MERIDIONAL OVERTURNING CIRCULATION: SOME BASICS AND ITS MULTI-DECADAL VARIABILITY

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OUTLINE:

- Describe thermohaline and meridional overturning circulations,
- Multi-decadal variability in the North Atlantic as depicted by the Atlantic Meridional Overturning Circulation (AMOC),
- Examples of climate impacts and potential predictability,
- Results from the NCAR Community Climate System Model (CCSM3) simulations,
- Summary

WHAT IS THERMOHALINE CIRCULATION (THC)?

It is that part of the ocean circulation which is driven by density differences (as opposed to wind and tides).

Because the ocean density is a function of temperature (thermo) and salinity (haline), this circulation is referred to as the themohaline circulation and indicates a driving mechanism.

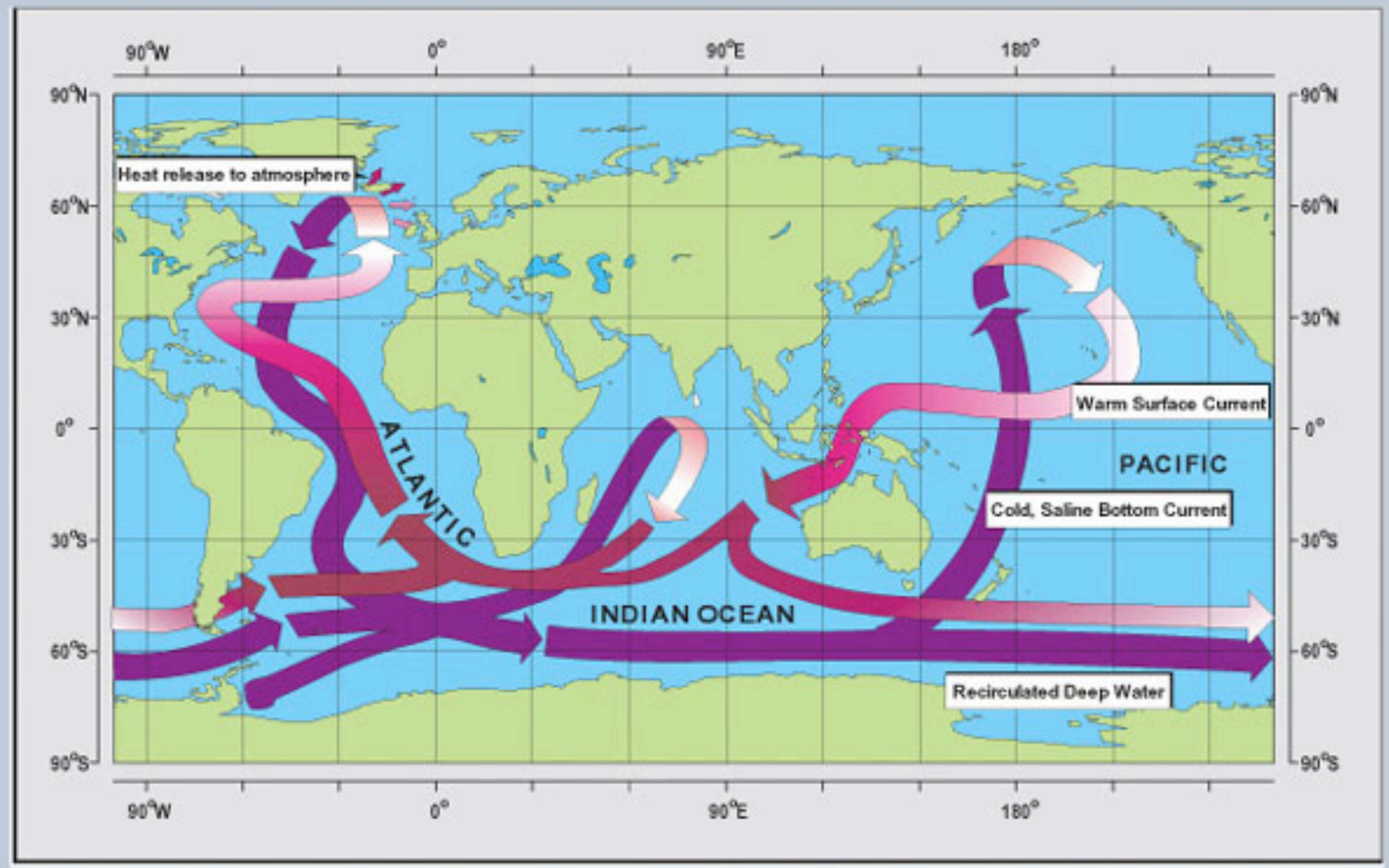
These density differences are primarily caused by surface fluxes of heat and freshwater and subsequent interior mixing.

The oceanic density distribution is itself affected by the currents and associated mixing. Thermohaline and wind driven currents interact with each other, and therefore cannot be truly separated.

THC IS NOT AN OBSERVATIONALLY MEASURABLE QUANTITY!

THERMOHALINE CIRCULATION PATHWAYS

"CONVEYOR BELT"



Schematic diagram of the global ocean circulation pathways, the 'conveyer' belt (after W. Broecker, modified by E. Maier-Reimer).

While temperature acts as the driver, salinity provides the break!

WHAT IS MERIDIONAL OVERTURNING CIRCULATION (MOC)?

It is a related field, referring to a streamfunction on the depth-latitude plane. It can be obtained from

$$\Psi(y,z,t) = \int_{z}^{0} dz \int_{west}^{east} V(x,y,z,t)\,dx$$

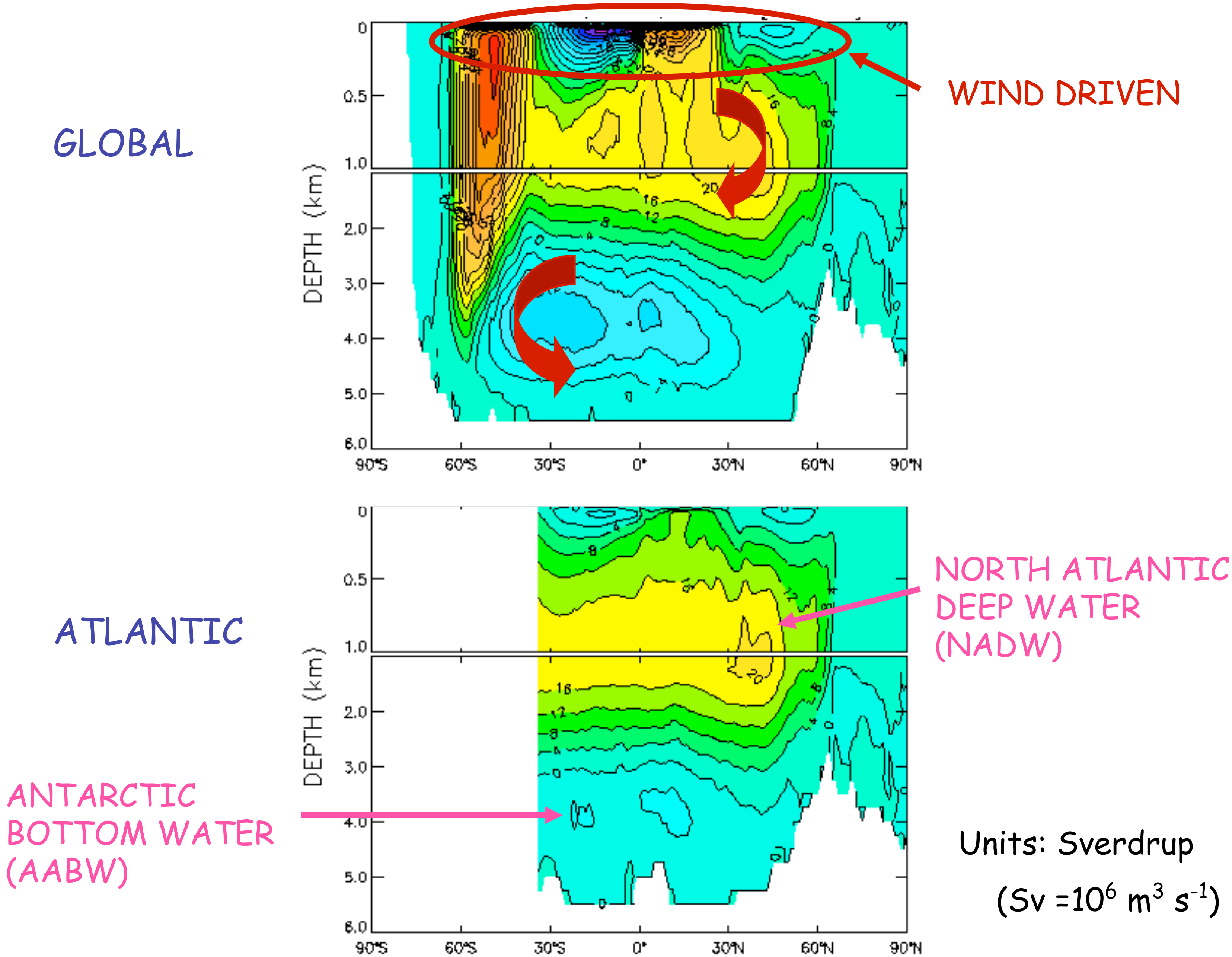
where

- x: longitudinal (zonal) direction (+ve eastwards)
- y: latitudinal (meridional) direction (+ve northwards)
- z: height (+ve upwards)
- t: time
- V: meridional velocity component

This field is often used in the modeling community, because it is easy to diagnose.

MOC INCLUDES WIND-DRIVEN CIRCULATION!

