Large-scale ocean circulation and climate: High-latitude climate variabilty

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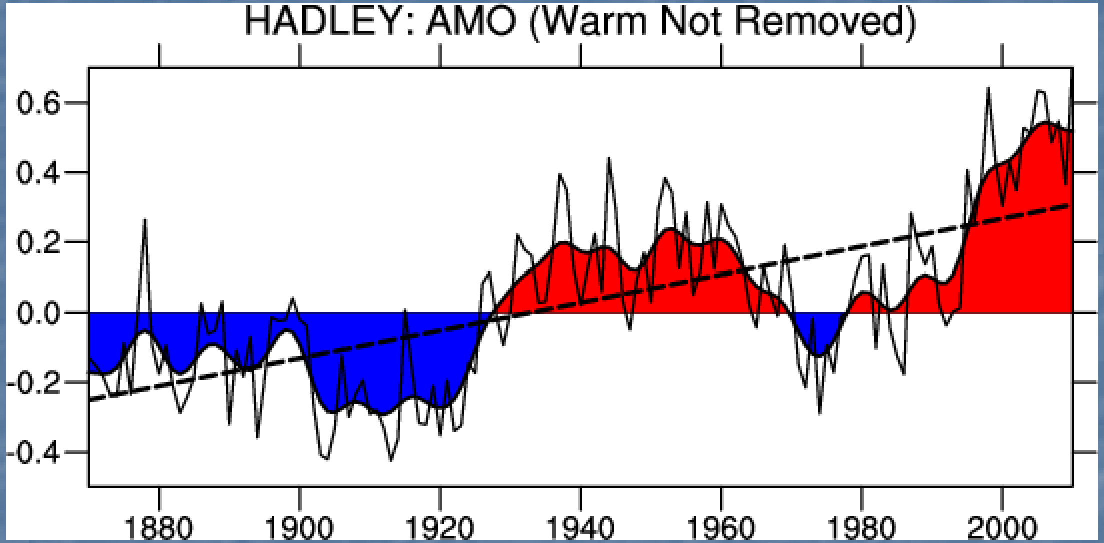
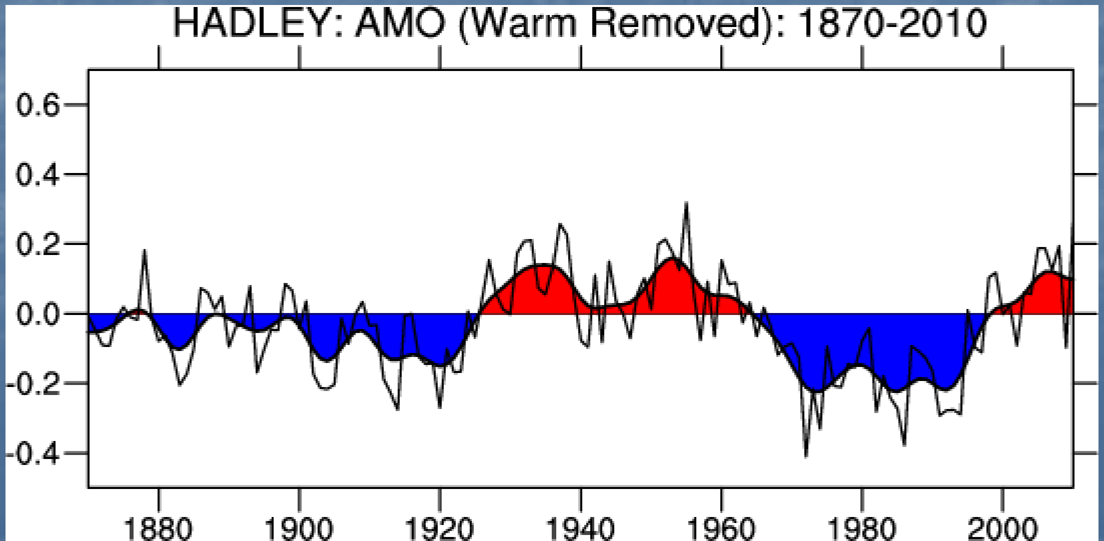
2023 ICTS Summer School on
Mathematical modeling of Climate Ocean
and Atmospheric Processes

Goals for today

- Understand some of the phenomenology of high-latitude variability in models and observations.
- Understand why it might matter
- Understand how winds, temperatures and salinity might come together to drive the variability.

Variability in North Atlantic temperature





Greenland cod catch

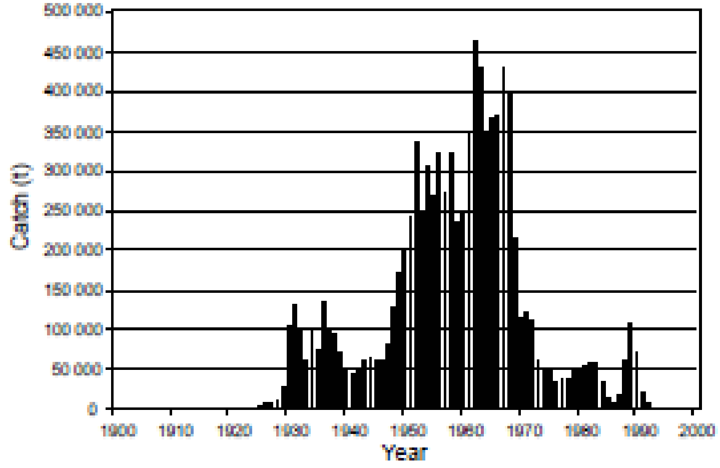
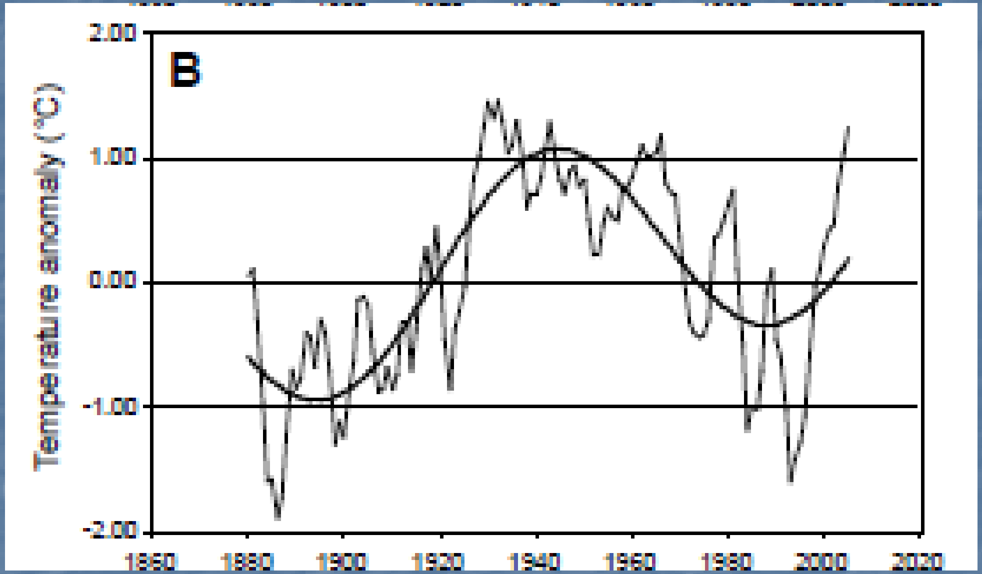


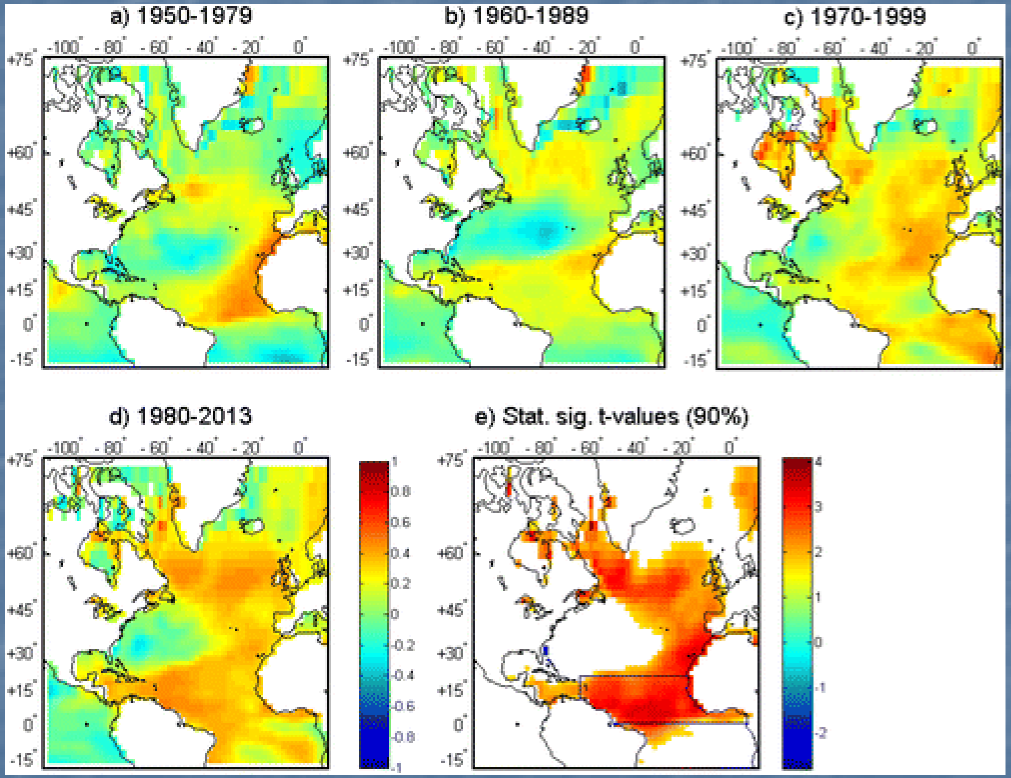
Fig. 15. Annual nominal catches of cod (*Gadus morhua*) in Greenland waters ; data: Table 6a in Horstedt (2000).



Stein, J. Northw. Atl. Fish. Sci., 2007

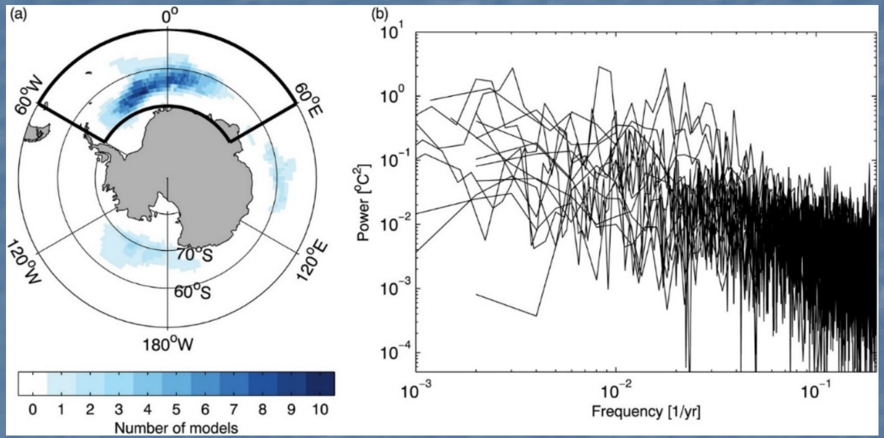
Is this merely coincidental?

