Variability of the Atlantic Meridional Overturning Circulation (AMOC)

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Thanks to: Ed Hawkins, Len Shaffrey, Jon Robson, Dan Hodson, Tom Delworth, …

Outline

- Introduction to the AMOC and its importance for climate
- Variability of the AMOC: Observations and Mechanisms
- AMOC response to radiative forcing
- Rapid change of the AMOC
- Climate impacts of AMOC variability and change
- Summary
- Outstanding research issues

Contrasting properties of the Atmosphere and Ocean

- Density:
  - At SLP ocean is ~ 1000x more dense than the atmosphere
- Heat capacity:
  - Specific heat capacity is ~1200x atmosphere
  - 2.5m of ocean has same heat capacity as whole atmosphere
- Velocities:

	Advective	mid-latitude internal Rossby waves
Atmos.	~10 m/s	~10 m/s
Ocean	~1-10 cm/s	~1cm/s

- **Ocean moves and adjusts ~1000x more slowly than the atmosphere – a source of *memory* (& hence *predictability*) in the climate system**

Ocean Circulation

Driven by:

- Windstress, τ

  curl of windstress ($\nabla x\tau$) is a key forcing of *vorticity* in the ocean

  = > horizontal "gyre circulation"

- "buoyancy" fluxes

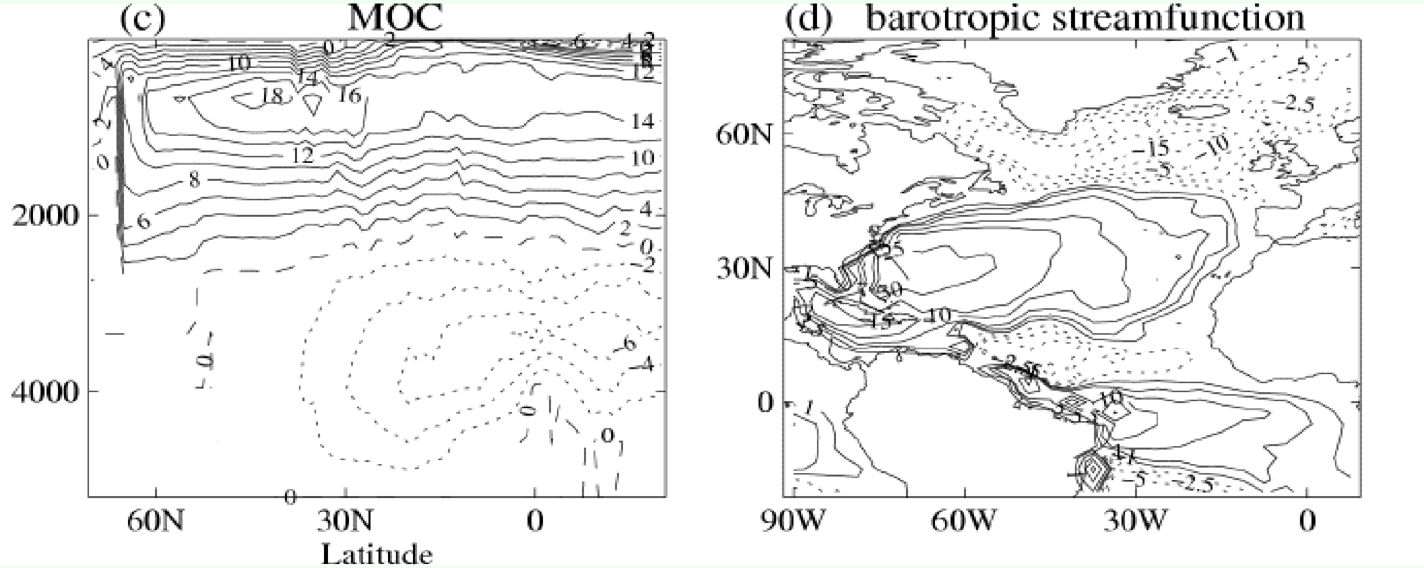
  heat and fresh water fluxes modify ocean temperature and salinity and hence density

  => resulting pressure gradients drive "thermohaline" or overturning circulation

Atlantic Ocean circulation

Overturning Circulation

Horizontal Gyre Circulation



HadCM3 climate model

(~1^{o} ocean resolution)

Mass circulation in Sverdrups

1 Sverdrup = 10^6 m^3/s

<u>NB</u>: Gyre and overturning circulations are not independent

The Thermohaline Circulation

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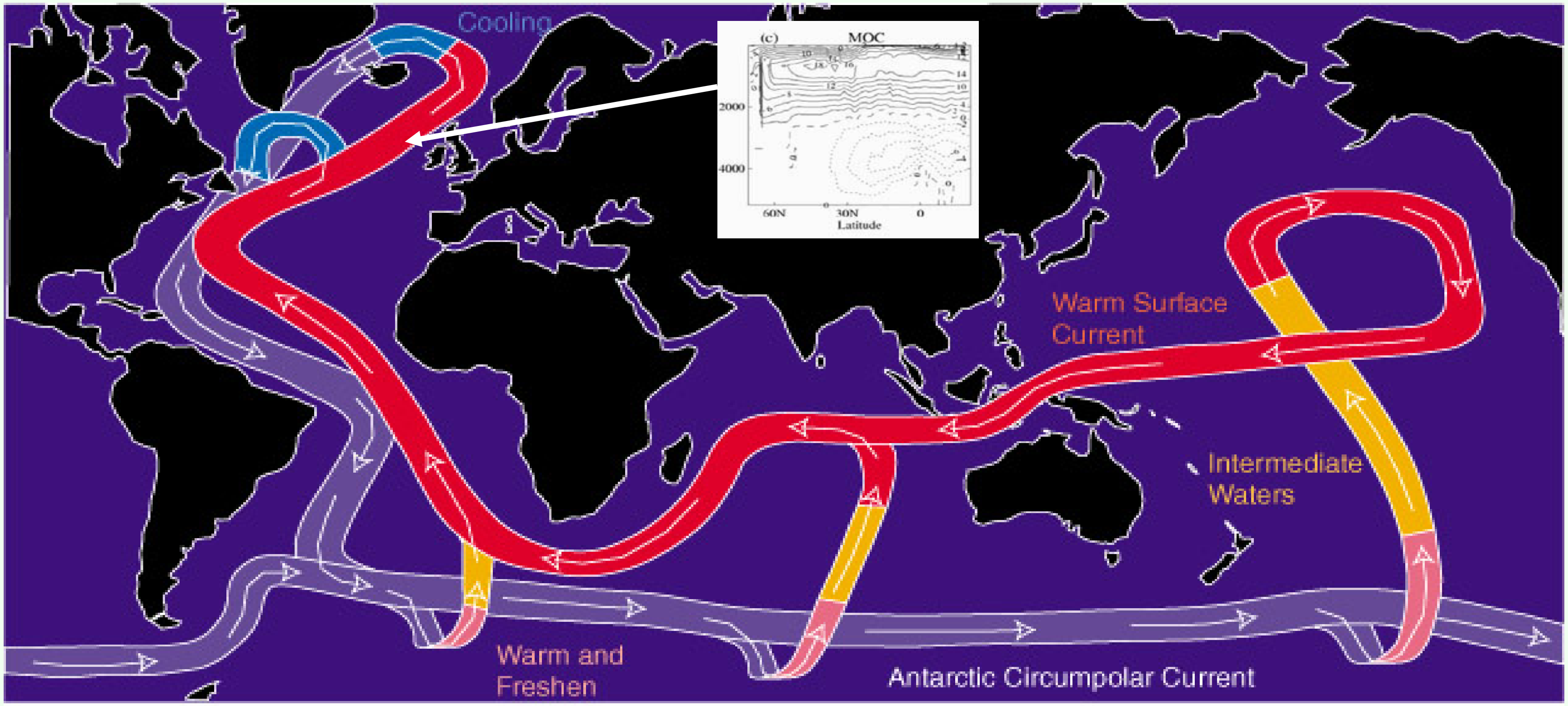


(Courtesy: D.J. Webb)

Thermohaline Conveyor Belt Mk II

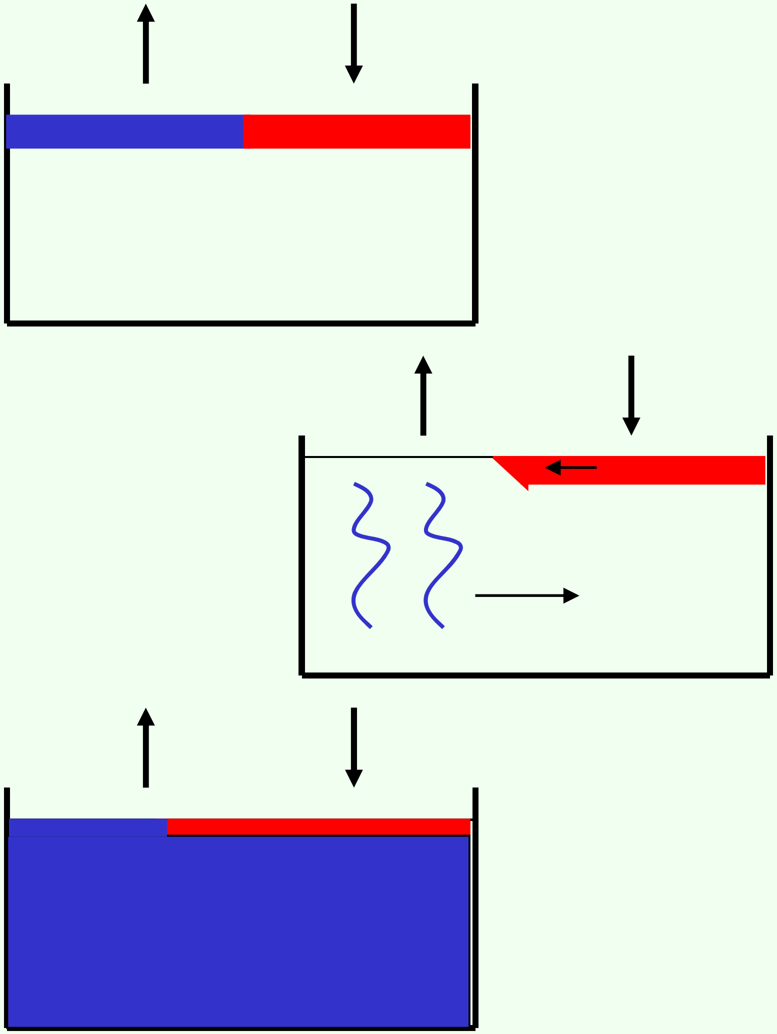
- THC involves a deep overturning circulation driven by contrasts in density, and hence pressure, between different regions
- THC is responsible for a large fraction of the ~O(1PW) northward heat transport of the Atlantic Ocean

Maintenance of Overturning Circulation

- Forcing by buoyancy fluxes generates only a very weak & shallow circulation

$$w\frac{\partial T}{\partial z} = K\frac{\partial^2 T}{\partial z^2}$$

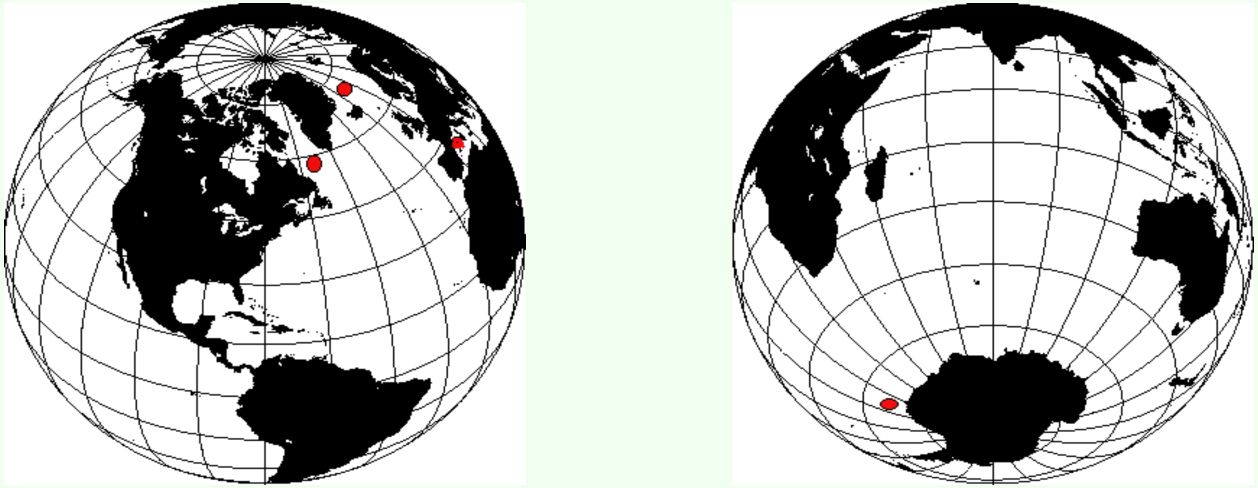
- Need downward mixing of heat to get a stronger deep circulation
- Mixing generated by flow over topography, tides, internal waves...



NB: Wind forcing & eddies in Southern Ocean also play a key role

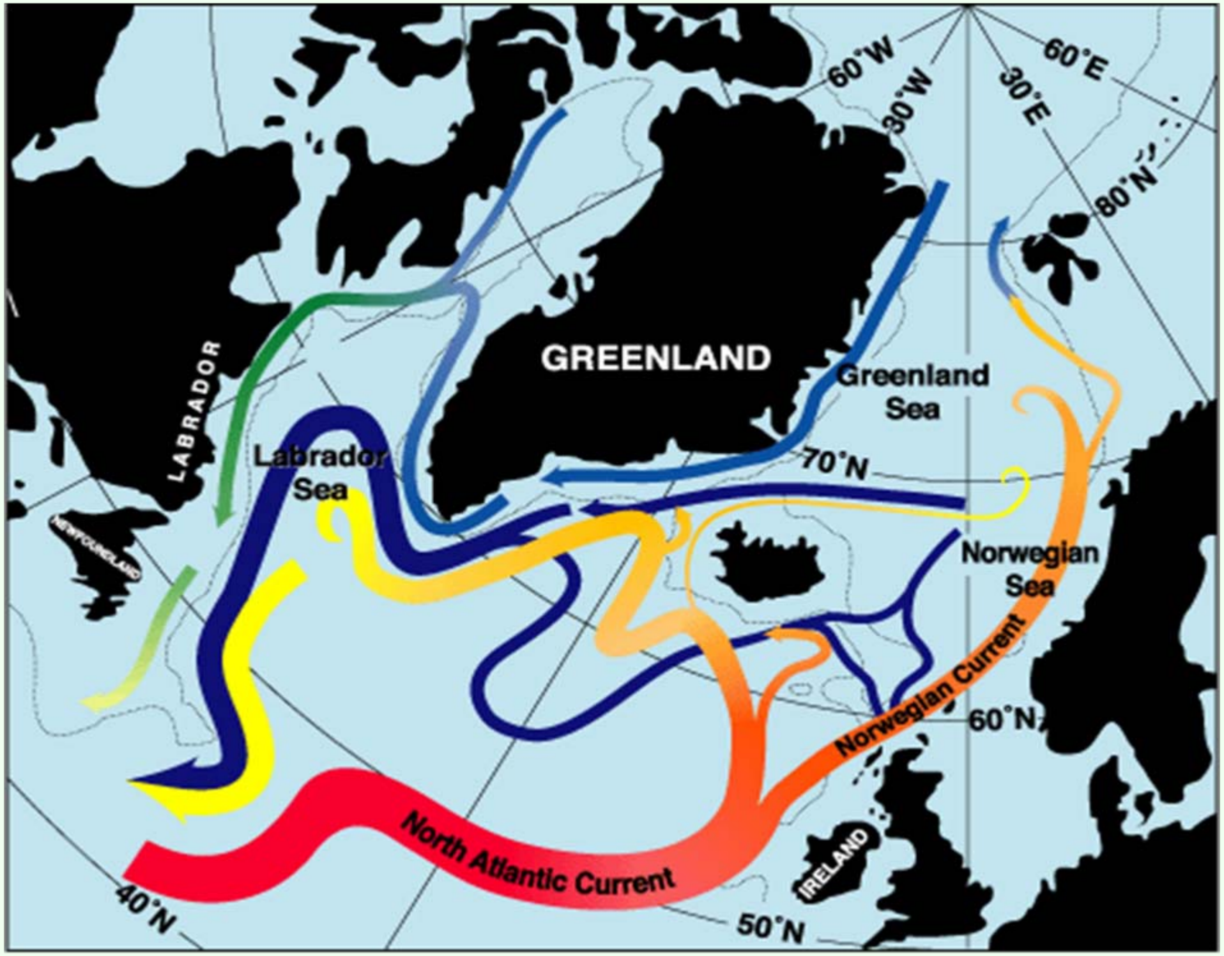
Formation of deep waters

- Sinking of dense waters fundamental to MOC. Deep ocean tends to fill up with the densest waters formed at the surface
- Dense water formation is associated with regions of deep convection (>1km) and/or shallow marginal seas - very few such regions worldwide



