Review of AMOC Fingerprints from Models and Observations

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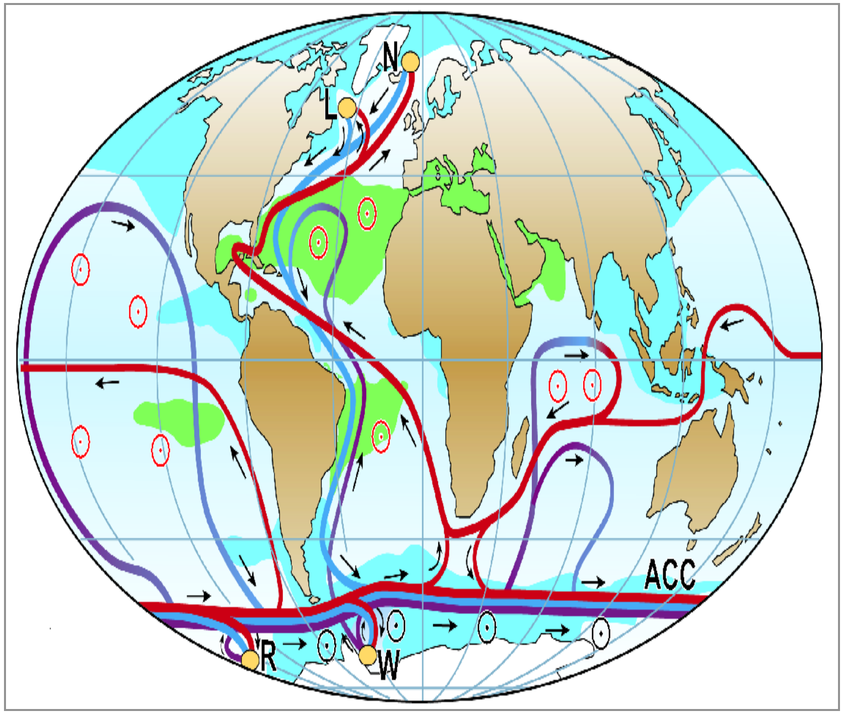
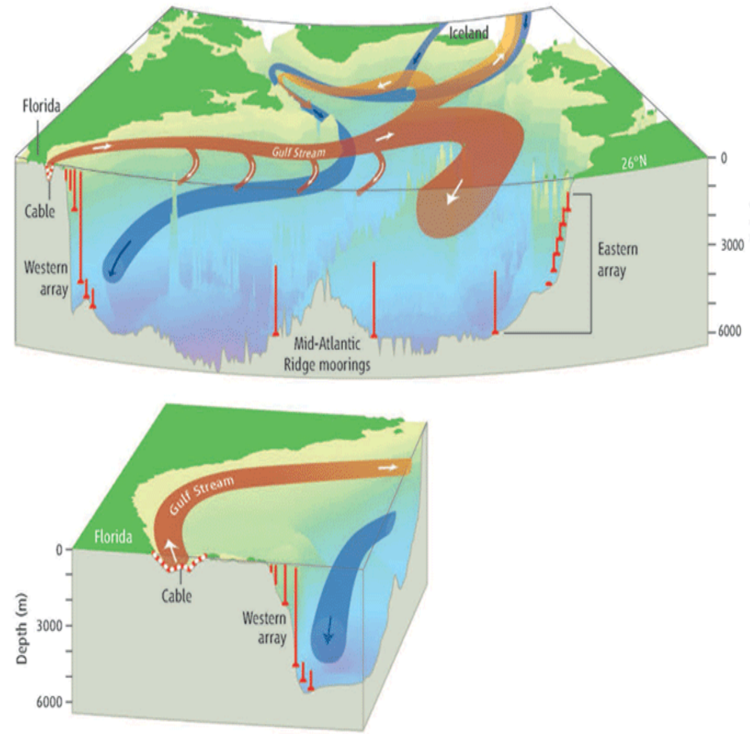
Atlantic Meridional Overturning Circulation (AMOC)





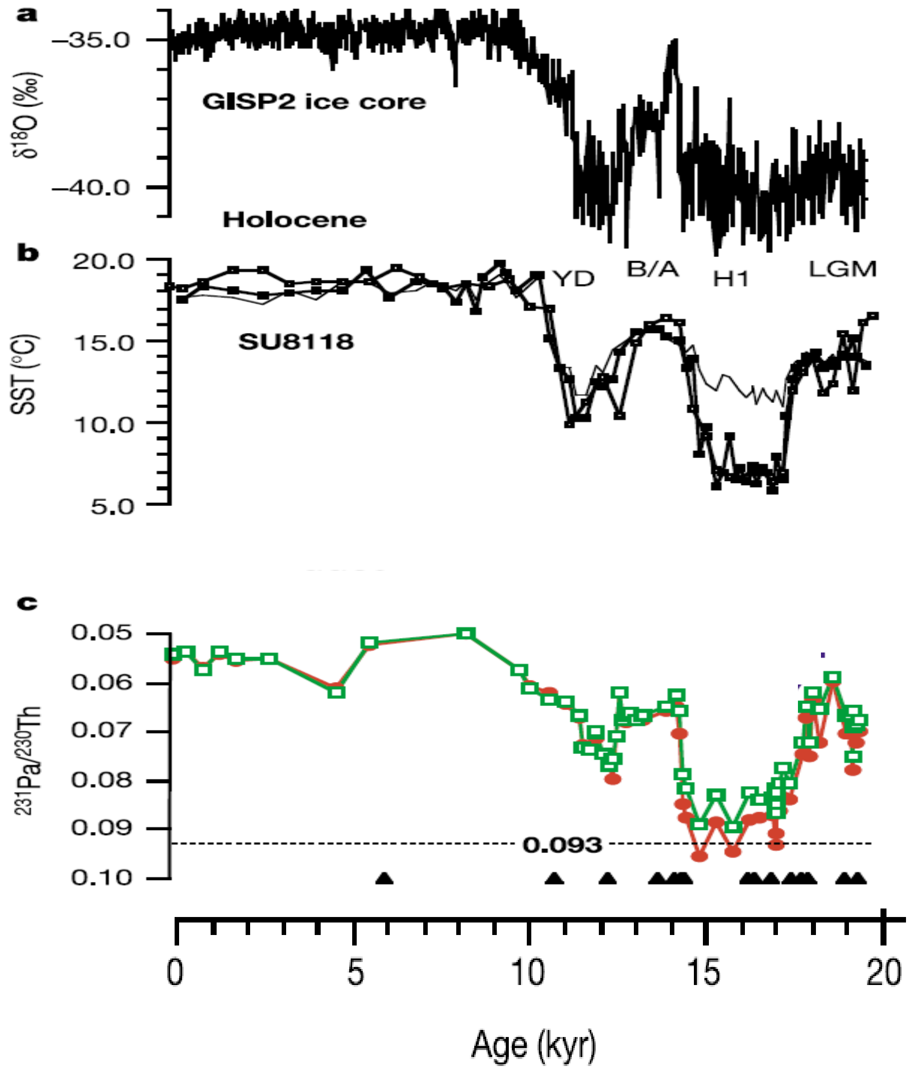
The RAPID program was established since 2004 to monitor AMOC variations at 26.5°N [Cunningham et al. 2007], and provides important information about seasonal and inter-annual AMOC variations. However, much less is known for the low frequency AMOC variations.

Atlantic Meridional Overturning Circulation (AMOC) Fingerprints

- 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.



Greenland ice core record

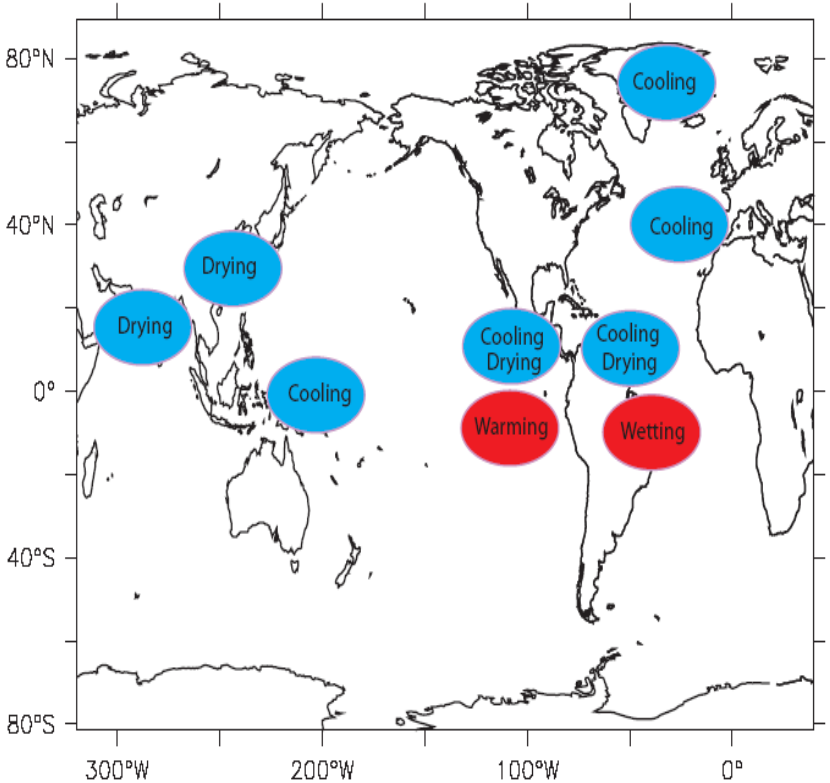
SST from subtropical northeast Atlantic

AMOC change

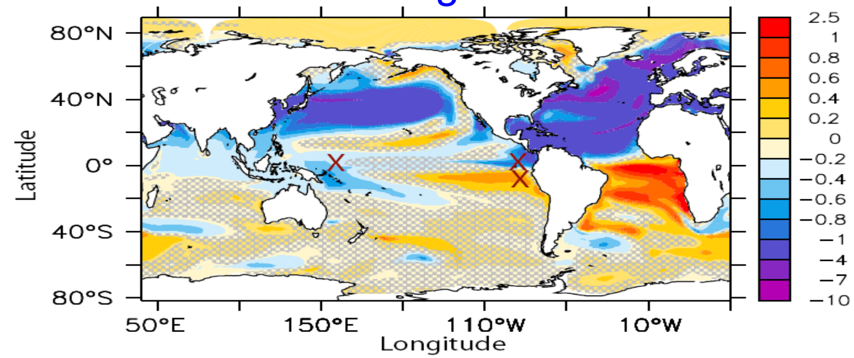
Paleo records from sediment cores in the North Atlantic suggest that the AMOC changes since LGM were coherent with the subtropical North Atlantic SST changes (McManus et al., Nature, 2004)

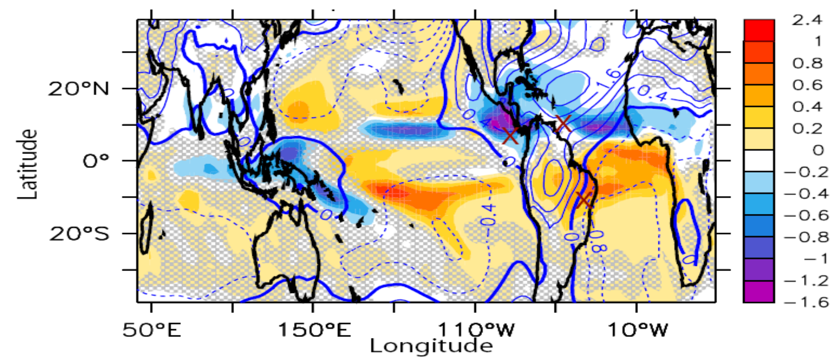
Global Synchronization of Abrupt Climate Change Indicated by Paleo Records is Consistent with Modeled Responses to the Weakening of AMOC

