AMOC Impacts on Climate

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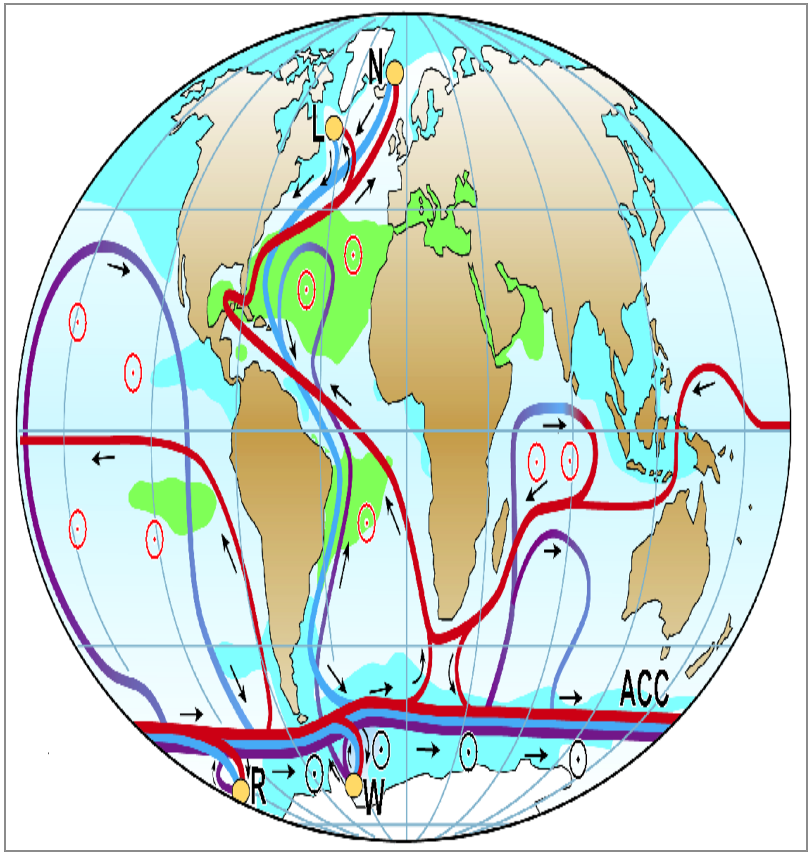
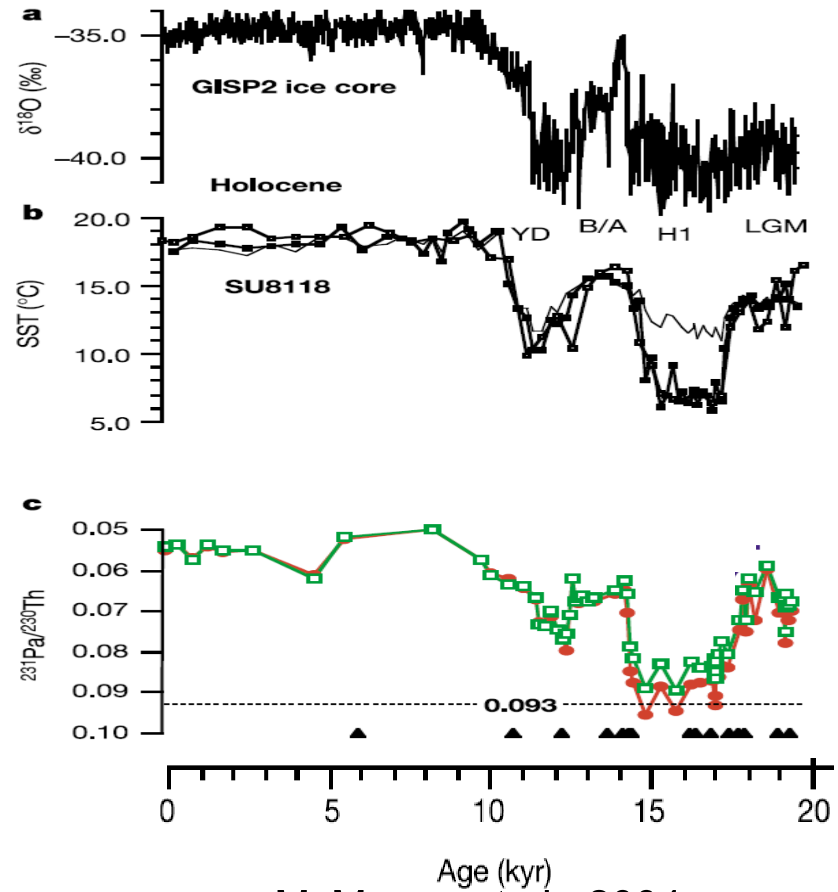
Paleo-AMOC Workshop, Boulder, CO, USA *May 24, 2016*

Atlantic Meridional Overturning Circulation (AMOC)



Kuklbrodt et al. 2007

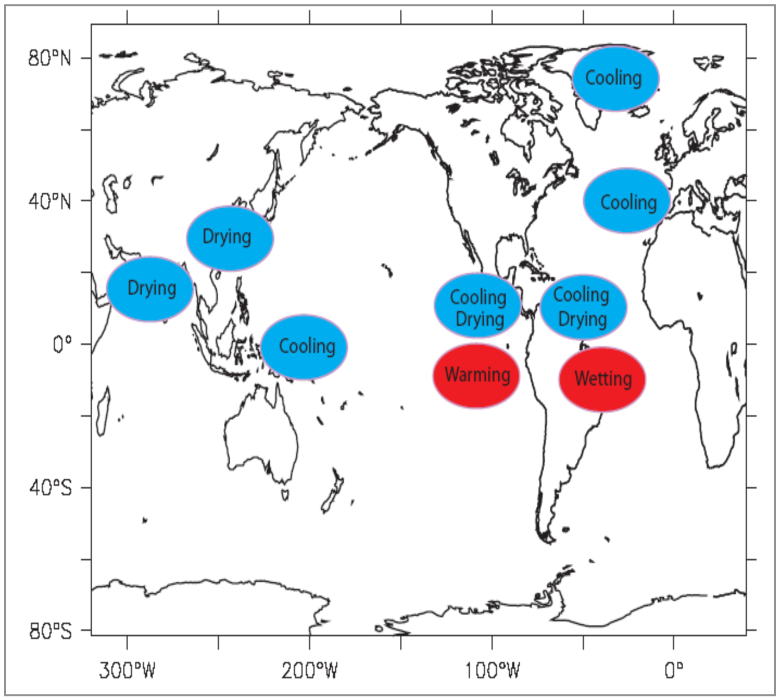


McManus et al., 2004

Paleo record from the subtropical North Atlantic suggests that AMOC was almost shutdown during the Heinrich event H1 and substantially weakened during the Younger Dryas

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

Schematic diagram of global synchronization of abrupt climate change indicated by paleo records



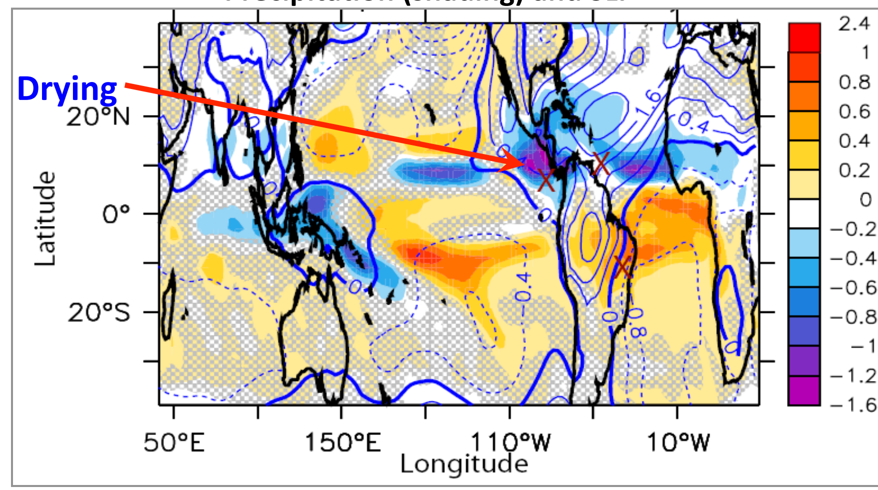
A substantial weakening of the AMOC is linked to:

- **Southward shift of ITCZ in both Atlantic and Pacific**
- **Weaker East Asia and Indian Summer Monsoons**