- Water must become more dense by:
  - Cooling
  - Increasing salinity

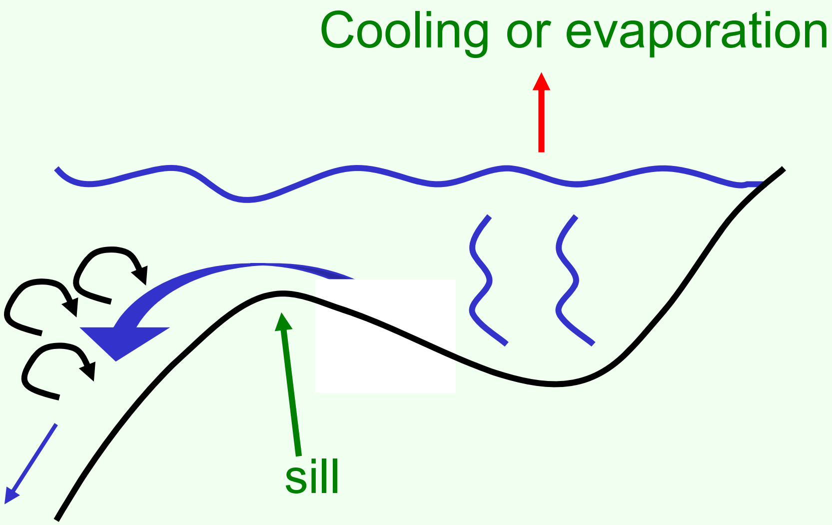
The North Atlantic “Transformation Pipeline”



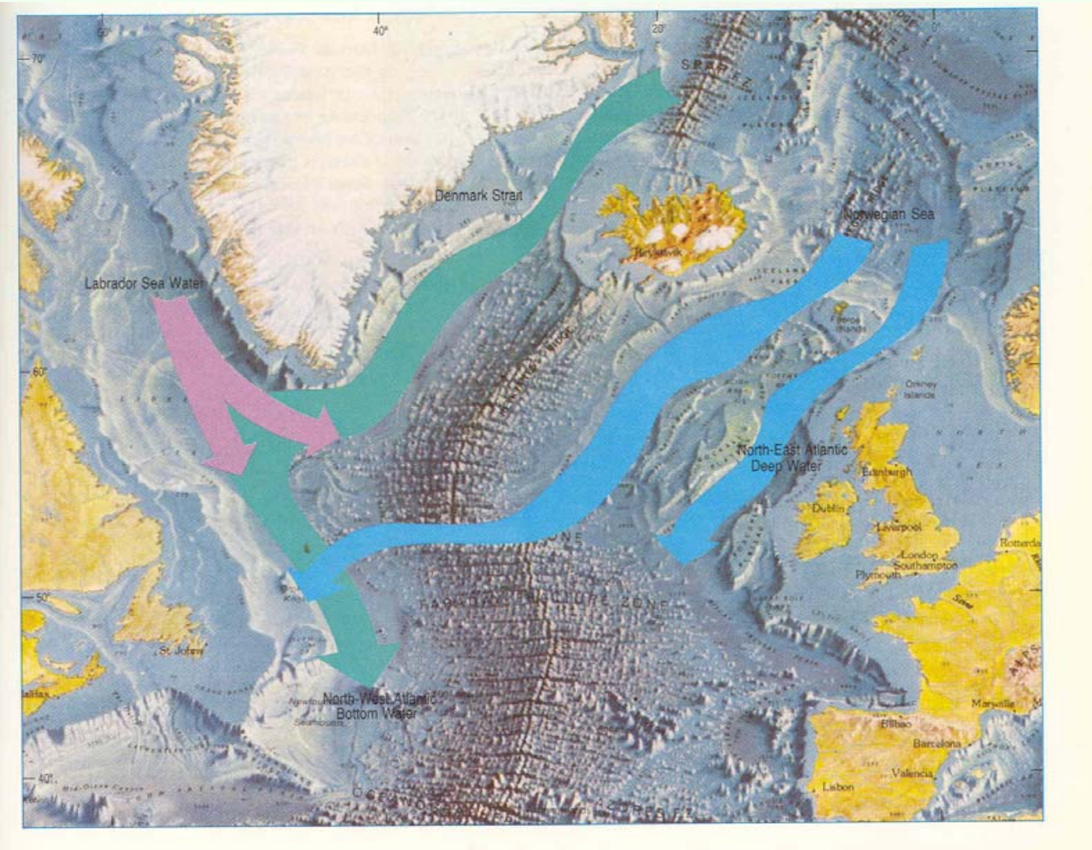
McCartney et al, 1996

Overflows

- Shallow marginal seas favour production of dense waters
- Waters then overflow sills, mixing with ambient waters as they descend


Cooling or evaporation

sill



Climatic importance of MOC: Poleward Heat Transport

- Forcing of the climate system by solar insolation generates equator-pole temperature gradient.
- Heat transport by the atmosphere and ocean reduces this gradient

Total: ~5PW

Ocean: ~ 1.5-2PW

(Trenberth & Caron 2001)

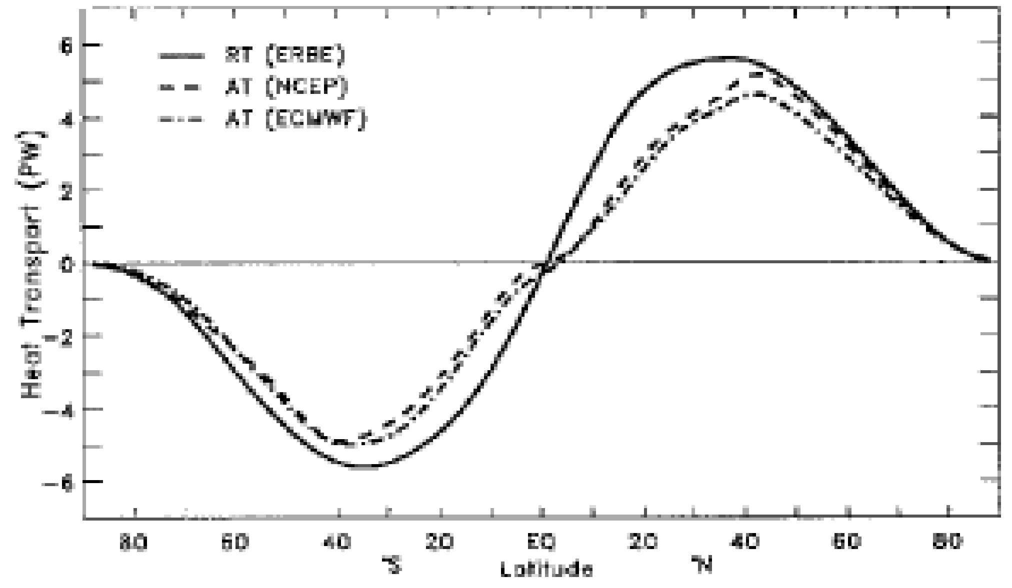


FIG. 2. The required total heat transport from the TOA radiation RT is given along with the estimates of the total atmospheric transport AT from NCEP and ECMWF reanalyses (PW).

Oceanic Heat Transport

- Atlantic Ocean transports heat northwards in both hemispheres
- Peak Atlantic Heat transport: ~ 1PW
- Heat released to atmosphere helps maintain mean clima

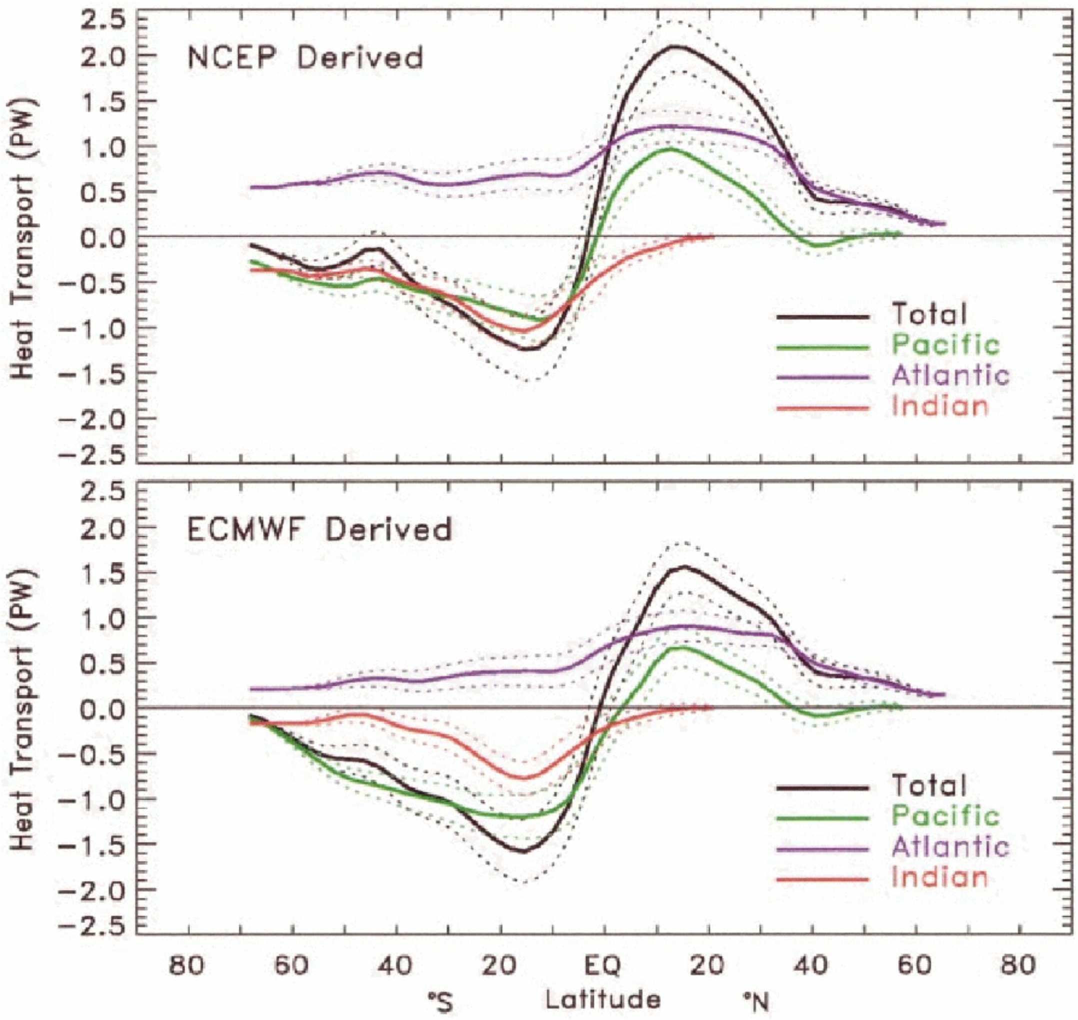
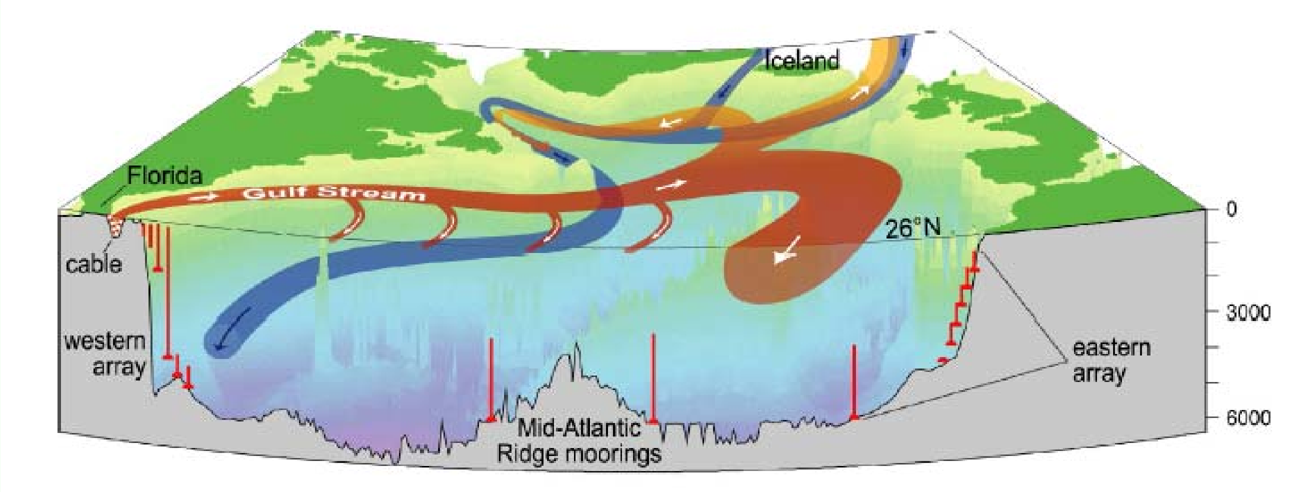


FIG. 5. Implied zonal annual mean ocean heat transports based upon the surface fluxes for Feb 1985–Apr 1989 for the total, Atlantic, Indian, and Pacific basins for NCEP and ECMWF atmospheric fields (PW). The 1 std err bars are indicated by the dashed curves.

Variability of the MOC

- Direct obs of the MOC very sparse in space & time, until recently



Schematic by L.Bell & N. White / CSIRO

UK/US RAPID array gives unprecedented time series since 2004
(but only at 26N)

Other estimates of MOC variability from models

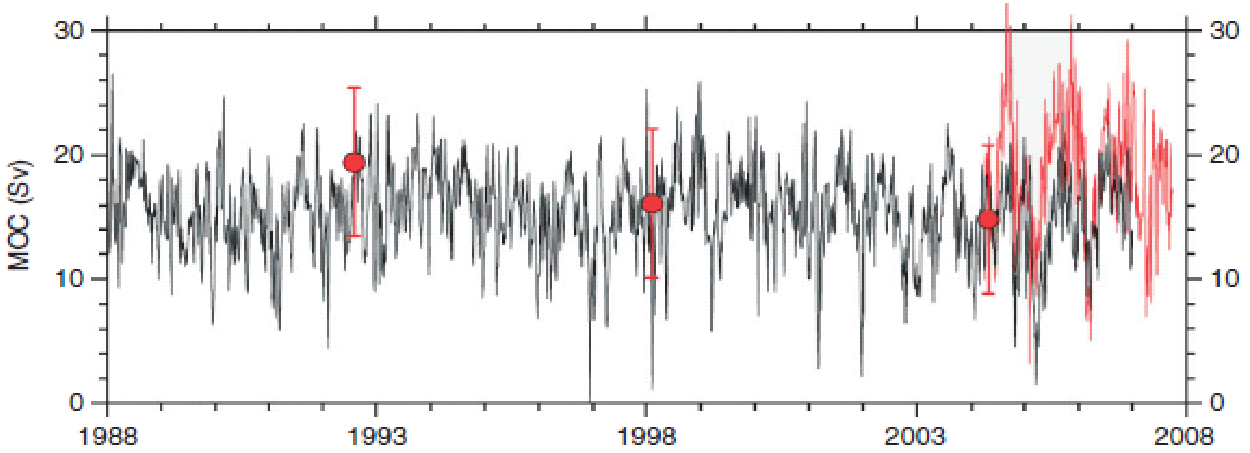
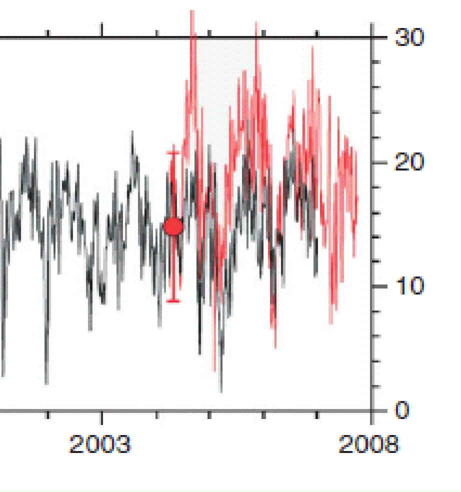
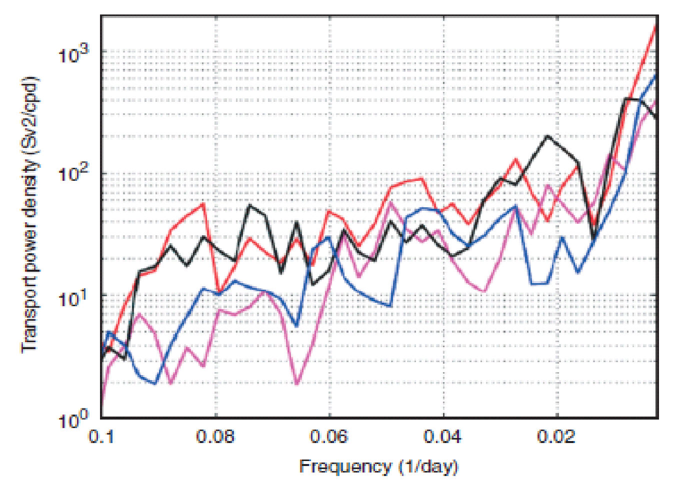


FIGURE 4 | Time series of 5-daily MOC strength at 26°N in the 1/12° OCCAM model, 1988–2006 (black line[57], alongside published estimates of the MOC in 1992, 1998 and 2004, with published error bars,[12] and RAPID array estimates twice daily from 2 April 2004 to 1 October 2007 (red line,[2]).