Schematic diagram of paleo records



Modeled SST change due to the weakening of AMOC

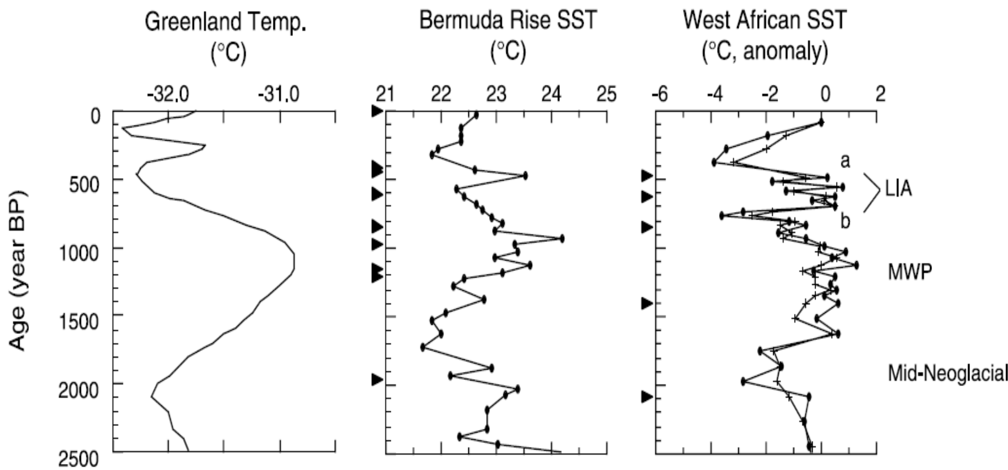




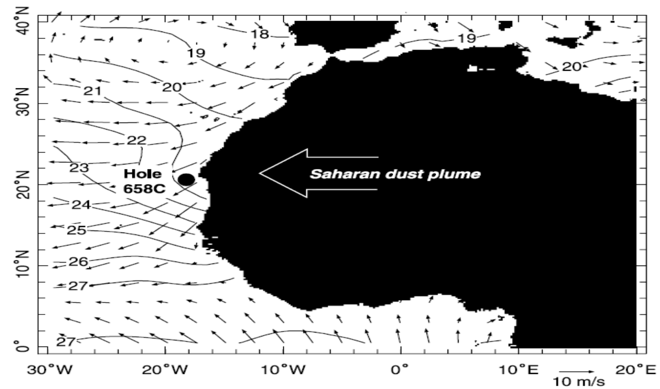
Modeled Precipitation Change due to the weakening of AMOC

Paleo records and modeling results (Zhang and Delworth, 2005) suggest that: Weaker AMOC is linked to a southward ITCZ shift in both Atlantic and Pacific. This inter-hemispheric asymmetry is another signature of AMOC changes.

Holocene North Atlantic Climate Variations

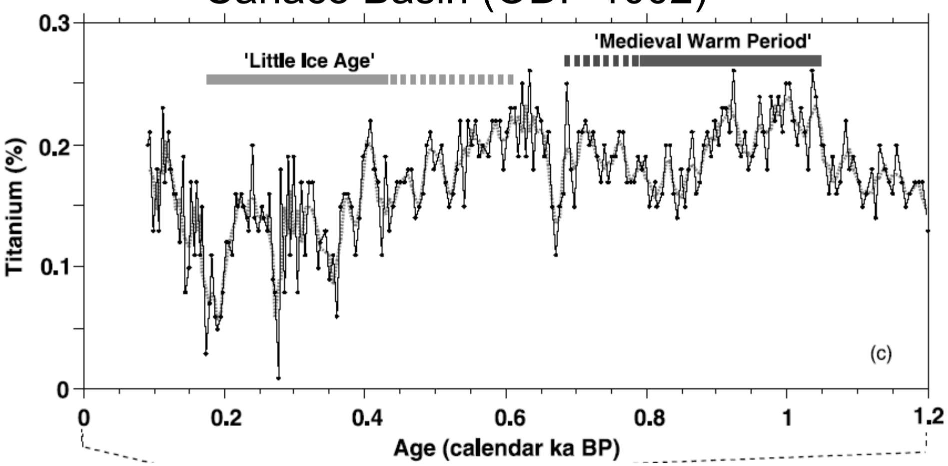


West African SST (ODP 658C)



In-phase link between high- and low-latitude Atlantic climate variations during the Holocene (DeMenocal et al, Science, 2000)

Cariaco Basin (ODP 1002)

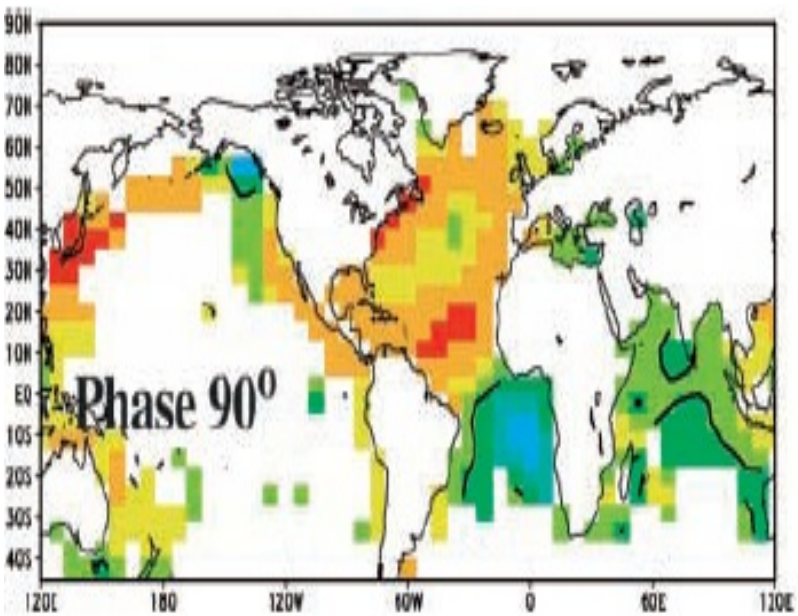


The Atlantic ITCZ shifted southwards during the Little Ice Age and northwards during the Medieval Warm Period (Haug, et al, Science, 2001)

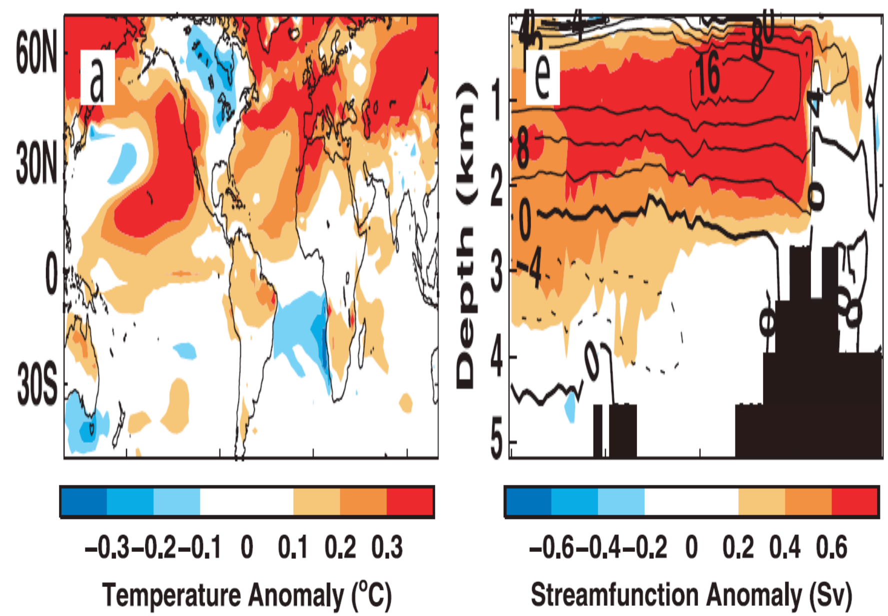
Atlantic Multidecadal Oscillation (AMO)

Proxy reconstructions of past 330 years show a 70-year mode (Delworth and Mann 2000). Instrumental records during the 20th century also show large-scale low frequency variability in the Atlantic SST, i.e. the AMO (Kushnir 1994; Kerr 2000). The observed AMO pattern is similar to simulated SST anomaly induced by the low frequency AMOC variations, implying that the AMO Index can be used to an AMOC fingerprint to reconstruct past AMOC changes (Latif et al. 2004, Knight et al. 2005).

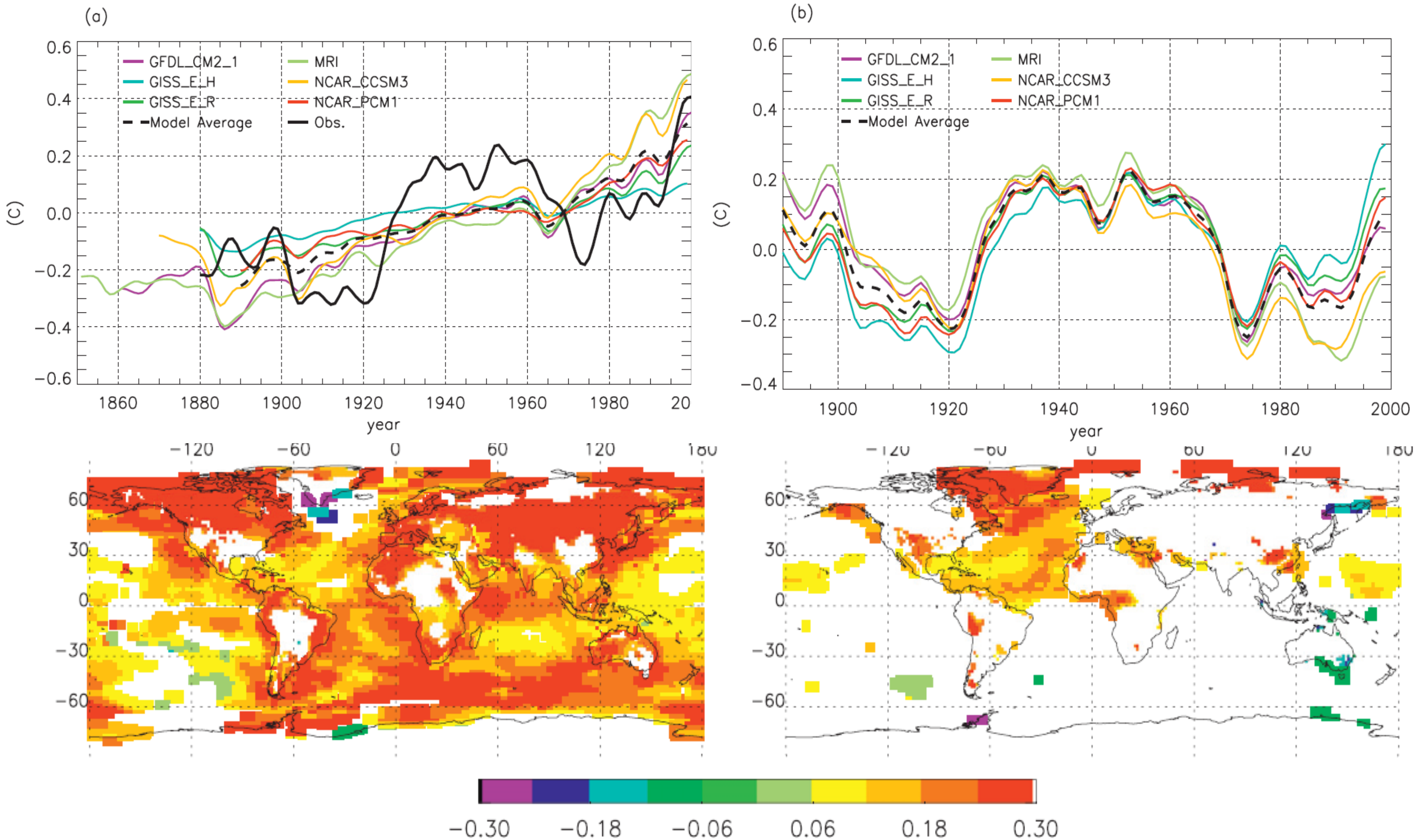
Reconstructed multidecadal SST anomaly (Delworth and Mann 2000)