MERIDIONAL OVERTURNING CIRCULATION

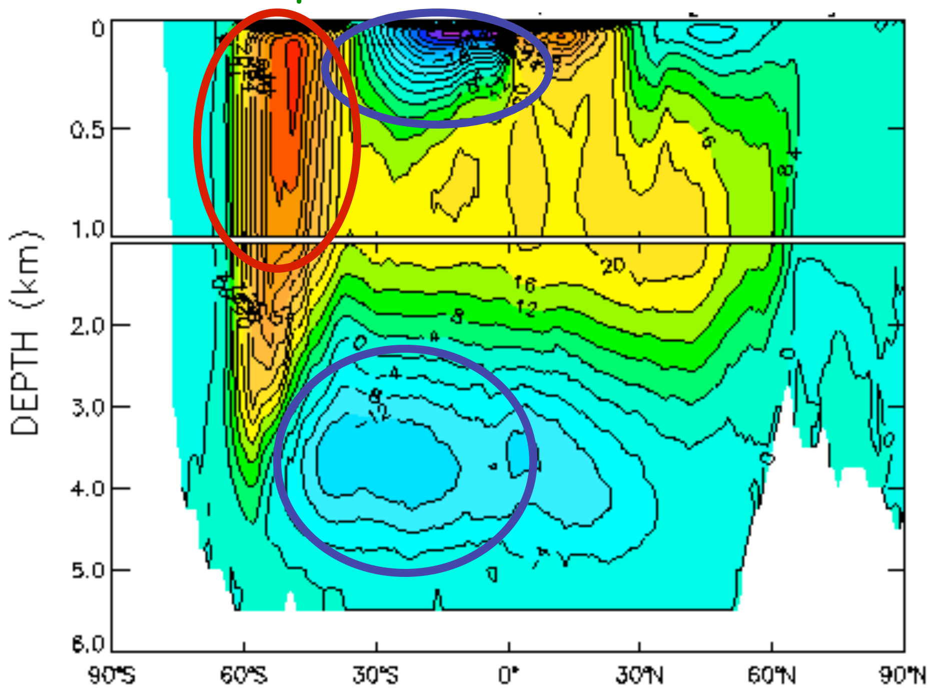


Units: Sverdrup

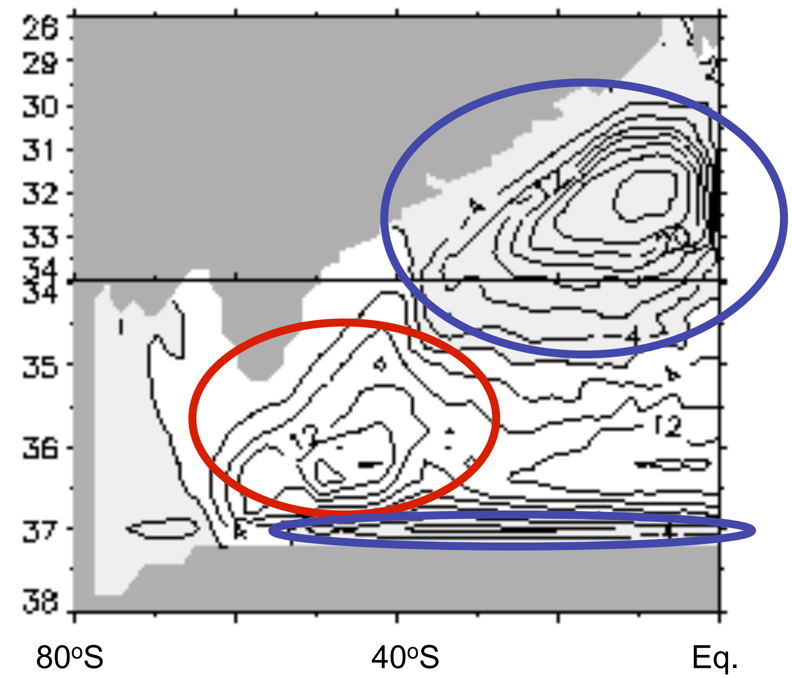
($Sv = 10^6\ m^3\ s^{-1}$)

MERIDIONAL OVERTURNING CIRCULATION

Depth – Latitude Plane

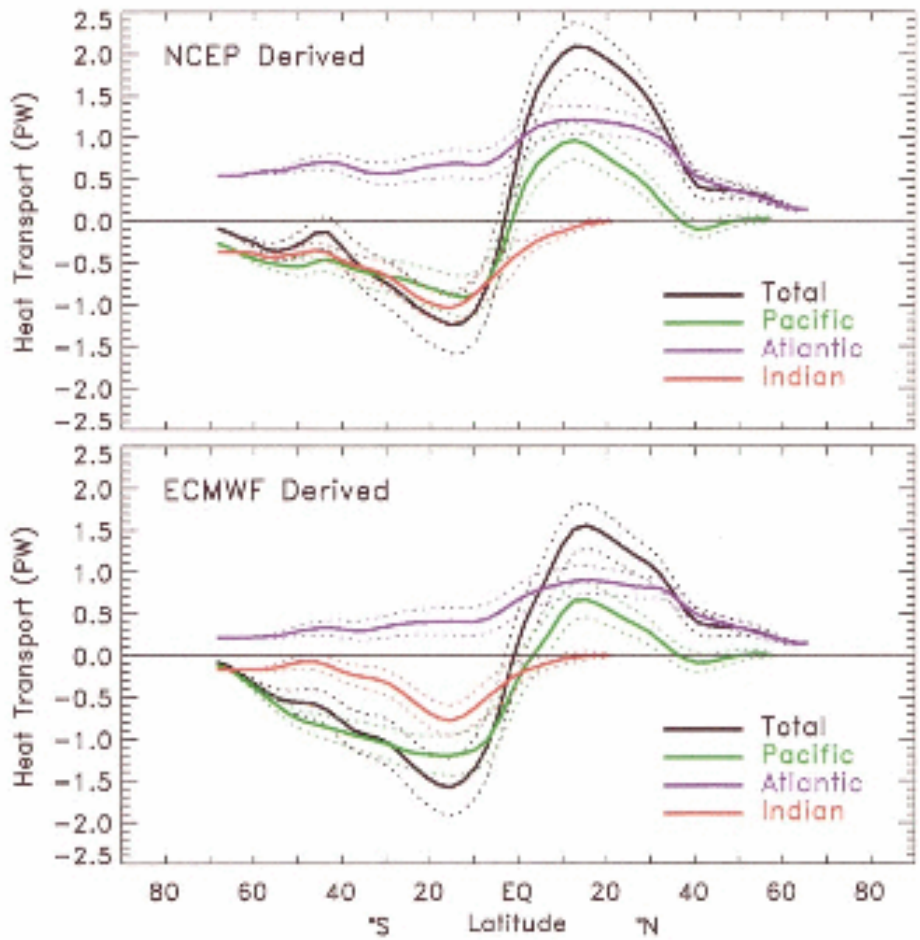


Density – Latitude Plane

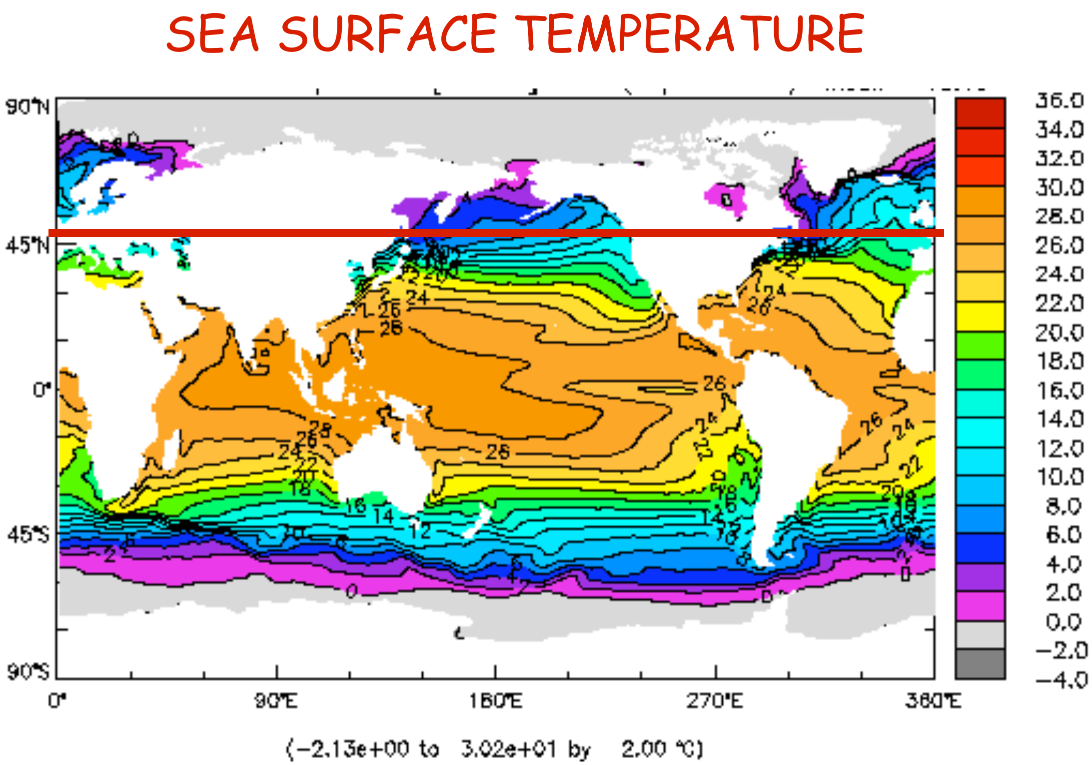


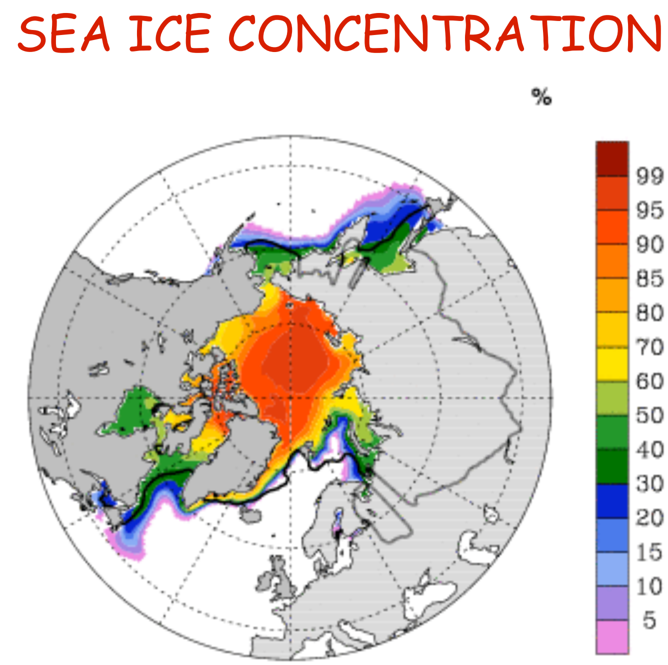
in Sv

OCEANIC NORTHWARD HEAT TRANSPORT



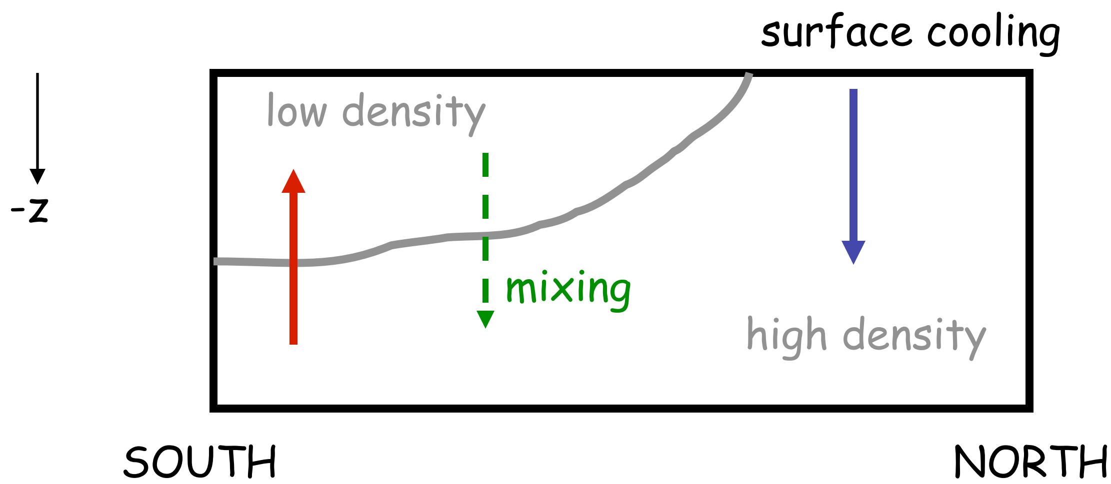
Trenberth and Caron (2001)


SEA SURFACE TEMPERATURE
90°N
45°N
0°
45°S
90°S
0°
90°E
180°E
270°E
360°E
36.0
34.0
32.0
30.0
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
−2.0
−4.0
(−2.13e+00 to 3.02e+01 by 2.00 °C)


SEA ICE CONCENTRATION
%
99
95
90
85
80
70
60
50
40
30
20
15
10
5

WHAT DRIVES THC / MOC?