Cunningham & Marsh 2010

Variability of the MOC





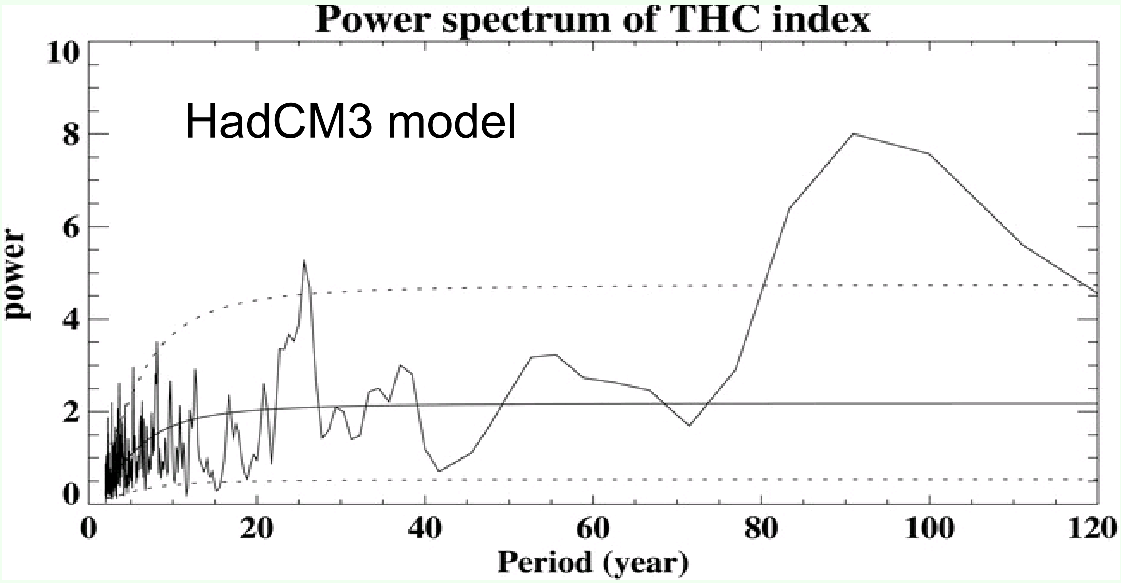
10 days

50 days

Cunningham & Marsh 2010

- Variability on a wide range of timescales
- Red spectra
- High frequency variability (<1 year) probably of little importance for climate

- Climate models typically show enhanced **decadal variability**, but dominant frequencies vary



Power spectrum of THC index

HadCM3 model

Dong & Sutton, 2005

Variability of the AMOC: estimates based on data assimilation

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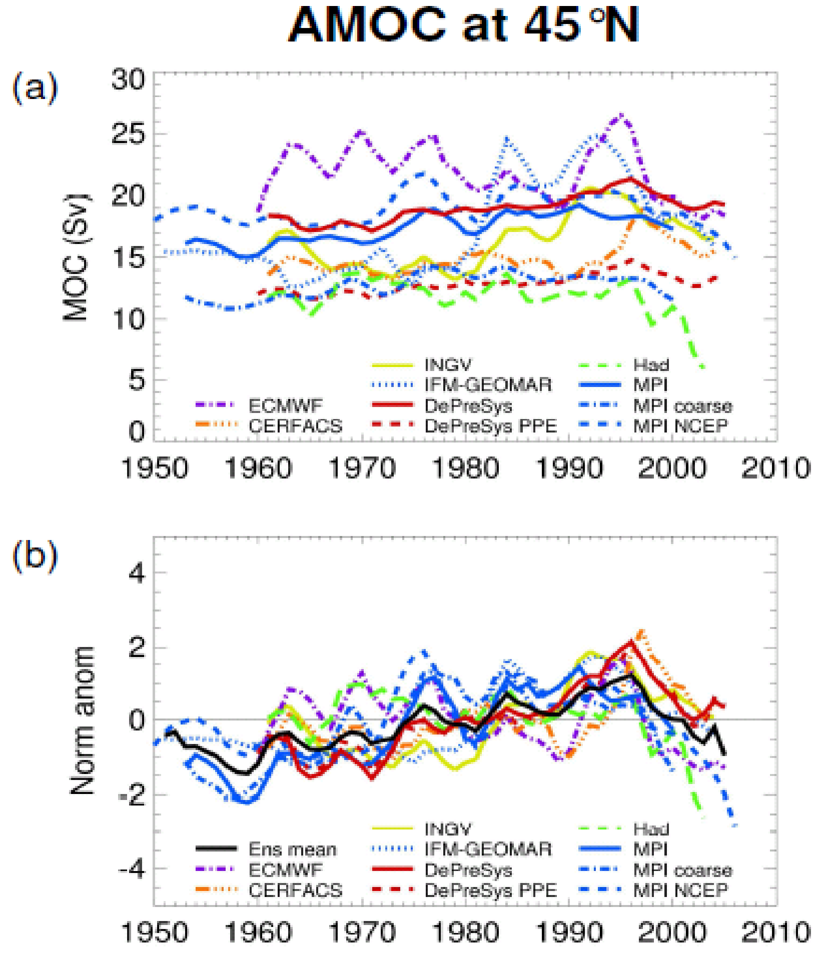
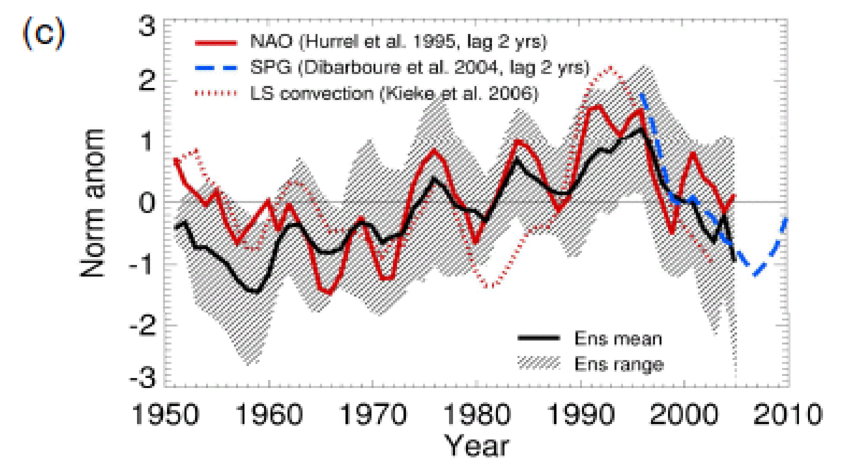
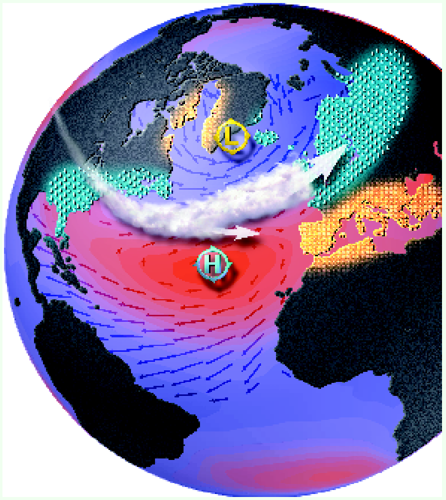
Holger Pohlmann, Met Office Hadley Centre

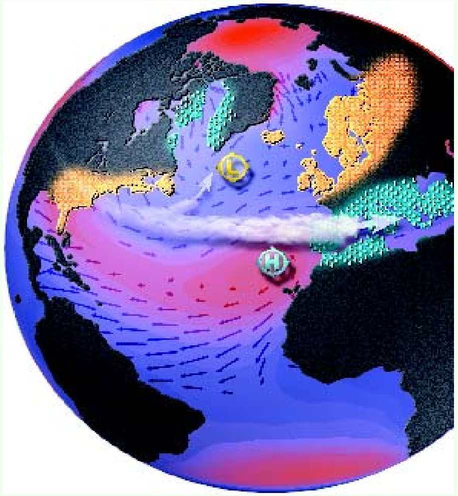
Relationship to North Atlantic Oscillation







NAO +



NAO -

All time series are 3-year running means

Indirect observational evidence of decadal variability in the AMOC

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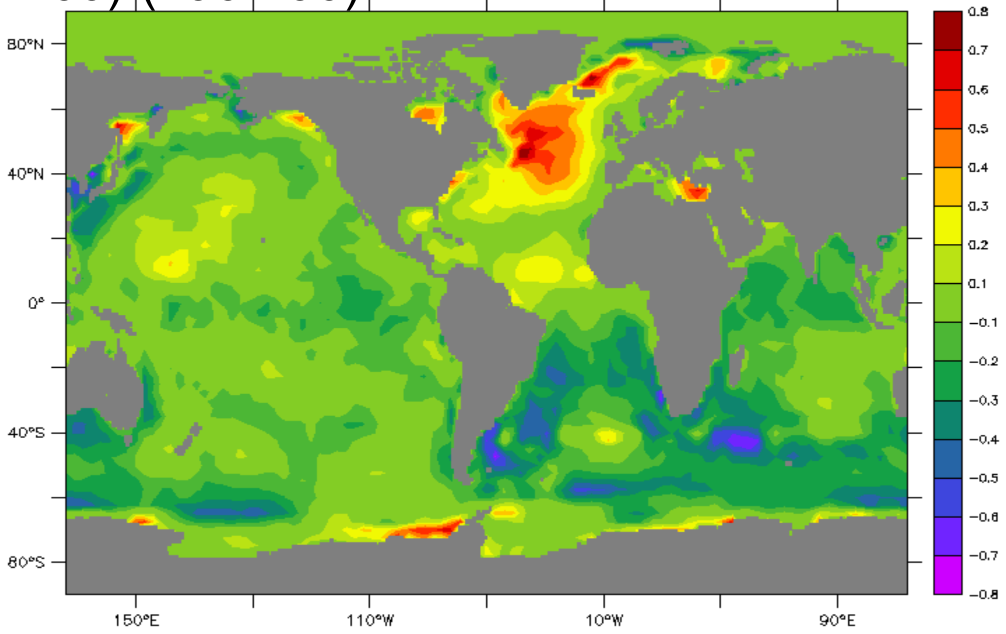
- Folland et al, 84, 86 ; Schlesinger & Ramankutty 94; Kushnir 94; Enfield et al, 2001 etc.

DJF SST anomalies (1931-60)-(1961-90)



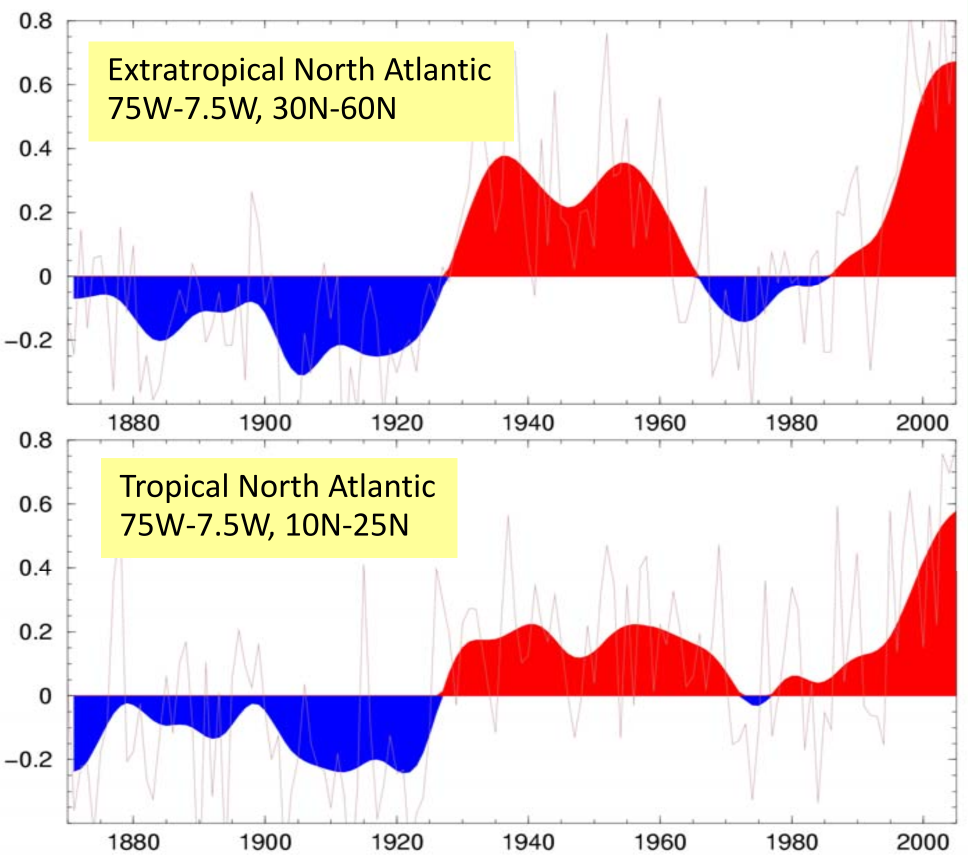


Fig courtesy of Tom Delworth

Indirect observational evidence of decadal variability in the AMOC

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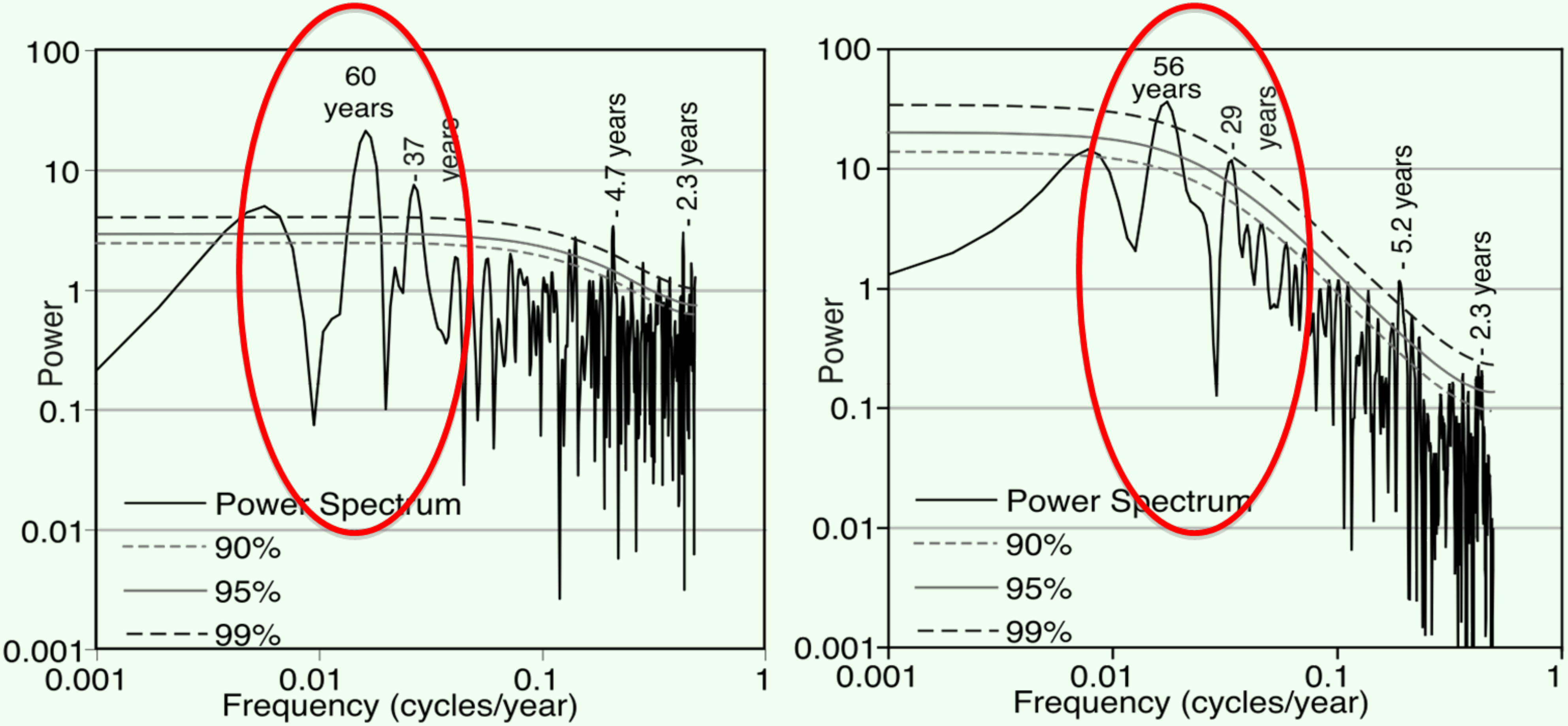

Spectra of paleoclimatic records from Puerto Rico corals (left) and Cariaco Basin (right). Both show distinct multidecadal variability.

