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The rapid warming of the North Atlantic in the mid 1990s: mechanisms and predictions

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Outline

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- Introduction: Warming of the North Atlantic
- Key Mechanisms
- Prediction (when things go wrong / when things go right)

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Introduction

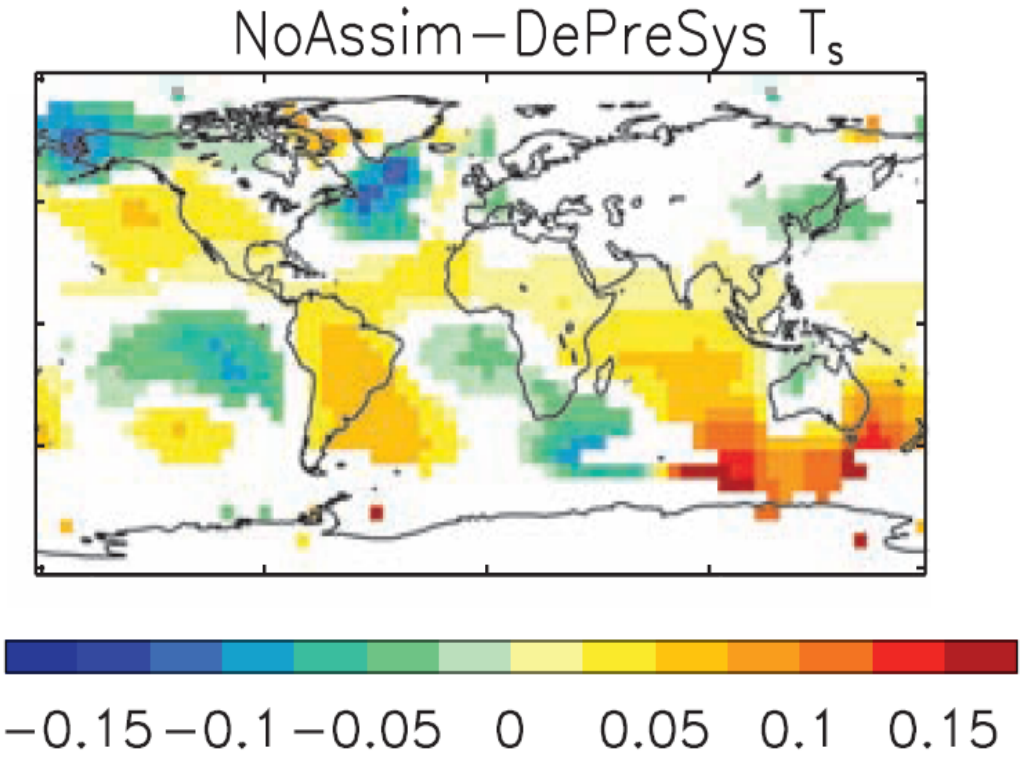
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Introduction and motivation

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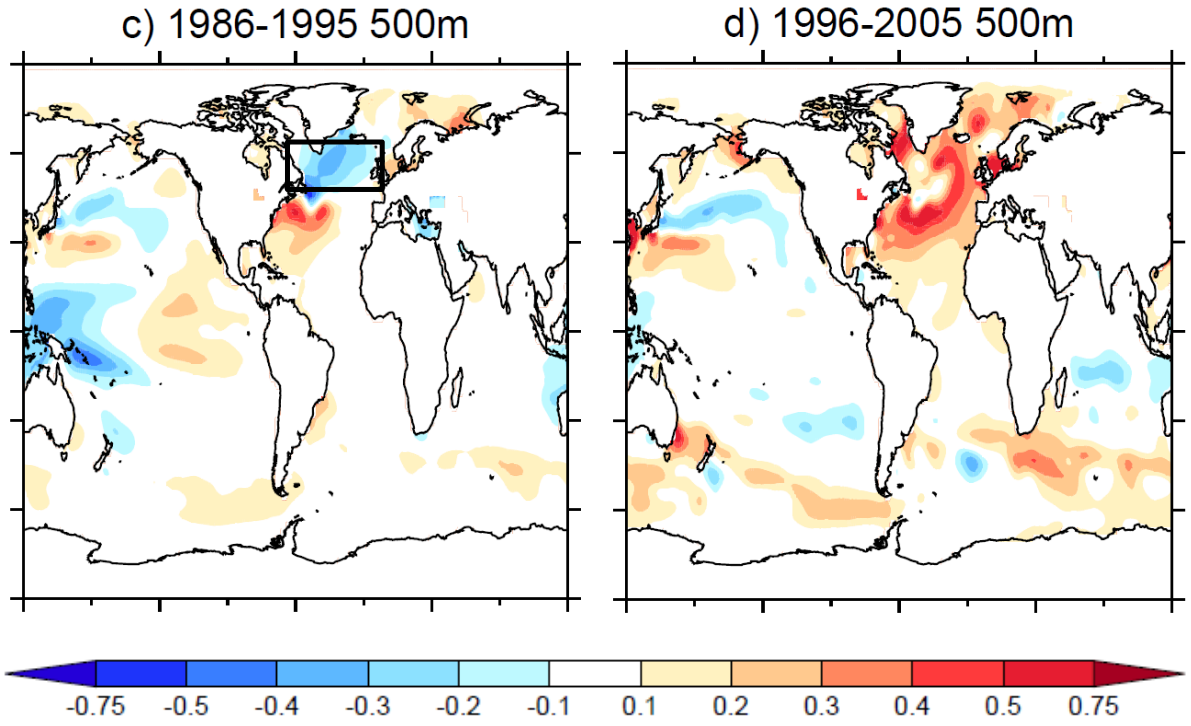
- Smith et al, 2007. showed that assimilating in the observed state of the climate improved forecasts of surface temperature relative to forecasts that do not assimilate information.
- However, skill does not improve everywhere
- Mean skill scores provide little insight



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Recent global changes

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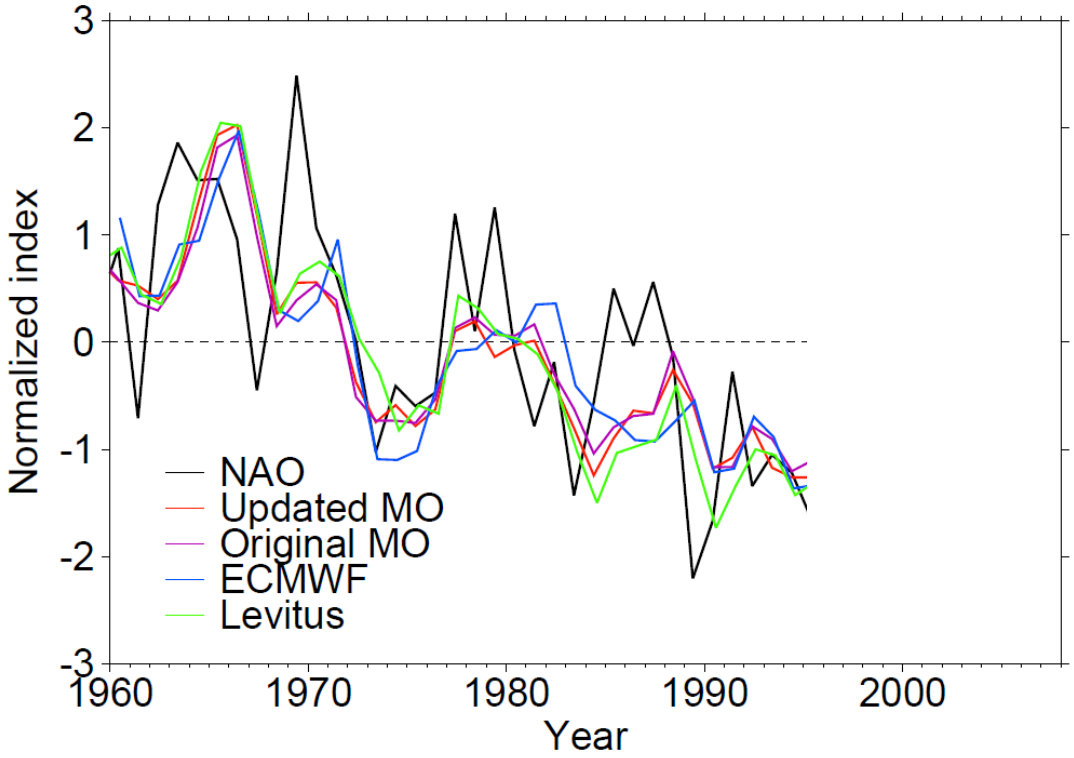
Mean temperature anomalies
All anomalies relative to 1961-1990 climatology

- The North Atlantic has undergone a rapid warming since the mid 1990s
- Warming is especially apparent in the subpolar gyre region
- Warming was important for increased melting of Greenland Ice sheet, reduced CO_2 uptake and possibly increased hurricane frequencies
- **What is the cause of this variability?**

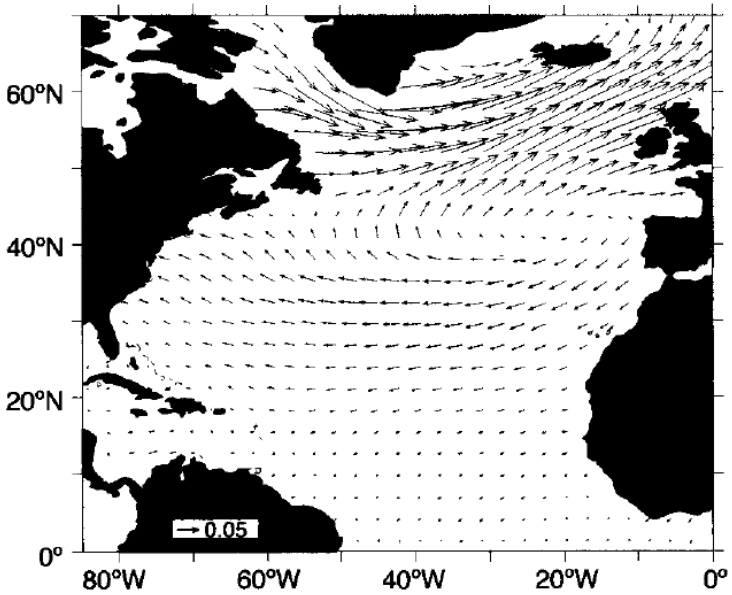
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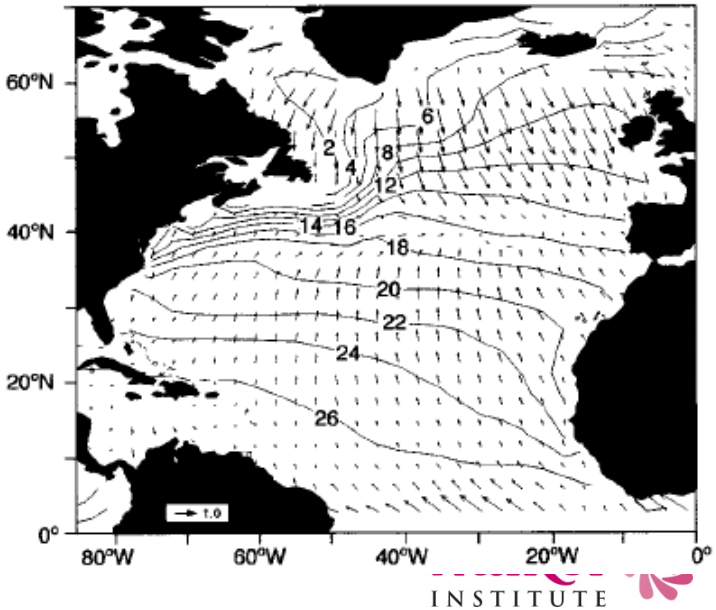
Subpolar gyre and the North Atlantic Oscillation (NAO)



