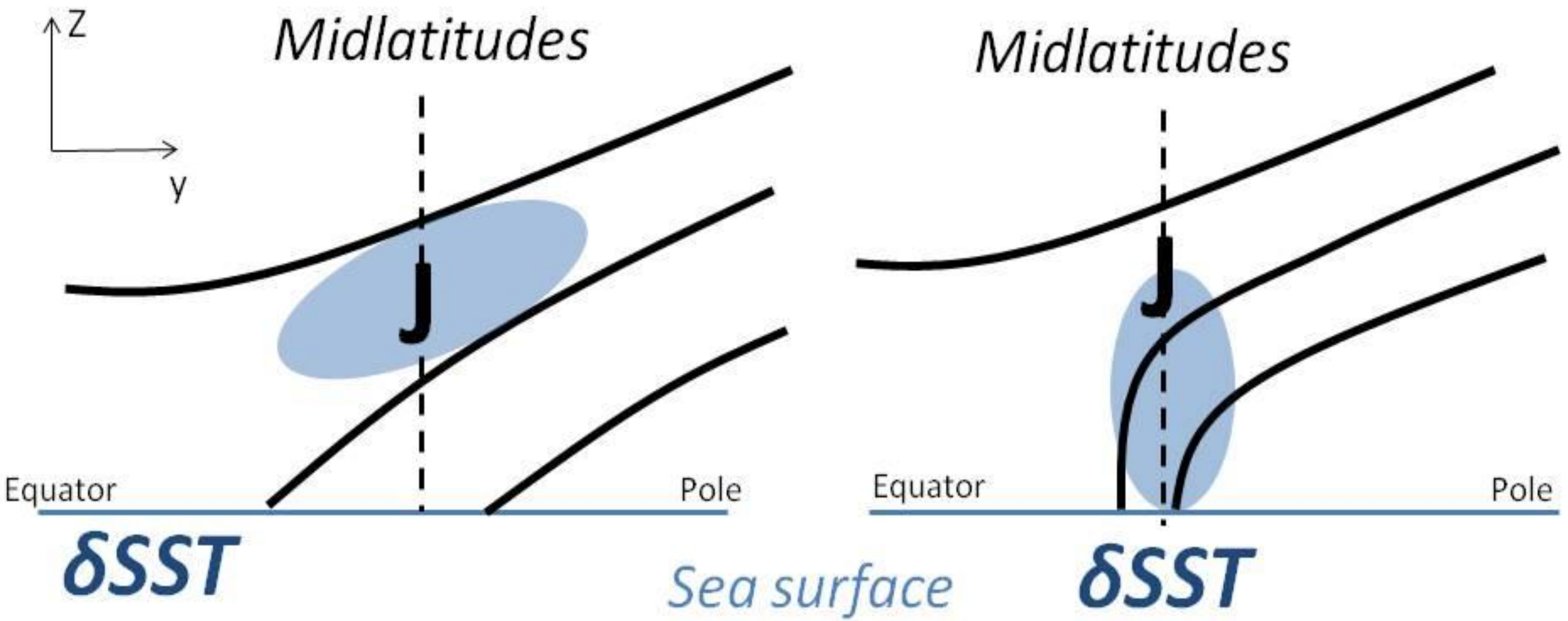


Wilson et al. (2009)