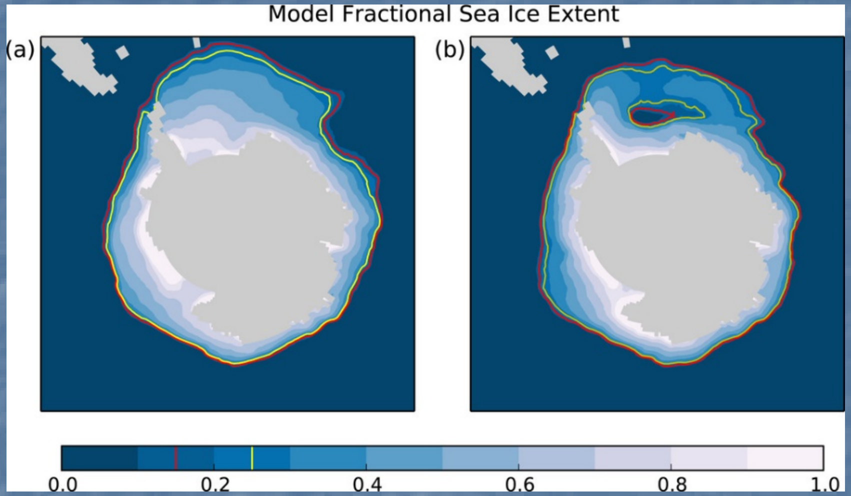
Correlation between number of hurricanes in Atlantic and SSTs



Davis, Xeng and Ritchie, Weather and Forecasting, 2015

Southern Ocean Variability





Reintges et al. (GRL, 2017) show Weddell Sea Sector of the Southern Ocean shows decadal convection in many models....

Characteristics of this variability are very different between models.

Zanowski et al. (2015)

Some evidence this may be happening in nature

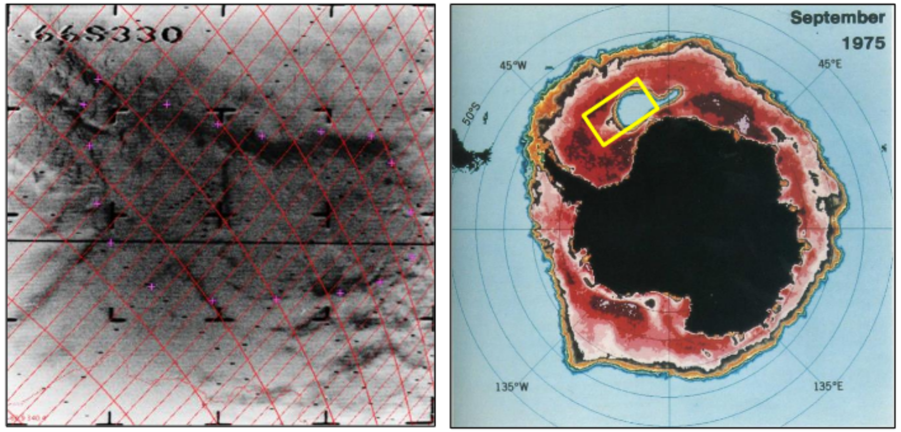
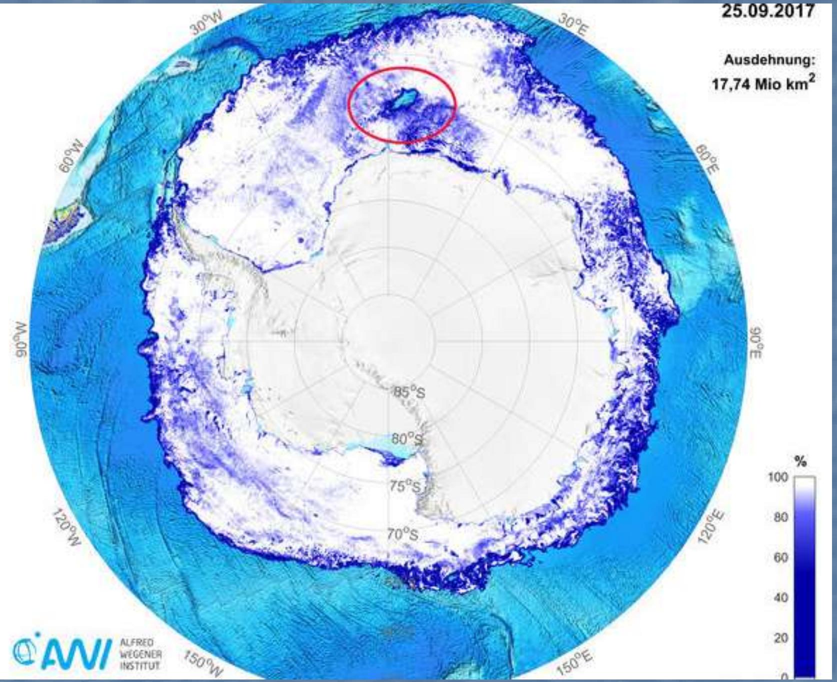


Fig. 5. Nimbus I image from the region of the Weddell Sea polynya (66° S, 330° E) in September 1964 (left), and the polynya seen in sea ice concentrations derived from passive microwave imagery in September 1975 (right); the yellow square indicates the approximate location of the 1964 scene, which covers an area of roughly 500 × 2000 km. The dark features in the Nimbus I image indicate potential low ice concentration, and the darkest areas appear to be open water. However, it is not clear if there was a polynya at or near the time of the image or just an indication of leads and clouds.

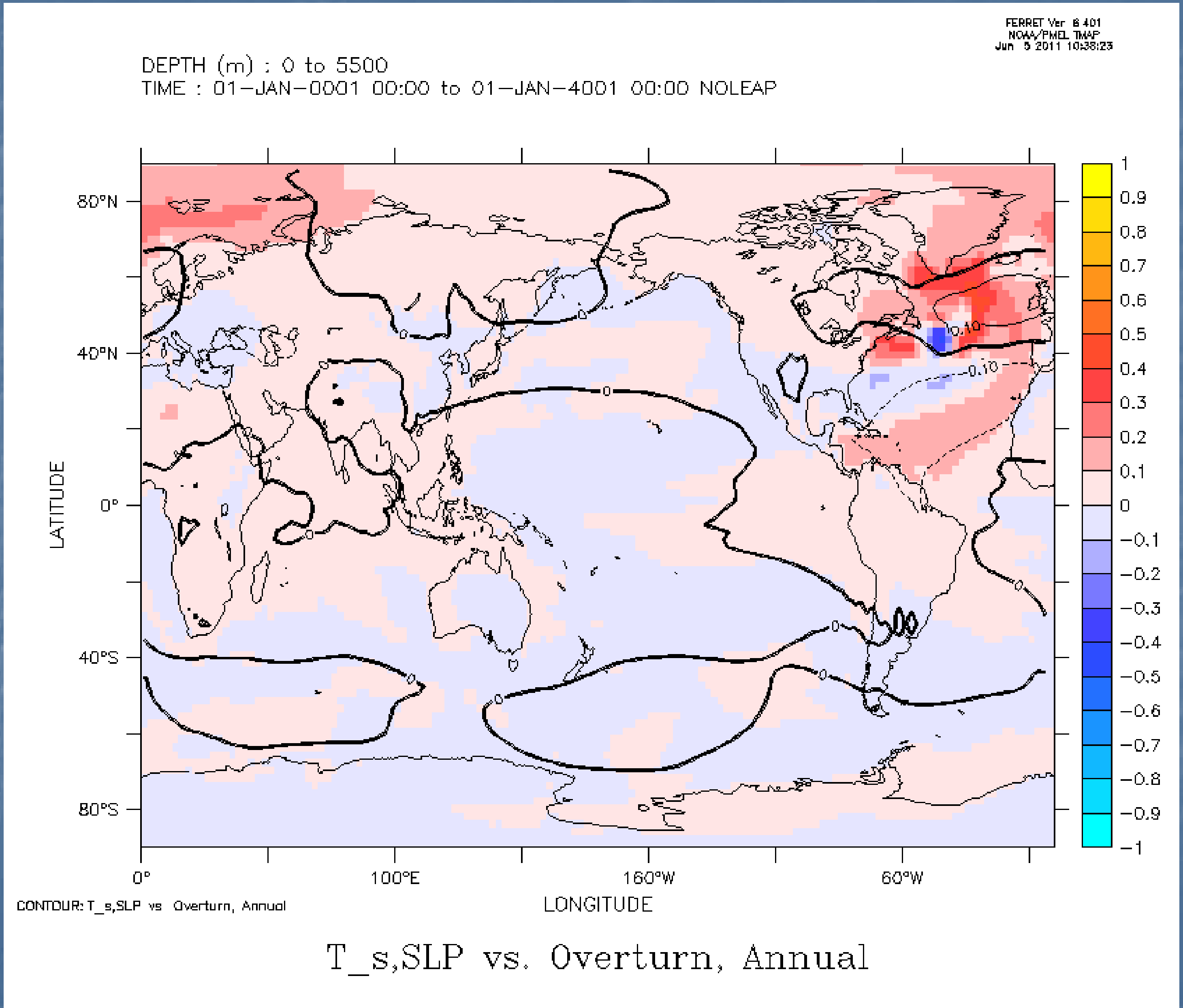


Meier et al., The Cryosphere, 2013

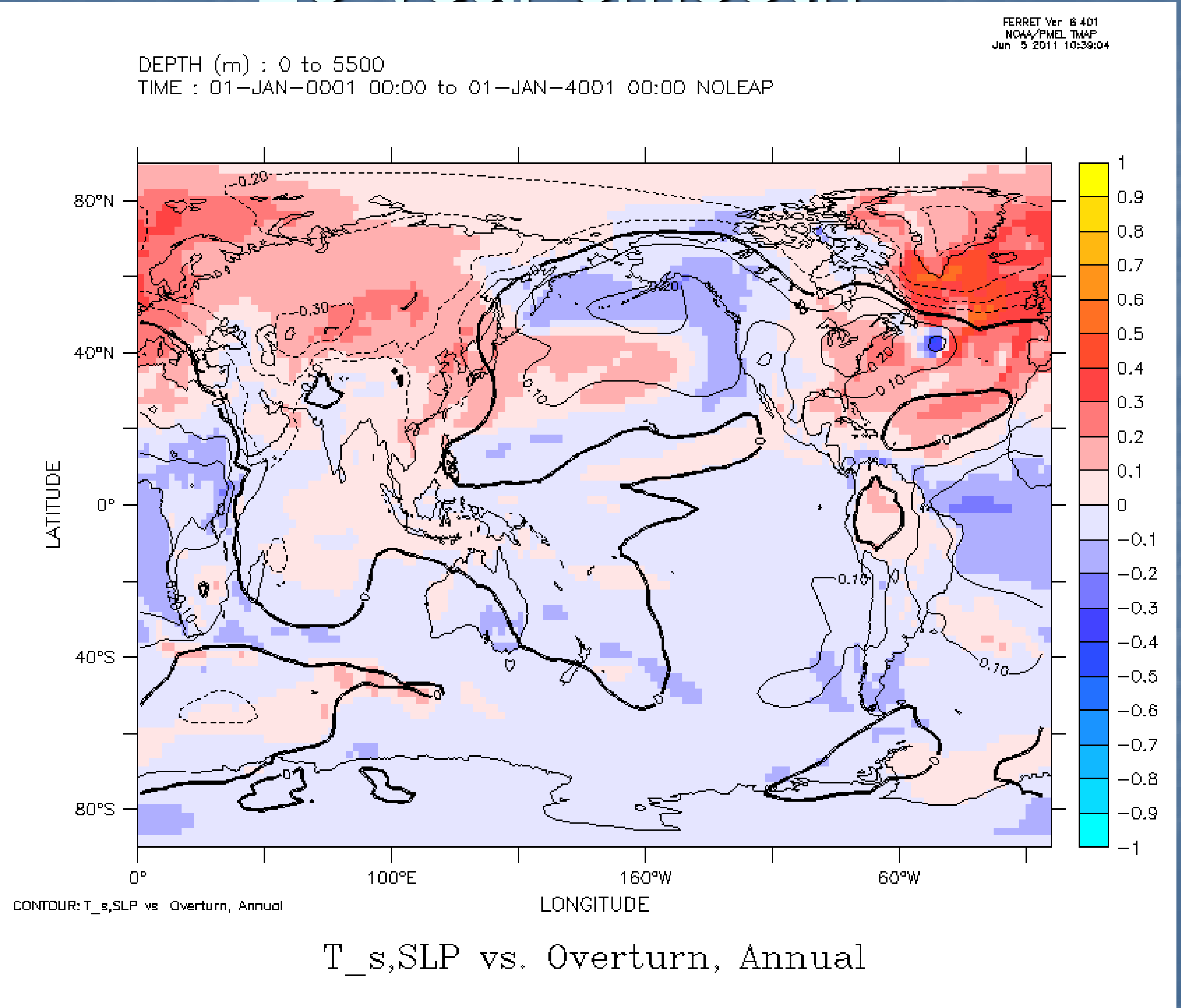
Part I: Atlantic overturning

- Climate model- solves equations of motion in both atmosphere and ocean.
- Developed at NOAA Geophysical Fluid Dynamics Lab by a small army of researchers (50+ people on documentation paper)
- Run for very long periods of time to develop natural variability.
- This model was one of the better models in the Fourth Assessment Report
- Good overall simulation of hydrography in Southern Ocean.
- Caveat- does not directly simulate eddies.