MECHANISM I: Cooling at high latitudes. For steady state, downward penetration of heat by mixing is necessary.

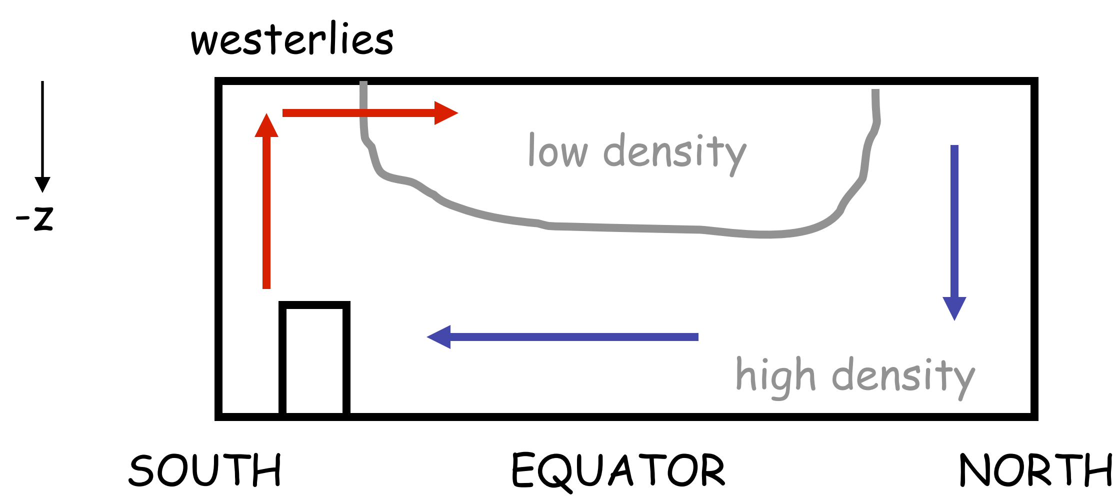


Turbulent mixing supplies energy.

WHAT DRIVES THC / MOC?

MECHANISM II: Westerly winds over the Southern Ocean. No meridional flow can be supported at intermediate depths at the latitude band of the Drake Passage due to lack of topographic barriers that can support east-west pressure gradients.

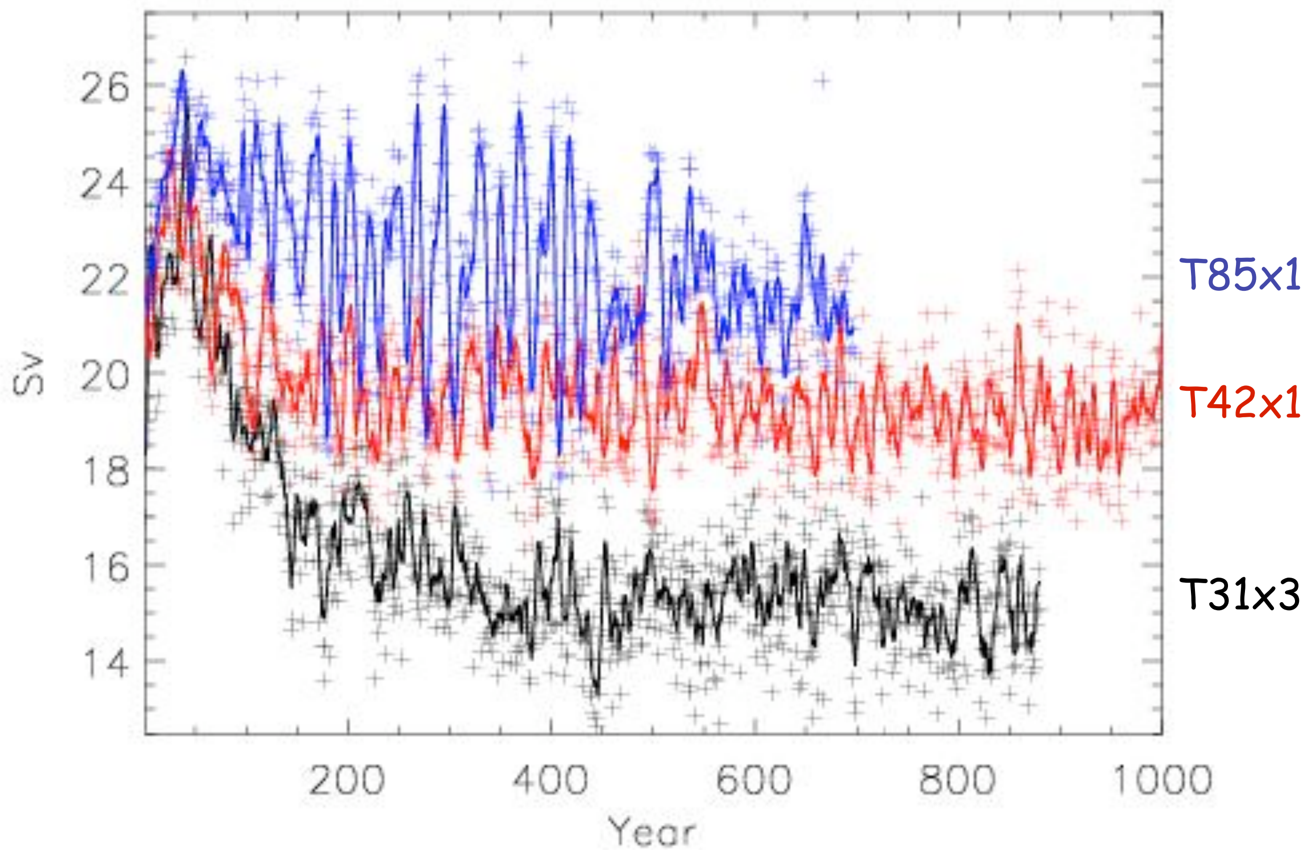
$$-f\,V = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$



Winds directly supply energy.

Many coupled general circulation models (CGCMs) exhibit multi-decadal or longer time scale (20 - 100+ years) variability in their AMOCs.

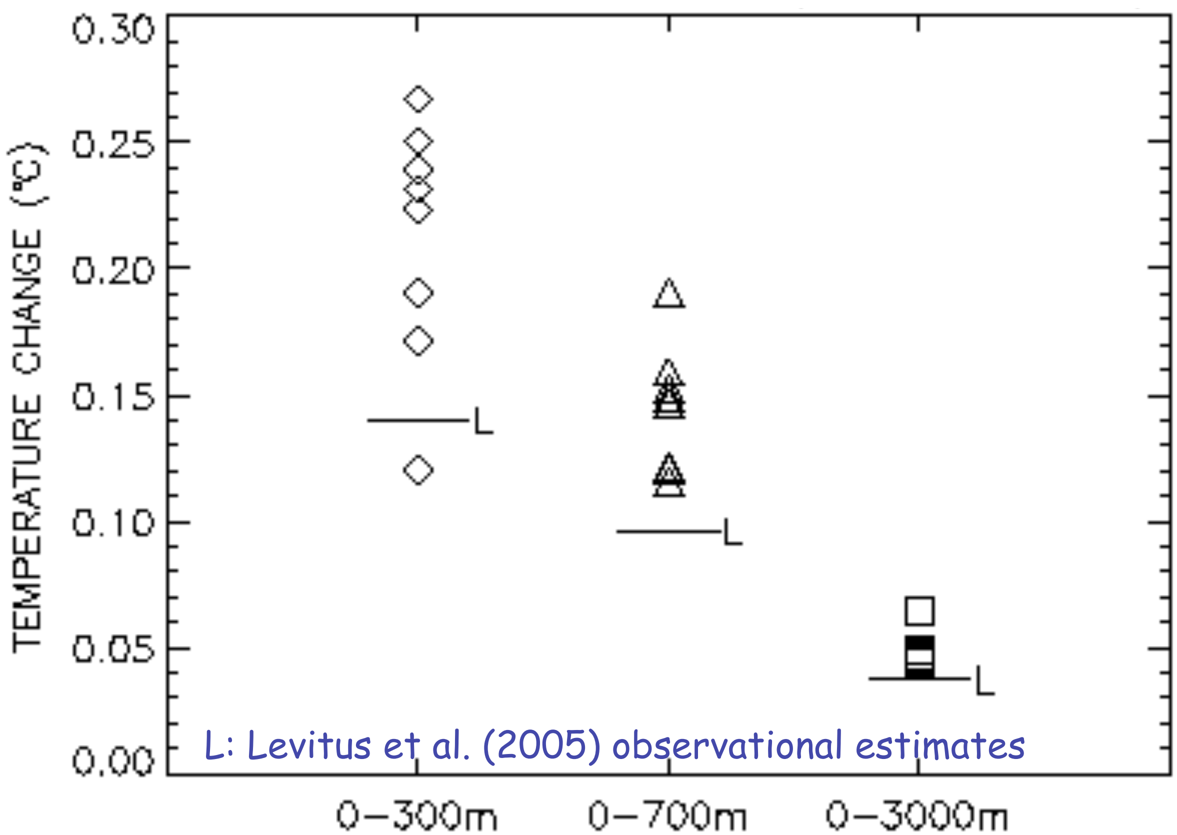
Time series of the AMOC maximum from CCSM3 present-day control simulations



Bryan et al. (2006, J. Climate)