Kilbourne et al, 2008; Slide courtesy of Tom Delworth

Mechanisms of decadal variability in the AMOC: atmospheric forcing

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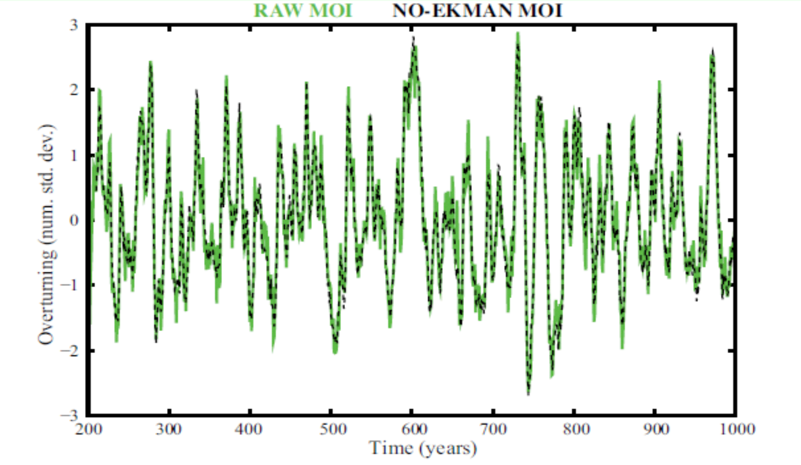
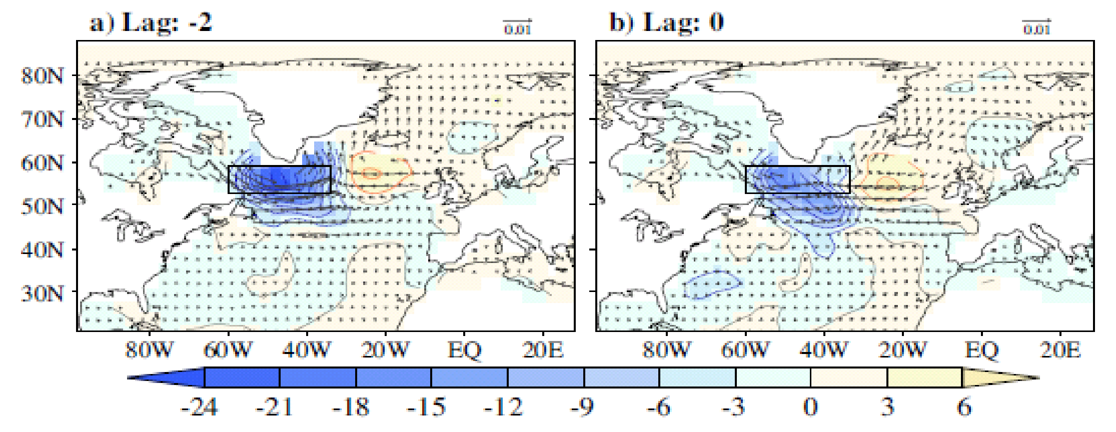
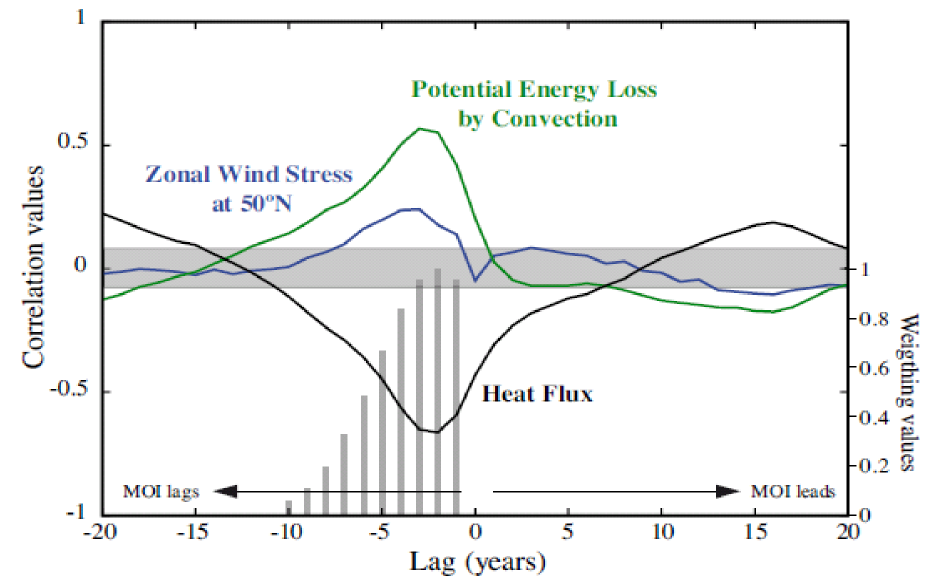
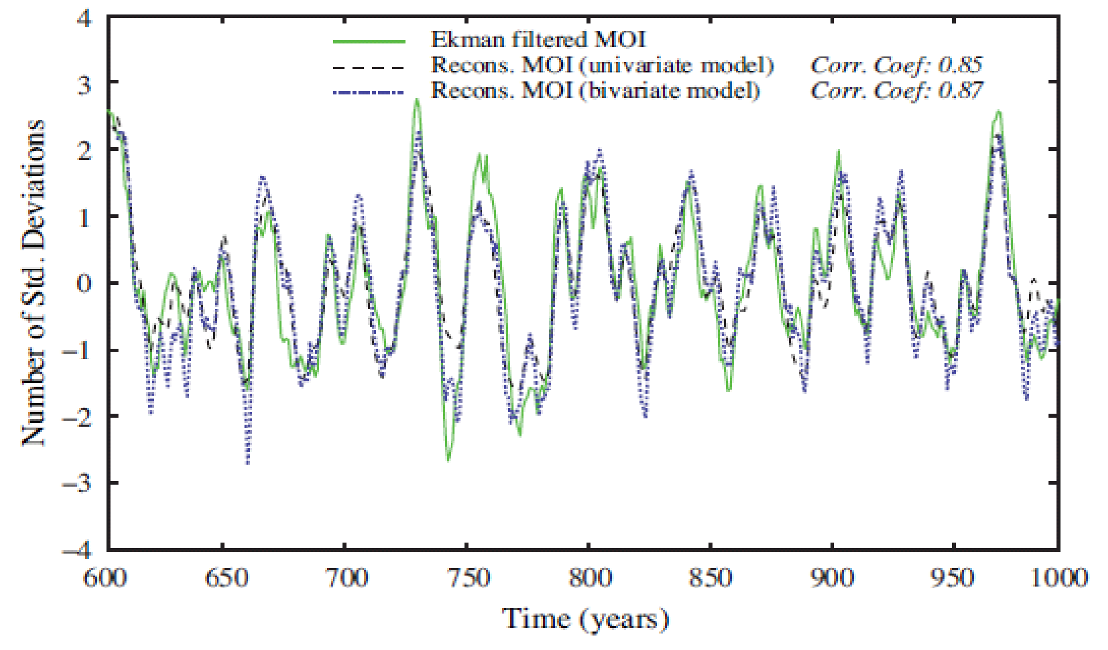




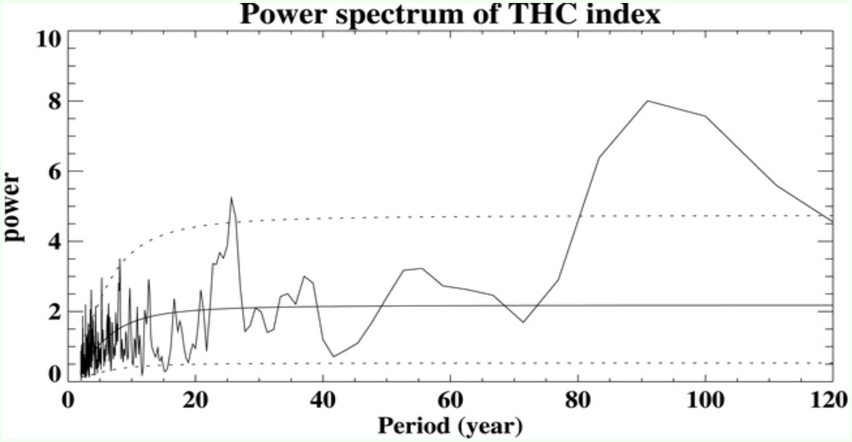




ECHO-G climate model. Ortega, Hawkins & Sutton, submitted 2010

Mechanisms of decadal variability in the AMOC: feedbacks

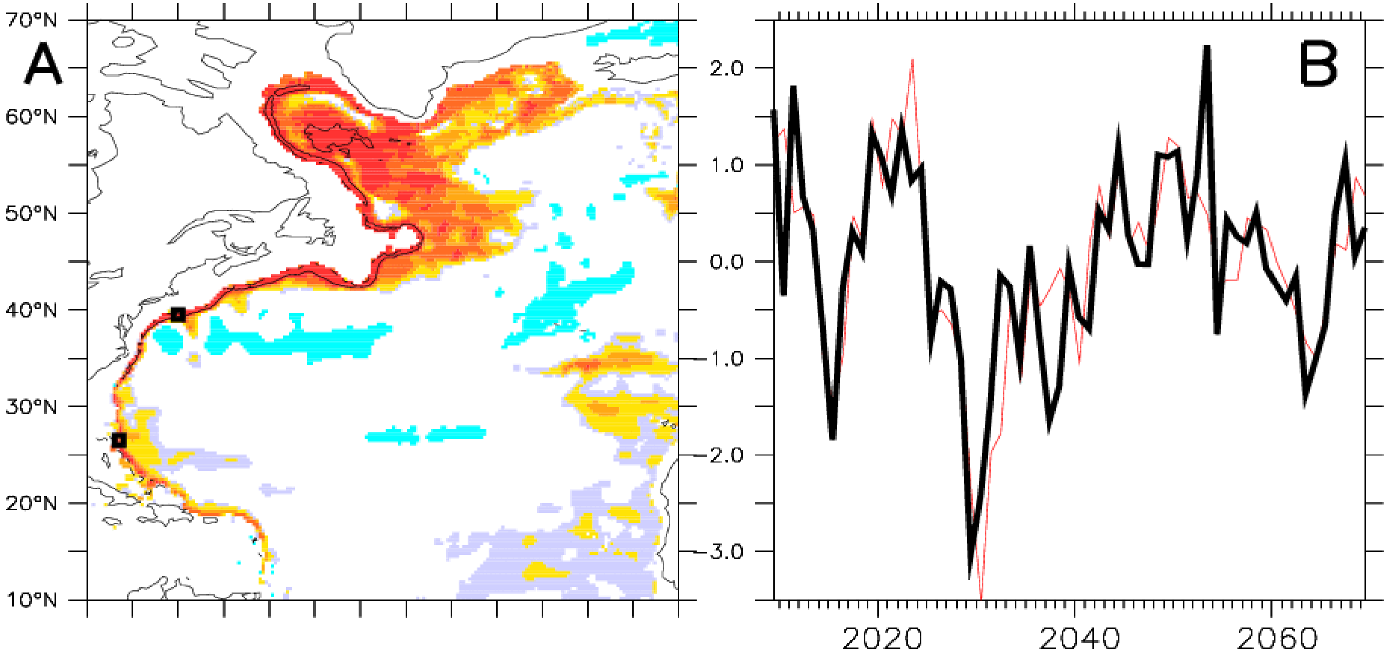
- Quasi-stochastic forcing by the atmosphere (buoyancy fluxes and wind stress) an important driver of MOC variability
- Simplest case gives red noise MOC spectrum
- But oceanic response is complex:
  - **adjustment through wave and advective processes may give rise to feedbacks and preferred timescales of response** (e.g. Delworth & Greatbach, 2000; Dong & Sutton, 2005)
- Coupled ocean-atmosphere feedbacks may also play a role (e.g. Timmerman et al, 98; Vellinga and Wu, 2004)



NB: The relevant processes are imperfectly captured in current climate models, and are *sensitive to resolution* - must treat results with due caution.

Overturning circulation in HiGEM

Atlantic meridional overturning at 40N



Density (800-3000m), correlated with boundary density @ 40N

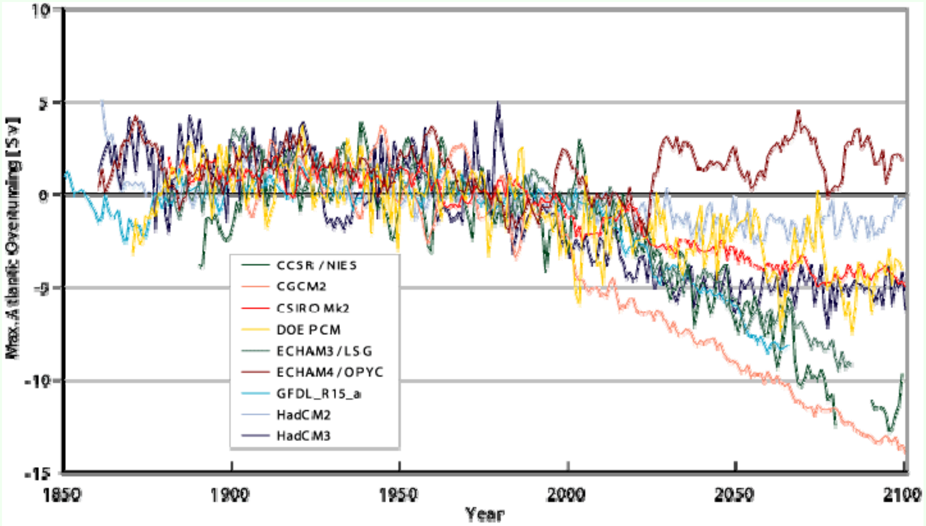
Overturning – black
Density index – red

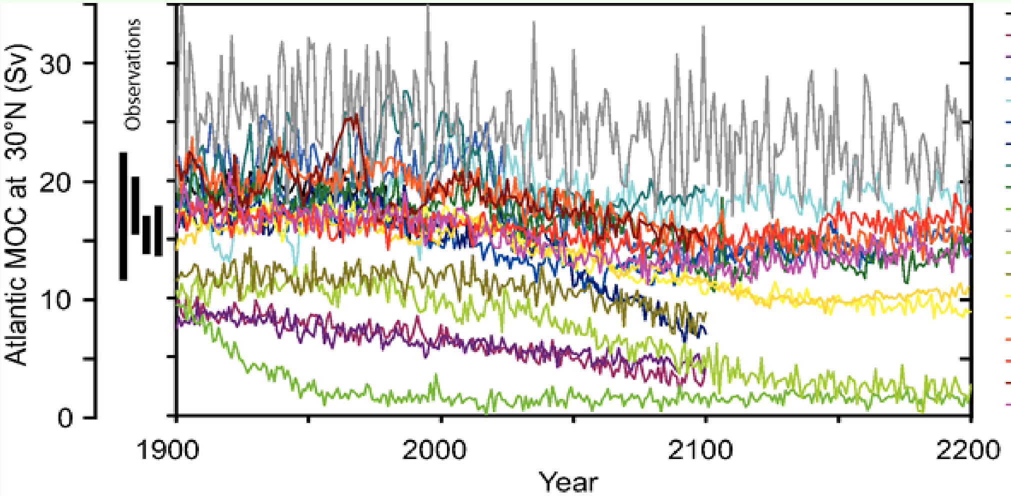
Dan Hodson

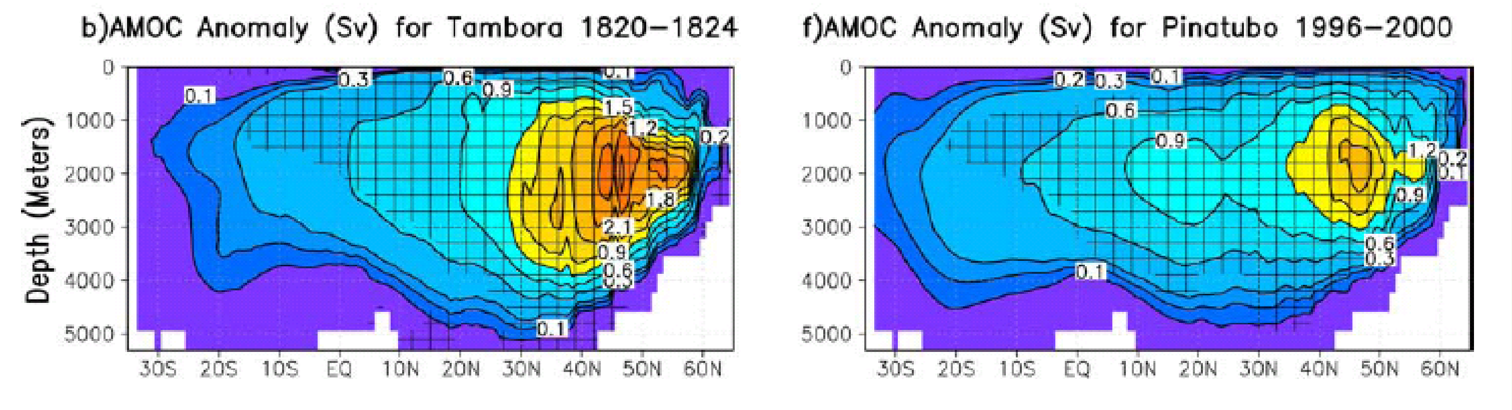
AMOC response to radiative forcing

- Natural (e.g. volcanic) and anthropogenic (e.g. GHG, aerosols) forcings can modify buoyancy fluxes, and influence AMOC