Wind stress anomaly



Ekman anomaly

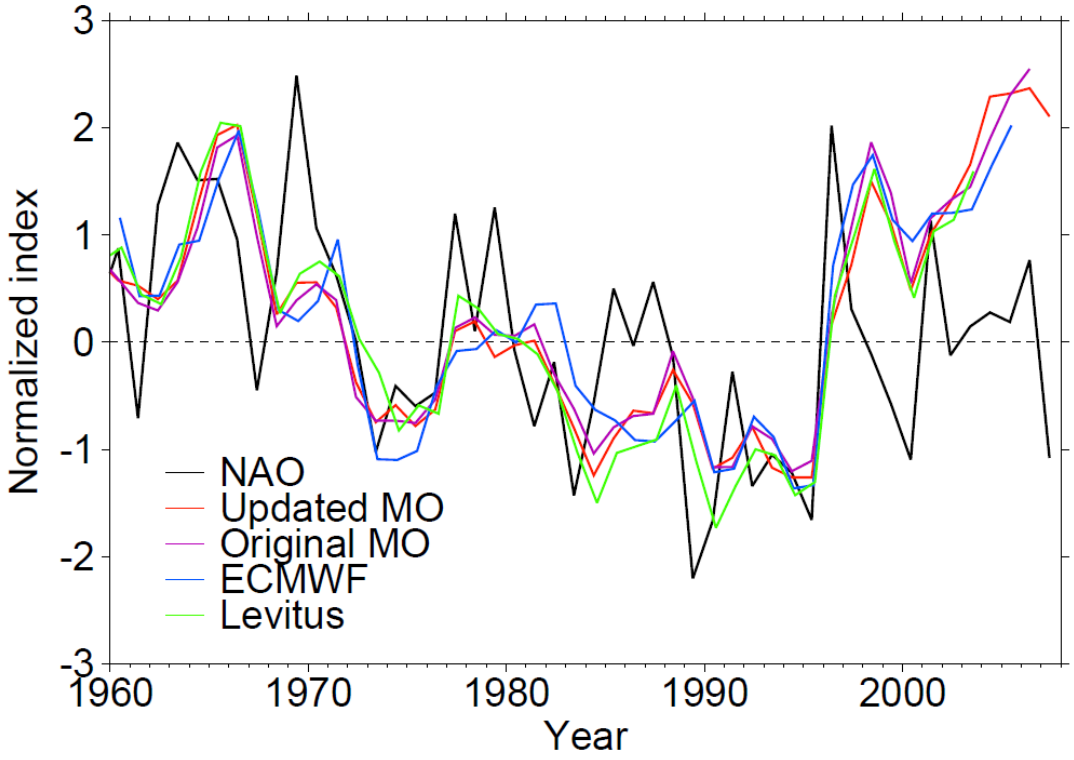


BLACK: *Inverted* NAO

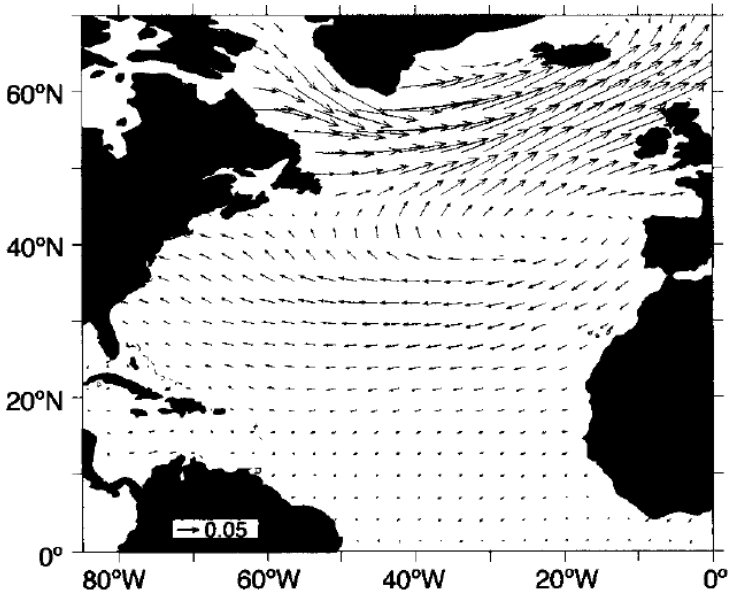
Temp anomaly of Subtropical gyre (60W-10W,50N-66N) from Levitus, ECMWF and Met Office

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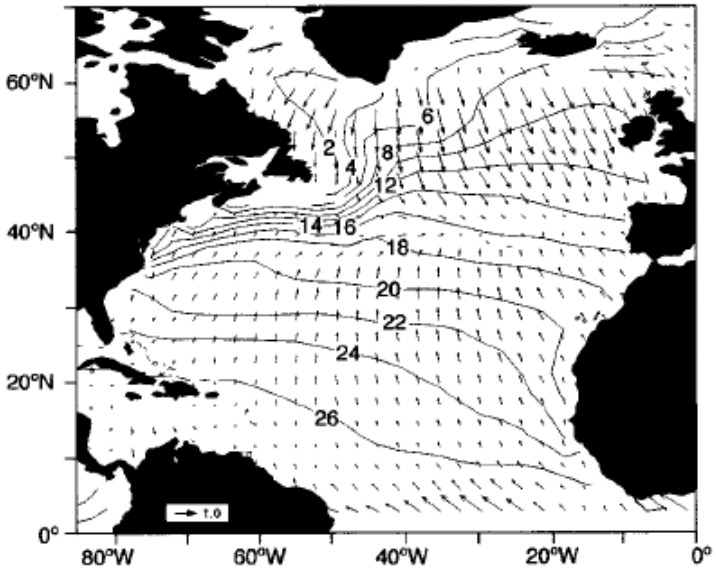
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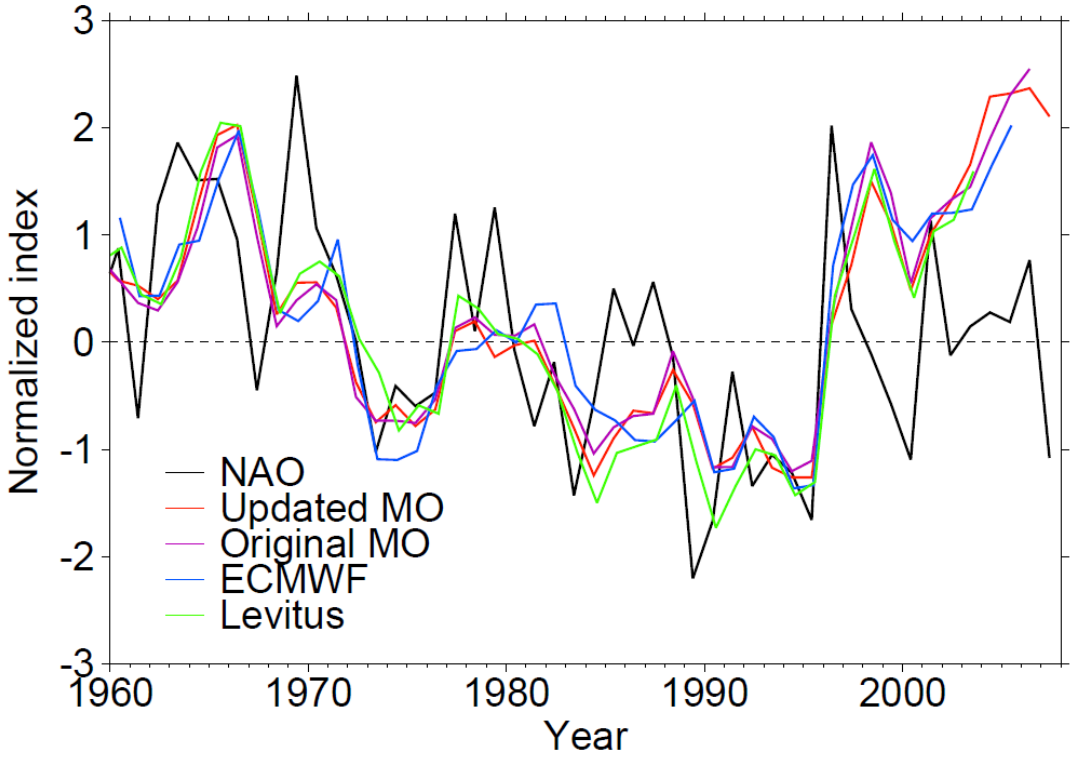


BLACK: *Inverted* NAO

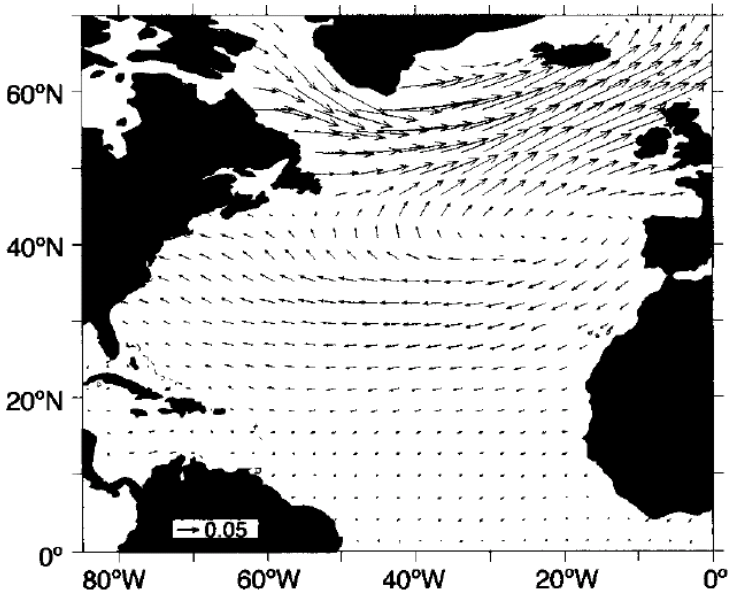
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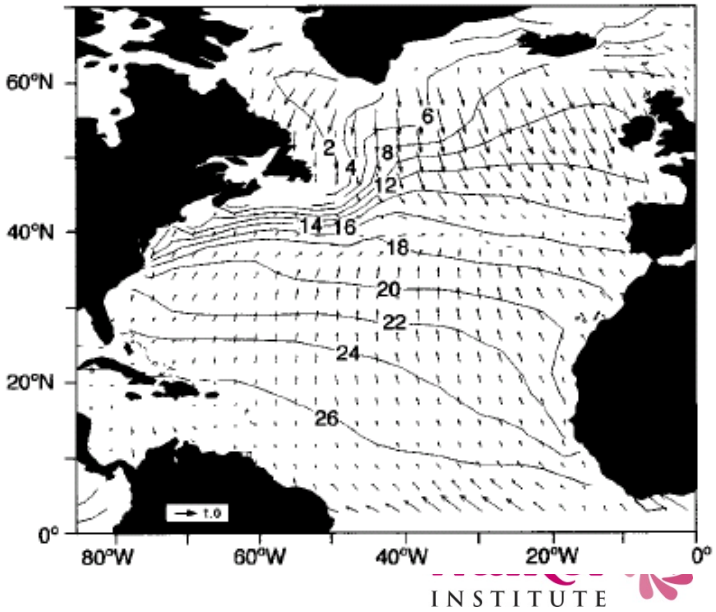
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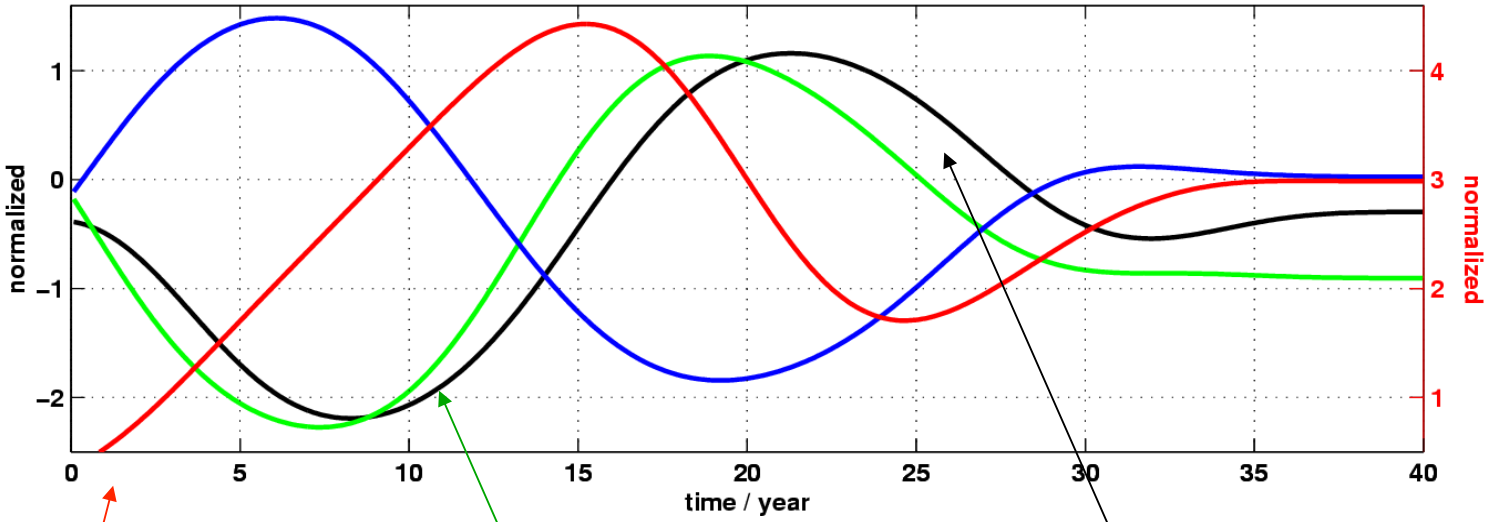
Was the warming of the North Atlantic an instantaneous response to the NAO- ?

