Atlantic Meridional Overturning Circulation and Climate

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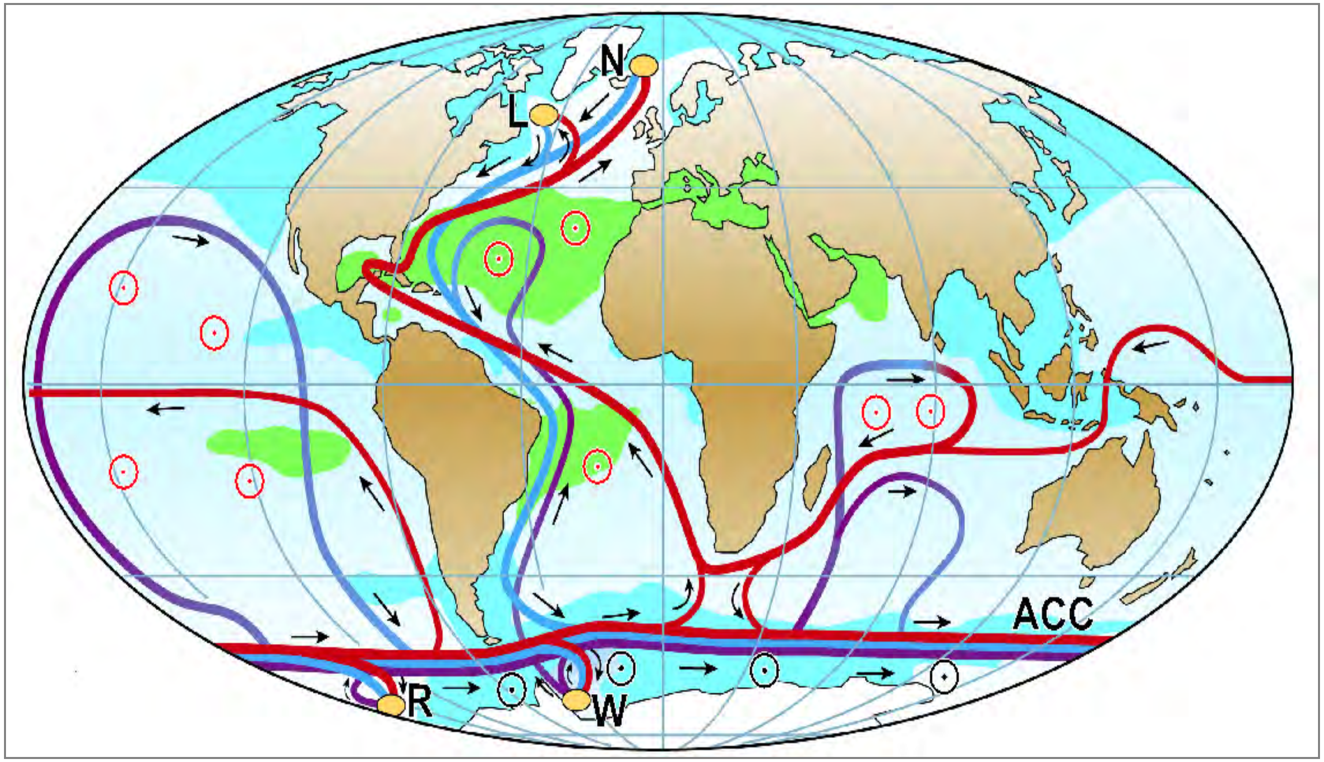
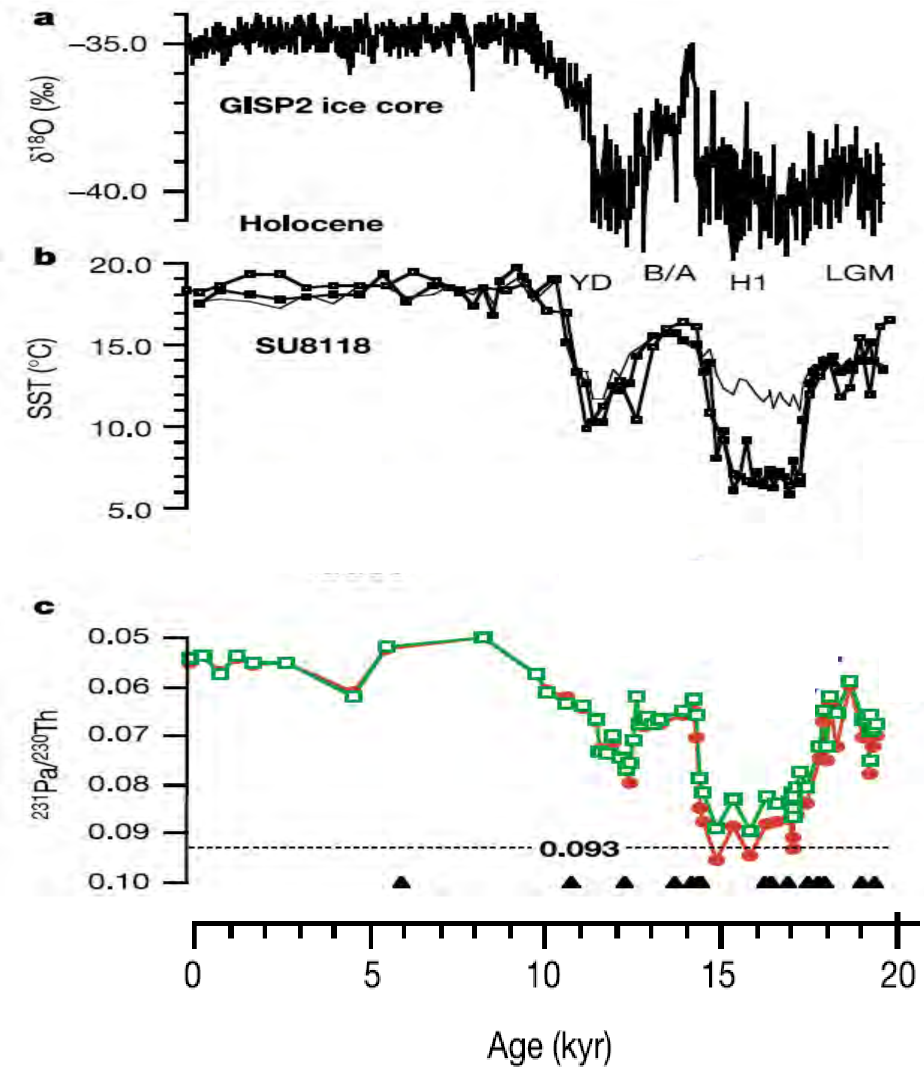
Atlantic Meridional Overturning Circulation (AMOC)



- Global Scale Impact in Paleo Climate
- Global Scale Impact in the 20th Century Climate
- Fingerprints and Latitudinal Dependence of AMOC Variations



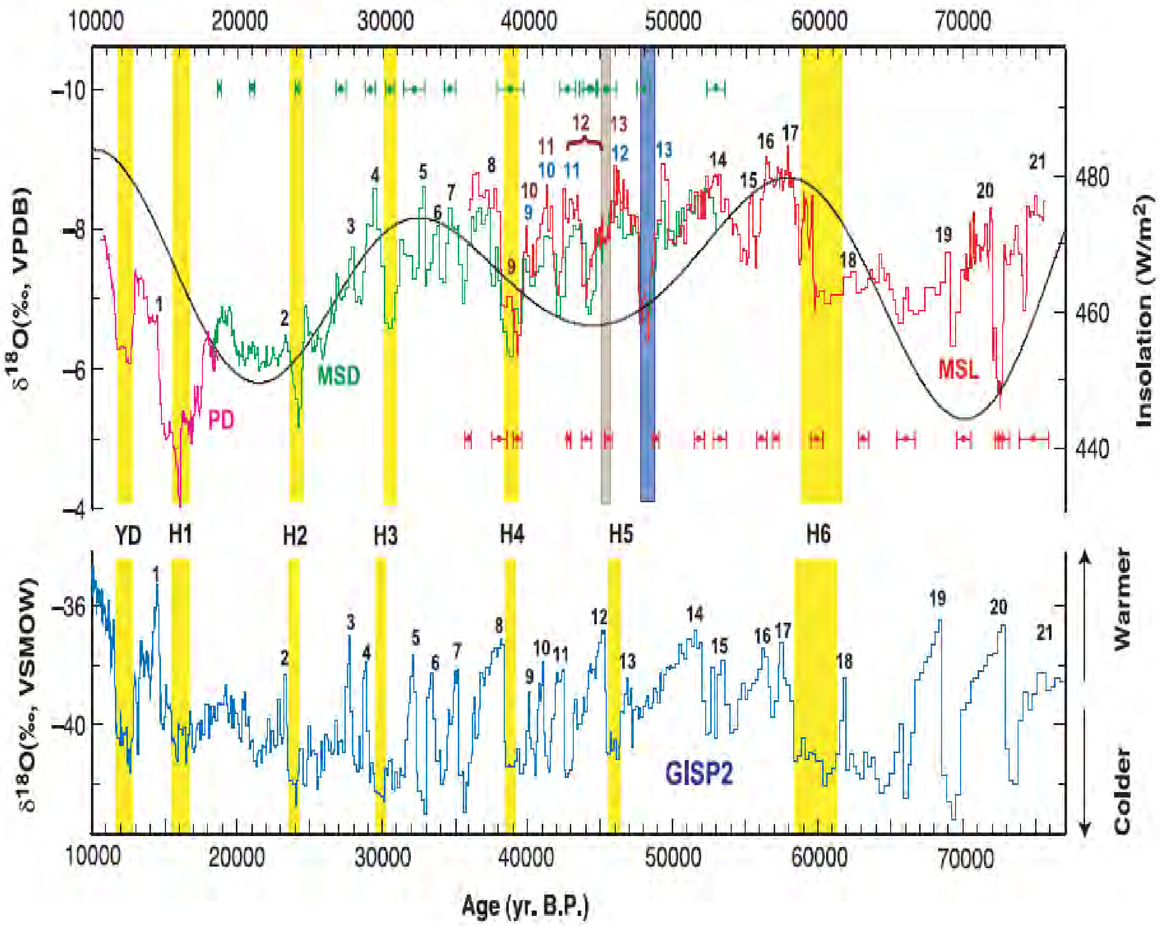
Greenland ice core record

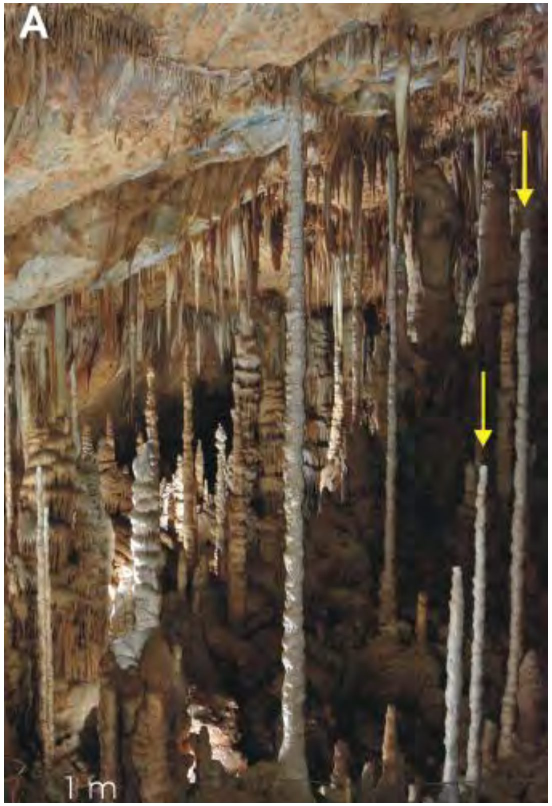
SST from subtropical northeast Atlantic

AMOC

Paleo record from a sediment core from the subtropical North Atlantic suggests that AMOC was almost shutdown during the Heinrich event H1 (McManus et al., 2004)

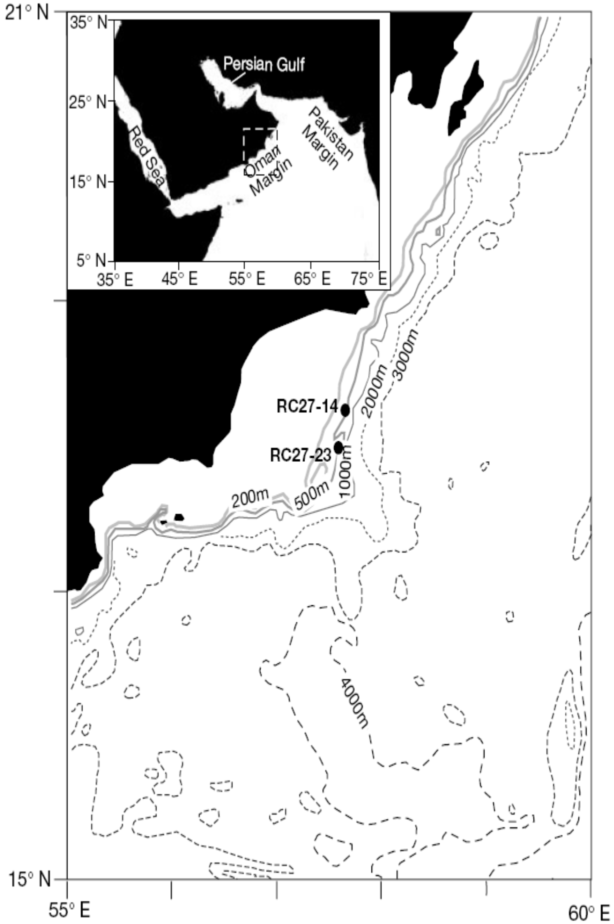
Asia – Hulu Cave Stalagmite

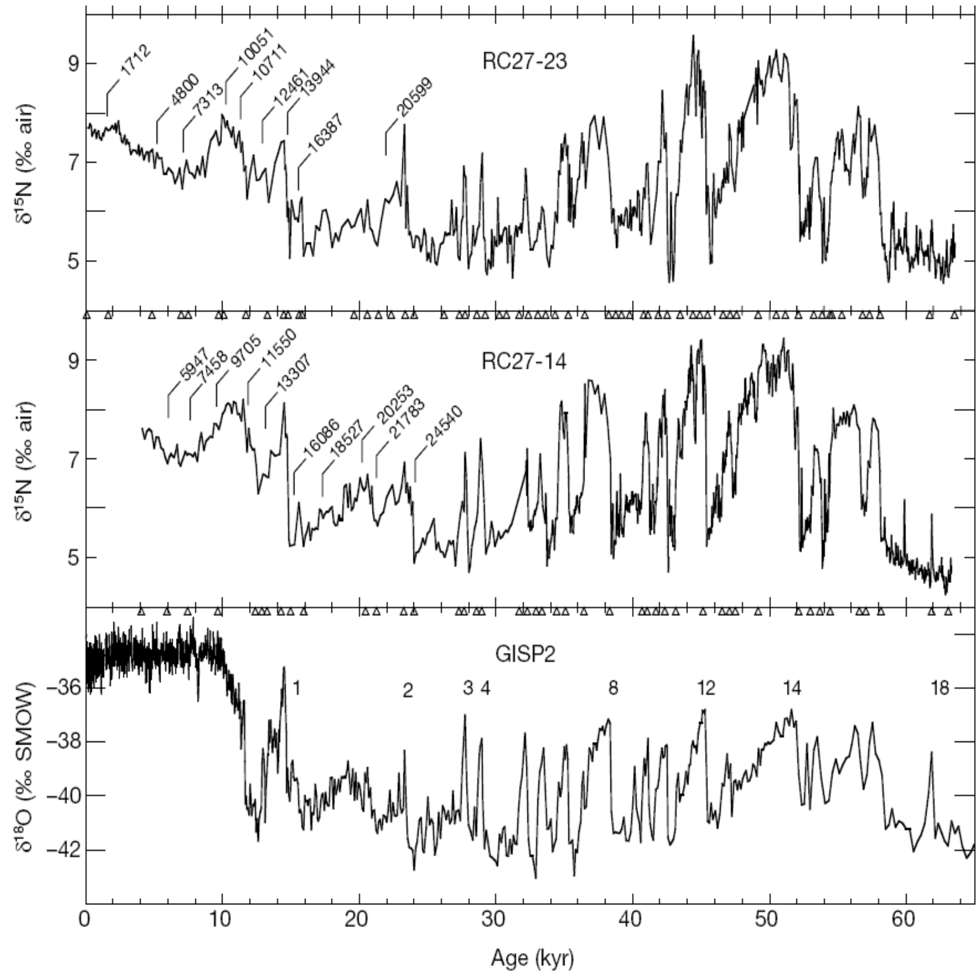




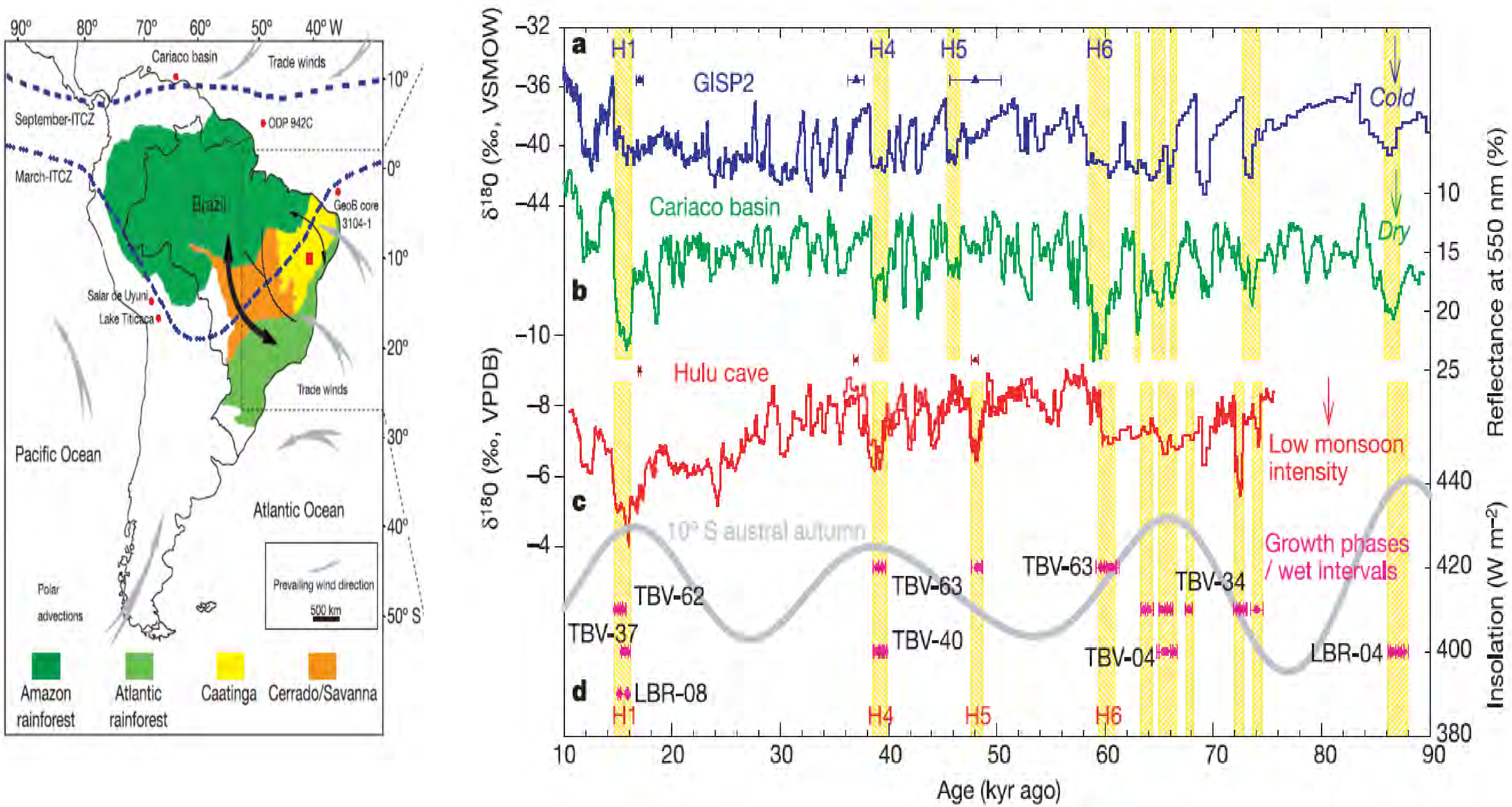
Oxygen isotope records of stalagmites from Hulu Cave in China shows a remarkable resemblance to oxygen isotope records from Greenland ice cores, suggesting that East Asian Monsoon intensity changed in concert with Greenland temperature. Weaker (stronger) East Asian monsoon is associated with colder (warmer) Greenland temperature (Wang et al. 2001).

$\delta^{15}N$ from Oman Margin





Paleo record from Oman Margin in Indian ocean suggests weakened coastal upwelling and weakened Indian summer monsoon occurred during Greenland cold periods (Altabel et al, 2002)



Wet periods in northeastern Brazil were associated with Heinrich events, cold periods in Greenland, periods of weak East Asian summer monsoons and decreased river runoff to Cariaco Basin (Wang et al. 2004)

Debate

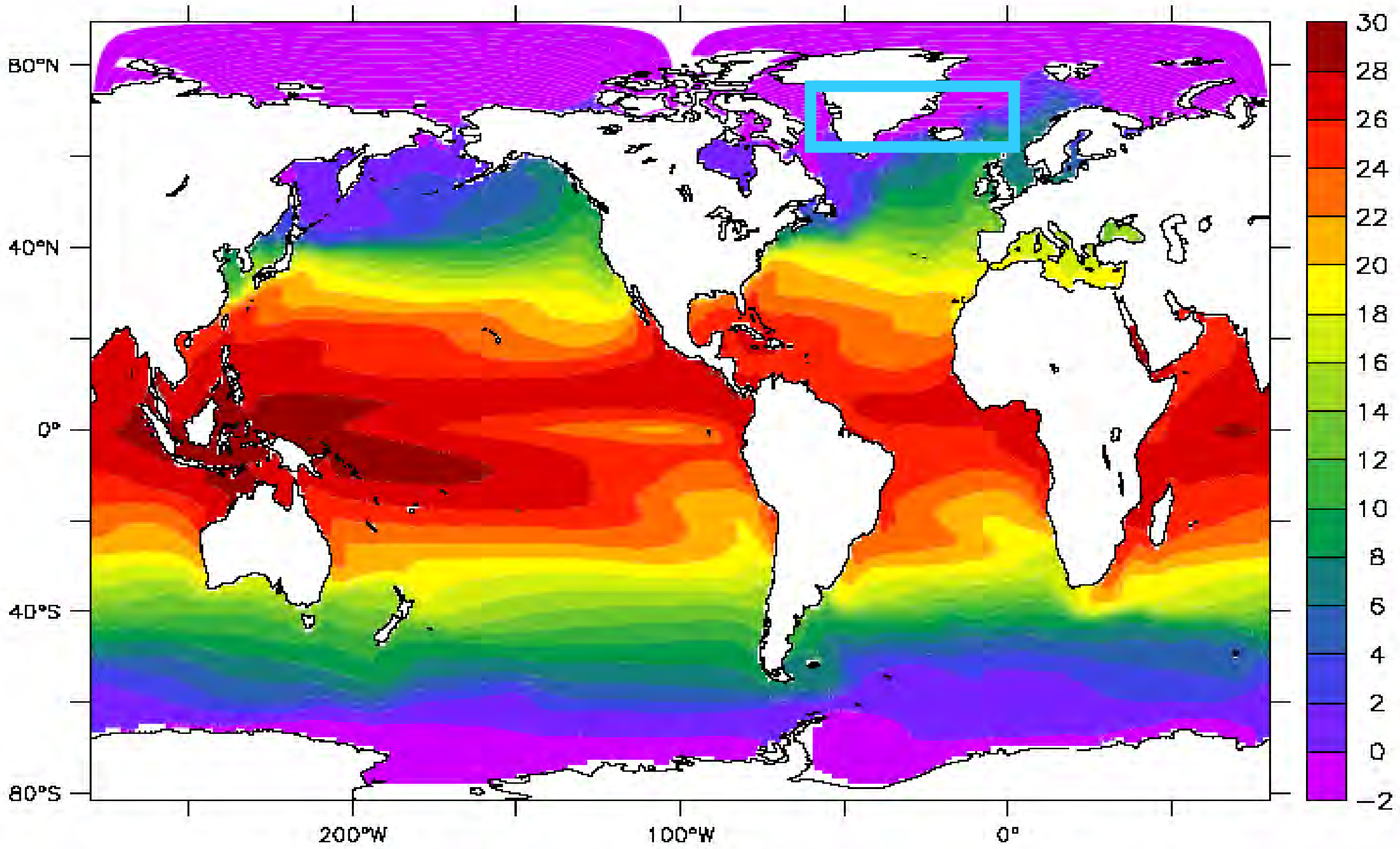
Two opposite hypotheses on Trigger for abrupt climate change:

1, North Atlantic high latitude variability associated with AMOC triggered tropical variability

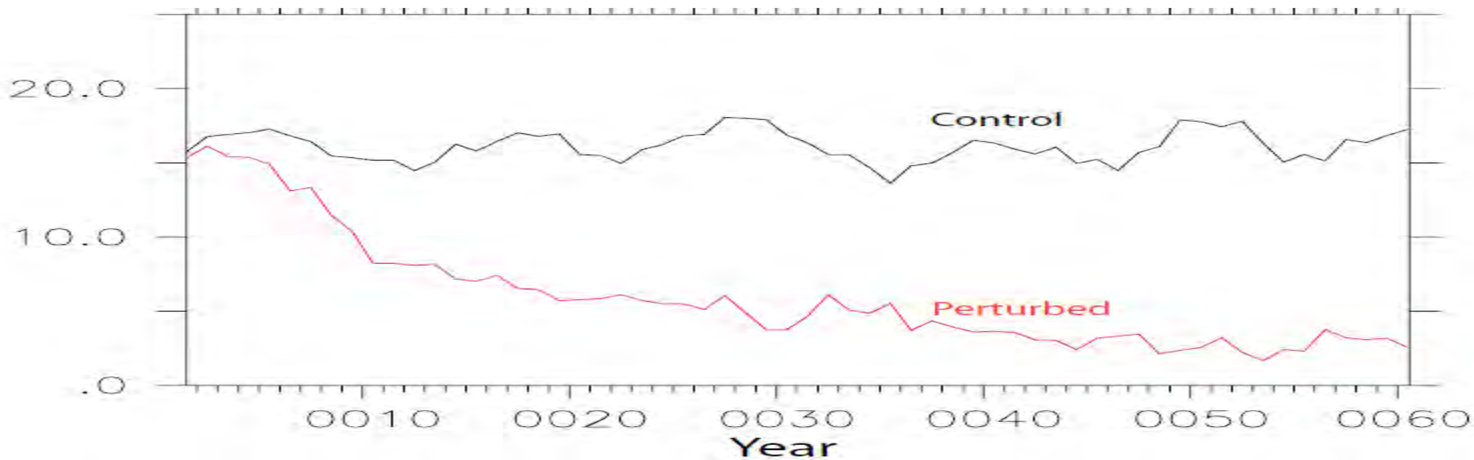
2, Tropical variability triggered North Atlantic high latitude variability

Modeling AMOC collapse (Zhang and Delworth 2005)

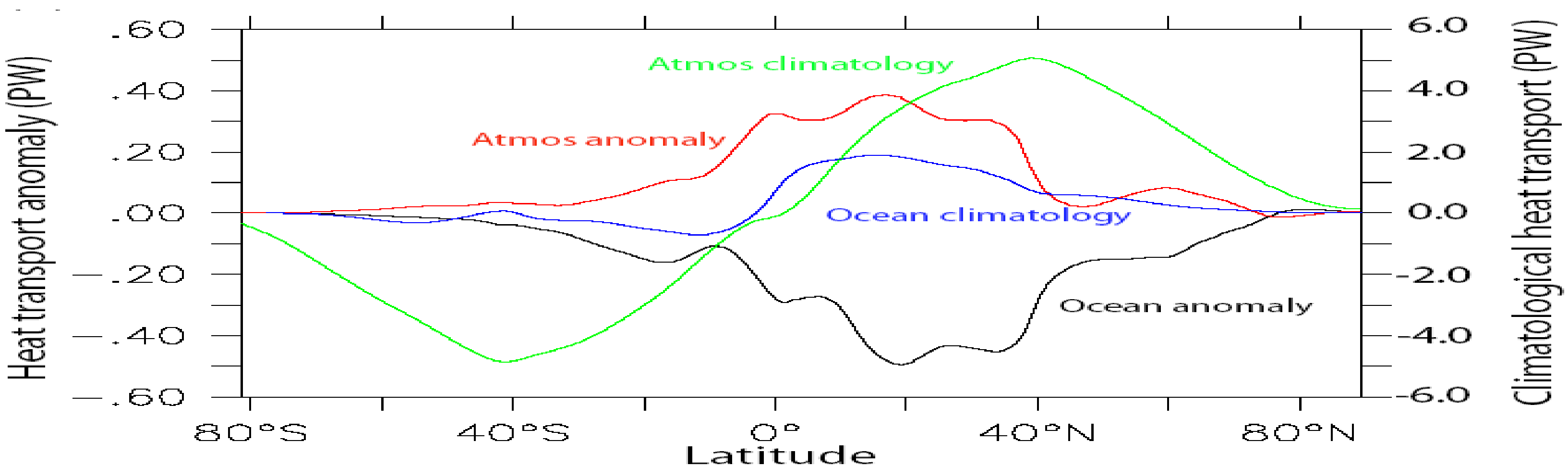
Using GFDL coupled model (CM2), we simulated the global response to a substantial weakening of the AMOC by adding freshwater forcing over the northern North Atlantic.