HEAT CONTENT CHANGES between mid-1990s and mid-1950s

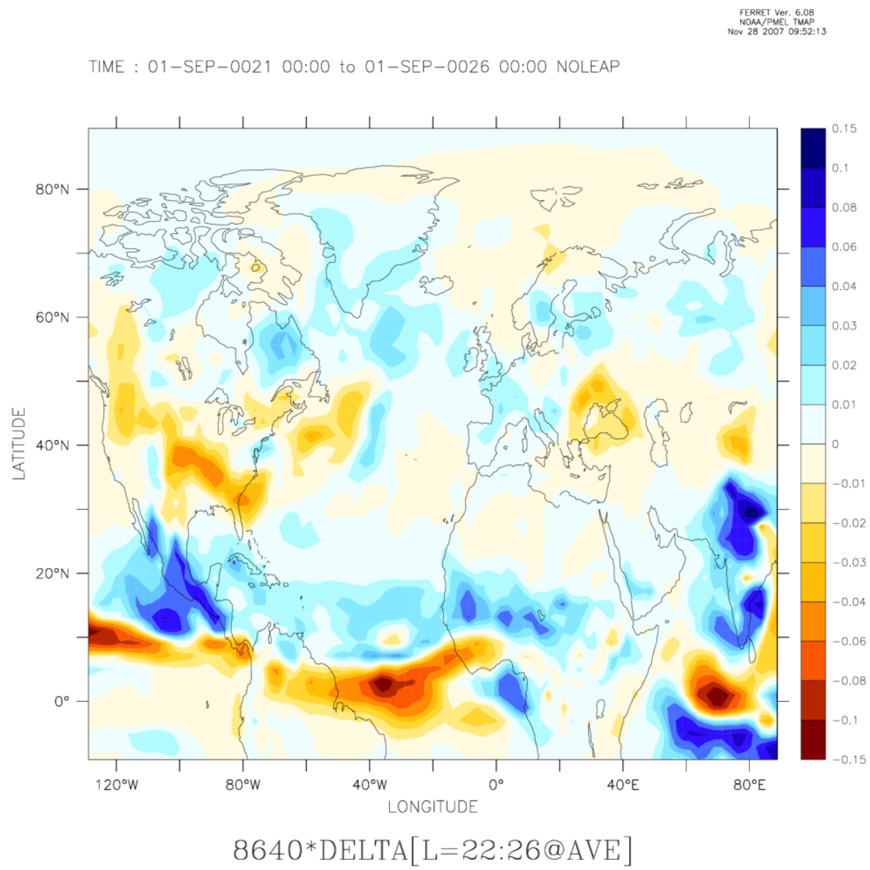
(CCSM3 20th Century simulations – 1870 control integration)



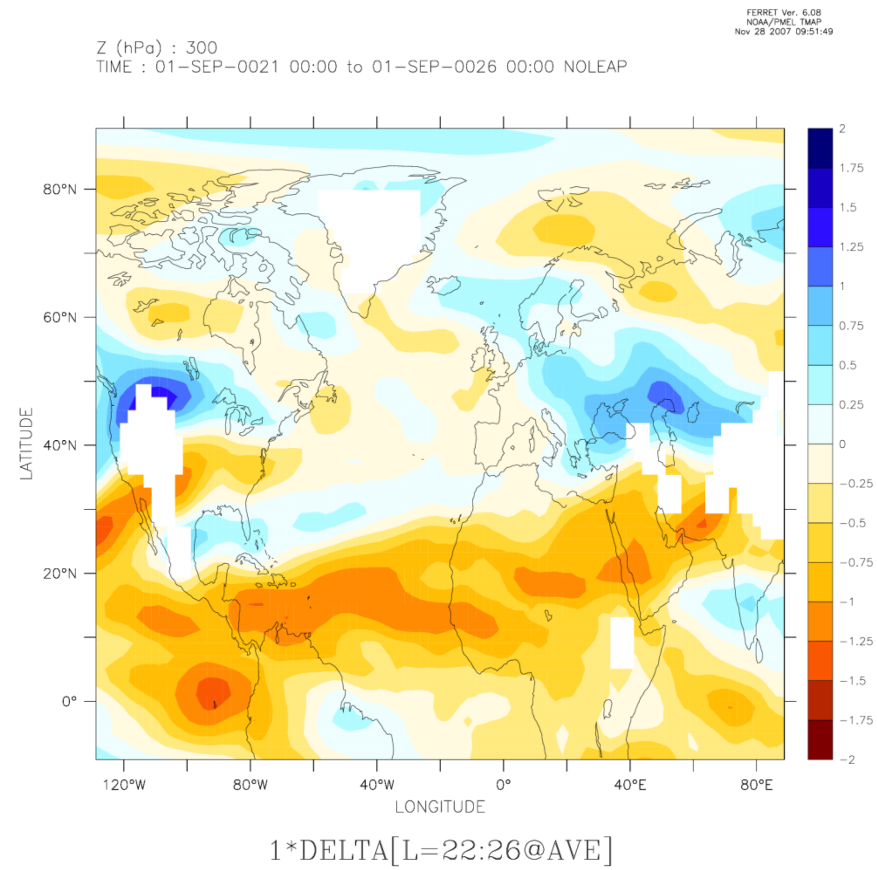
Gent et al. (2006, J. Climate)

CHANGE IN SOME FIELDS BETWEEN HIGH AND LOW AMOC PERIODS IN THE GFDL CM2.1 CONTROL SIMULATION

Rainfall (cm day^{-1})



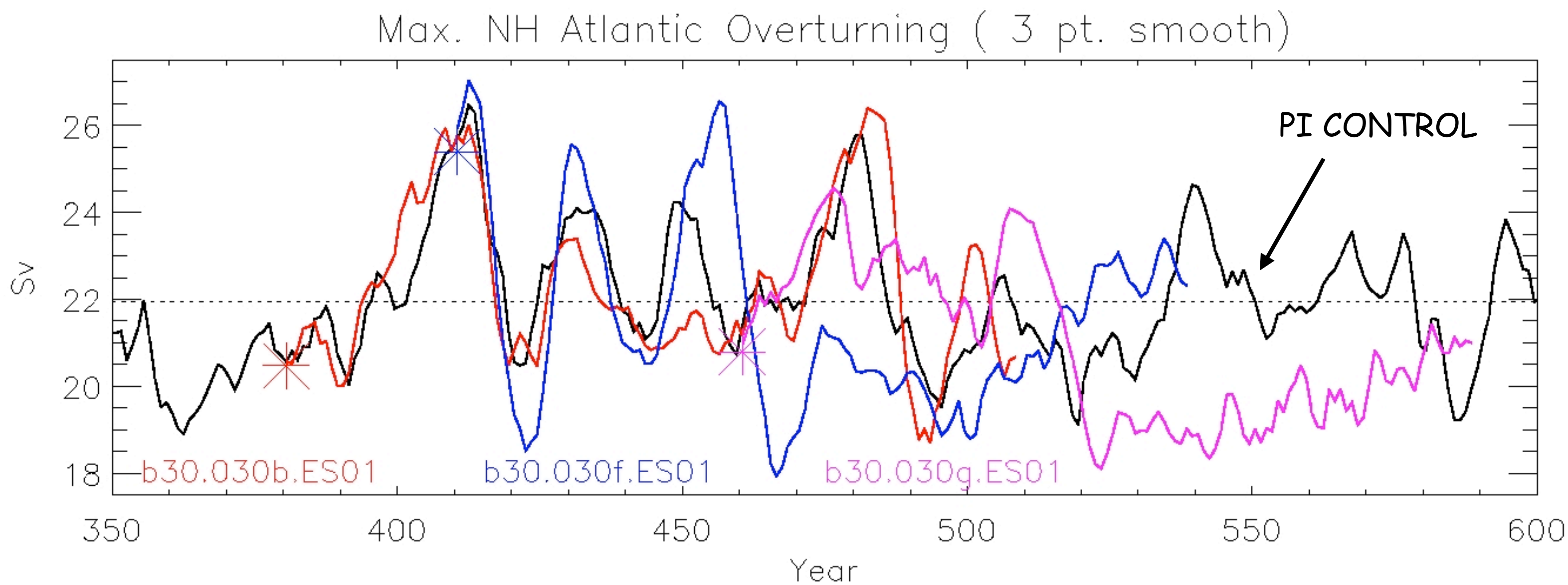
Vertical shear of zonal wind (m s^{-1})

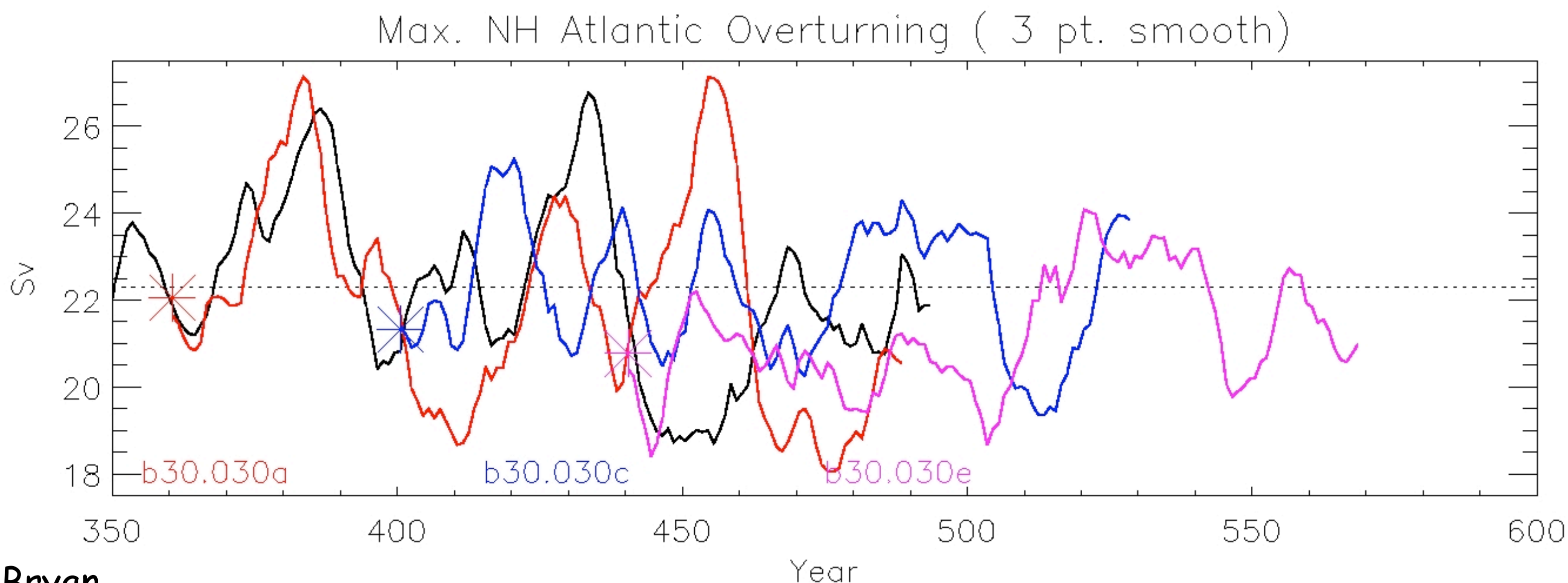


Vertical shear computed for 300 hPa – 850 hPa.