Response to GHG forcing: slow down due to warming and freshening **Source: IPCC**



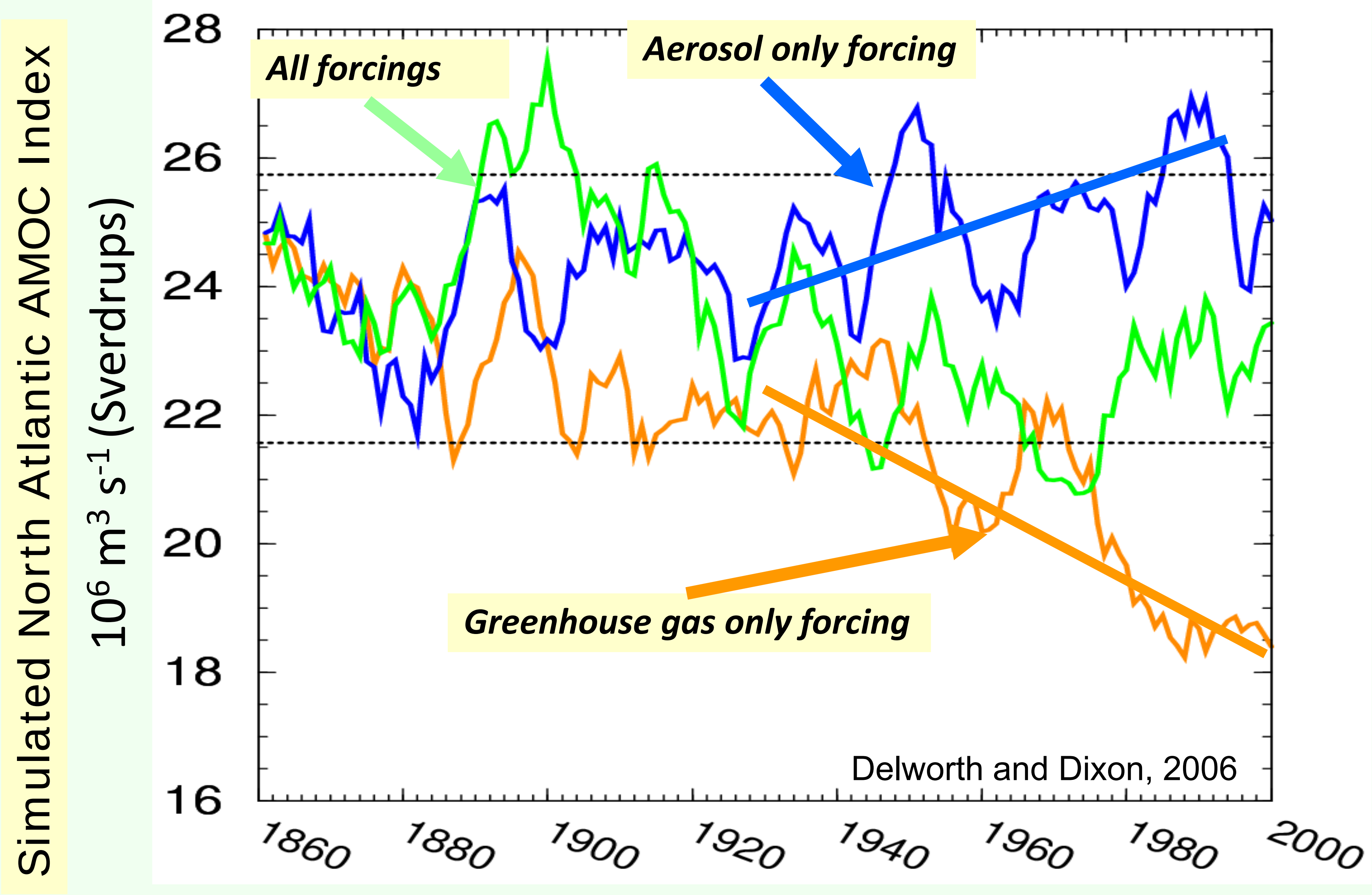




Response to Volcanic forcing

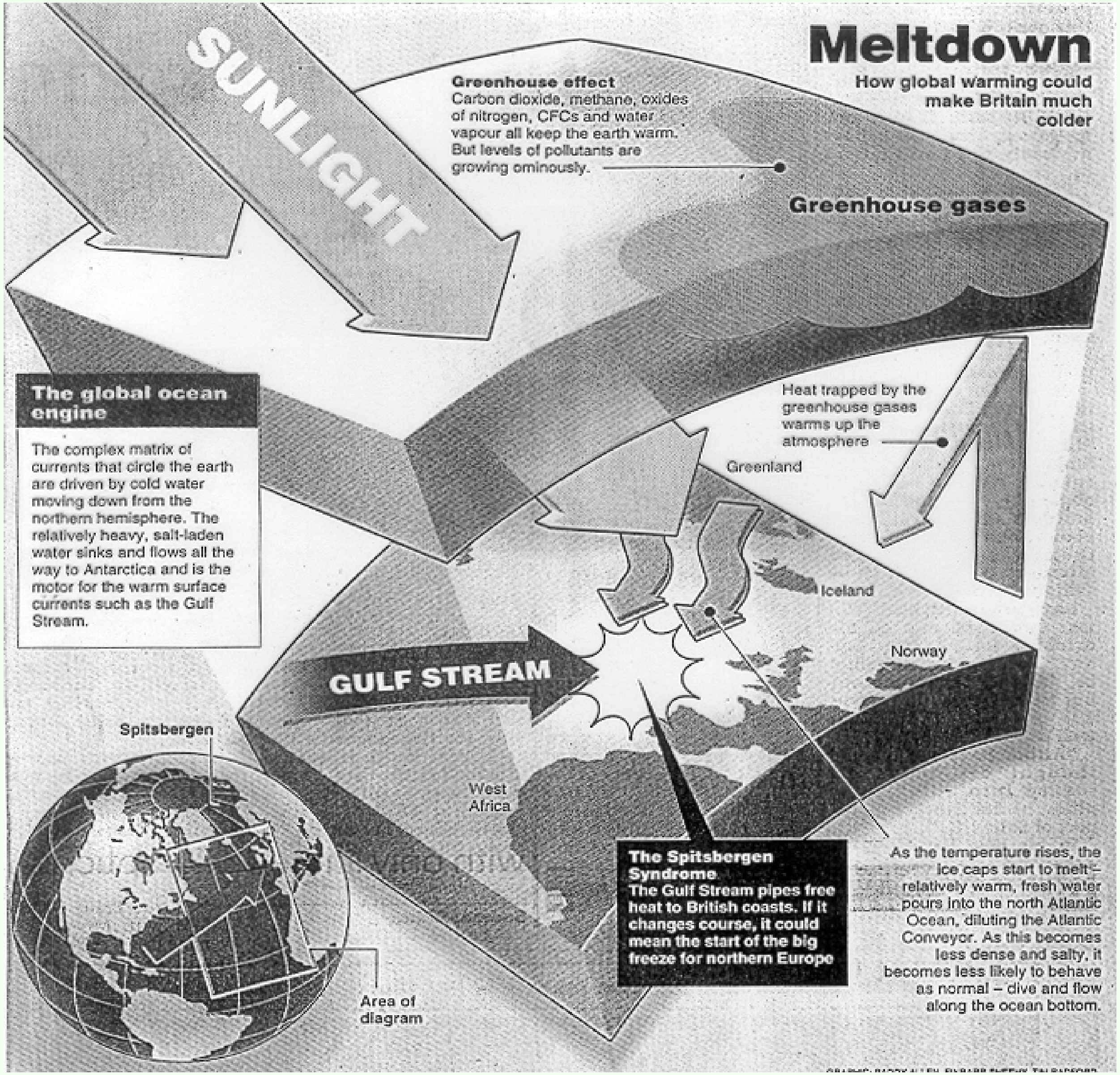
Stenchikov et al, 2009

AMOC response to radiative forcing



Delworth and Dixon, 2006

Potential for Rapid change of the MOC



Meltdown

How global warming could make Britain much colder

Greenhouse effect
Carbon dioxide, methane, oxides of nitrogen, CFCs and water vapour all keep the earth warm. But levels of pollutants are growing ominously.

Heat trapped by the greenhouse gases warms up the atmosphere

The global ocean engine

The complex matrix of currents that circle the earth are driven by cold water moving down from the northern hemisphere. The relatively heavy, salt-laden water sinks and flows all the way to Antarctica and is the motor for the warm surface currents such as the Gulf Stream.

The Spitsbergen Syndrome
The Gulf Stream pipes free heat to British coasts. If it changes course, it could mean the start of the big freeze for northern Europe

As the temperature rises, the ice caps start to melt – relatively warm, fresh water pours into the north Atlantic Ocean, diluting the Atlantic Conveyor. As this becomes less dense and salty, it becomes less likely to behave as normal – dive and flow along the ocean bottom.

Summer in SpitsBritain

EARLIER this year, the Department of the Environment painted a picture of the effects of global warming on Britain, *writes Tim Radford*.

The experts spoke of a climate appropriate to the Loire Valley, starting in the south of England and gradually making its way north over the decades.

But from the start, climate scientists have had reservations. Britain's place in the sun depends entirely on an oceanic accident: the curl of the Gulf Stream transporting tropical heat from the Bermuda triangle to the Bristol Channel.

With global warming and the Gulf Stream, there would be a landscape of sunflower fields and vineyards.

With global warming but without the Gulf Stream, the picture would be very different.

Now the scientists of Columbia University have at least taken a guess. In a Spitsbergen summer, temperatures sometimes soar to 15C and ships have even been known to land visitors there.

In winter, temperatures fall to -13C or lower — occasionally a lot lower.

There would be consolations in a SpitsBritain: rainfall in the northern islands would be relatively light at an average of about an inch a month. Tiresome trees would not obscure the view: only little polar willows and stunted dwarf birch would grow amid the mosses and lichens.

Birdwatchers would see snow buntings, ptarmigan, sandpipers and eider ducks.

Instead of red deer and badgers, there would be musk-ox and polar bears. There would be no crops, but hardly any weeding either.

(from *The***Guardian**)

Dansgaard-Oeschger Cycles

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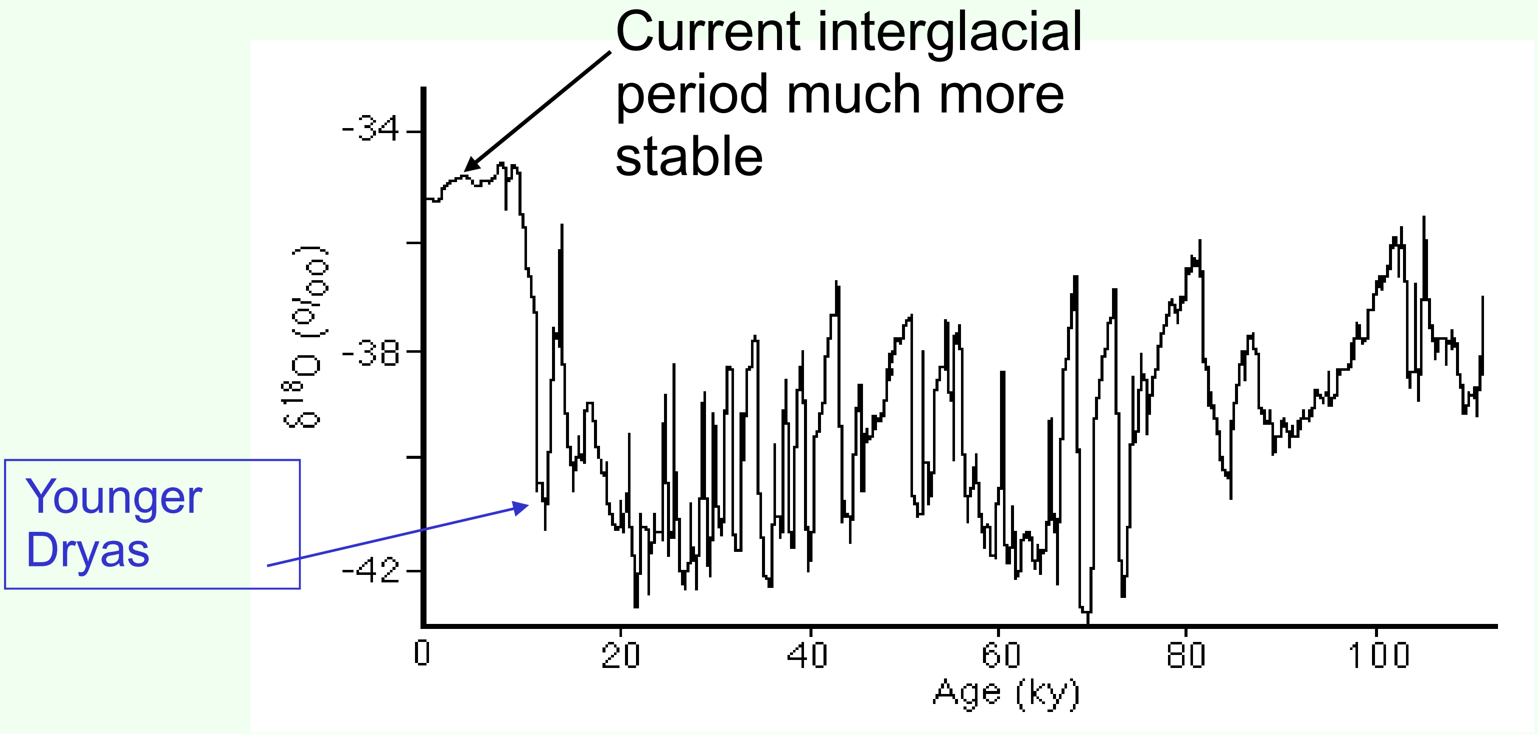


Oxygen isotope record from Greenland Ice Core

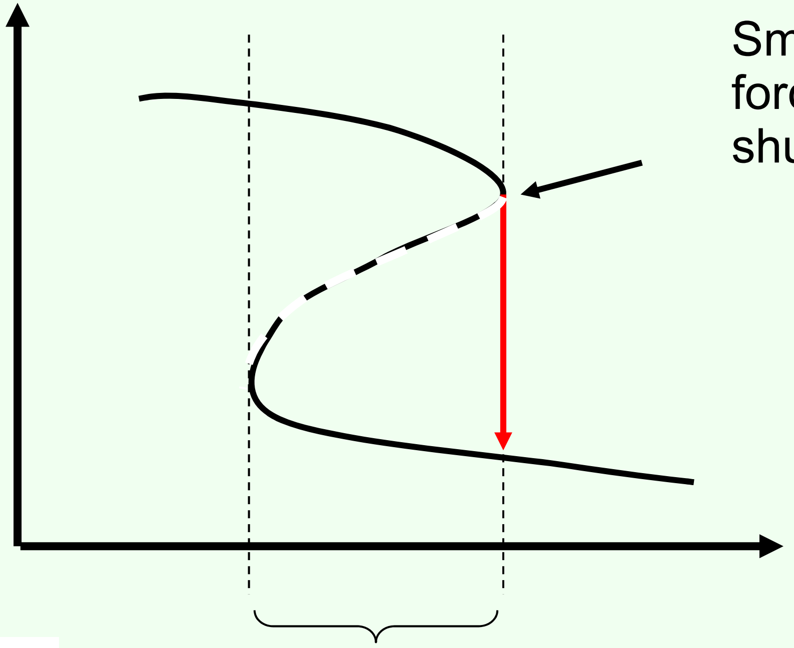
- Records from Greenland show high frequency spikes in glacial periods
- Amplitudes imply a warming of the air temperature of 6-7 degrees C, half the glacial-interglacial range.
- Rapid (~decades) onset (warming), more gradual cooling

- **Rapid change of the MOC a leading theory to explain D-O events**

Multiple equilibria & rapid change

Evidence that the MOC has multiple stable states

Stationary states of the MOC (from a simple model):