SST anomalies induced by AMOC variations (Knight et al 2005)



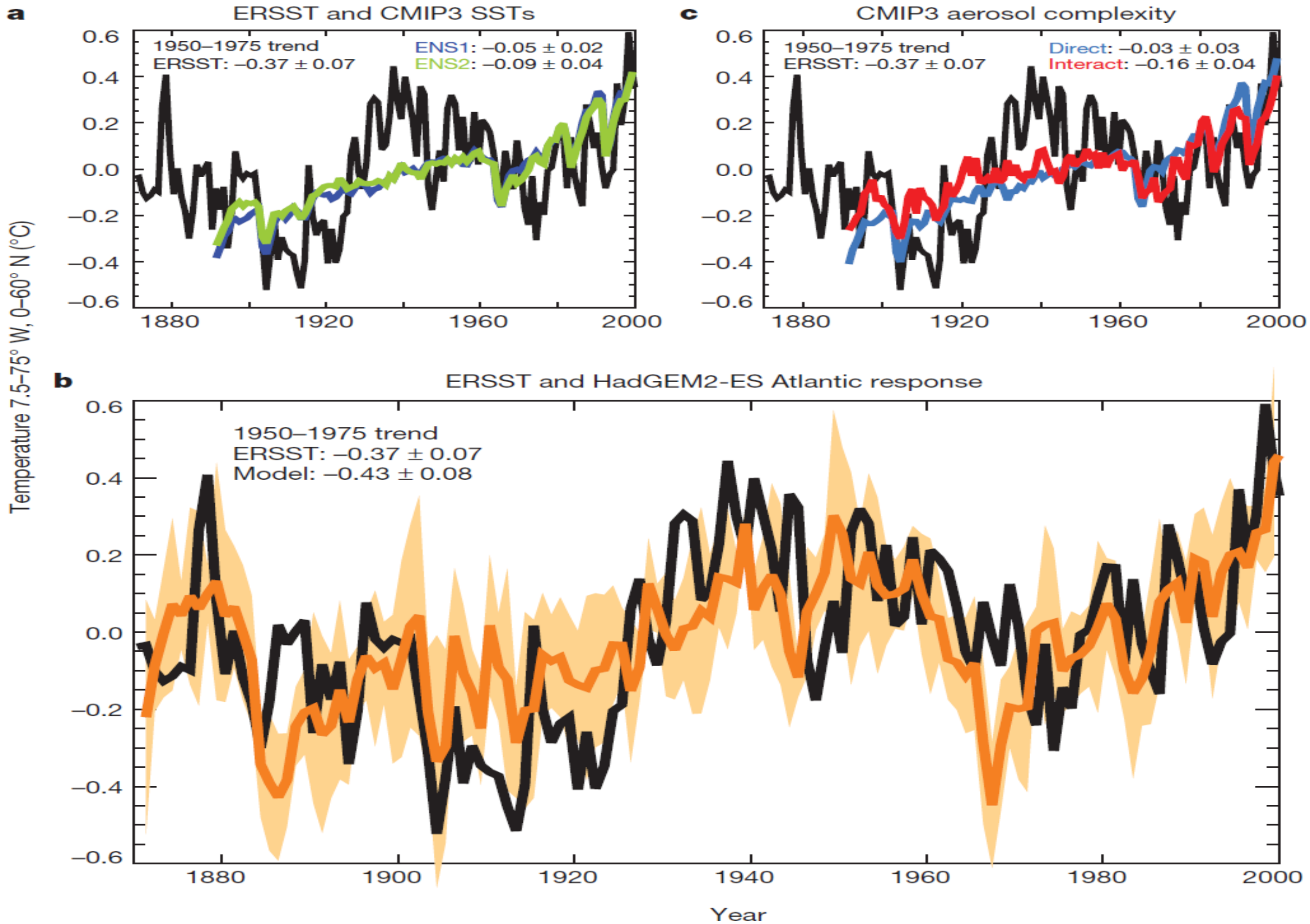
Forced and natural North Atlantic variability using signal-to-noise maximizing EOF analysis (Ting et al. 2009)



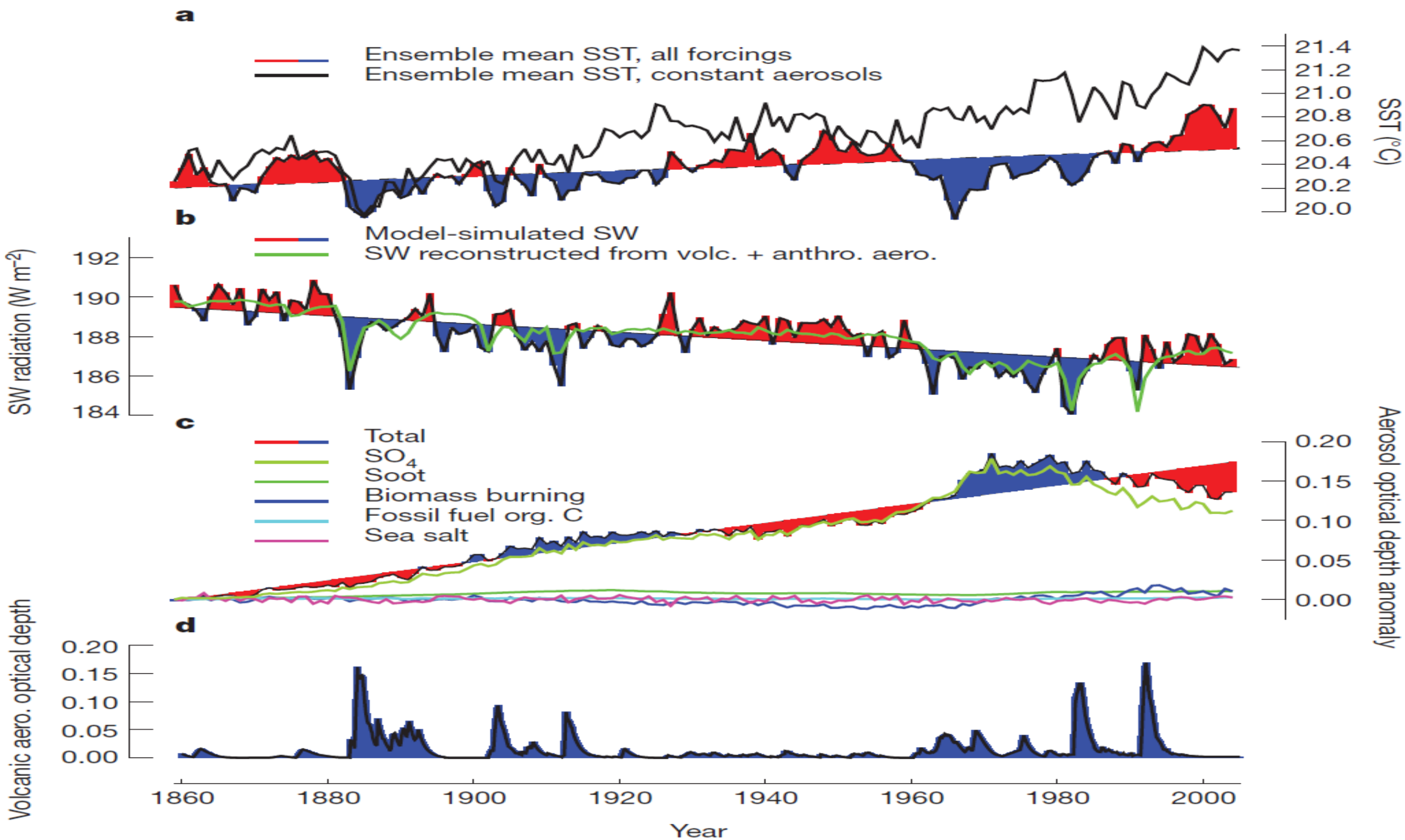
Forced Response

Natural Variability

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

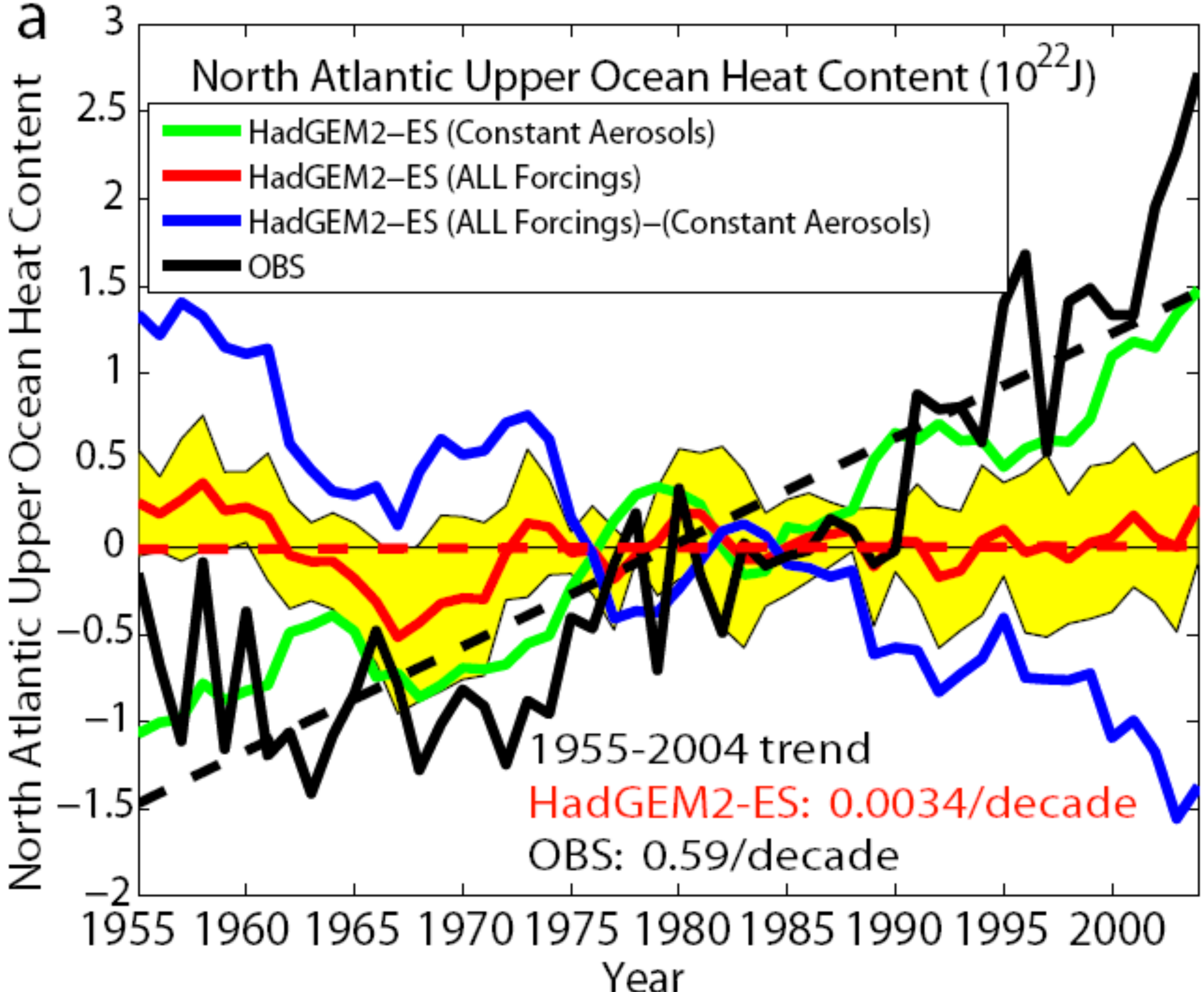


The HadGEM2-ES climate model closely reproduces the observed multidecadal variations of area-averaged North Atlantic sea surface temperature (NASST) in the 20th century.