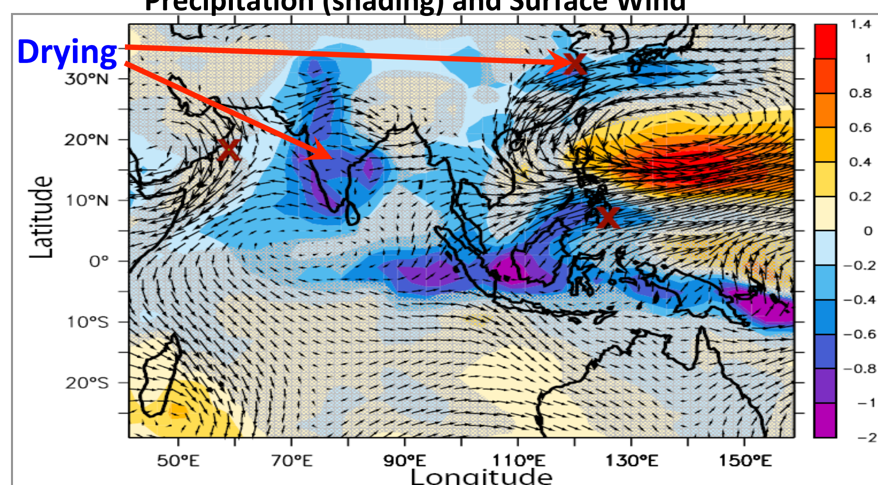
Zhang and Delworth 2005

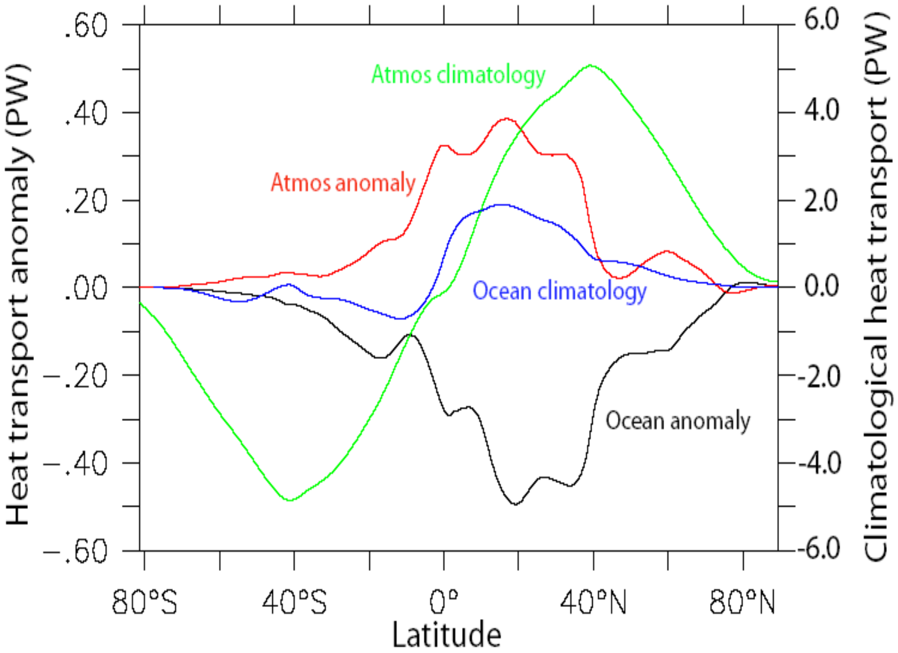
Modeled responses due to the weakening of AMOC

Precipitation (shading) and SLP



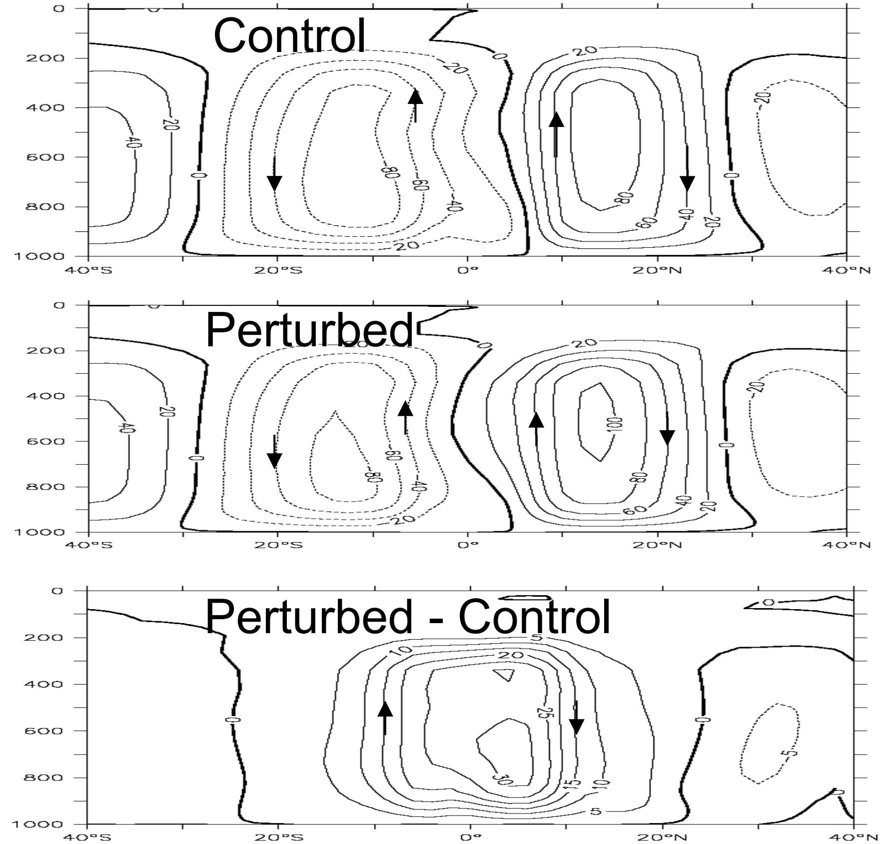
Precipitation (shading) and Surface Wind





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

Zhang and Delworth, 2005

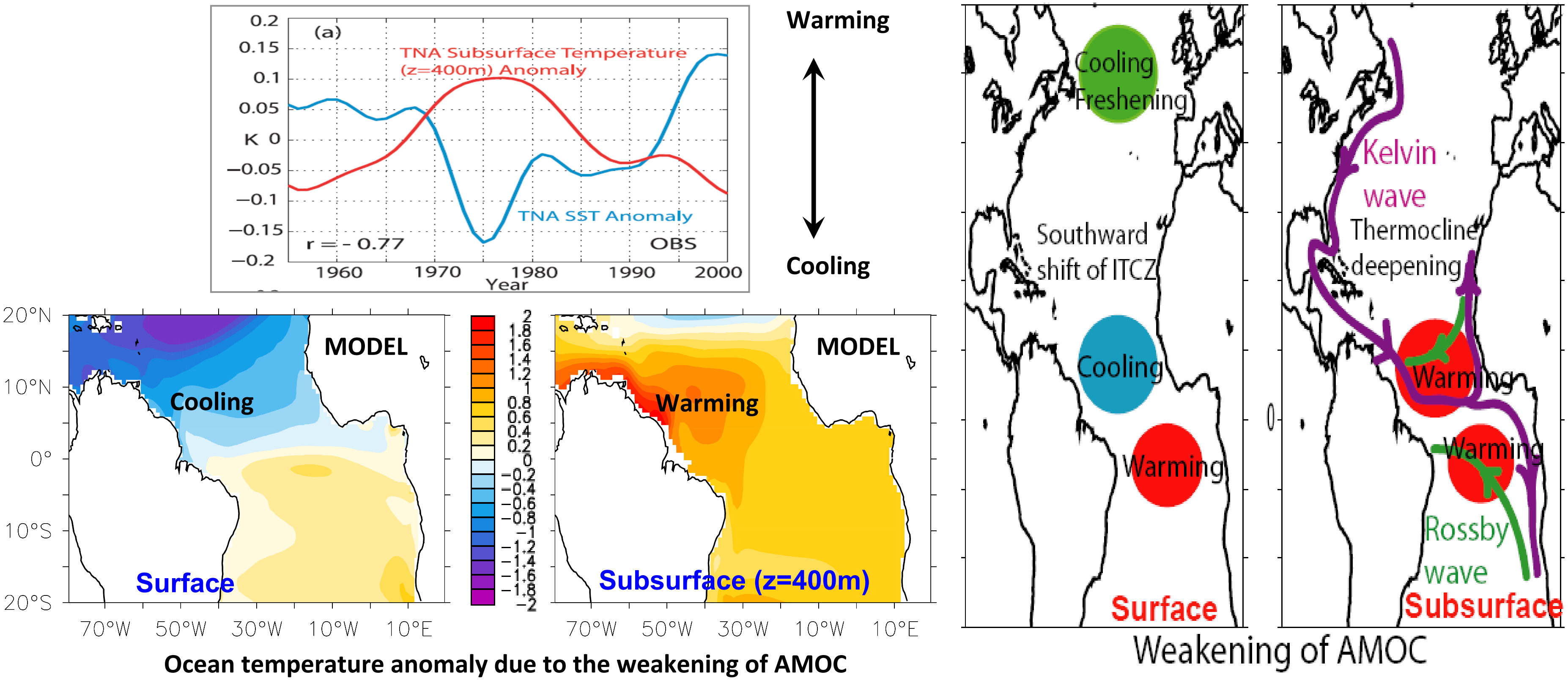


Annual mean global zonal integrated atmosphere stream function ($10^9 Kg/s$)

- The zonally integrated Hadley circulation become more symmetric about the equator when the AMOC is substantially weakened

- The contribution of the AMOC/ocean heat transport to the asymmetry of the ITCZ position is supported in more recent observational and modeling studies (Marshall et al. 2013; Frierson et al. 2013)

