What We've Learned from the AMOC Modeling Efforts about AMOC Processes and its Role in Weather and Climate

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GFDL/NOAA

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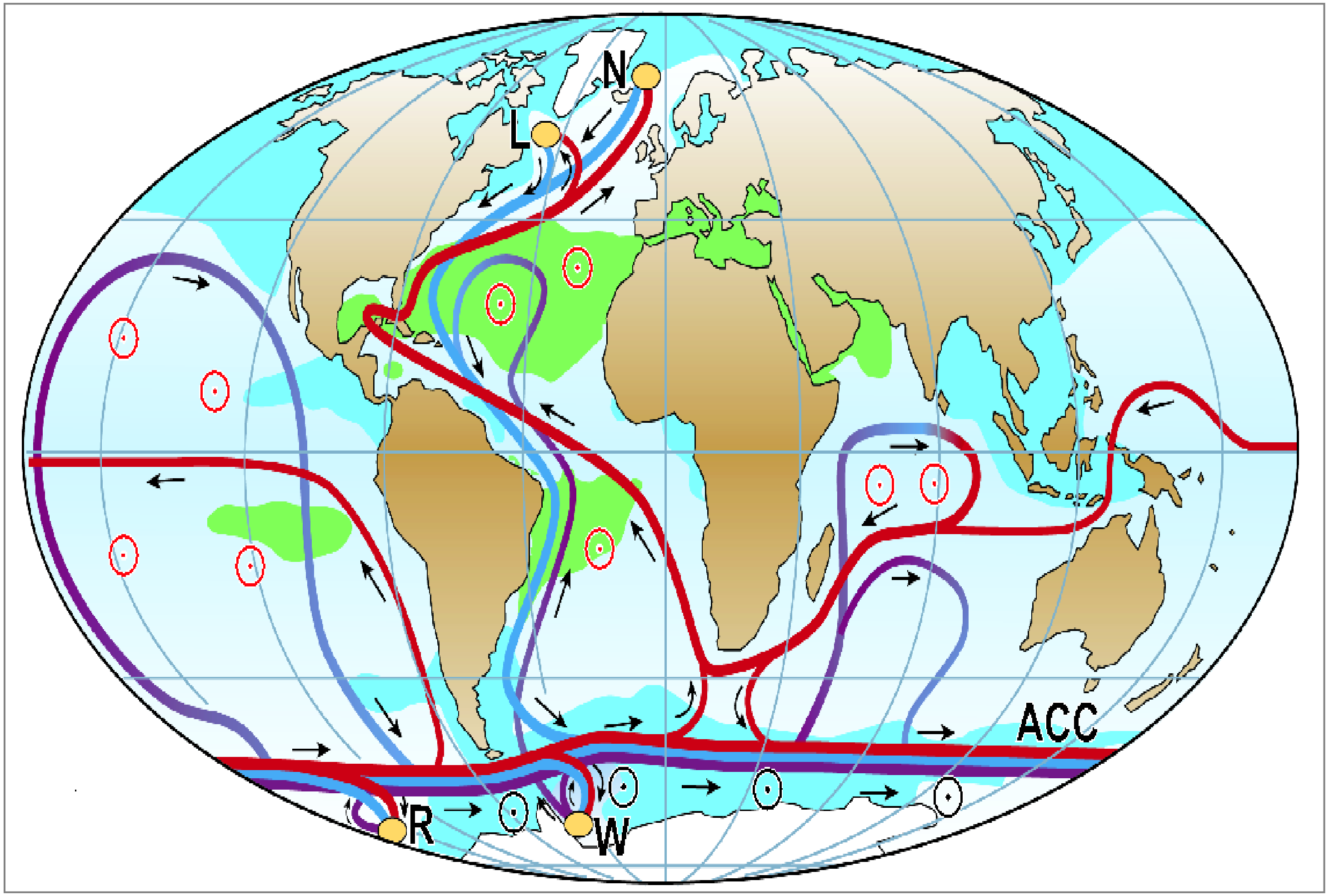
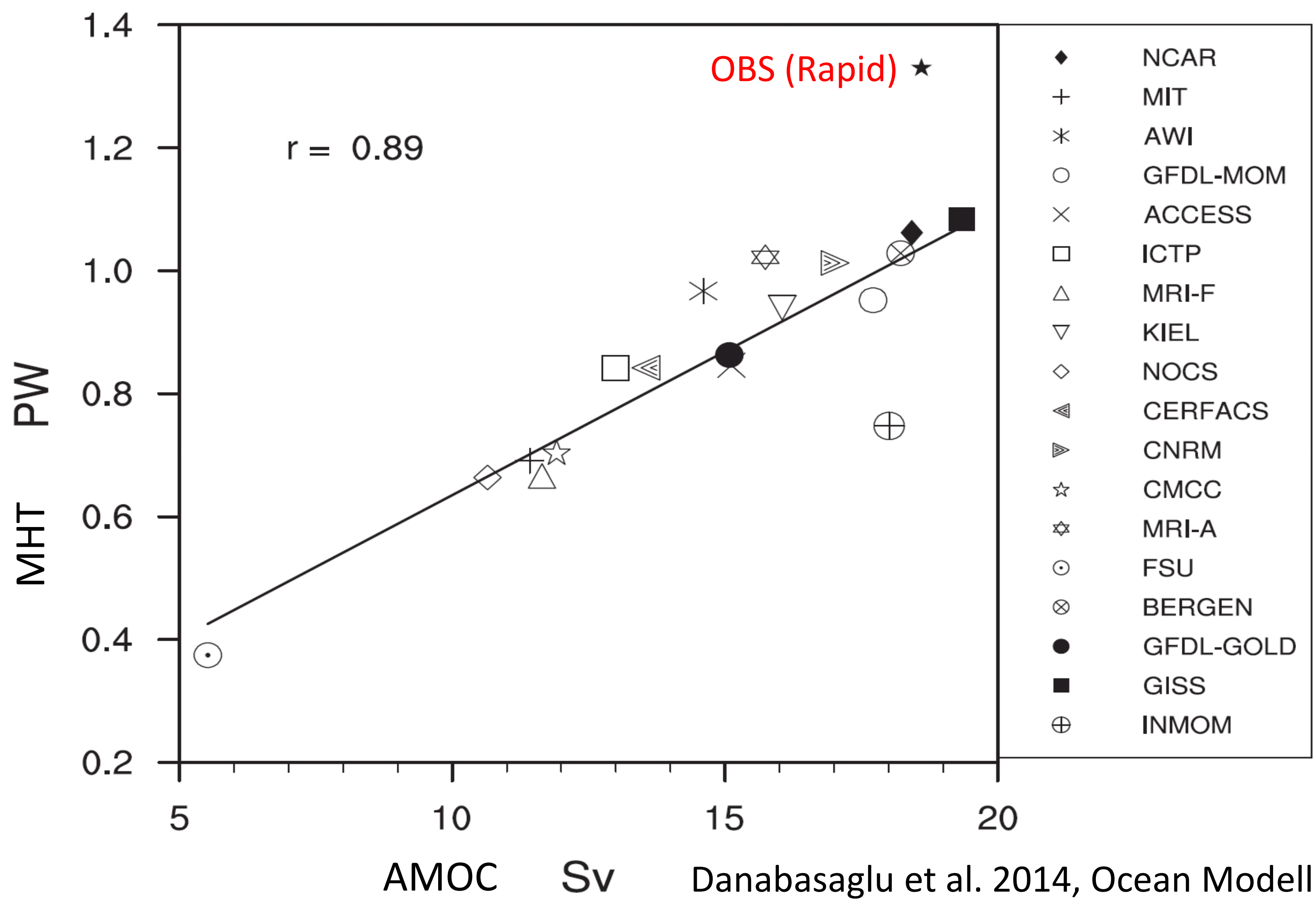
Atlantic Meridional Overturning Circulation (AMOC)