Tom Delworth

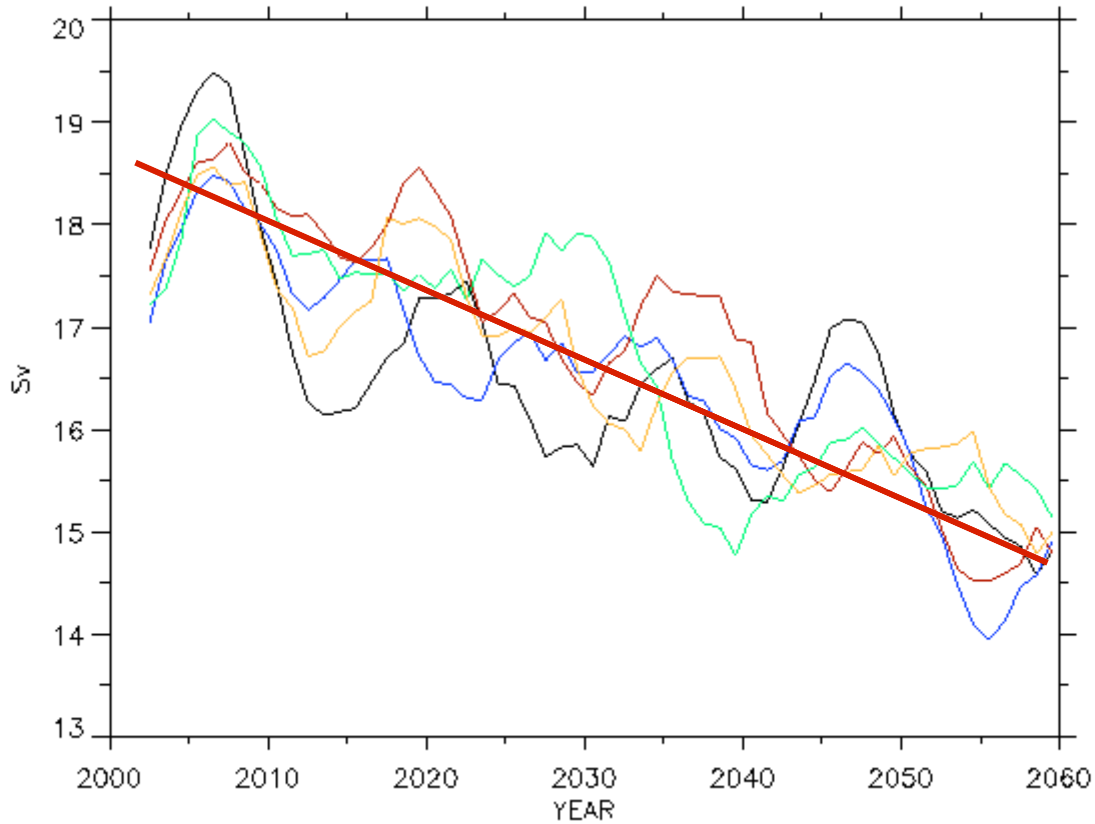
AMOC IN THE 20th CENTURY ENSEMBLE INTEGRATIONS

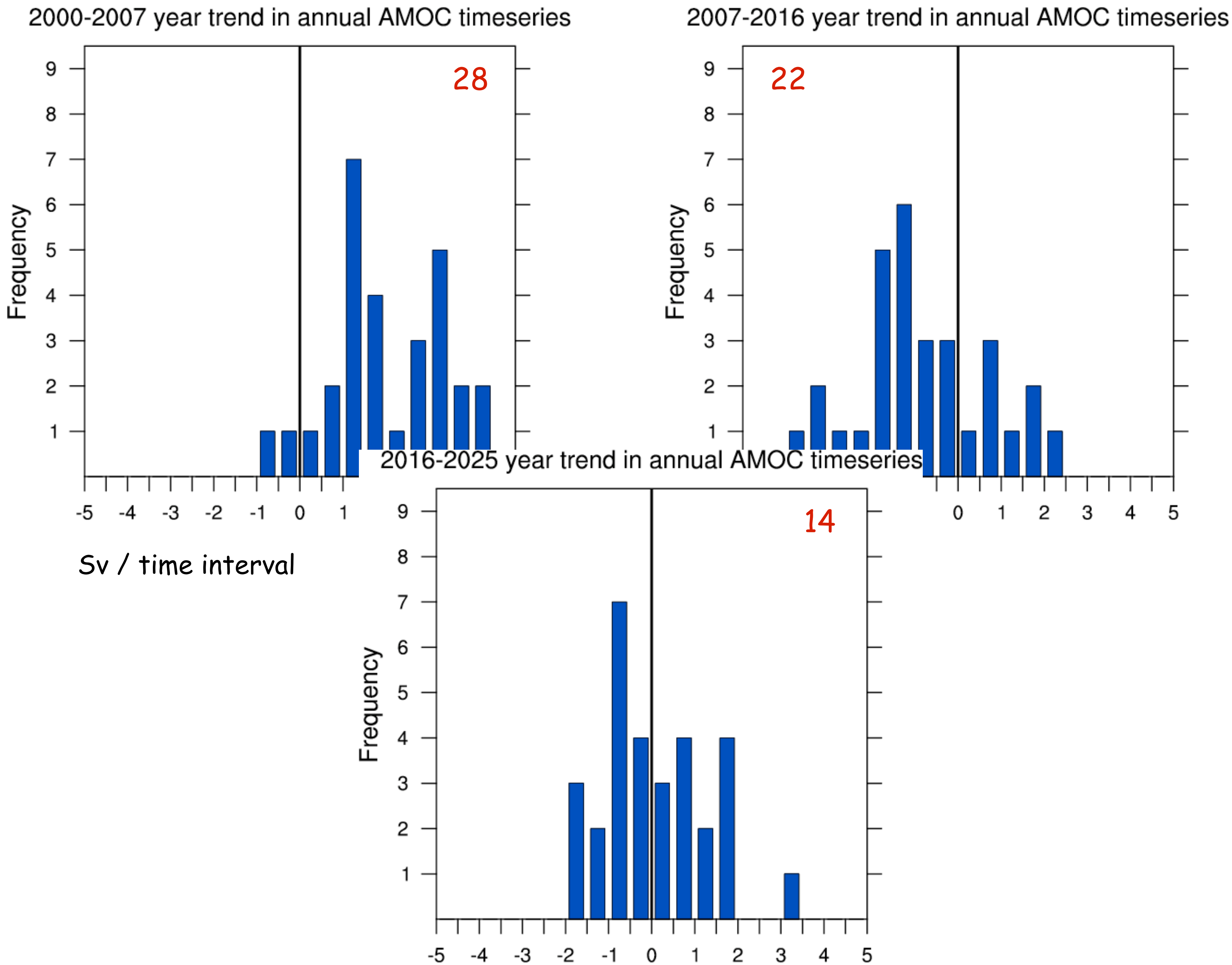




Frank Bryan

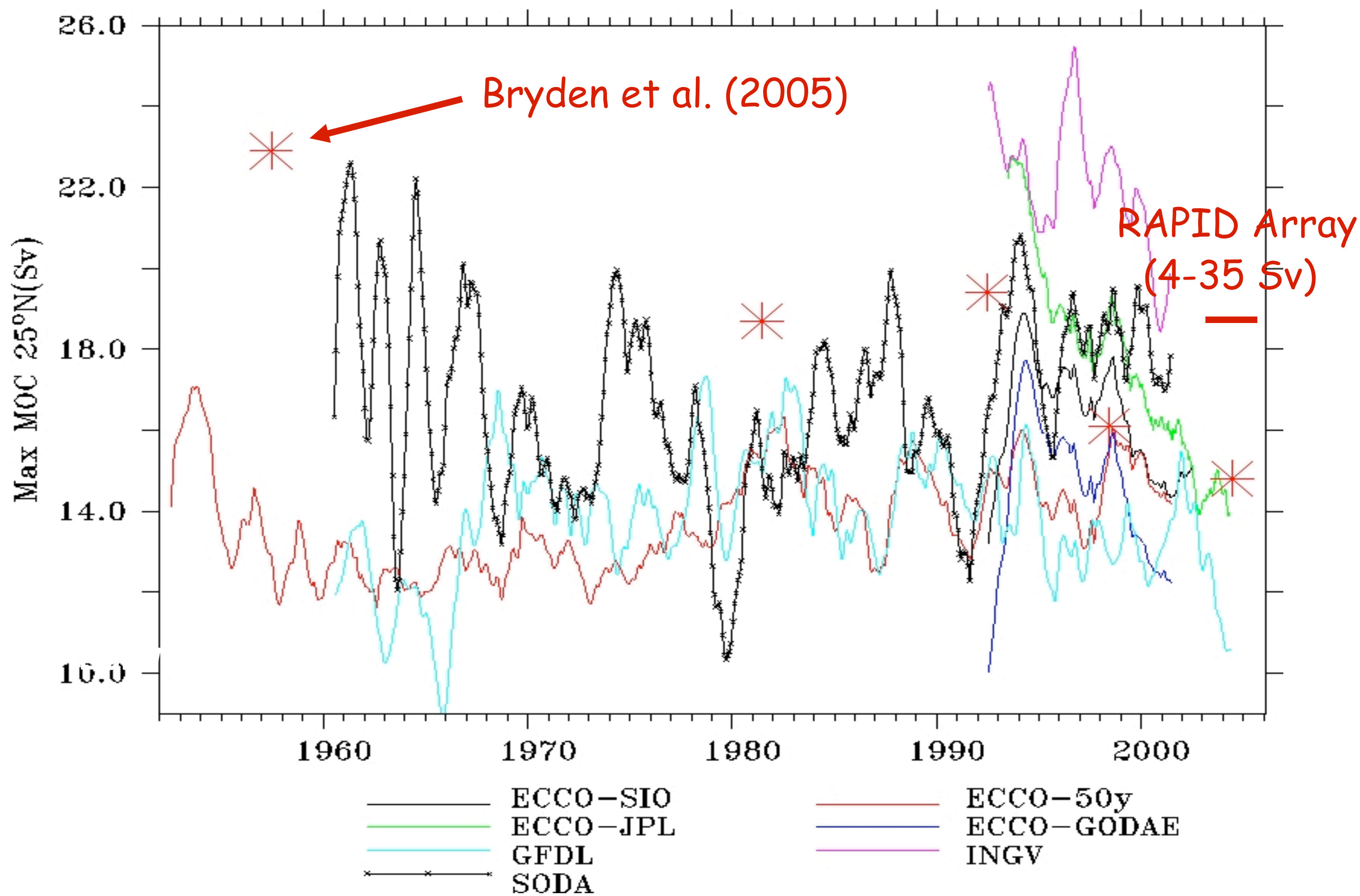
Time series of AMOC maximum from 5 members of a 30-member ensemble of CCSM3 (T42x1) A1B scenario simulations