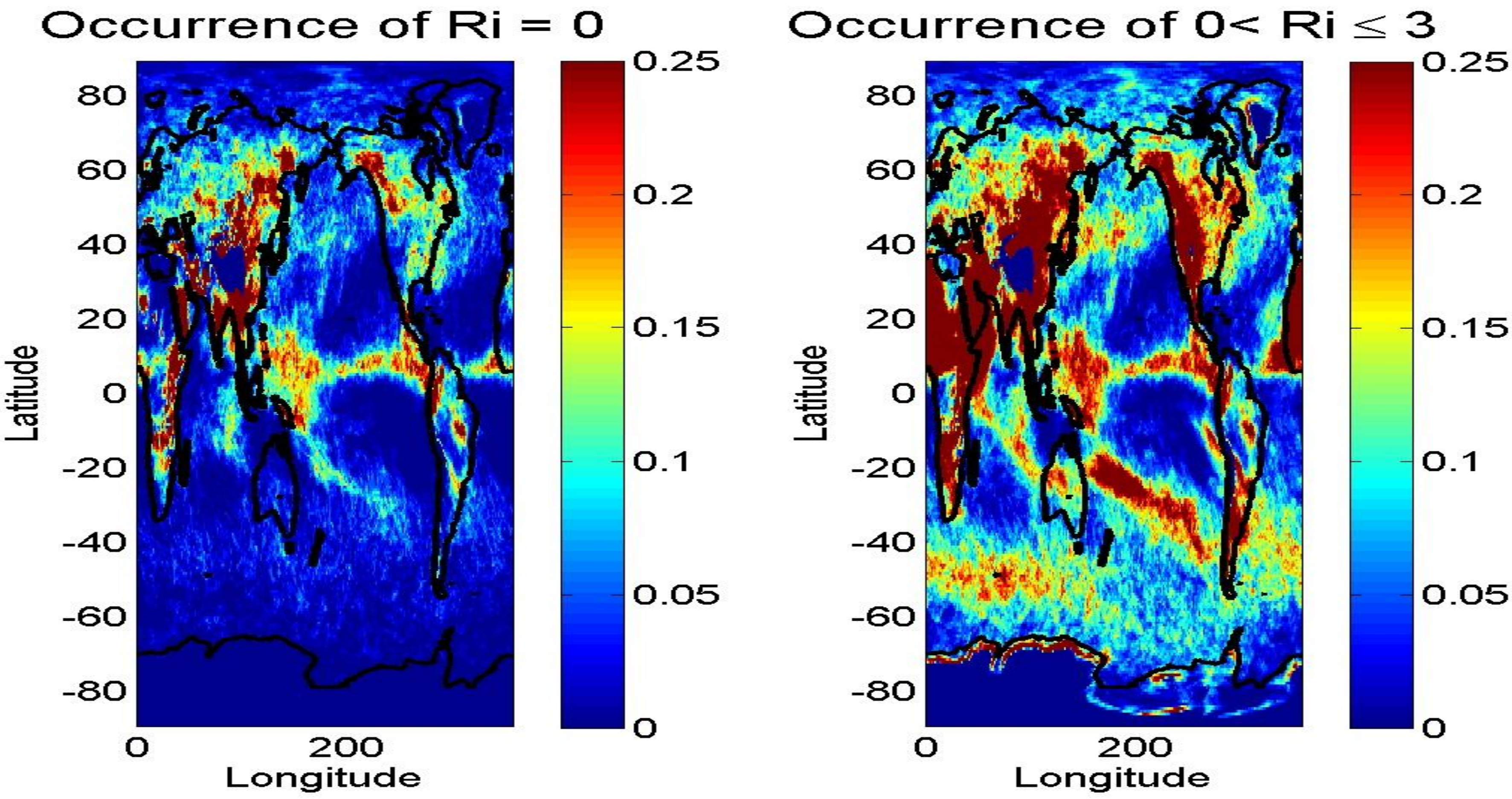

SST
Active ocean circulation
(or >0 Atlantic SST tripole)
Latitude of maximum
surface westerlies
ΔT
y
Equator
Pole
No ocean
circulation
(climatological
slab ocean)
Air parcel displaced
equatorward