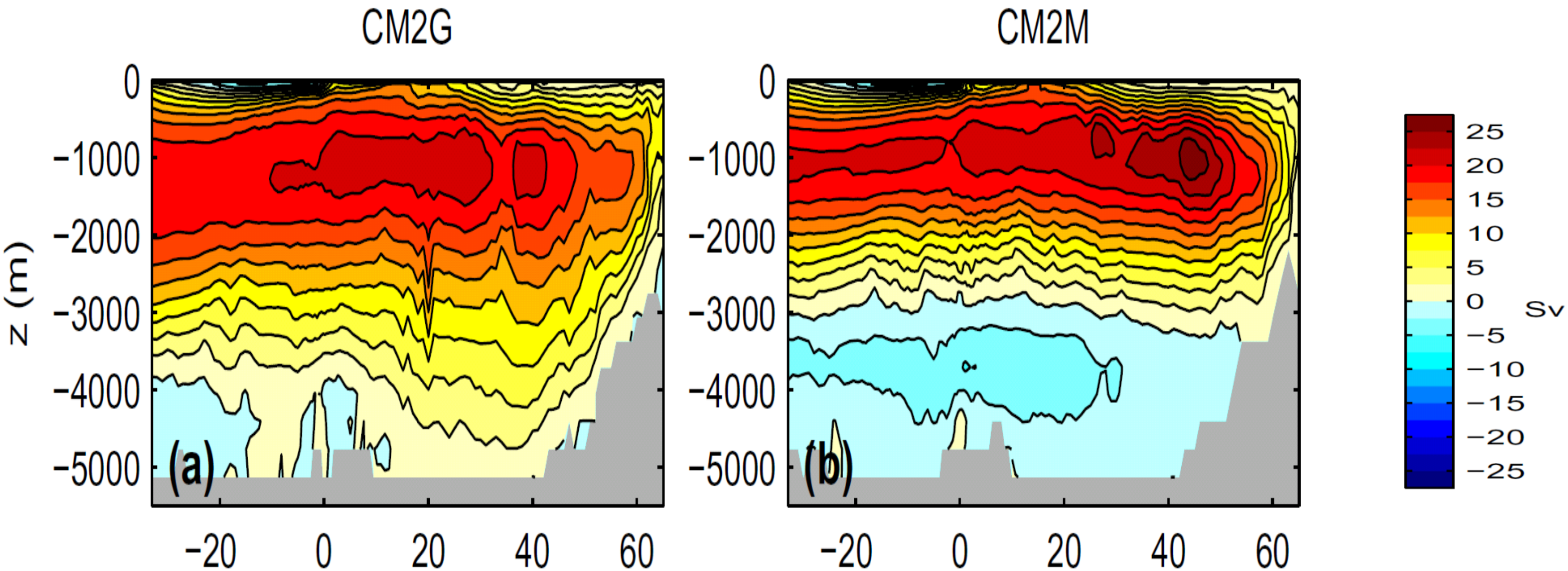


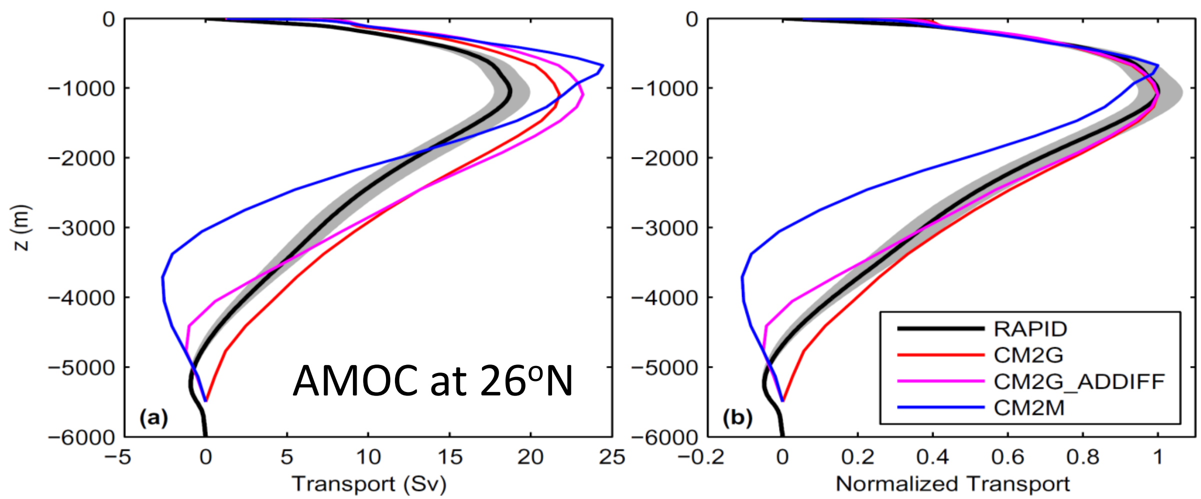
Kuklbrodt et al. 2007, Reviews of Geophysics



Danabasaglu et al. 2014, Ocean Modelling

Most ocean general circulation models can simulate a proportional relationship between the meridional heat transport (MHT) and the maximum AMOC transport at 26^{o}N, although the regression ratio among models is lower than that observed

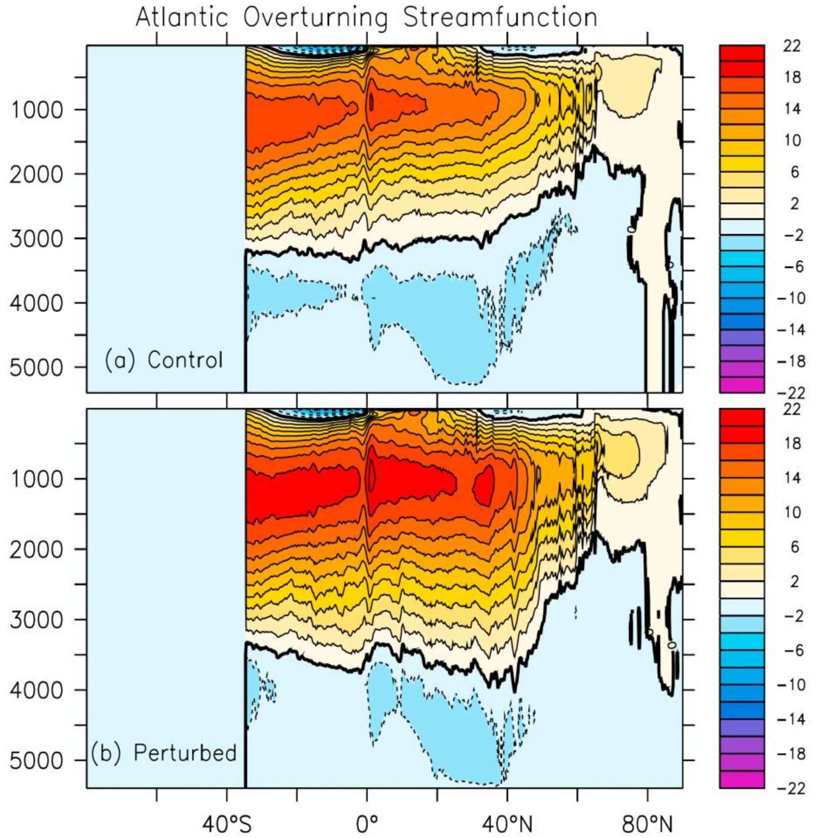


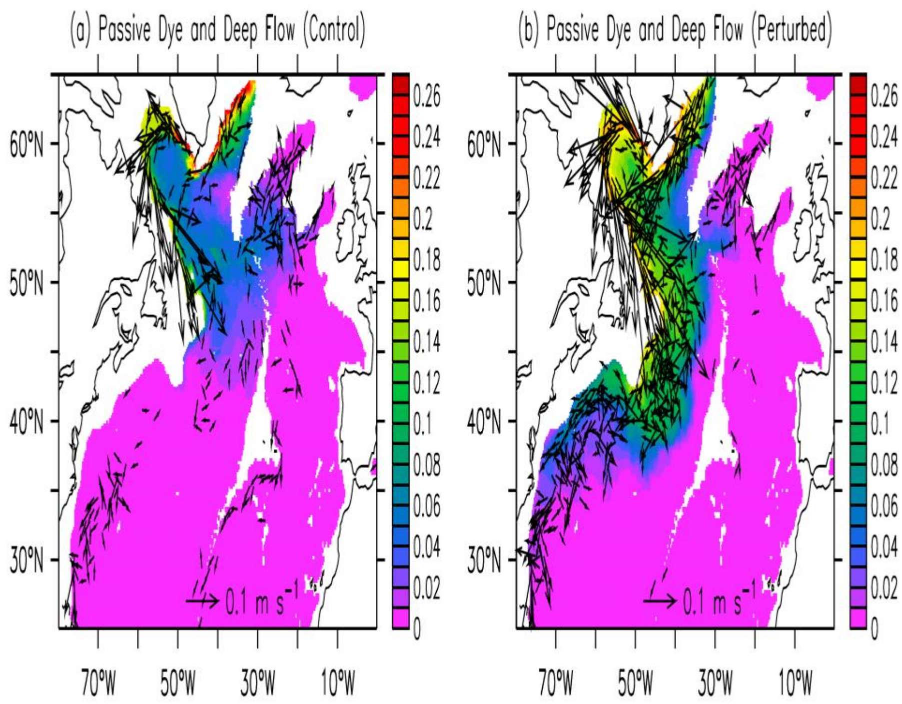


Wang et al. 2015,
Ocean Modelling

Climate models with z-coordinate ocean components often simulate a shallower AMOC than that observed, whereas climate models with isopycnal-coordinate ocean components (e.g. GFDL CM2G, ESM2G) can simulate a deep AMOC as that observed due to a better simulation of the Nordic Sea overflow