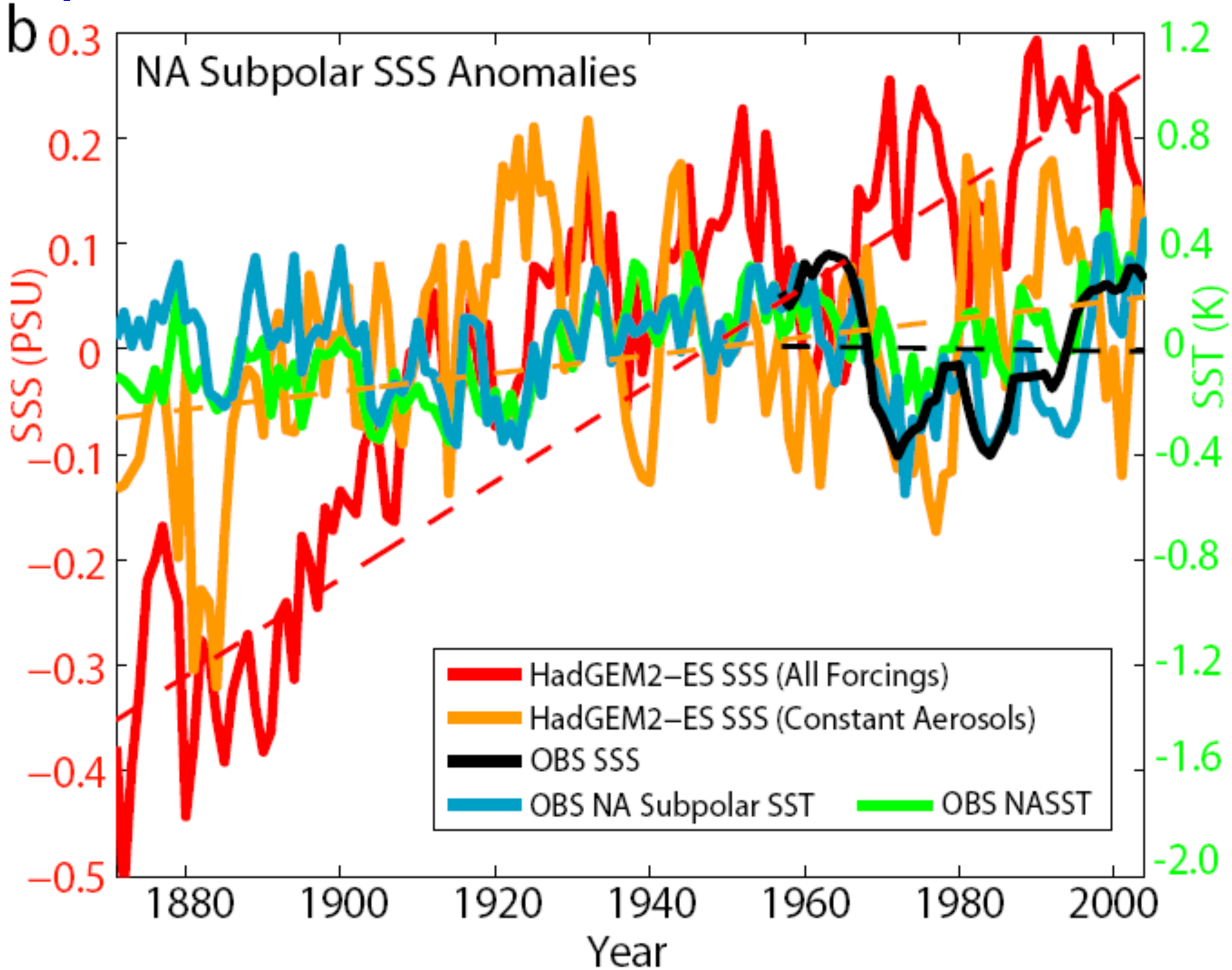
The multidecadal variations simulated in HadGEM2-ES are primarily driven by aerosol indirect effects that modify net surface shortwave radiation (Booth et al. 2012).

Key Discrepancies between HadGEM2-ES Simulations and Observations



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.

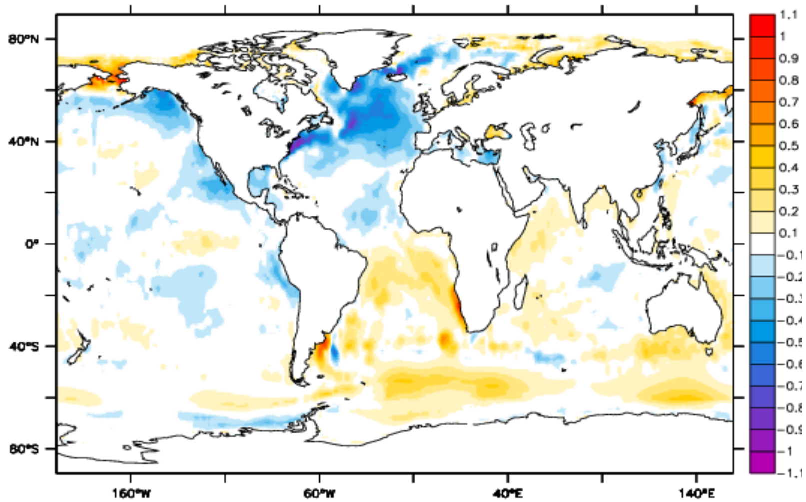
Key Discrepancies between HadGEM2-ES Simulations and Observations



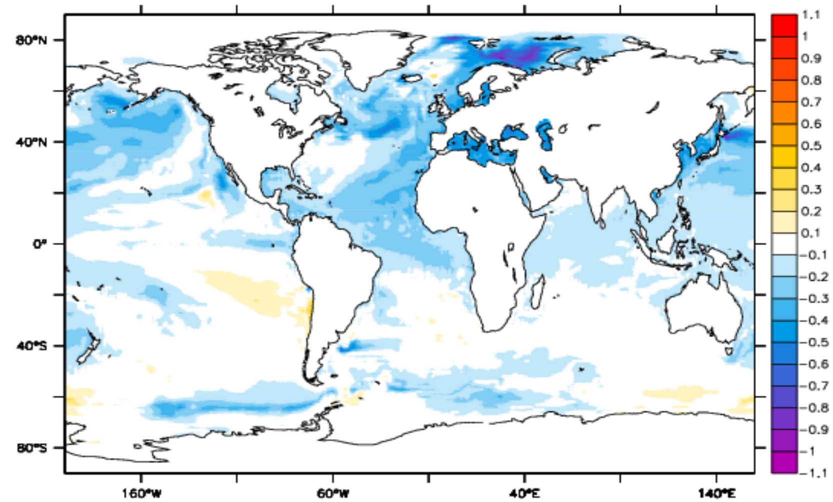
The simulated subpolar NA SSS in HadGEM2-ES shows an unrealistic positive trend, mainly due to the aerosol response. The discrepancies in subpolar NA SSS suggest aerosol effects are strongly overestimated in HadGEM2-ES.

Key Discrepancies between HadGEM2-ES Simulations and Observations

OBS

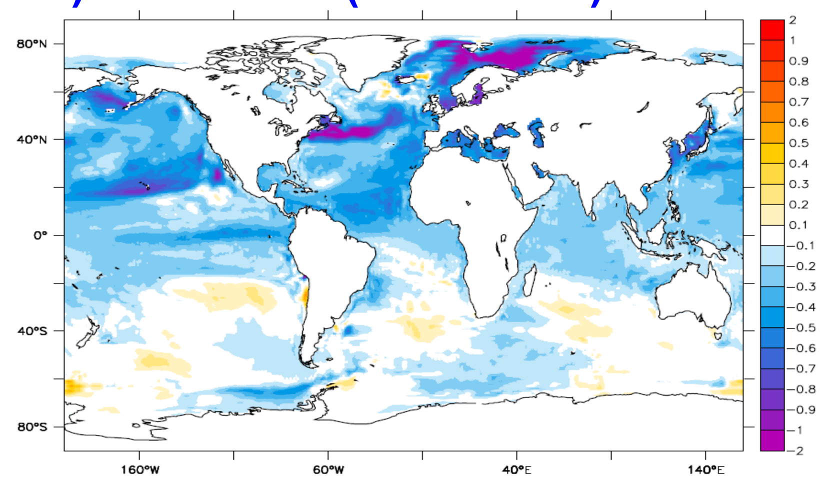


HadGEM2-ES (All Forcings)



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.

The Linkage Between multidecadal NASST variations and AMOC is Highly Debated

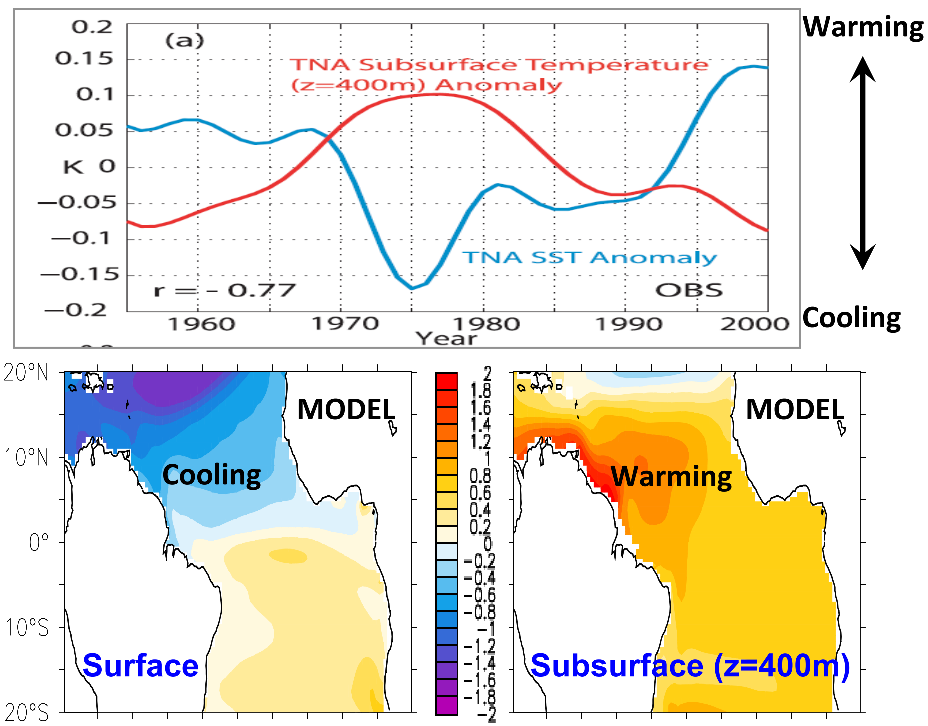
- Some suggested that they are driven by changes in the radiative forcing (Mann and Emanuel, 2006; Booth et al. 2012).