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Large scale changes: AMOC

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- Evidence for a lagged response of the Atlantic Meridional overturning circulation to the positive NAO (i.e. Dong and Sutton, 2005)
- Lohmann et al, 2009 gave a nice example by forcing the ocean with persistent NAO+



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Hypotheses for the warming of the subpolar gyre

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A. Instantaneous response to the decline in the NAO (especially 95/96):

- Thermodynamic response to surface buoyancy fluxes
- Dynamic response

B. Lagged response to the persistent high NAO conditions that preceded the warming

B is best for predictability

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What were the key mechanisms?

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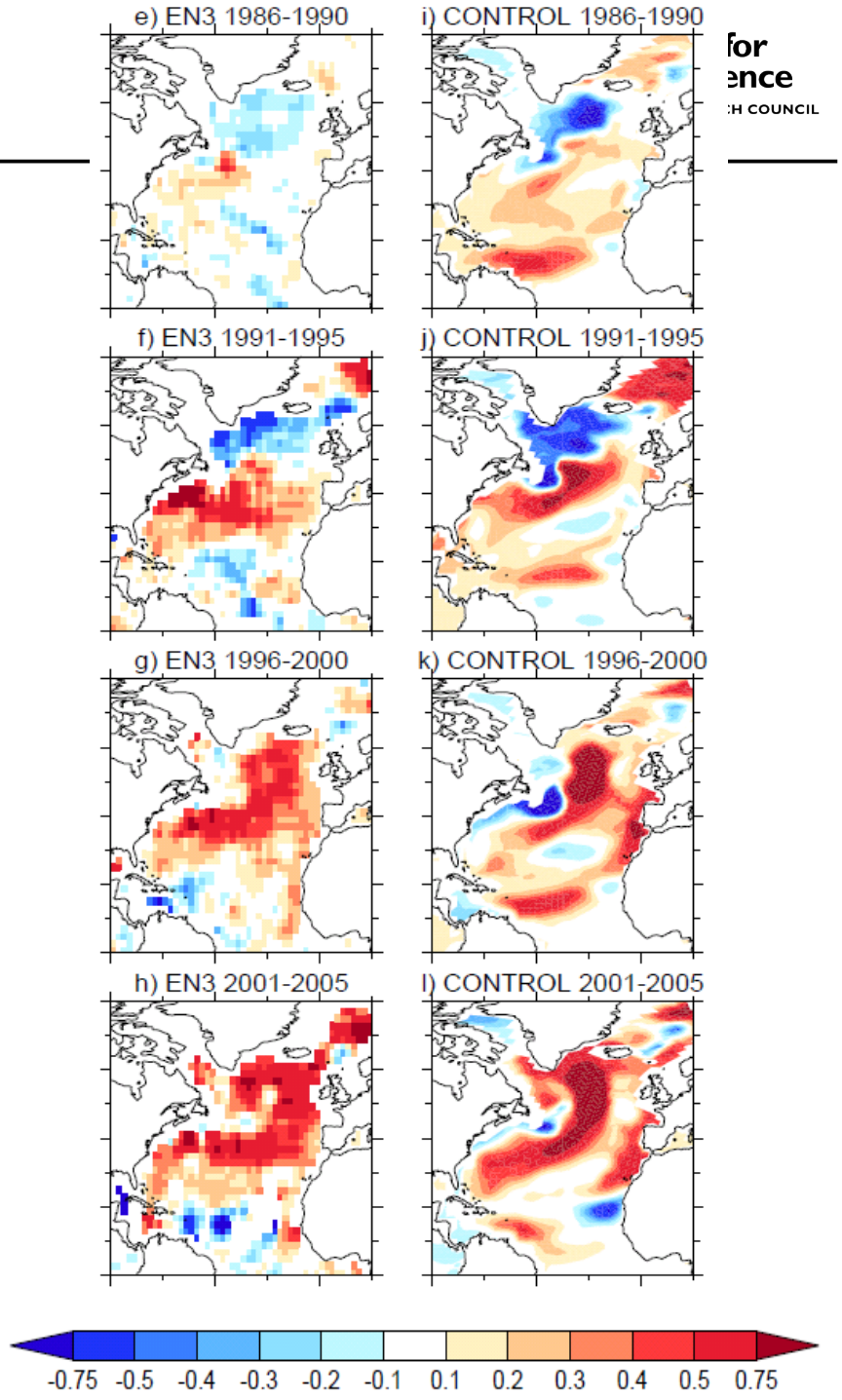
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Experimental design and comparison

- MICOM 2.4° resolution, ~150km in the Atlantic

Historical experiments

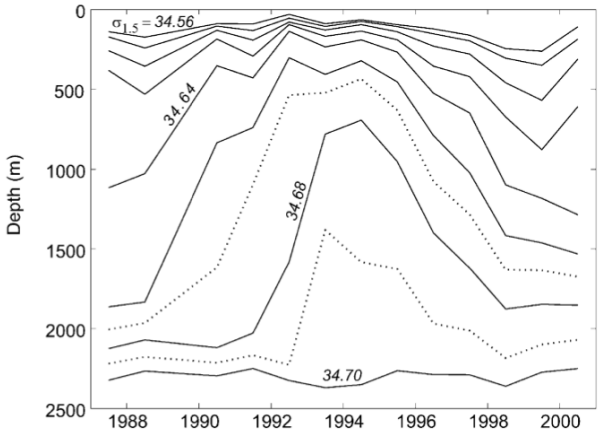
- **CONTROL** - Ocean forced with realistic daily fluxes taken from NCEP reanalysis from 1948-2006



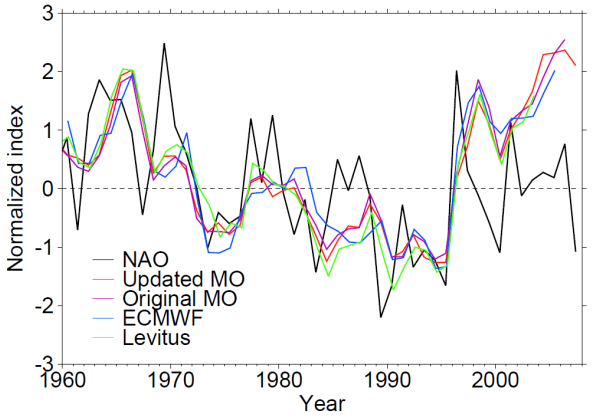
The model also recreates the sub surface cooling (1000-2500m)

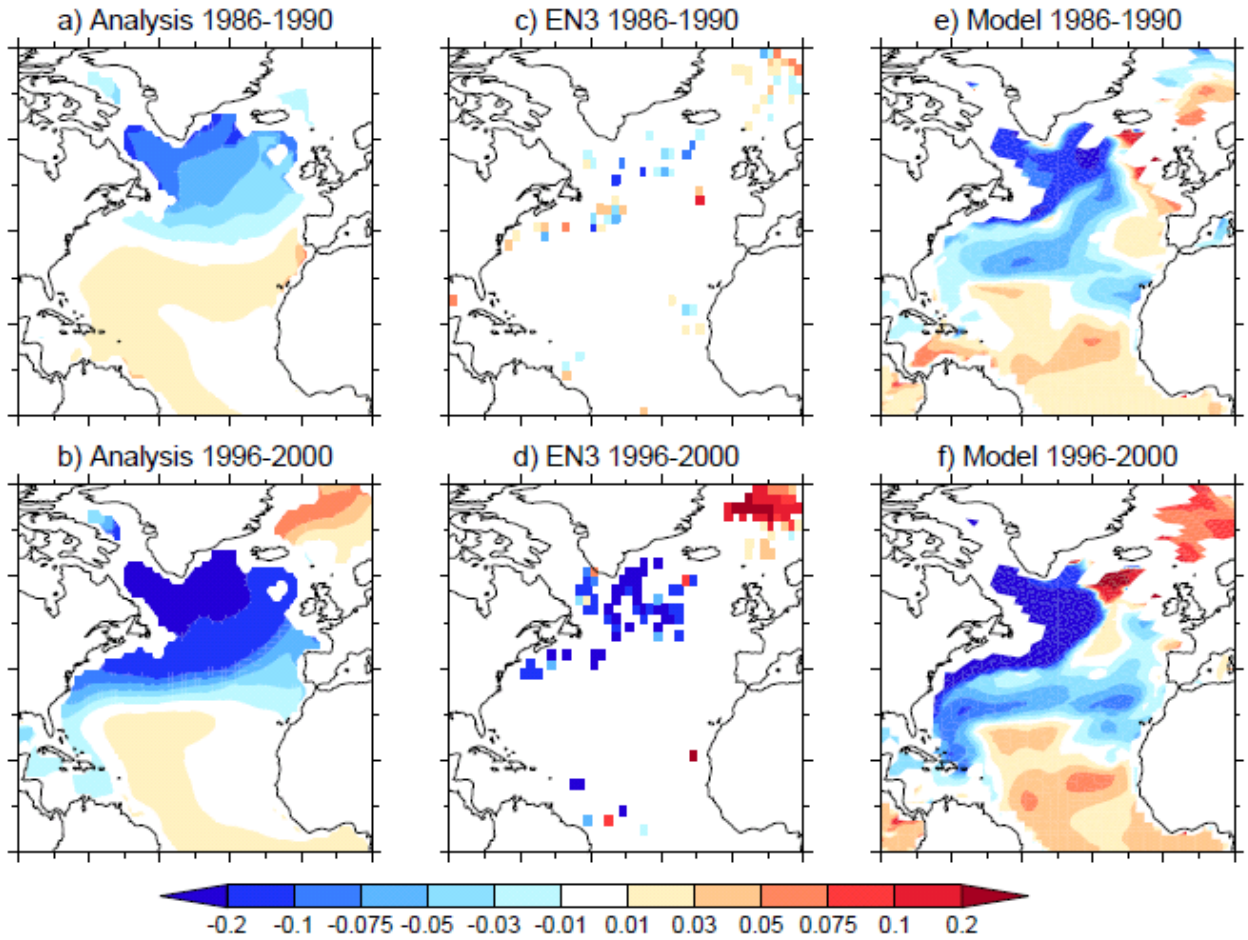
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Depth of isopycnals in Labrador sea



(Lazier et al, 2002)