GFDL Eddy-Permitting Coupled Model CM2.5

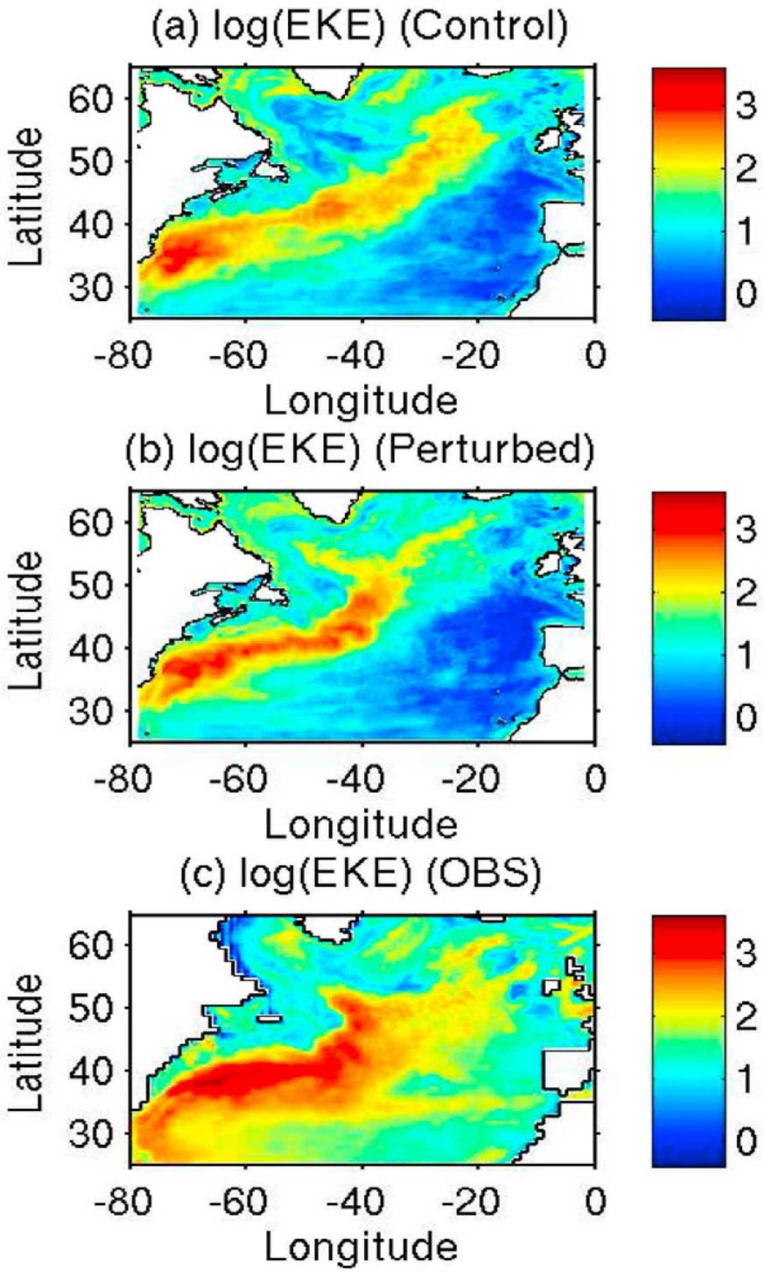


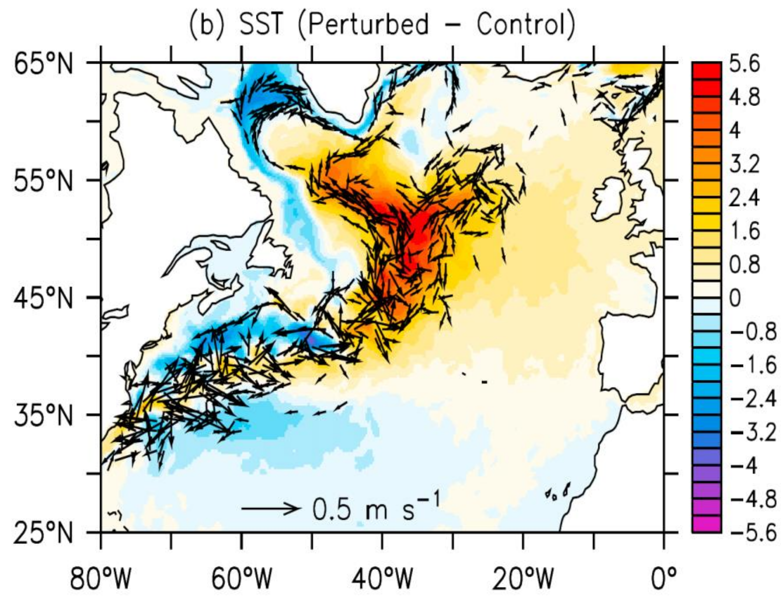


Zhang et al. 2011, JGR-Oceans

- A stronger and more realistic Nordic Sea overflow can lead to deeper AMOC and enhanced meridional ocean heat transport (MHT) (Zhang et al. 2011)
- Similar impact of Nordic Sea overflow on AMOC depth and MHT is also found in NCAR CCSM4 with overflow parameterization (Yeager and Danabasoglu, 2012)

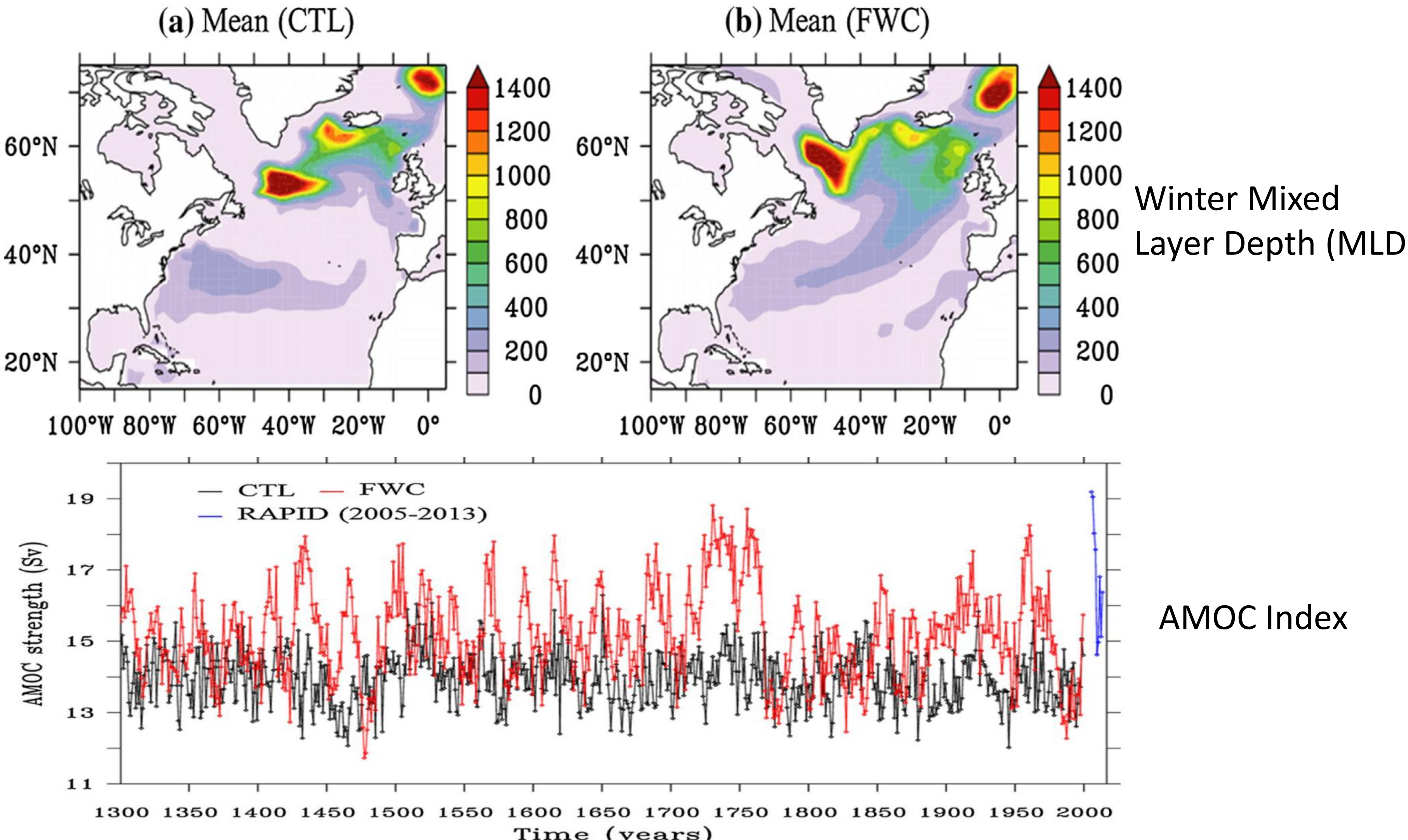
GFDL Eddy-Permitting Coupled Model CM2.5





Zhang et al. 2011, JGR-Oceans

- Most CMIP5 models simulate a strong SST cold bias in mid-latitude North Atlantic, due to simulated bias in AMOC (Wang et al. 2014)
- A stronger and more realistic Nordic Sea overflow can lead to stronger/deeper AMOC and more realistic North Atlantic Current (NAC) pathways, thus reduced SST cold bias in mid-latitude North Atlantic (Zhang et al. 2011)

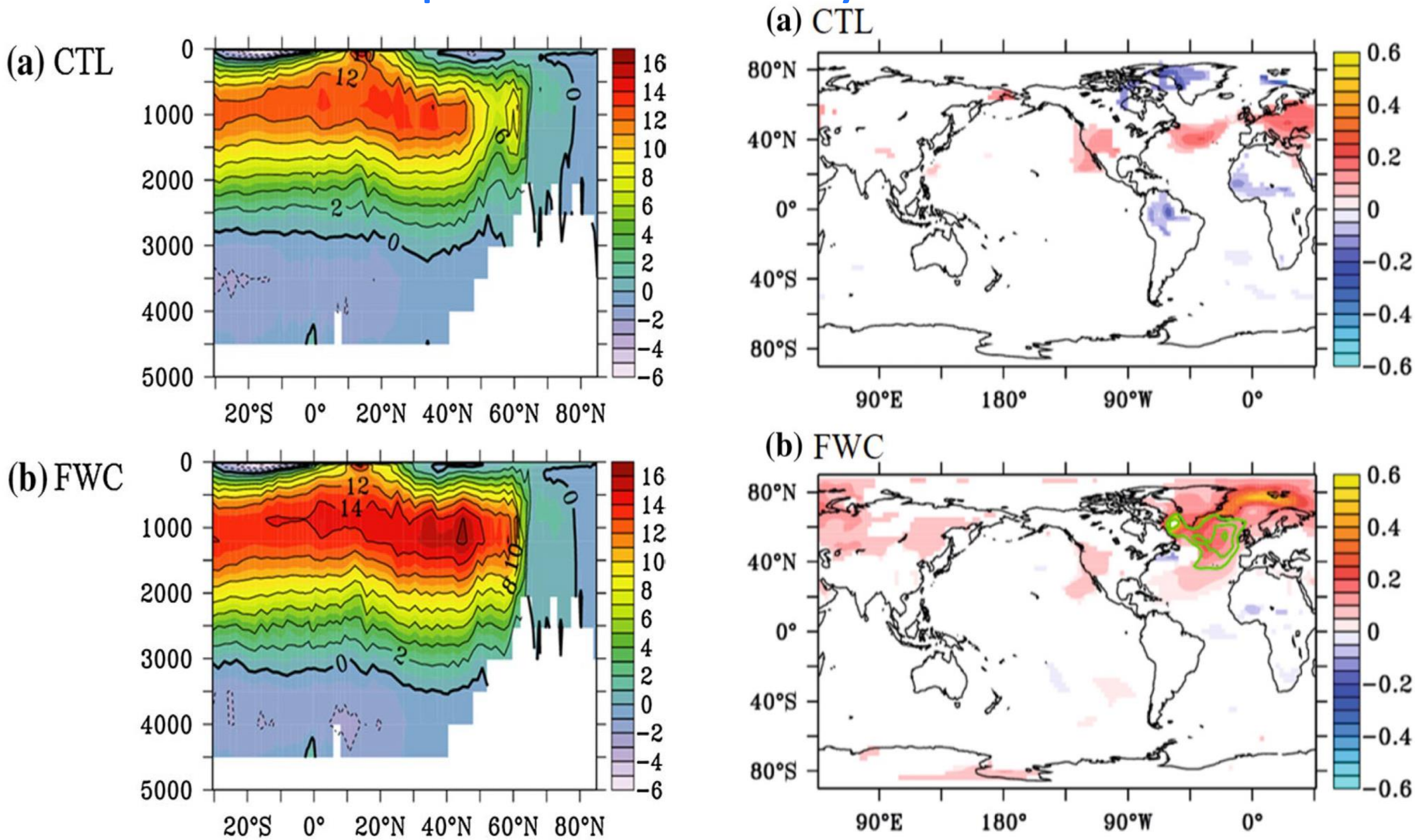


Park et al. 2016, Climate Dynamics

Kiel Climate Model

Climate model with corrected mean state North Atlantic SSS has better mean state deep water formation, reduced SST cold bias in the North Atlantic, and can simulate stronger and more realistic AMOC variability (Park et al. 2016)