- 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; Ting et al. 2012).

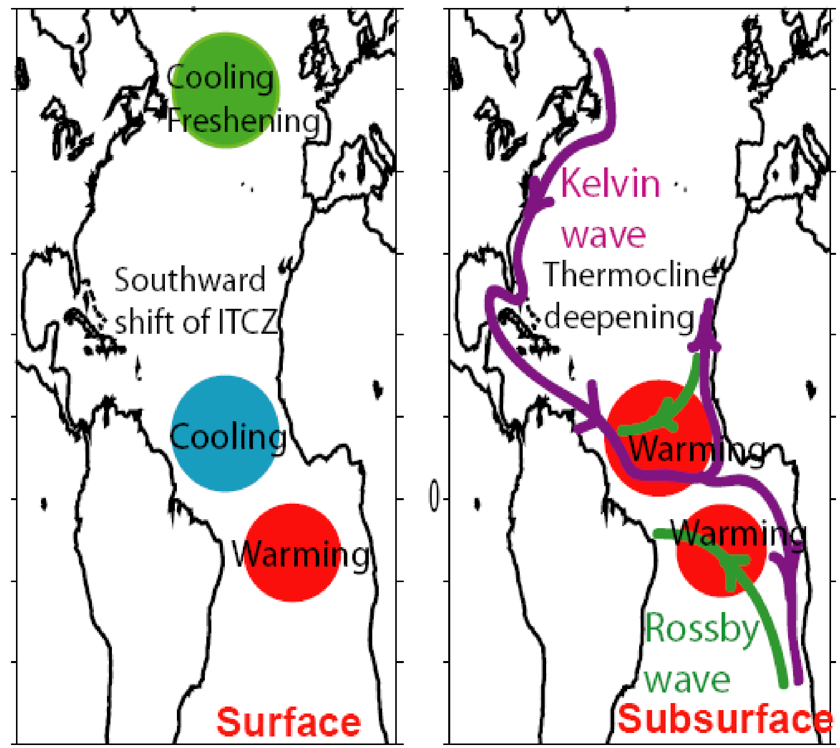
- Reconstruction AMOC variability using fingerprints are crucial for understanding the origin and the attribution of NASST variations.

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 coupled model simulations, indicating observed TNA SST fluctuations may be AMOC-related (Zhang 2007).

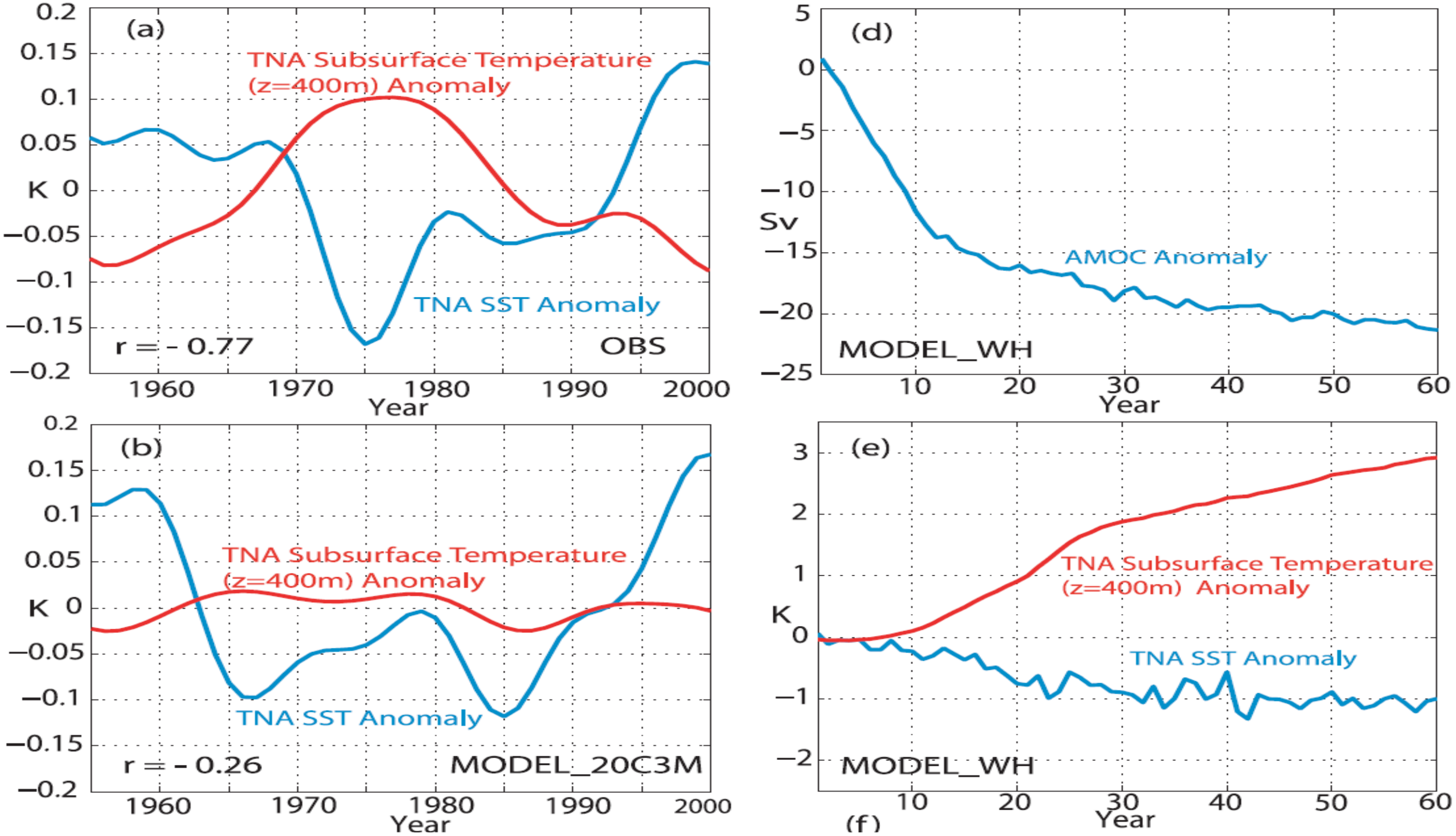


Ocean temperature anomaly due to the weakening of AMOC from GFDL CM2.1 water hosing experiment



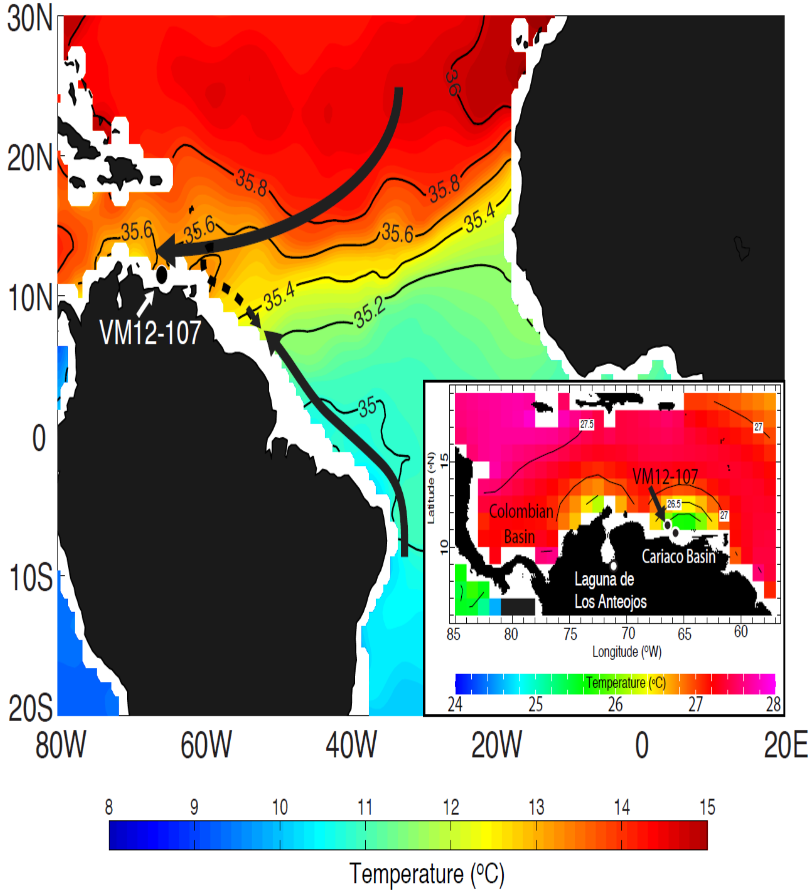
Weakening of AMOC

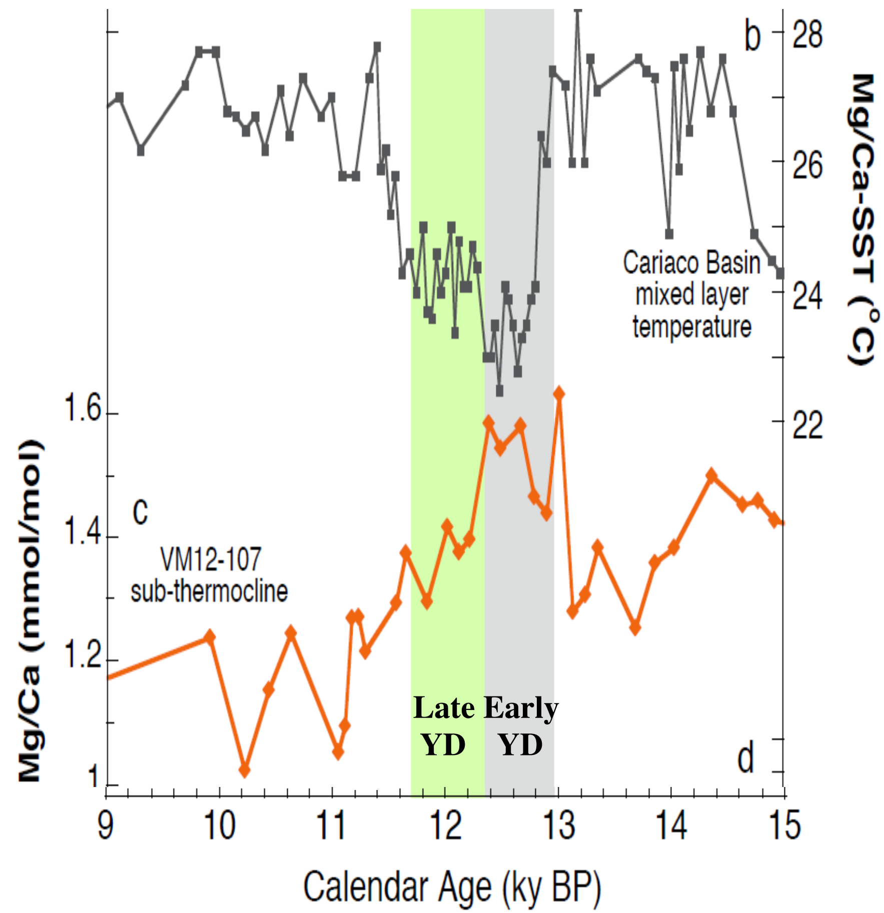
The weakening of the AMOC leads to a southward shift of the Atlantic ITCZ, TNA surface cooling, and thermocline deepening and subsurface warming in the TNA



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).