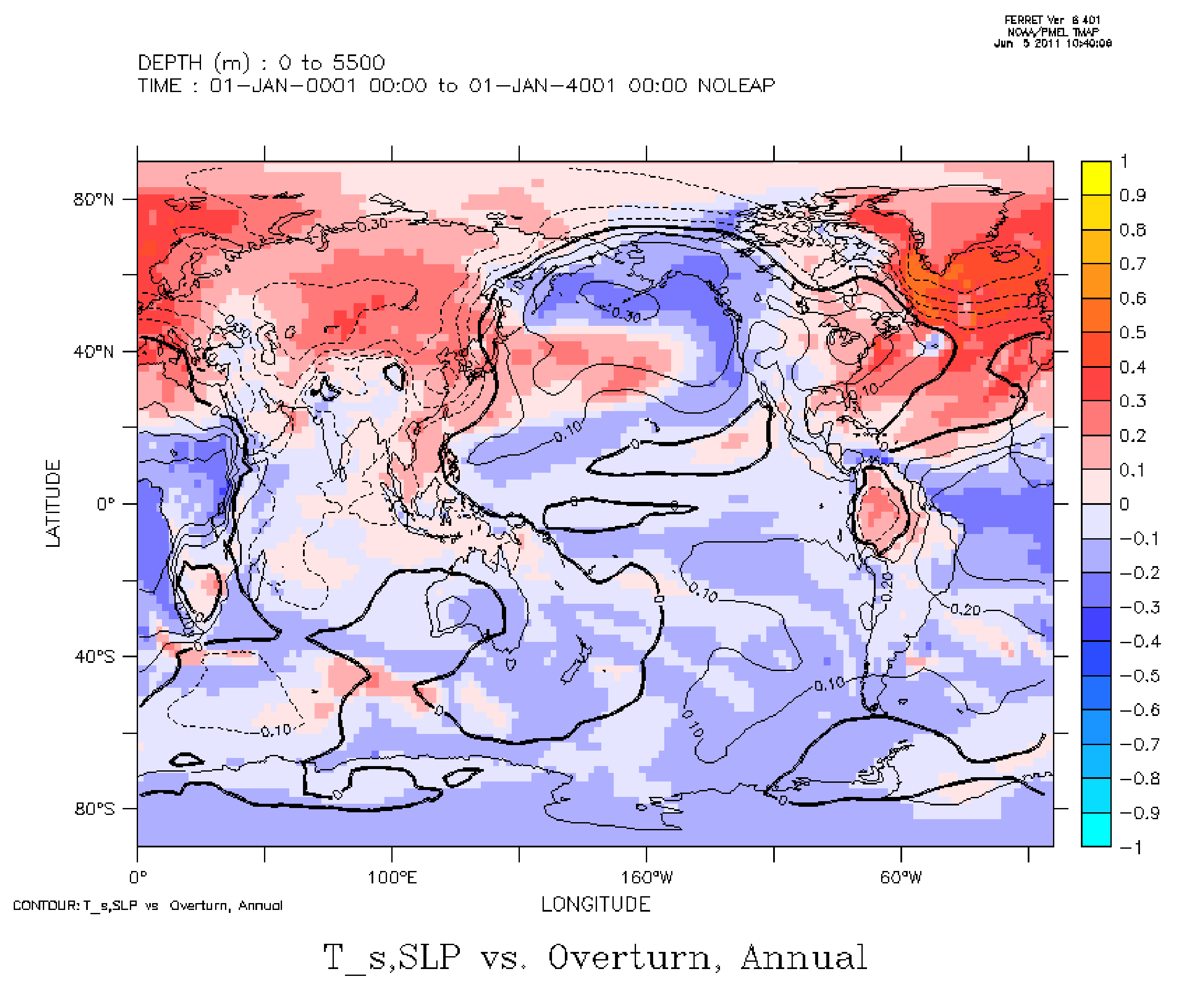
Correlation of overturning and SST:GFDL model



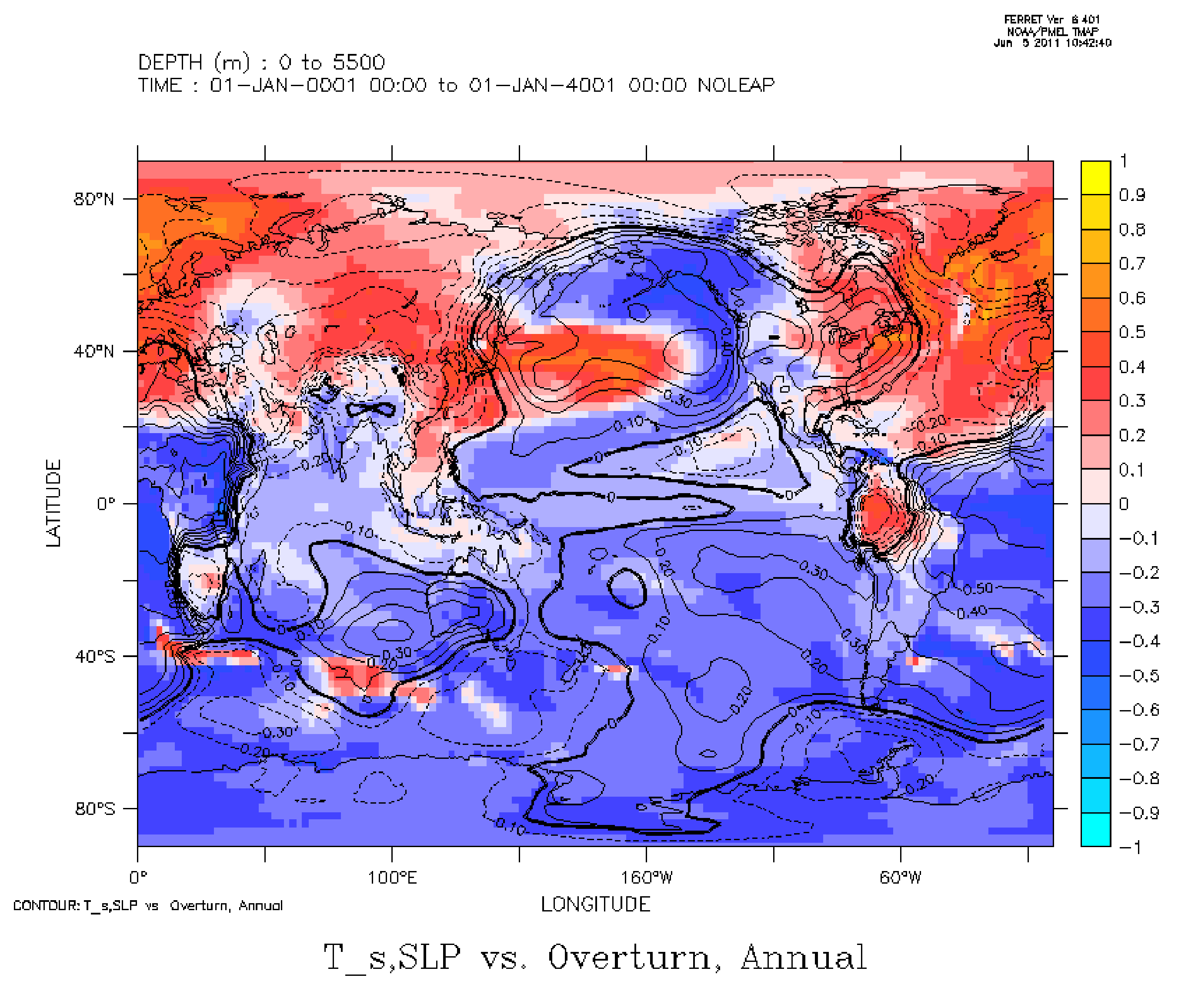
Correlation of overturning and SST 10 year smooth



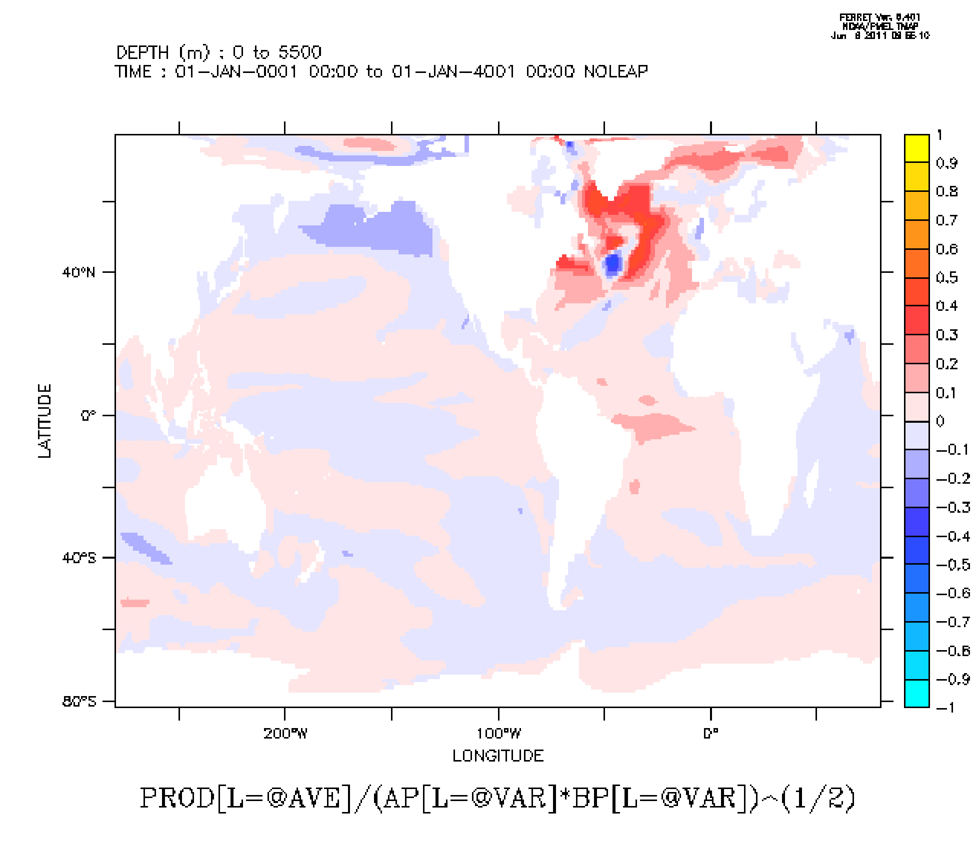
Correlation of overturning and SST
20 year smooth