Tropical Fingerprint of AMOC Variations



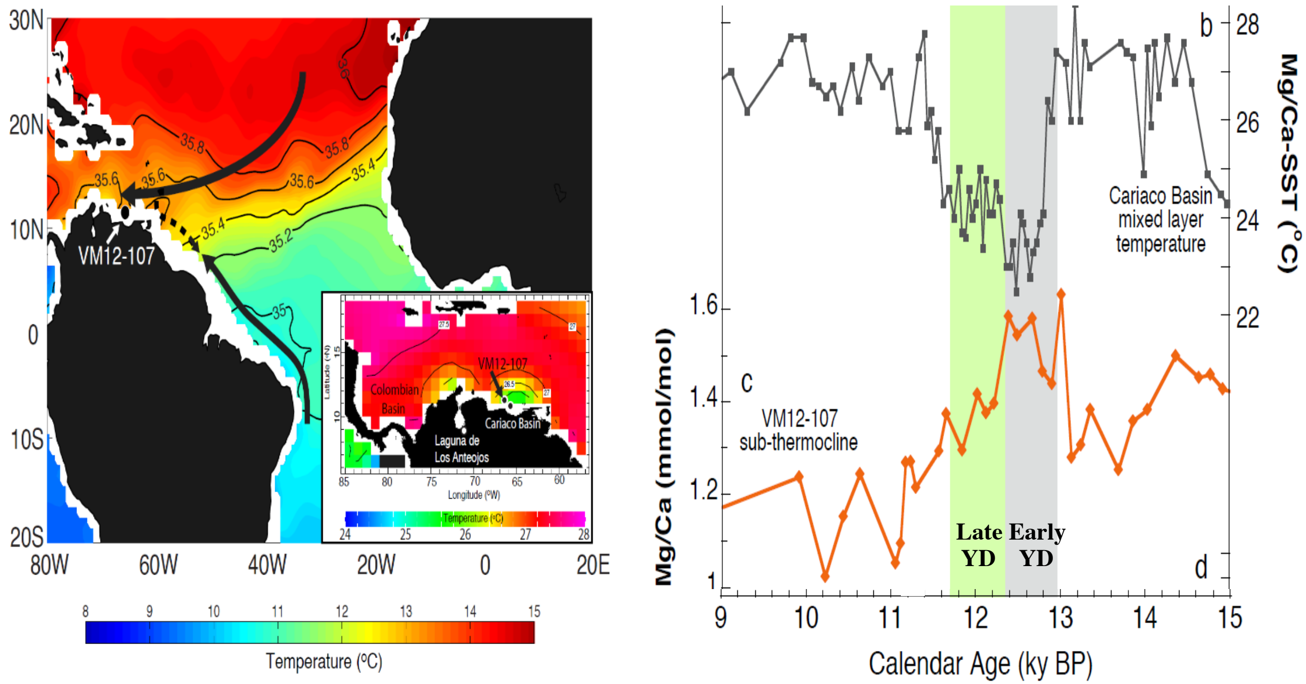
Ocean temperature anomaly due to the weakening of AMOC

from GFDL CM2.1 water hosing experiment

Zhang, 2007

- Observed Tropical North Atlantic (TNA) SST is anti-correlated with TNA subsurface ocean temperature
- The anti-correlated variations is shown to be a fingerprint of AMOC variations, suggesting the AMOC was weakened during the 70’s and strengthened since then

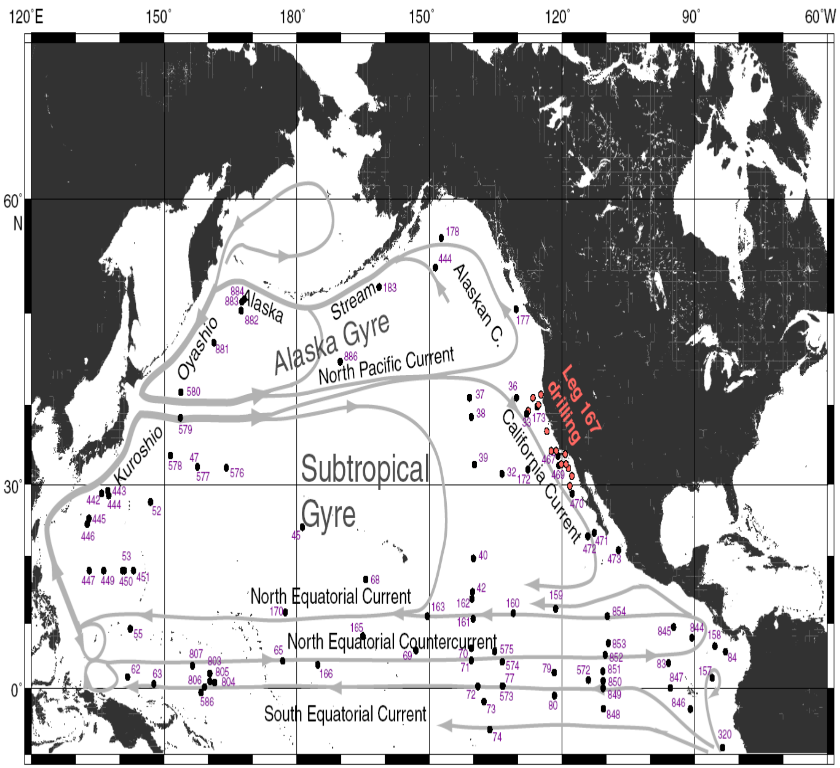
Anticorrelated Tropical North Atlantic (TNA) Surface and Subsurface Temperature



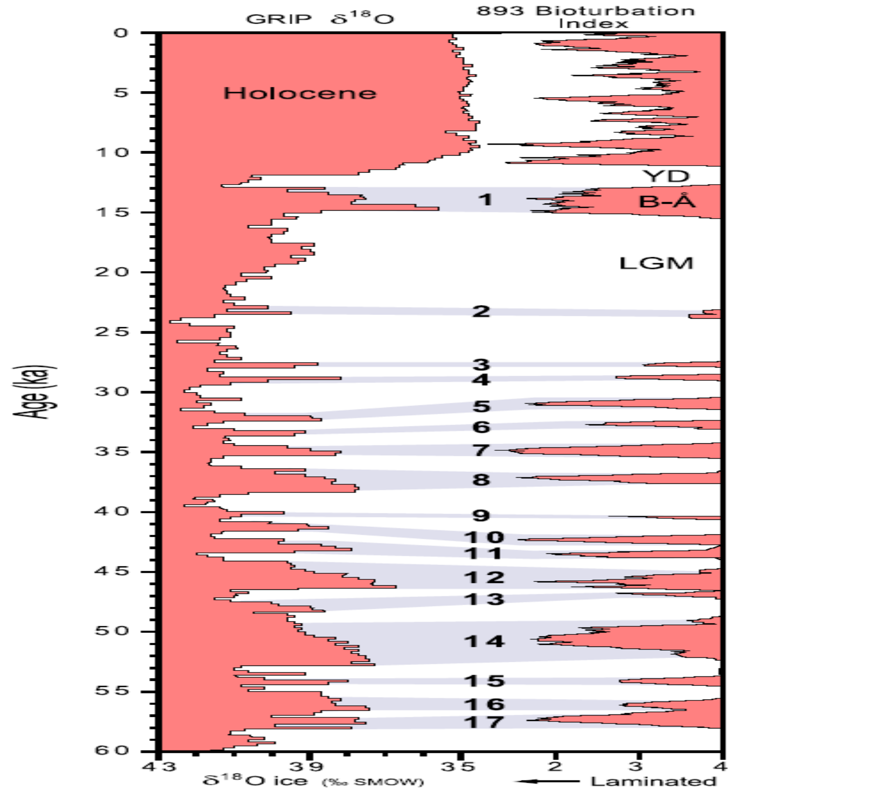
Schmidt et al. 2012, PNAS

High-resolution temperature records from a southern Caribbean sediment core show that warmer subsurface temperatures correspond to colder surface temperature and weaker AMOC during the Younger Dryas

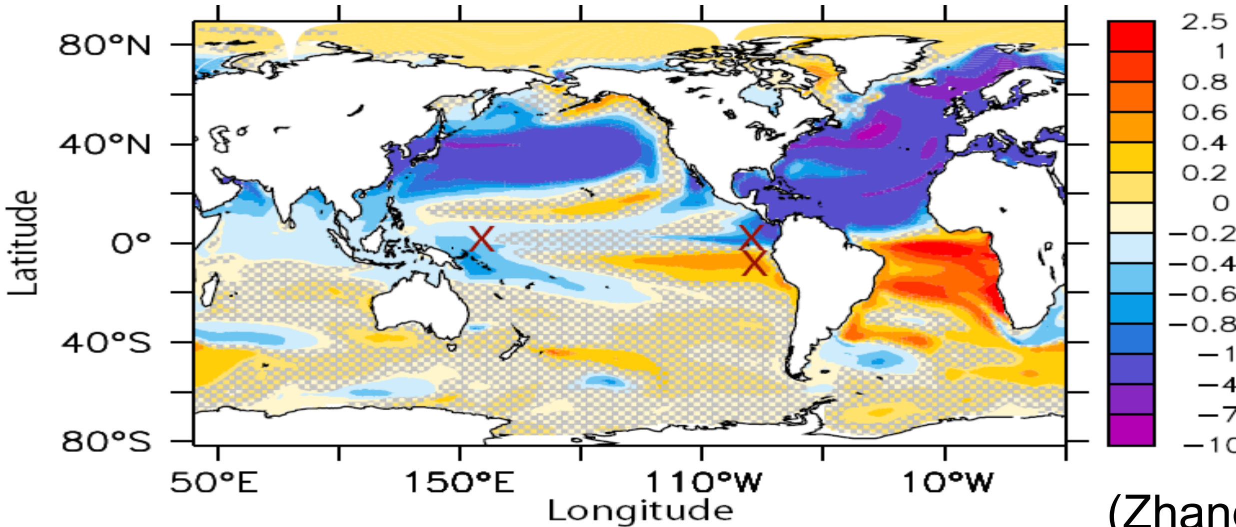
Schematic diagram of modern North Pacific ocean circulation