Part 3: Frontal ocean – atmosphere coupling

O(1000 km), Ri>>1 | *O(100 km), Ri≈1*



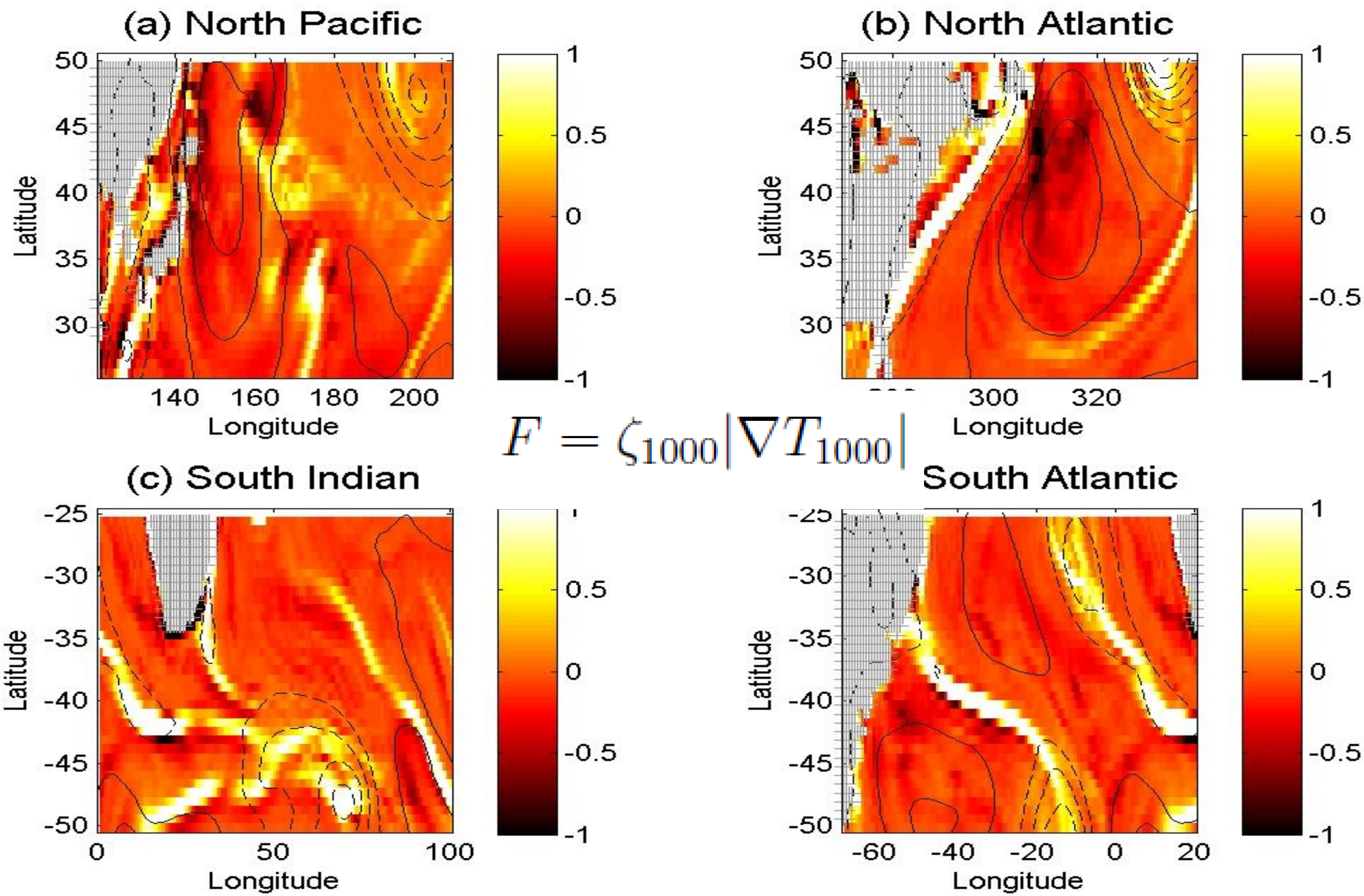
Low Ri processes are as frequent in the extra-tropics than convection is at low latitudes



Analysis at 700mb based on ERAint data (DJF 2003-04)

A simple diagnostic for fronts

Snapshot on a given winter day : normalized F (colour) & SLP anomaly (ci=5mb)