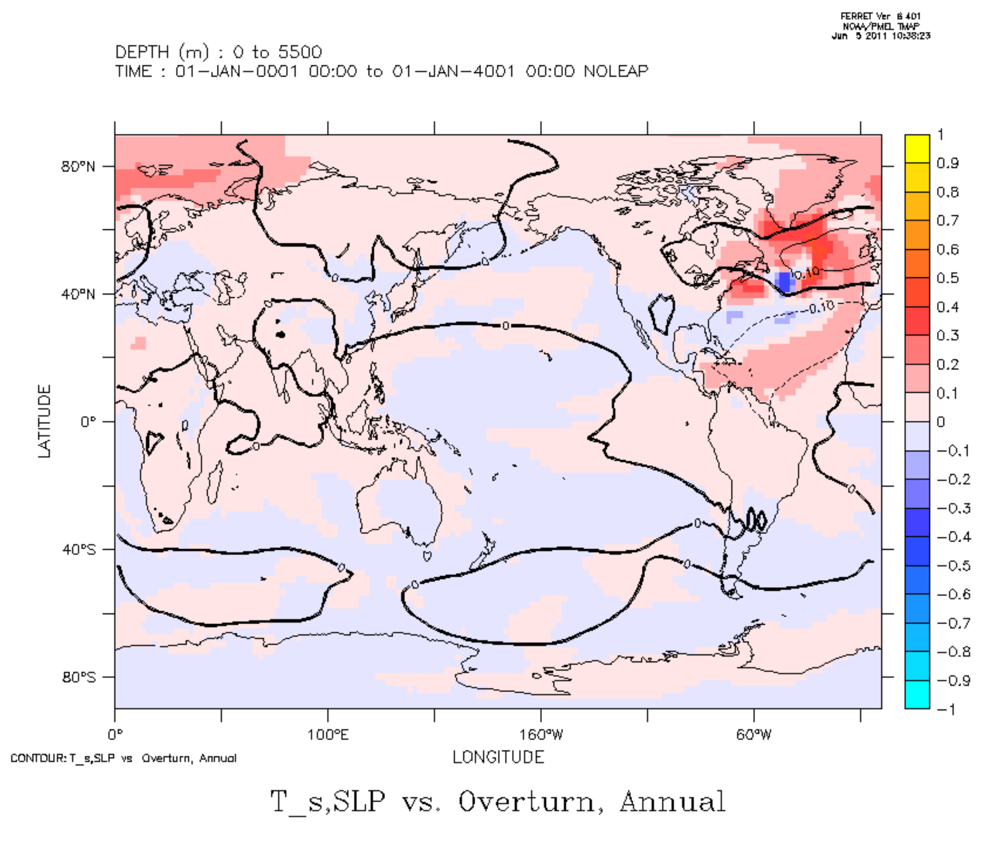


Correlation of overturning and SST
100 year smooth

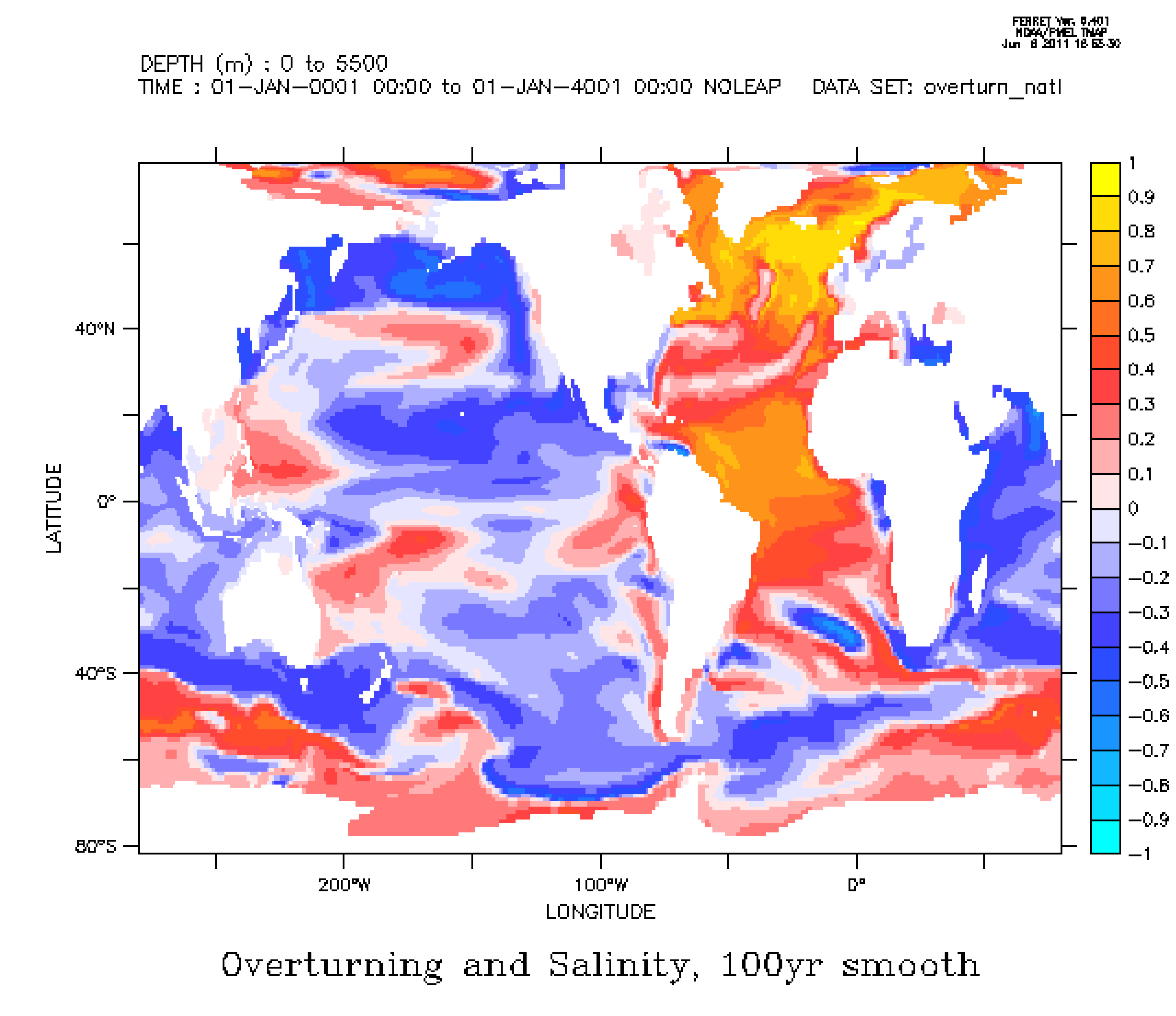


Salinity shows a similar pattern as temperature





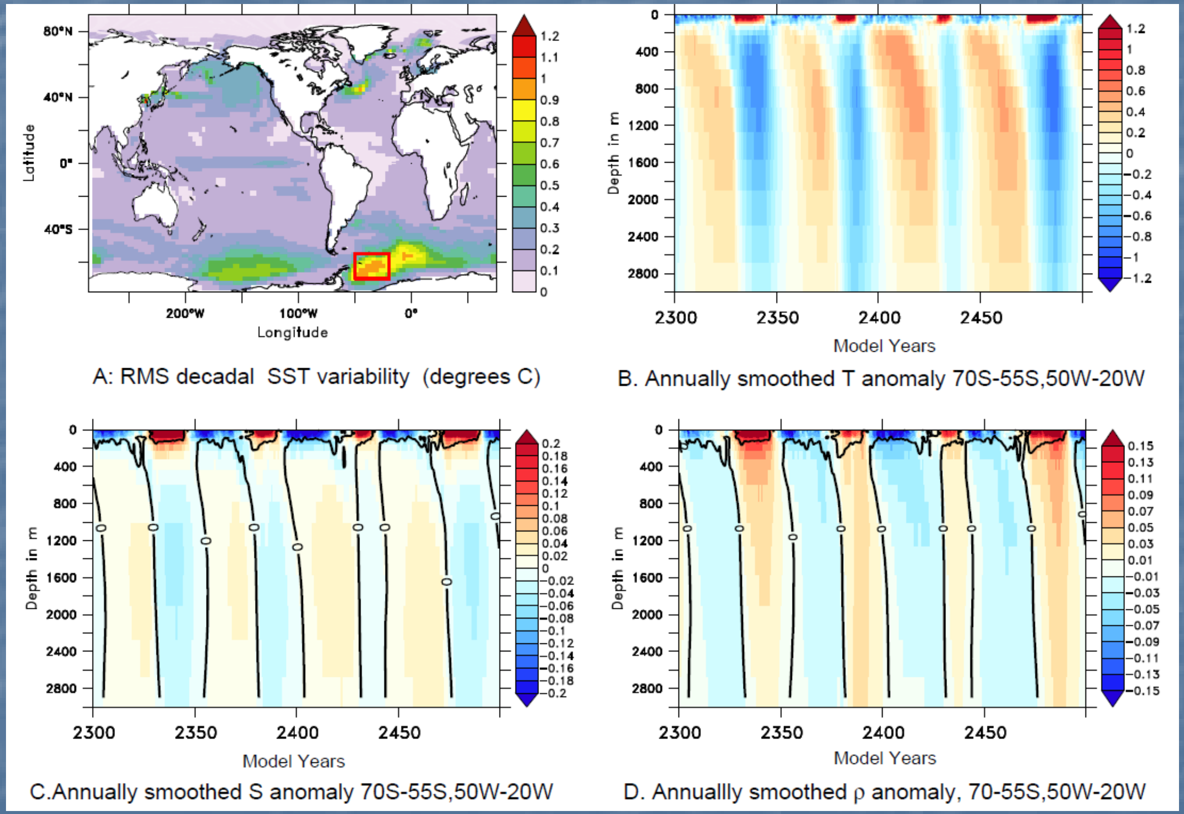
.. Though correlations are higher!



Southern Ocean variability within a climate model

- Coarse resolution version of GFDL ESM2M model.
- Realistic representations of a wide range of physical processes.
  - Model ACC transport, mean density gradient across ACC, winds better than most CMIP5 models
- Low (potentially realistic) parameterized lateral diffusion in Southern Ocean.
- Caveats: Does not resolve eddies or capture deep overflow dynamics.

Variability in this model

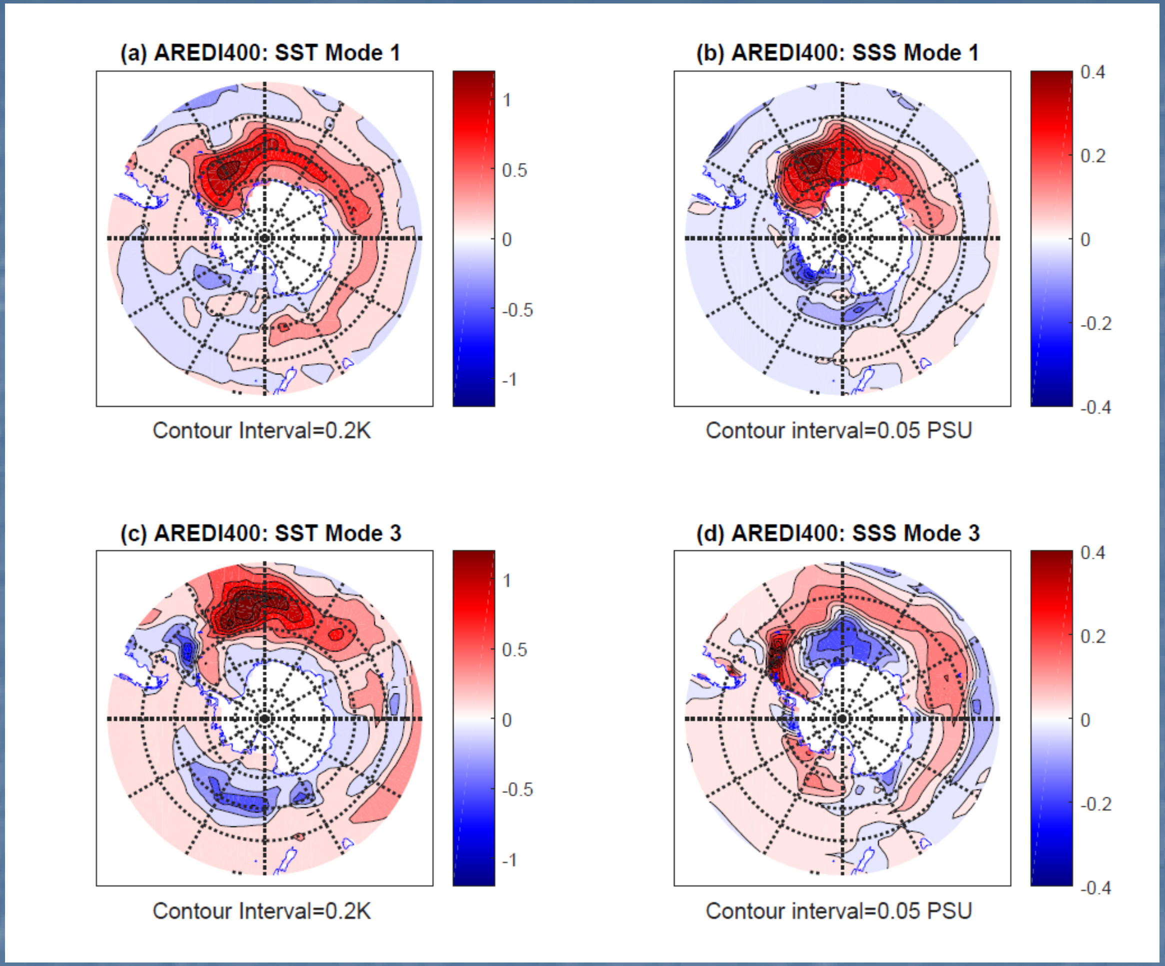


- Largest interdecadal variability in Weddell Sea
- Variation is very regular, with period of about 50 years
- Convection associated with removal of heat from below.
- Salinity anomaly much bigger at surface, leads convection.
- Density driven from surface.