Maximum AMOC (Sv)

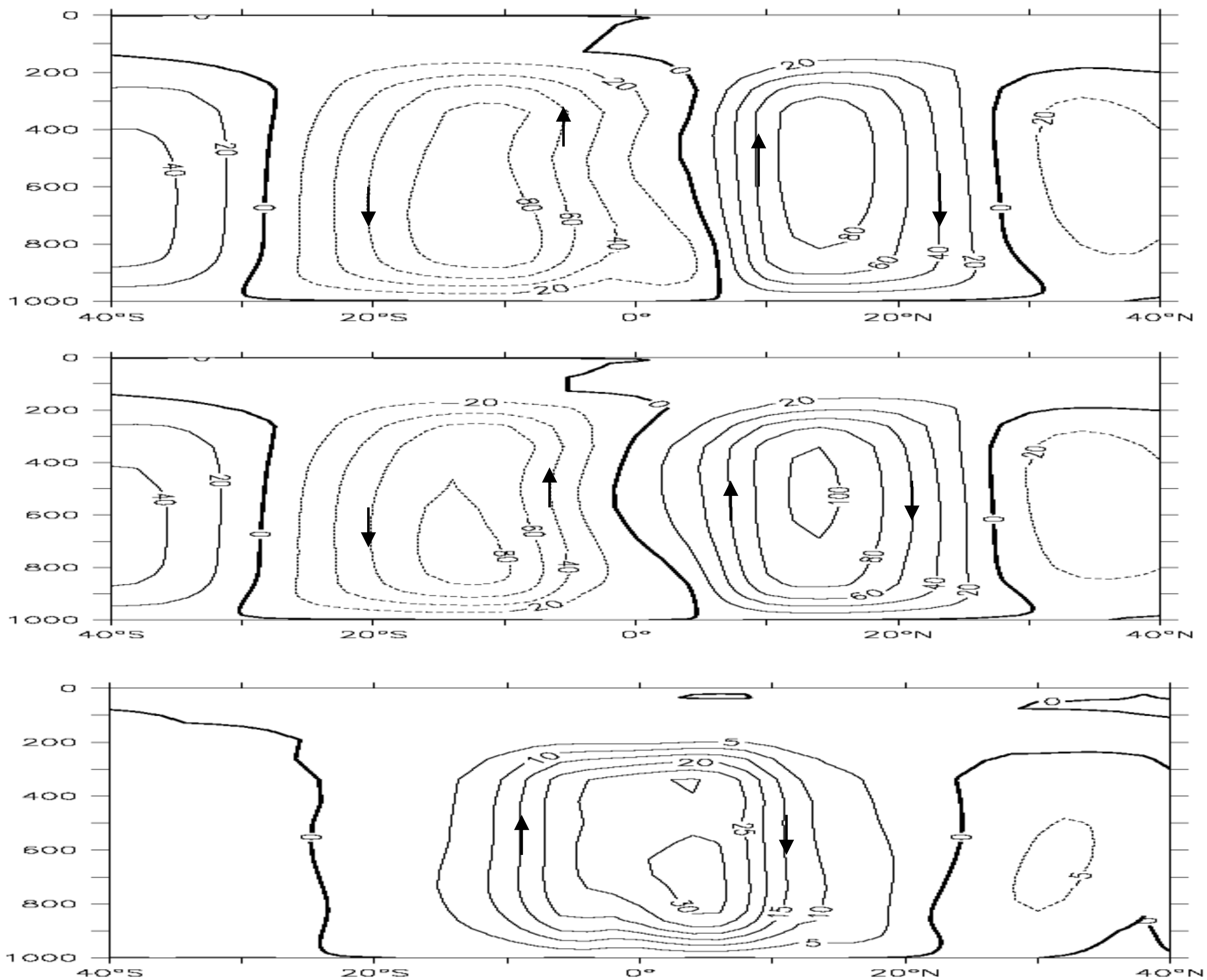


The AMOC is substantially weakened in the perturbed experiment



The ocean heat transport across the equator is reduced and the atmospheric heat transport is enhanced for compensation.

Annual mean global zonal integrated atmosphere stream function ($10^9 Kg/s$).



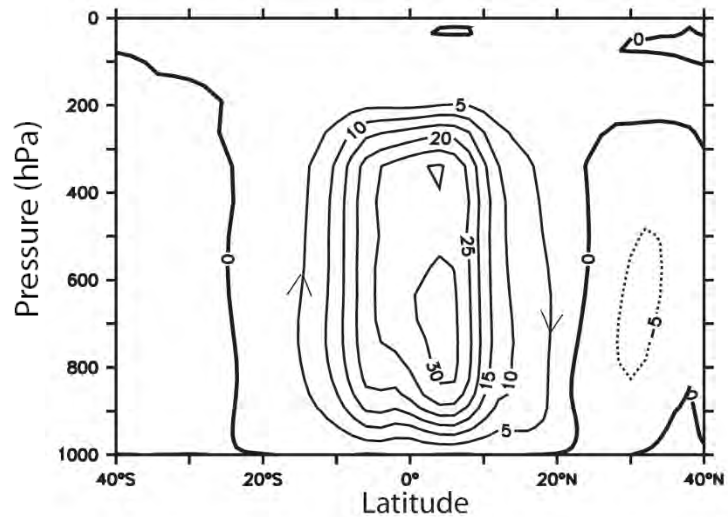
Control

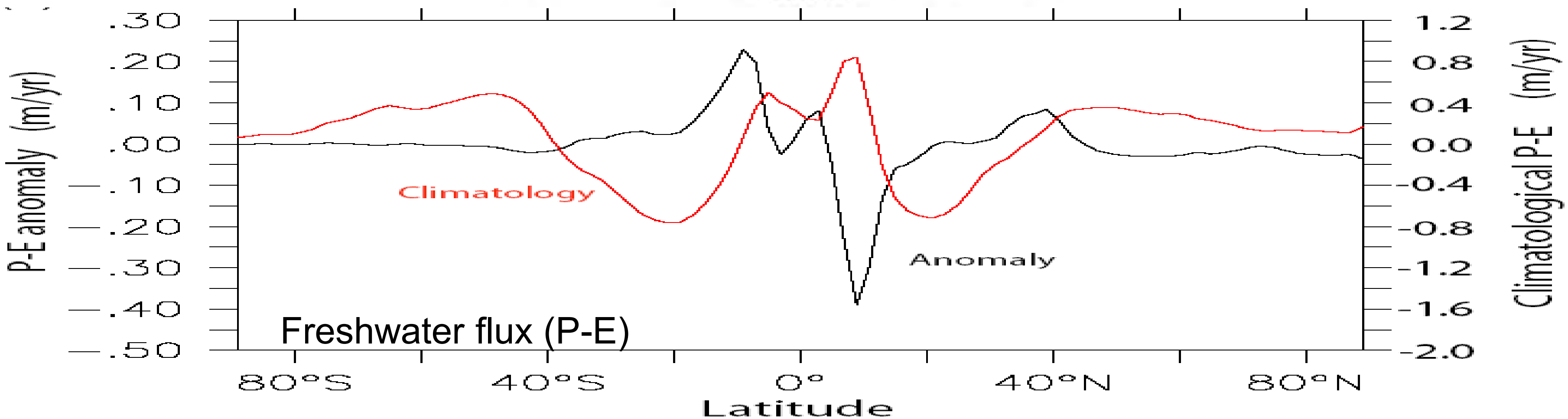
Perturbed

Perturbed - Control

The annual mean zonally integrated Hadley circulation becomes more symmetric about the equator when the AMOC is substantially weakened.

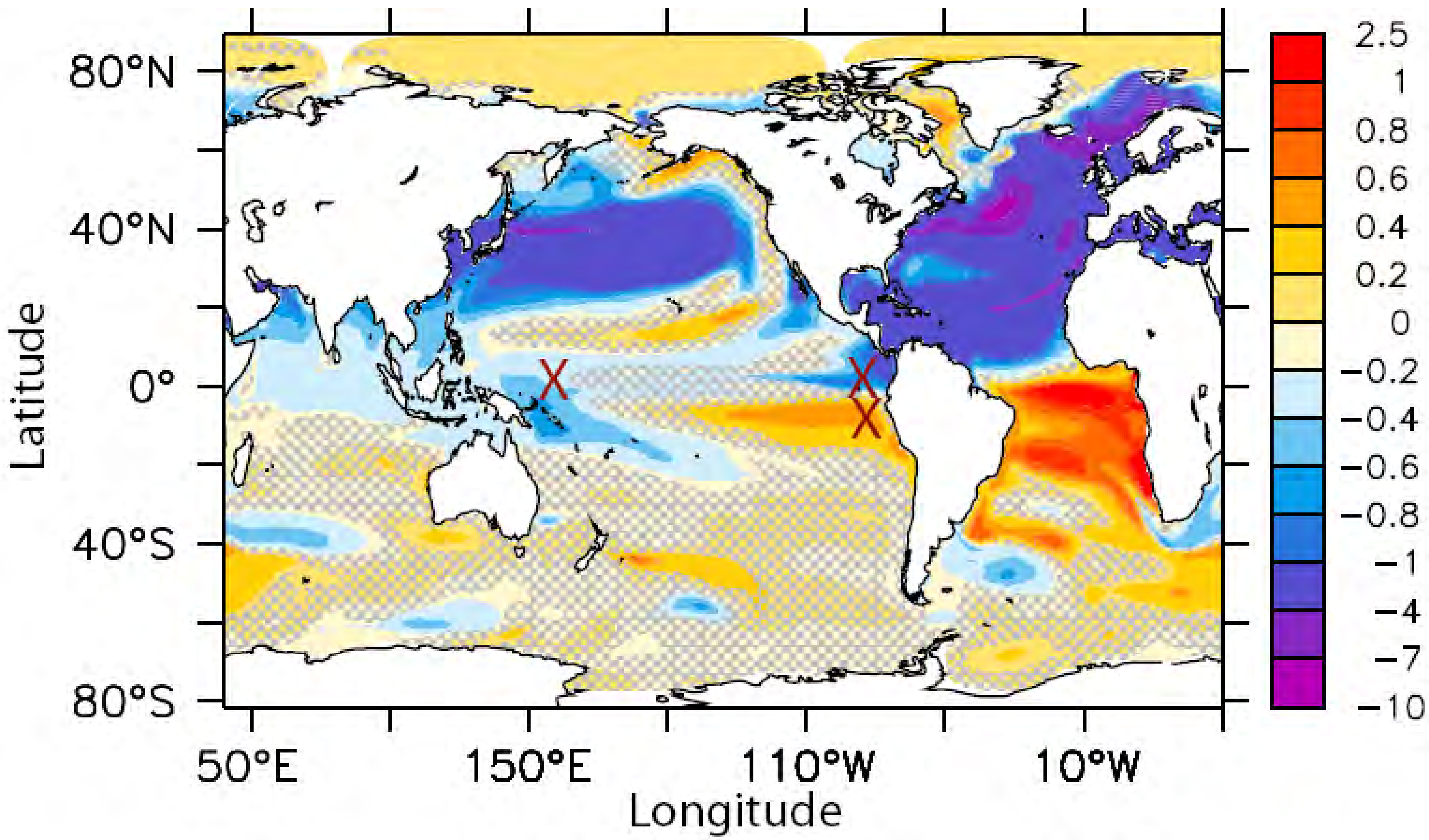
Annual mean global zonal integrated atmosphere stream function anomaly ($10^9 Kg/s$).





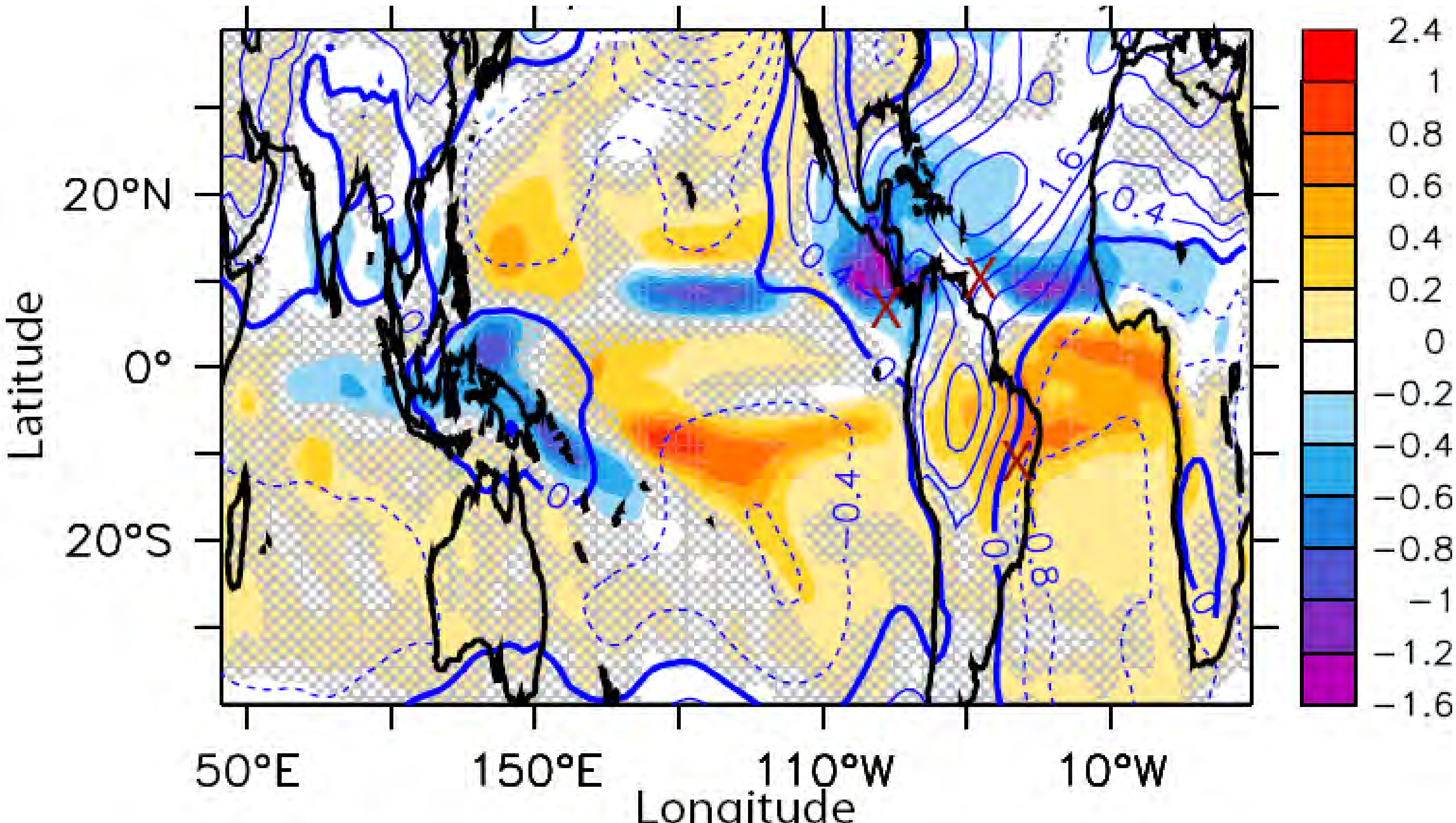
The anomalous Hadley cell is consistent with the enhanced northward atmospheric heat transport and the southward shift of the zonal averaged ITCZ.

Annual mean SST anomaly (°C)



Both cross-equatorial SST contrast in the eastern tropical Pacific and east–west SST contrast in the southern tropical Pacific are reduced.

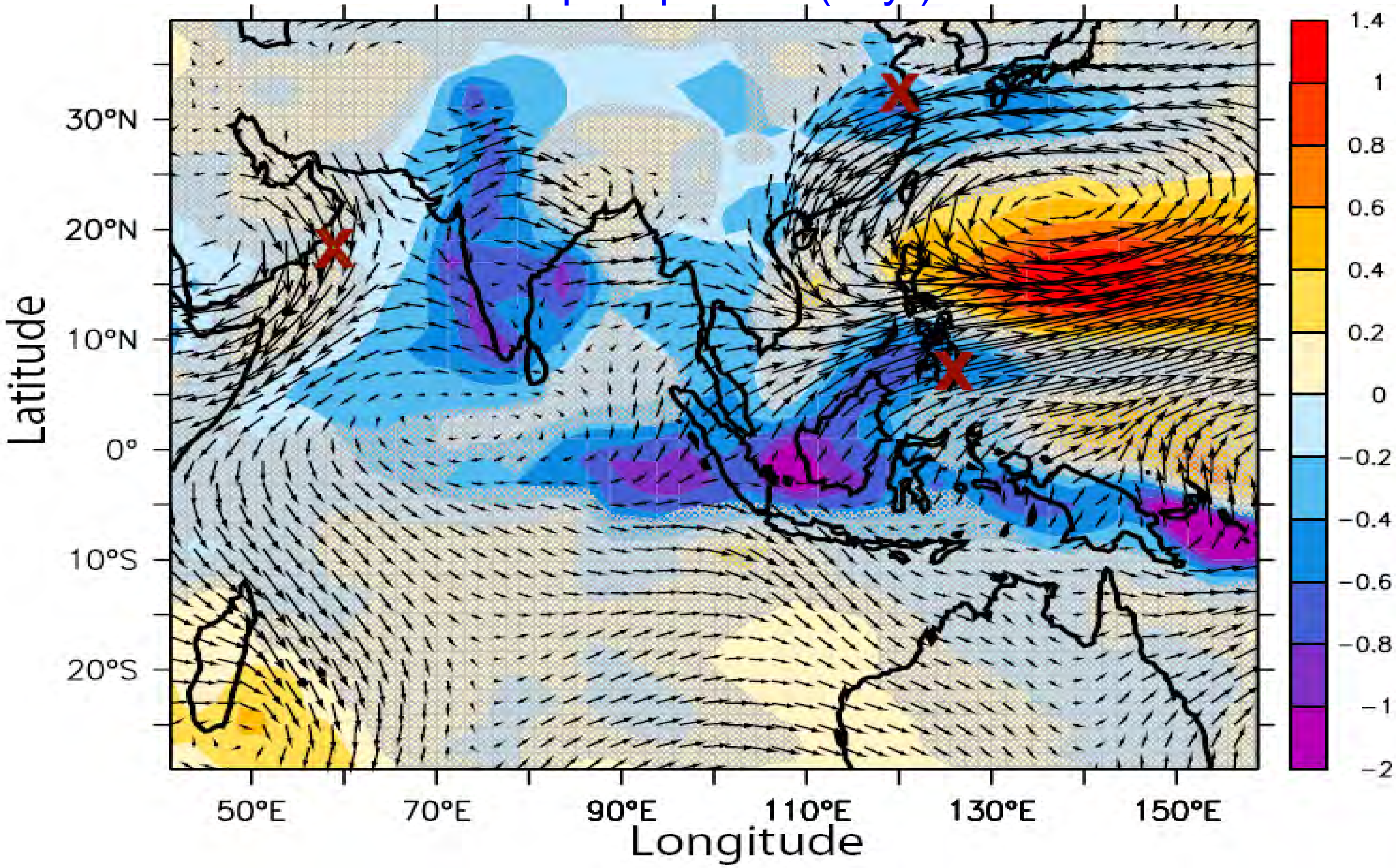
Annual mean precipitation (m/yr) anomaly and SLP anomaly (blue contour)



A southward shift of the ITCZ over both the tropical Atlantic and the tropical Pacific, a weakened Walker circulation in the southern tropical Pacific, a stronger Walker circulation in the northern tropical Pacific

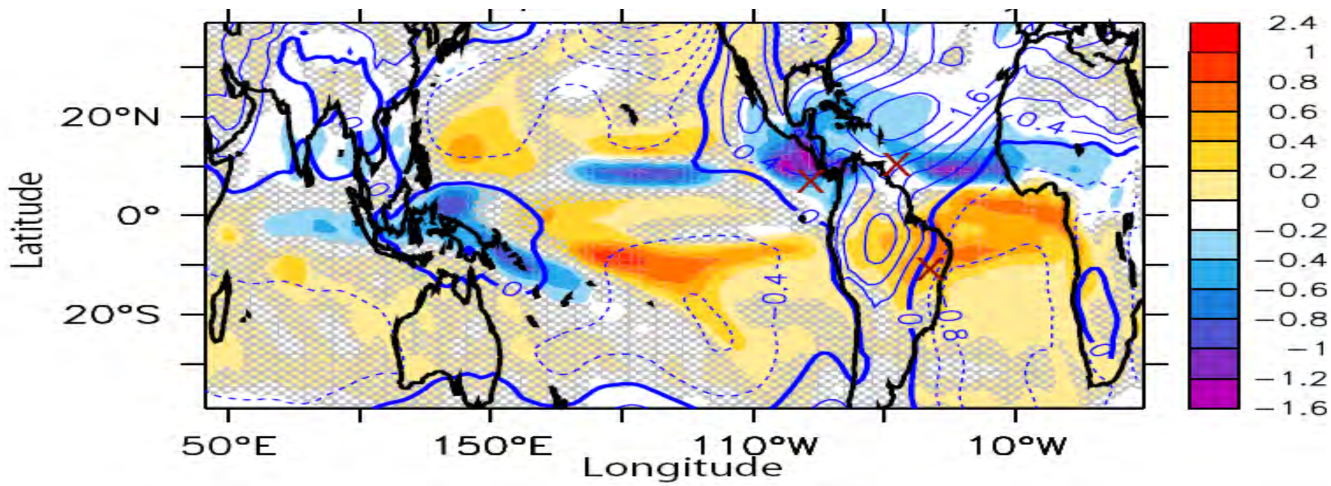
Remote Impacts on Indian and Eastern Asian Summer Monsoons

Anomalous summer precipitation (m/yr) and flow at 925 hPa

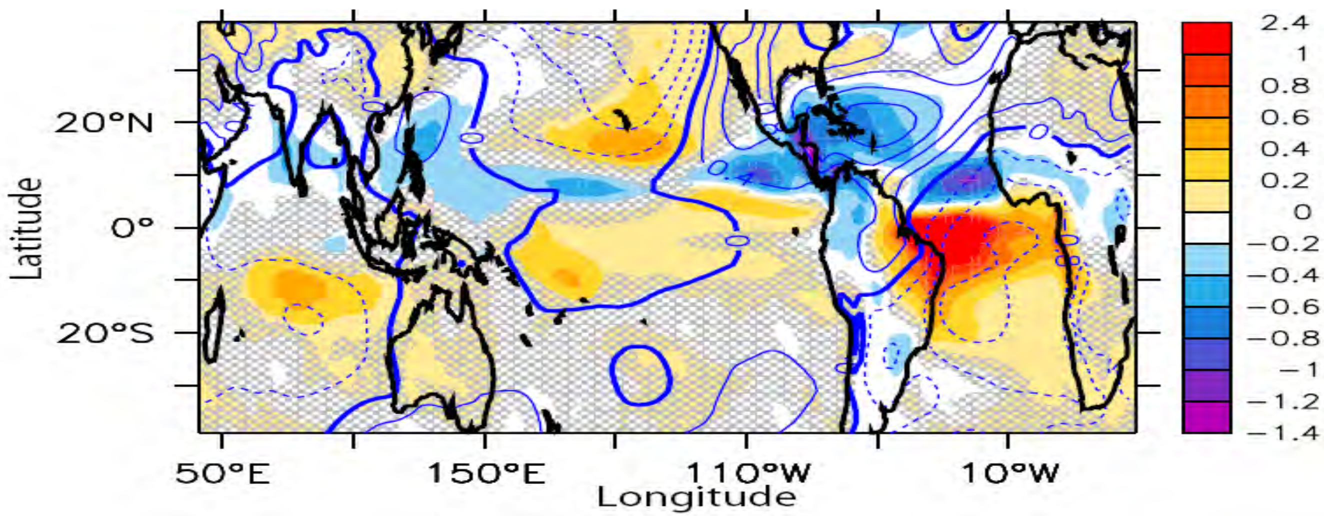


The modeled Indian and eastern Asian summer monsoons are significantly weakened in response to the substantial weakening of AMOC

Anomalous annual mean precipitation (m/yr, color) and SLP (blue contour)



Coupled model (CM2.0)