Comparison of ODP Site 893A bioturbation index with Greenland ice core records

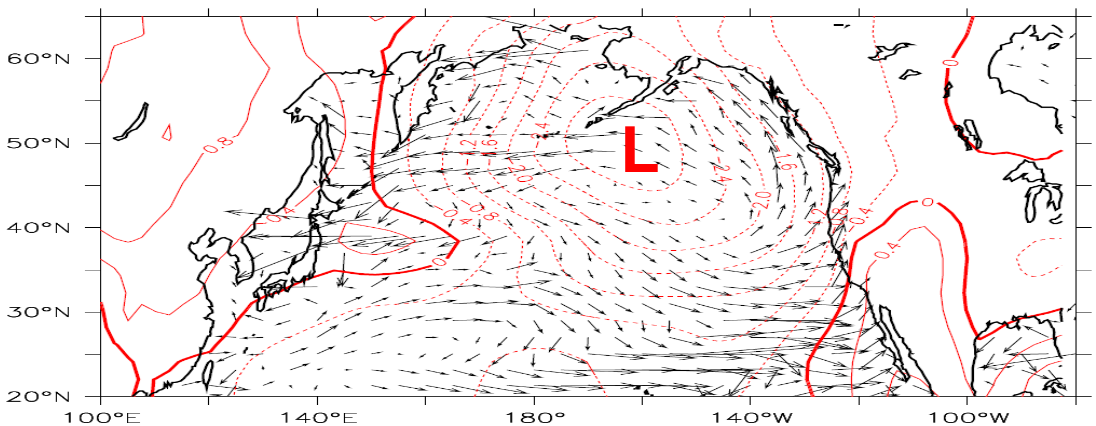


Higher oxygen levels in the northeast Pacific, indicating reduced upwelling and reduced California Current, were synchronous with Greenland stadials (Behl and Kennett, Nature, 1996)



SST anomaly from the water-hosing experiment

(Zhang and Delworth, 2005)



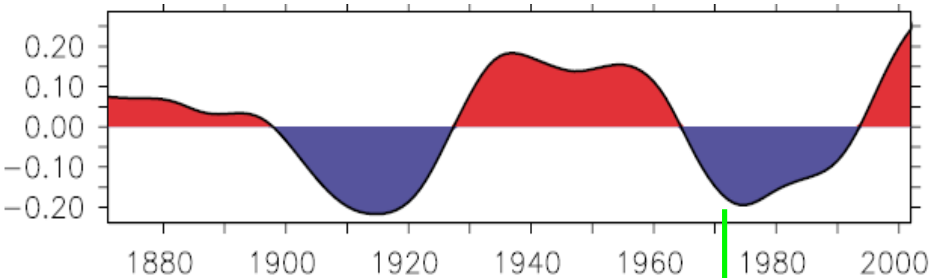
Anomalous North Pacific ocean surface currents from the water-hosing experiment

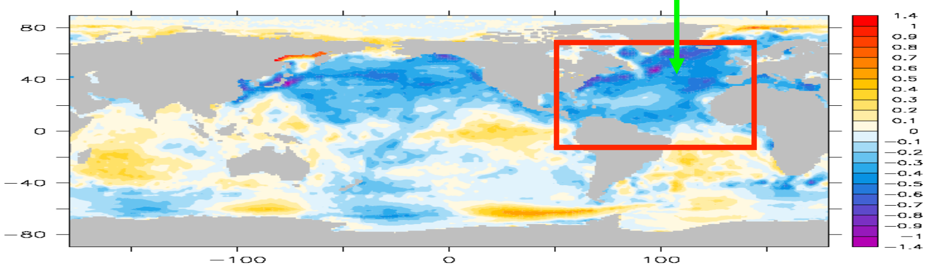
The weakening of the AMOC leads to anomalous low SLP, reduced California Current, reduced upwelling along North American west coast, and large-scale cooling in central North Pacific

Impacts in Modern Climate

Large-scale low frequency variability in the Atlantic SST has been observed during the 20th century - Atlantic Multidecadal Oscillation (AMO)

Observed AMO Index (Sutton and Hodson, Science, 2005)





Observed Multidecadal SST Difference (1971-1990) – (1941-1960) (HadISST, detrended)

Many observational and modeling studies suggest that the AMOC variability is a prime driver of the AMO (Kushnir, 1994; Delworth and Mann, 2000; Knight et al., 2005; Latif et al., 2006)

The AMO reflects coherent multivariate variability observed in the Atlantic, including correlated variations in the subpolar North Atlantic heat/salt content, ocean-driven surface turbulent heat fluxes, and anticorrelated variations in the TNA subsurface temperature (Zhang 2007, 2008; Wang et al. 2010, Robson et al. 2012; Zhang et al. 2013; Gulev et al. 2013; Wang and Zhang, 2013).