Gnanadesikan et al., JPO, (2020)

How to reduce this to a comprehensible system?

- Empirical Orthogonal Functions: (Similar to principal components)
  - Identify the major “axes” of variability (look at what variables are strongly correlated or anticorrelated with each other)
  - Corresponds to computing a covariance matrix between points and taking the eigenvectors.
  - 1st PC has the most variance, 2nd the next, etc.
  - Can “rotate” EOFs to localize patterns.
- This reduces the dimensionality of the system. We can then look at how changes in modes with are related to other modes, and find “Principal Oscillation Patterns”.

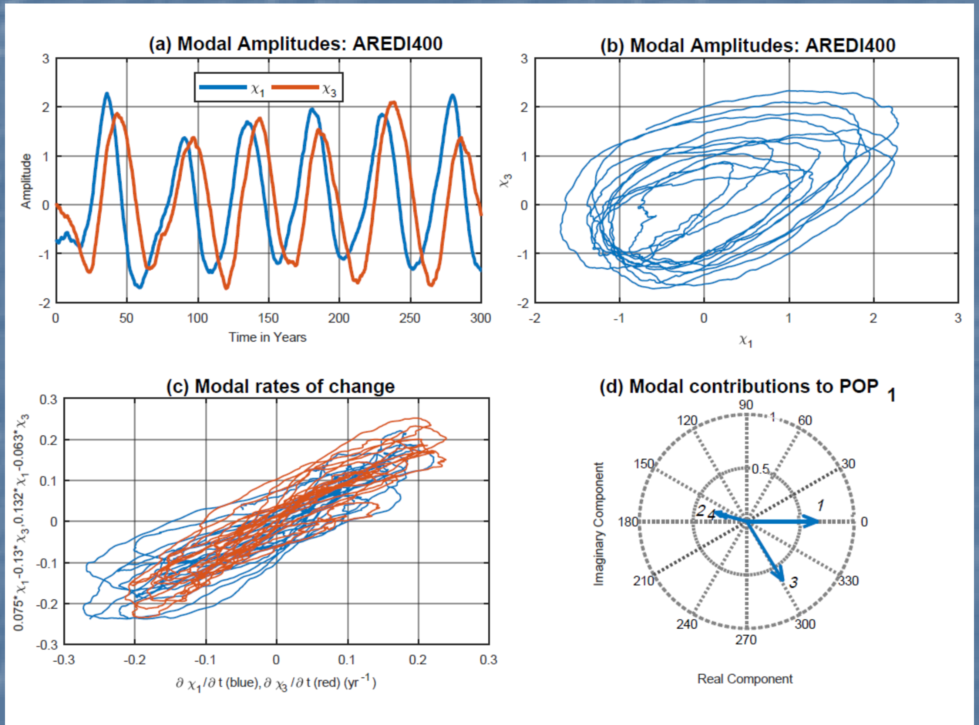


Identifying dominant patterns

1st rotated EOF shows covariation of SST and SSS in Weddell Sea.

3rd rotated EOF shows variation in salinity and temperature spatially offset from 1st EOF

Isolating the dynamics- Principal Oscillation Pattern Analysis



Gnanadesikan et al., rev. JPO

1st and 3rd EOFs are out of phase.

Can fit this with an oscillatory analysis.

$$\frac{\partial \chi_1}{\partial t} = 0.075yr^{-1} * \chi_1 - 0.128yr^{-1} * \chi_3$$

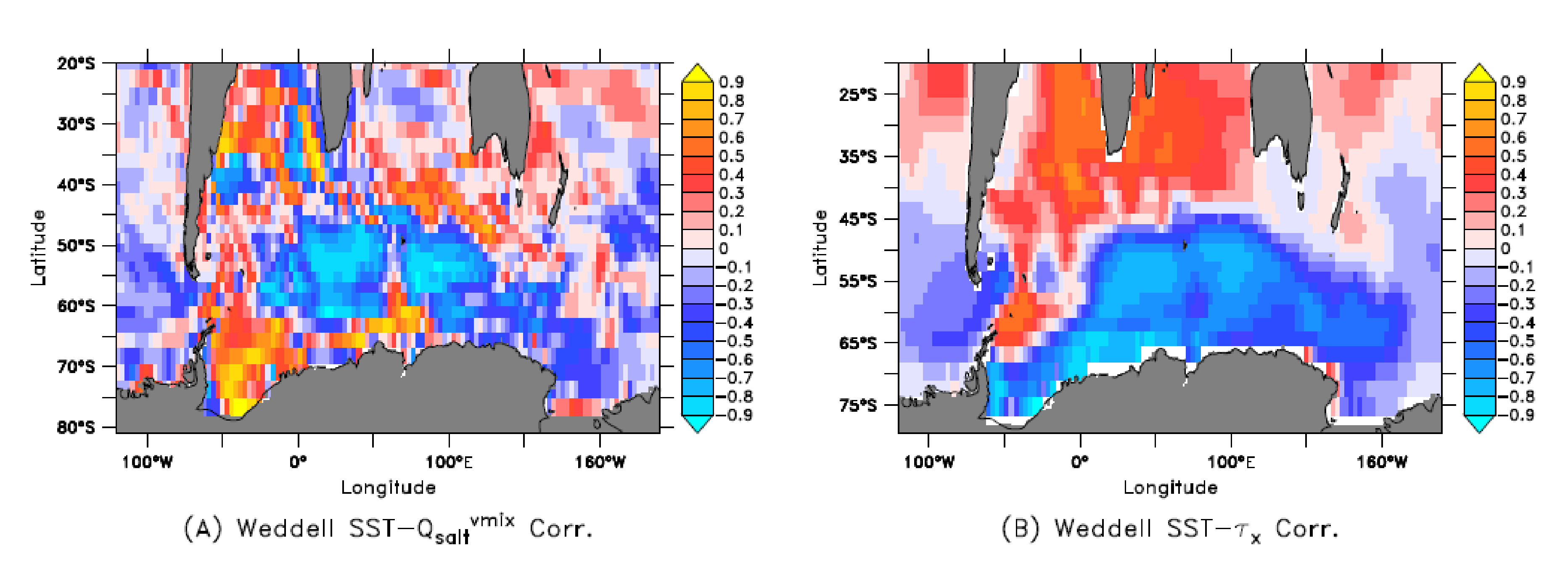
$$\frac{\partial \chi_3}{\partial t} = 0.132yr^{-1} * \chi_1 - 0.063yr^{-1} * \chi_3$$

Can be used to isolate a mode of variability with a period of 57 years.

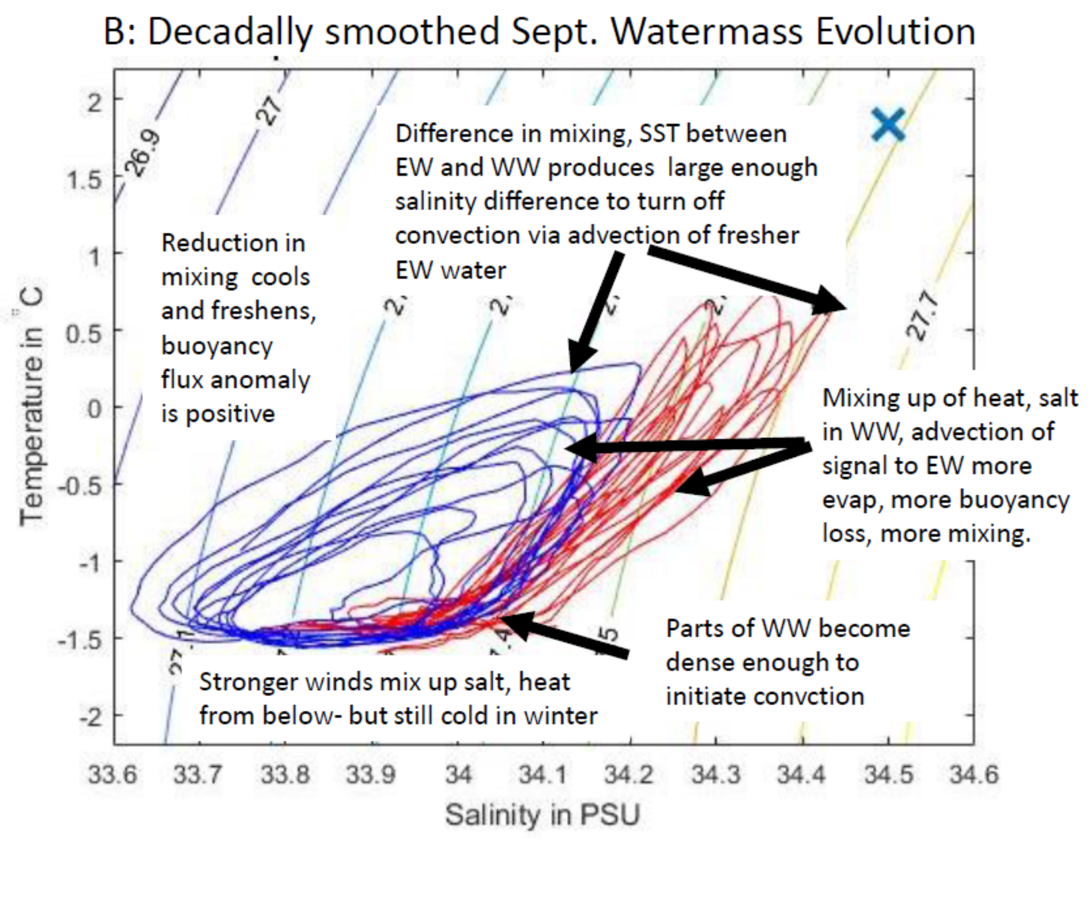
Basic story

- Convection in Weddell Sea corresponds to warm, salty water at surface.
- Results in increasing pattern with warmer water to north, fresher water to east.
- Fresh water to east advects into Weddell Sea and shuts off convection.