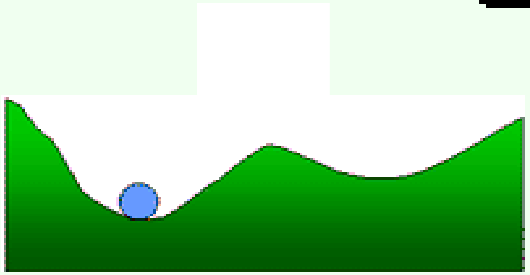


Overturning strength

Freshwater forcing

Small increase in freshwater forcing can trigger abrupt shutdown of overturning

3 stationary states (2 stable)



stronger overturning

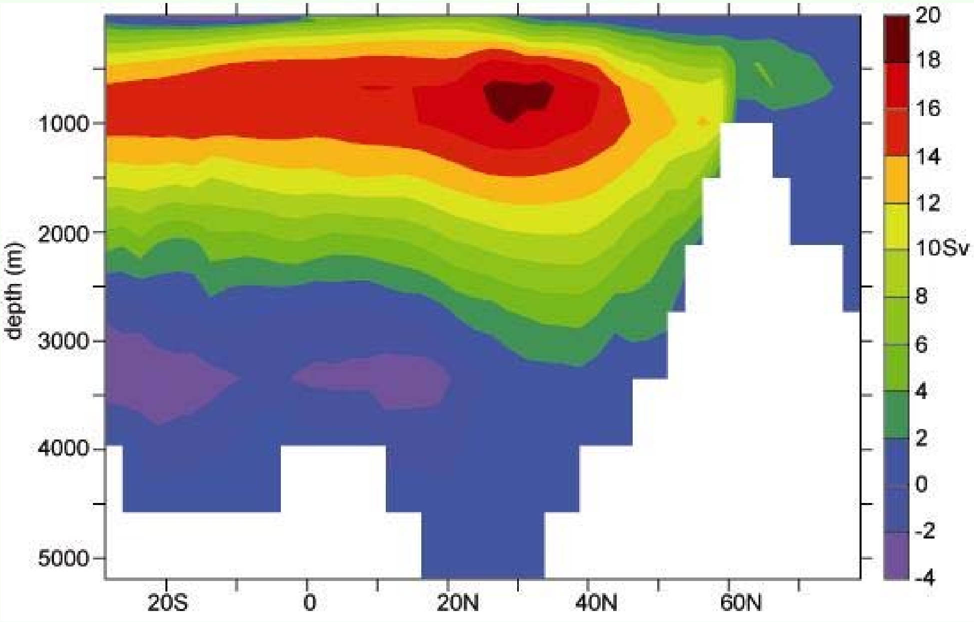
Animation from:

http://www.ncdc.noaa.gov/paleo/abrupt/story2.html

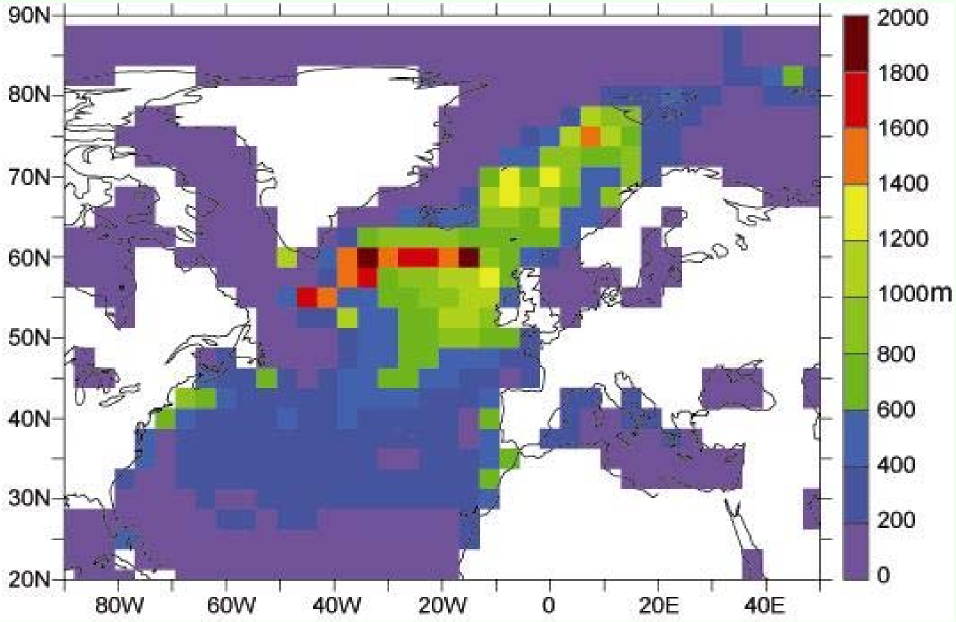
AMOC hysteresis in a coupled GCM

Ed Hawkins, R. Smith, J. Gregory, L. Allison, T. Woollings
NCAS-Climate & University of Reading
J. Rodriguez, R. Wood
Met Office Hadley Centre

FAMOUS – a low res version of HadCM3:
Atmos: 5.0° x 7.5°, 11 levels
Ocean: 2.5° x 3.75°, 20 levels



Atlantic overturning streamfunction



Winter mixed-layer depths

Smith et al. (2009)

Experimental design

The following runs were performed with FAMOUS:

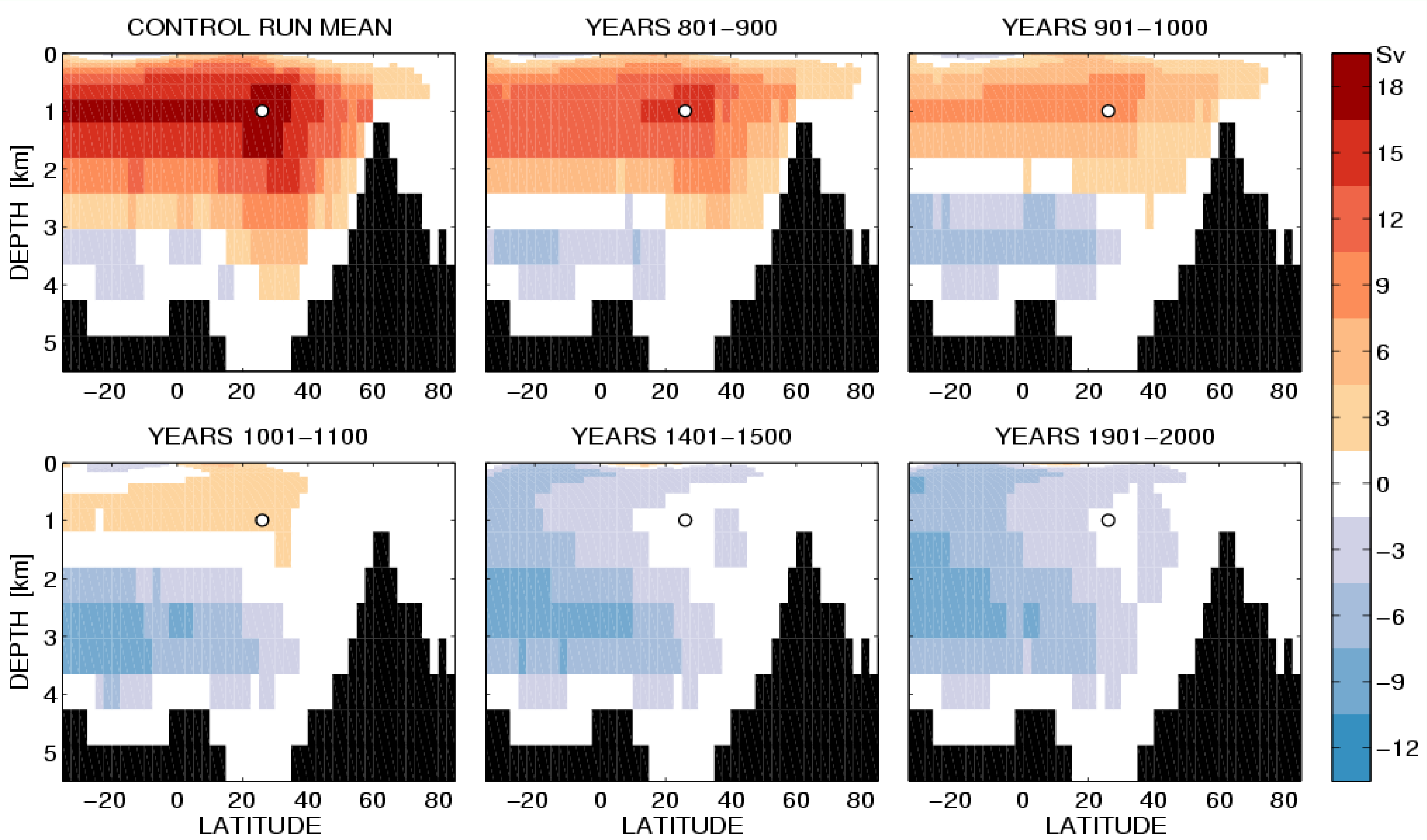
- **CONTROL** – 4000 year run with no hosing
- **HOSING** – add freshwater to North Atlantic between 20°-50°N
  - **TRANSIENT RAMP UP** – increase hosing from 0Sv to 1Sv over 2000 years
  - **TRANSIENT RAMP DOWN** – reduce hosing from 1Sv to 0Sv over 2000 yrs
  - **CONSTANT HOSING** – spun off at various points to check equilibrium state

Important design aspects:

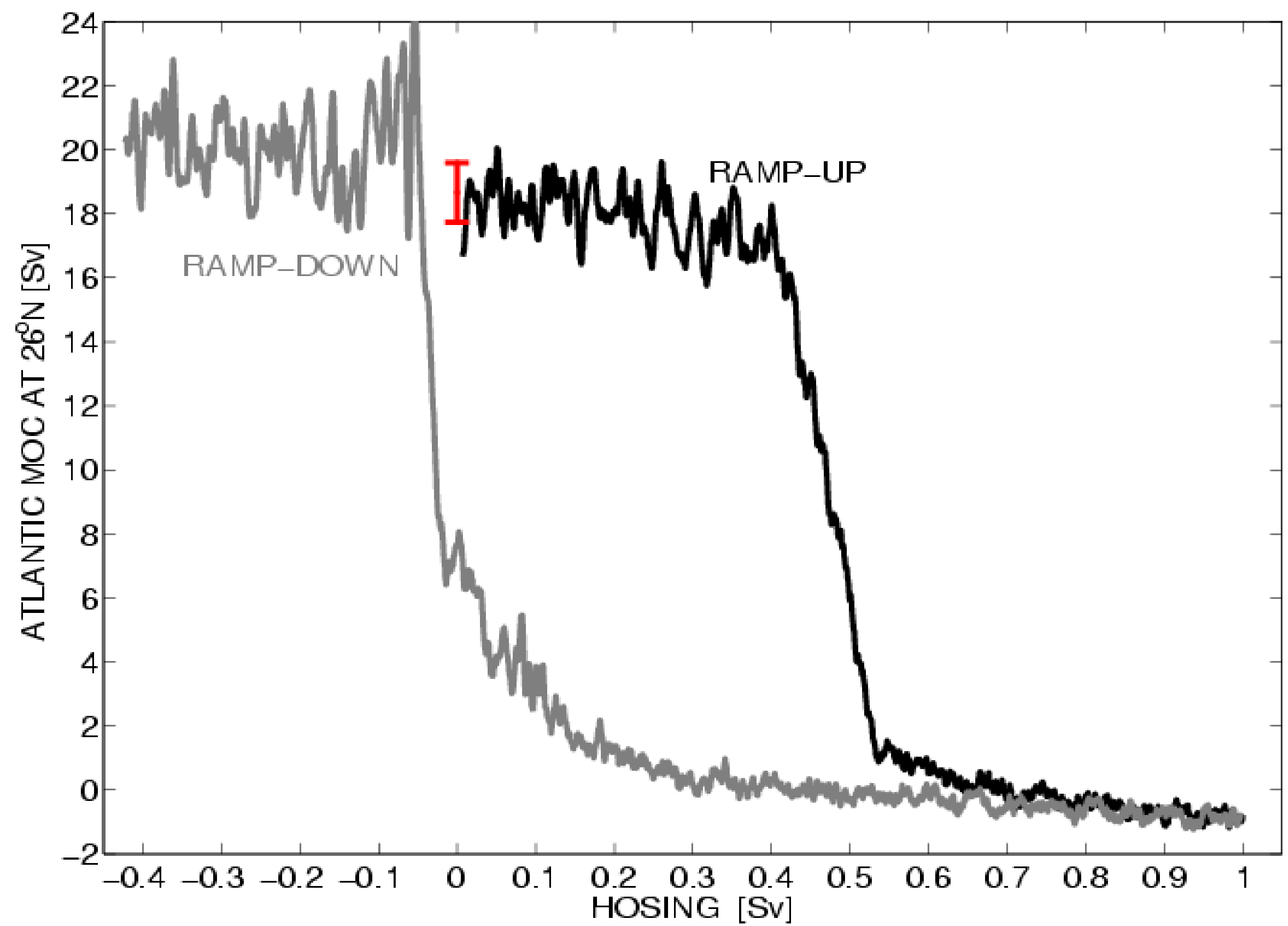
- **COMPENSATION** – in all runs the total freshwater flux is zero
  - Hosing compensated by a small evaporative flux over the rest of the ocean surface (≈ 0.3 psu/year for 1Sv hosing)

Transient ramp-up of hosing

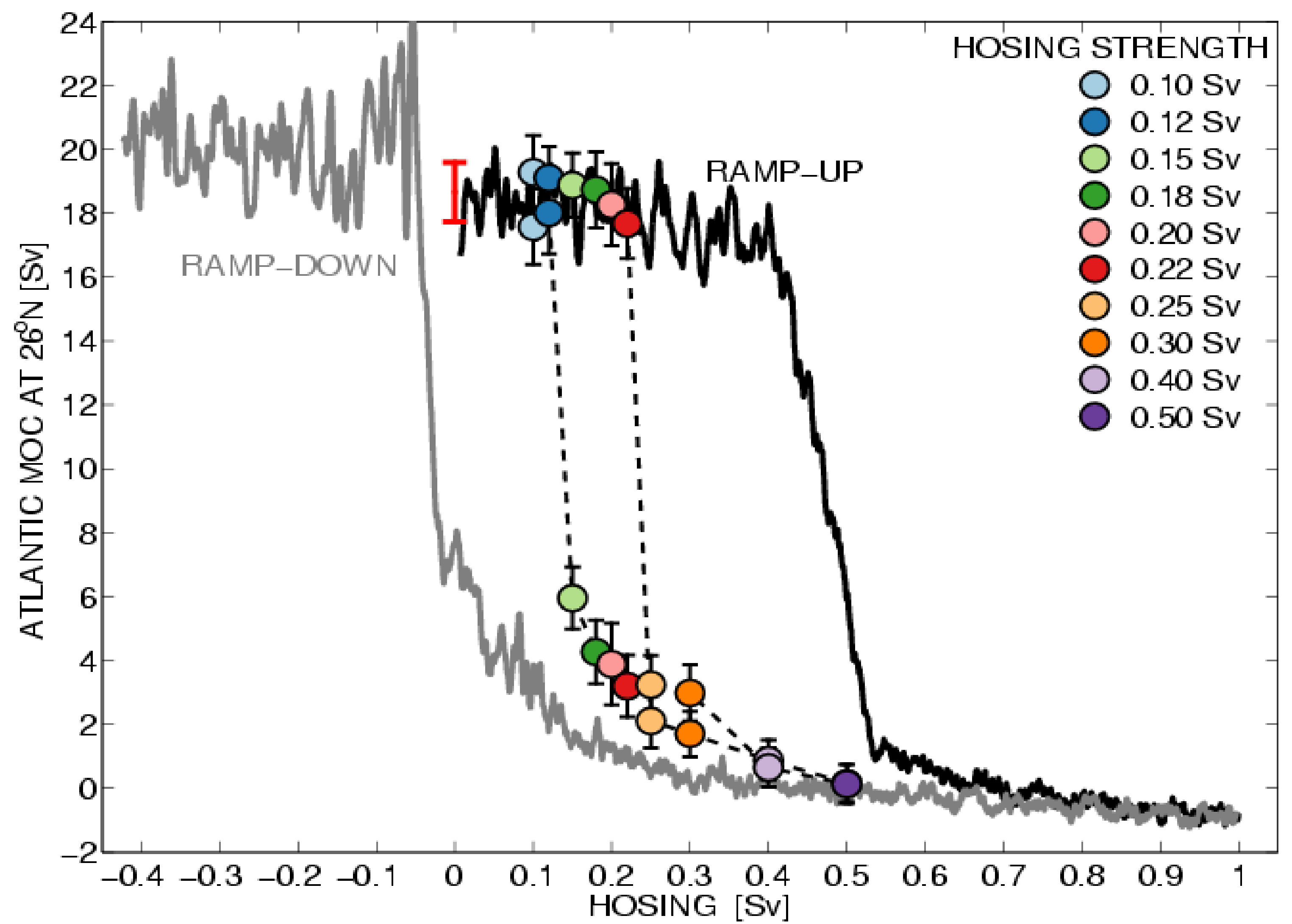
Atlantic MOC



Transient experiments



Transient and equilibrium experiments



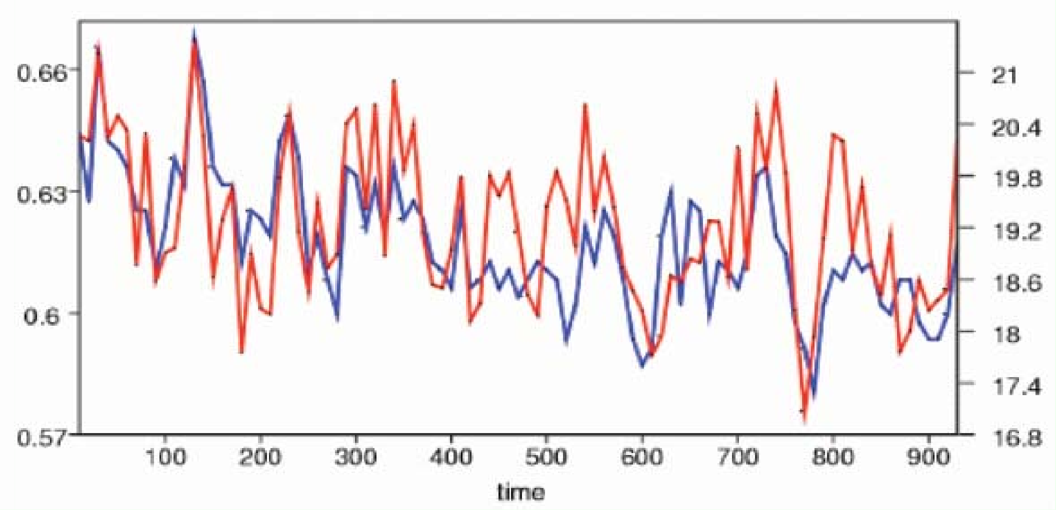
Relevance to current climate change?