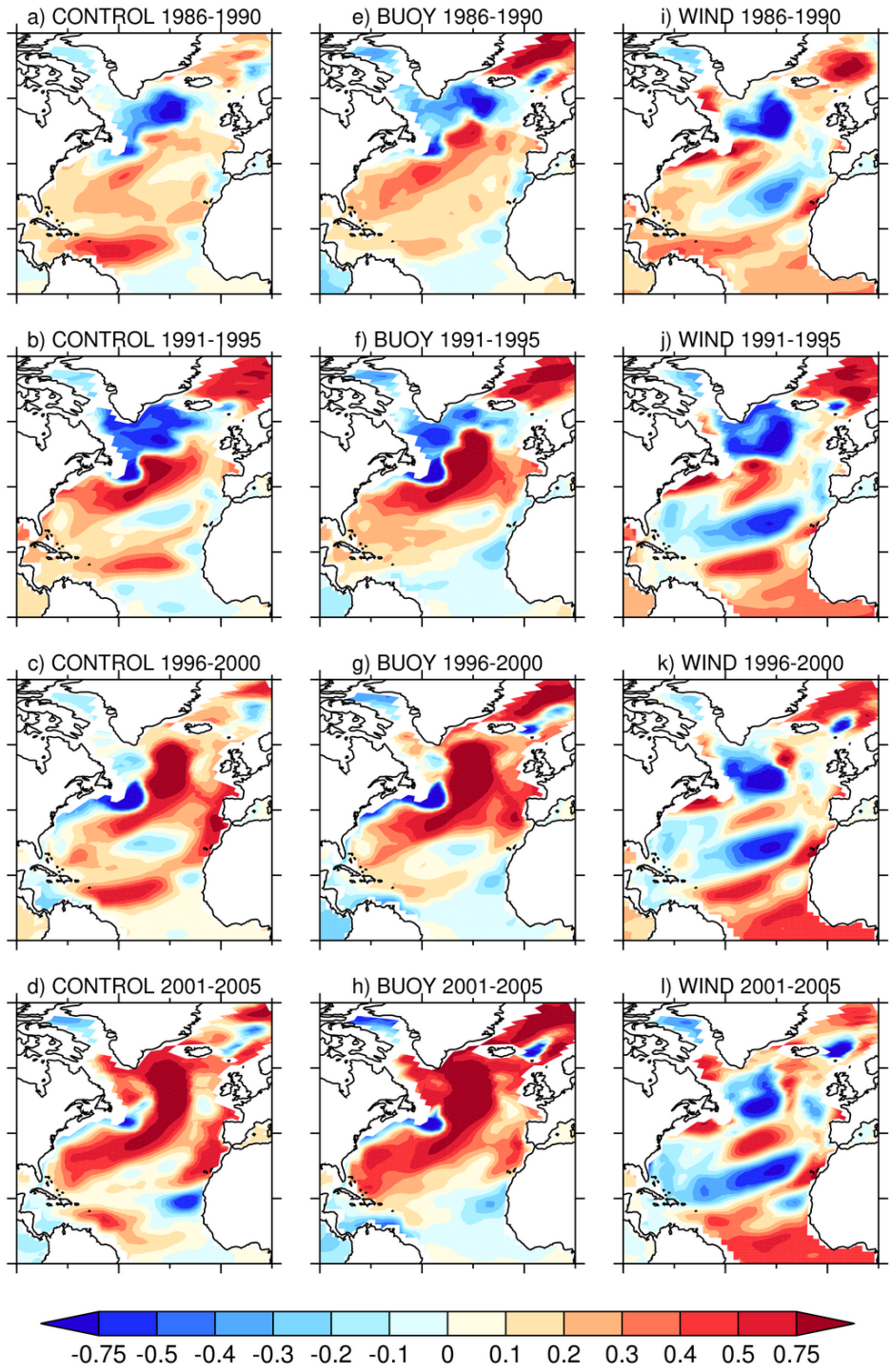




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0-500 heat content anomalies

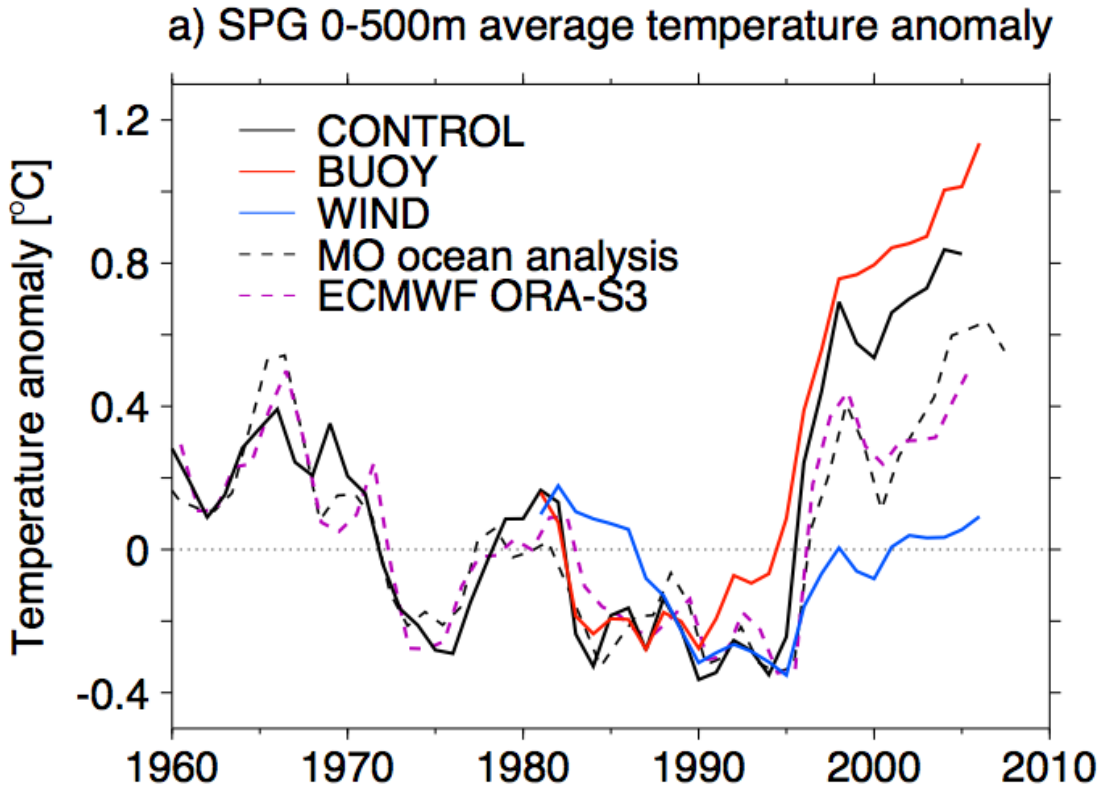
- Two extra ocean only integrations where either the wind stress **or** the buoyancy forcing is allowed to vary – started in 1980 from the CONTROL
  - **BUOY** – climatological wind stress - Buoyancy fluxes vary
  - **WIND** – climatological buoyancy fluxes – wind stress varies
- The buoyancy forcing is key to recreating the heat content
- *The pattern is not just caused by changes in the surface heat fluxes*
- **Ocean dynamics are important**



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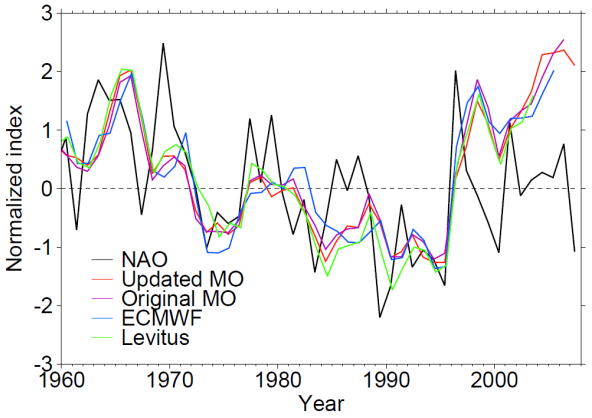
What are the changes in the North Atlantic subpolar gyre?

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The ocean experiments also capture the timing and rapidity of the warming

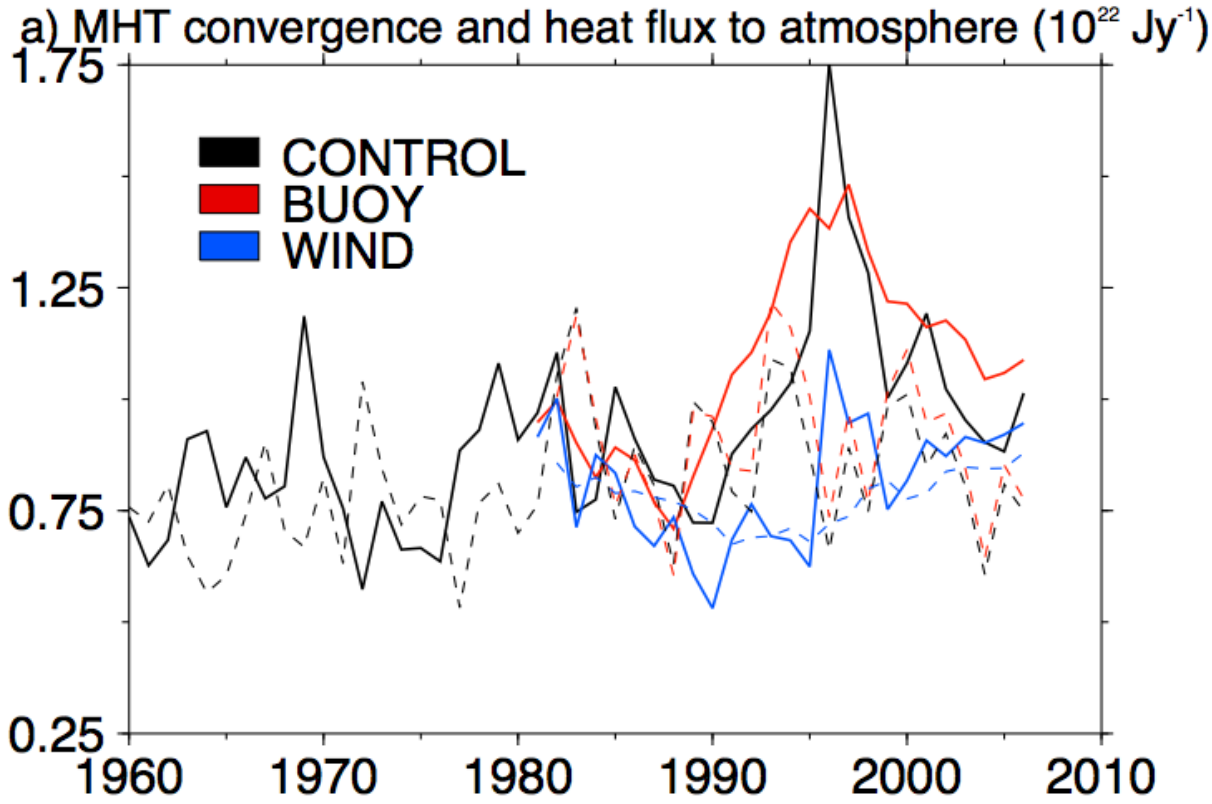
how important is the surface energy flux for the *timing* of the warming?



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Energy Budget of the Subpolar gyre

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- Solid = ocean heat transport convergence (H_O)
- Dashed = atmospheric heat loss (H_A)

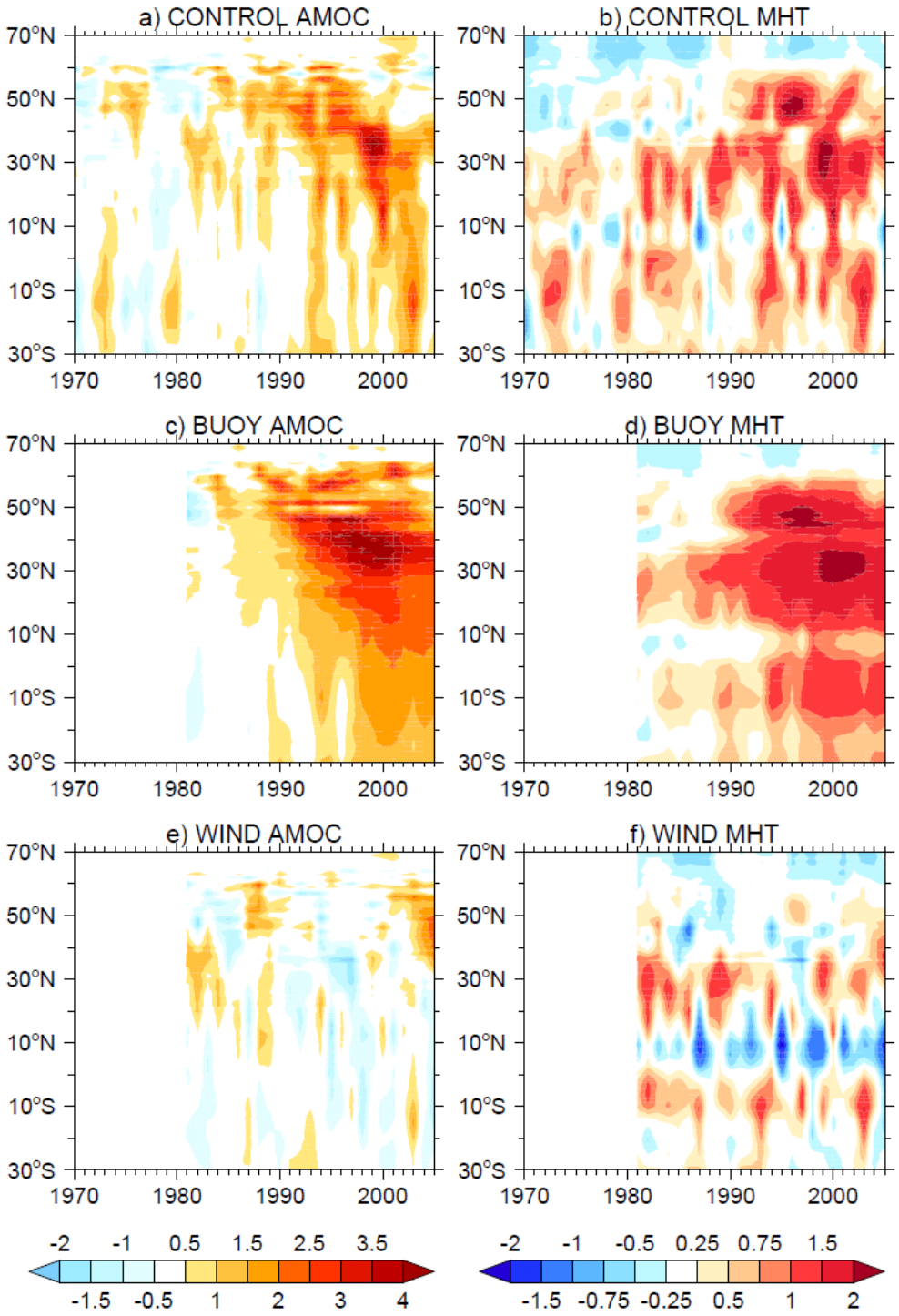
What is the reason for the increase in the ocean heat transport convergence?