Driver of changes likely wind stress

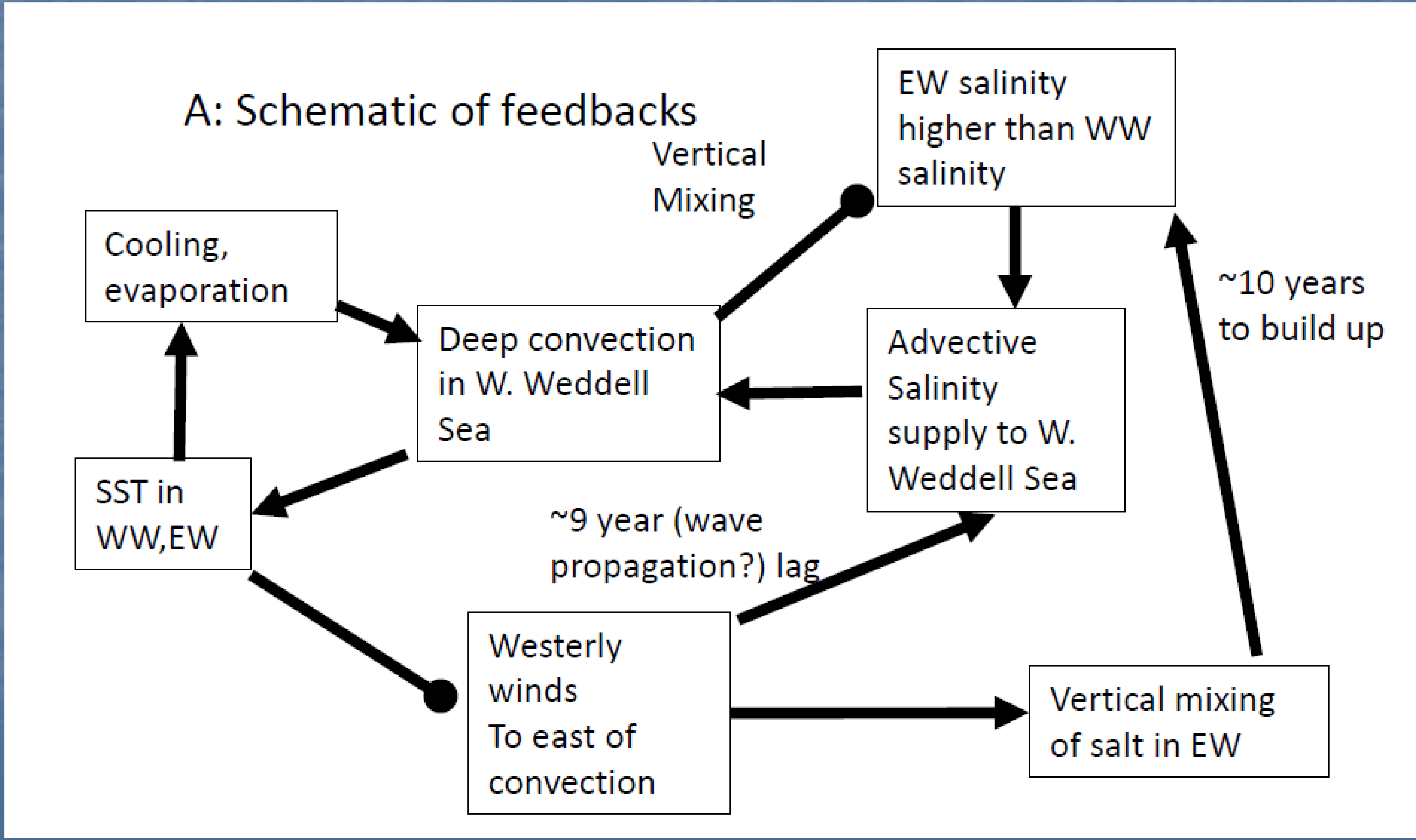


Schematic in watermass space



Eastern and Western Weddell proceed counterclockwise, in phase around these loops.

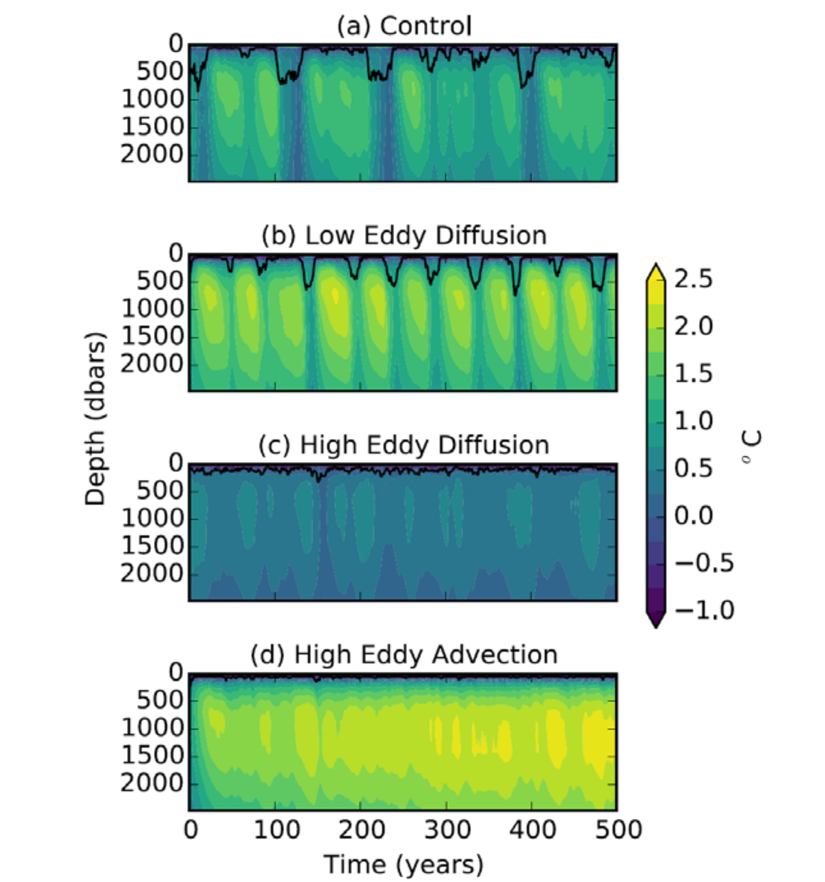
Summary Feedback Diagram

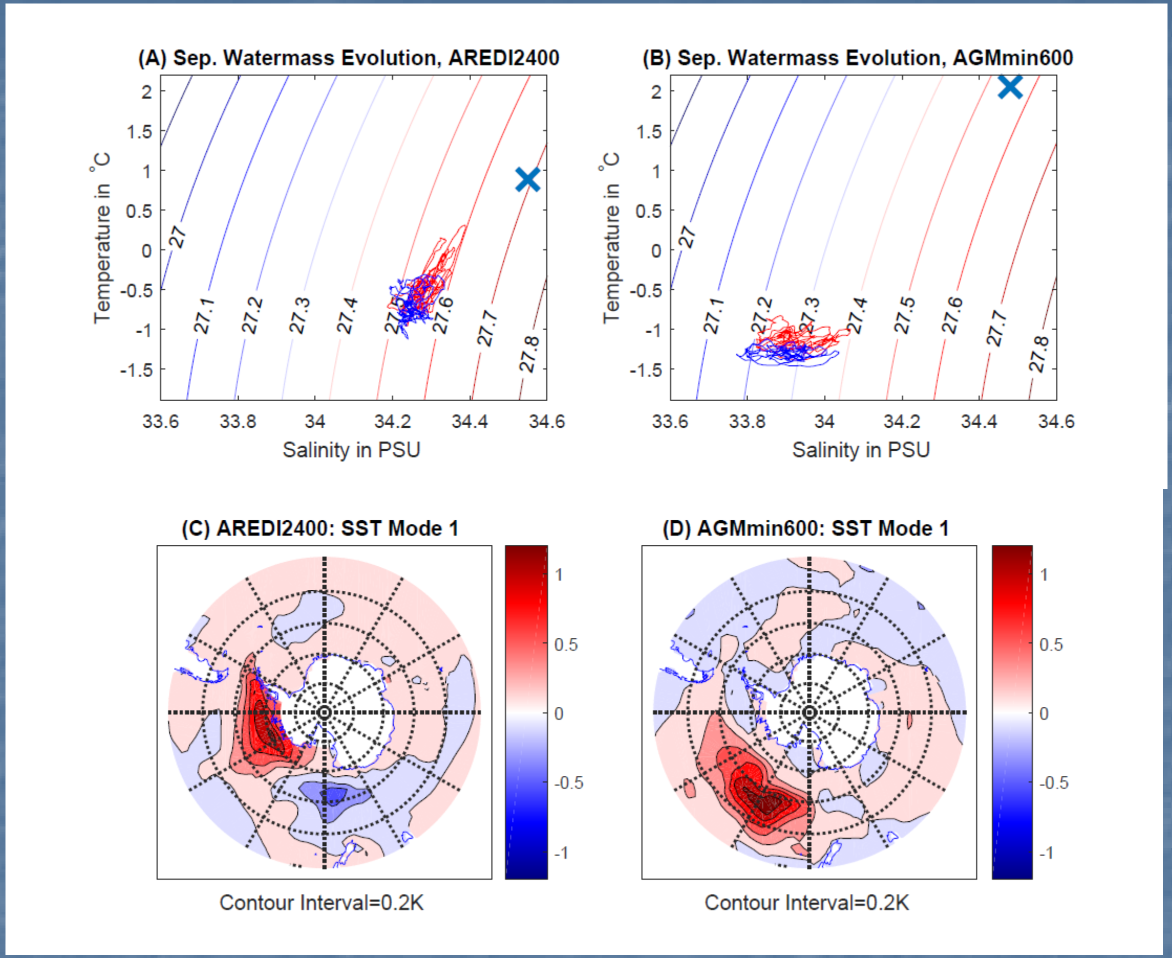


Changing mixing

- As we increase tracer diffusion variability in Weddell weakens.
- As we increase thickness diffusion variability also weakens.

(Thomas, Waugh and Gnanadesikan, J. Climate, 2018)





Gnanadesikan et al., J. Phys. Oceanogr., 2020

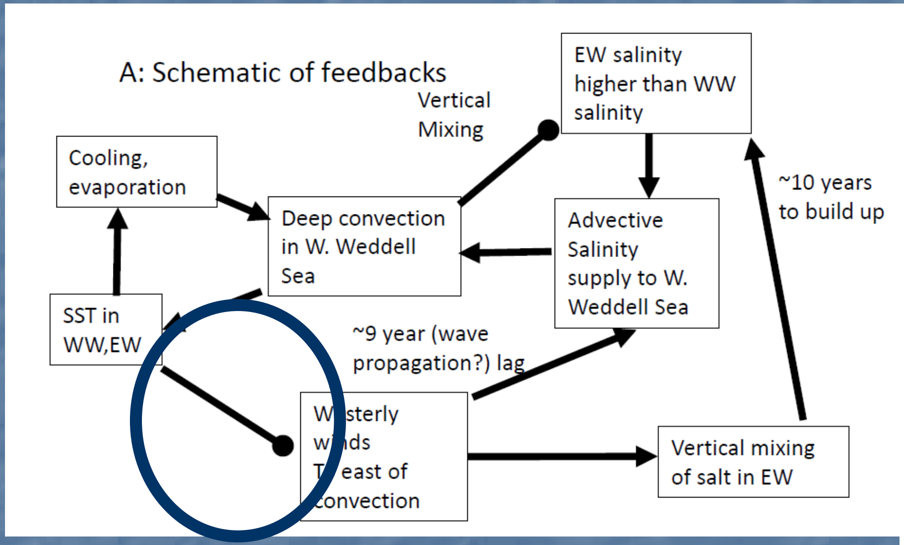
Brief analysis

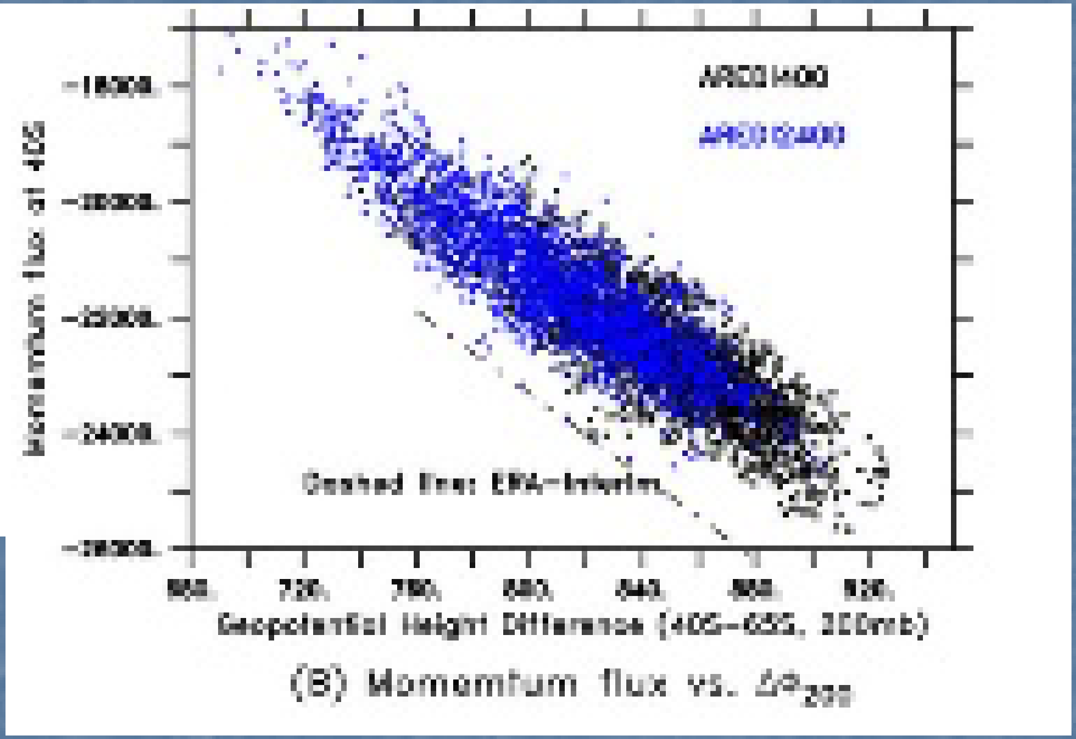
High tracer mixing is always in “convection on “ part of the cycle. Low gradients between regions mean advective mechanism gets suppressed.