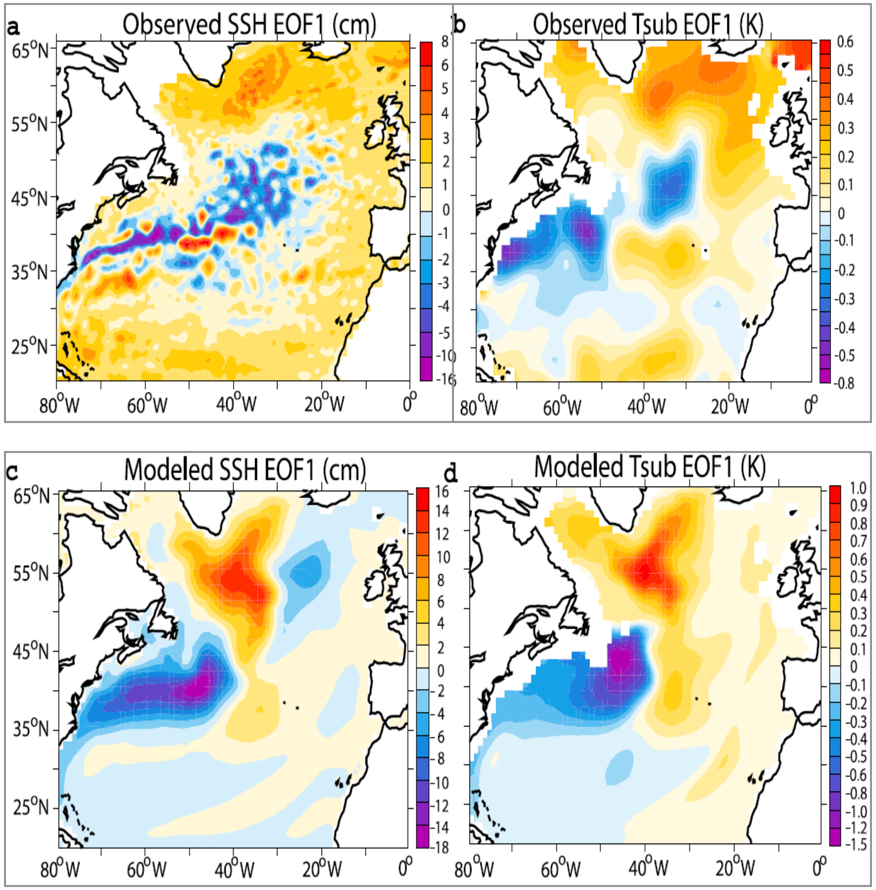
Anticorrelated TNA Surface and Subsurface Temperature



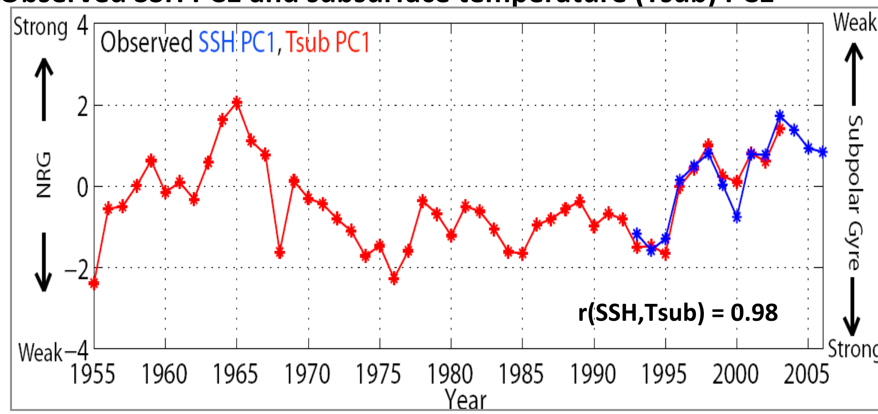


High-resolution temperature records of the last deglacial transition from a southern Caribbean sediment core show that warmer subsurface temperatures correspond to colder surface temperature and weaker AMOC during the Younger Dryas (Schmidt et al. 2012, PNAS, In Press)

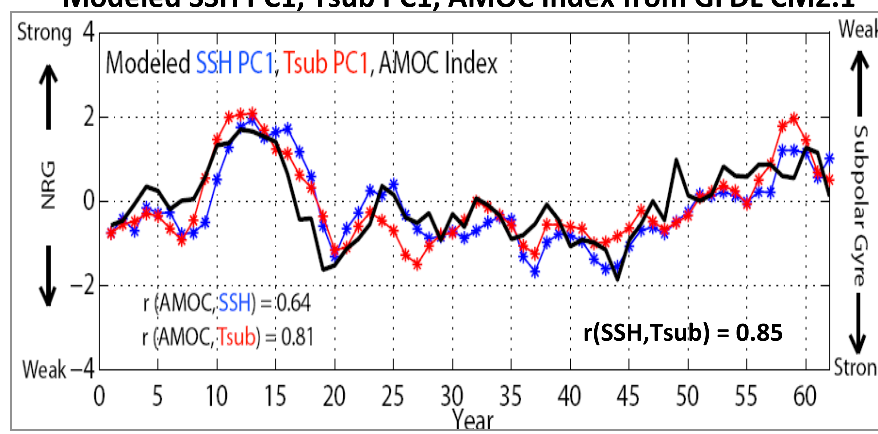
Extra-Tropical Fingerprint of AMOC variations



Observed SSH PC1 and subsurface temperature (Tsub) PC1

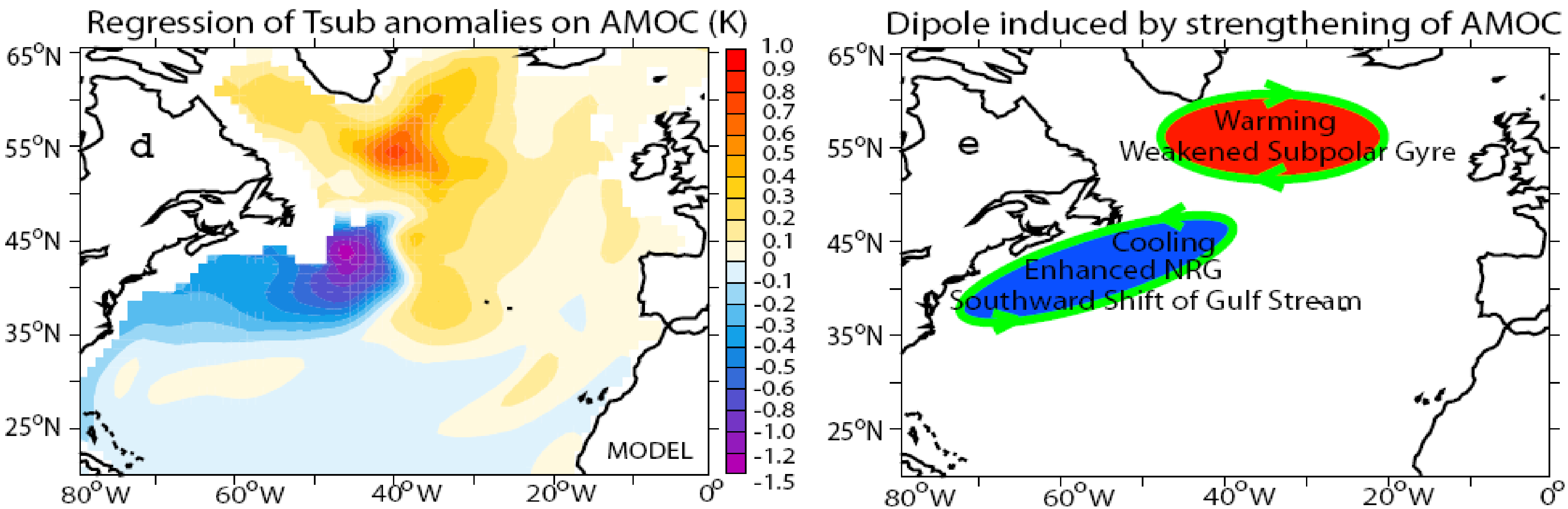


Modeled SSH PC1, Tsub PC1, AMOC Index from GFDL CM2.1



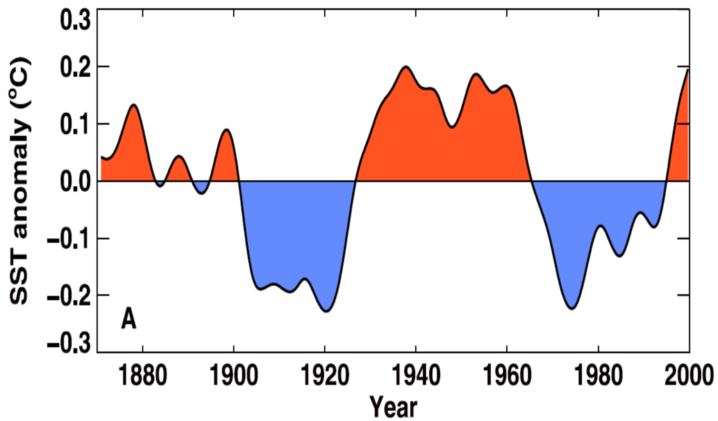
The leading modes of SSH and subsurface temperature (Tsub) constitute a fingerprint of AMOC variations, and might be used as a AMOC proxy. It indicates that during the 60's and the recent decade, the AMOC was stronger, and the recent slowdown of the subpolar gyre is a multidecadal variation (Zhang 2008).

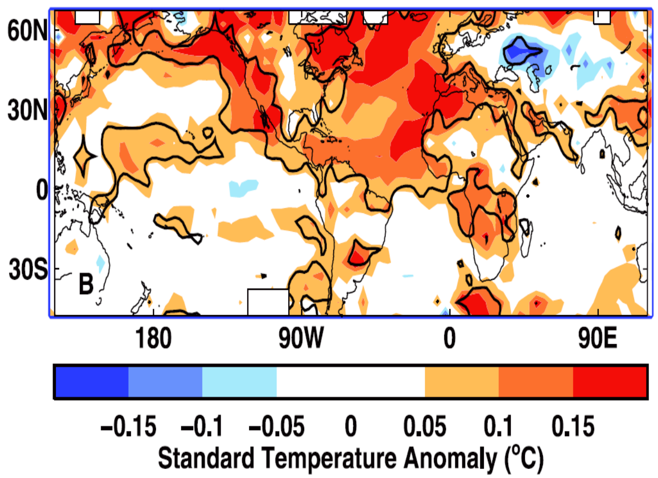
Regressions of Tsub anomalies on the AMOC Index show similar dipole patterns, i.e. warmer Tsub in the subpolar gyre and colder Tsub near the Gulf Stream path when AMOC is stronger.