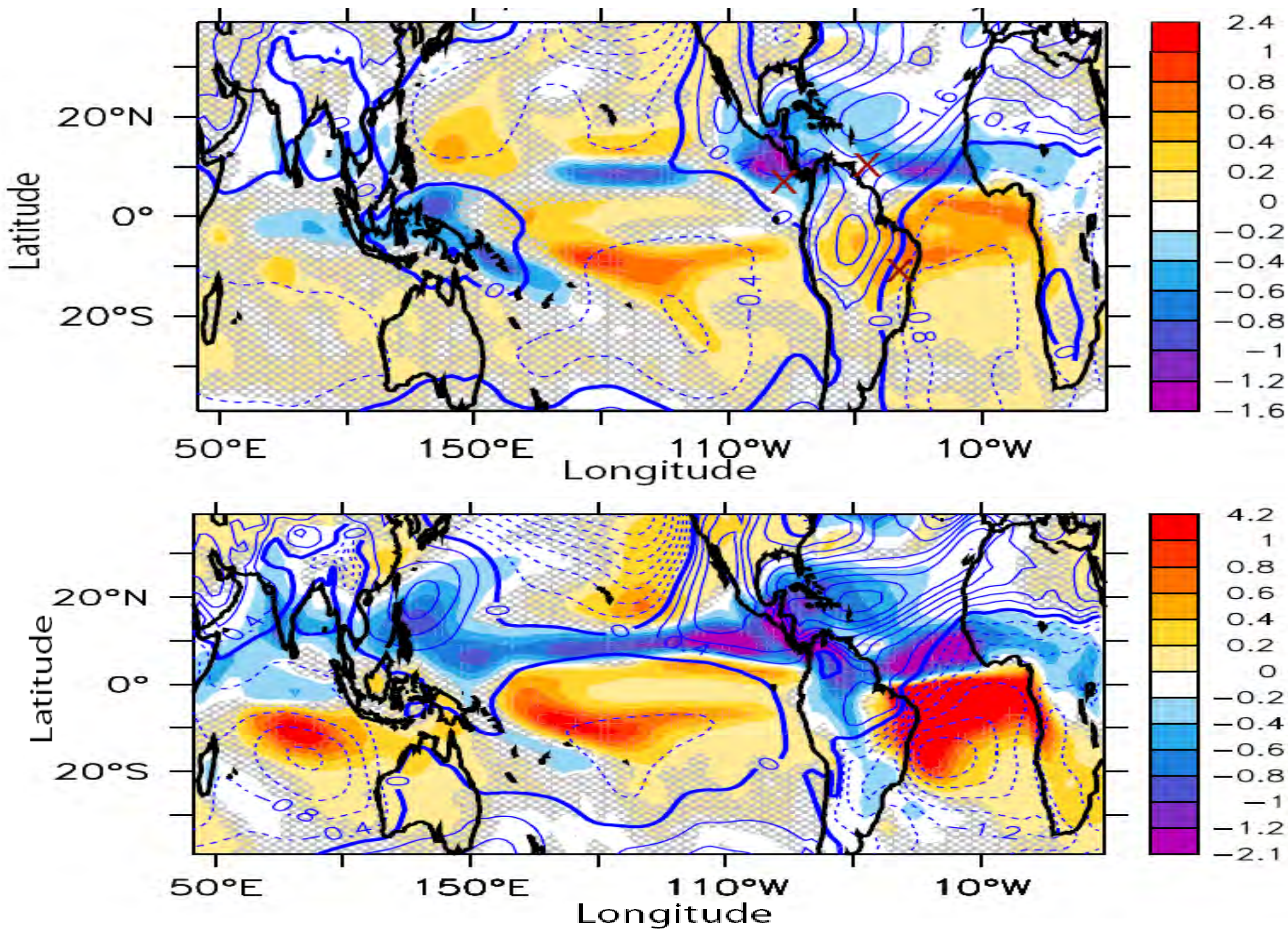


Coupling with a slab ocean

1x qflux anomaly

Ocean dynamics is important for amplifying the tropical Pacific response. When coupled with a slab ocean with the same heat flux forcing, the tropical Pacific response is much smaller

Anomalous annual mean precipitation (m/yr, color) and SLP (blue contour)



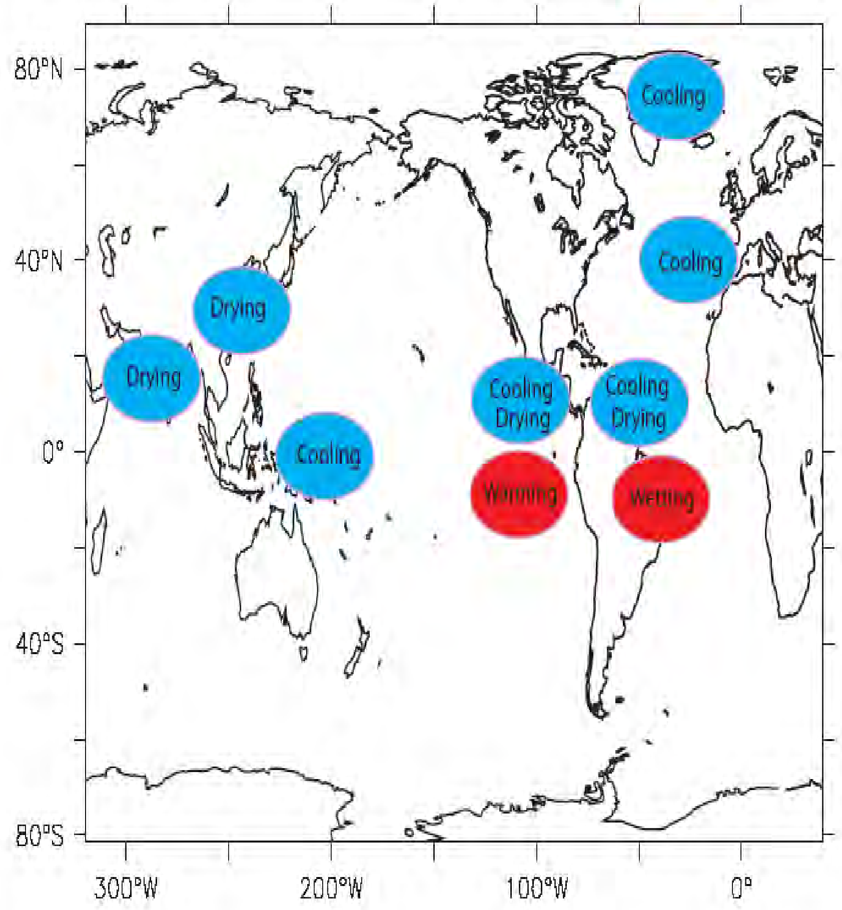
Coupled model (CM2.0)

Coupling with a slab ocean

2 x qflux anomaly

When coupled with a slab ocean with twice the heatflux forcing, the tropical Pacific response is more zonally symmetric, thus no weakening in East Asian Summer Monsoon

Global Synchronization of Abrupt Climate Change Indicated by Paleo Records is Consistent with Modeled Responses to the Weakening of AMOC (Zhang and Delworth 2005)



Schematic diagram of paleo records

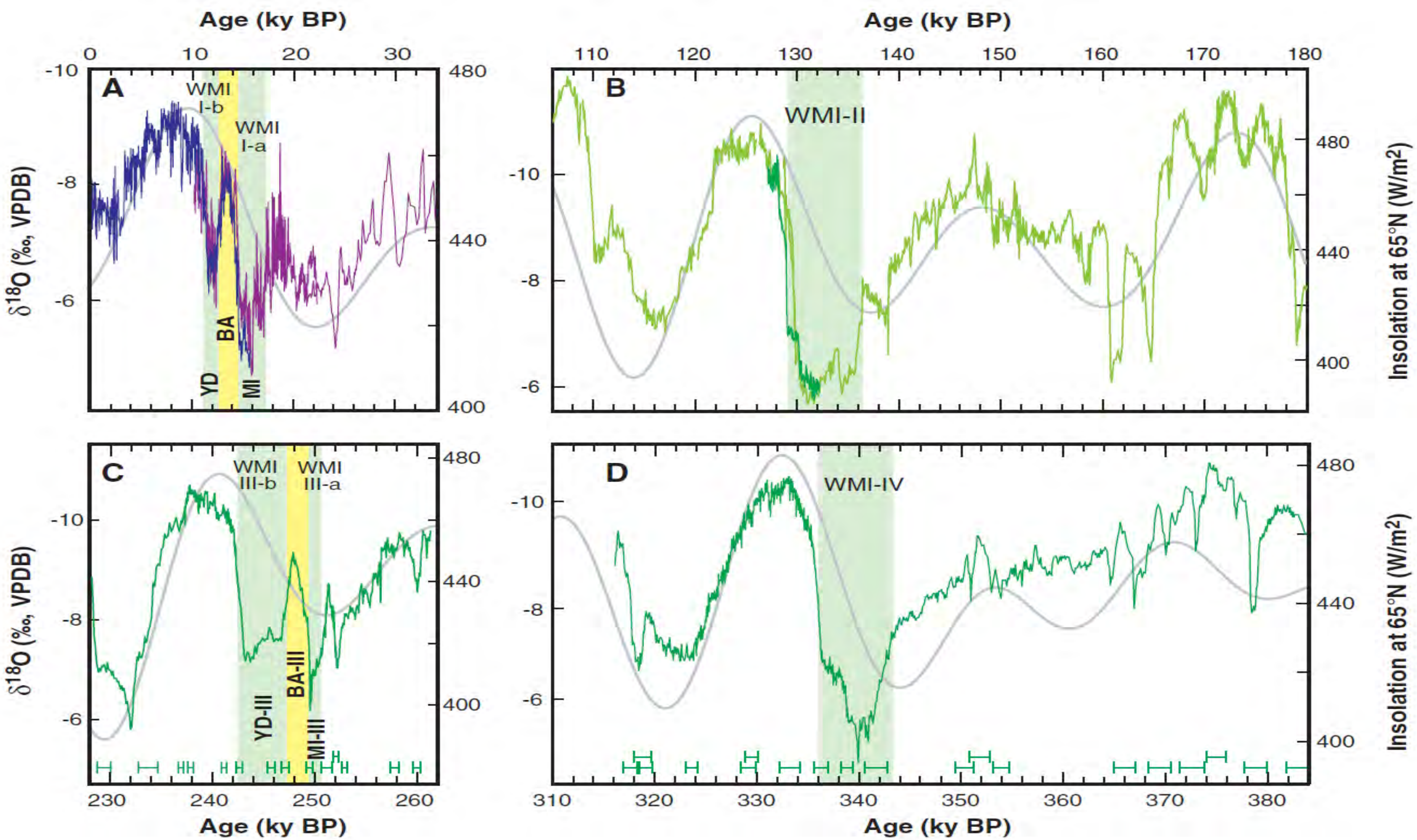
- Substantial cooling in the North Atlantic and slight warming in the South Atlantic
- Southward shift of the ITCZ over both tropical Atlantic and Pacific
- Reduced east-west SST contrast in the southern tropical Pacific
- Weakened Indian and eastern Asian summer monsoons

- Tropical Pacific response is asymmetric about the equator, unlike those induced by ENSO events

- Ocean dynamics is important for amplifying the tropical Pacific response. When coupled with a slab ocean, the tropical Pacific response is much smaller

The Past is the Key to the Present

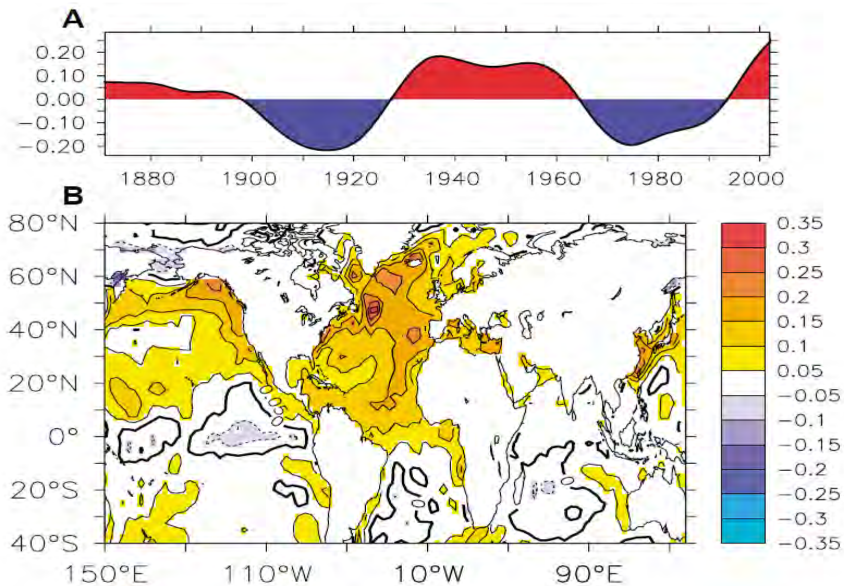
Role of AMOC in Ice Age Terminations



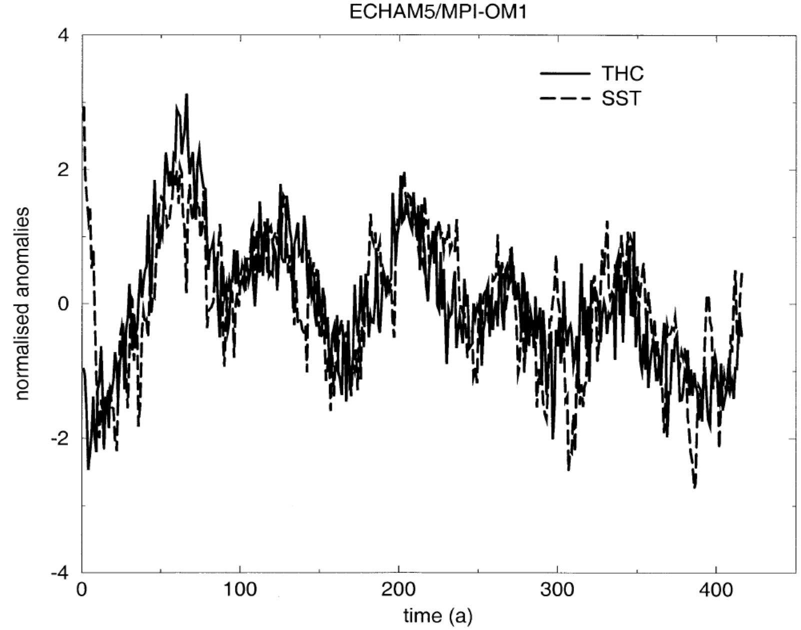
All four past glacial terminations coincide with a major Heinrich Event and Weak Asian Monsoon Interval (WMI), suggesting the crucial role of AMOC in ice age terminations (Cheng et al. 2009, Science)

Atlantic Multidecadal Oscillation (AMO)

AMO Index and Pattern



Sutton and Hodson, 2005



Latif et al. 2004

Instrumental records during the 20th century show large-scale low frequency variability in the North Atlantic SST– the so called Atlantic Multidecadal Oscillation (AMO). The observed AMO pattern is similar to numerical simulated SST anomaly induced by the low frequency AMOC variations (Knight et al. 2005). The AMO can be used as an AMOC fingerprint to reconstruct low frequency AMOC changes (Latif et al. 2004).

Observational analysis suggested that the multidecadal Atlantic Hurricane activity is strongly associated with AMO (Goldenberg et al. 2001)

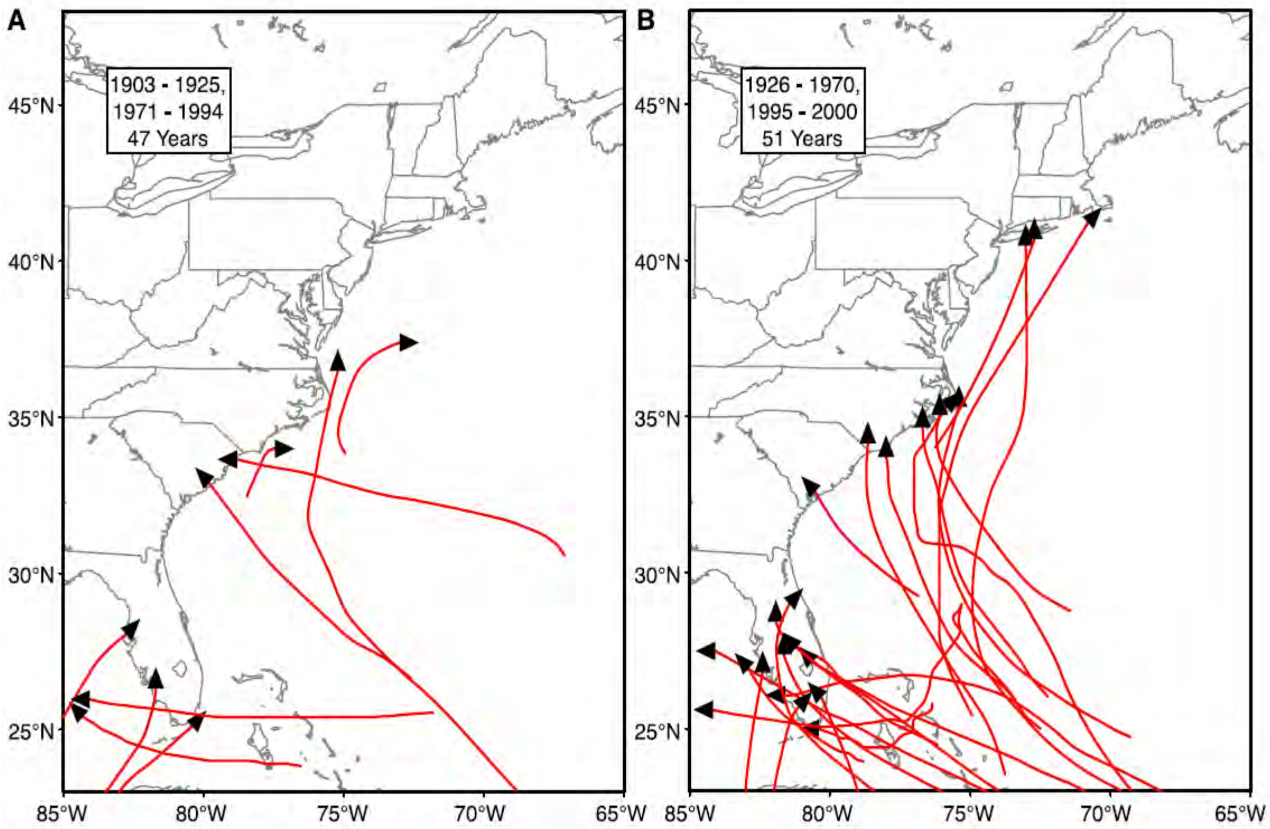
Negative AMO Phase

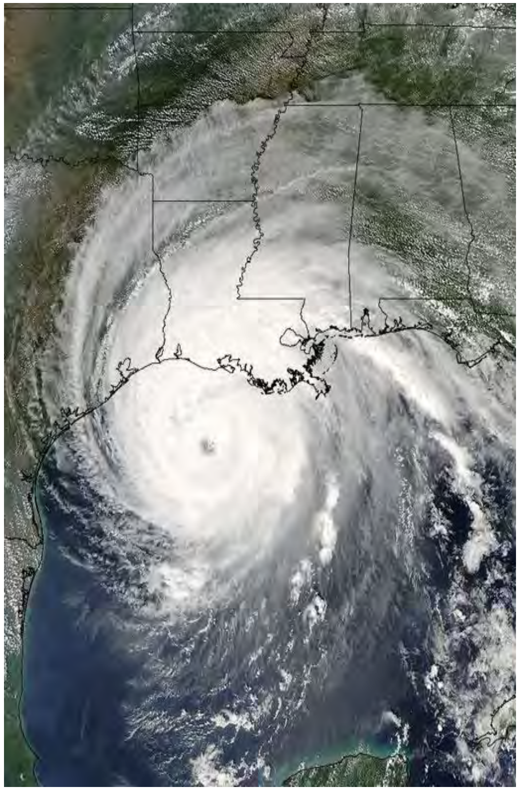
Cold North Atlantic

Positive AMO Phase

Warm North Atlantic

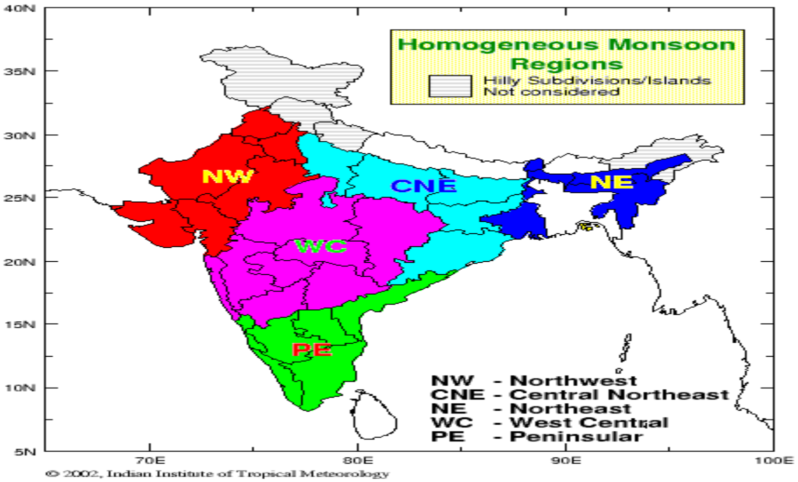
Hurricane Rita,
Sept. 23, 2005. (NASA)

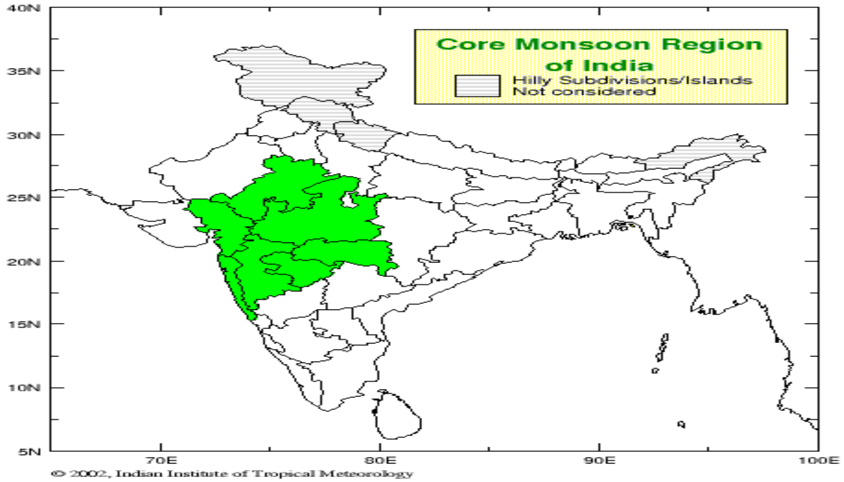




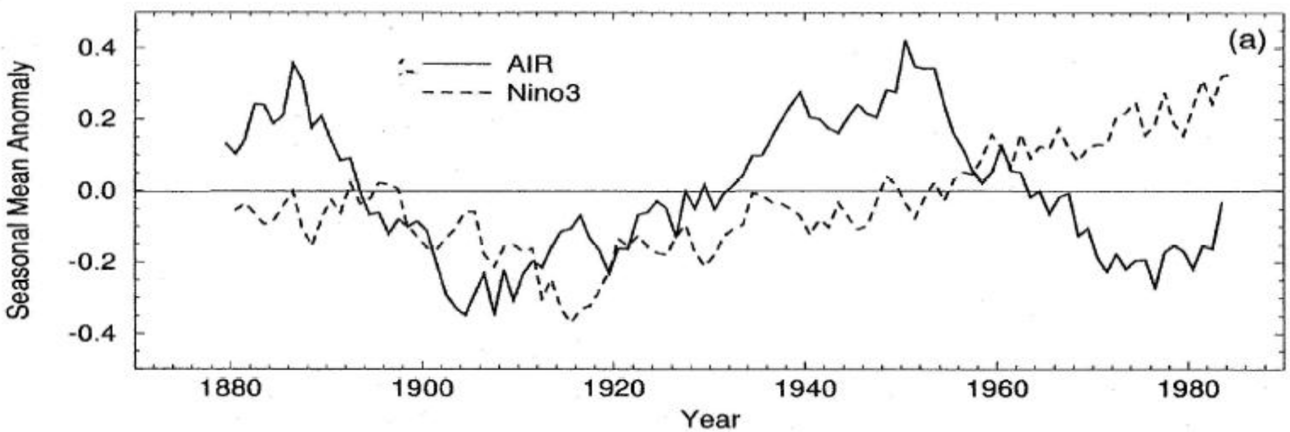
Contrast of U.S. East Coast major hurricane landfalls during the negative (left) and positive (right) AMO phase.