High thickness mixing is in convection off part of cycle. Variability never manages to break through pycnocline.

Region of variability shifts

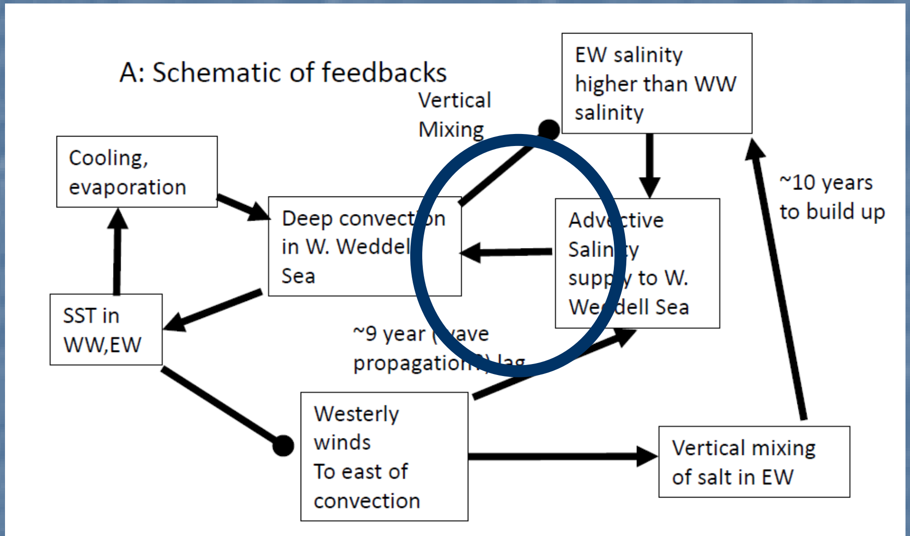
Realism of various parts of the mechanism



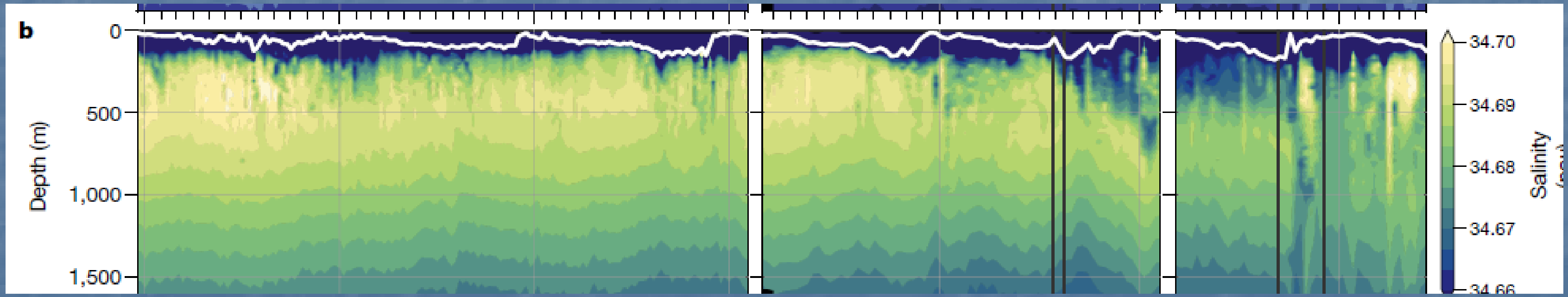


Ragen, Pradal and Gnanadesikan (JPO, 2020)

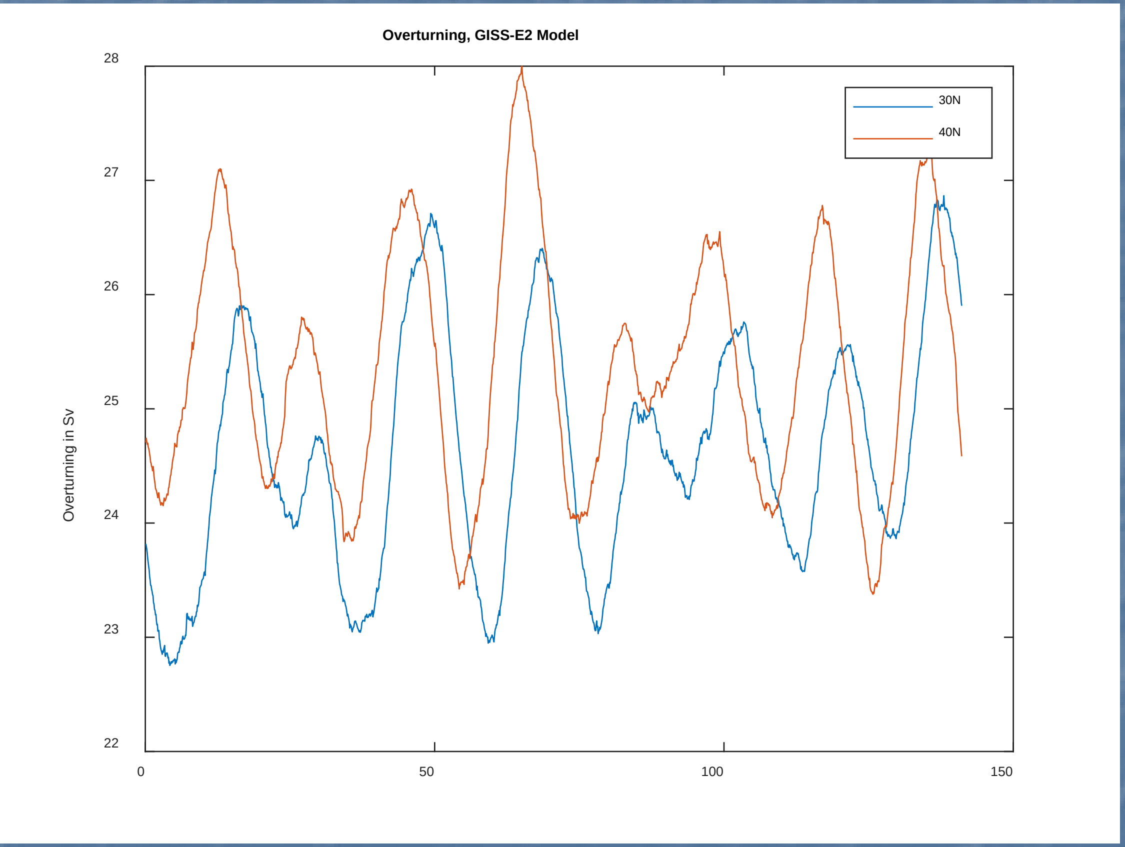
Realism of various parts of the mechanism



Campbell et al. (2019)



Can we apply this to the North Atlantic (work in progress)



- GISS model shows decadal scale variability in overturning circulation.
- Model also shows tipping point behavior under low CO2 forcing.

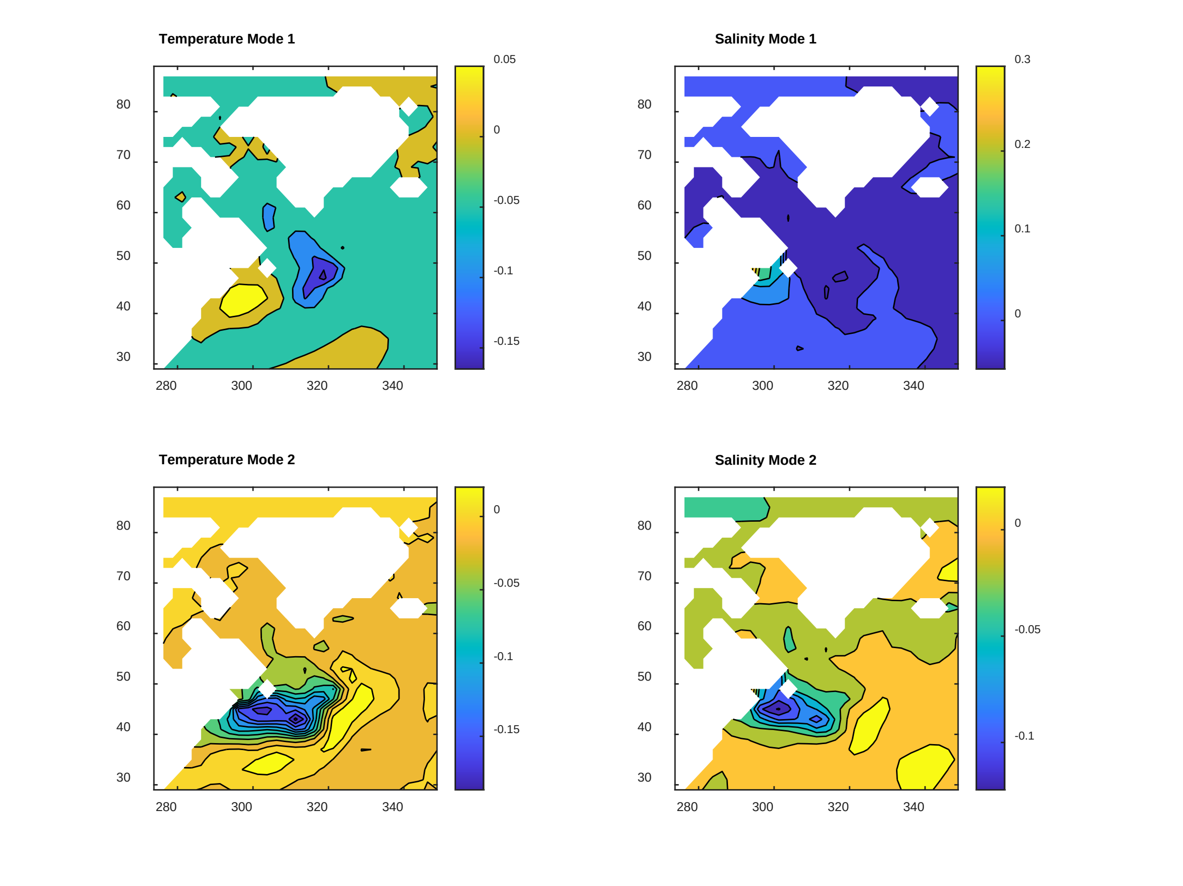
Modal analysis

Analysis of surface temperature/salinity shows major modes of variation that are linked to each other.

Increase in mode 1 associated with negative mode 2.

Increase in mode 2 associated with positive mode 1…

Oscillator!



Expanding the modal analysis

Period of oscillation when computed from linear eigenvalue analysis of tendency matrix of 1st ten modes mirrors this analysis.

Period still off- hints of nonlinearity? Koopman/NN analysis potentially helpful?

Plan- examine projections of variations in PI-Control to see whether they give predictors of tipping.... or whether mechanism is entirely different.