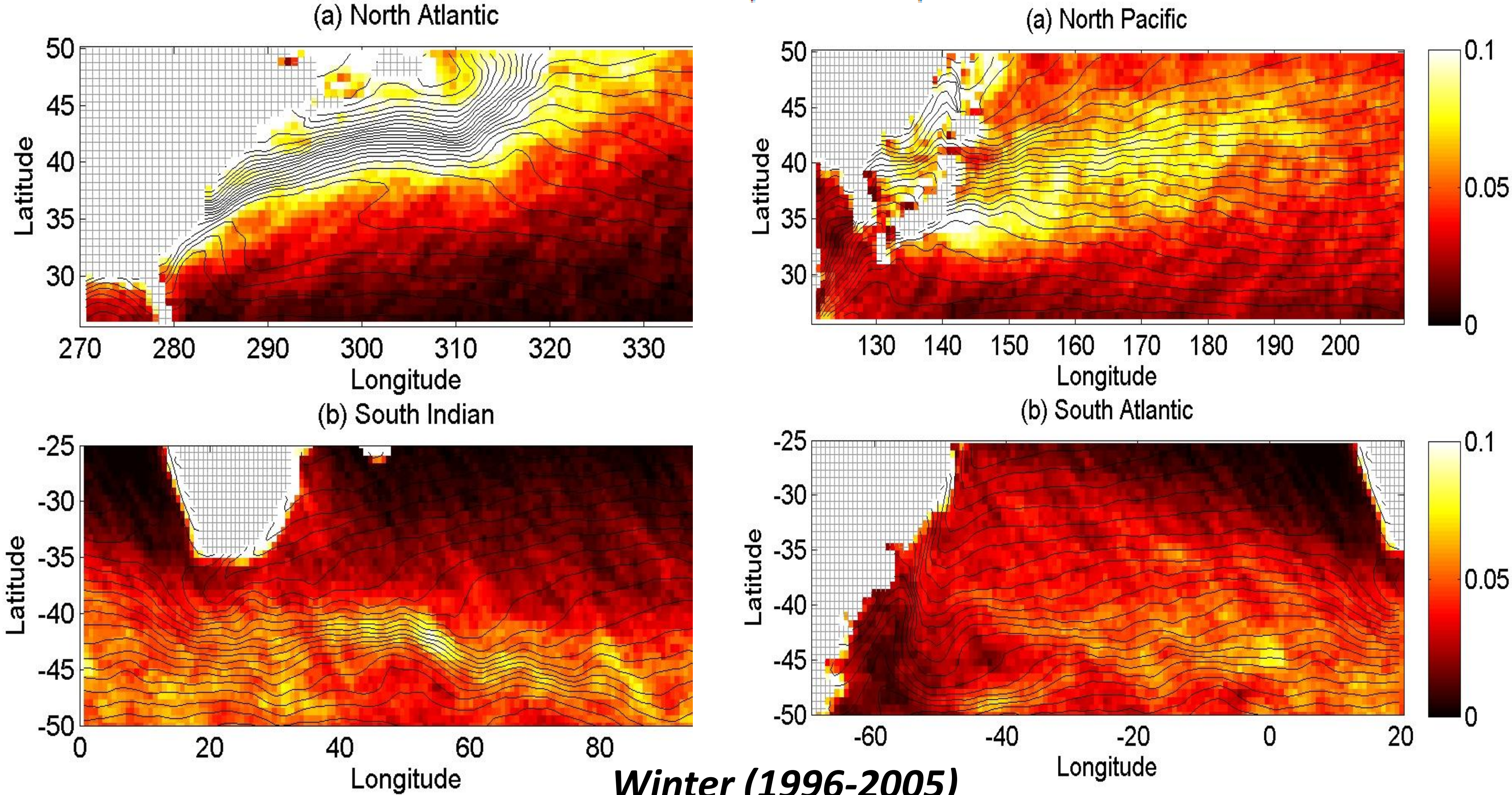


$$F = \zeta_{1000} |\nabla T_{1000}|$$

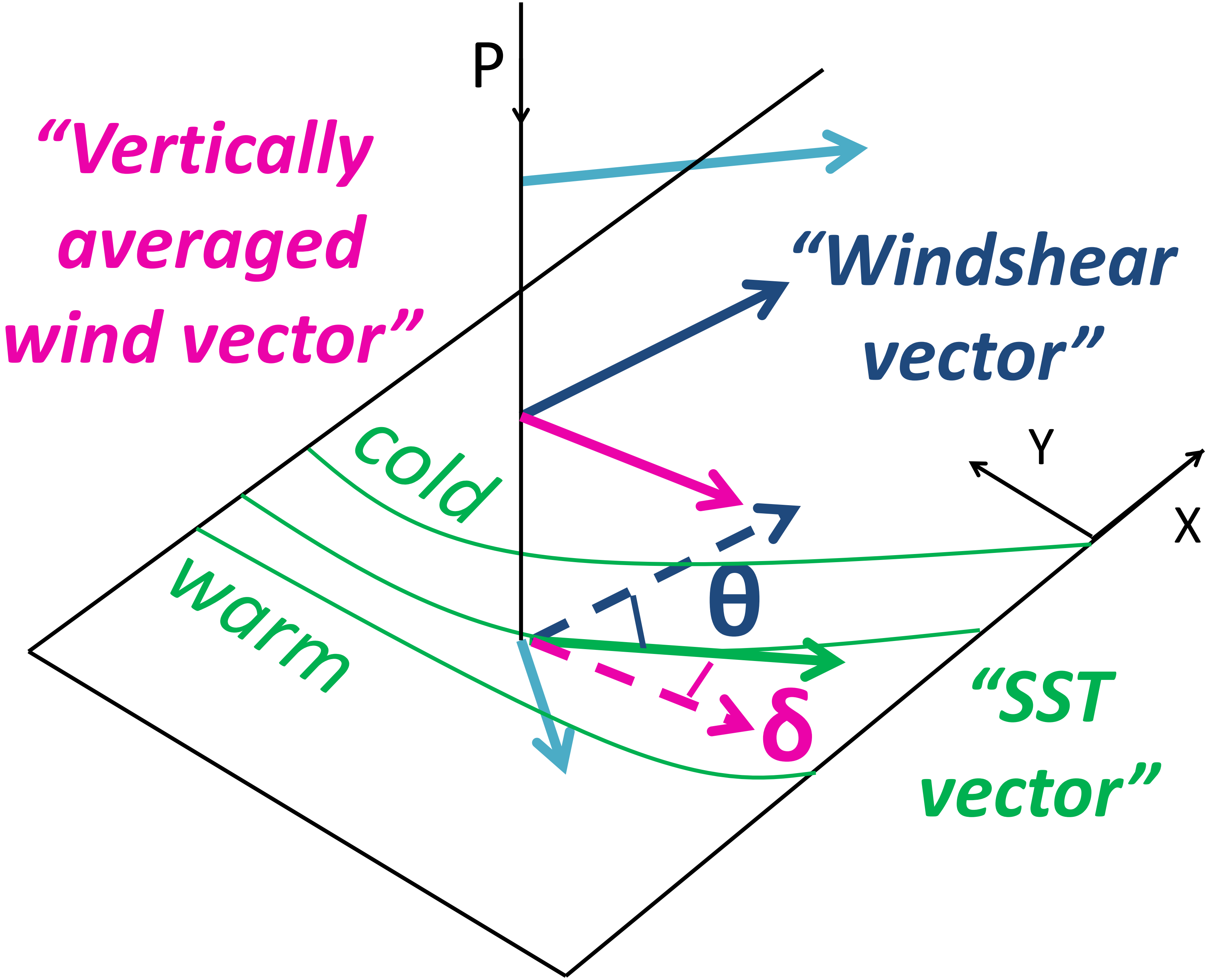
A simple diagnostic for fronts

Frequency of occurrences F>1 (colour) and mean SST (ci=1K)