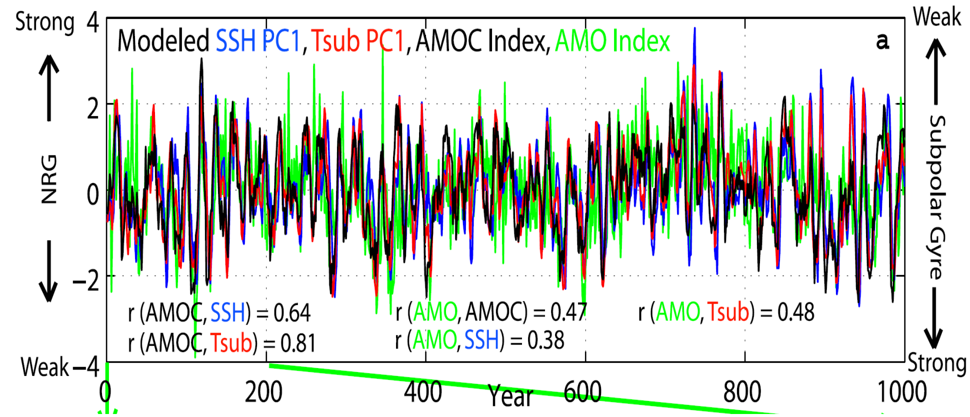
The stronger AMOC is associated with a stronger DWBC, which leads to the strengthening of the cyclonic NRG and a southward shift of the Gulf Stream path, thus leads to cooling/ decreased SSH. The enhanced AMOC lags stronger deep convection in the Labrador Sea or in the Nordic Sea by several years. When denser deep current propagates into south and east of Greenland a few years later, it increases the vertical stratification thus reduces mixed layer depth in the subpolar gyre, resulted in a weakening of the subpolar gyre and thus warming/increased SSH.

Indirect verification using AMO

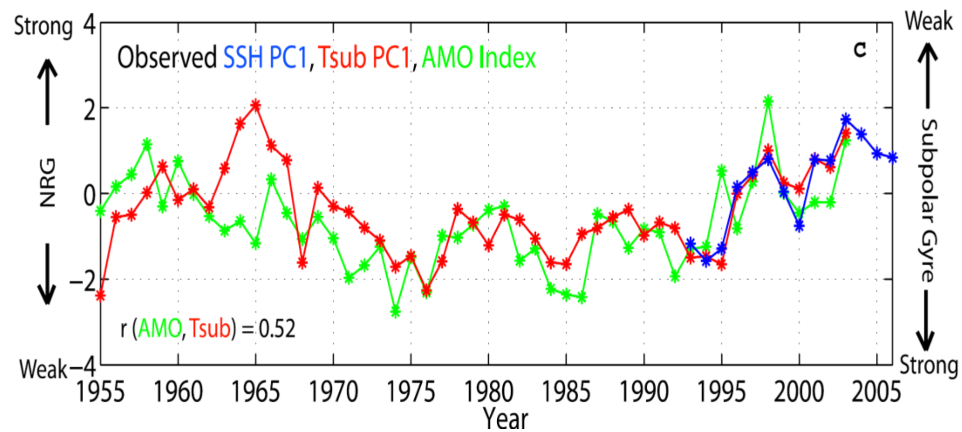




Modeled AMO Index has significant correlations with modeled AMOC Index, Tsub PC1, SSH PC1.

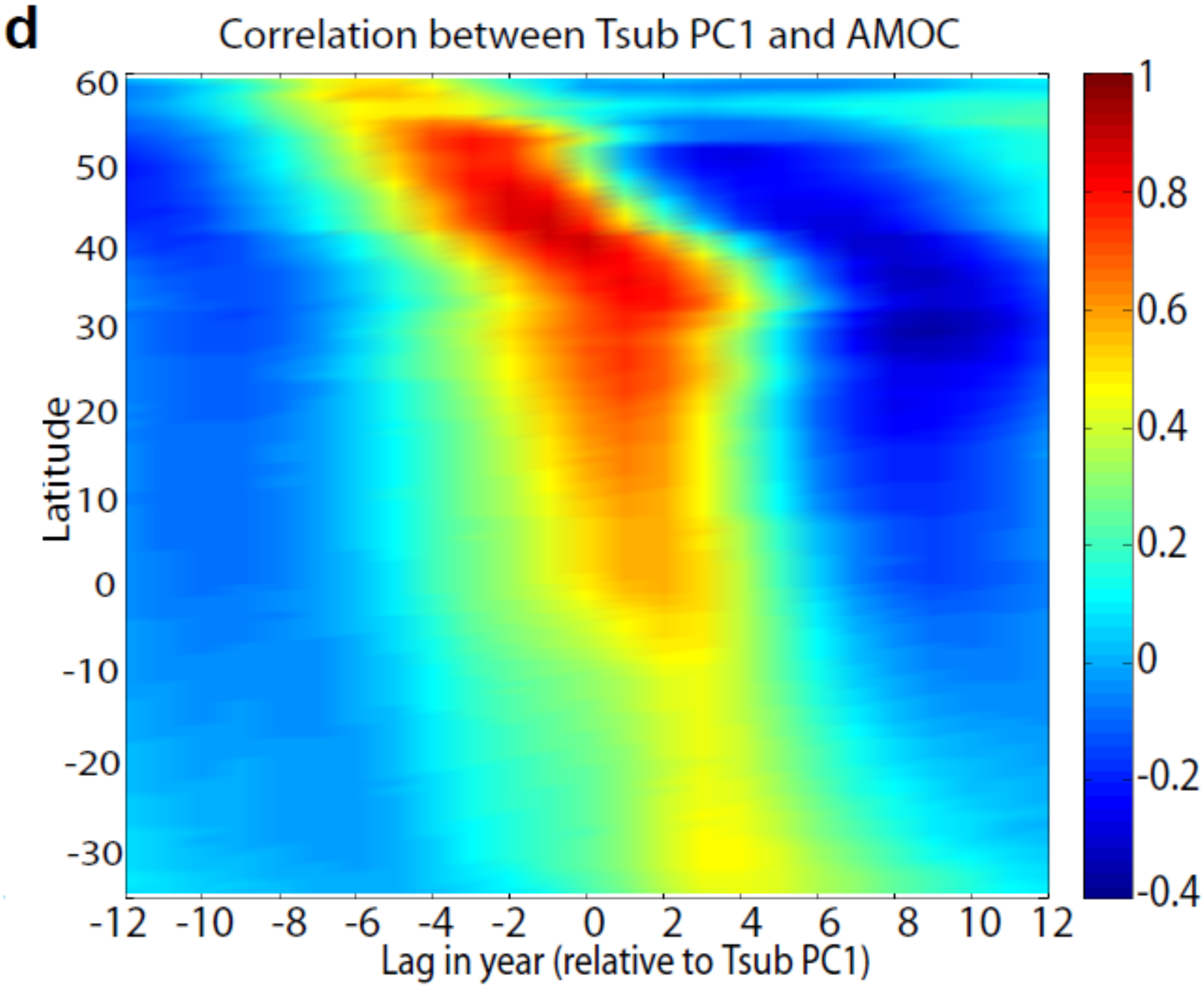


Observed AMO Index has significant correlations with observed Tsub PC1for 1955–2003



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

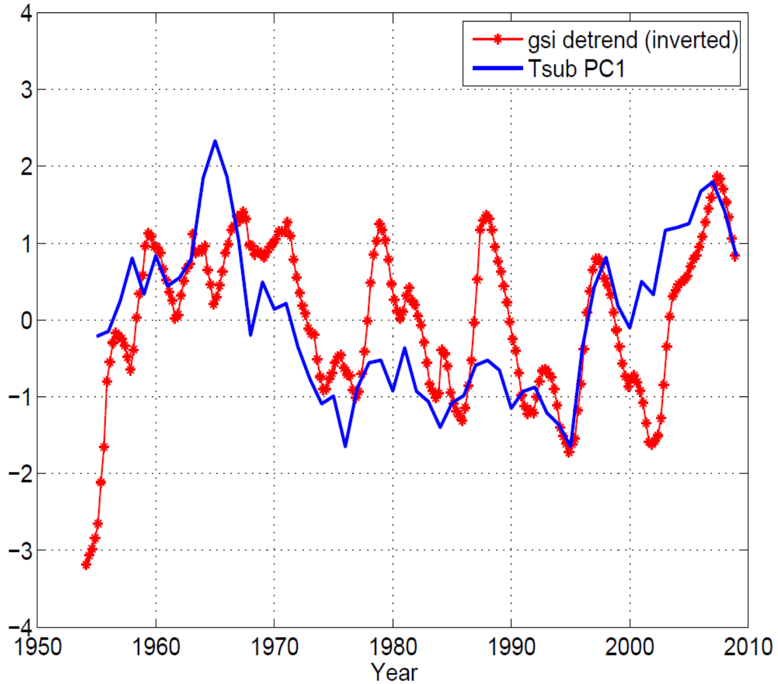
Cross Correlation between the AMOC Fingerprint (Tsub PC1) and AMOC Variations at Various Latitudes (Zhang, 2010)

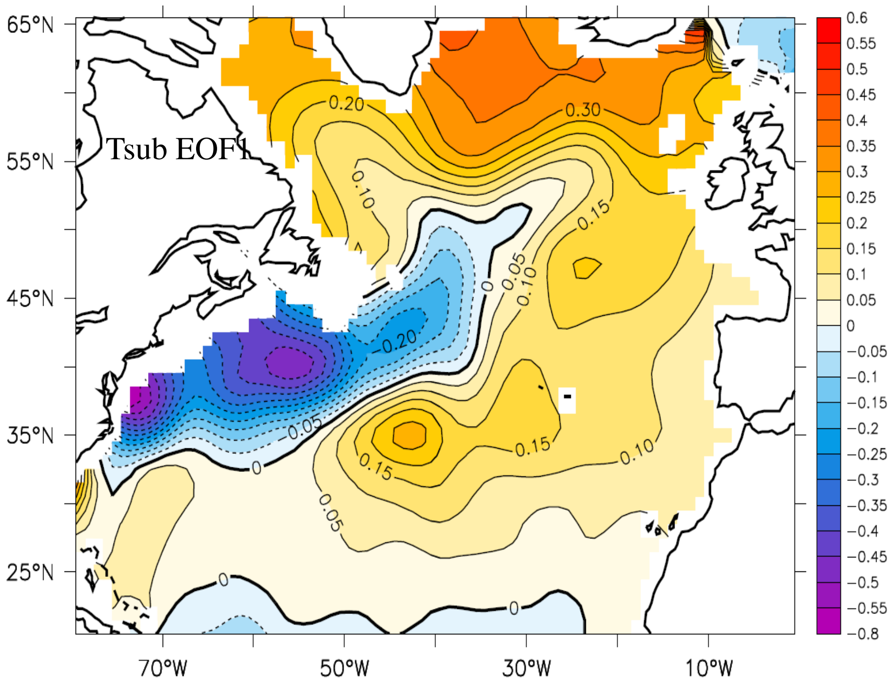


GFDL CM2.1 Control Simulation

AMOC and Western Boundary Currents

Gulf Stream path and Tsub PC1



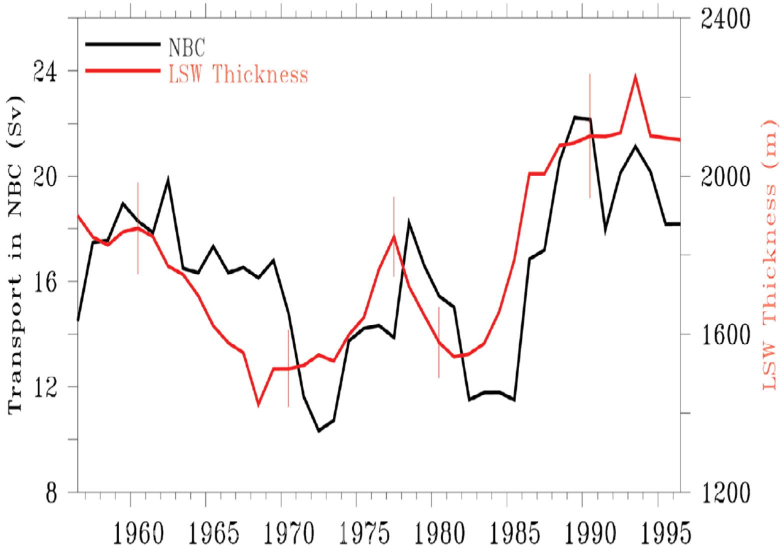


The time series of the leading mode of the observed North Atlantic subsurface temperature at 400m is significantly correlated (r=0.62) at 95% with the ***negative*** of the observed GS path index at 200m *(Joyce & Zhang, 2010).*