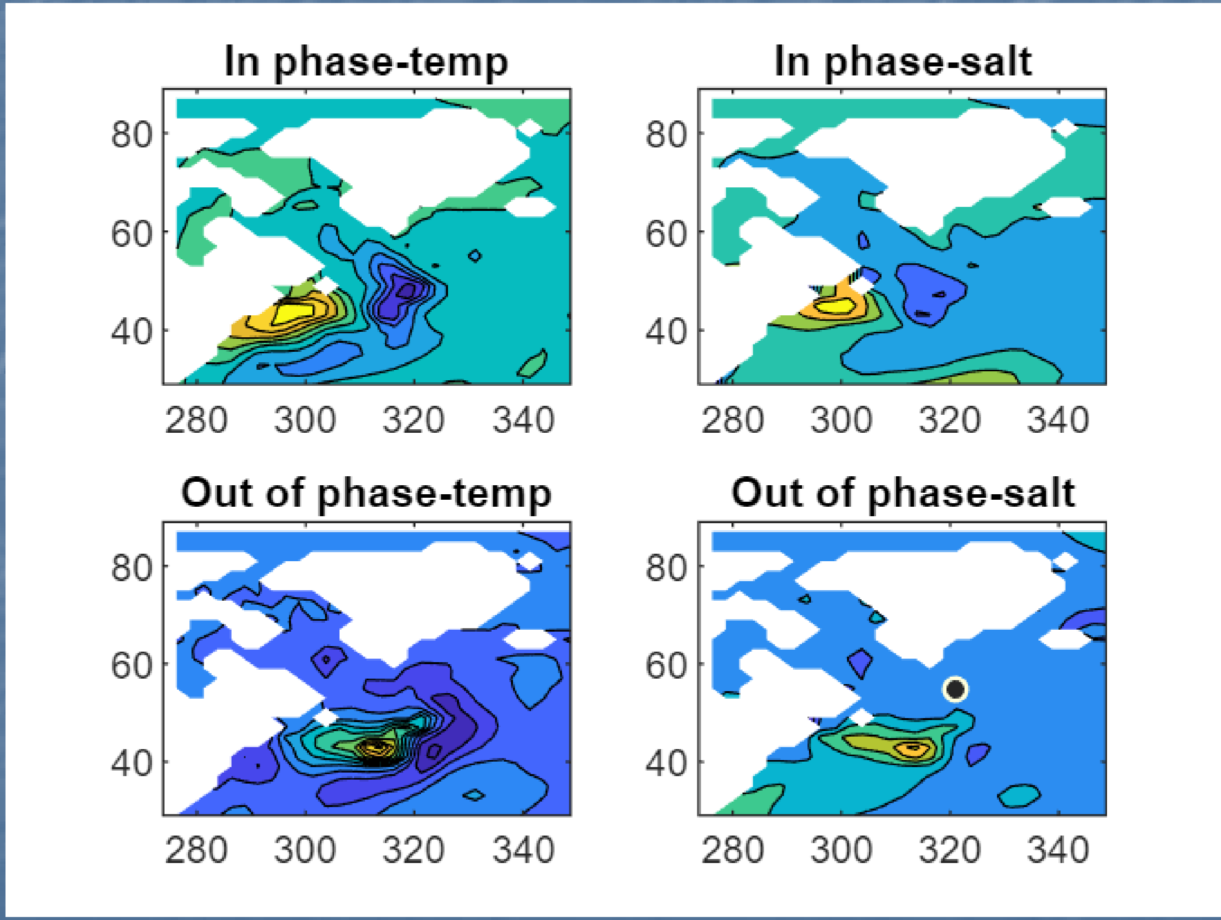


Illustration of the mechanism

Positive
feedback loop

Anomalous convection/
overturning

Anomalous salinity
in convective region S1

Changes in atmospheric/
Oceanic circulation

$$\frac{\partial S_2}{\partial t} = \frac{S_2}{\tau_2} + \lambda_1 * S_1 - a * Noise$$

Anomalous salinity in
remote region
(where?)

Negative
feedback loop
with delay

$$\frac{\partial S_2}{\partial t} = -\frac{S_1}{\tau_1} - \lambda_2 * S_2 + b * Noise$$

Problem...

Analysis predicts far too long a period (~50 years rather than ~20). Why?

One thing we are examining is the role of nonlinearity in the system... there is literature in the mathematics community looking at a using neural networks rather than linear models to predict variation.

Additional questions raised by this analysis

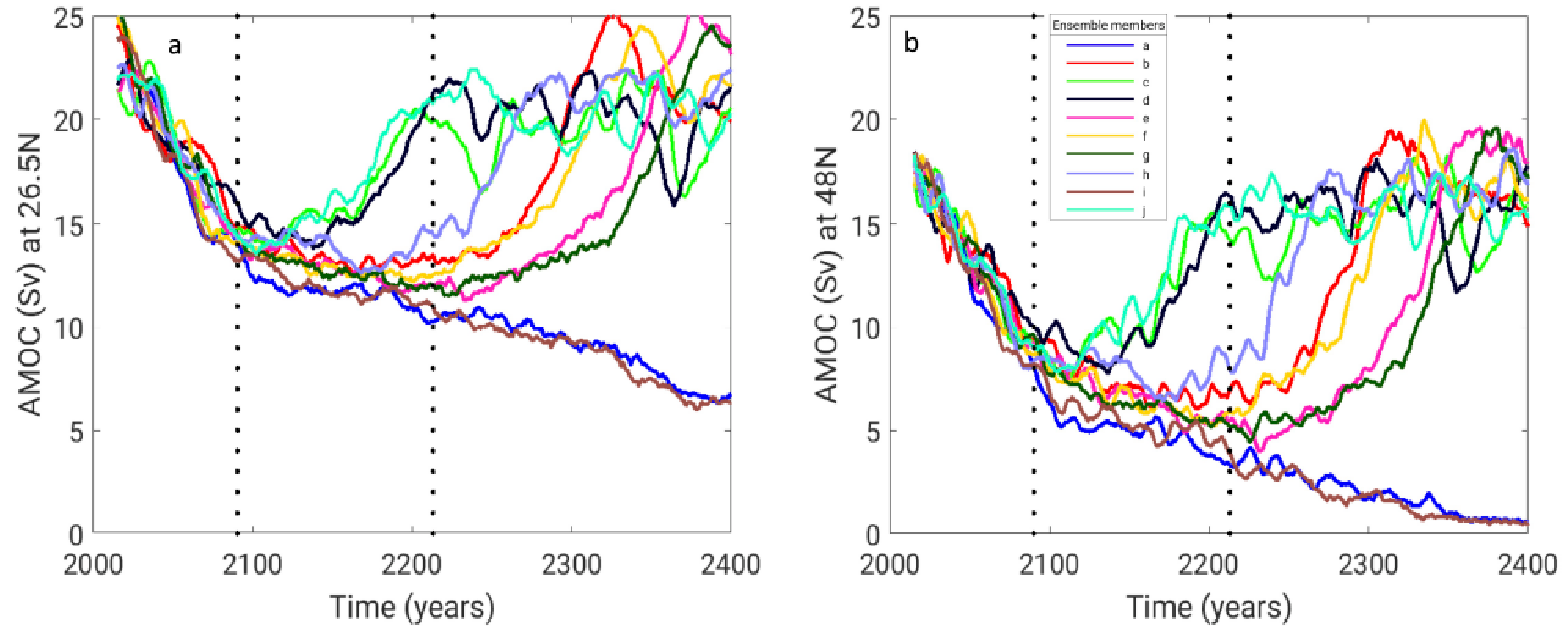
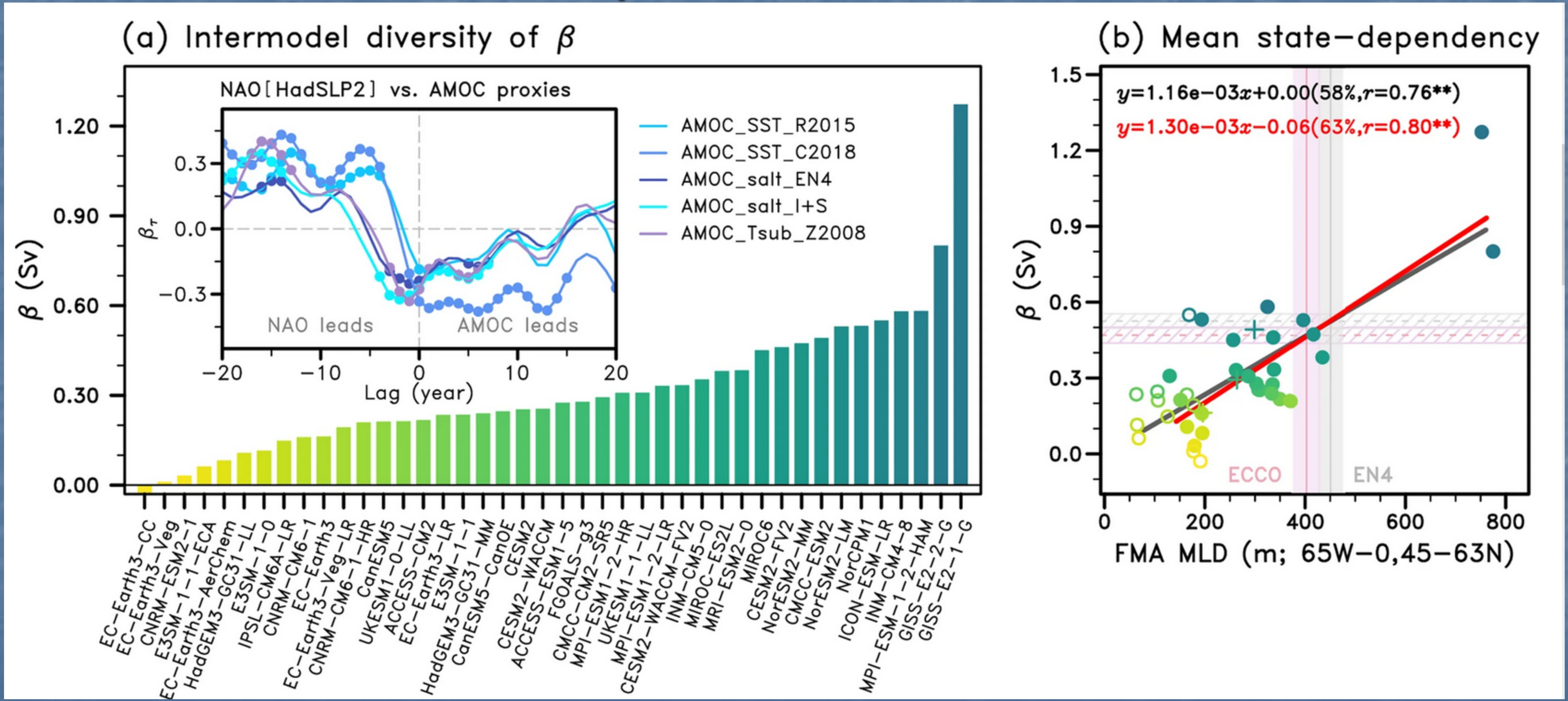


FIG. 1. AMOC strength, defined as the maximum overturning streamfunction below 500m, at (a) 26.5°N and (b) at 48°N, from 10 ensemble members of the SSP2-4.5 scenario simulation. Vertical dotted lines correspond to times of change in GHG forcing (see Fig. 2a). All fields are smoothed using a 10-year moving average filter.

Can modal analysis help explain this?

- Preliminary work suggests that modes are different as we warm planet
- Original modal structure showed little impact from salinity in Arctic- “modern” simulation does.
- Insofar as changes in circulation produce changes in pressure systems and winds (Icelandic low)....
  - In cold climates this may just blow more or less cold air over Arctic, little change in ice melt.
  - In warm climates the air may be warm enough to generate variability in ice melt, create anomalies that can turn off the circulation.

Recent paper suggests GISS model is an outlier in response to winds



Conclusions

- Long-period polar variability (decadal-centennial scale) is hinted at in a lot of observations, appears in some (but not all!) models in both Northern and Southern Hemisphere.
- Oscillator theory can be fit to at least one model in one hemisphere- suggesting coupling between temperature, winds and salinity.
- But a lot more remains to be done to see if this is a productive way of thinking about such phenomena more broadly.
- Key questions remain regarding “tipping points”.