Map of Indian Summer Monsoon Region



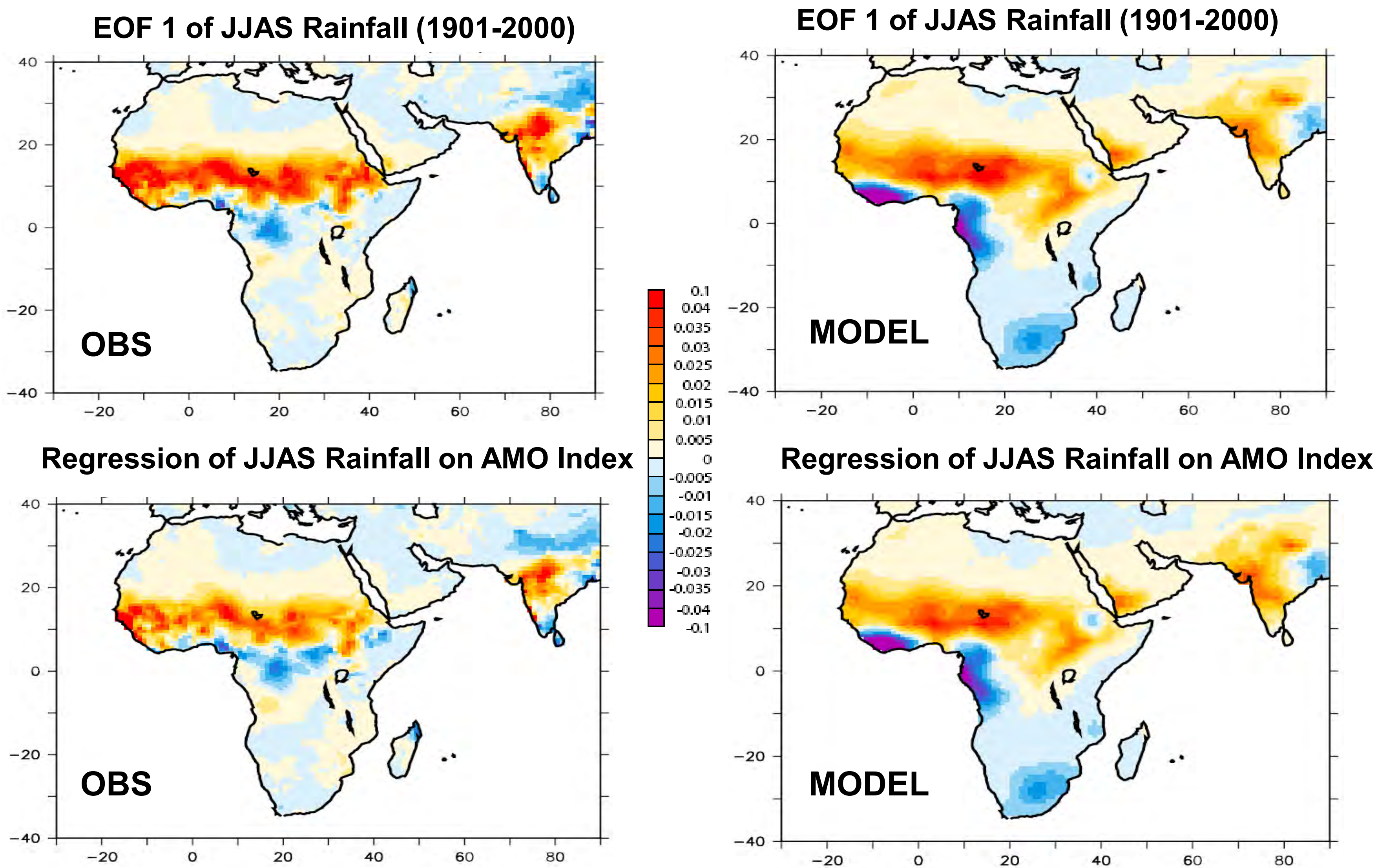


Observed Low Frequency All India Summer Monsoon Rainfall (Slingo 1999)

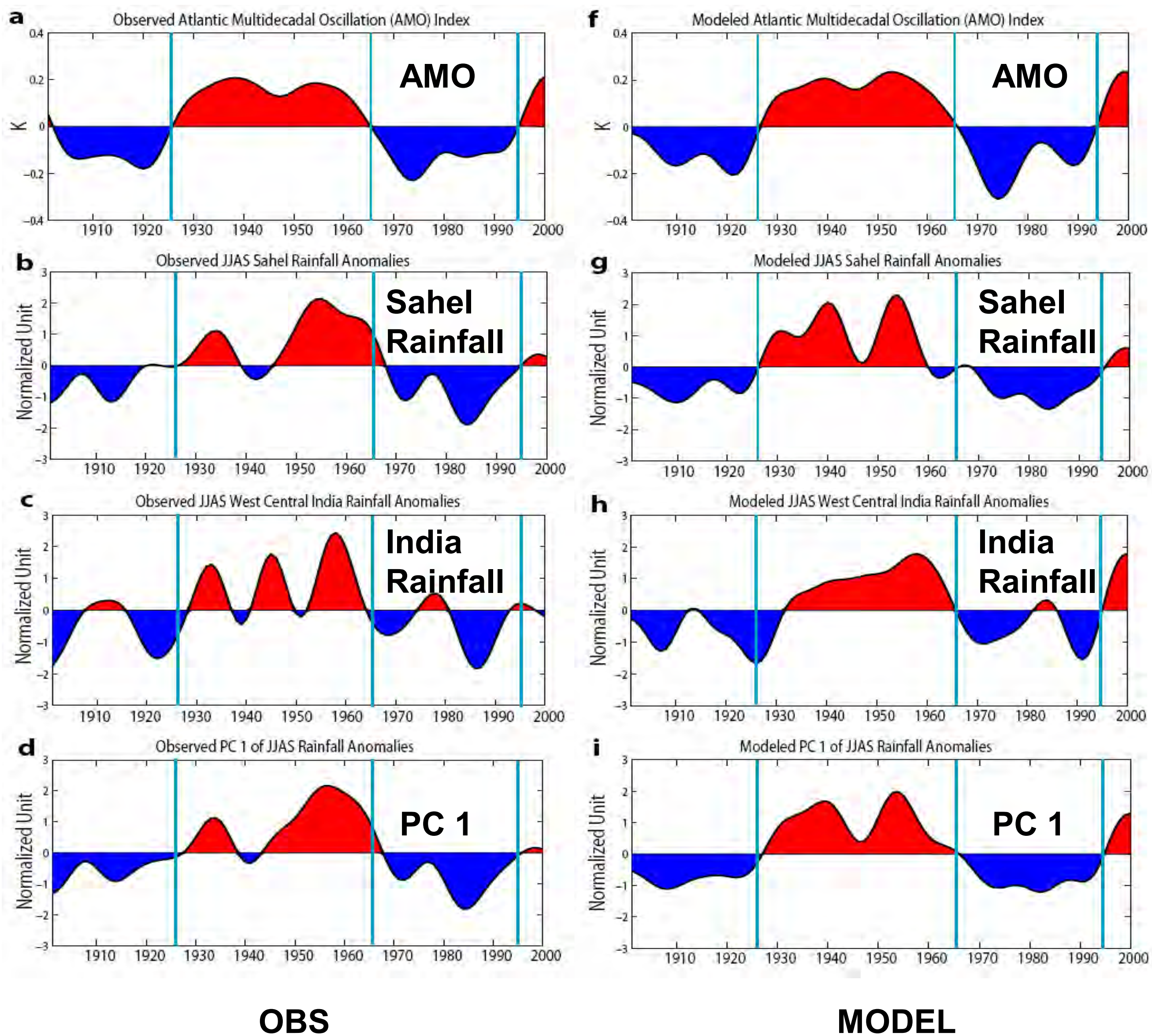


Observed low frequency Indian Summer Rainfall does not have a long term trend and does not appear to be related to ENSO variability (Slingo 1999).

Impact of AMO on India and Sahel Summer Rainfall



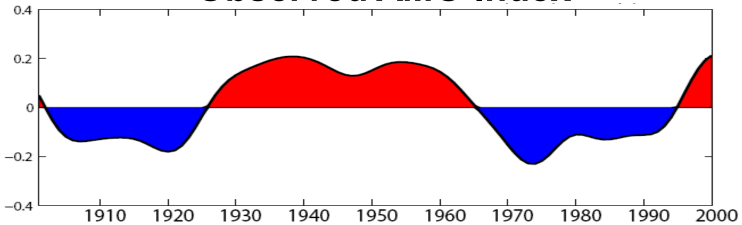
We study the causal link between AMO and other variations by prescribing the observed AMO-like variations in the Atlantic. Positive AMO phase leads to an increase of the Sahel and India Summer Monsoon Rainfall (Zhang and Delworth 2006).



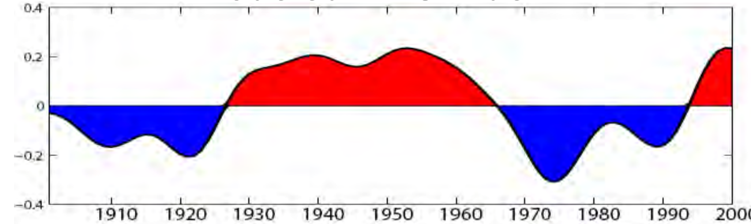
Zhang and Delworth 2006

Impact of AMO on Atlantic Hurricane Activity

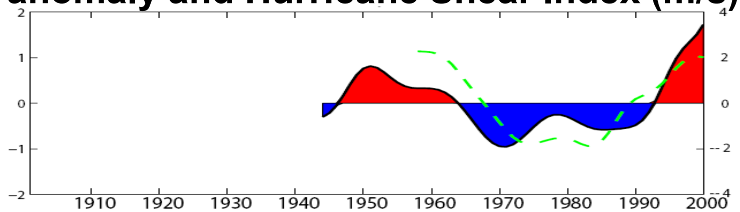
Observed AMO Index



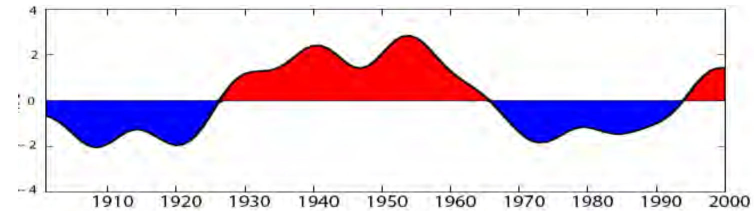
Modeled AMO Index



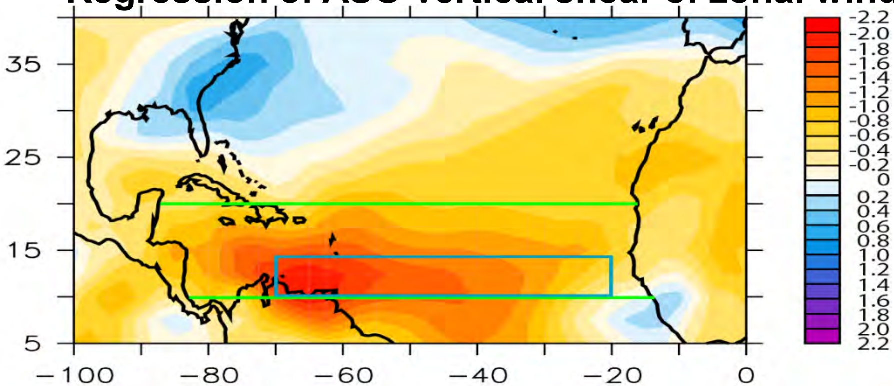
Observed major Hurricane number anomaly and Hurricane Shear Index (m/s)



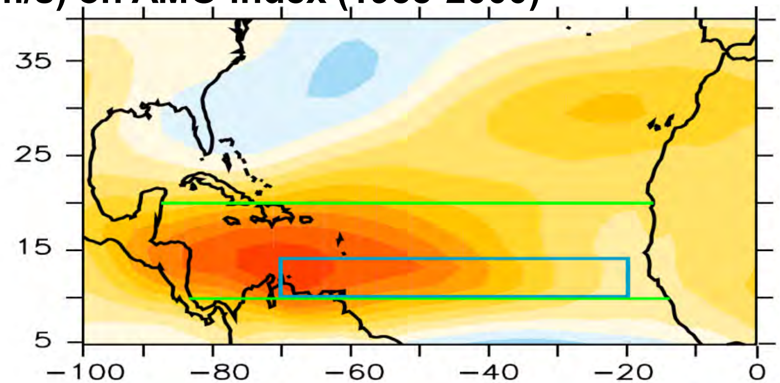
Modeled Hurricane Shear Index (m/s)



Regression of ASO vertical shear of zonal wind (m/s) on AMO index (1958-2000)



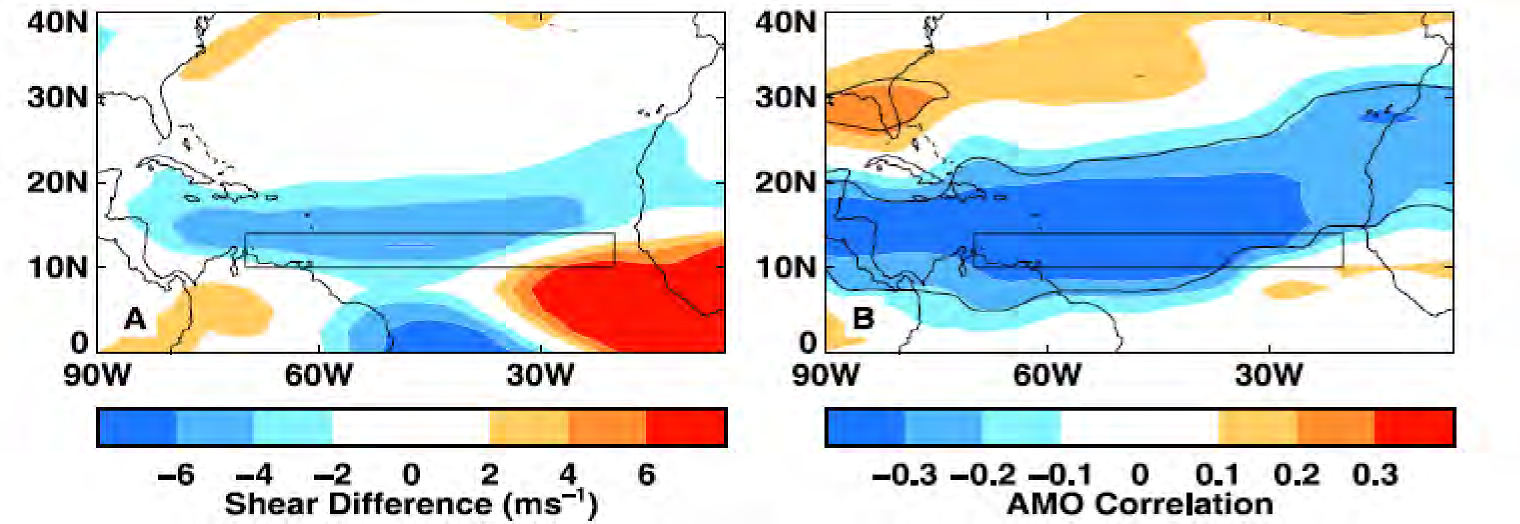
ECMWF 40-yr Reanalysis



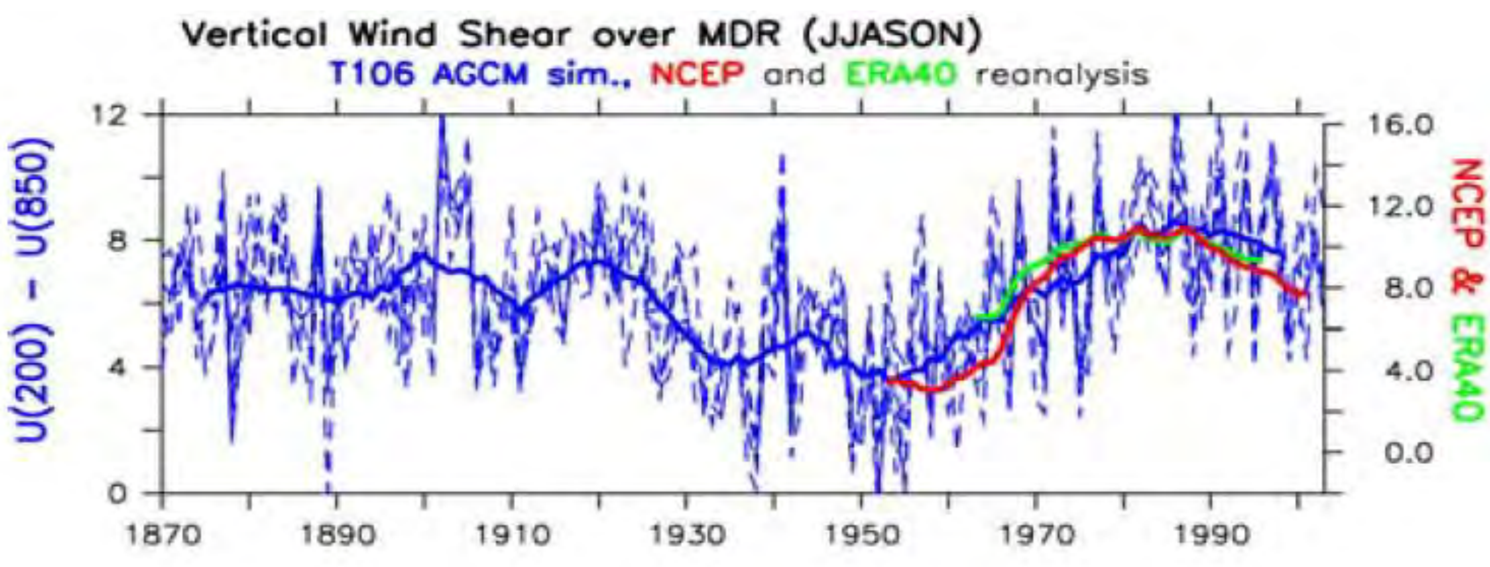
MODEL (10-member ensemble mean)

Positive AMO phase leads to a reduction of the vertical shear over the tropical North Atlantic Main Development Region (MDR) (Zhang and Delworth 2006).

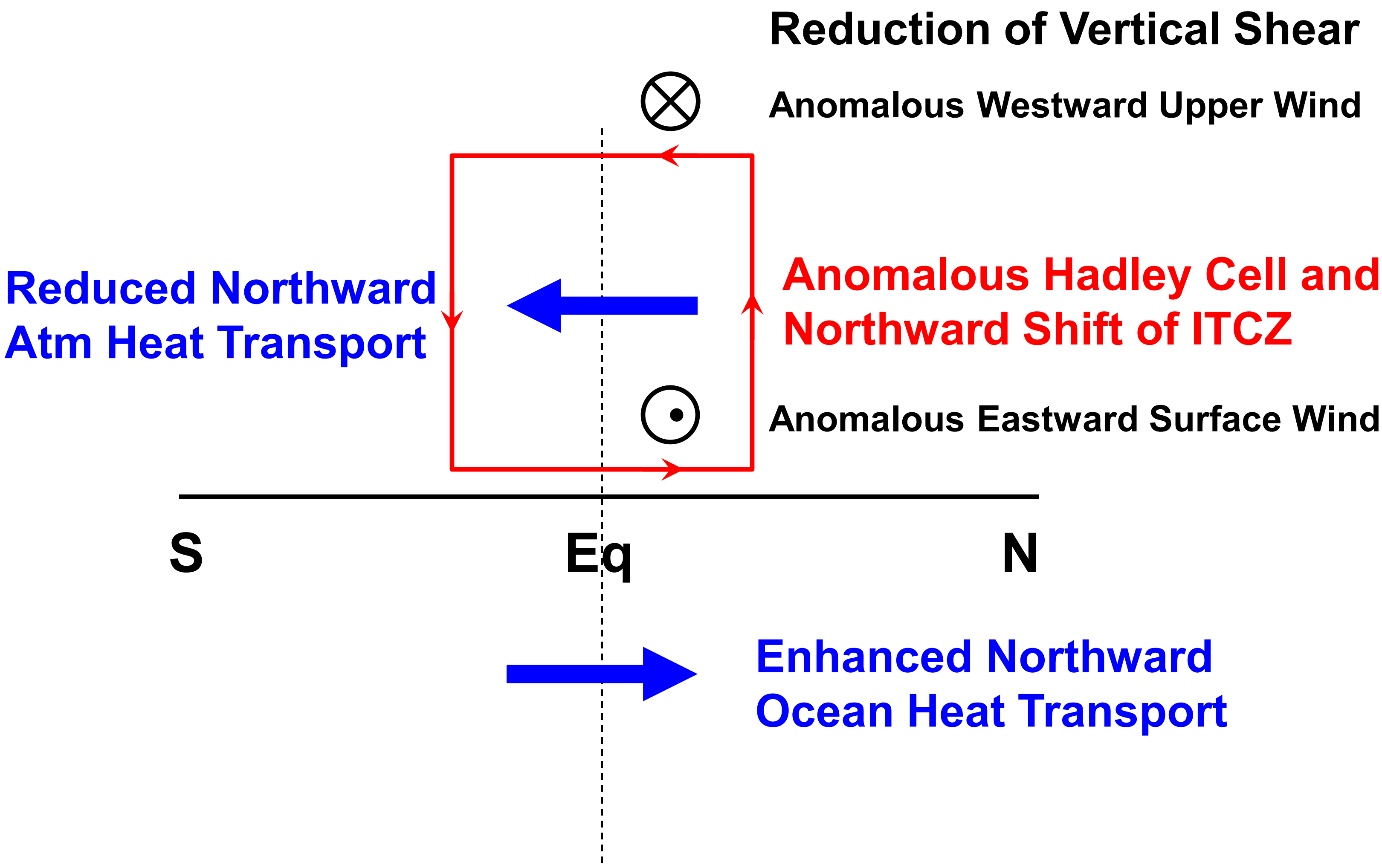
Wind shear pattern associated with positive AMO (Knight et al. 2006)



Simulated wind shear forced by observed SST (Latif et al. 2007)



Schematic Diagram of Mechanism



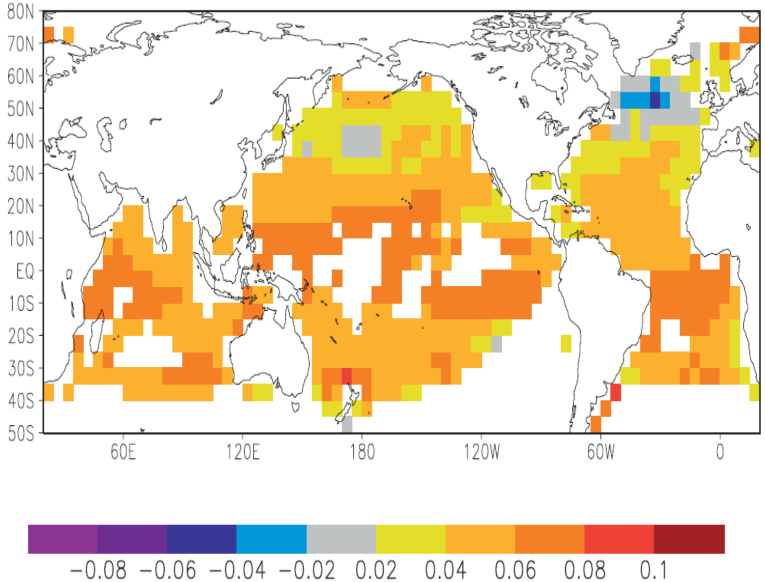
Positive AMO Phase

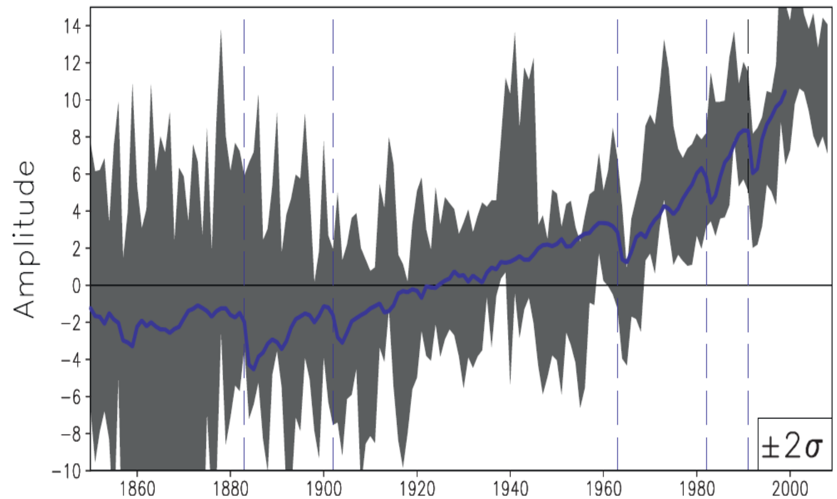
The Linkage Between NASST Variations and AMOC is Highly Debated

- Some suggested that they are driven by changes in the radiative forcing (Mann and Emanuel, 2006; Booth et al. 2012).

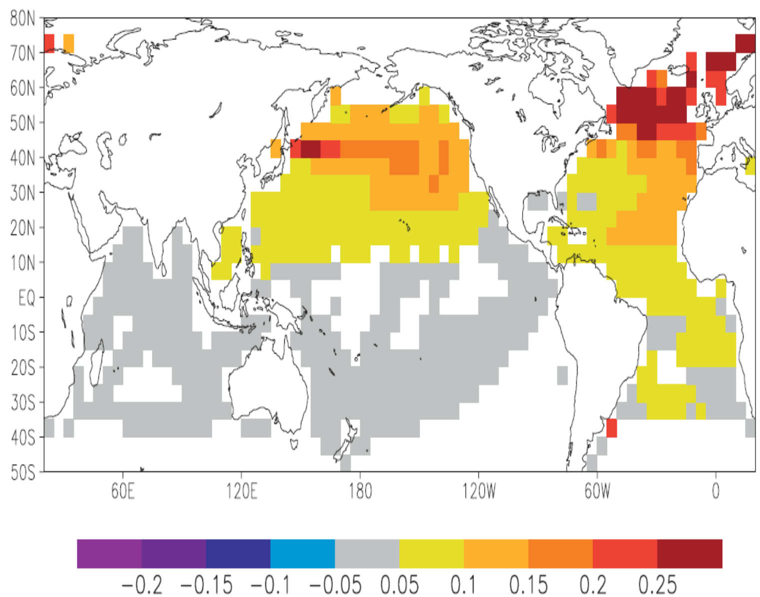
- Various approaches are proposed for quantitative attribution of NASST variations to a radiatively forced part and a part arising from AMOC variability (Kravtsov and Spannagle 2008; Ting et al. 2009; Zhang and Delworth 2009; Delsole et al. 2011; Wu et al. 2011; Ting et al. 2012).