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Changes in the AMOC

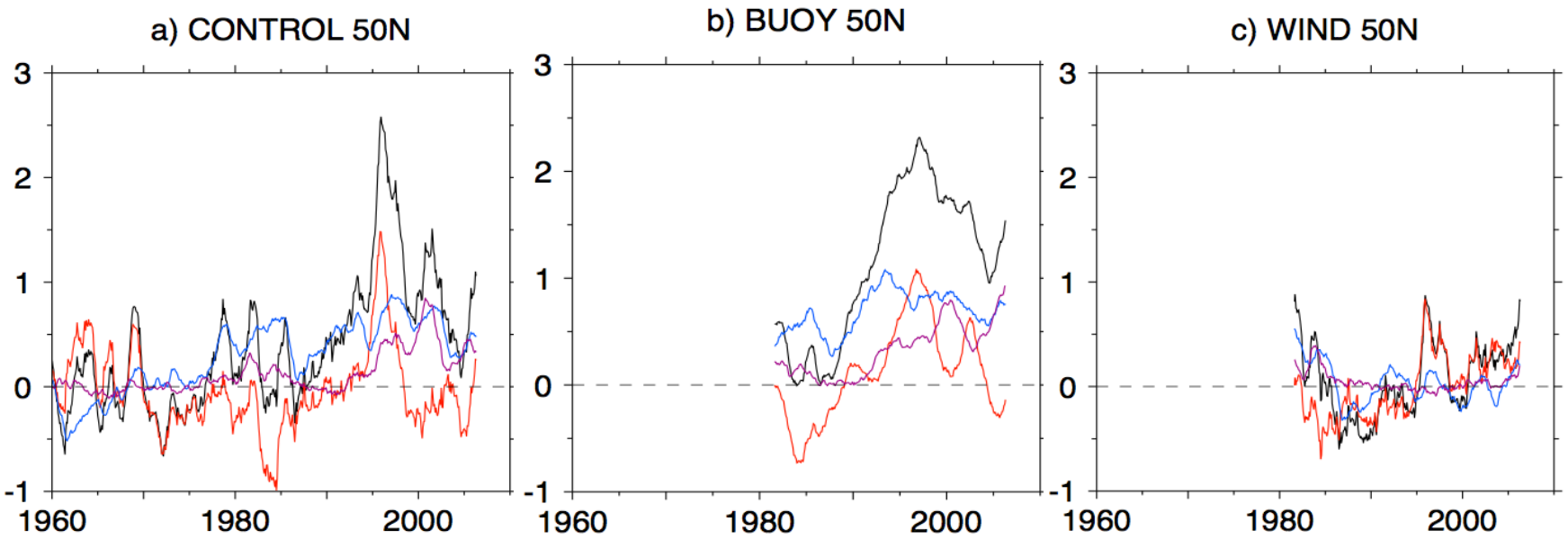
- CONTROL shows an increase in the AMOC and an increase in MHT
- Low frequency strengthening of the AMOC is due to the *buoyancy forcing*
- Wind forces higher frequency variability which modulates the AMOC and MHT



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Role for the NAO-

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$V' \bar{T}$ = Red

$\bar{V} T'$ = Blue

$V'T'$ = Purple

Ocean heat transport 1 x 10^{14} W

Negative NAO key for the rapidity of the warming, but warming would have been inevitable

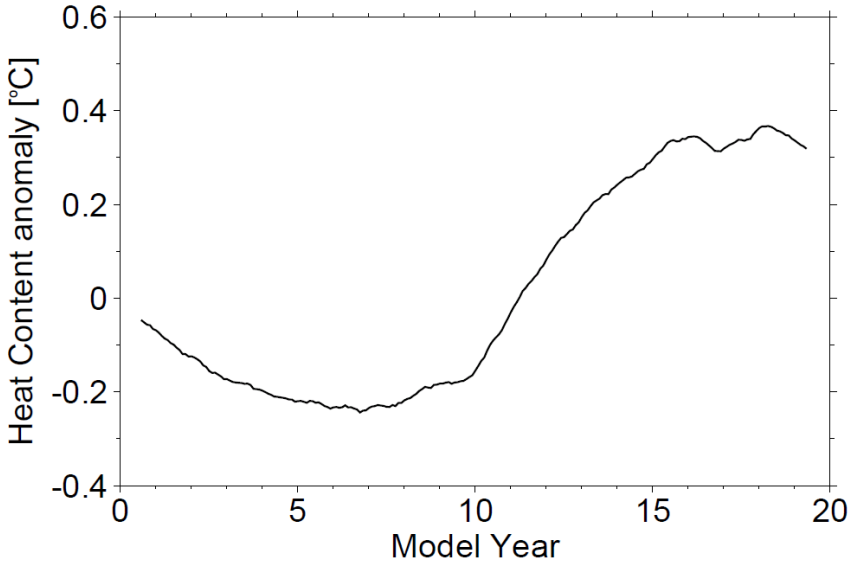
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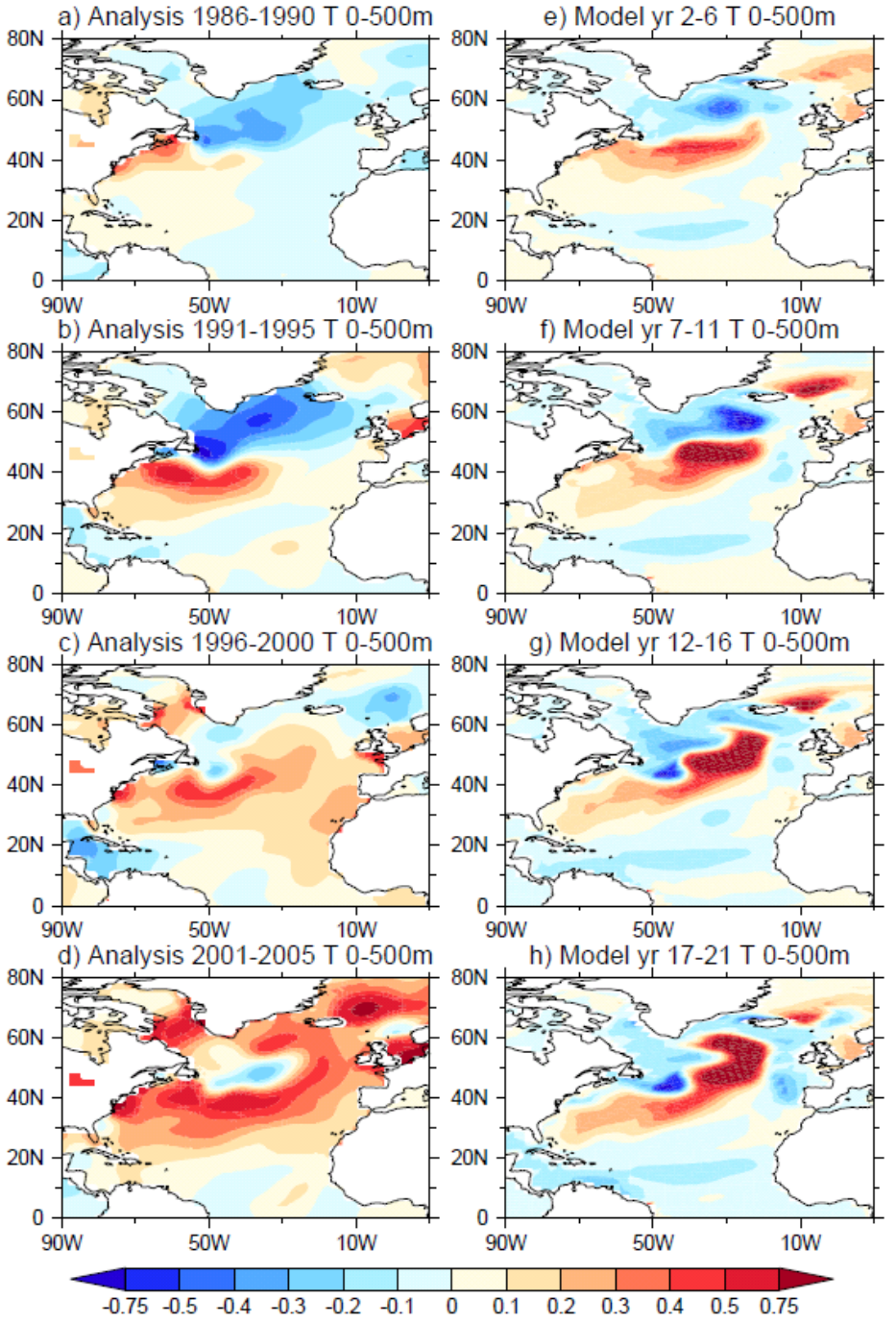
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Can we recreate the warming with just NAO + forcing?

- Forcing the ocean with persistent positive NAO also recreates the warming of the North Atlantic
- However, the warming of the subpolar gyre is not as rapid.

Subpolar gyre 0-500m T





Summary part I

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- The North Atlantic Subpolar gyre underwent a large and rapid warming in the mid-1990s
- Changes in the ocean dynamics was the main driver of the warming event, not changes in local surface heat fluxes
- The warming was affected by both the NAO+ and the NAO-
  - The NAO- of 1995/1996 contributed to the rapidity
  - But the buoyancy forcing associated with the NAO+ which preceded the warming was **key** to the increase in the heat transport
  - Importance of the NAO+ suggests that this event could have been predictable?

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Was the event predictable?