Multidecadal Atlantic Hurricane Activity and AMO

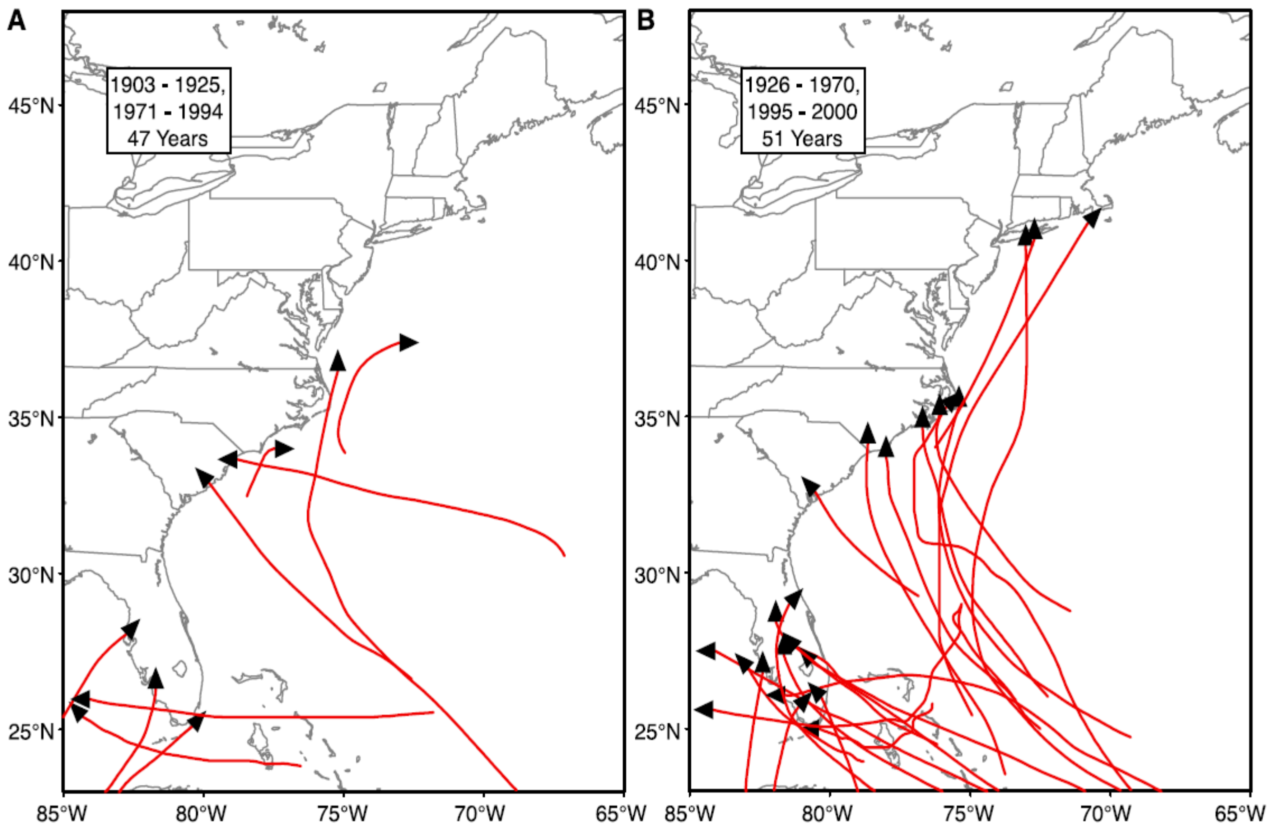
Negative AMO Phase

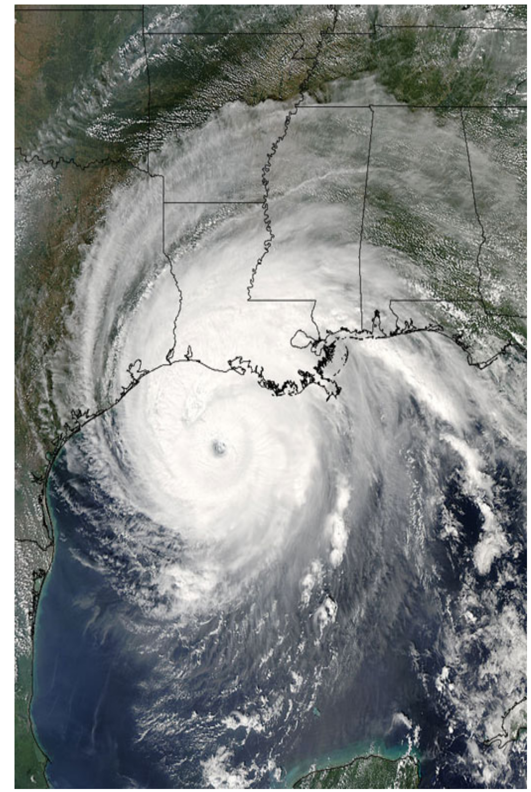
Cold North Atlantic

Positive AMO Phase

Warm North Atlantic

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



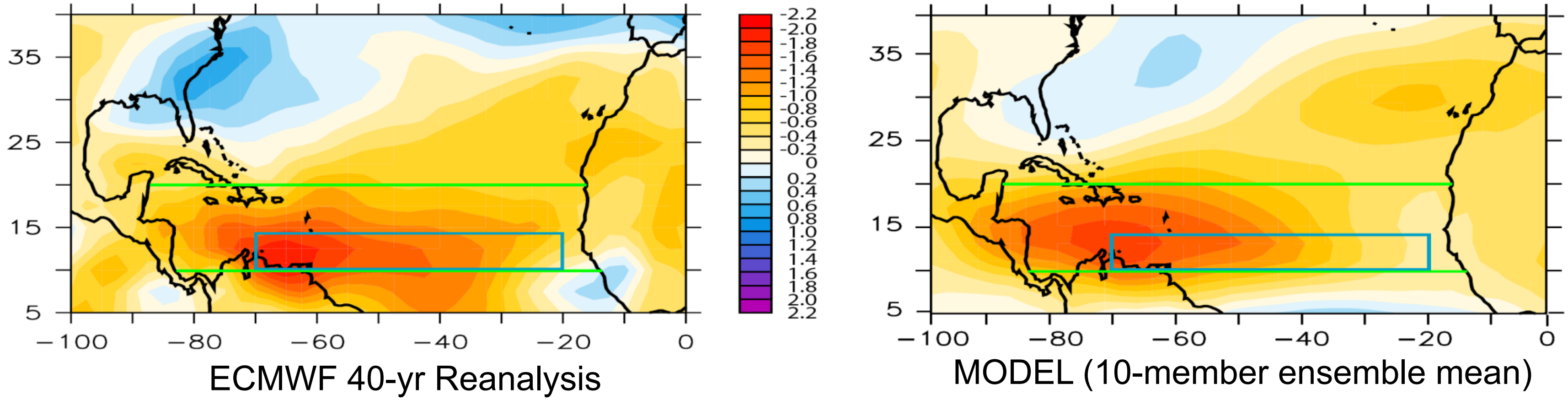


Goldenberg et al. 2001

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

Impact of AMO on Atlantic Hurricane Activity and India/Sahel Summer Rainfall

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



Regression of JJAS Rainfall on AMO Index

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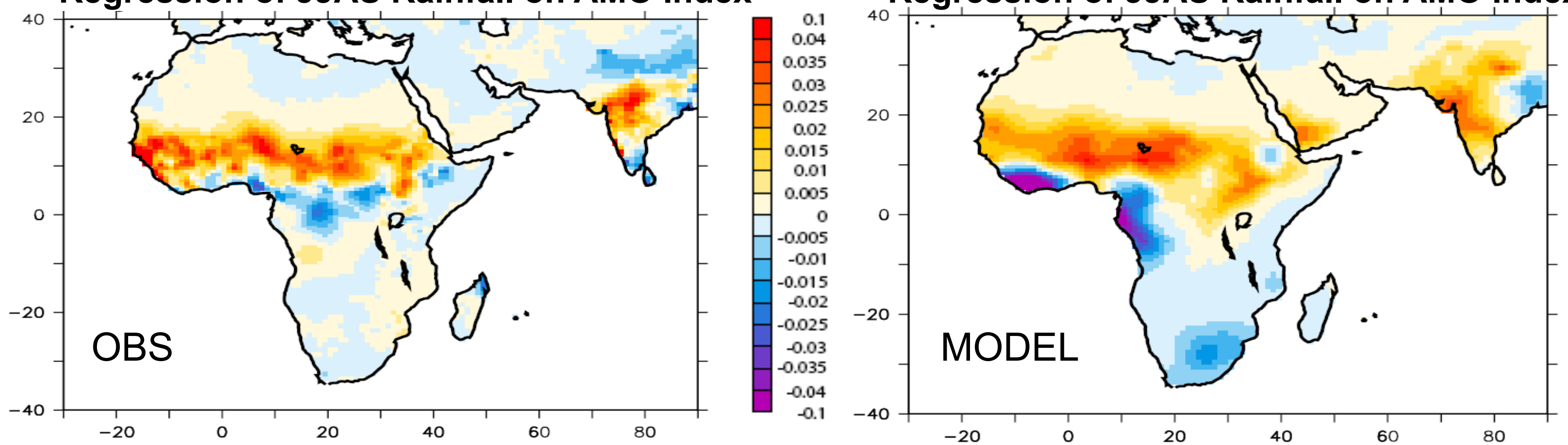


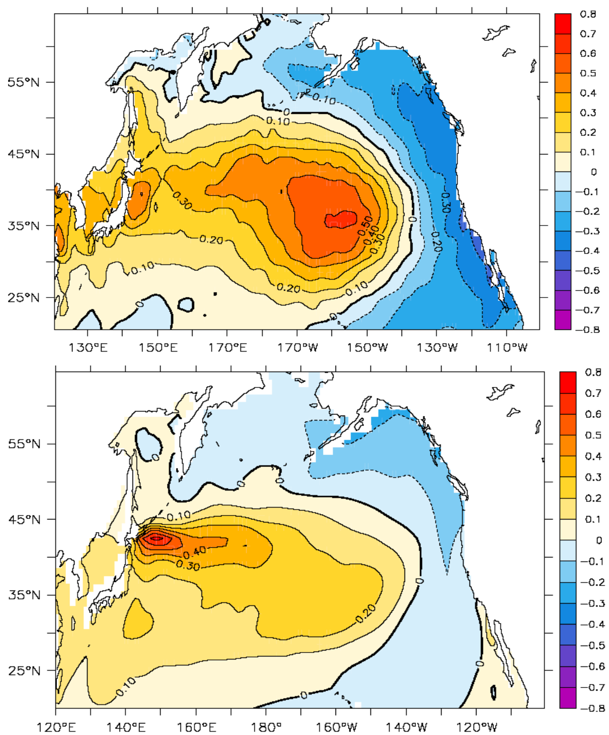
Zhang and Delworth 2006

Both observations and modelling results suggest that the AMO plays a leading role in generating coherent multidecadal variations of India/Sahel summer rainfall, and Atlantic Hurricane activity

Impact of AMO on Northern Pacific Low Frequency Variability

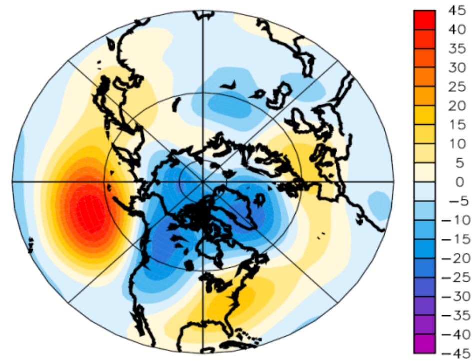
- Can the AMO influence the Pacific Decadal Oscillation (PDO) ?
- Where does the *multidecadal* time scale of the PDO come from?