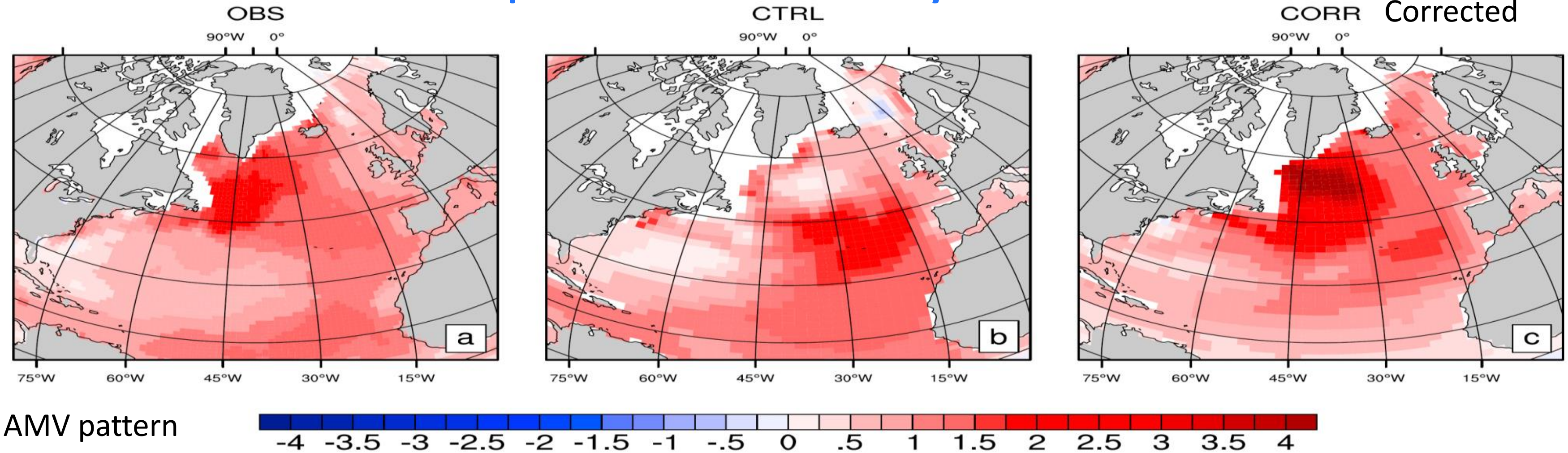
Impact of AMOC Variability on AMV



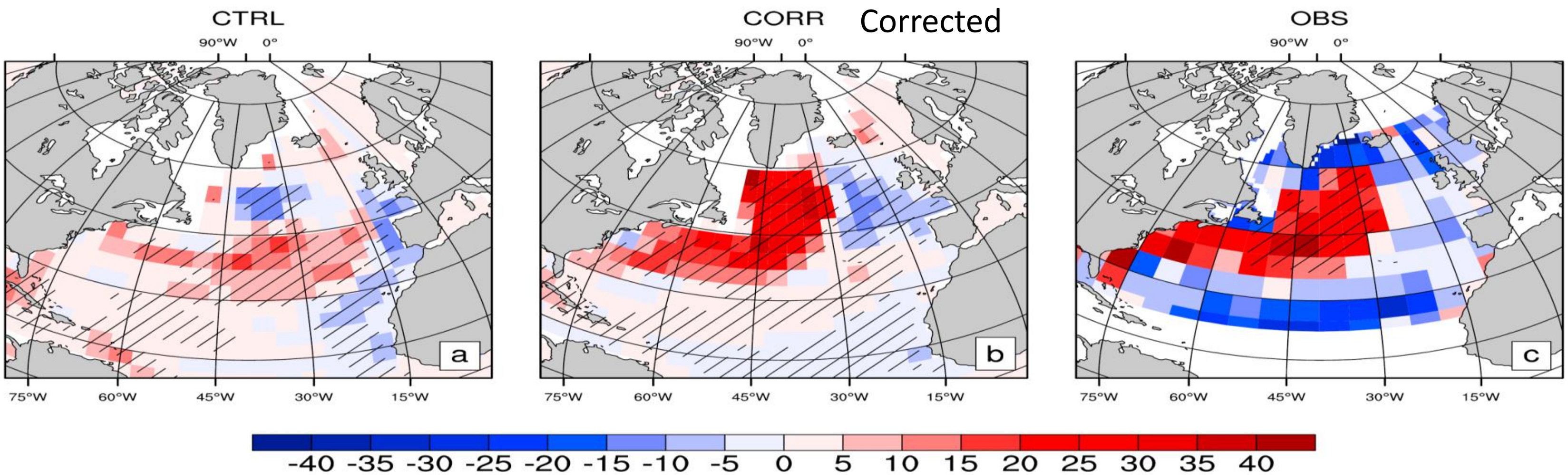
Park et al. 2016, Climate Dynamics   Kiel Climate Model

Climate model with corrected mean state North Atlantic SSS can simulate deeper AMOC and more realistic pattern/amplitude of AMV induced by AMOC variability (Park et al. 2016)

Impact of AMOC Variability on AMV



AMV pattern



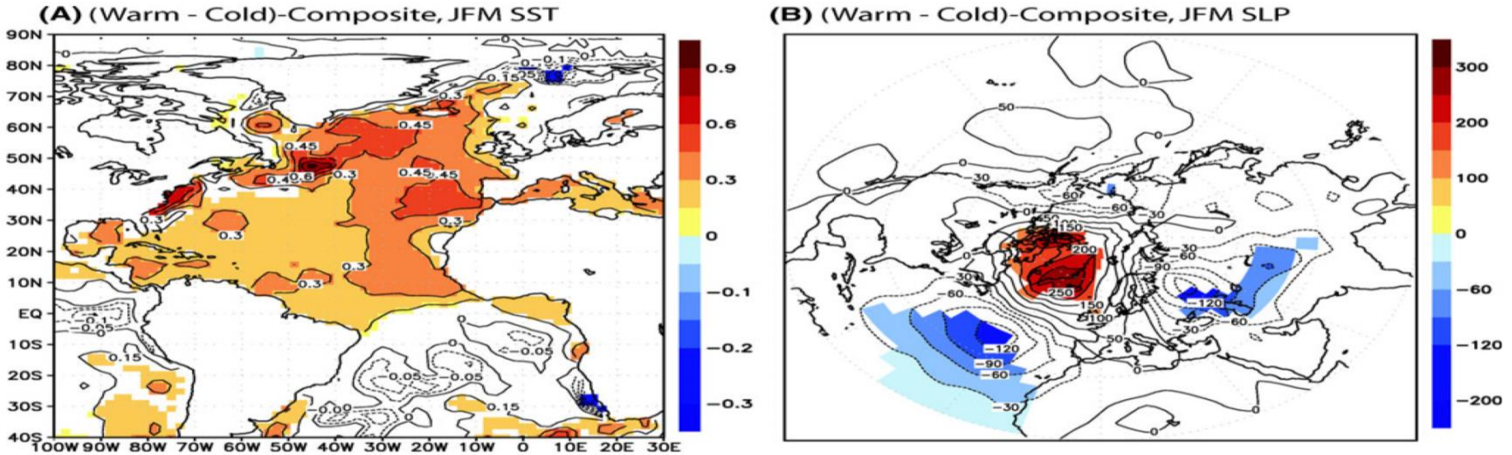
Turbulence heat flux anomalies associated with AMV

Drews and Greatbatch, 2016, GRL

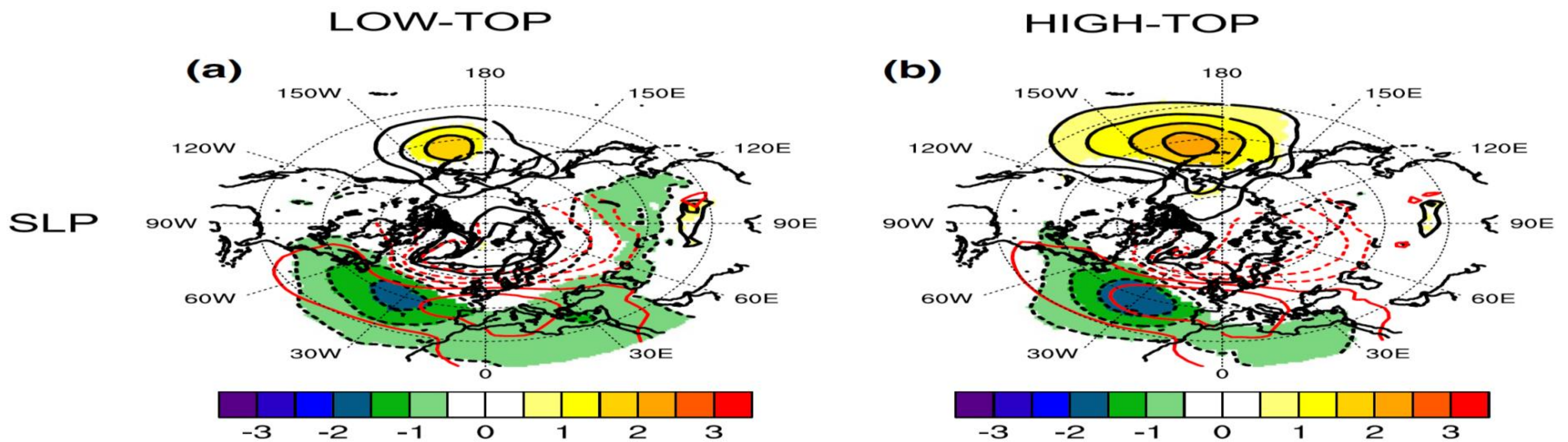
Kiel Climate Model

Climate model with corrected mean state North Atlantic Current (NAC) pathways can simulate more realistic pattern/amplitude of AMV and associated surface turbulence heat flux anomalies induced by AMOC variability (Drews and Greatbatch 2016; 2017)