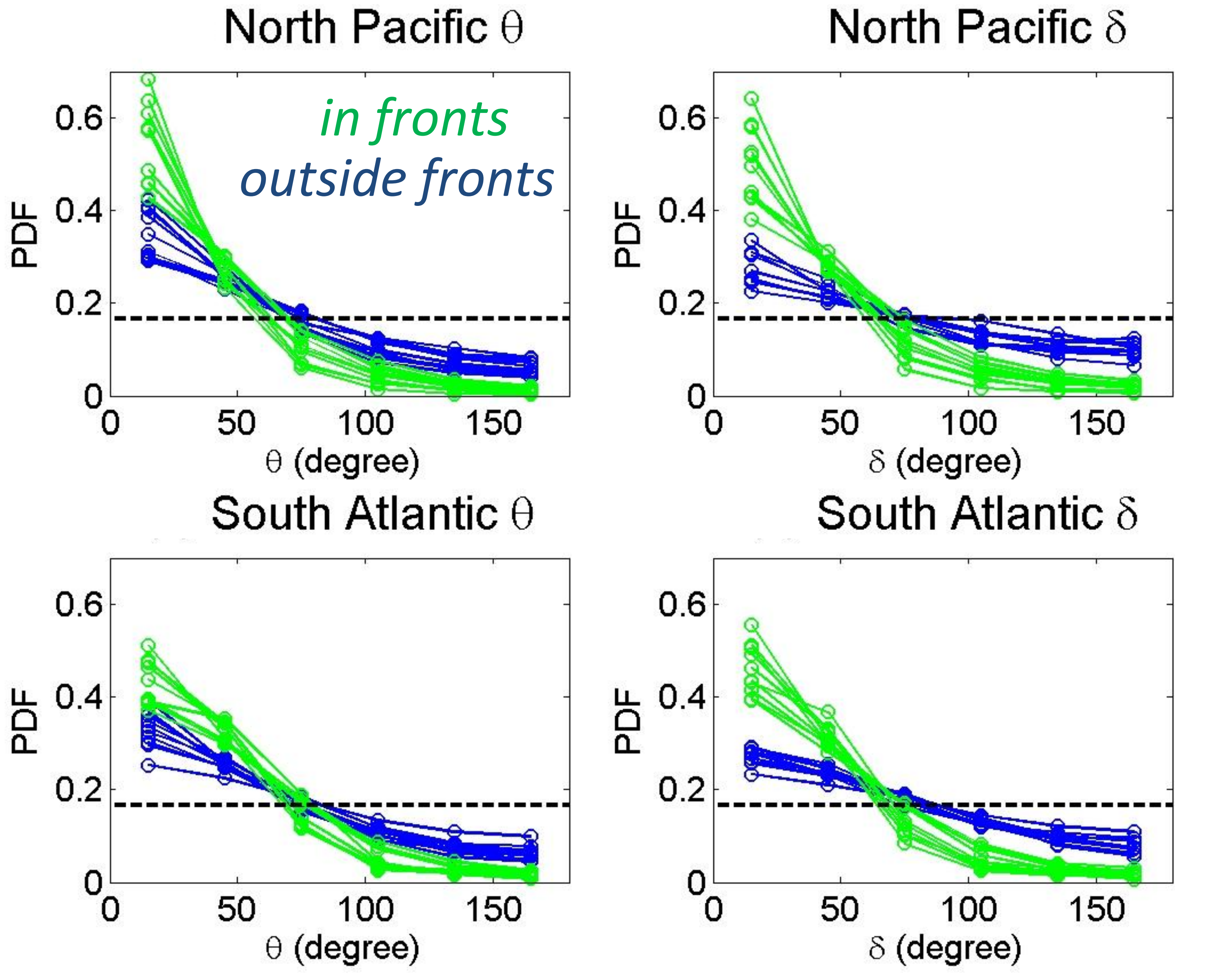
$$F = \zeta_{1000} |\nabla T_{1000}|$$



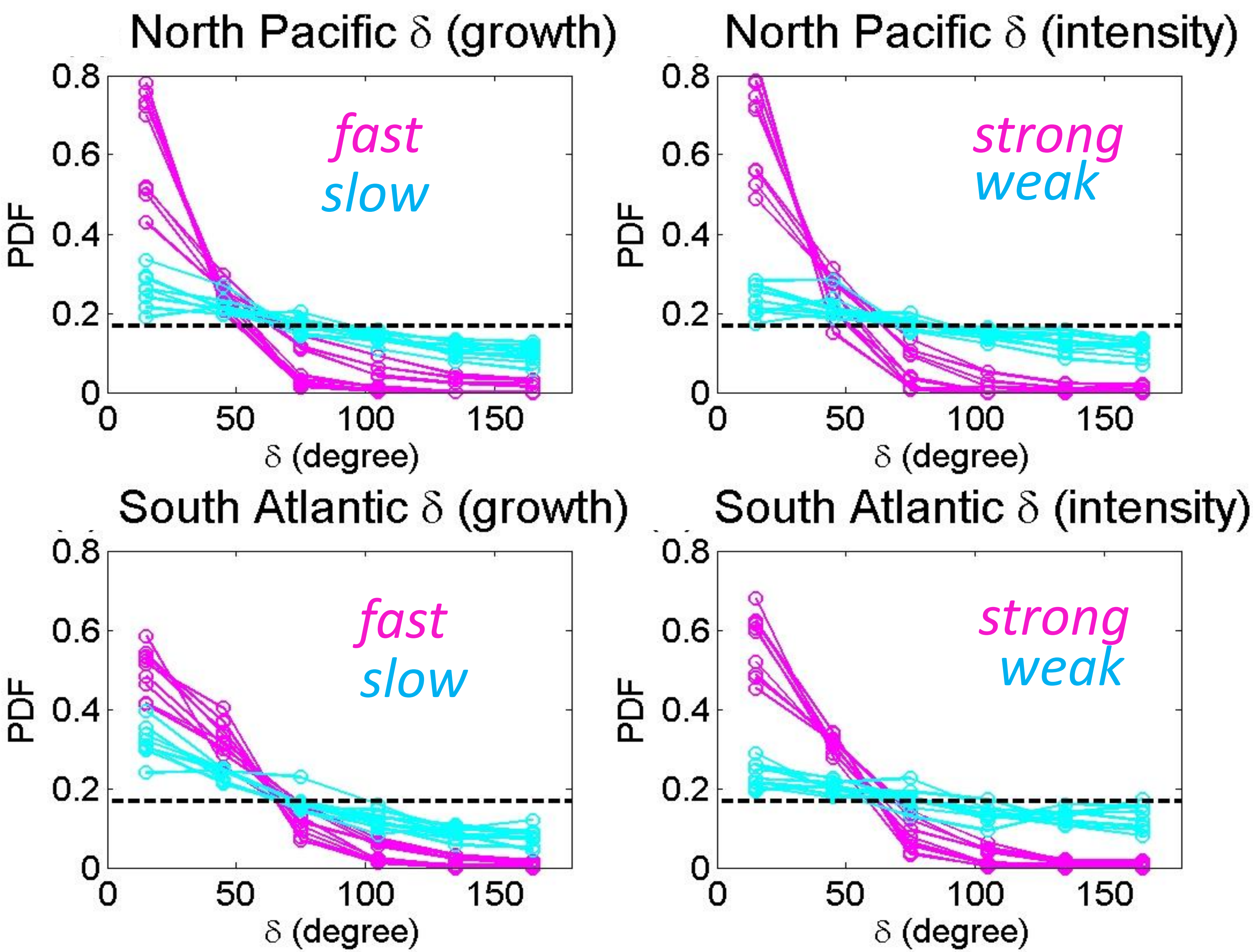
Winter (1996-2005)


P
“Vertically averaged wind vector”
“Windshear vector”
cold
warm
θ
δ
Y
X
“SST vector”