EOF 1 of Northern Pacific winter SST (1901-2000) - PDO

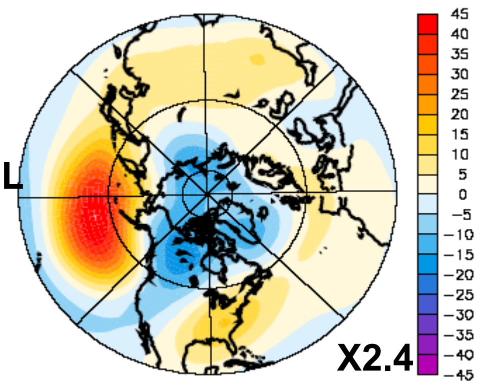


Regression of DJF 500mb geopotential height on PDO (1949-2000)

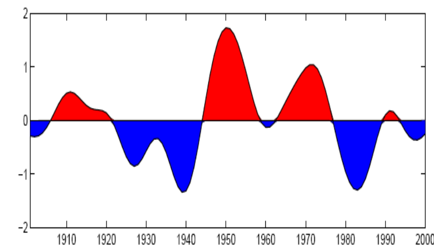
OBS



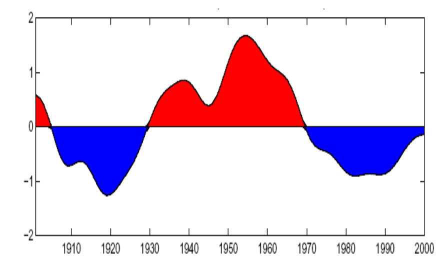
MODEL



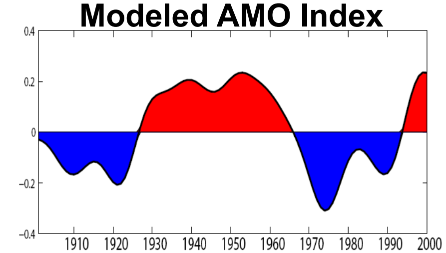
Observed PDO Index



Modeled PDO Index



Modeled AMO Index



Zhang and Delworth 2007

Modeling results suggest that the AMO can contribute to the PDO and Pacific/North American (PNA) pattern, and provides a source of multidecadal variability to the North Pacific

Observed Multidecadal Variations in Arctic Surface Air Temperature

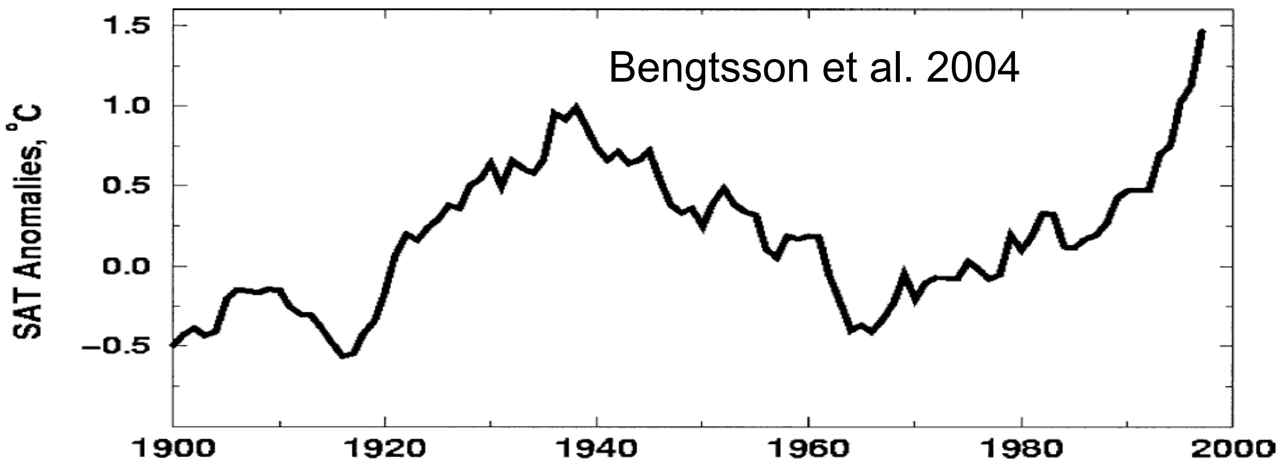
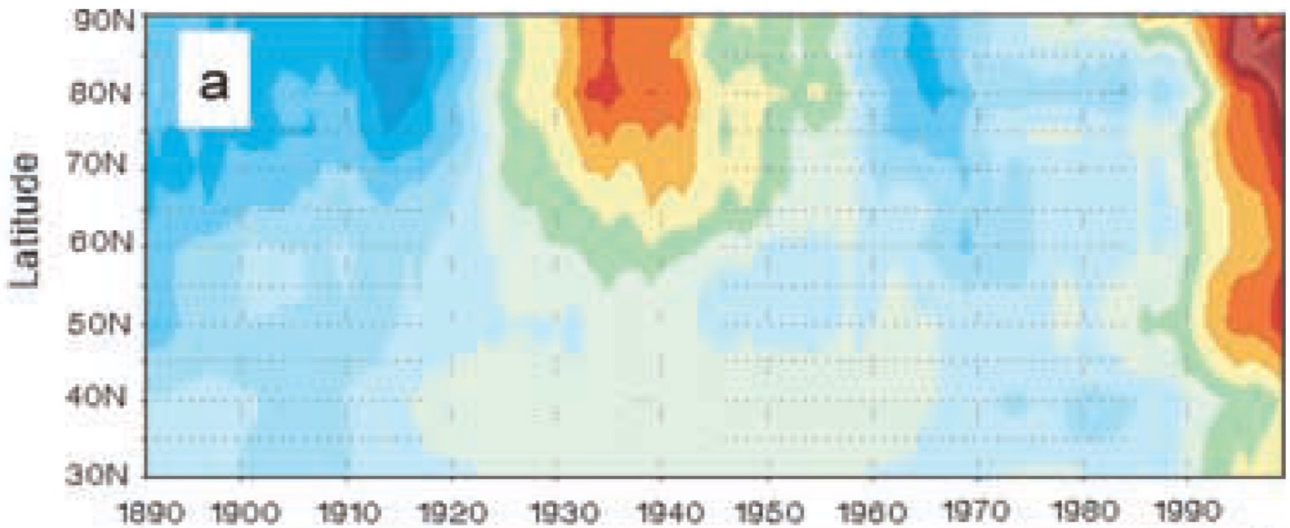


FIG. 1. Annual mean Arctic SAT anomalies (°C, area averaged from 60°–90°N) from Johannessen et al. (2004), 5-yr running mean.

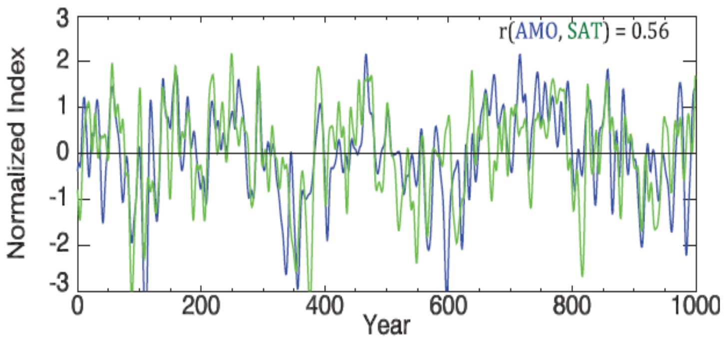


Johannessen et al. 2004

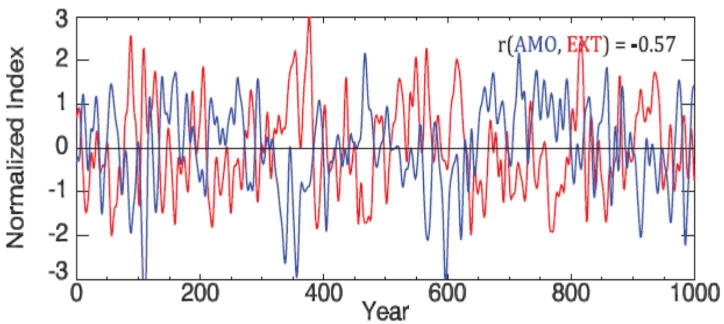
What is the role of low frequency AMOC variability in the observed multidecadal variations of Arctic climate and observed Arctic sea ice decline?

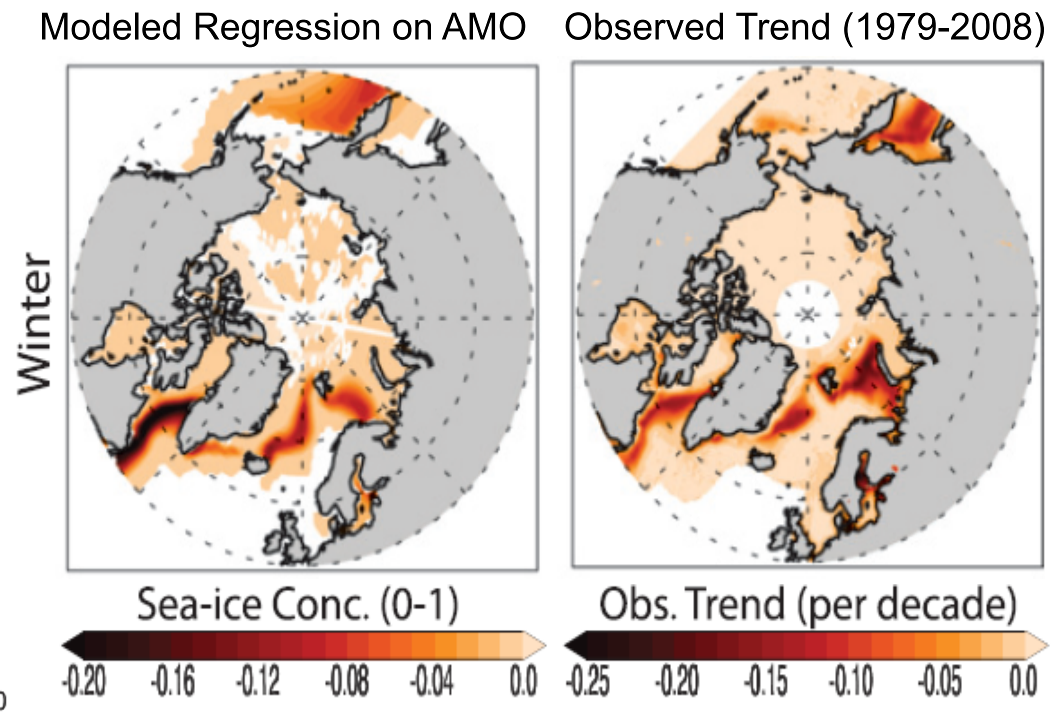
Impact of AMOC on Winter Arctic Sea Ice Variability