Impact of AMOC/AMV on Winter NAO



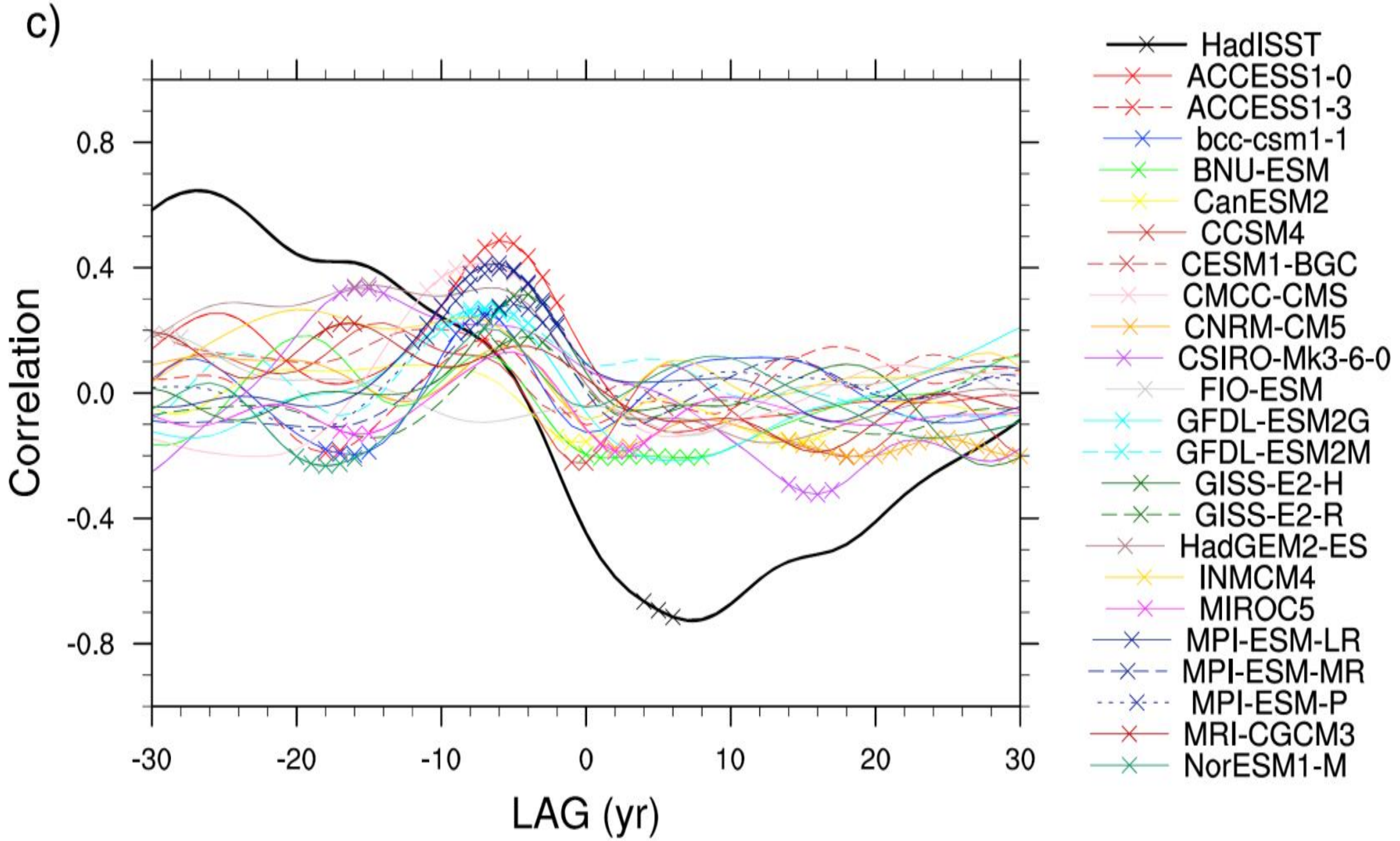
Omrani et al. 2014, Climate Dynamics



Peings and Magnusdottir, 2016, Climate Dynamics

- AMIP experiments with prescribed observed SST anomalies associated with AMV can induce anti-correlated winter NAO response (Omrani et al. 2014; Peings and Magnusdittir 2016)
- Gastineau and Frankignoul, 2012 also shows that a positive AMOC can induce a positive AMV and a significant but weak negative winter NAO and vice versa in coupled models

Impact of AMOC/AMV on Winter NAO

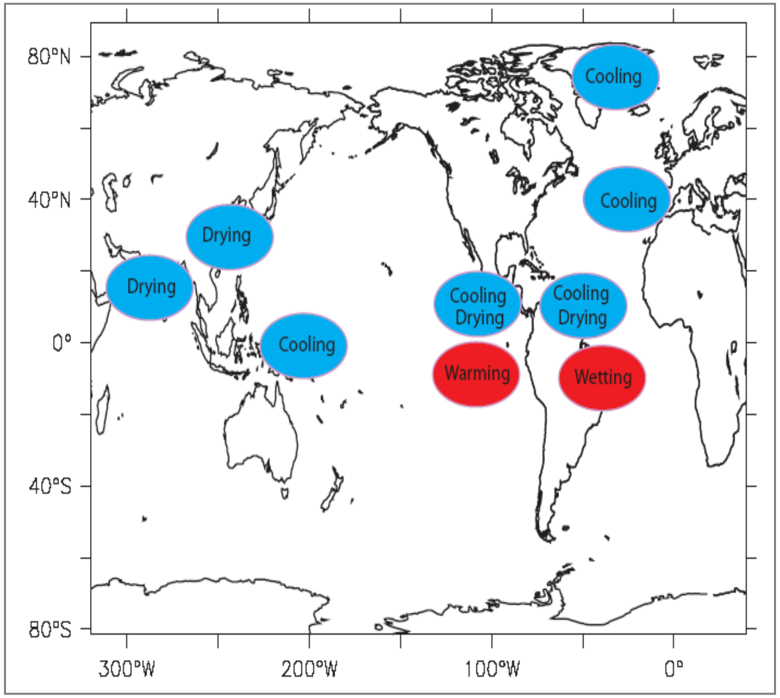


Correlations between the AMV index and the decadal winter NAO index in CMIP5 models and in observations (black) (Peings et al. 2016, JGR-Atmospheres)

Observations show that the observed AMV leads the anti-correlated decadal winter NAO by several years. CMIP5 coupled climate models underestimate the internally generated AMV signal and its associated impact on winter NAO (Peings et al. 2016)

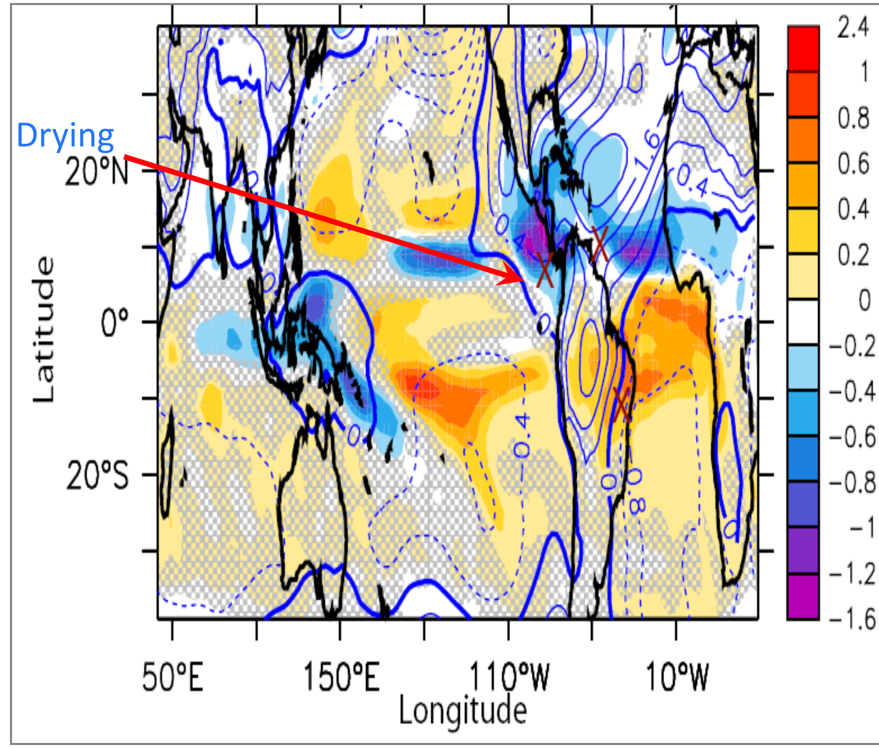
Impact of AMOC on ITCZ

Schematic diagram of global response to AMOC weakening indicated by paleo records



Modeled responses due to the weakening of AMOC

Precipitation (shading) and SLP



A substantial weakening of the AMOC is linked to:

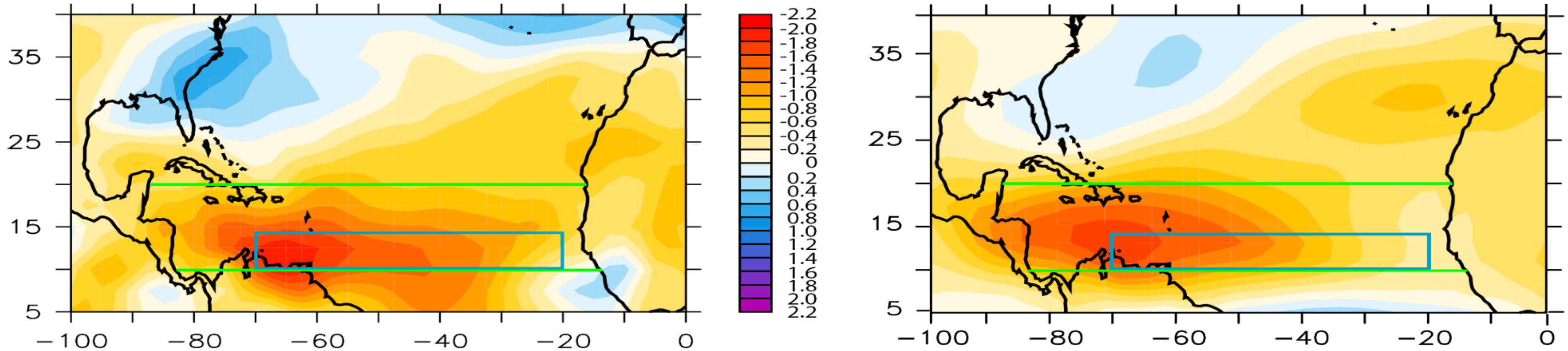
- **Southward shift of ITCZ in both Atlantic and Pacific**
- **Weaker East Asia and Indian Summer Monsoons**

Zhang and Delworth, 2005, Journal of Climate

- The impact of AMOC/ocean heat transport on the ITCZ position is supported in more recent observational and modeling studies (Marshall et al. 2013; Frierson et al. 2013)
- The ITCZ response is amplified by low cloud feedback (Zhang et al. 2010)

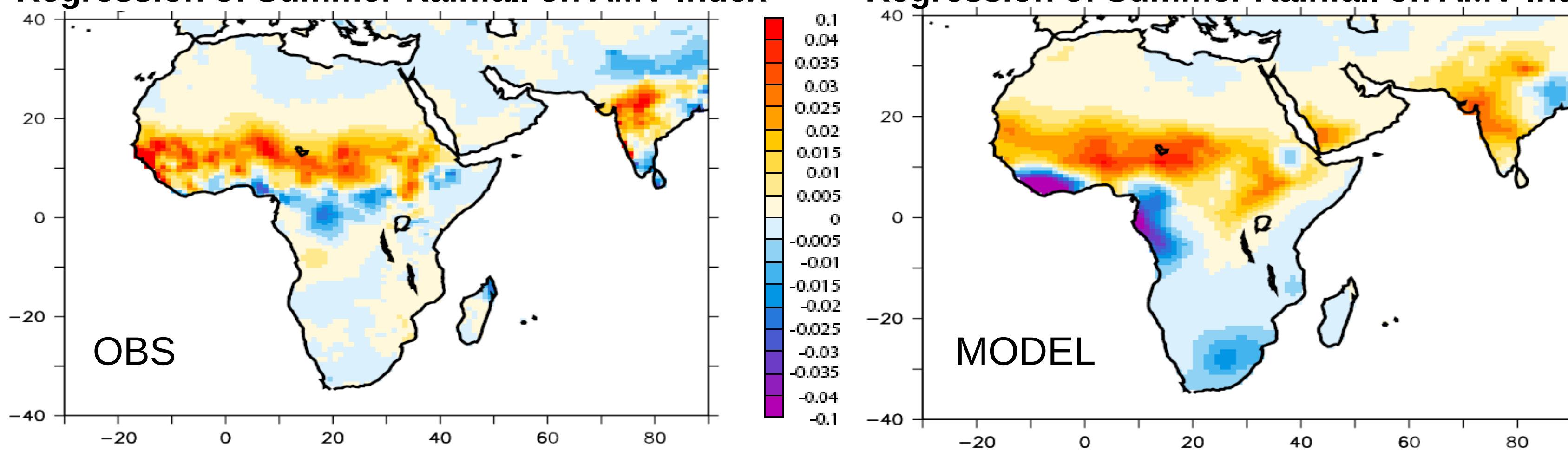
Impact of AMV on Atlantic Hurricane Activity and India/Sahel Summer Rainfall

Regression of hurricane season vertical shear of zonal wind (m/s) on AMV index (1958-2000)



ECMWF 40-yr Reanalysis | MODEL (10-member ensemble mean)

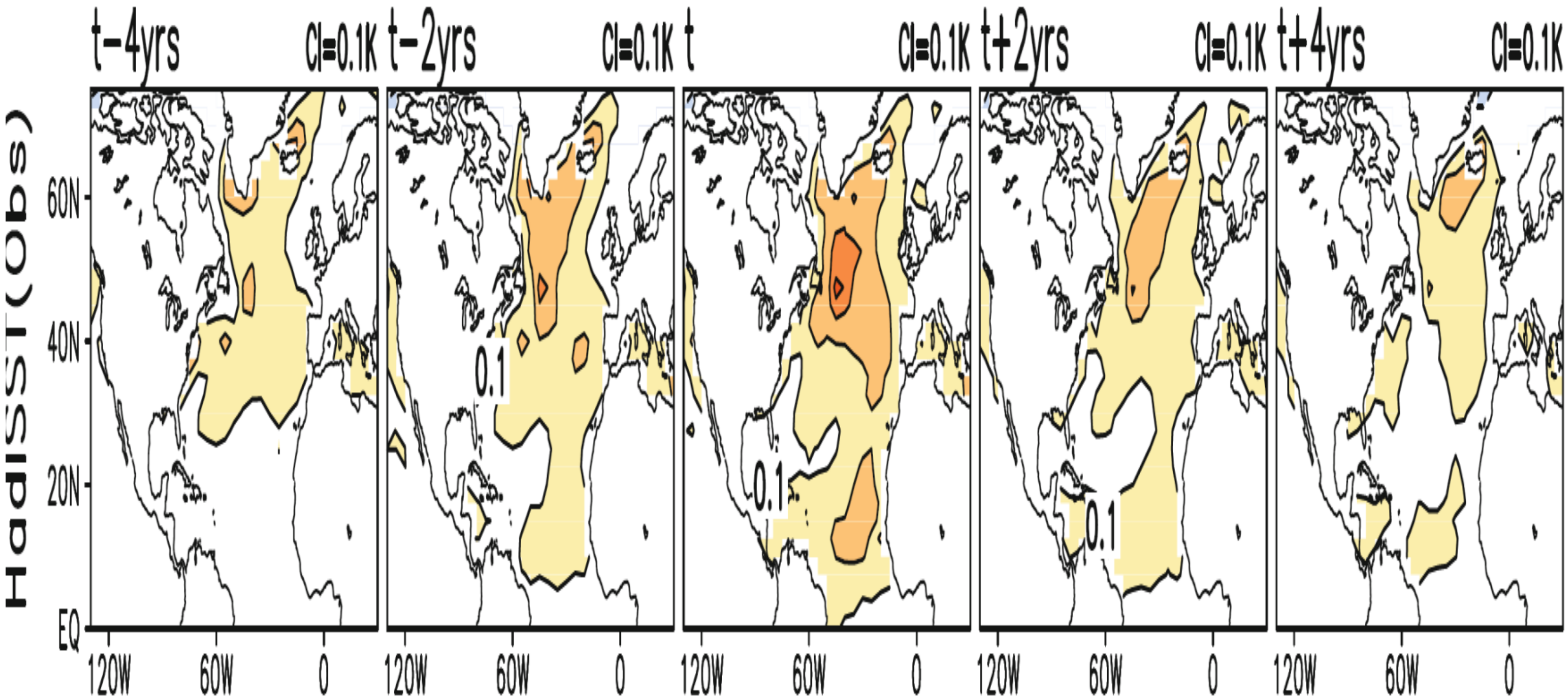
Regression of Summer Rainfall on AMV Index | **Regression of Summer Rainfall on AMV Index**



Zhang and Delworth, 2006, GRL

Both observations and modelling results suggest that the AMV plays a leading role in generating coherent multidecadal variations of India/Sahel summer rainfall, Atlantic ITCZ shift, and Atlantic Hurricane frequency (Zhang and Delworth 2006; Ting et al. 2011)