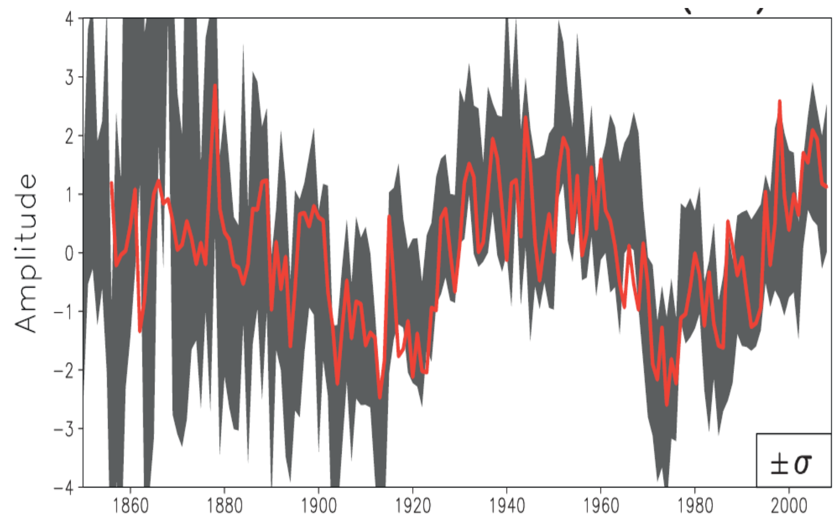
Forced and Natural North Atlantic Variability





Response to External Forcing

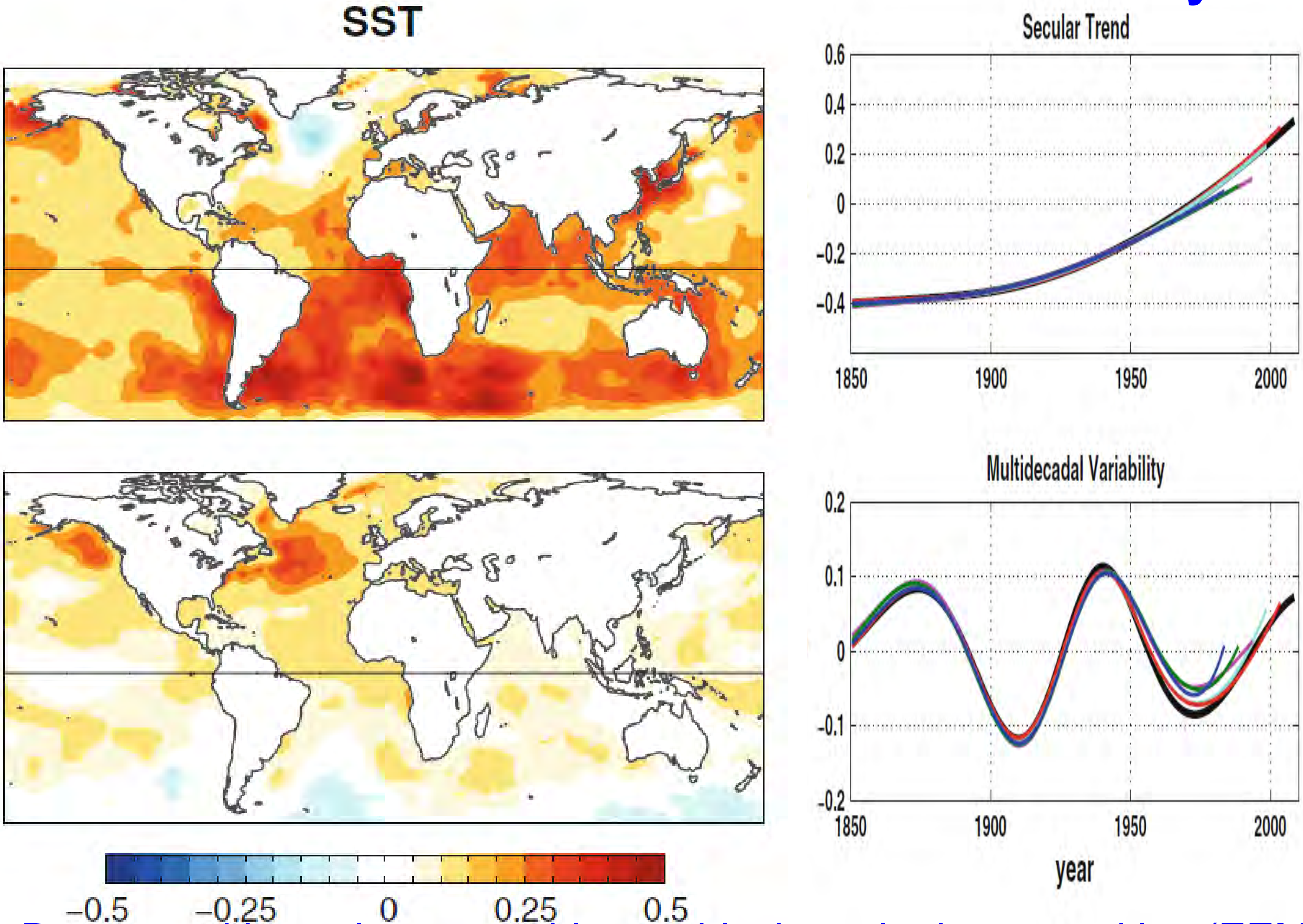




Internal Multidecadal Pattern (IMP)

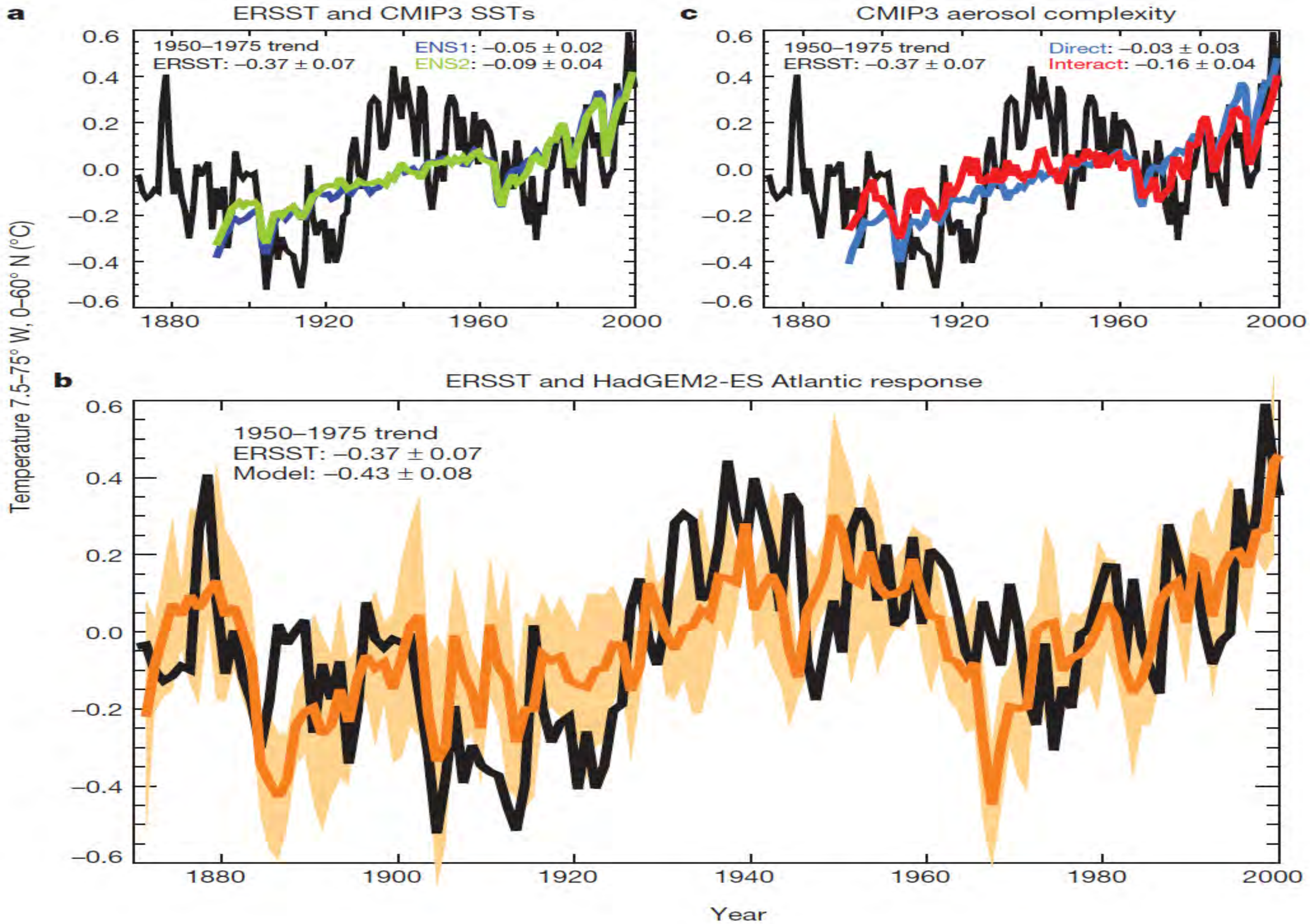
Delsole et al 2011

Forced and Natural North Atlantic Variability

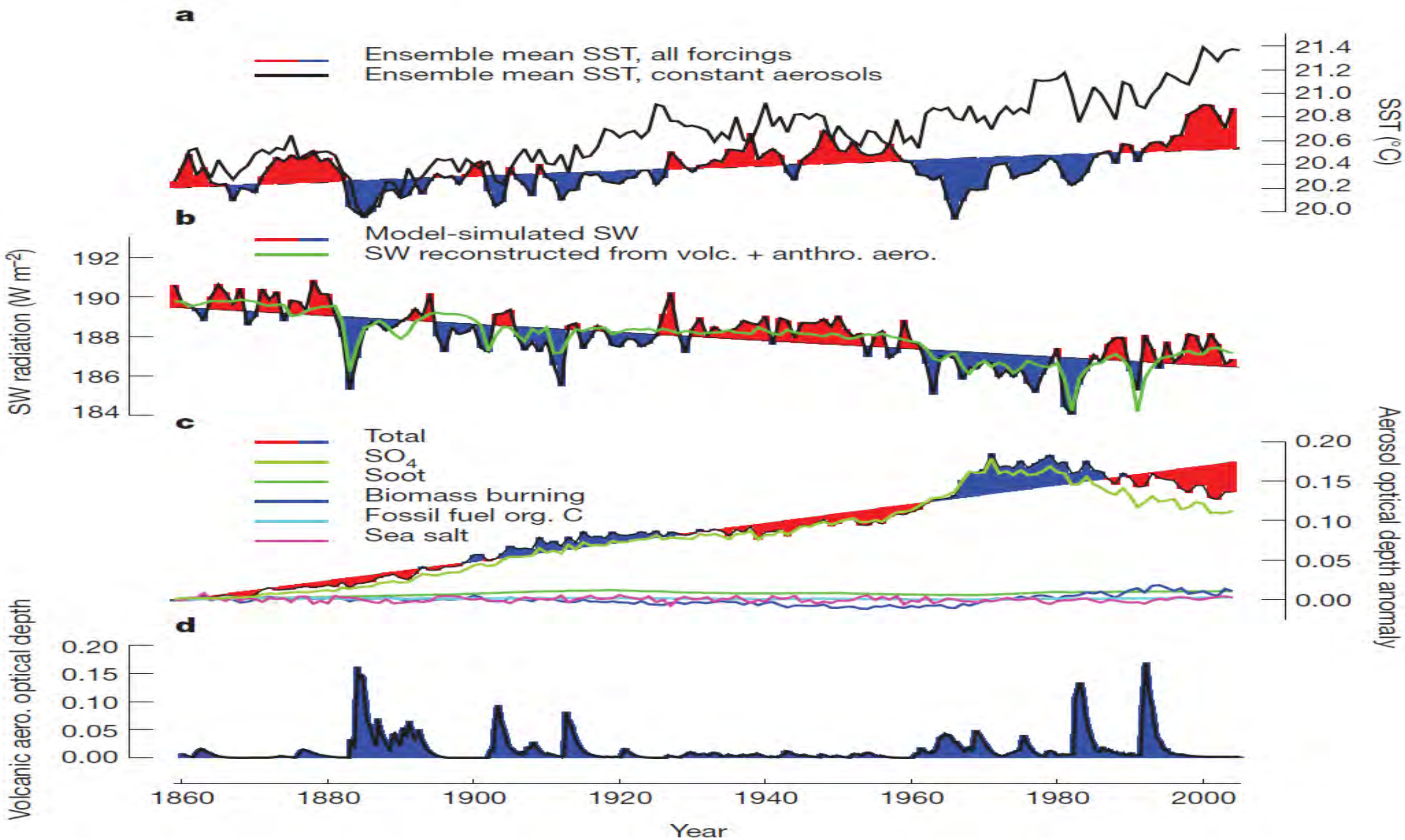


Decomposition using ensemble empirical mode decomposition (EEMD) (Wu et al. 2011)

“Aerosols Implicated as a Prime Driver of Twentieth-Century North Atlantic Climate Variability” (Booth et al. 2012)



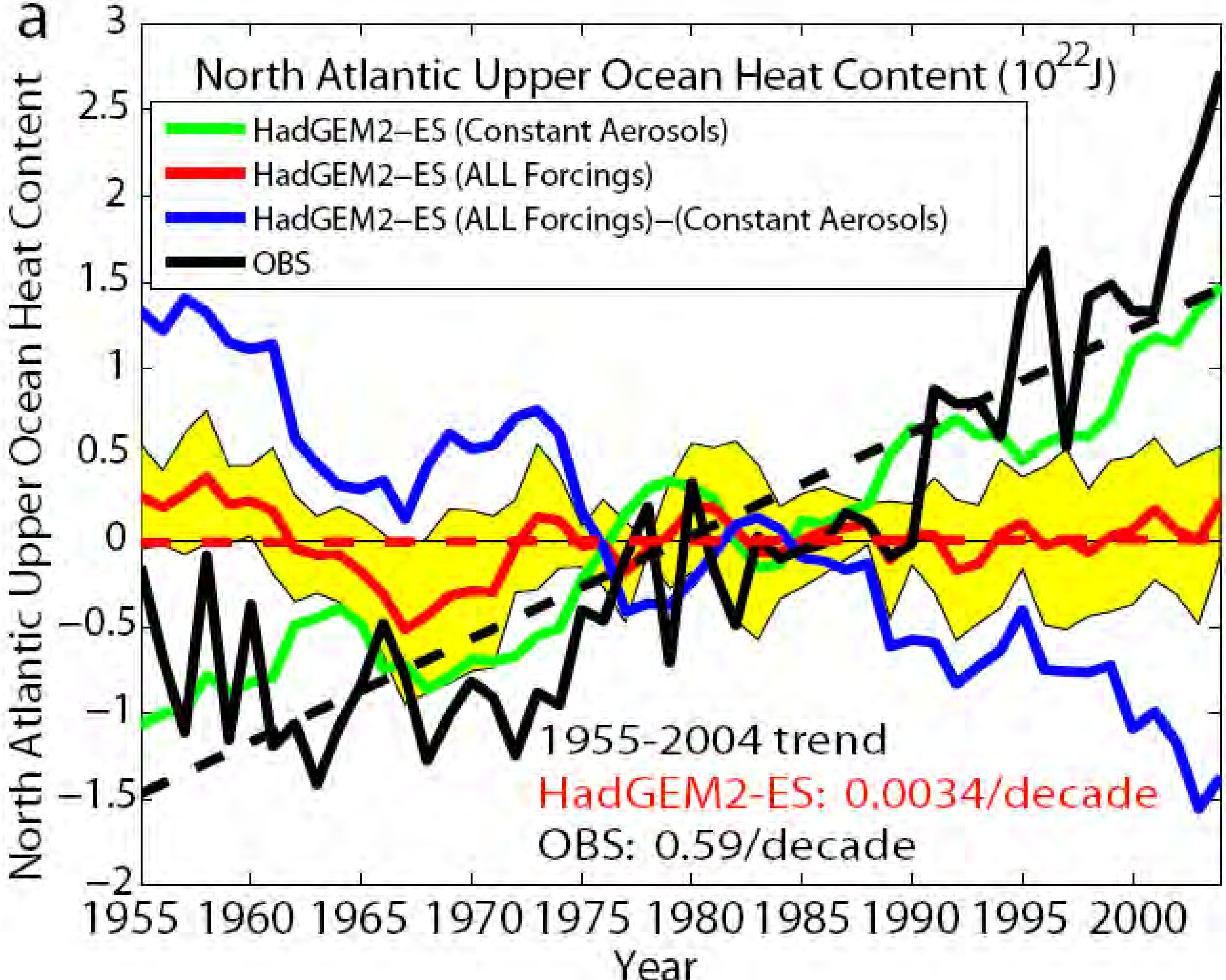
The HadGEM2-ES climate model closely reproduces the observed multidecadal variations of area-averaged North Atlantic sea surface temperature (NASST) in the 20th century.



The multidecadal variations simulated in HadGEM2-ES are primarily driven by aerosol indirect effects that modify net surface shortwave radiation (Booth et al. 2012).

Key Discrepancies between HadGEM2-ES Simulations and Observations

(Zhang et al. 2012)

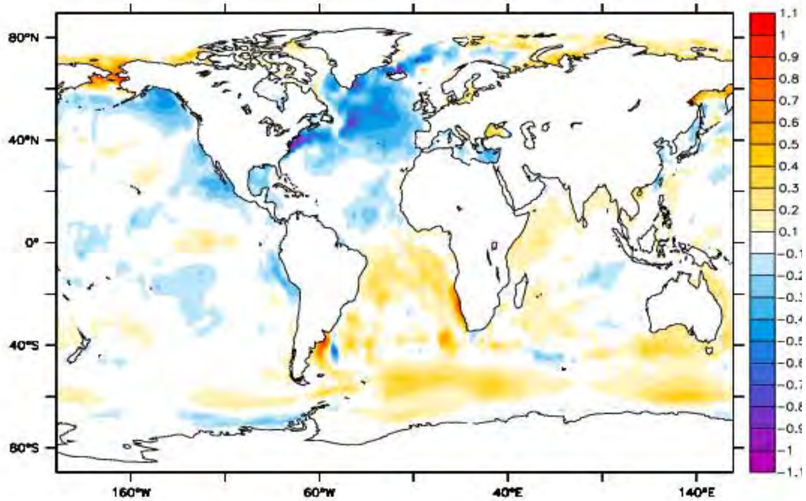


The HadGEM2-ES simulations show no trend in North Atlantic upper ocean heat content, in contrast to the substantial warming trend seen in observations. The discrepancy is mainly due to anthropogenic aerosols and suggests that aerosol effects are strongly overestimated in HadGEM2-ES.

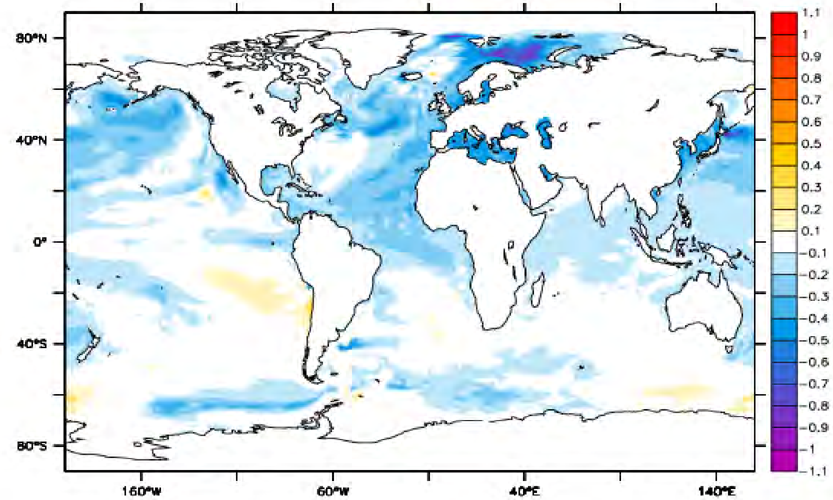
Key Discrepancies between HadGEM2-ES Simulations and Observations

(Zhang et al. 2012)

OBS



HadGEM2-ES (All Forcings)

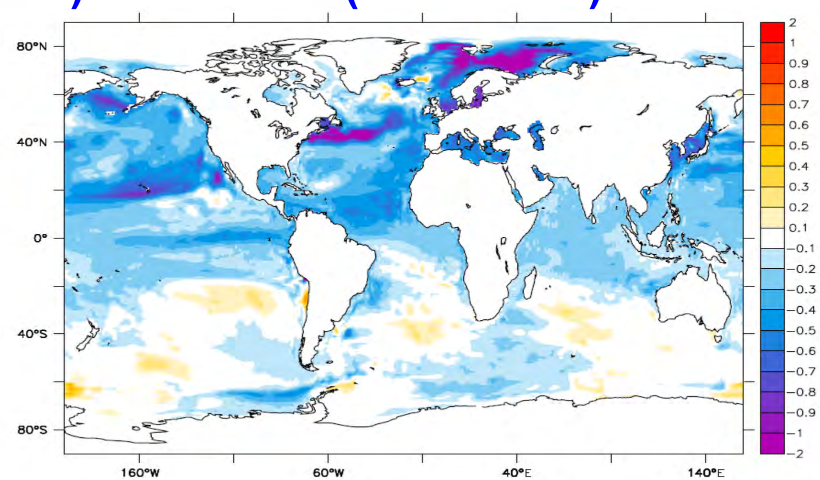


SST Difference Between Cold (1961-1980) and Warm (1941-1960) Periods

HadGEM2-ES

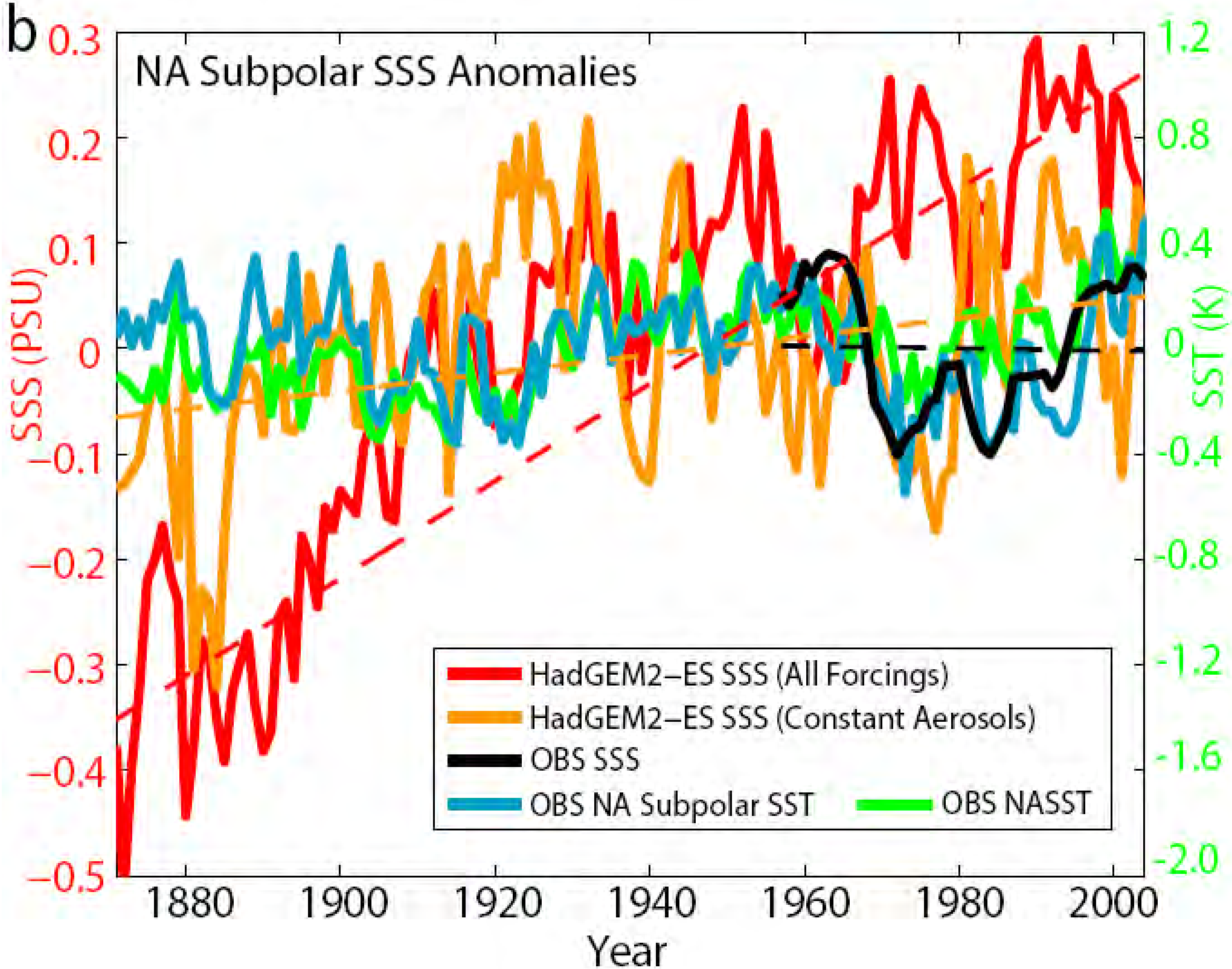
(All Forcings)-(Constant Aerosols)

net aerosol response



The observed pattern is suggestive of an important role for AMOC variations, and related variations in Atlantic heat transport. The net aerosol response in HadGEM2-ES shows excess cooling in most ocean basins, and can not explain the observed pattern.

Key Discrepancies between HadGEM2-ES Simulations and Observations



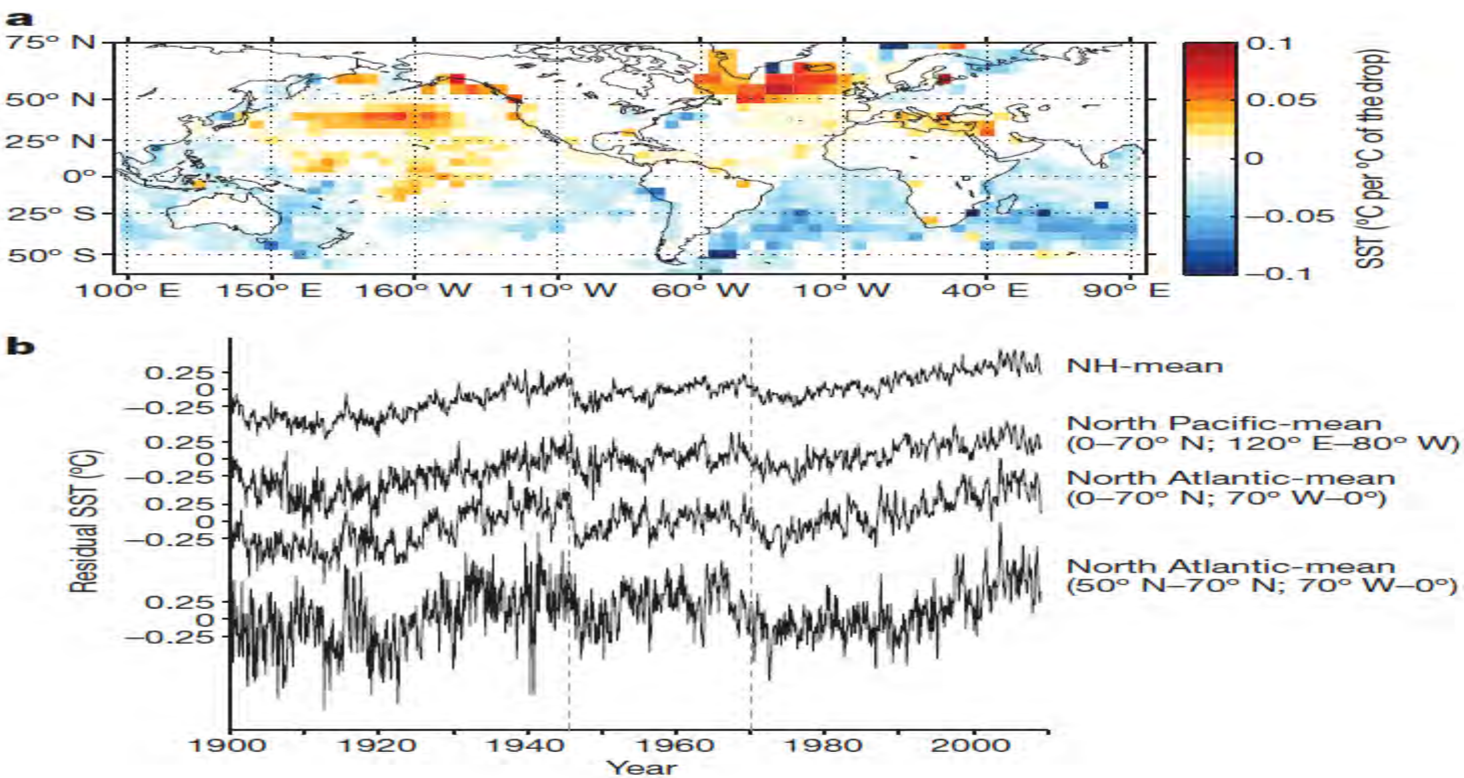
The simulated subpolar NA SSS in HadGEM2-ES shows an unrealistic positive trend, mainly due to the aerosol response. The discrepancies in subpolar NA SSS suggest aerosol effects are strongly overestimated in HadGEM2-ES.