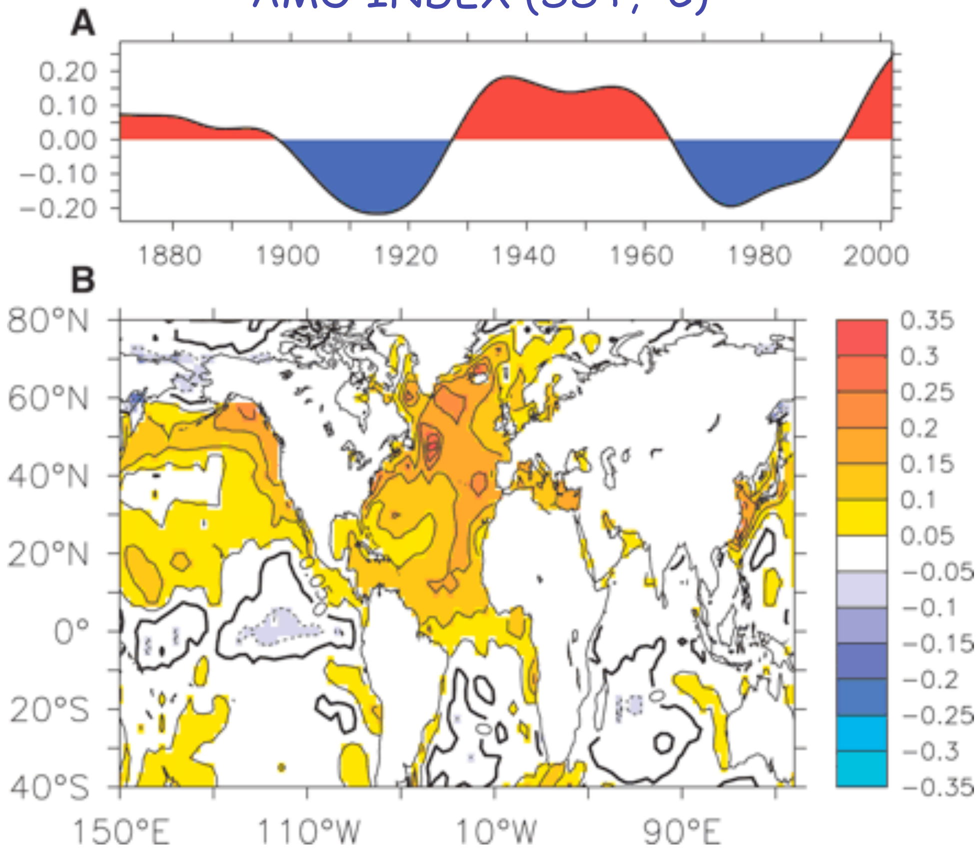
2000-2007 year trend in annual AMOC timeseries
28
2007-2016 year trend in annual AMOC timeseries
22
2016-2025 year trend in annual AMOC timeseries
14
Frequency
Sv / time interval

TIME SERIES OF NORTH ATLANTIC MOC AT 25°N



ATLANTIC MULTI-DECADAL OSCILLATION (AMO)

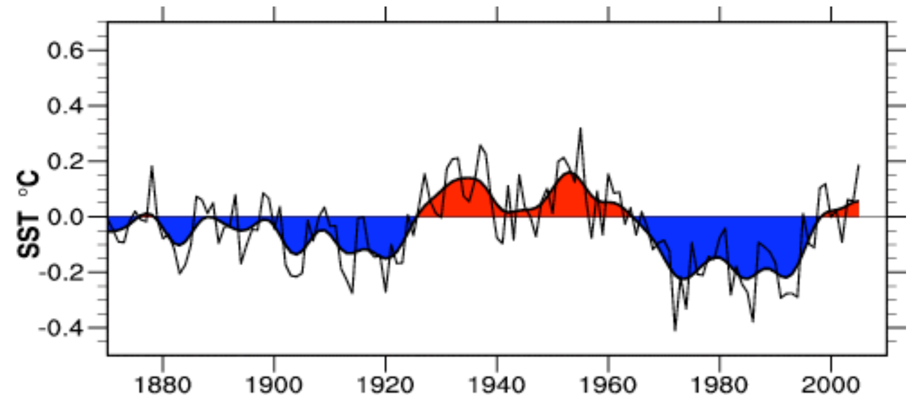
AMO INDEX (SST, °C)



SST vs AMO INDEX REGRESSION (°C/SD)

Sutton & Hodson (2005)

AMO INDEX



Trenberth & Shea (2006)

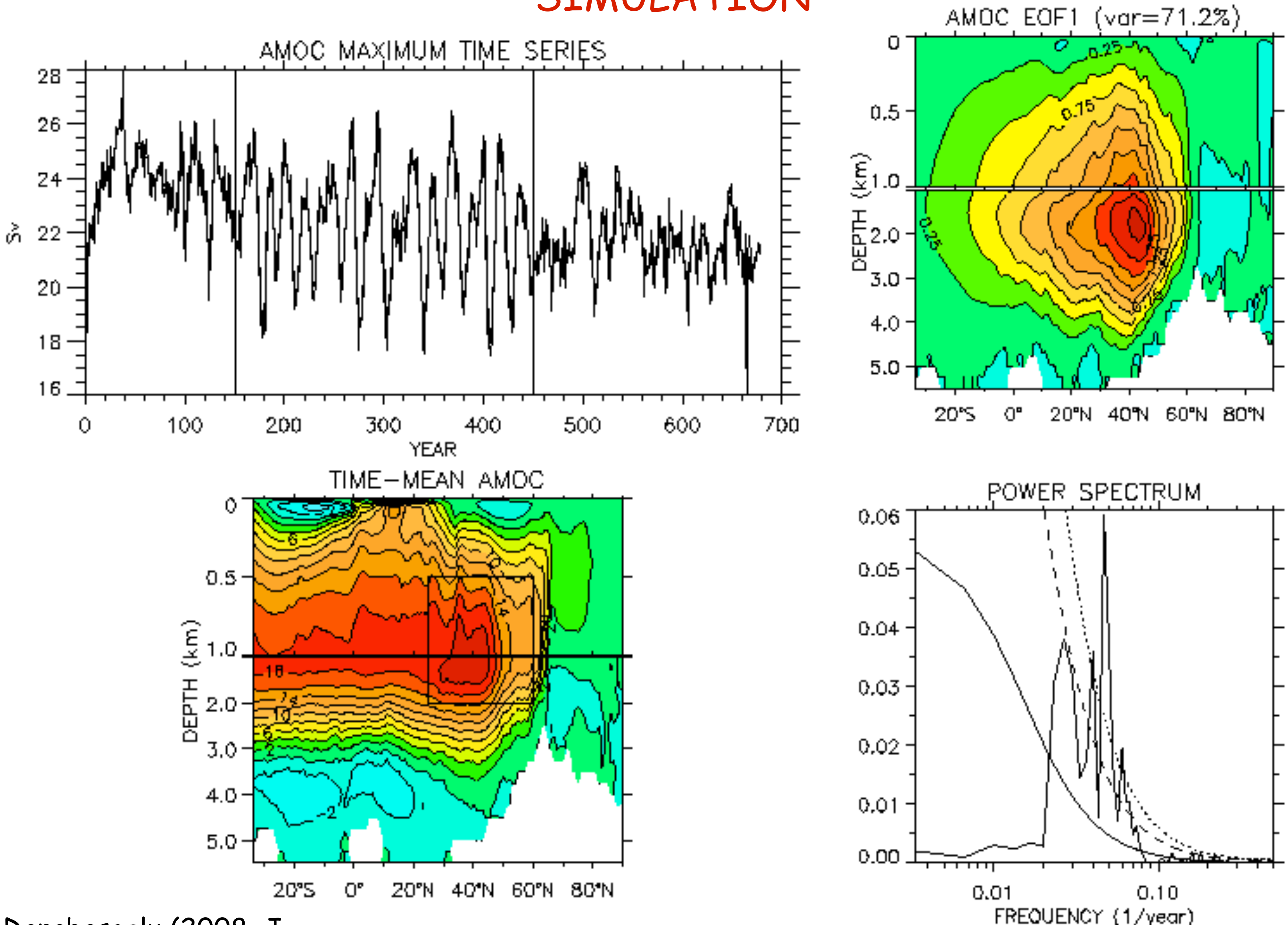
QUESTIONS

Since Delworth et al. (1993) study, there is a broad consensus that the density anomalies in the "sinking region" of the AMOC drives this variability.

However, many fundamental questions still remain largely unanswered:

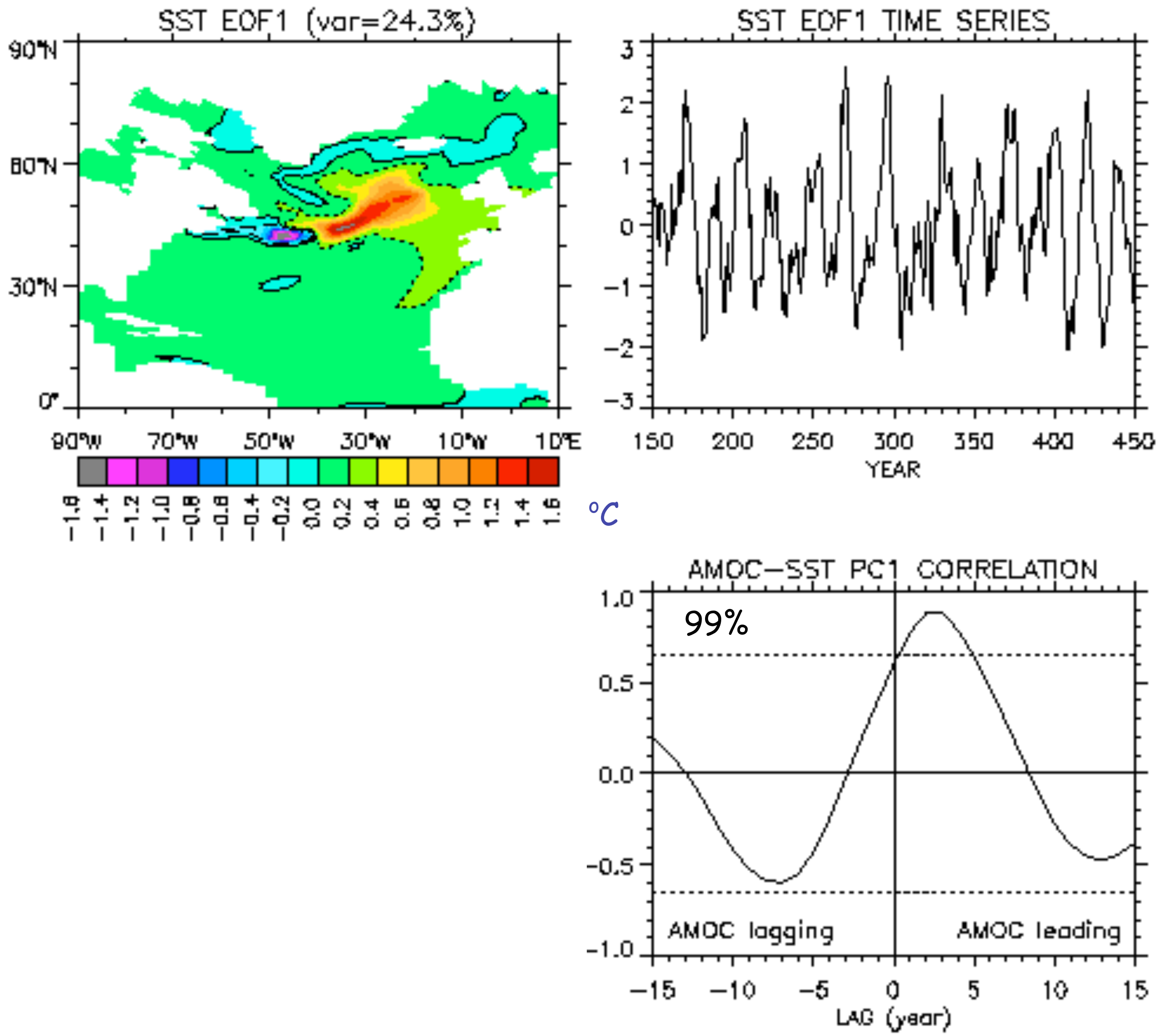
- mechanism [nature of this mode, role of atmospheric variability],
- robustness of mechanism,
- time-scale,
- implications for initialization (and predictability),
- implications for our assessments of 20th century, future scenario, etc. climates,
- ……