Time-series: AMO index and Arctic Surface Air Temperature (SAT)



Time-series: AMO index and Arctic sea-ice extent (EXT)



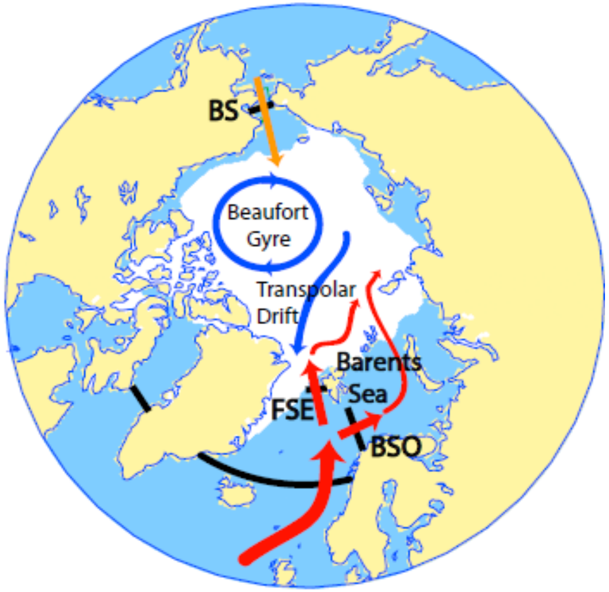


GFDL CM2.1 1000-year control simulation (Mahajan, Zhang, and Delworth, 2011)

- Winter Arctic sea ice in the Atlantic side declines with an intensified AMOC
- Similar spatial patterns suggest a possible role of the AMOC in the observed winter sea ice decline
- The anti-correlation between AMO and winter Arctic sea ice is further found in other climate models (Day et al. 2012) and paleo records (Miles et al. 2014)

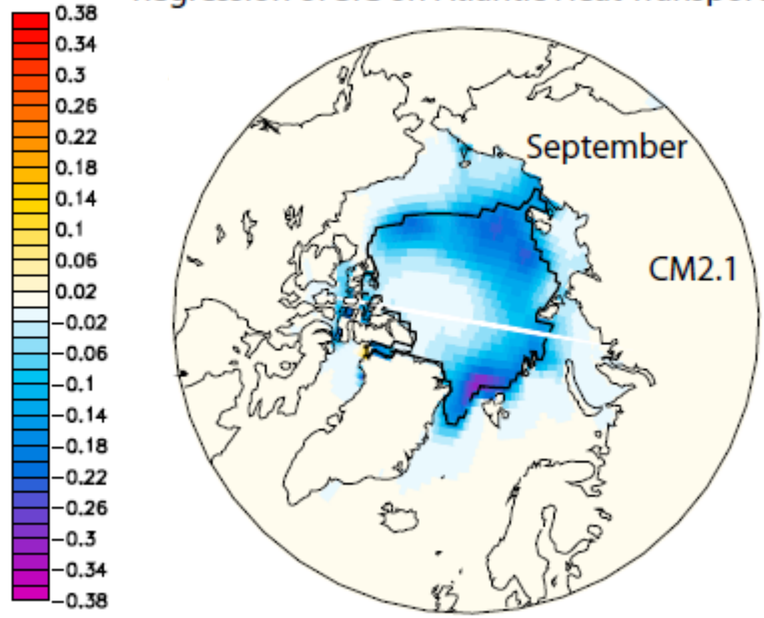
Impact of AMOC on Summer Arctic Sea Ice Variability

Atlantic and Pacific Inflow and Arctic Ocean Circulation

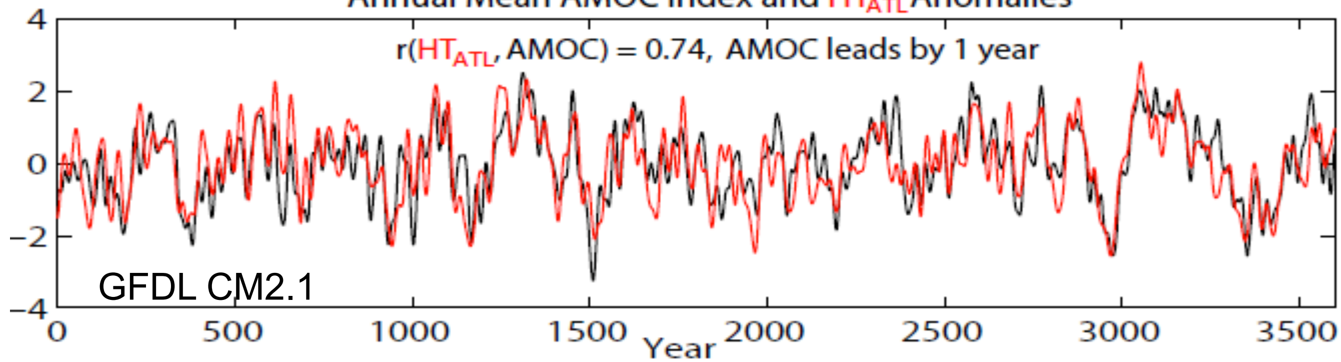


Zhang, 2015, PNAS

Regression of SIC on Atlantic Heat Transport



Annual Mean AMOC Index and HT_{ATL} Anomalies

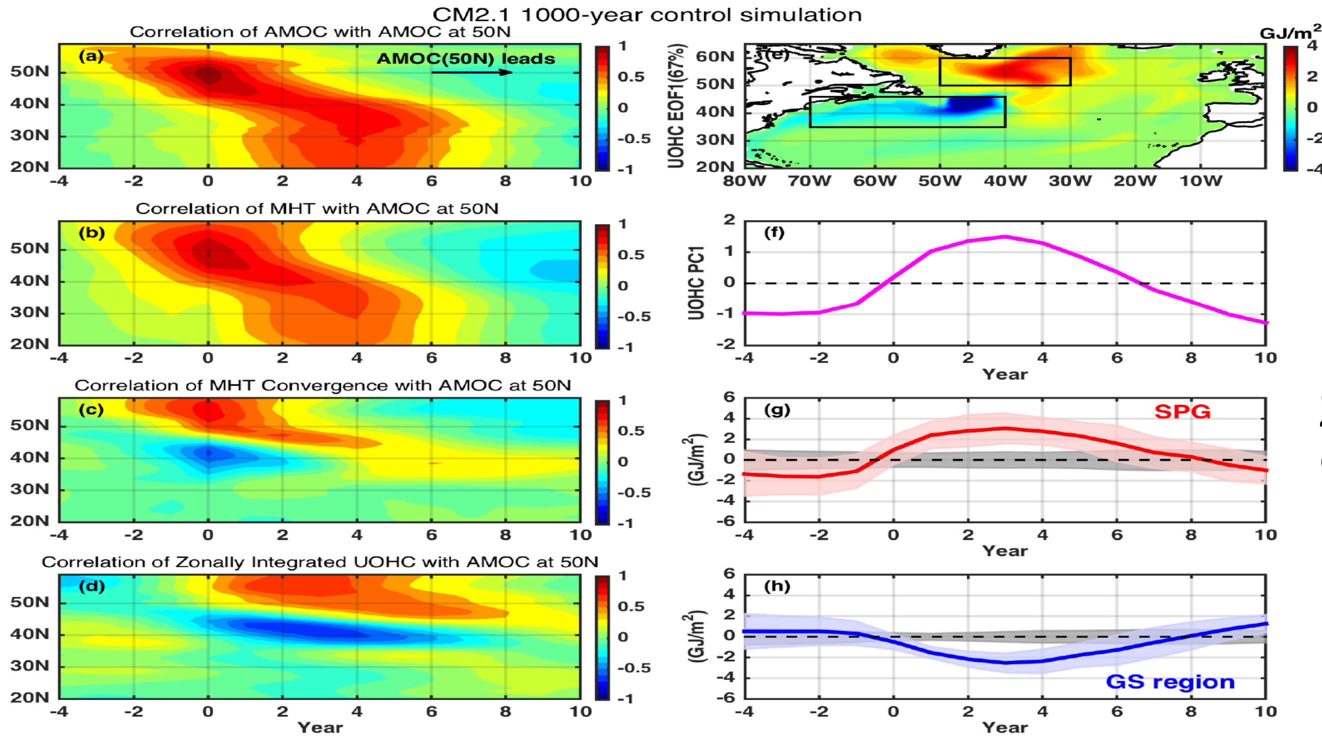


The AMOC variability and associated Atlantic heat transport into the Arctic also play a significant role in the low frequency variability of summer Arctic sea ice extent