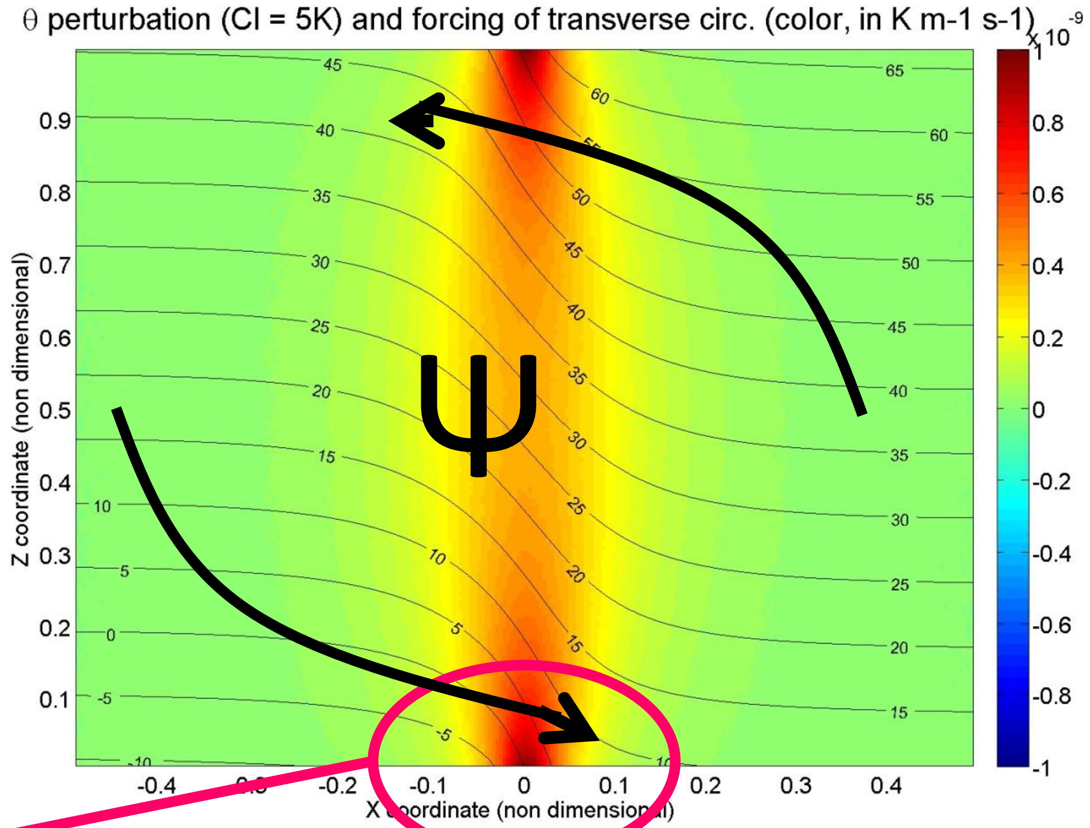
Temperature alignment ***Wind alignment***