Climate impacts of AMOC variability and change

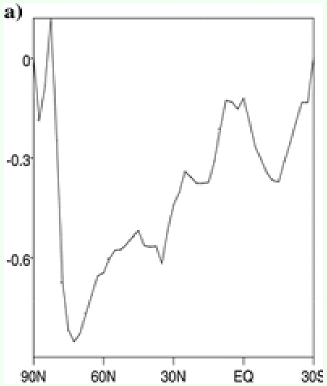
Climate Impacts of AMOC variability

Northward energy transport

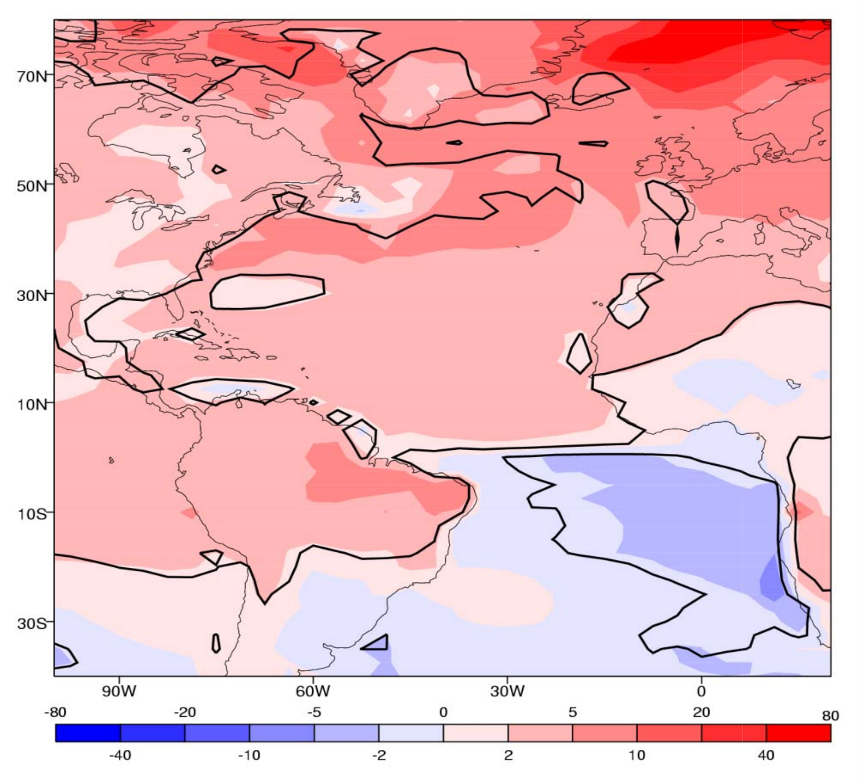
HadCM3: Max AMOC and northward heat transport (30s-70N); decadal correlation: 0.85



Atmospheric energy transport is *anti-correlated* on decadal timescales (Bjerknes compensation)



Shaffrey and Sutton, 2006



Regression on North Atlantic OHT index

$T_{surface}$ (K.PW^{-1})

Climate Impacts of AMOC variability

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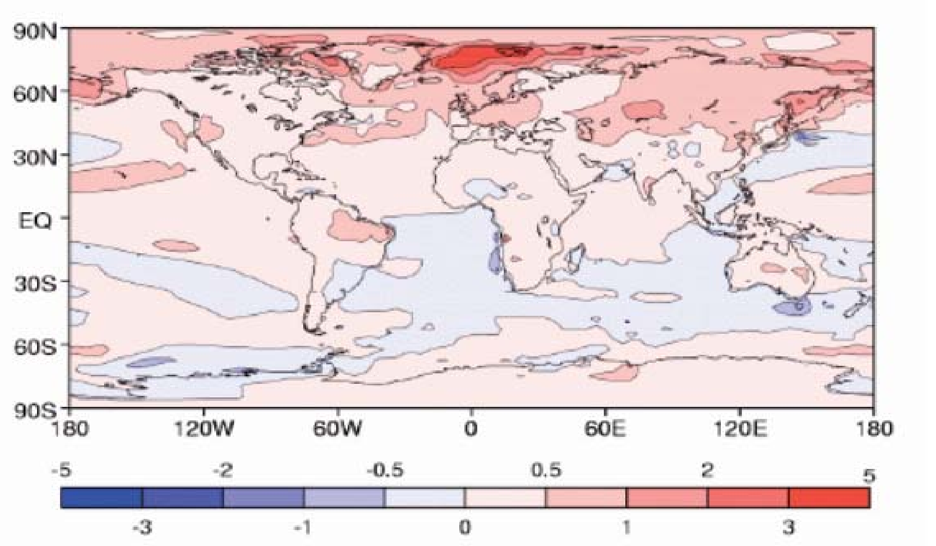
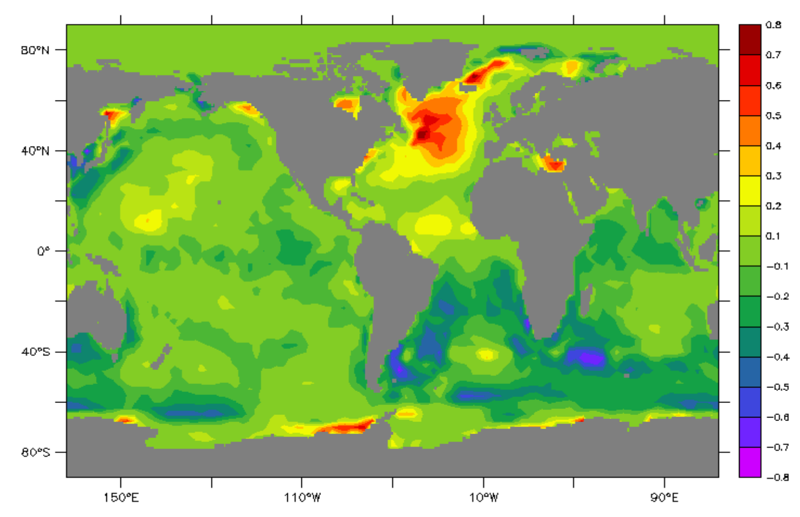
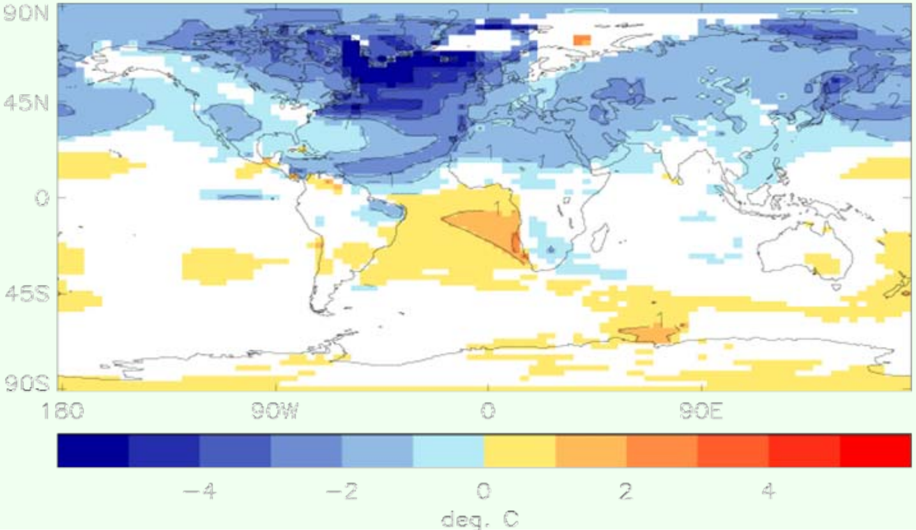
- Surface temperature



Observed DJF SST anomalies (1931-60)-(1961-90)



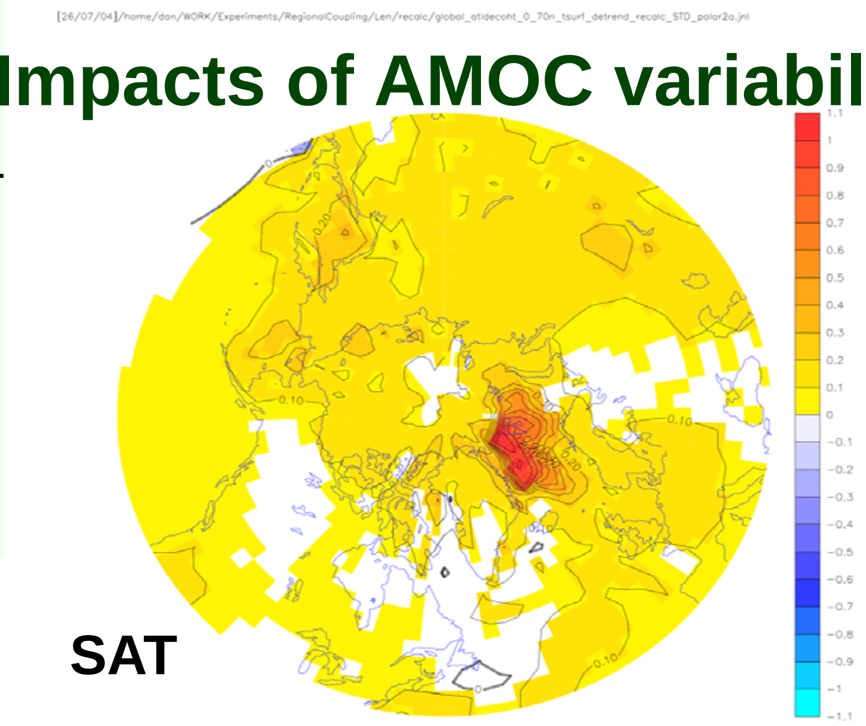


Impact of THC shutdown
Vellinga and Wood, 2002

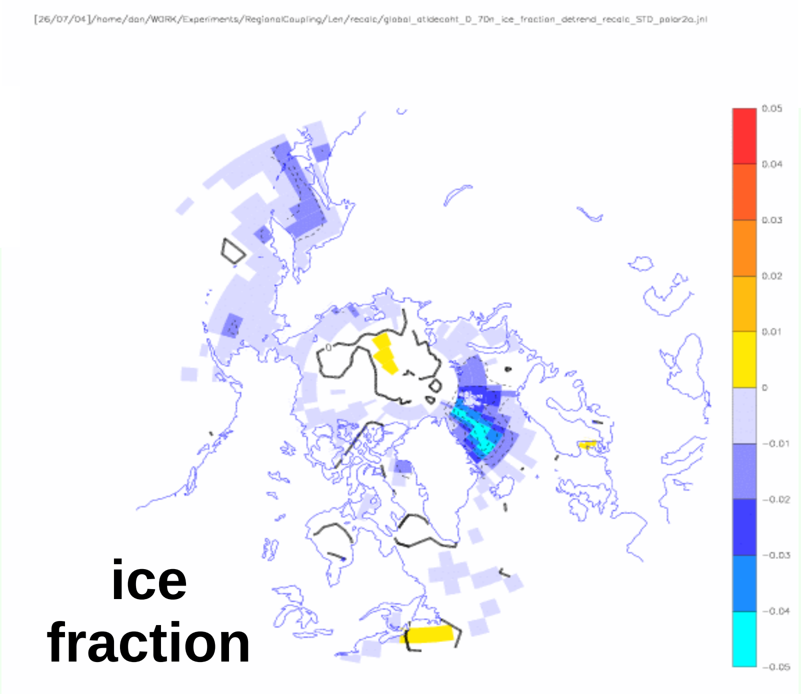
Climate Impacts of AMOC variability

High latitude changes

Regression of HadCM3 winter fields on index of decadal variability in Atlantic Ocean northward heat transport

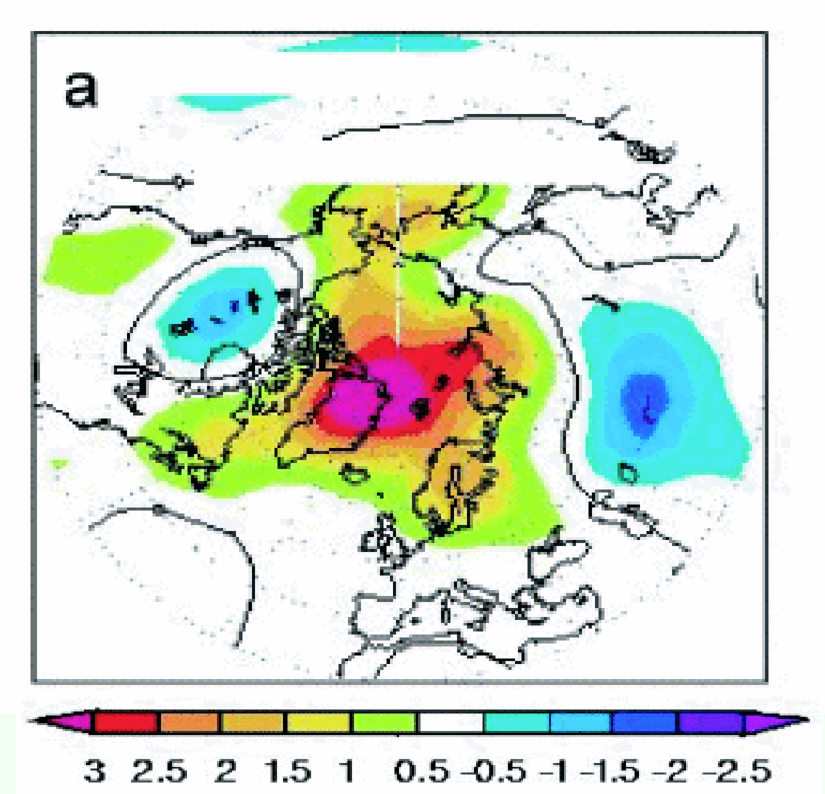


SAT



ice fraction

1920-39 observed trend in winter (Nov-Apr) (Johannessen et al, 2004)