AMOC IN CCSM3 T85x1 RESOLUTION, PRESENT-DAY CONTROL SIMULATION

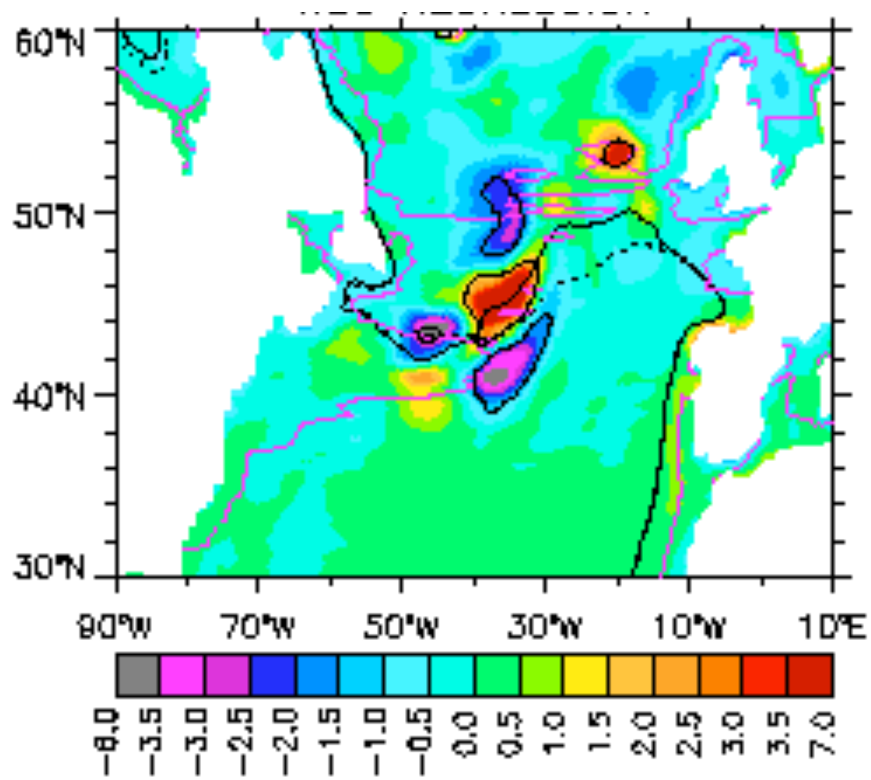


Danabasoglu (2008, J. Climate)

SEA SURFACE TEMPERATURE (SST)

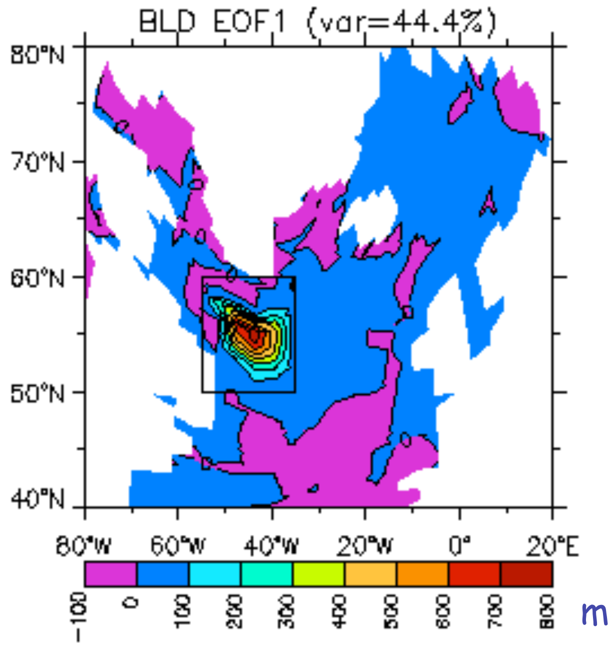


NORTH-SOUTH GYRE BOUNDARY FLUCTUATION and WIND STRESS CURL SIMULTANEOUS REGRESSION

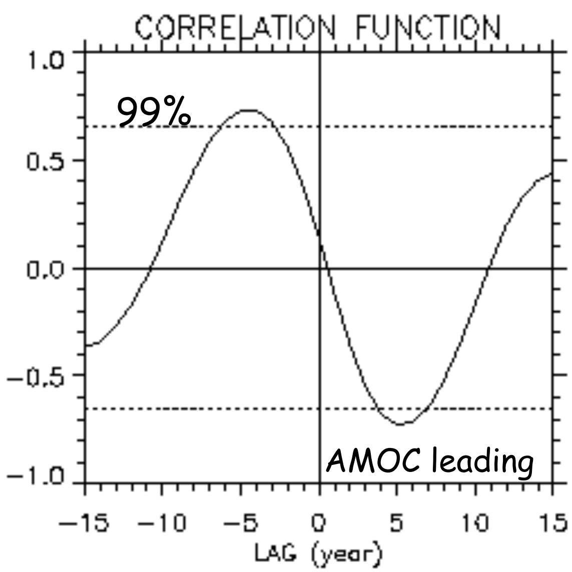


$\times 10^{-8}$ N m^{-3} / ° lat

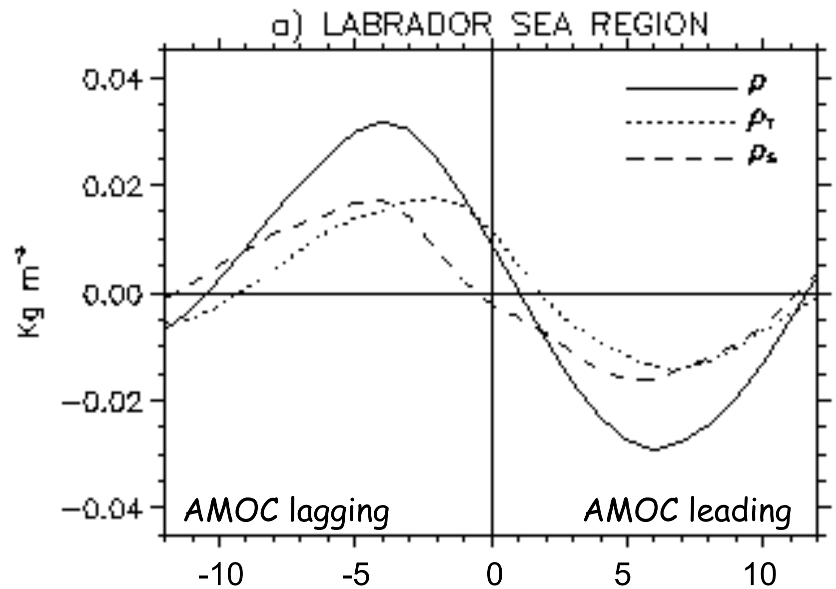
MARCH-MEAN BOUNDARY LAYER DEPTH (BLD)



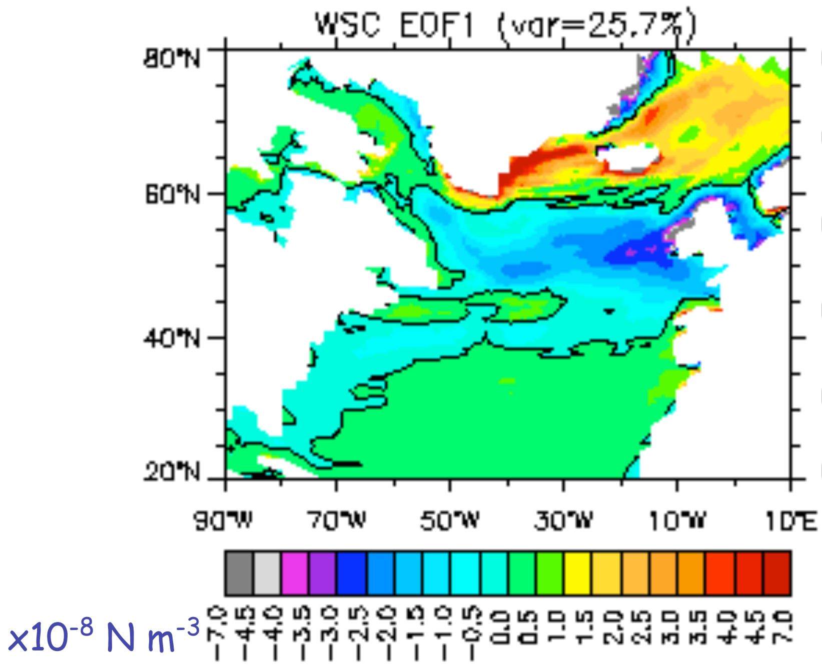
BLD and AMOC PC1 time series

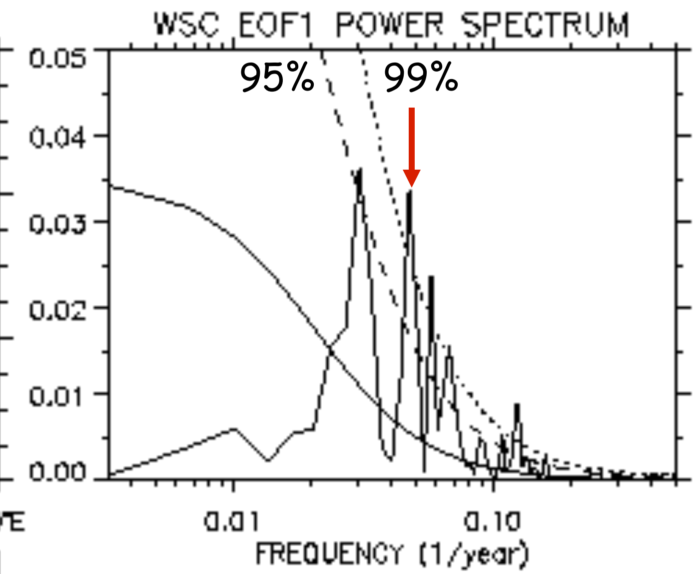


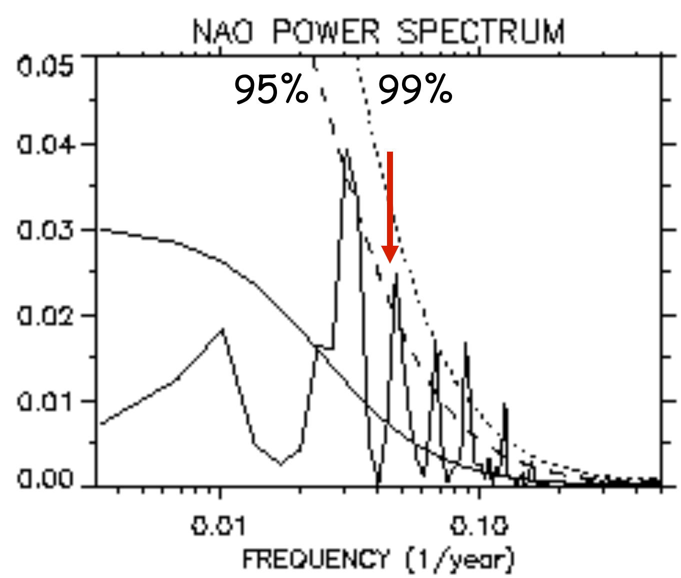
DENSITY REGRESSIONS WITH AMOC PC1 TIME SERIES