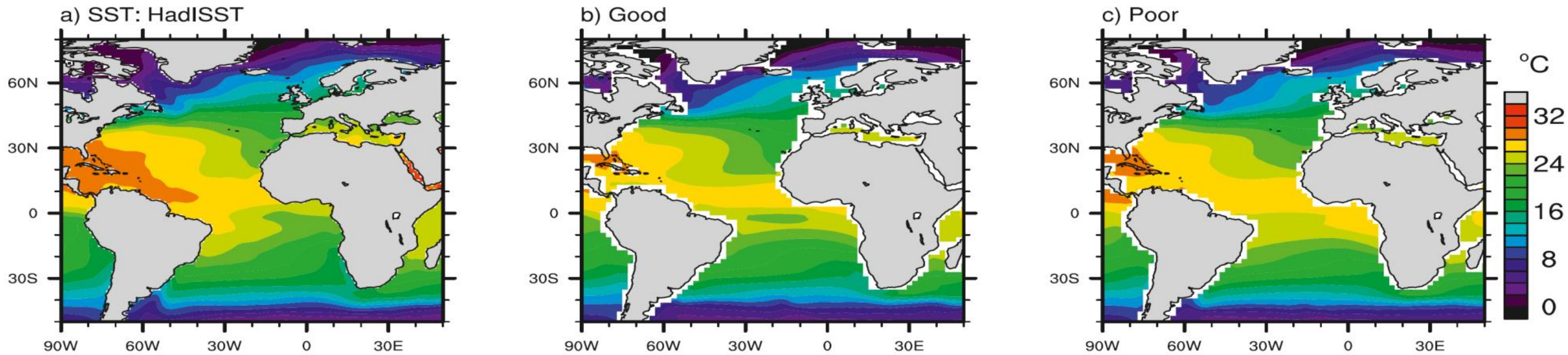
Evolution of the Observed AMV



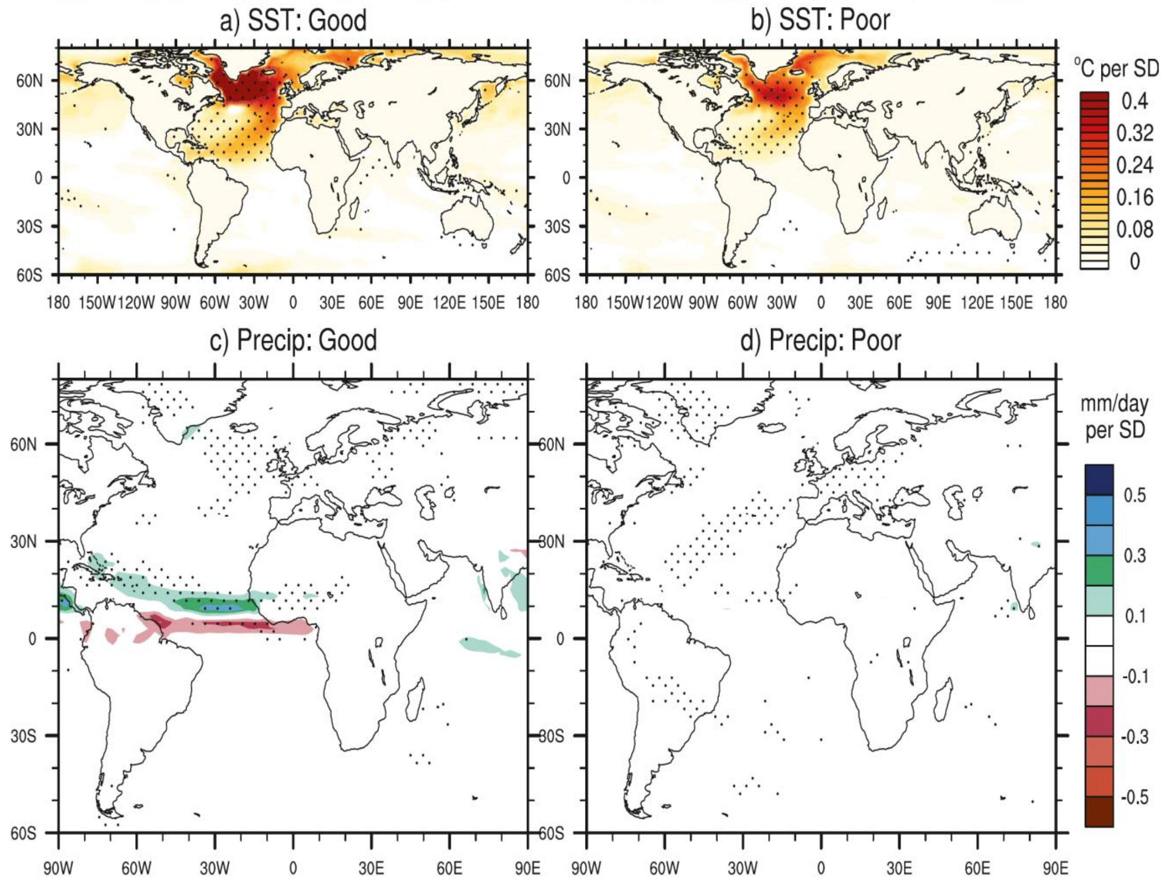
Ruiz-Barradas et al. 2013, Climate Dynamics

The weaker low-latitude AMV signal responds to the stronger subpolar AMV signal through combined oceanic and atmospheric teleconnections, e.g. WES feedback and cloud feedback (Zhang, 2007; Dunstone et al. 2011; Wang et al. 2012; Hodson et al. 2014, Yuan, et al. 2016; Brown et al. 2016)

Mean State SST Bias in Tropical North Atlantic and Impact of AMOC/AMV on ITCZ

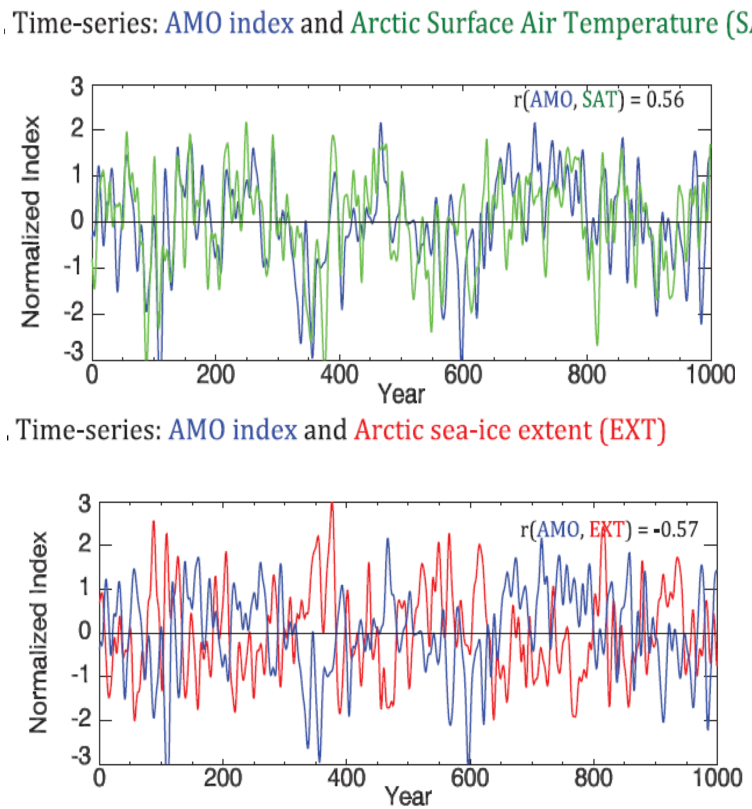


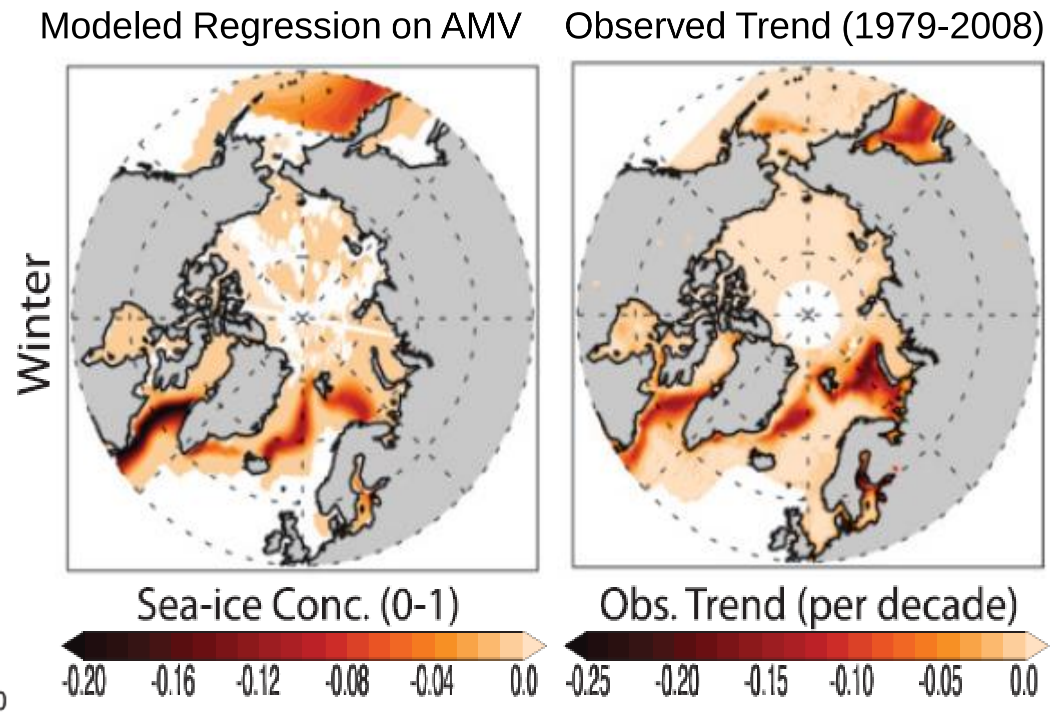
Martin et al. 2014,
Journal of Climate



Climate models with less mean state SST bias in tropical North Atlantic, can simulate better the linkage between the AMOC variability/subpolar AMV signal and the tropical AMV signal/associated ITCZ shift (Martin et al. 2014)