- When things go wrong
- When things go right

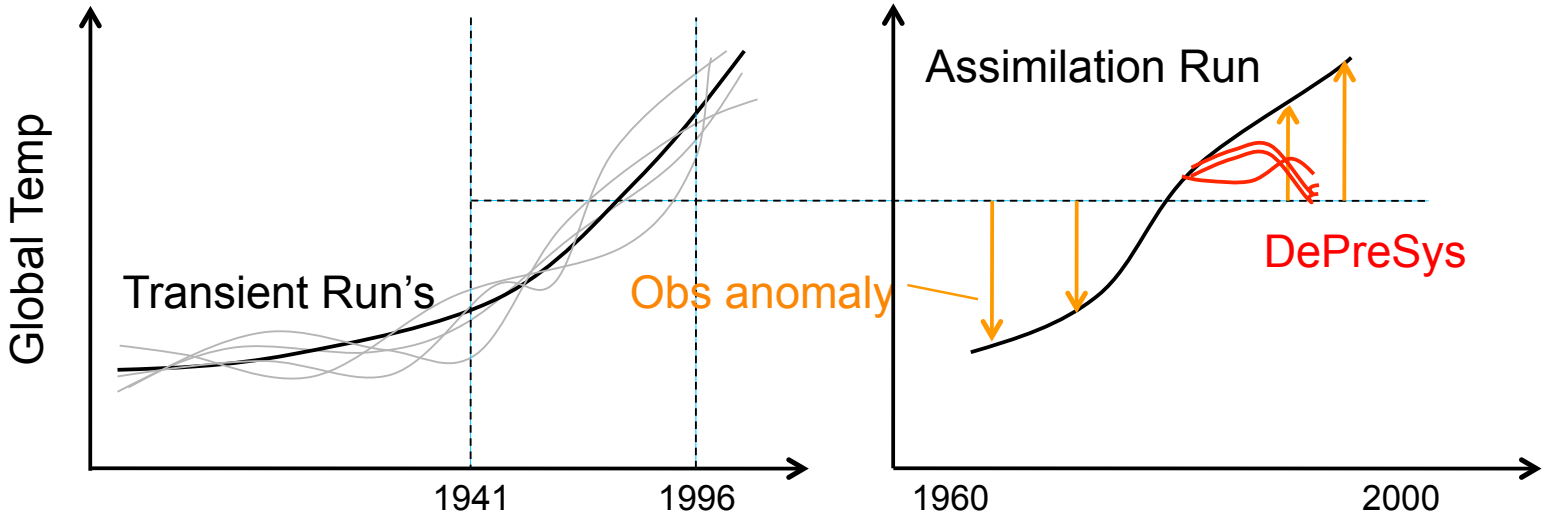
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DePreSys

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- Fully coupled decadal forecast system, based on HadCM3
  - Atmosphere = 2.5° x 3.75°, 19 levels, Ocean = 1.25° x 1.25°, 20 levels
- Initialised from the observed climate but also forced by anthropogenic emissions (SRES B2 scenario), previous 11 year solar cycle and volcanic aerosol (which is decayed in the forecast).
- There are no future volcanoes in the forecasts
- **Assimilates observed anomalies onto the model climate to avoid drift**

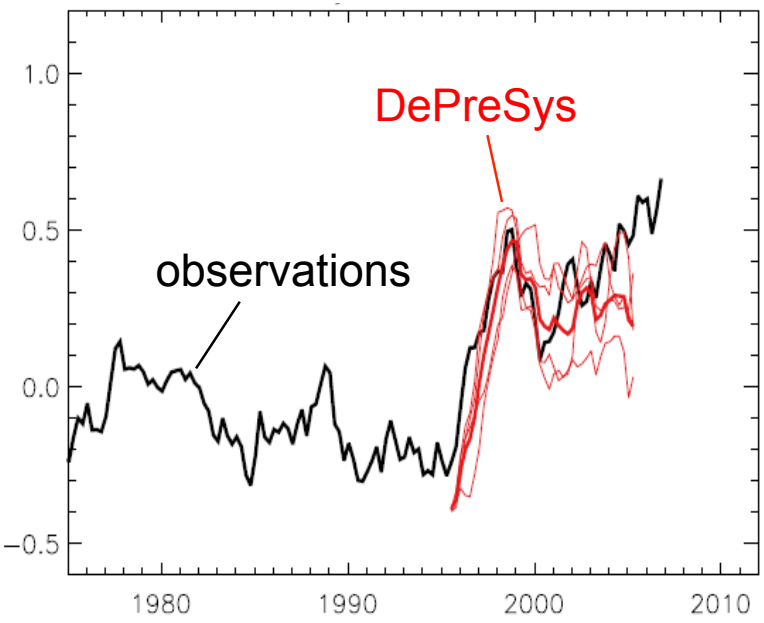


Predictions of the subpolar gyre

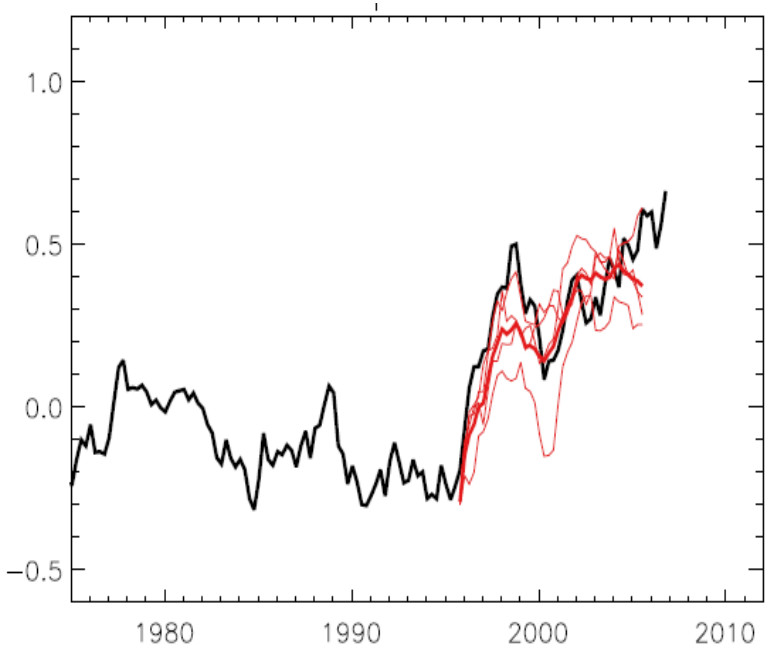
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subpolar gyre 0-500m heat content anomalies

June 1995



Sept 1995



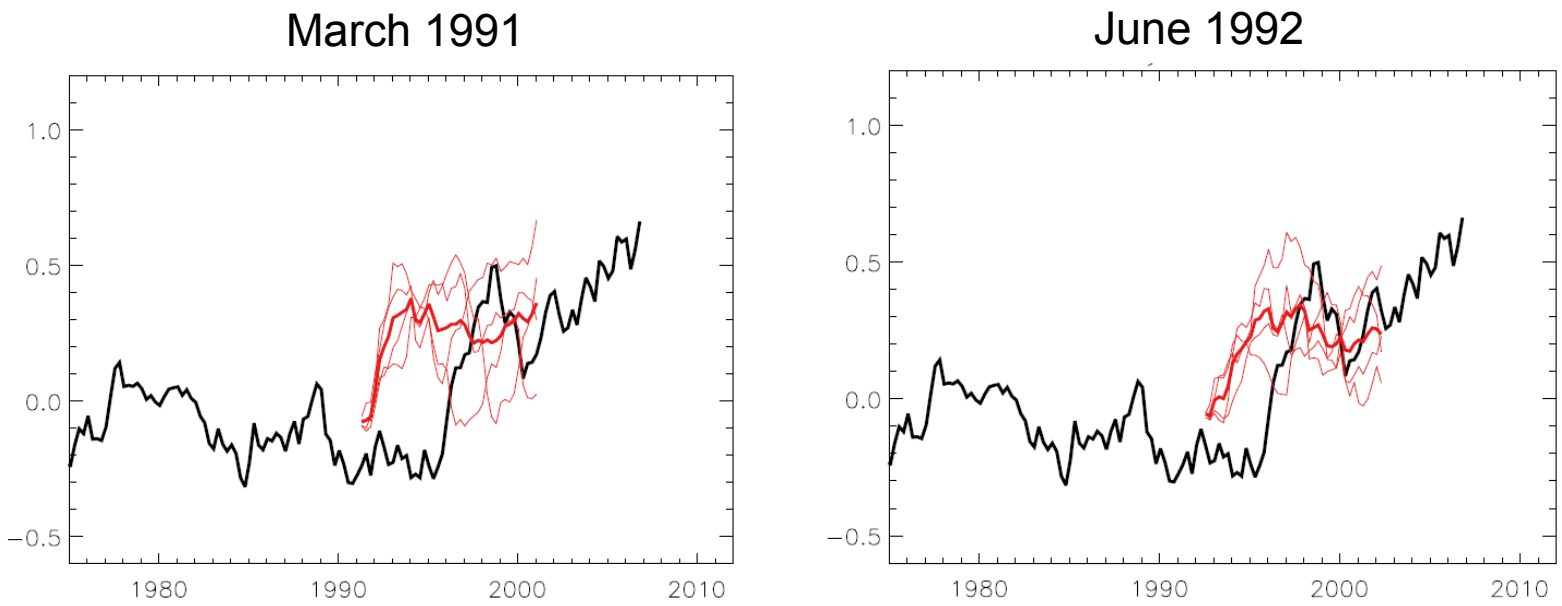
Initial analysis suggested that original DePreSys had remarkable skill at predicting the warming

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However, it did not get it right all the time

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- Most original DePreSys hindcasts initialised between 1990-1995 warm rapidly as soon as they are initialised

What is the reason for the early warming hindcasts?

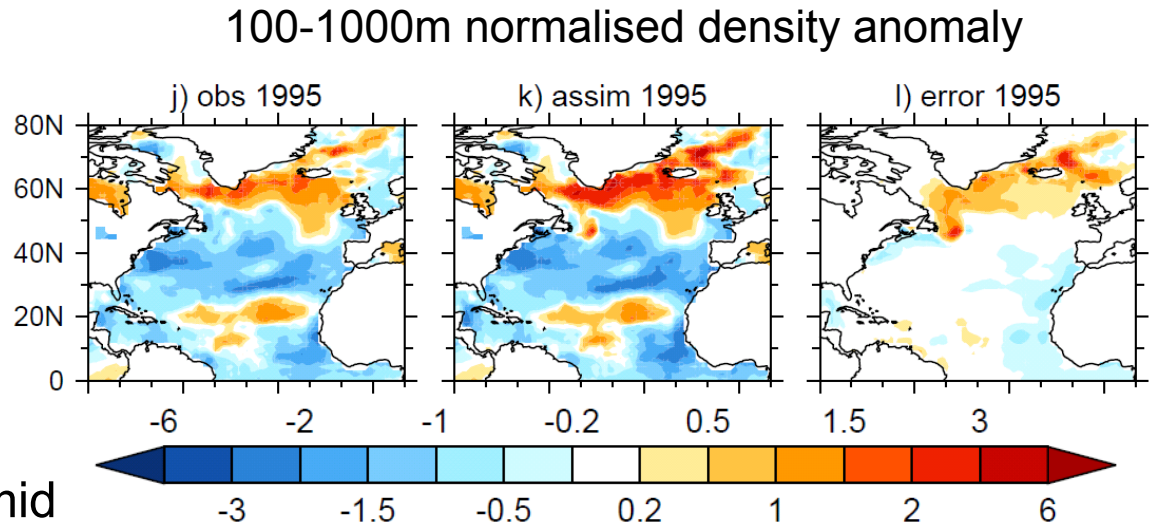
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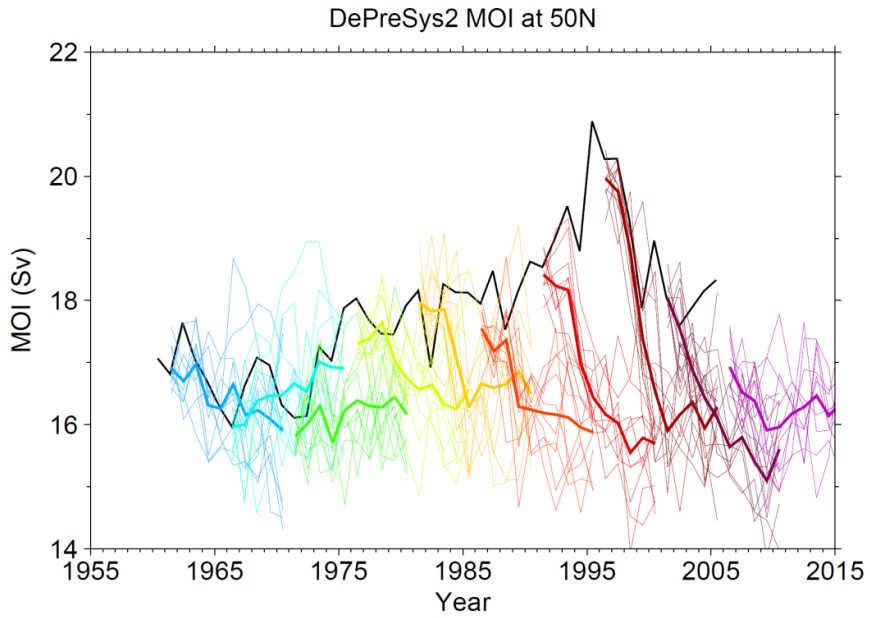
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When things go wrong

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- **Errors in the assimilated density anomalies**
  - Anomaly assimilation ignores the non-linear equation of state for sea water
  - Over estimate of subpolar density anomalies in the mid 1990s
- **Model adjustment**
  - Imbalance in the initial state
  - Climatology used in the assimilation was derived from a drifting transient run