Broad Climate Impacts of AMO

- Multidecadal variations in U.S. rainfall and drought frequency (Enfield et al., 2001; McCabe et al. 2004)
- Multidecadal variations in summer climate over North America and Europe (Sutton and Hodson, 2005, 2007; Sutton and Dong, 2012)
- Multidecadal variations in northern hemispheric mean surface temperature (Zhang et al. 2007; Semenov et al., 2010)
- Influence on equatorial Pacific decadal variability (Kucharski et al. 2015) and multidecadal ENSO variability (Dong and Sutton, 2007; Kang et al. 2014)
- Multidecadal winter NAO response (Gastineau and Frankignoul, 2012; Hodson et al. 2014; Omrani et al., 2014, 2016)

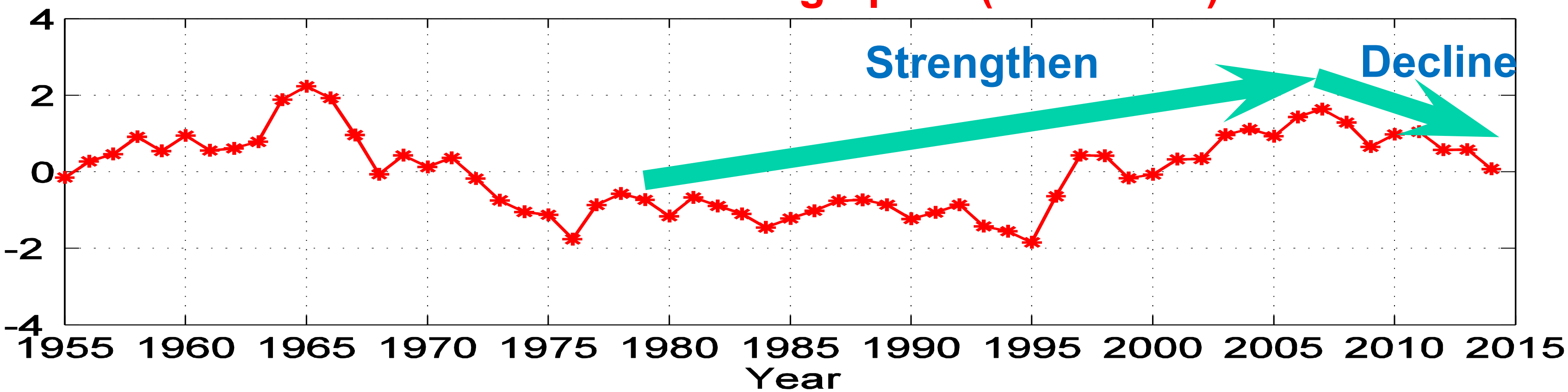
Extra-tropical AMOC Fingerprint – Leading Mode of Upper Ocean Heat Content



Zhang and Zhang, GRL, 2015

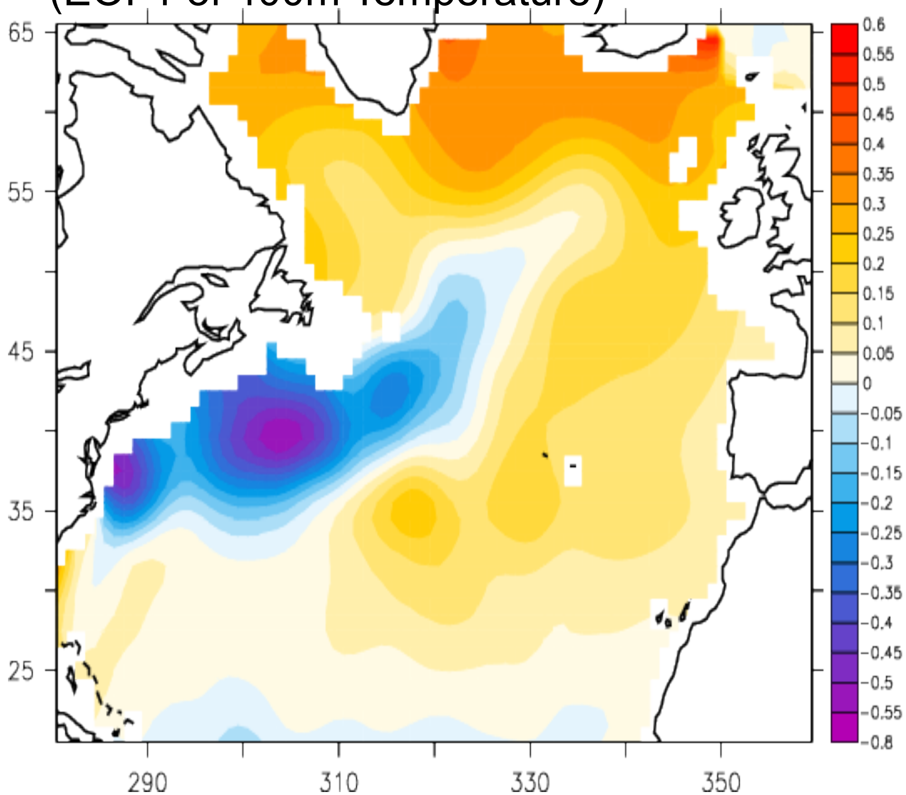
Similar southward AMOC propagation also exists in isopycnal coordinate model GFDL CM2G (Wang et al., 2015), and high-resolution models GFDL CM2.5 (Zhang et al., 2011)

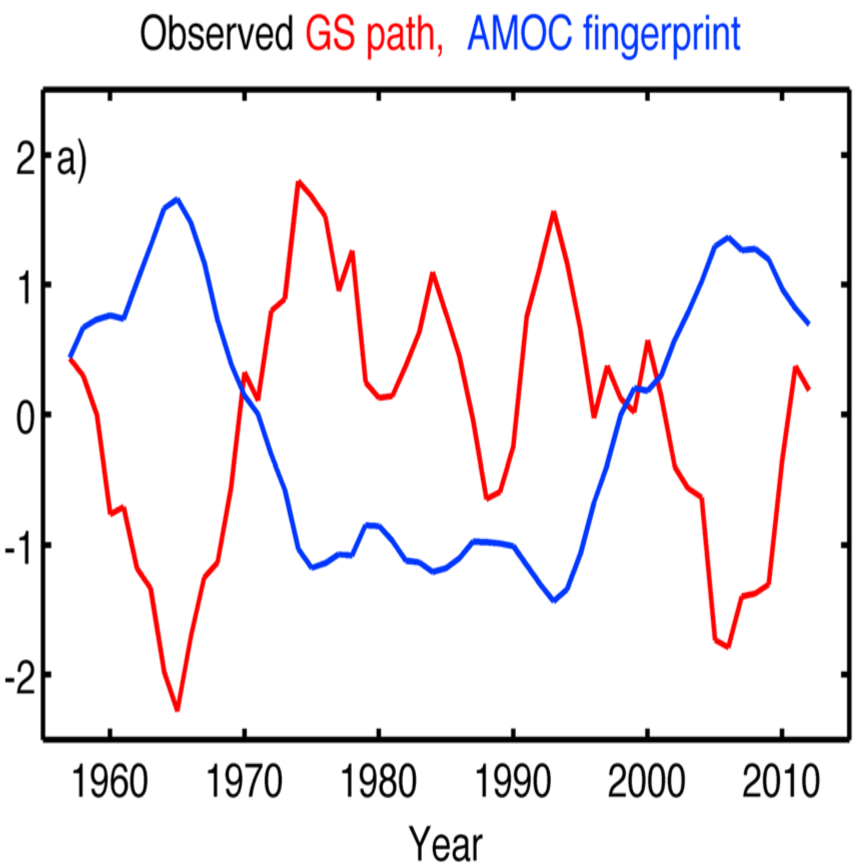
Observed AMOC Fingerprint (1955-2014)



Extra-Tropical AMOC Fingerprint and Anti-Correlation between Gulf Stream (GS) Path and AMOC Strength

Pattern of observed AMOC fingerprint (EOF1 of 400m Temperature)





(Zhang, 2008; Sanchez-Franks and Zhang, 2015)

- AMOC fingerprint - leading mode of extra-tropical N. Atlantic subsurface temperature
- Stronger AMOC leads to a southward shift of the GS path at decadal time scale in both observations and coupled climate models

Summary and Discussions

- Simulated global synchronization of abrupt climate change due to the AMOC weakening is consistent with that indicated by paleo records (such as changes in ITCZ position, Indian/east Asian summer monsoon, SST contrast in tropical Pacific, and North Pacific ocean circulation)

- The AMO associated with AMOC variability has played an important role in many multidecadal climate fluctuations during the 20th century over tropical, mid-latitudes, and polar regions. The AMOC impacts on climate appear robust across a wide range of time scales

- Independent AMOC fingerprints bring more evidence that the observed AMO is linked to AMOC variations, and indicate that the AMOC strengthened since mid 70's and weakened over the last decade