LETTER

doi:10.1038/nature09394

An abrupt drop in Northern Hemisphere sea surface temperature around 1970

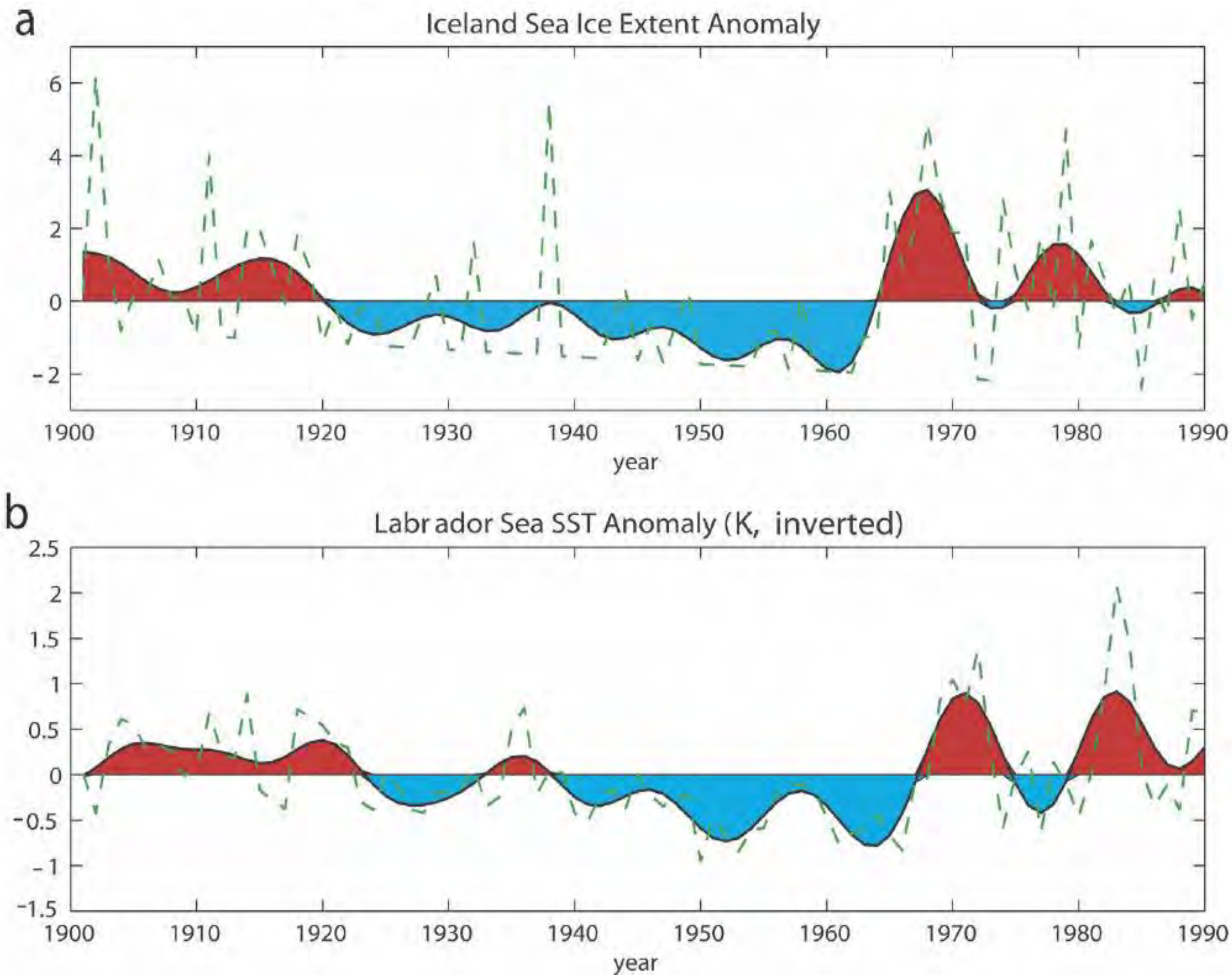
David W. J. Thompson[1], John M. Wallace[2], John J. Kennedy[3] & Phil D. Jones[4]



Thompson et al. Nature, 2010:

"Its amplitude is largest over the northern North Atlantic. The timing of the drop corresponds closely to a rapid freshening of the northern North Atlantic in the late 1960s/early 1970s (the 'great salinity anomaly') "

Great Salinity Anomaly (GSA) Events (Zhang and Vallis, 2006)



Atlantic Meridional Overturning Circulation (AMOC) Fingerprints

- Reconstruction AMOC variability using fingerprints are crucial for understanding the origin and the attribution of NASST variations.

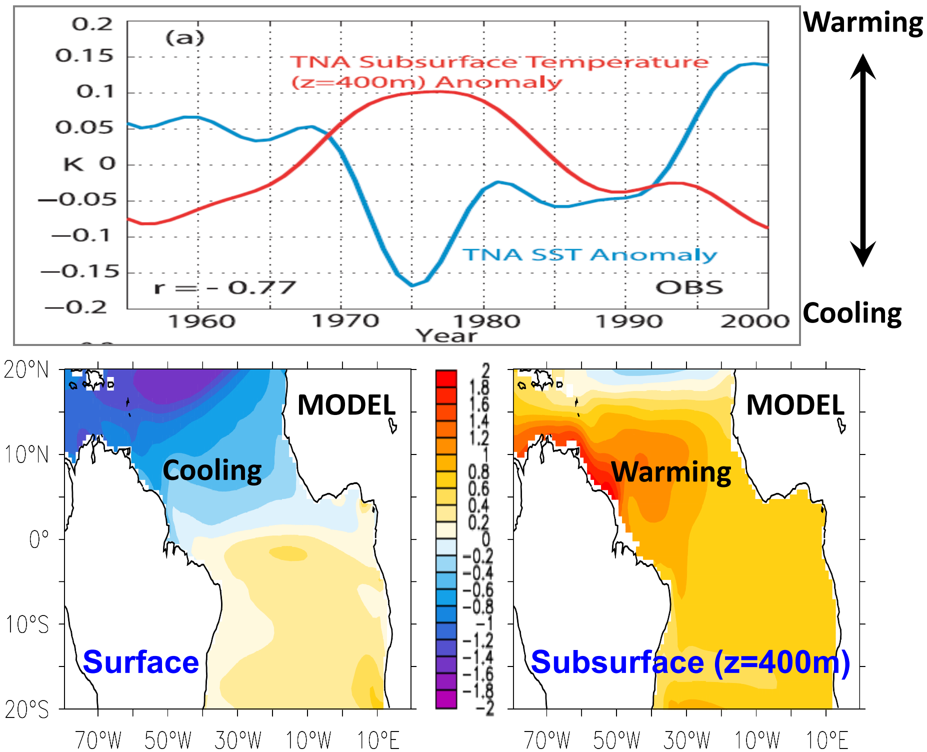
- To reconstruct the past AMOC variations when no direct observations are available, as well as to evaluate future AMOC impacts, it will be very useful to develop fingerprints for AMOC variations.

- The fingerprints need to be variables that can be derived from both climate models and observations. The fingerprints would link the AMOC with variables that are observed extensively.

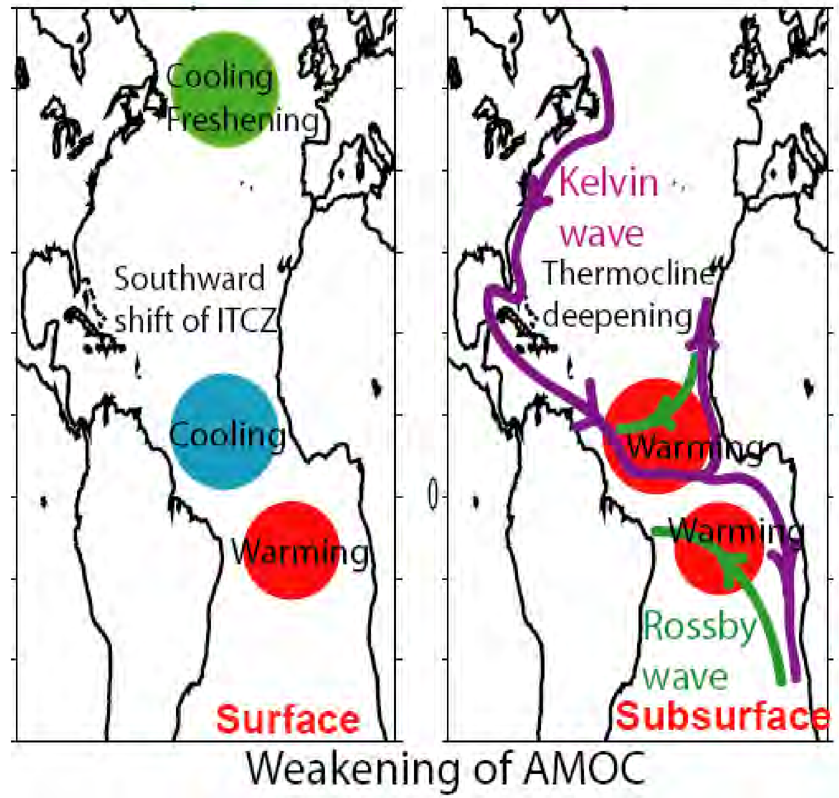
- Identification of such fingerprints will contribute to the monitoring of AMOC variations, and improve assessments of the impacts of AMOC variability on global climate change.

Tropical Fingerprint of AMOC variations

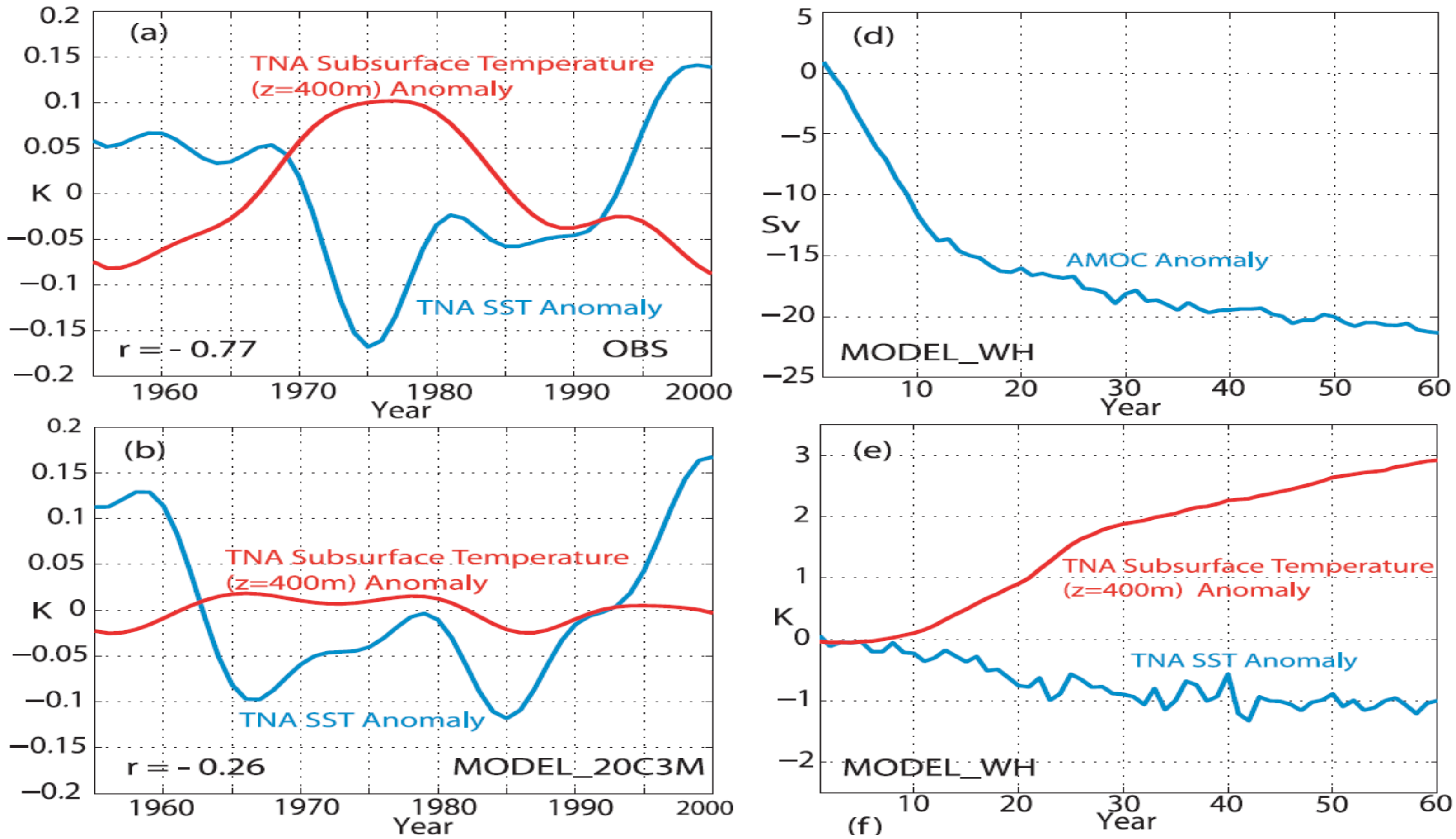
Observed Tropical North Atlantic (TNA) SST is anticorrelated with TNA subsurface ocean temperature. The anticorrelation is a fingerprint of AMOC variations in GFDL coupled model simulations, indicating observed TNA SST fluctuations may be AMOC-related (Zhang 2007).



Ocean temperature anomaly due to the weakening of AMOC from GFDL CM2.1 water hosing experiment

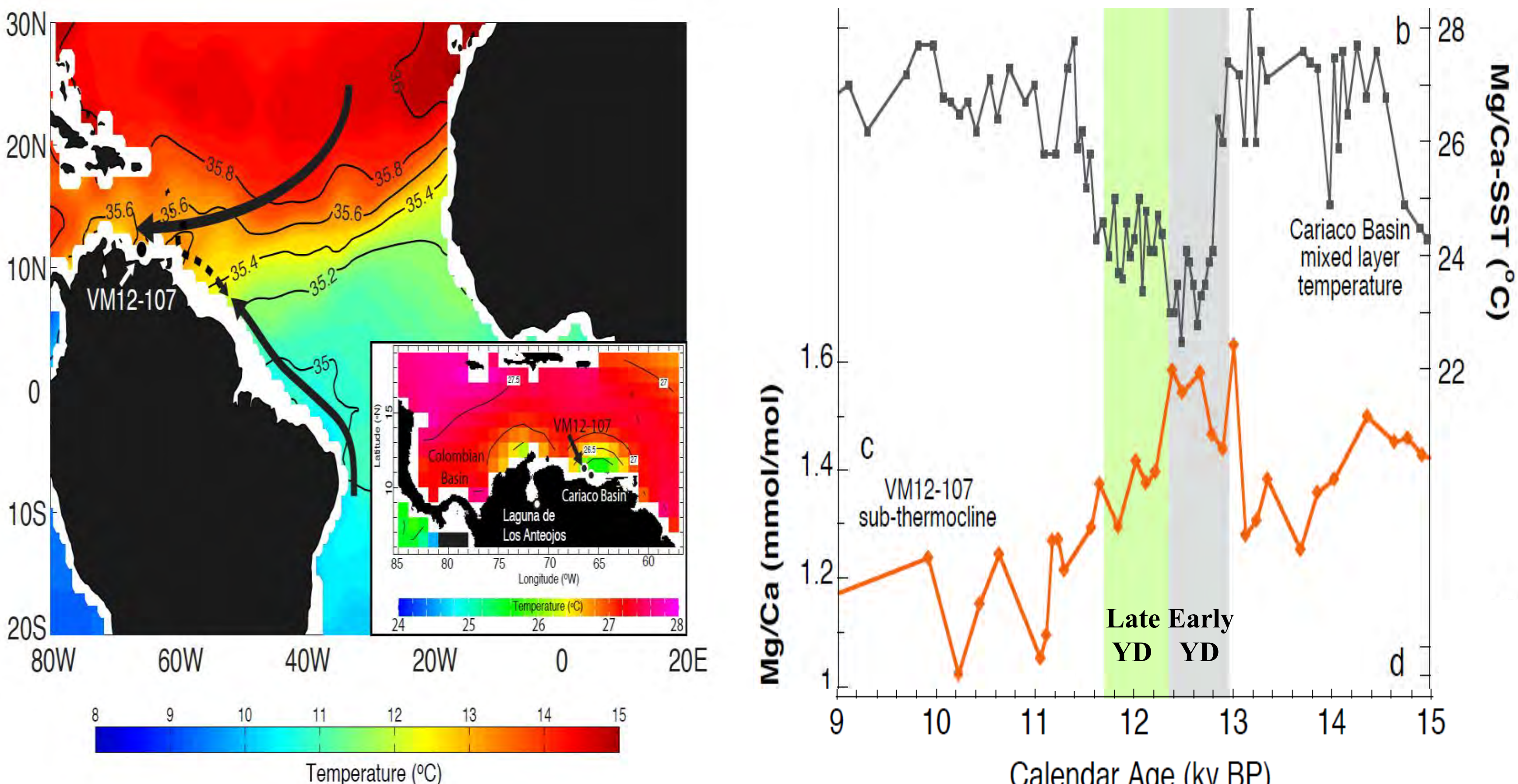


The weakening of the AMOC leads to a southward shift of the Atlantic ITCZ, TNA surface cooling, and thermocline deepening and subsurface warming in the TNA



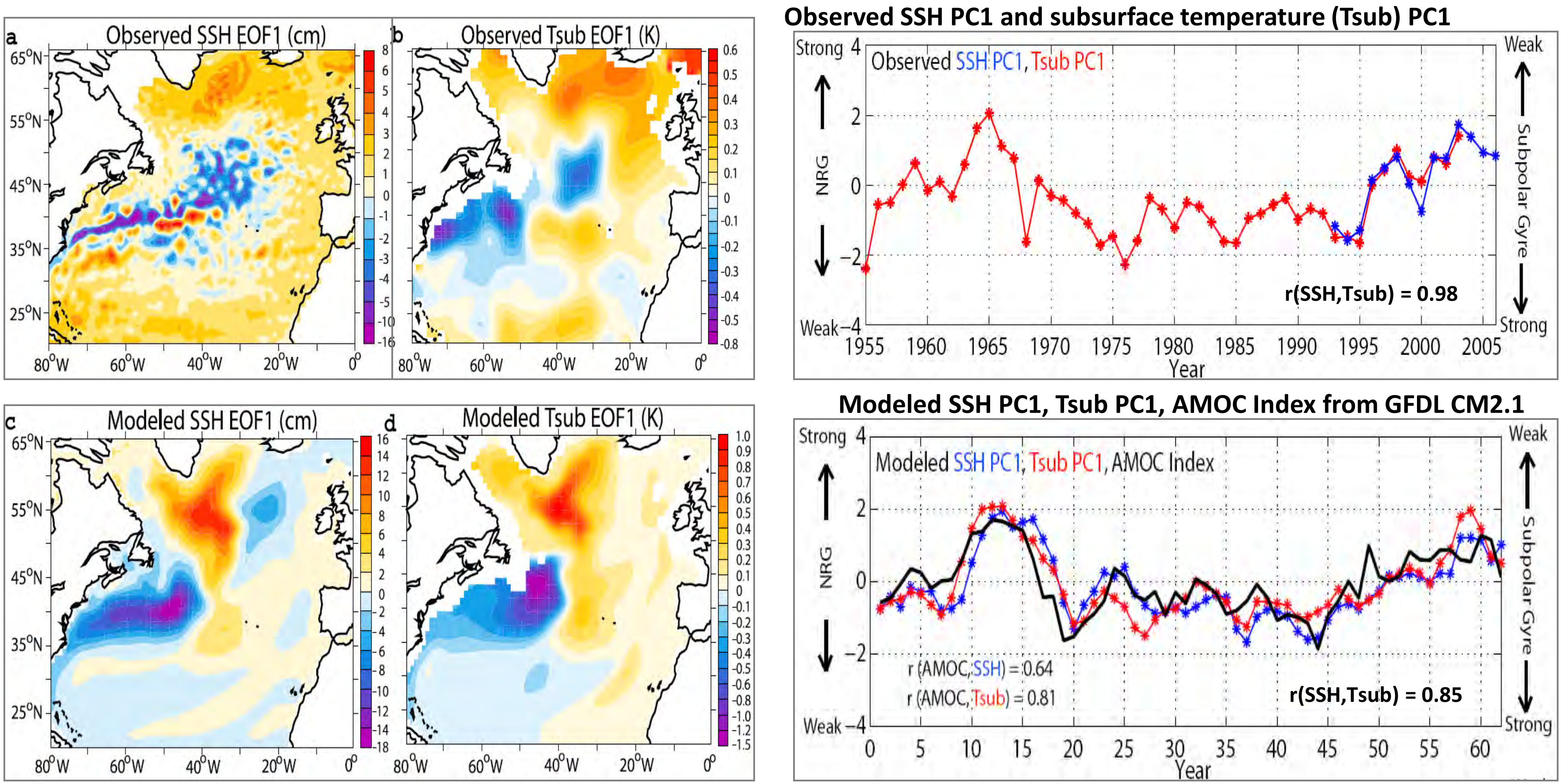
Simulations driven by external radiative forcing changes do not generate anticorrelated surface and subsurface TNA variations. The observed anticorrelation between TNA surface and subsurface temperature indicates AMOC variations (Zhang 2007). Similar AMOC-induced anticorrelated surface and subsurface TNA variations have also been found in CCSM3 coupled model simulations (Chiang et al. 2008).

Anticorrelated TNA Surface and Subsurface Temperature



High-resolution temperature records of the last deglacial transition from a southern Caribbean sediment core show that warmer subsurface temperatures correspond to colder surface temperature and weaker AMOC during the Younger Dryas (Schmidt et al. 2012, PNAS, In Press)

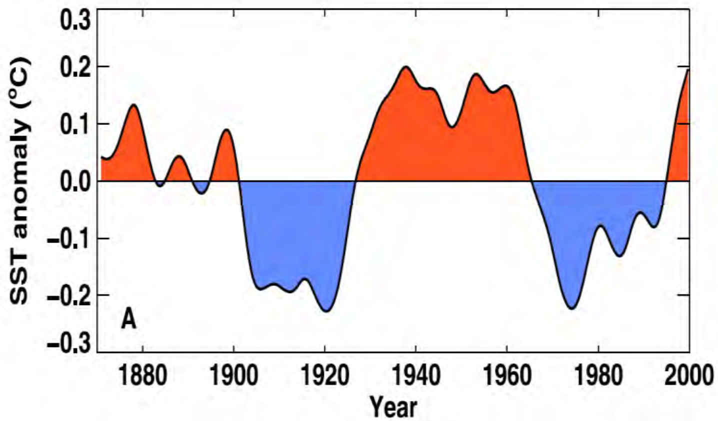
Extra-Tropical Fingerprint of AMOC variations

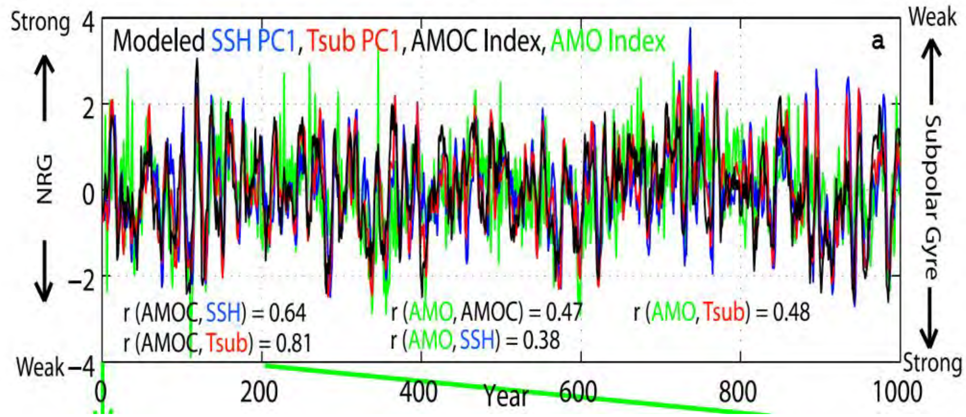


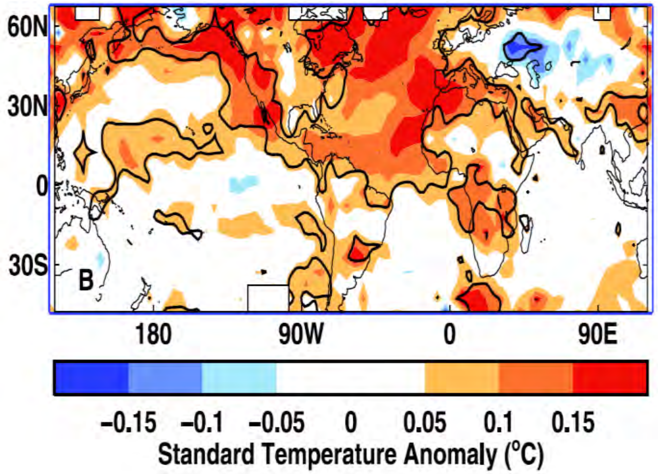
The leading modes of SSH and subsurface temperature (Tsub) constitute a fingerprint of AMOC variations, and might be used as a AMOC proxy. It indicates that during the 60's and the recent decade, the AMOC was stronger, and the recent slowdown of the subpolar gyre is a multidecadal variation (Zhang 2008).

Indirect verification using AMO

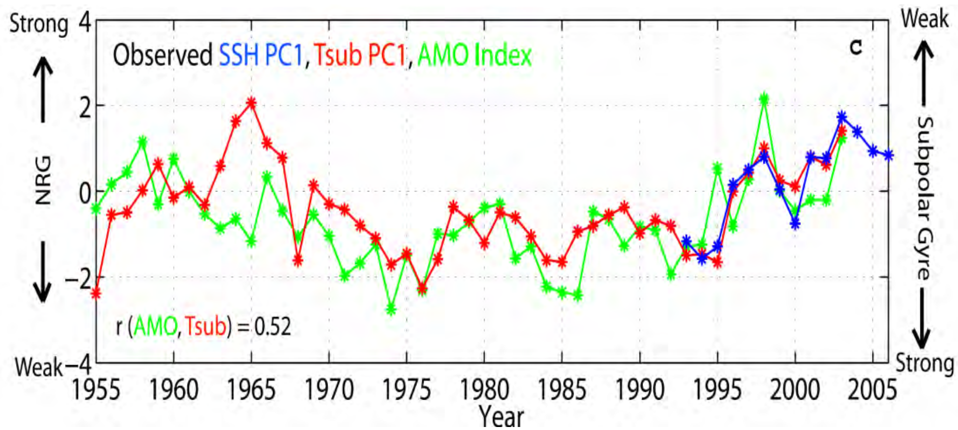
Modeled AMO Index has significant correlations with modeled AMOC Index, Tsub PC1, SSH PC1.