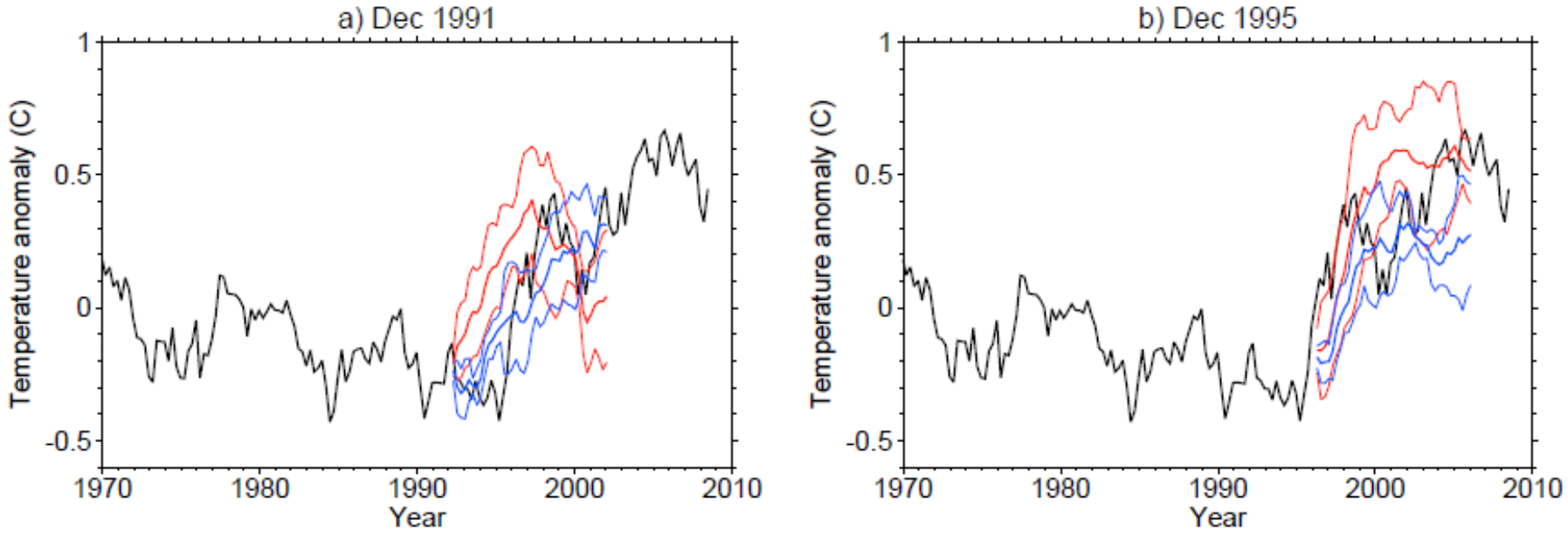


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Sensitivity to the climatology used in the assimilation

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Red: Using original climatology based on <u>one</u> drifting transient run (400 years of spin up)

Blue: Using an "improved" climatology of 6 transient runs with 1500 years of spin up

Drift is reduced when using an "improved" climatolgy

DePreSys is still able to predict the warming
but does not warm so rapidly, especially in the December 1991 hindcast

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Prediction: When things go right

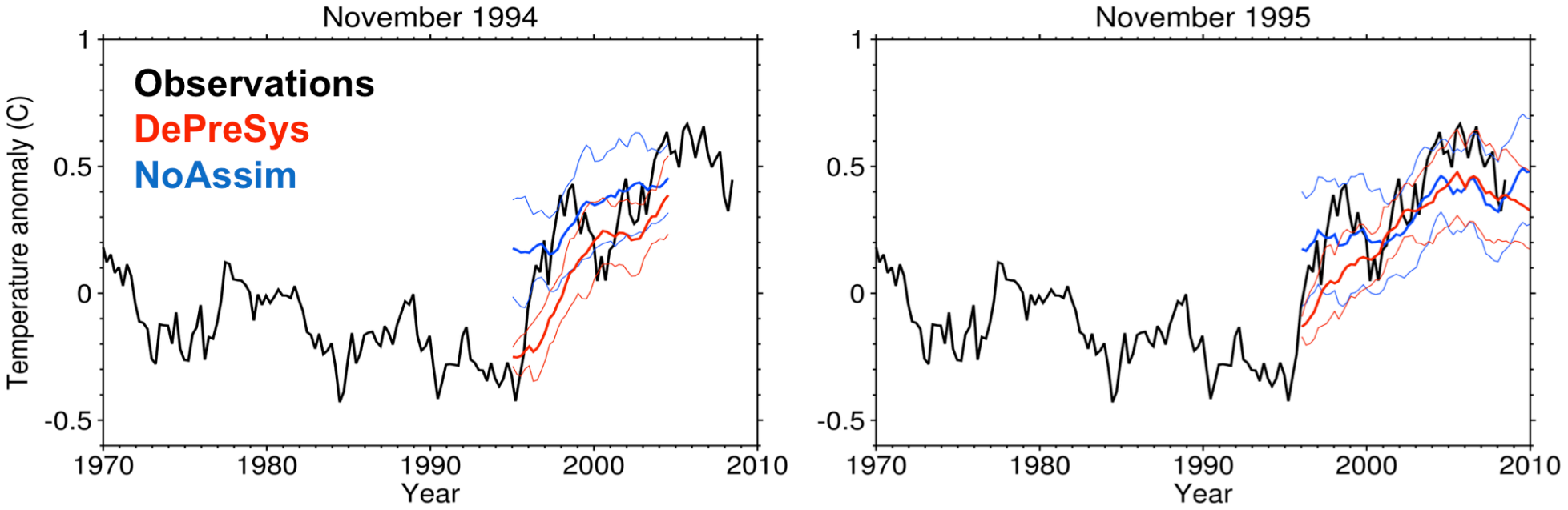
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Hindcasts made using DePreSys PPE

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- Newer version of DePreSys which uses an ensemble of 9 perturbed physics versions of HadCM3
- Hindcasts every year 1960-2005
- Reduced adjustment compared to the original DePreSys
- Is DePreSys actually predicting the warming, or is it just warming to it's preferred climate?

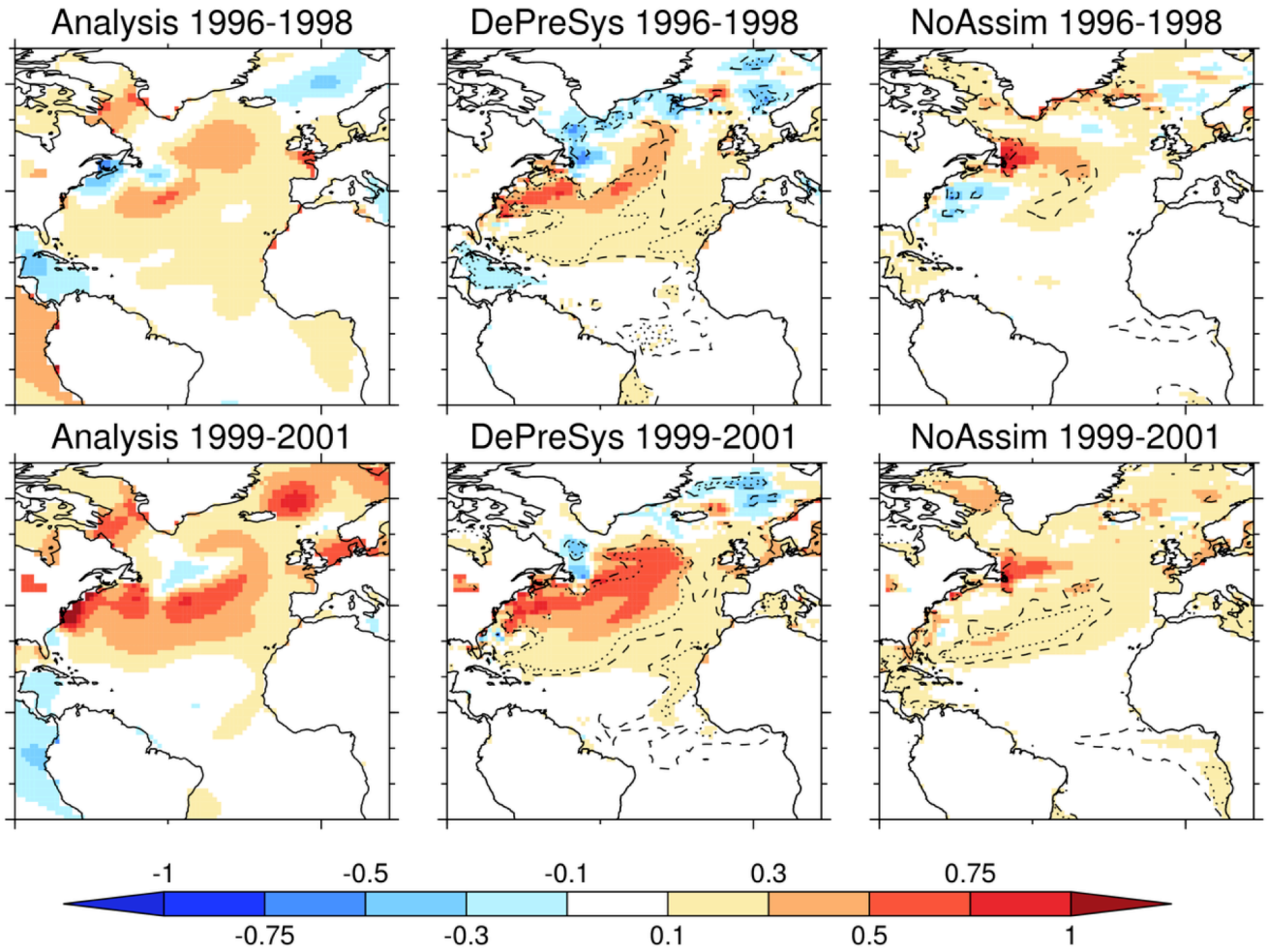


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0-500m heat content anomalies

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DePreSys is apparently able to capture the pattern of the warming

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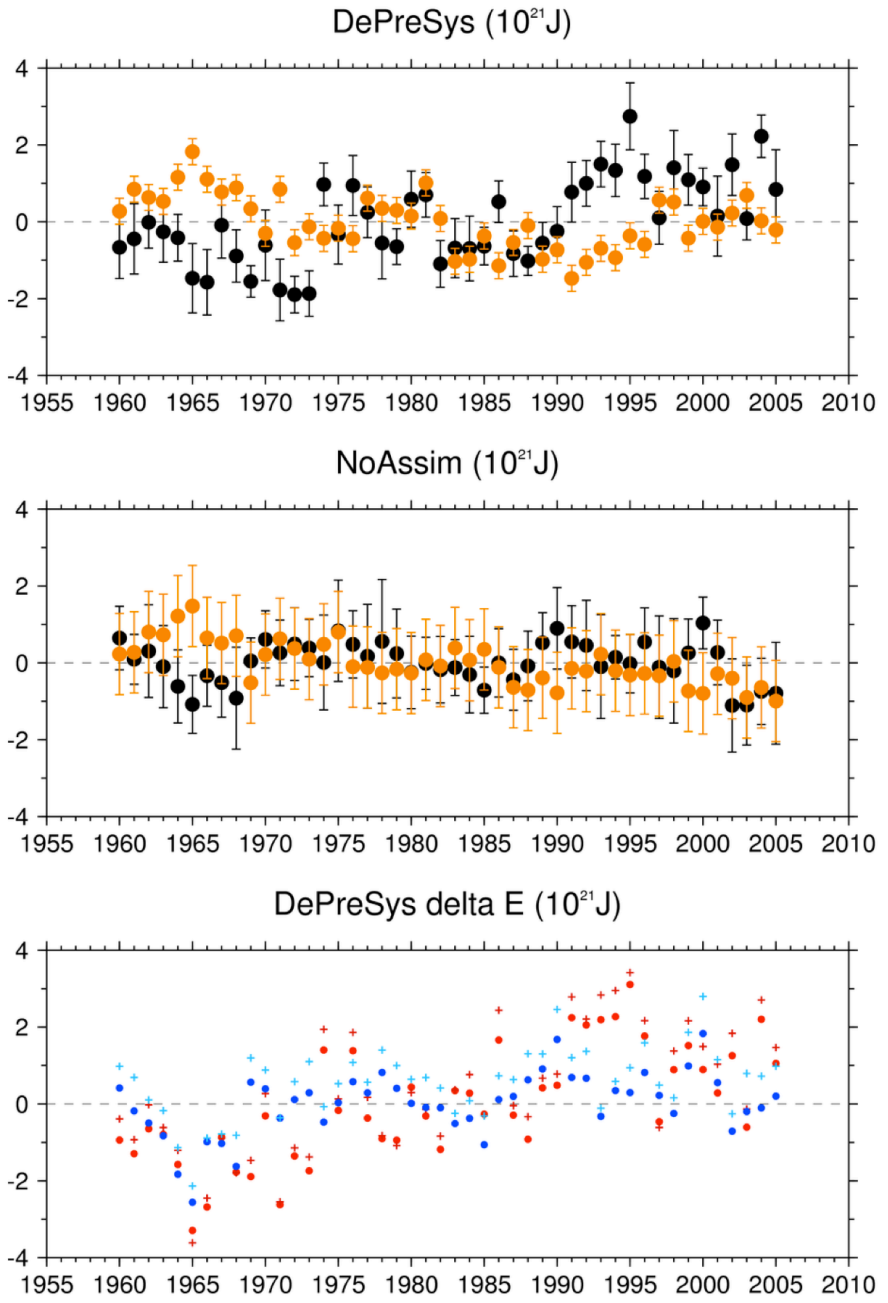
Subpolar heat budget

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Ocean heat transport convergence and **atmospheric heat loss** integrated over the subpolar gyre

Ocean heat transport convergence plays a key role in the successful prediction of the SPG warming

What is the mechanism?