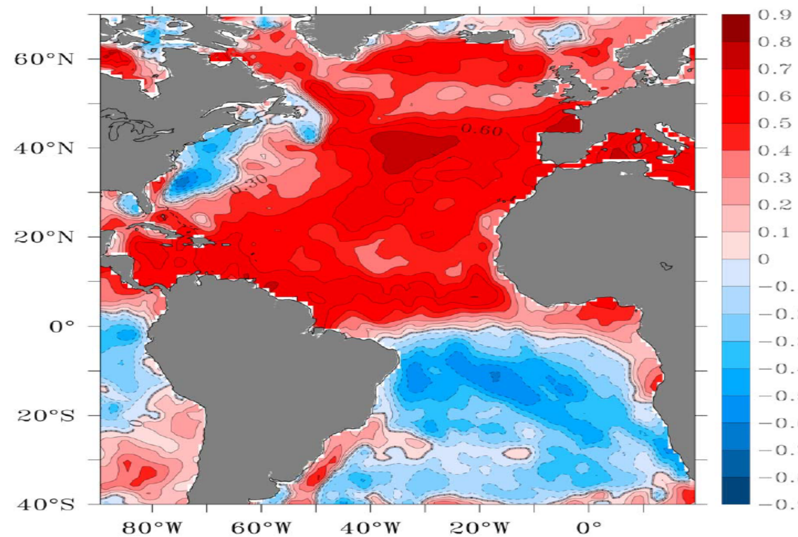
AMOC and Western Boundary Currents

AMOC and North Brazil Current (NBC)

NBC and LSW Thickness



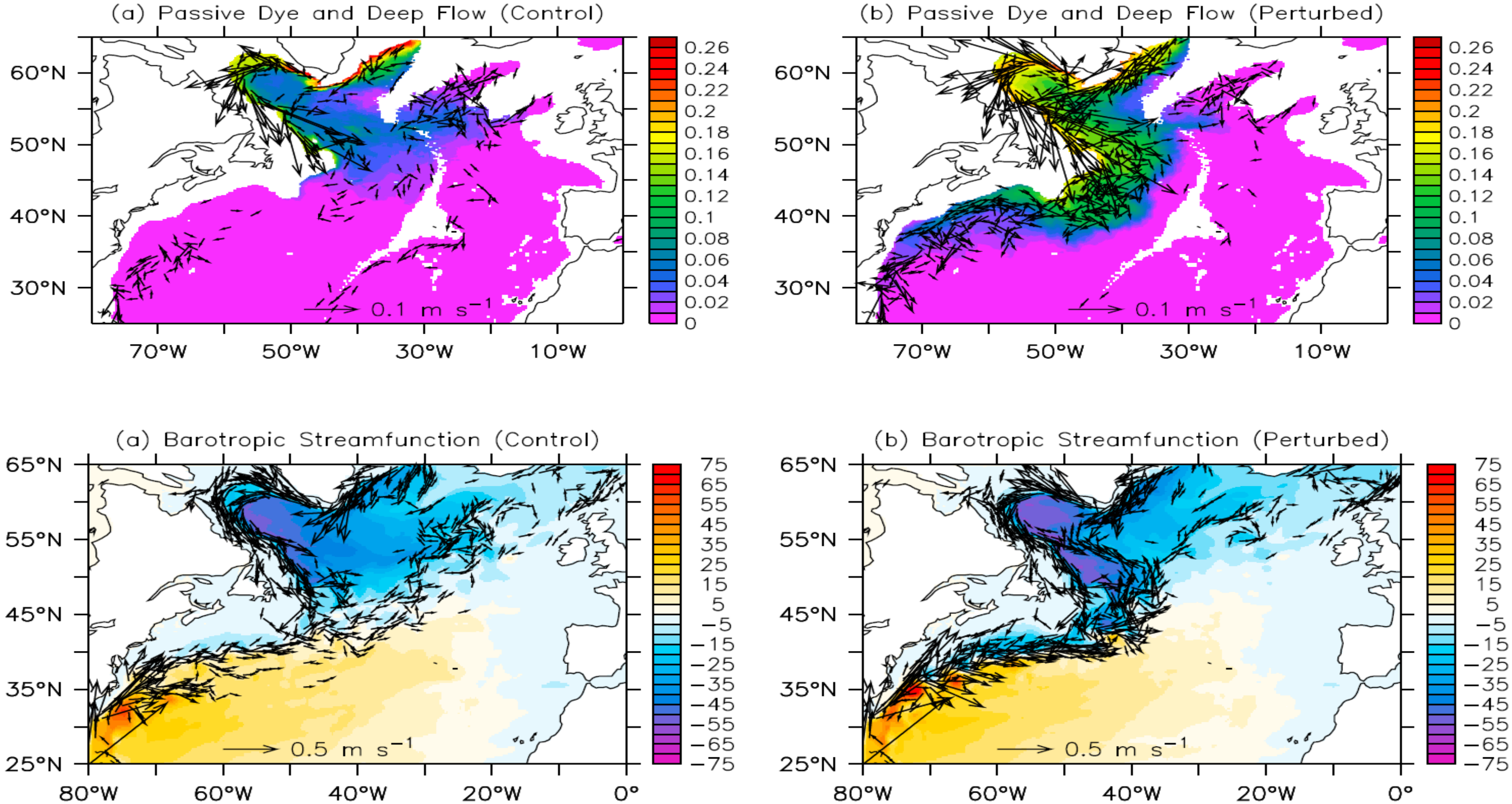
Correlation between NBC and SST



Zhang et al. 2001, JGR shows that a multidecadal NBC variability lags Labrador Sea Water Thickness by a few years. The NBC transport is coherent with the AMO. Both model and observational results suggest that the variability of NBC transport is a good index for AMOC variations.

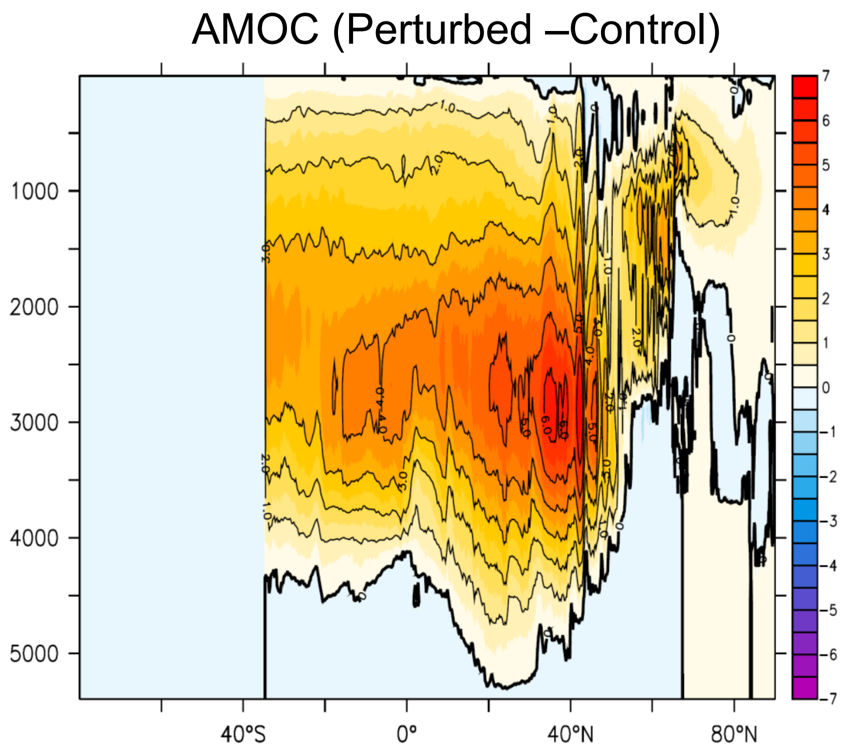
Nordic Sea Overflow and Subpolar Gyre

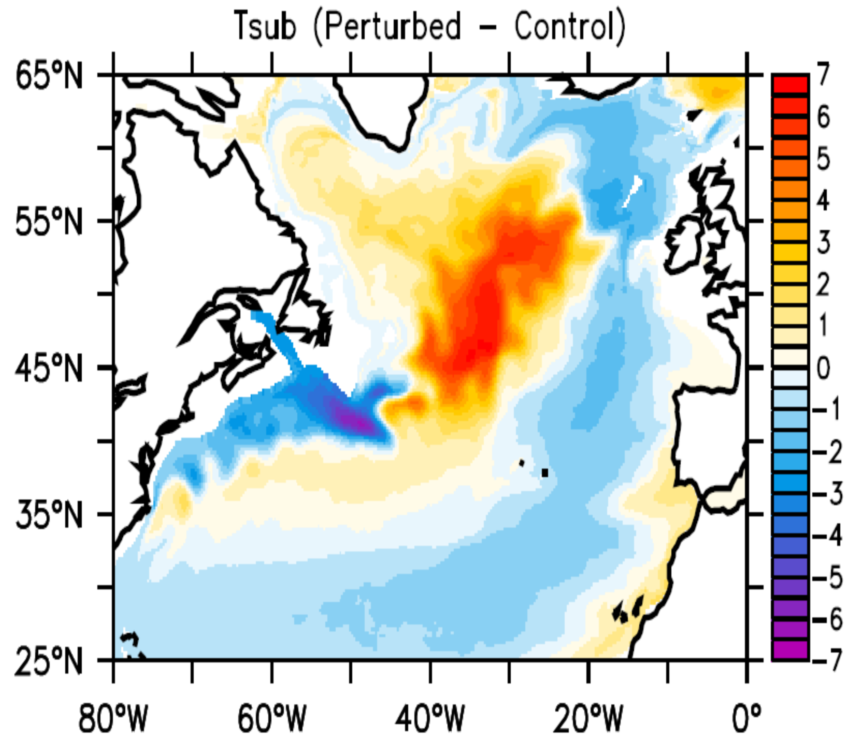
The high resolution global coupled model (GFDL CM2.5) shows that a stronger/weaker Nordic Sea overflow leads to a contracted/expanded subpolar gyre (Zhang et al 2011), consistent with the relationship indicated by sediment core records of the last millennium from Iceland Basin (Moffa Sanchez et al 2011)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



Weaker Overflow and expanded subpolar gyre (SPG)

Stronger Overflow and contracted subpolar gyre (SPG)





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.

Summary and Future Studies

- The NASST has been shown to be a good indicator of AMOC variations using both paleo records and climate models. However, the origin of the 20th century multidecadal NASST variations is highly debated, due to the complication of anthropogenic forcings.
- Independent AMOC fingerprints have been identified, using variables such as altimetry SSH, subsurface temperature, western boundary currents, subpolar gyres, and bring new evidence that the observed multidecadal NASST variations are indeed linked to AMOC variations rather than merely a 20th century artifact of changes in radiative forcing.
- A high priority is to develop a multivariate fingerprint of the AMOC using those variables that are (or have been) observed extensively or can be reconstructed from paleoclimate archives.
- A synthesis effort is needed to evaluate currently available observations in comparison with climate modeling results to reconstruct a longer proxy record of AMOC variations.