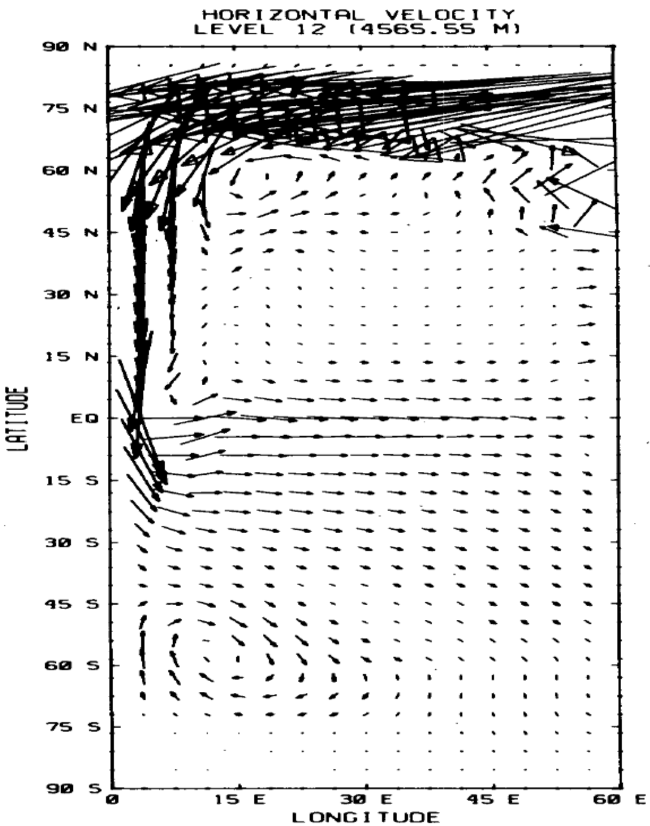
Observed AMO Index has significant correlations with observed Tsub PC1 for 1955–2003



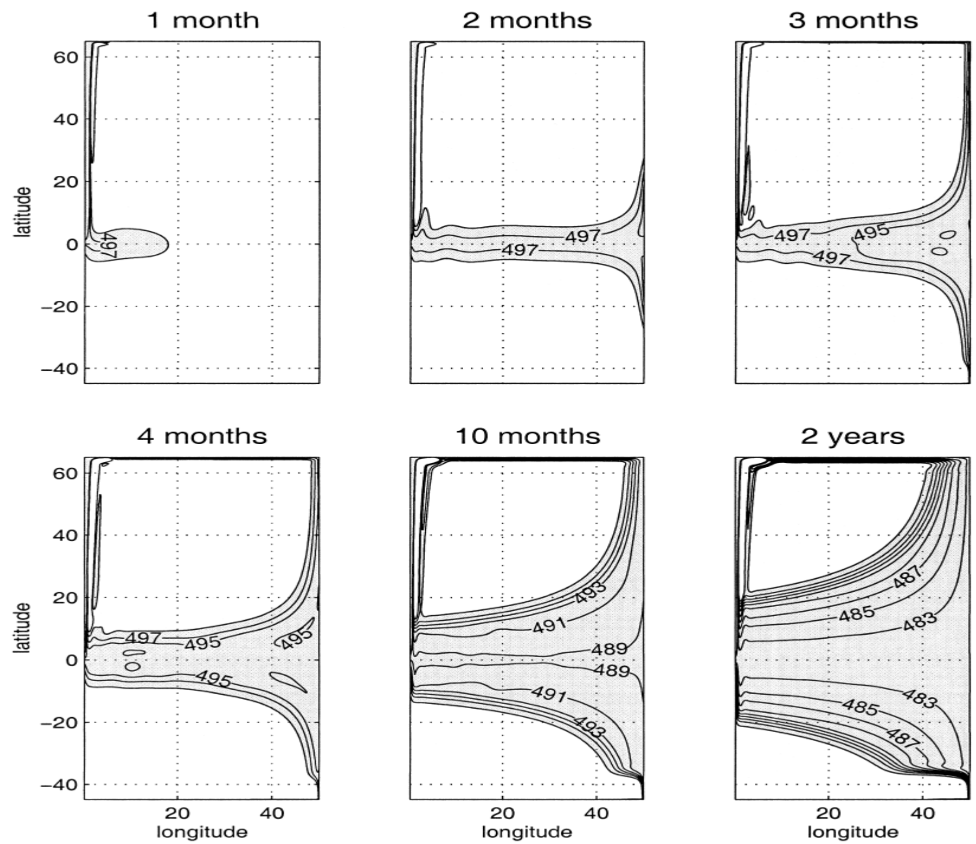
The AMOC variations inferred from the observed Tsub PC1 are consistent with those inferred from the observed AMO index (Zhang 2008).

Classic Picture of the Meridional Propagation of AMOC Variations

AMOC variations are often thought (Kawase, 1987; Johnson and Marshall, 2002; etc.) to propagate with the Kelvin wave speed, resulting in a short time lead (less than a few months) between AMOC variations at high and low latitudes and the predictability from the short time lead is less useful.

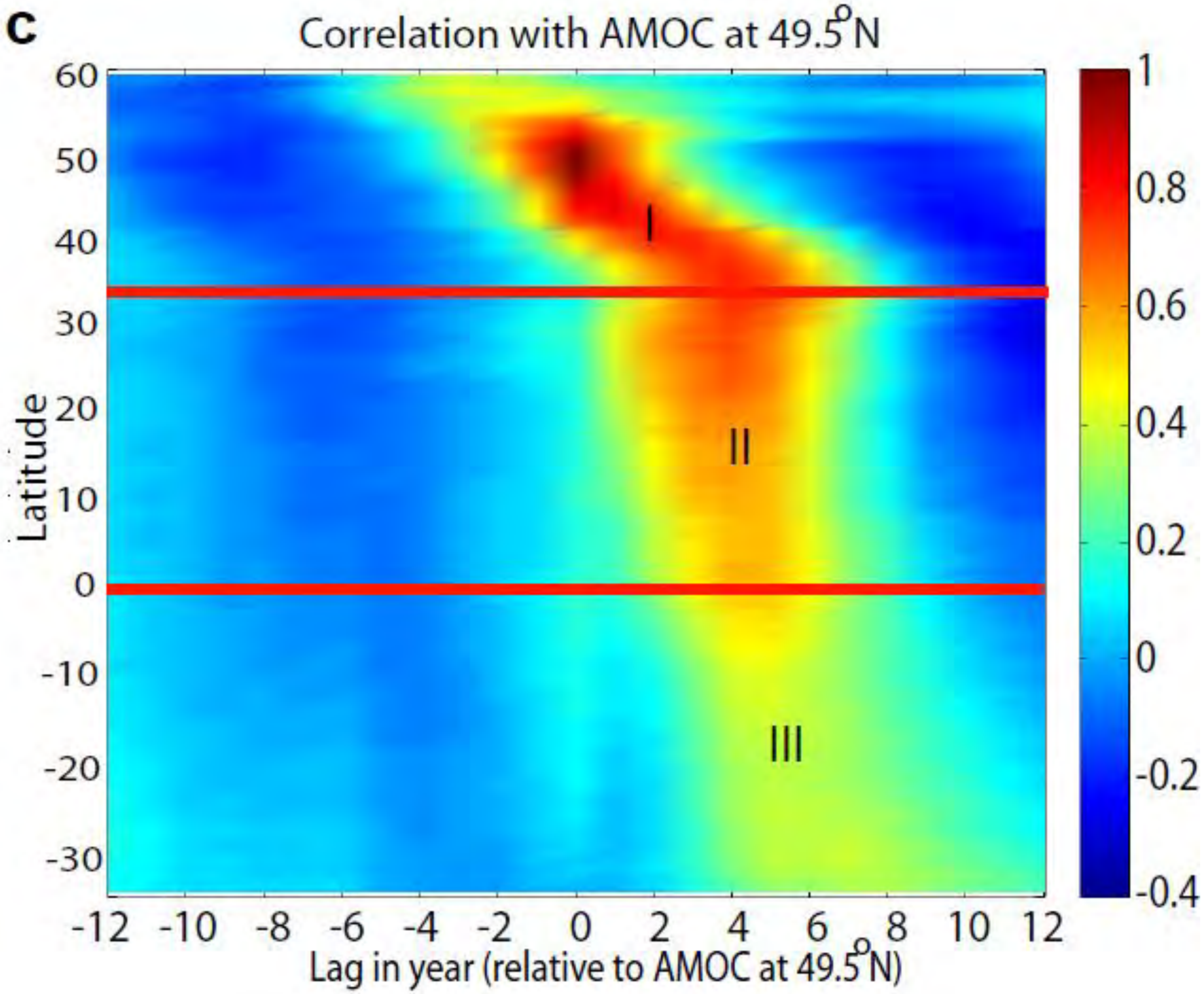


(Bryan, 1986)



(Johnson and Marshall, 2002)

The southward propagation of AMOC variations associated with changes in the NADW formation can be classified into three regimes (Zhang, 2010)



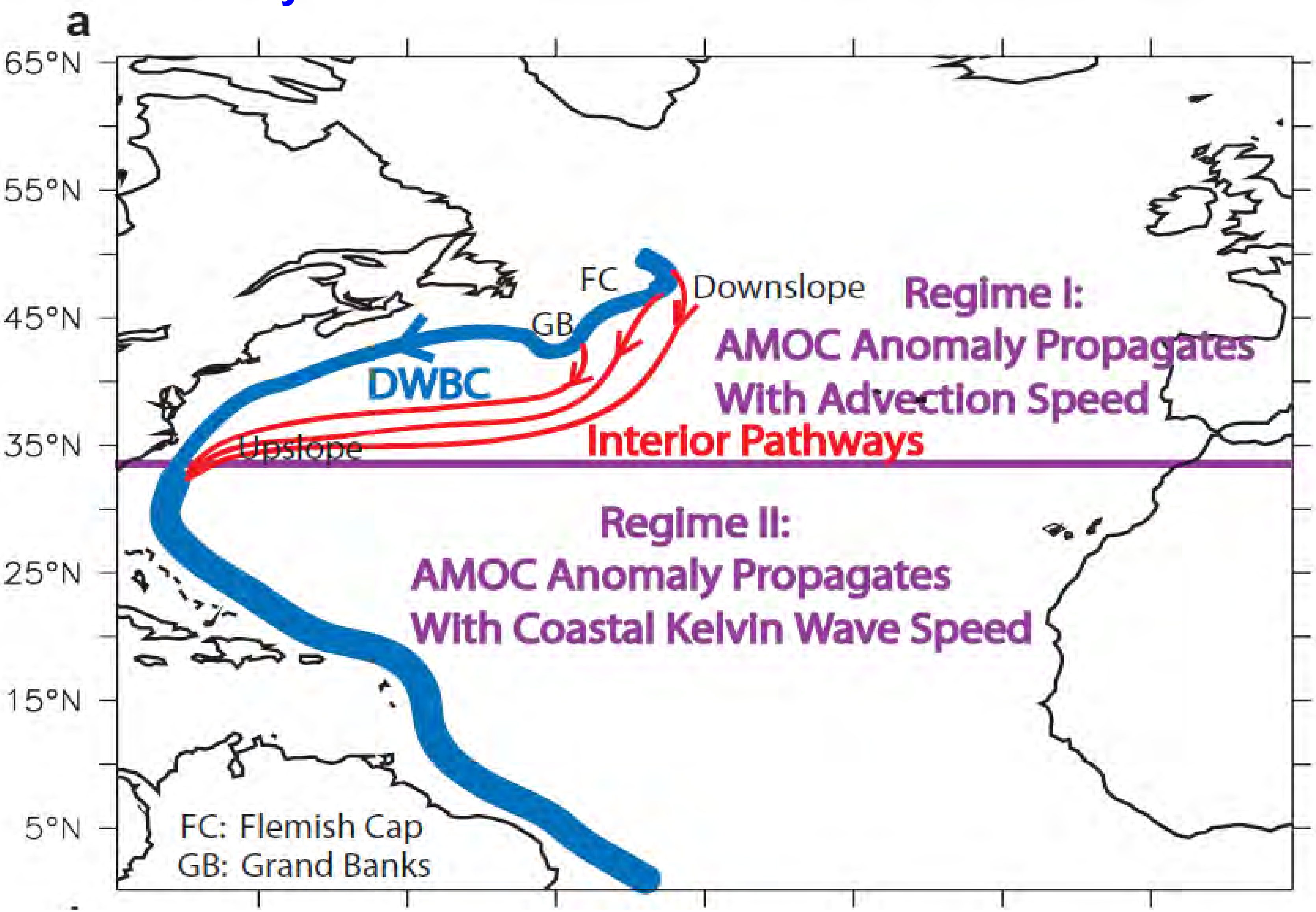
Regime I: advection speed

Regime II: Kelvin wave speed

Regime III: Rossby wave speed

Cross Correlation between the AMOC variation at 49.5°N and AMOC Variations at Various Latitudes (GFDL CM2.1 Control Simulation).

Schematic Diagram of the Propagation a Positive AMOC Anomaly Associated with Enhanced NADW Formation



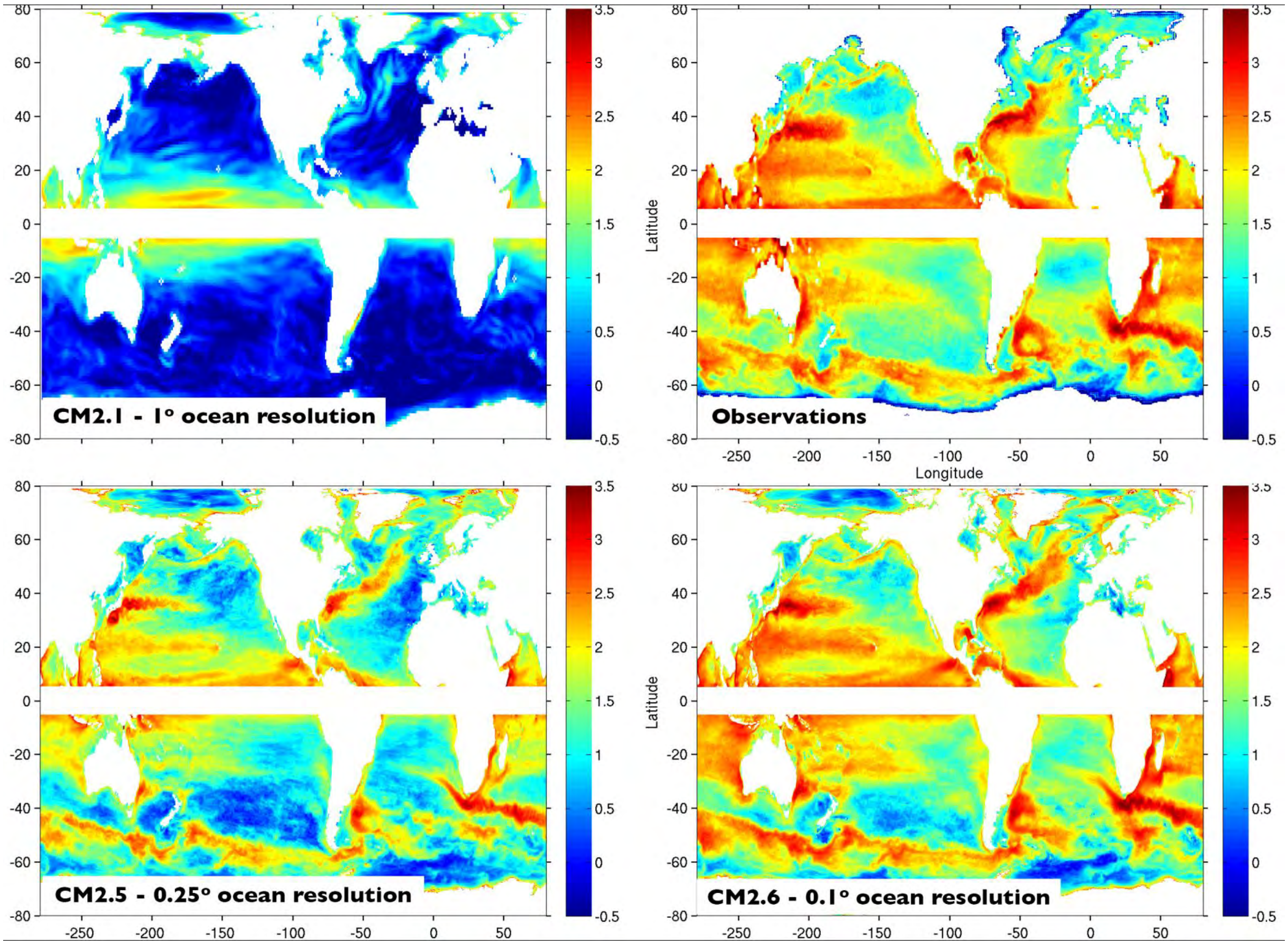
Zhang, 2010

GFDL High Resolution Global Coupled Climate Model

(Delworth et al. 2011)

	Ocean	Atmos	Land	Status
CM2.1	100 Km	250 Km	LM2	Running
CM2.5	10-25 Km	50 Km	LM3	Running
CM2.6	4-10 Km	50 Km	LM3	Running

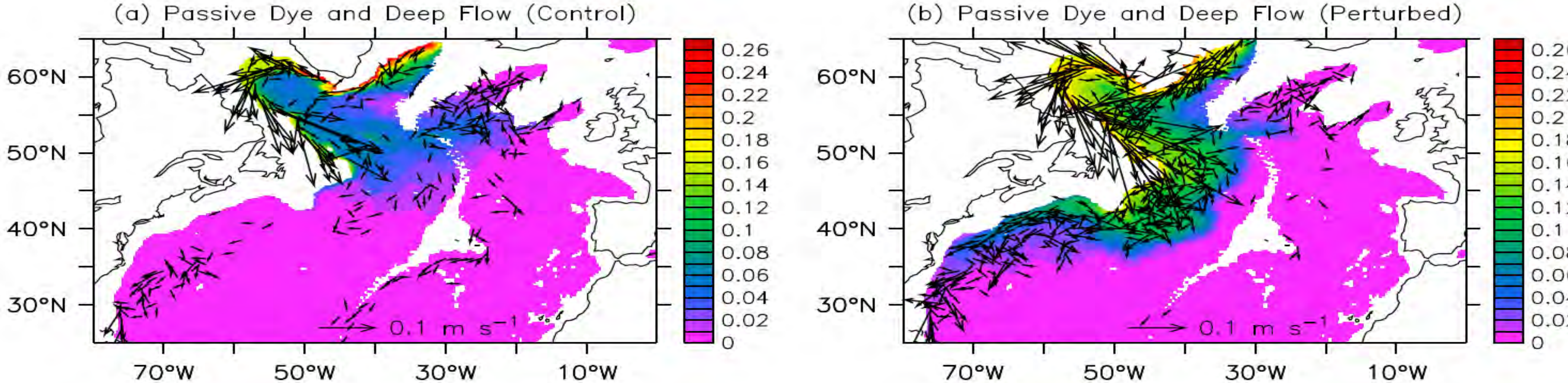
Eddy Kinetic Energy from Satellite Records and Models

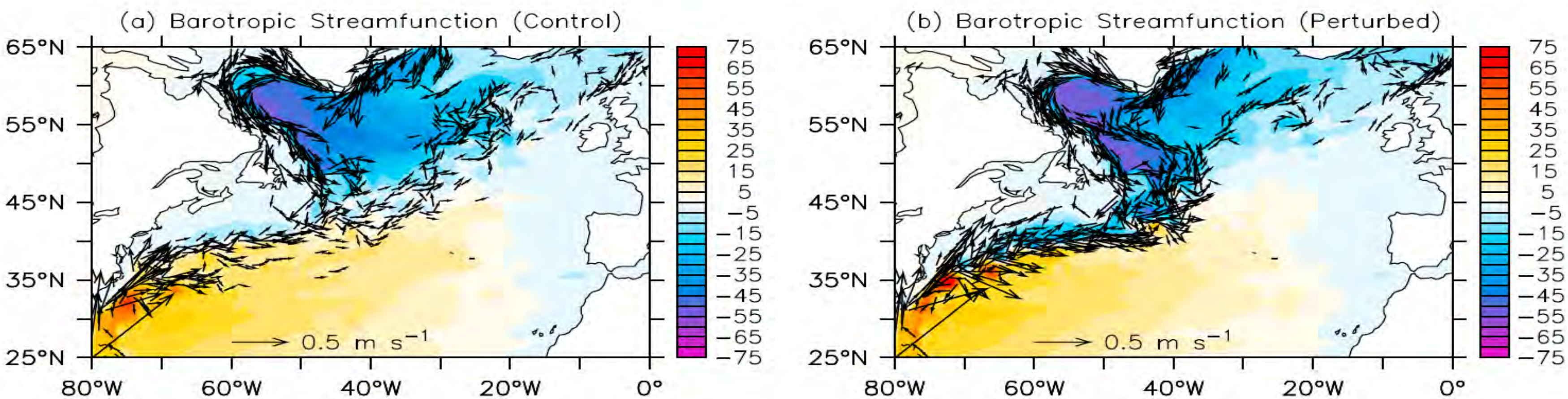


Log scale, units: $cm^2\ s^{-2}$

Nordic Sea Overflow and Subpolar Gyre

The high resolution global coupled model (GFDL CM2.5) shows that a stronger/weaker Nordic Sea overflow leads to a contracted/expanded subpolar gyre (Zhang et al 2011), consistent with the relationship indicated by sediment core records of the last millennium from Iceland Basin (Moffa Sanchez et al 2011) .

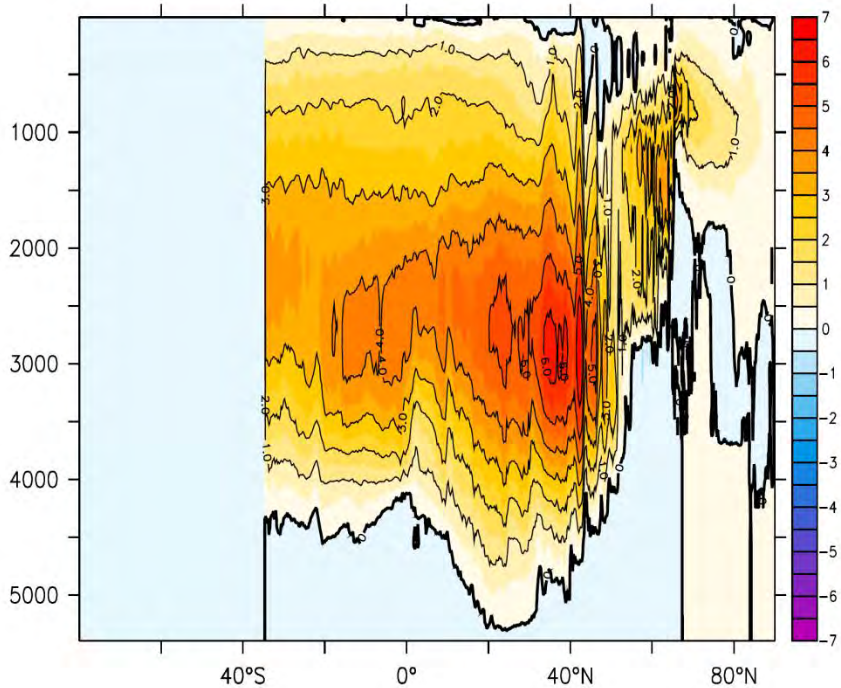




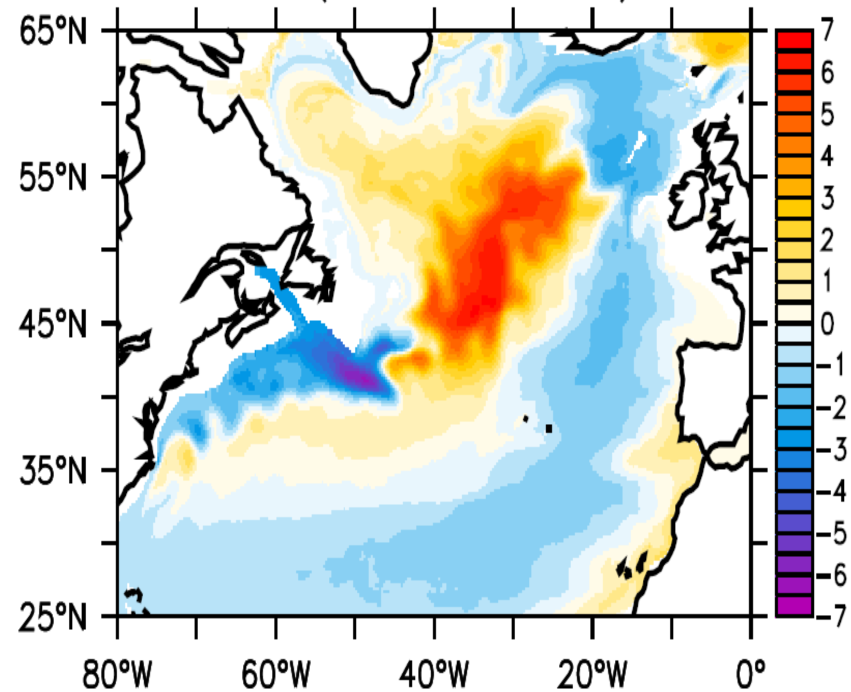
Weaker Overflow and expanded subpolar gyre (SPG)

Stronger Overflow and contracted subpolar gyre (SPG)

AMOC (Perturbed –Control)

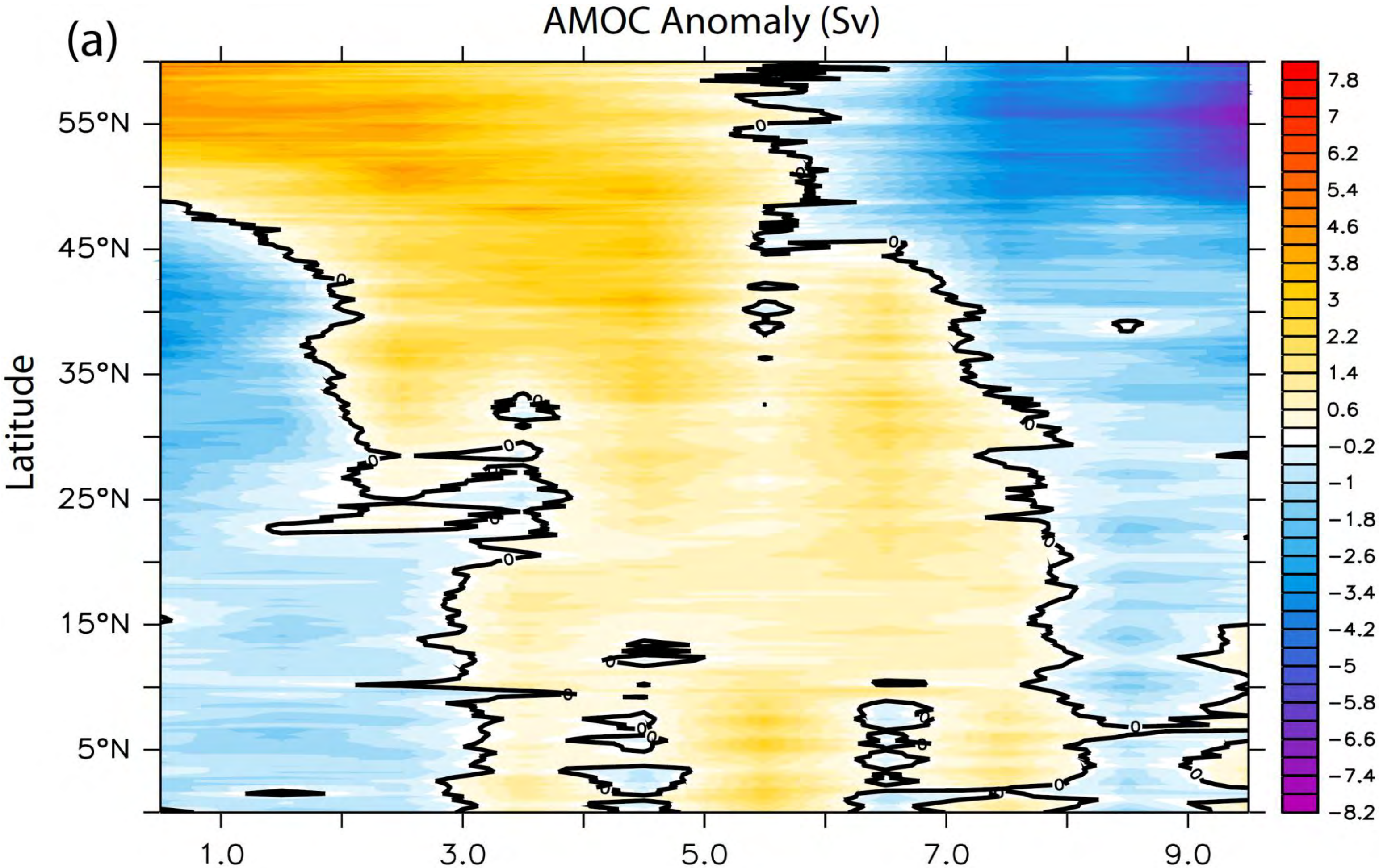


Tsub (Perturbed – Control)



The high resolution global coupled model (GFDL CM2.5) shows that a stronger and deeper-penetrating Nordic Sea overflow leads to a stronger and deeper AMOC, a westward shift of the North Atlantic Current (NAC), and a southward shift of the Gulf Stream, and a similar dipole pattern in the subsurface temperature as that found in the coarse resolution model.