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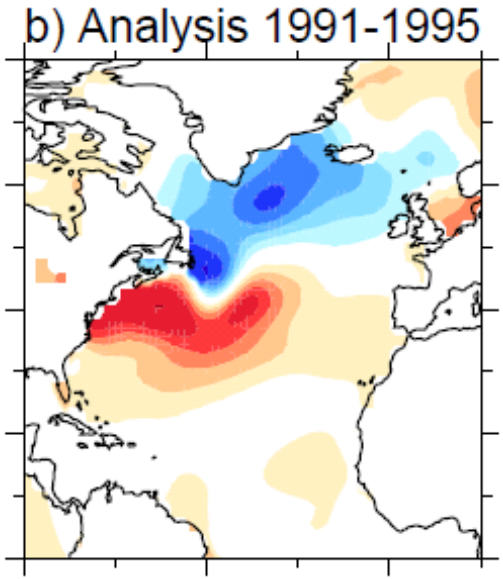
Subpolar heat budget

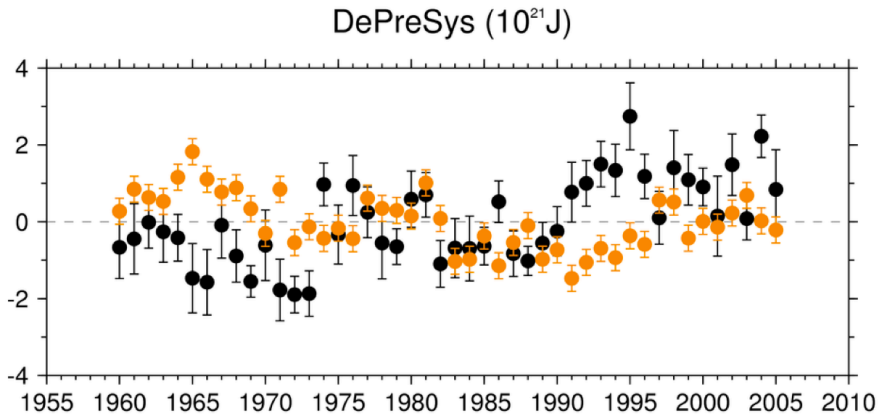
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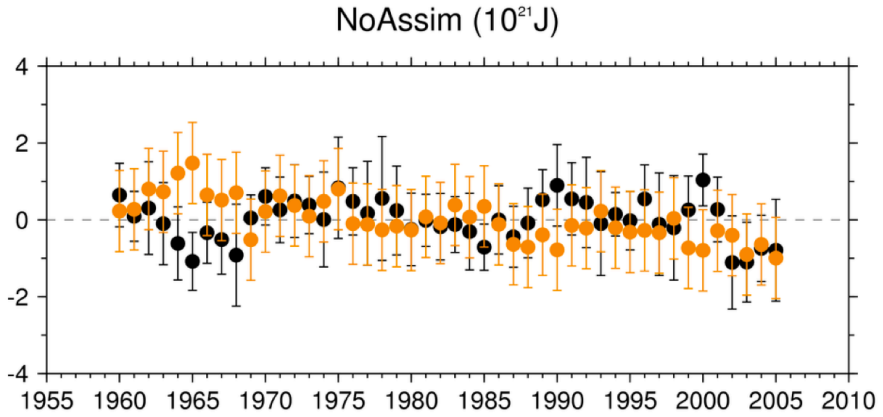
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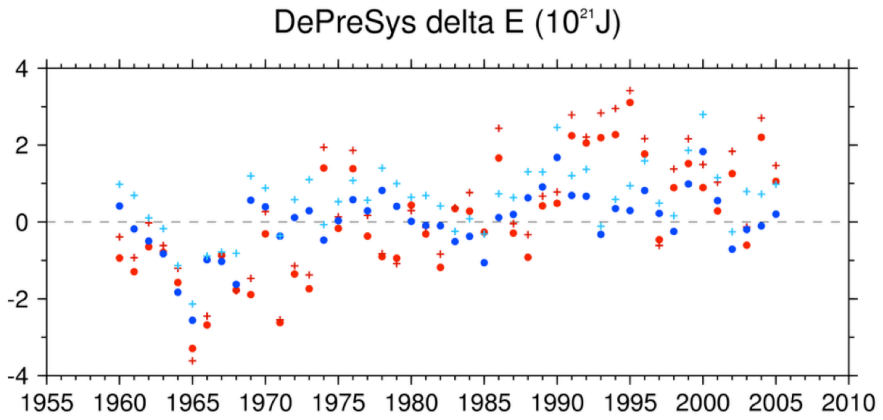
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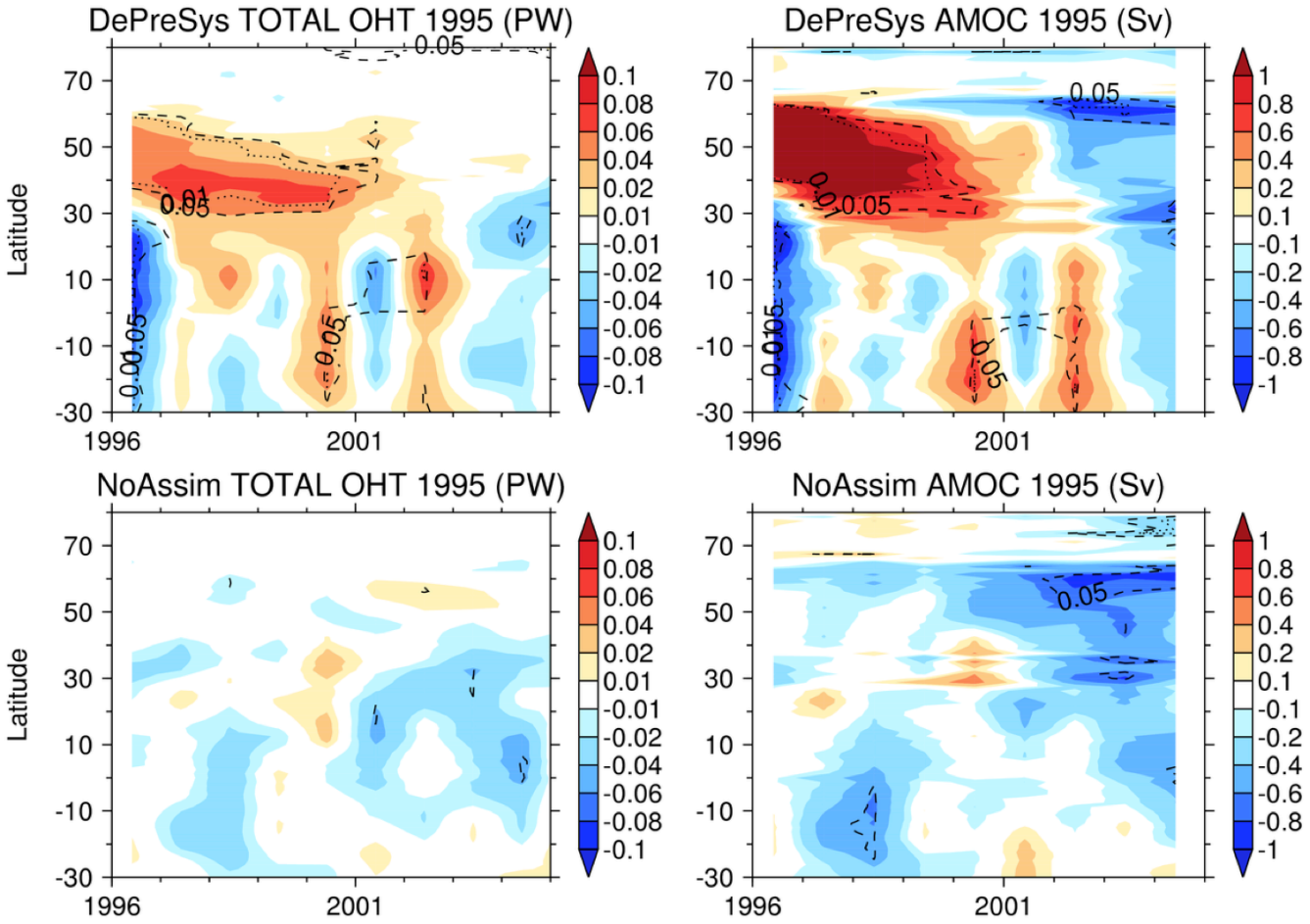




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Heat transport

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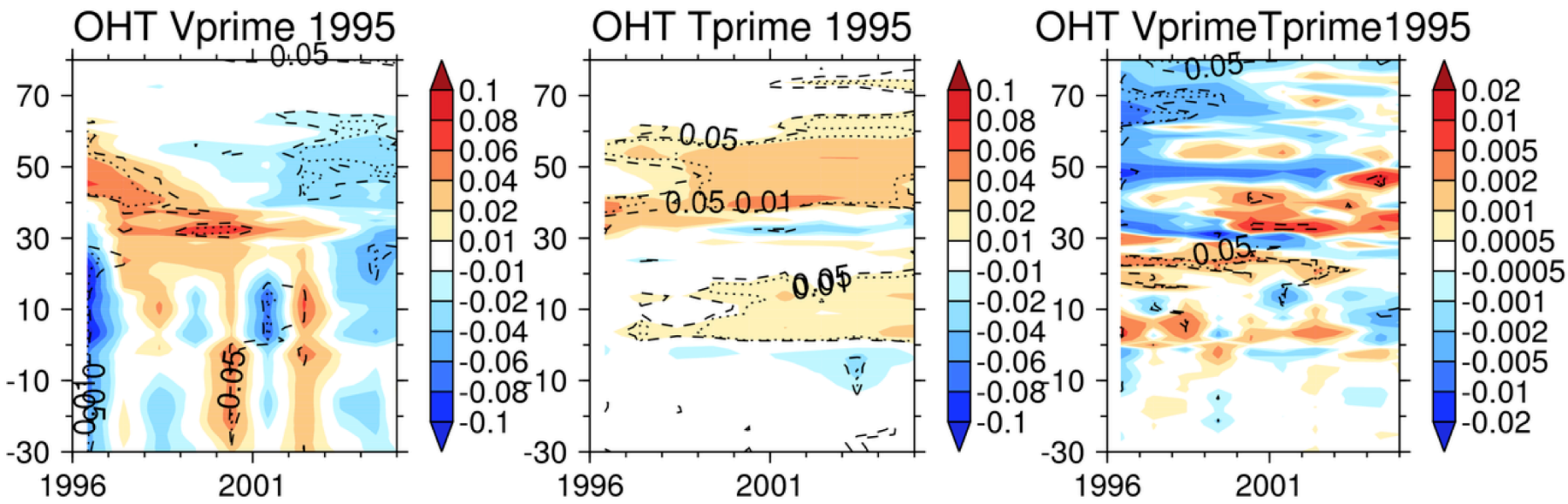
But can we attribute the increase in heat transport to a dynamical change in the ocean circulation

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What's driving increase in the OHT

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Initialization of ocean velocities are important → Dynamical prediction

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Summary part 2

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- Using case studies to validate decadal hindcasts is an important route for understanding and improving decadal predictions
- DePreSys does seems capable of predicting the warming of the subpolar gyre in advance
- Ocean heat transport is important for the prediction of the warming – **not just the atmosphere**
- In particular it is the ocean circulation, i.e. strong AMOC, that is important → **dynamical prediction at decadal timescales** is possible in the North Atlantic
- However, there are limitations still to overcome with anomaly assimilation

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Thank you for your attention!

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