WIND STRESS CURL







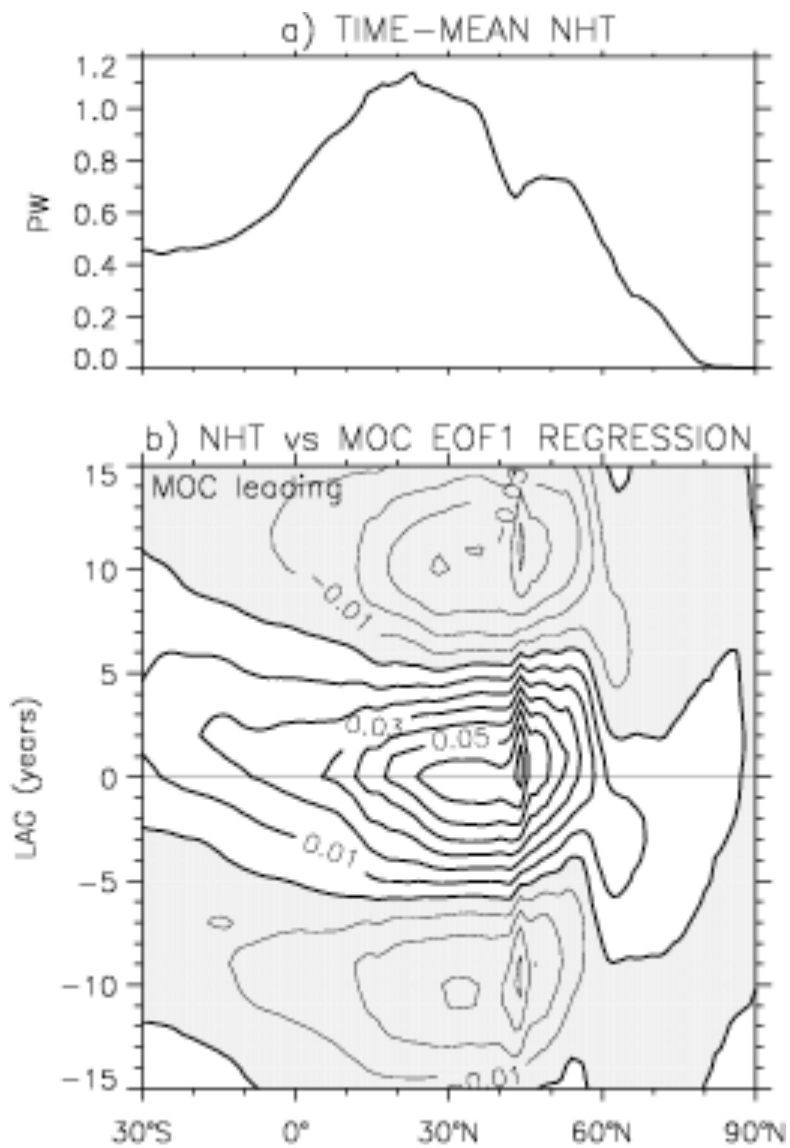
SUMMARY

- Although they refer to different concepts, THC and MOC are often used as synonyms.
- There are no long-term observational estimates of the MOC transport.
- Many CGCMs exhibit multi-decadal or longer time scale variability in their AMOCs.
- This variability is usually associated with variations in the ocean heat transport, ocean heat content, North Atlantic SSTs (e.g. AMO), climate changes over North America, Western Europe, and Africa.
- There are indications of potential predictability.

IN CCSM3 T85x1 RESOLUTION, PRESENT-DAY SIMULATION:

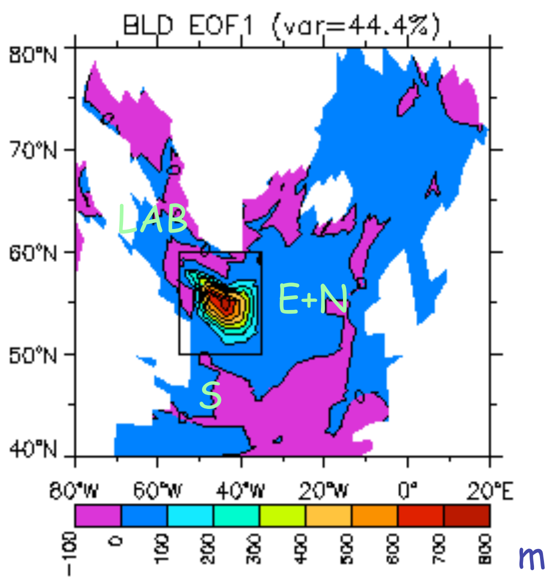
- This multi-decadal variability shows rather large amplitudes in both AMOC and SST. Comparisons of the latter with observations indicate that neither the pattern nor the magnitude of the SST anomalies is realistic. However, the role of the mean-state biases remains unclear.
- These SST anomalies are created by the fluctuations of the subtropical -subpolar gyre boundary driven by small scale WSC anomalies.
- The present results do not support an ocean mode that relies on a phase lagged relationship between temperature and salinity in their contributions to the total density in the model's associated deep water formation region.
- Atmospheric variability associated with the model's NAO appears to play a prominent role in maintaining this variability.
- It is likely that the processes setting the 21-year time scale have oceanic origins.

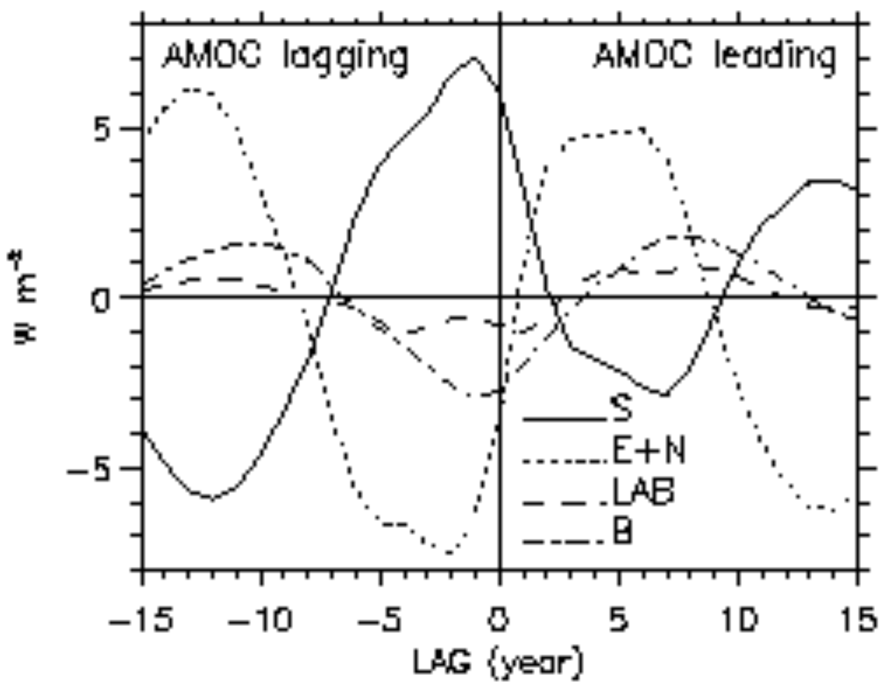
ATLANTIC NORTHWARD HEAT TRANSPORT (NHT)



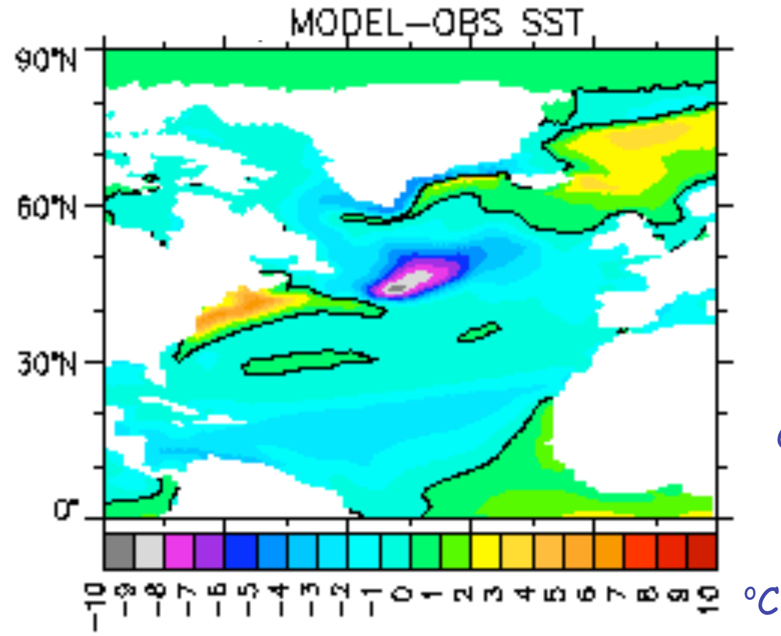
PW / AMOC PC1 variance

LABRADOR SEA ADVECTIVE HEAT FLUX REGRESSIONS WITH AMOC PC1 TIME SERIES



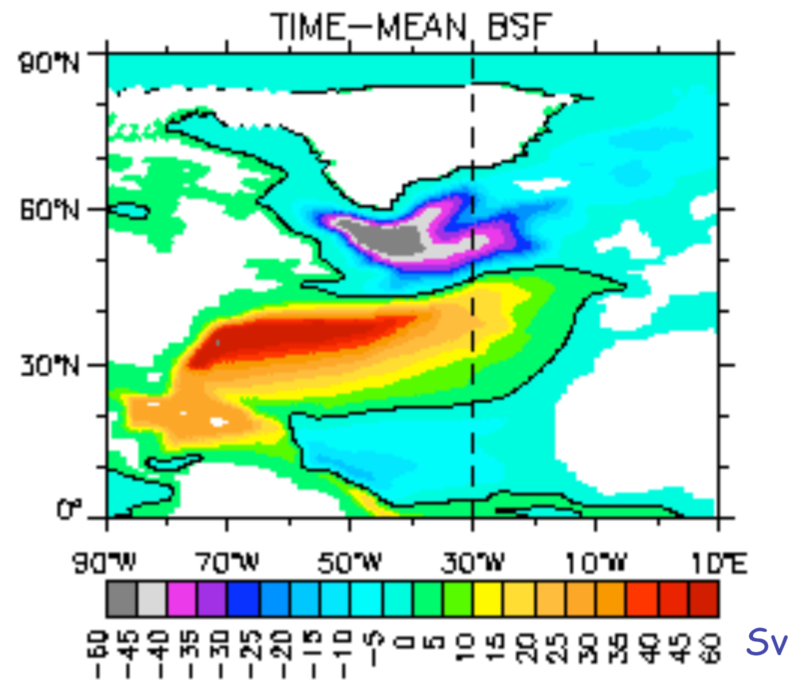


MEAN SST BIAS



OBS: Levitus et al. (1998)
& Steele et al. (2001)

BAROTROPIC
STREAMFUNCTION



SIMPLIFIED DIAGRAM OF PHASE RELATIONSHIPS