AMOC Anomaly between perturbed and control experiments as a function of latitude



The AMOC anomaly at subtropics lags changes at high latitudes by several years due to the slow advection adjustment, similar to that in coarse resolution model.

Summary

- Simulated global synchronization of abrupt climate change due to the AMOC collapse is consistent with that indicated by paleo records. The response includes a southward shift of the ITCZ in both the Atlantic and the Pacific, and weakening of the Indian and East Asian summer monsoons. Ocean dynamics is important for amplifying the tropical Pacific response. When coupled with a slab ocean, the tropical Pacific response is much smaller.

- Observational analyses and modeling results suggest that the AMO has played an important role in many global and regional scale multidecadal climate fluctuations during the 20th century. In particular, a central impact of AMO is to alter the position of ITCZ.

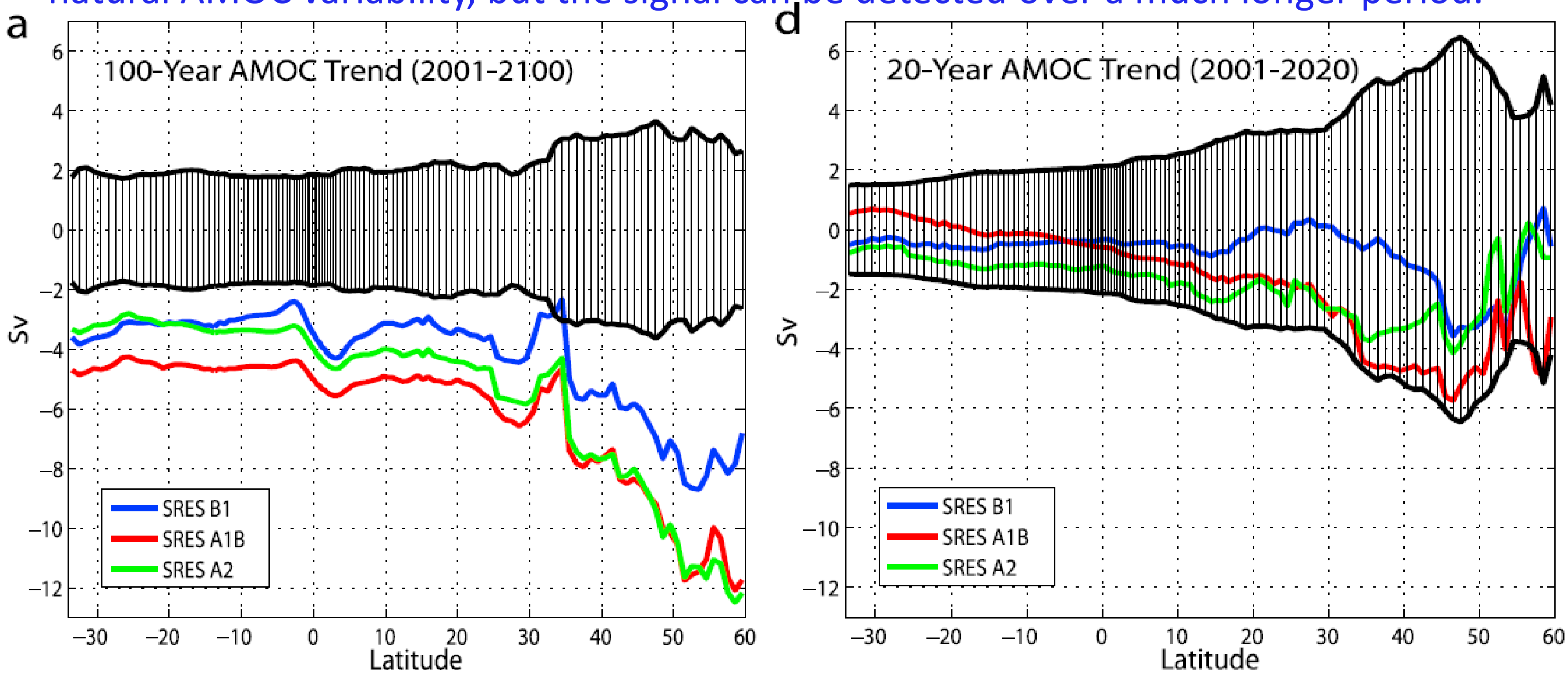
- The origin of the observed 20th century AMO is highly debated, due to the complication of anthropogenic forcings. Independent AMOC fingerprints have been identified, using variables such as altimetry SSH, subsurface temperature, and bring new evidence that the observed AMO are indeed linked to AMOC variations.

•The AMOC fingerprints (SSH/Tsub) could be used for reconstructing AMOC variations in the past and monitoring AMOC variations in the future. Observed fingerprints of AMOC variability show that the AMOC was stronger during the 60's and the recent decade, and weaker during the 70's and 80's.

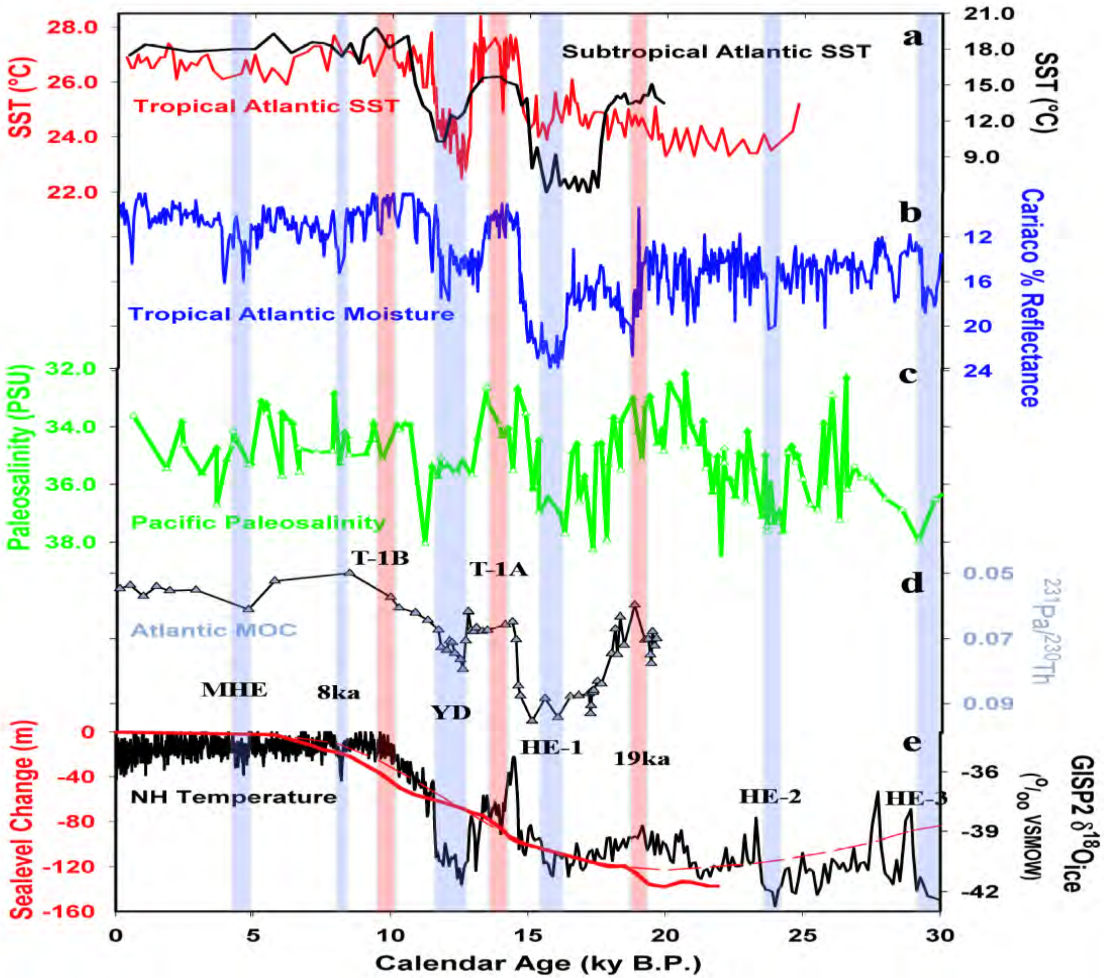
•Due to the existence of interior pathways, AMOC variations propagate with the slow advection speed, resulting in a much longer time lead (several years) between subpolar and subtropical AMOC variations. The longer time lead provides a more useful predictability.

•The high resolution global coupled model (GFDL CM2.5) shows that a stronger and deeper-penetrating Nordic Sea overflow will lead to a contracted/expanded subpolar gyre (SPG), a stronger and deeper AMOC, westward shift of the North Atlantic Current (NAC), southward shift of the Gulf Stream, warmer SST east of Newfoundland, and colder SST south of the Grand Banks.

Over the 21st century, in response to the increasing greenhouse gases, the AMOC weakens most at northern high latitudes. For the first 20 years, the simulated AMOC weakening under anthropogenic forcing can not be distinguished from that induced by natural AMOC variability, but the signal can be detected over a much longer period.



Areas covered with thin black lines represent the range of AMOC trends expected from natural AMOC variability



SST from Cariaco Basin and subtropical northeast Atlantic SU8118

Reflectance of Cariaco Basin, ODP 1002

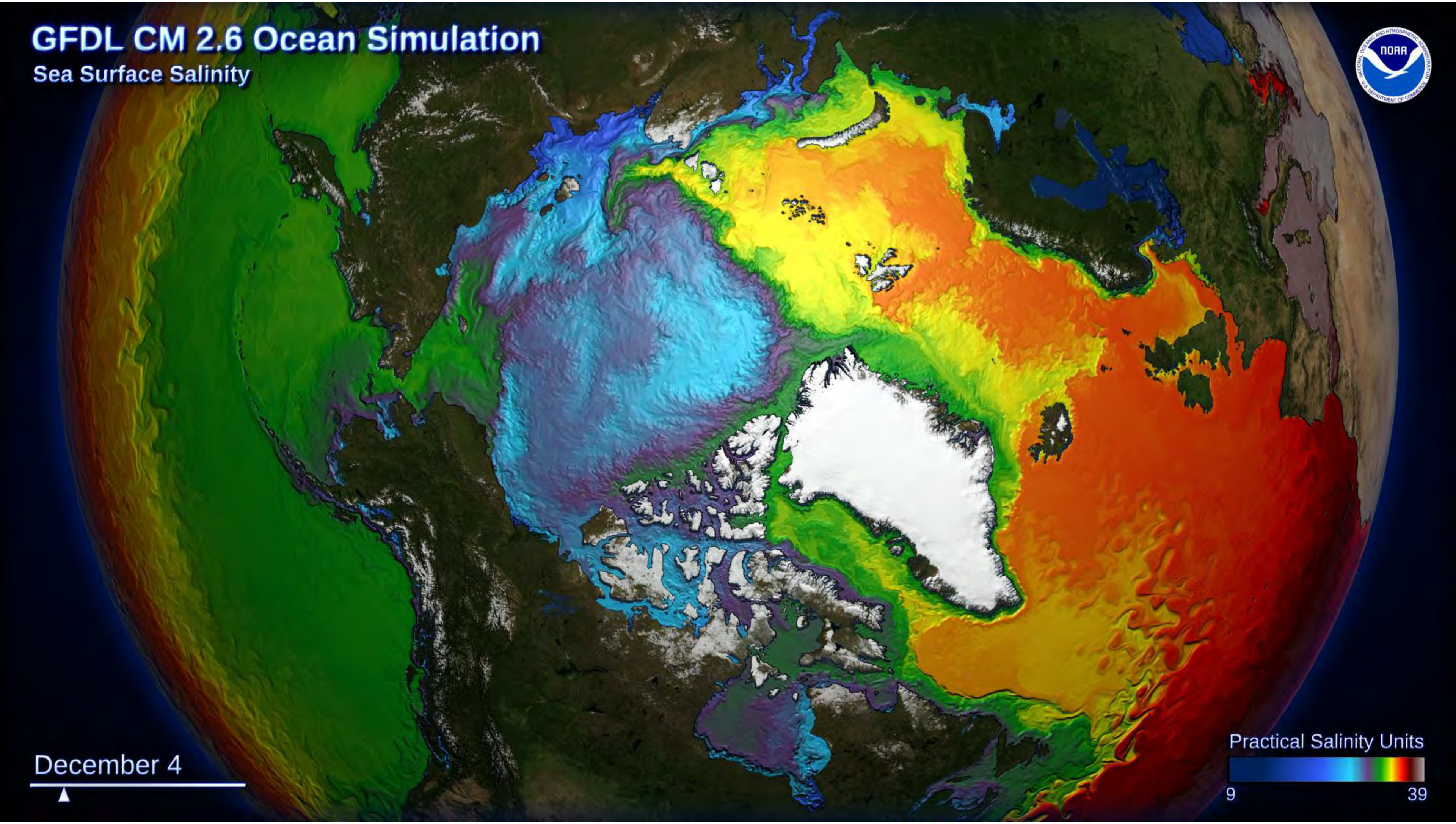
Merged paleosalinity estimates from ME0005A-43JC and ODP 1242

AMOC from Bermuda Rise

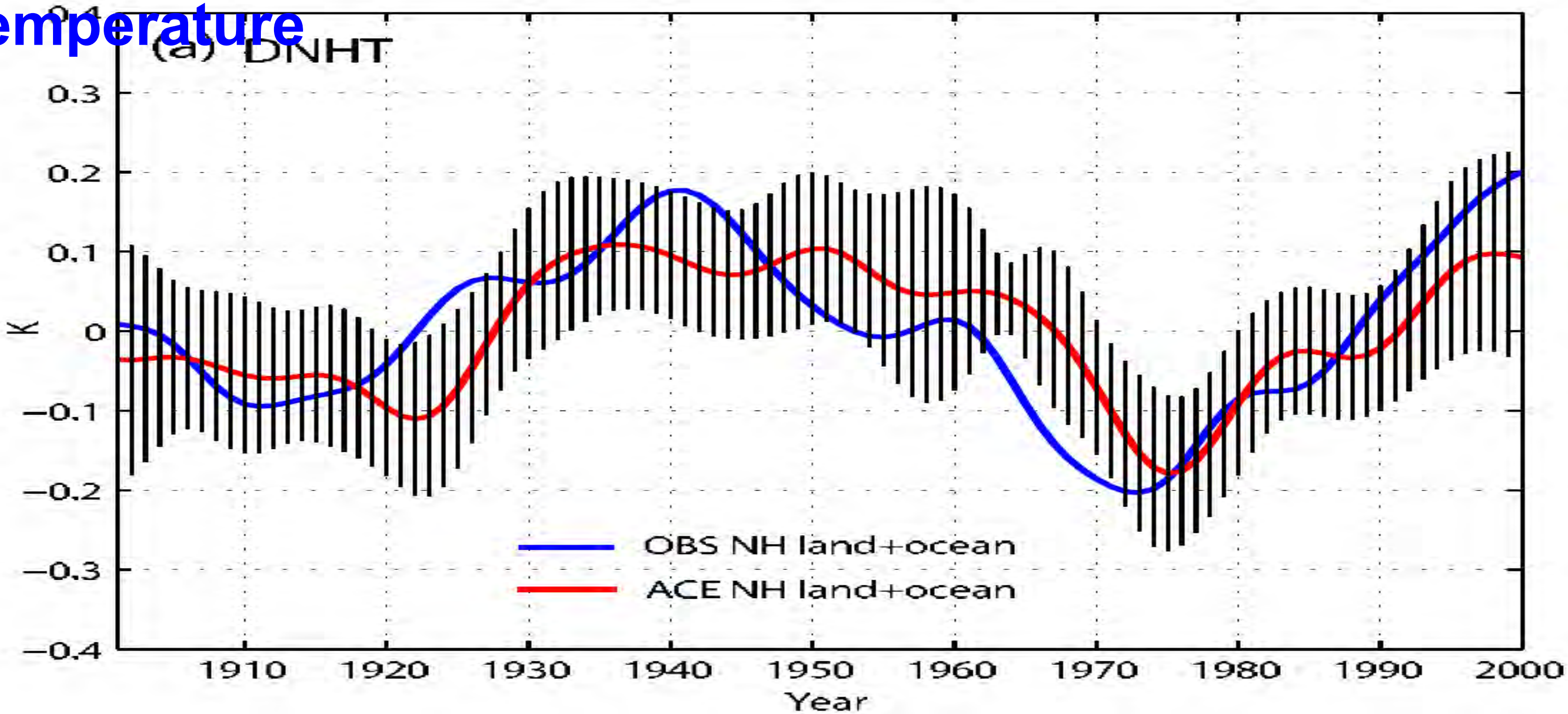
GISP2 ice core record and sea level curves

Drying conditions in the northeastern tropical Pacific west of Central America were synchronous with YD and Heinrich events (Benway et al, 2006)

GFDL Global High Resolution Coupled Model CM2.6

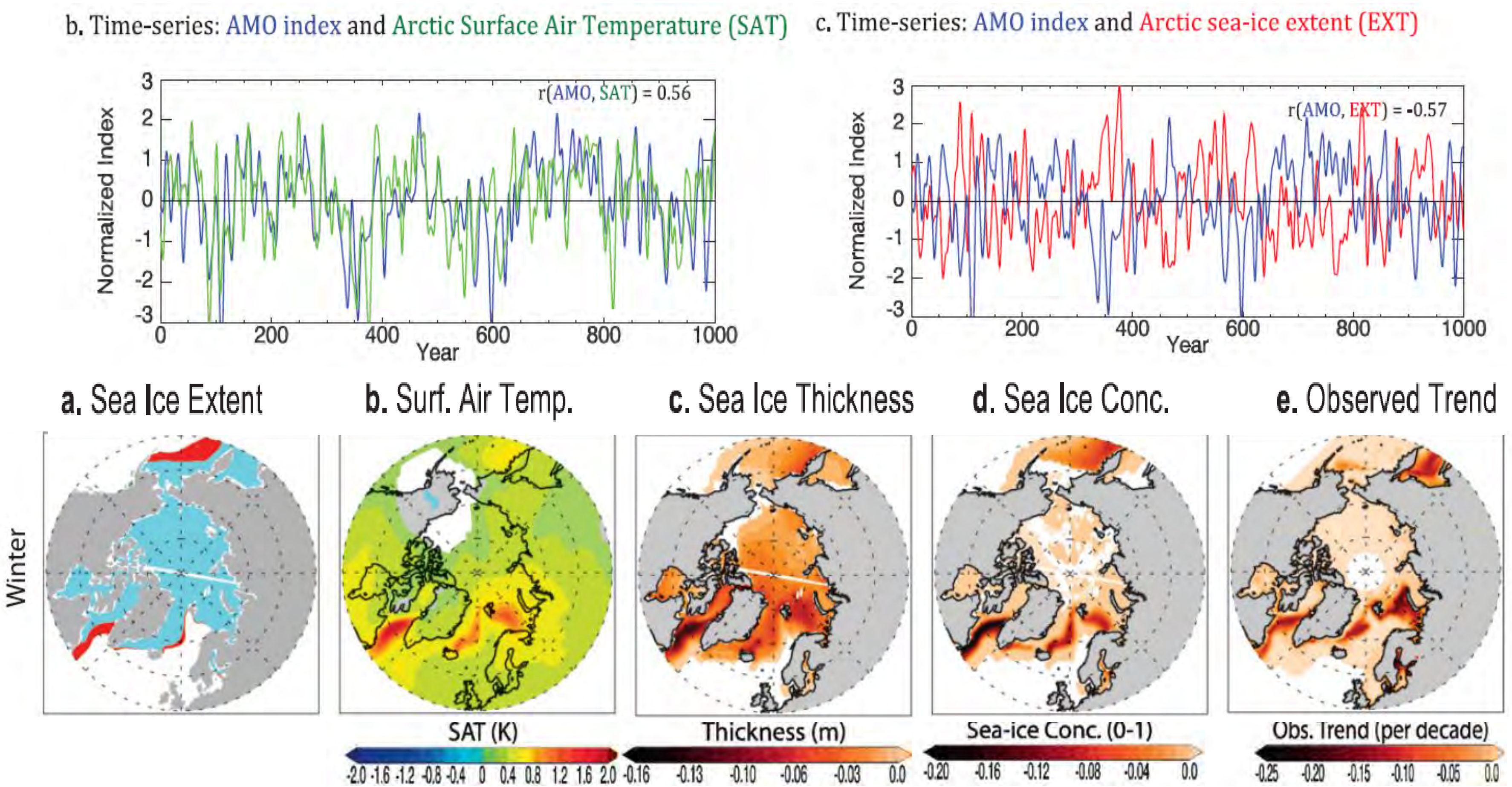


Impact of AMO on Detrended Northern Hemispheric Mean Su Temperature



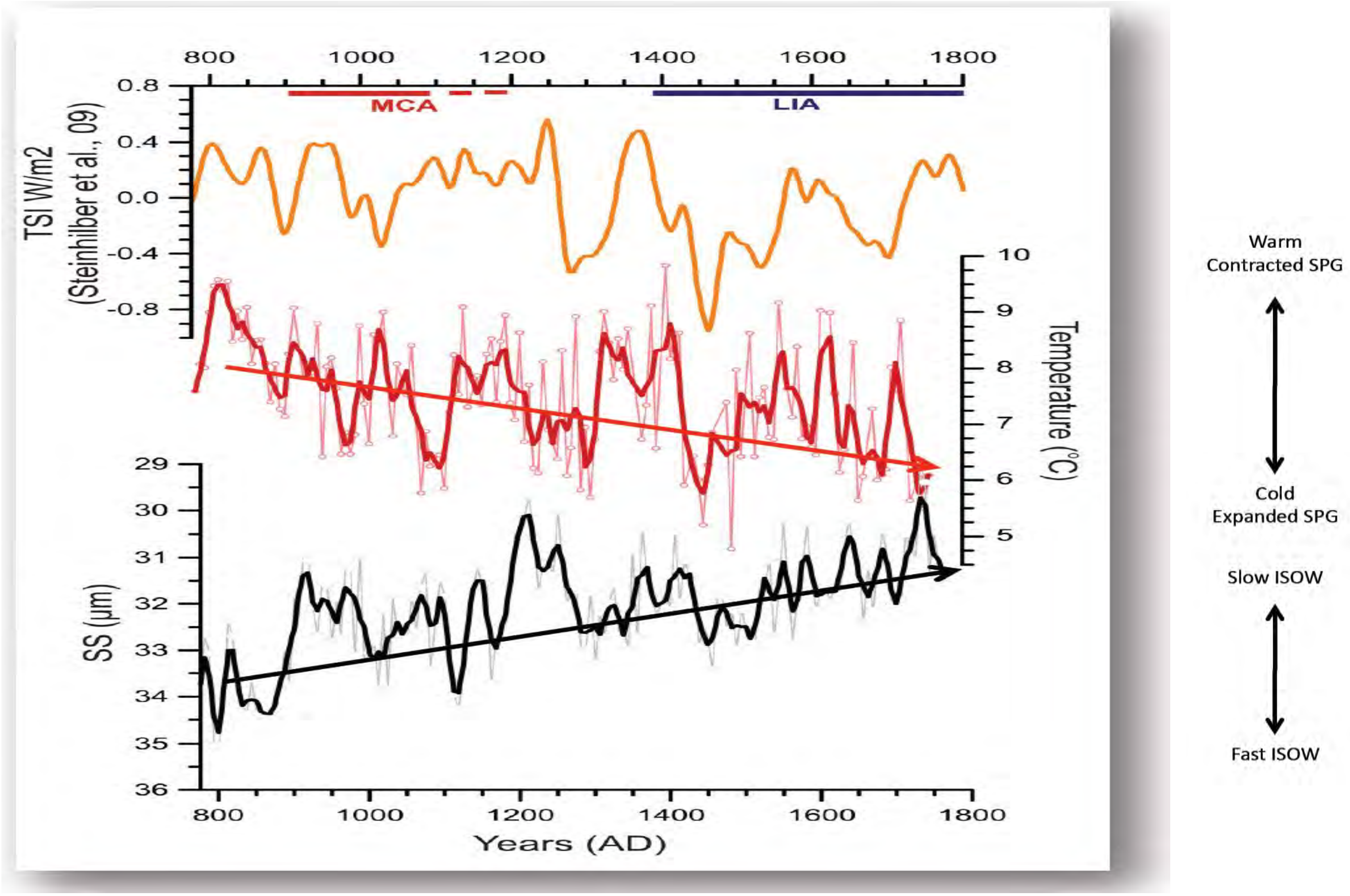
temperature fluctuations, such as the early 20th century warming, the pause in hemispheric-scale warming in the mid-20th century, and the late 20th century rapid warming (Zhang, Delworth, and Held 2007).

Impact of the AMO on Arctic Sea Ice Variations



In the GFDL CM2.1 control simulation, winter Arctic sea ice in the Atlantic side declines with an intensified AMO. The similar spatial patterns suggest a possible role of the AMO in the observed sea ice declining trend in these regions over the recent decades (Mahajan et al. 2011).

Nordic Sea Overflow and Subpolar Gyre



Proxy reconstruction of the last millennium from sediment cores in the Iceland Basin suggest a covariance between SPG and Nordic Sea overflow: expanded SPG-slow overflow; contracted SPG – fast overflow (Moffa Sanchez et al 2011)