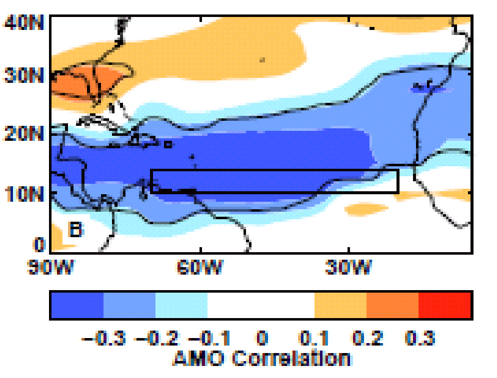


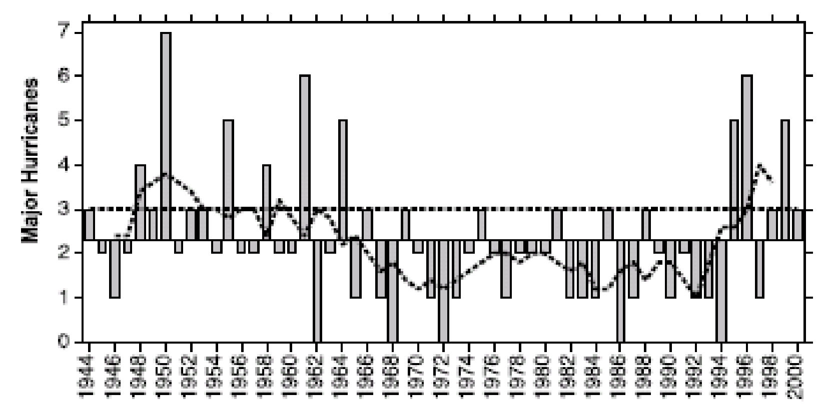
Climate Impacts of AMOC variability

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Other N. Atlantic Impacts

Vertical Shear & Hurricane numbers





Goldenberg & Shapiro 2001

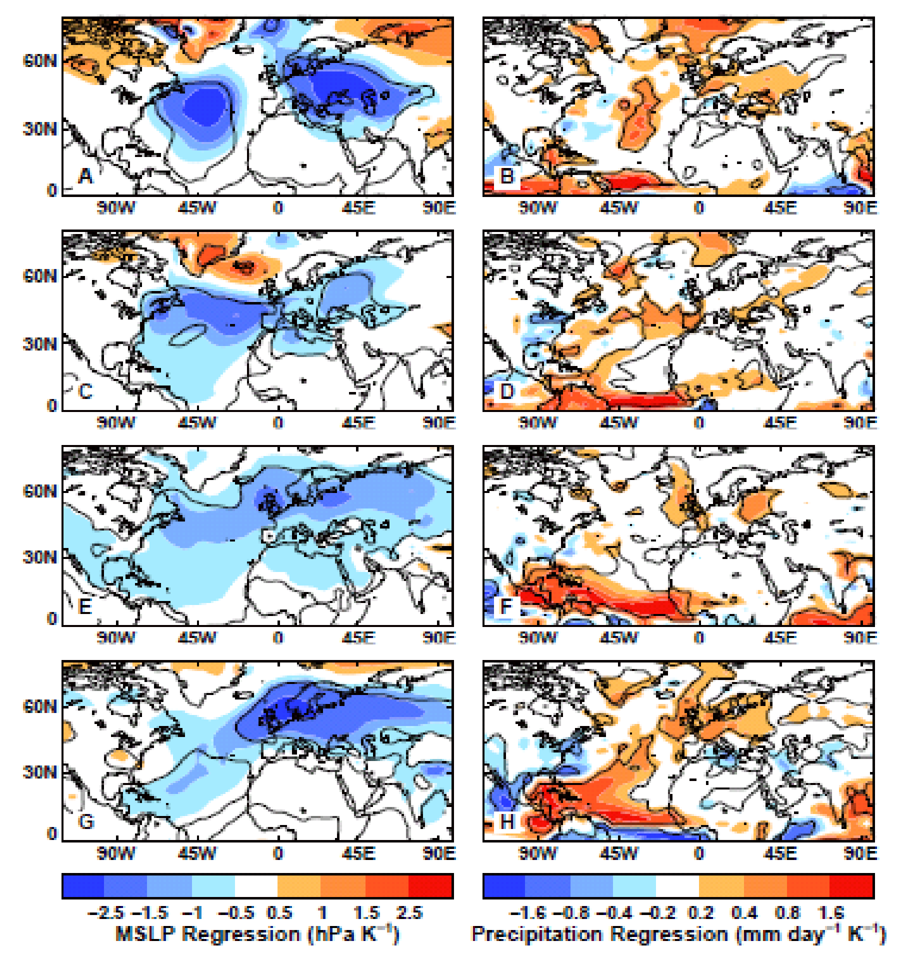
SLP **precipitation**

DJF

MAM

JJA

SON



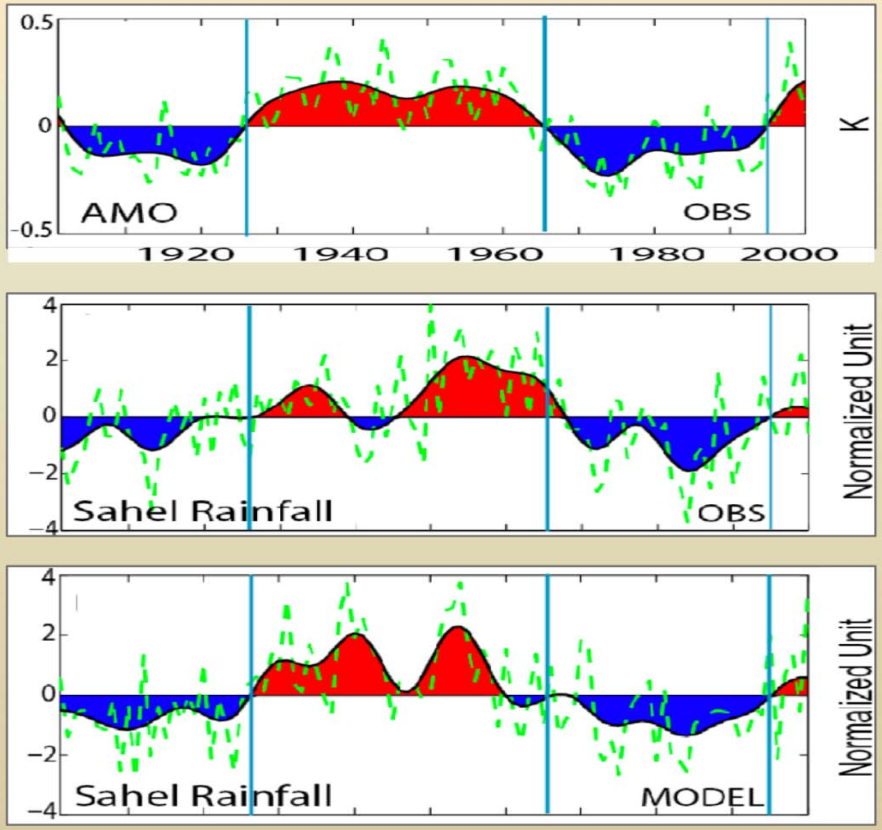
Knight et al, 2006

Climate Impacts of AMOC variability

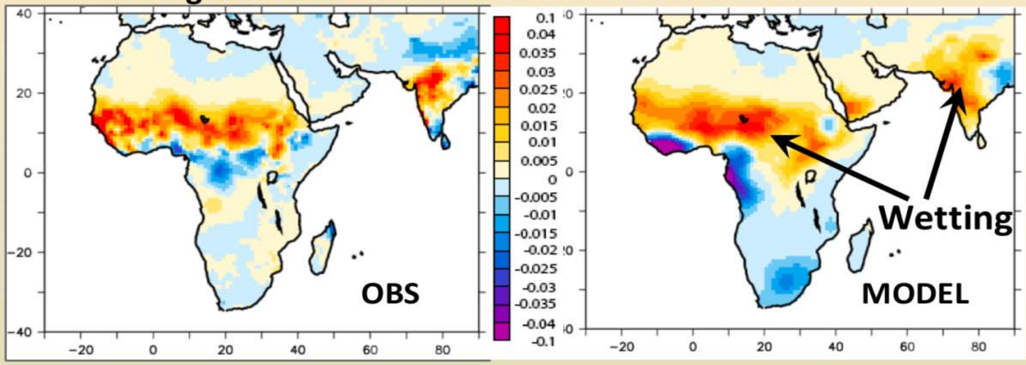
- Other climate impacts:
  - N. American precipitation / drought (Enfield et al, 2001; Sutton & Hodson, 2005)
  - Wider tropical precipitation: Sahel, S. & E. Asian monsoons (Zhang & Delworth)
  - ENSO variability (Dong & Sutton, 2007; Timmerman et al, 2007)
- Beyond climate:
  - Sea level
  - Ecosystems
  - Greenland Ice Sheet?

Atmospheric Impact of Atlantic Multidecadal Oscillation (AMO)

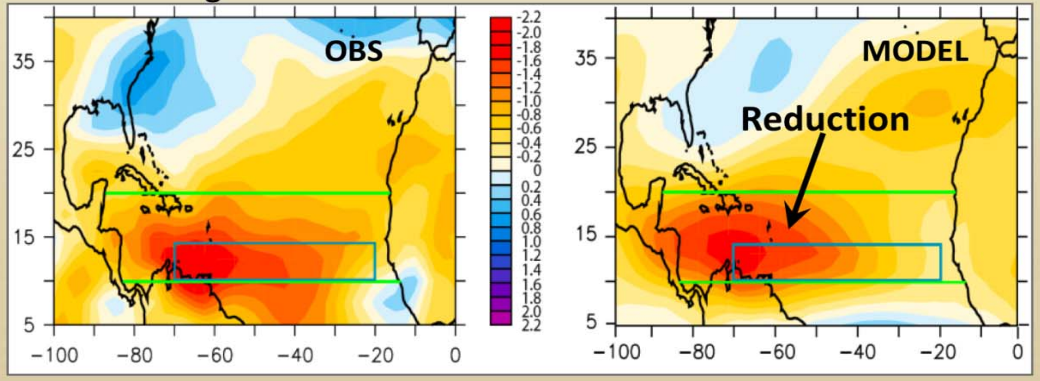
(or Atlantic Multidecadal Variability, AMV)



Regression of Summer Rainfall on AMO Index



Regression of vertical shear on AMO index

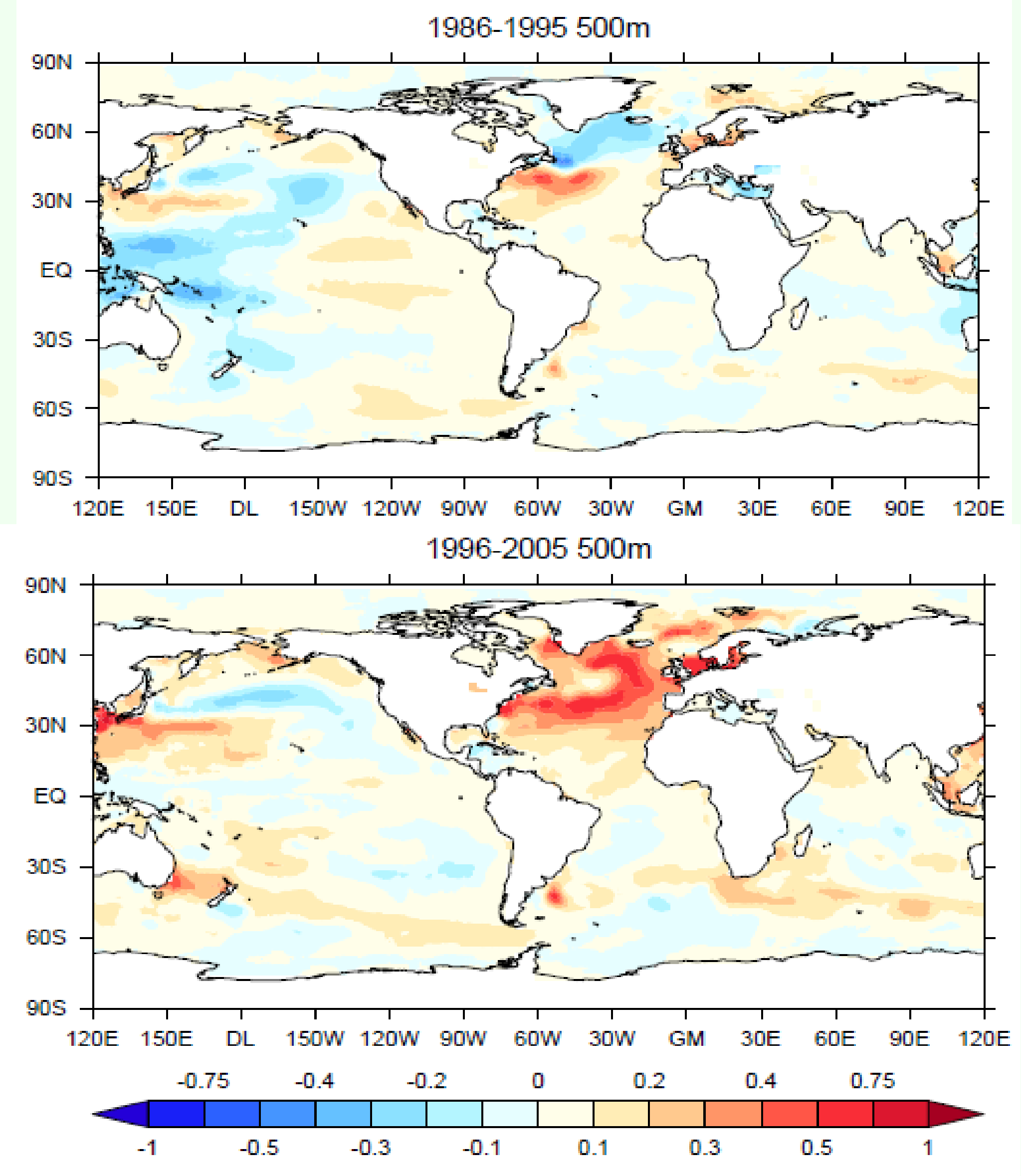


The AMO (area averaged detrended SST anomalies over the North Atlantic) can lead to:

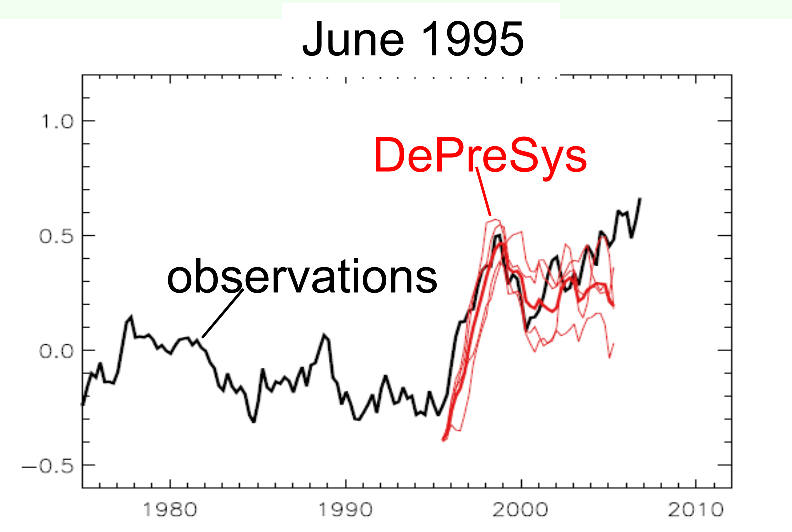
- **Multidecadal variations in Sahel and India summer rainfall, and vertical shear over the Atlantic Hurricane MDR** *(Zhang and Delworth 2006)*
- **Northern Hemispheric mean surface temperature fluctuations** *(Zhang et al. 2007)*
- **Multidecadal variations in the Northern Pacific** *(Zhang and Delworth 2007)*

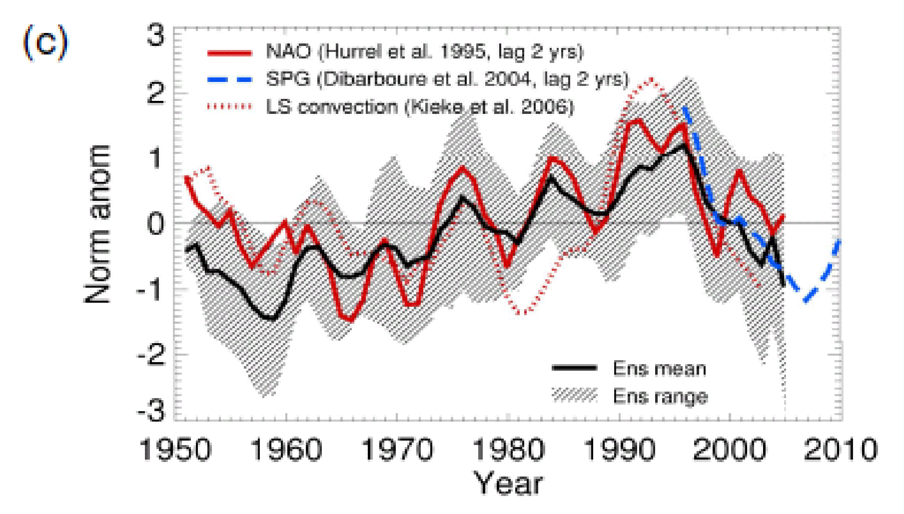
Slide courtesy Rong Zhang

Role for AMOC in recent N. Atlantic change?



Subpolar gyre 500m heat content





Jon Robson

Evidence of *predictability* suggests important role for oceanic memory in rapid warming

Summary

- AMOC exhibits variability on timescales from days to decades; red spectrum, possibly with decadal or longer timescale peaks
- Decadal/longer timescale variability of greatest importance for climate (including *predictability*).
- Mechanisms of natural variability involve quasi-stochastic forcing by the atmosphere + oceanic and/or coupled feedbacks. Large model uncertainty.
- AMOC is sensitive to natural & anthropogenic radiative forcing. Potential to trigger rapid change? Large model uncertainty.
- Evidence for important climate impacts *globally*

Outstanding research issues

- Mechanisms:
  - Large model uncertainty concerning natural variability of the AMOC and the response to radiative forcings. Sensitivity to resolution (e.g. boundary currents; overflows) one important dimension.
  - which are the dominant feedbacks and their associated timescales? Is AMOC variability quasi-periodic?
  - What is the role of exchanges with the Arctic?
  - What is the role of the Southern Ocean?
- Climate impacts:
  - multiple coupled mechanisms, poorly understood
  - attribution: separating AMOC influence from others
- Observations and synthesis:
  - Improving analyses
  - Relating observations at different latitudes
- Predictability