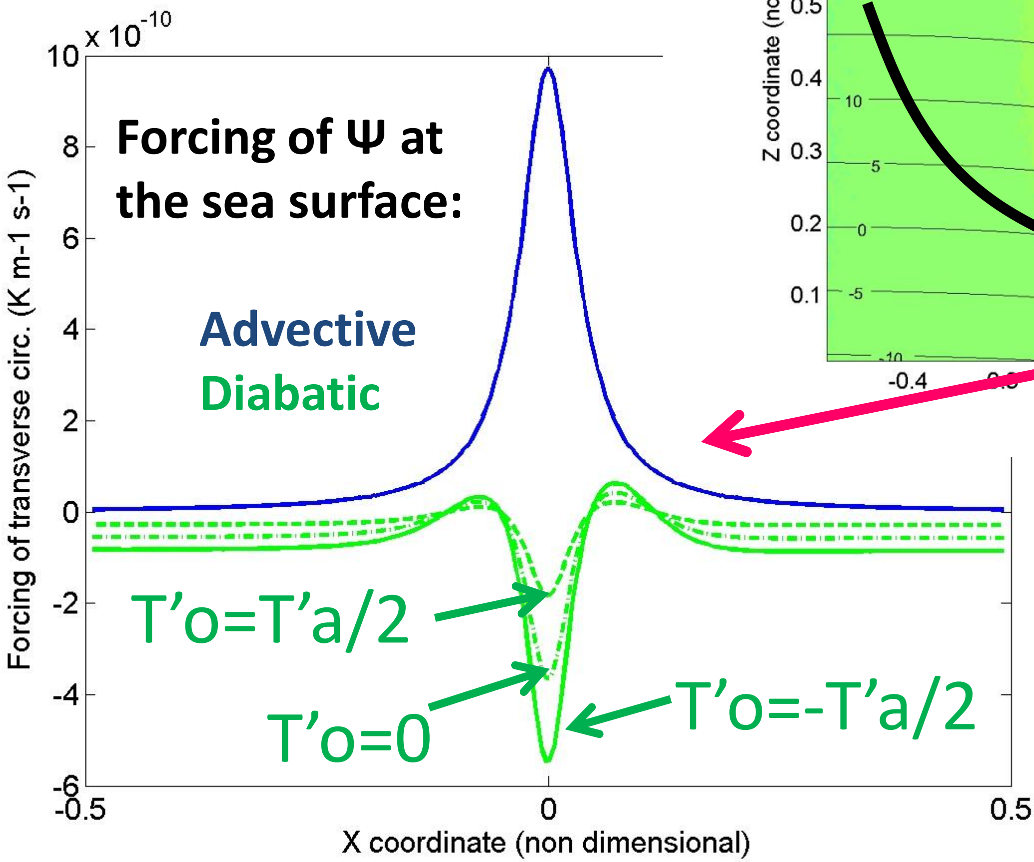


Steering of fronts by SST contours



Impact of air-sea interactions in the Hoskins-Bretherton model (1972)



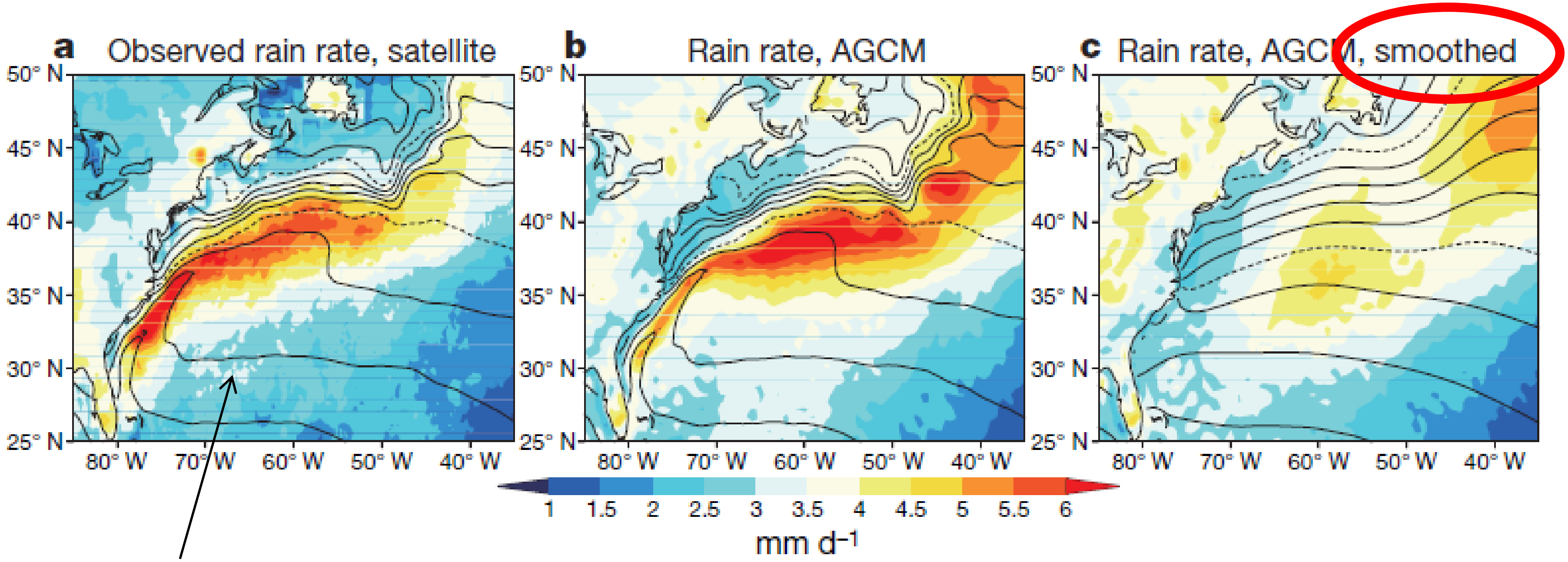


Fronts aligned with sea surface isotherms are less damped by air-sea heat fluxes

Application: Minobe's (2008) simulations

Observations
(TRMM satellite)

Model
("Earth's simulator" T239, L48)



Sea surface temperature
(contours, CI=2K)

Annual mean rainfall
(colour, mm per day)

Conclusion

- An exciting time to work on extra-tropical air sea interactions.
- New mechanisms of coupling / actual oceanic impacts are studied / found in “old models” (moving away from wave mean flow interaction).
- New parameterizations/idealized model studies are needed to capture air-sea interactions occurring over atmospheric fronts.