Impact of AMOC/AMV on Winter Arctic Sea Ice Variability

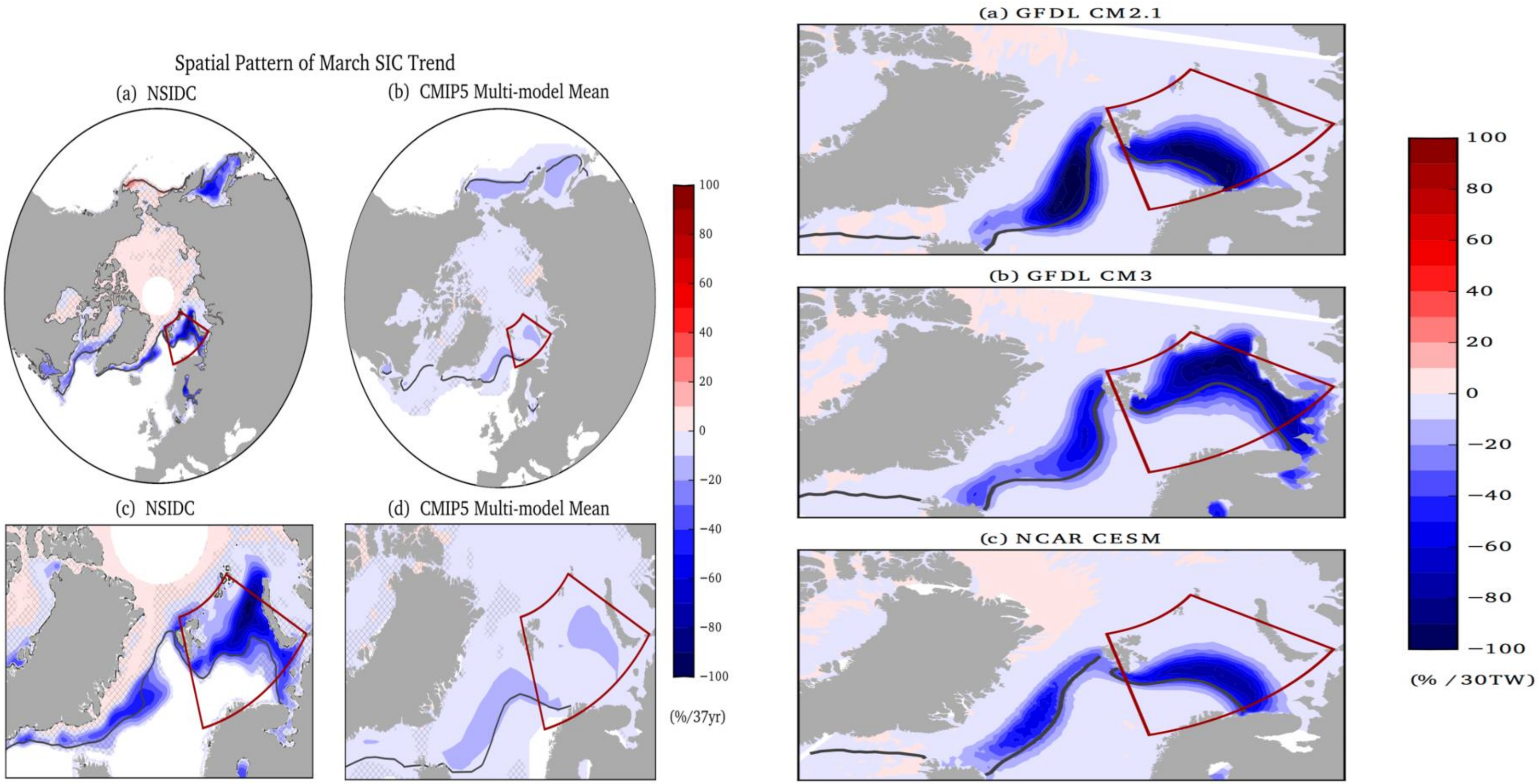




GFDL CM2.1 1000-year control simulation (Mahajan, Zhang, and Delworth, 2011, JOC)

- 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 AMV and winter Arctic sea ice is further found in other climate models (Day et al. 2012), paleo records (Miles et al. 2014), and decadal prediction experiments (Yeager et al. 2015)

Discrepancy between Observed and CMIP5 Simulated Winter Sea Ice Decline



Li, Zhang, and Knutson, 2017, Nature Communications

CMIP5 externally forced winter SIC trend in individual regions (especially in Barents Sea) differs substantially from that observed

Internal variability may have played a leading role in the observed winter Barents Sea SIC decline. The amplitude of internal variability is underestimated in coupled models

Other Climate Impacts of AMV

- Multidecadal variations in U.S. rainfall and drought frequency (Enfield et al., 2001; McCabe et al. 2004; Ruprich-Robert et al. 2017)

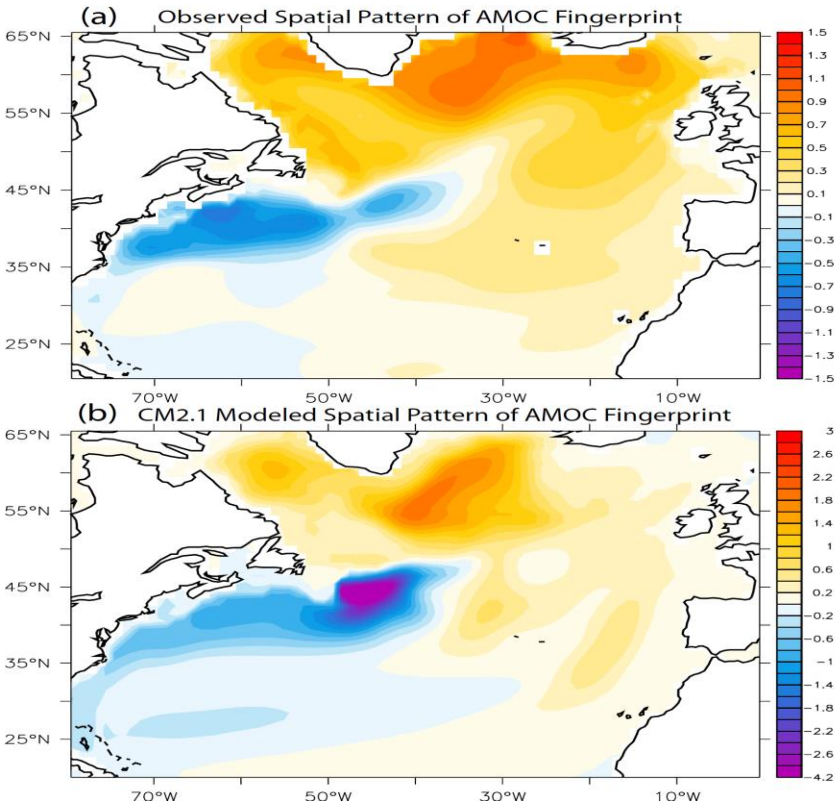
- Multidecadal variations in summer climate over North America and Europe (Sutton and Hodson, 2005, 2007; Sutton and Dong, 2012)

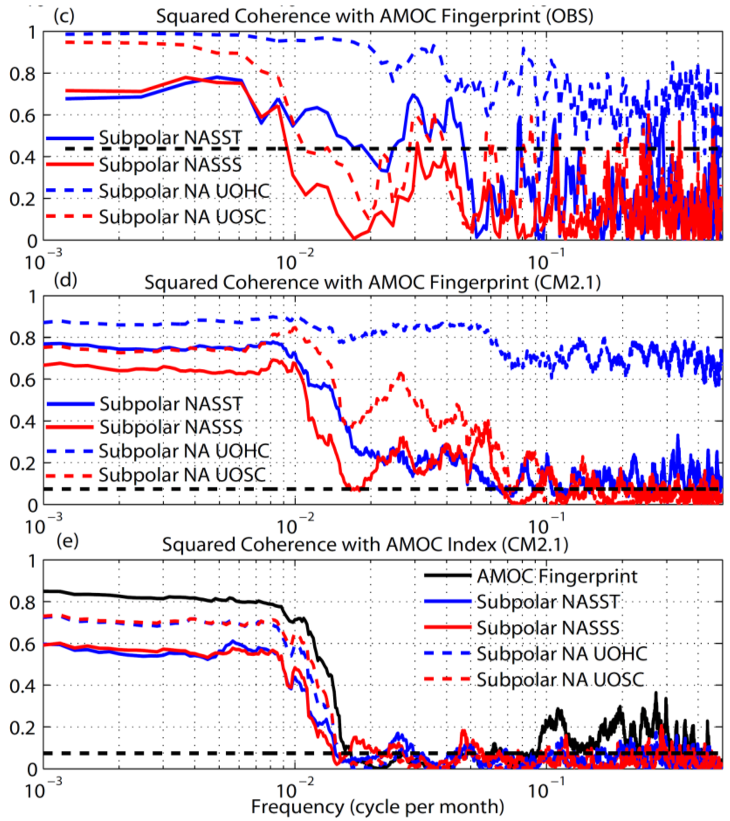
- Multidecadal variations in northern hemispheric mean surface temperature (Zhang et al. 2007; Semenov et al., 2010)

- Influence on Pacific decadal variability and multidecadal ENSO variability (Zhang and Delworth, 2007; Dong and Sutton, 2007; Kang et al. 2014; Kucharski et al. 2015; Ruprich-Robert et al. 2017)

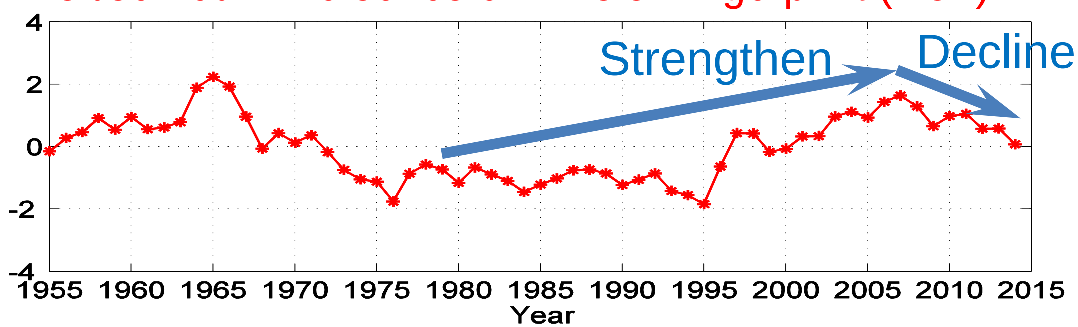
Observed and Simulated Pattern of AMOC Fingerprint: EOF1 of Upper Ocean Heat Content

Zhang, 2017, GRL





Observed Time series of AMOC Fingerprint (PC1)



High coherence among Subpolar NA SST, SSS, UOHC/UOSC anomalies associated with the AMV and the AMOC fingerprint at low frequency provides more evidence for AMOC variability being a key driver for the AMV

Summary and Discussion

- Most CMIP5 models with z-coordinate ocean components simulate a strong SST cold bias in mid-latitude North Atlantic, due to incorrect North Atlantic Current pathways induced by weaker/shallower AMOC and unrealistic Nordic Sea overflow

- A stronger and more realistic Nordic Sea overflow (such as that simulated in climate models with isopycnal-coordinate ocean components) can lead to deeper AMOC, enhanced meridional ocean heat transport, more realistic pathways of the North Atlantic Current, and reduced SST cold bias in mid-latitude North Atlantic

- Climate models with corrected mean state North Atlantic ocean circulation can simulate stronger and more realistic AMOC variability, and thus more realistic pattern/amplitude of AMV and associated surface turbulence heat flux anomalies

- Observations and AMIP experiments show that the AMV leads to anti-correlated winter NAO response at low frequency. CMIP5 coupled climate models underestimate the internally generated AMV signal and its associated impact on winter NAO

Summary and Discussion

- Climate models with better mean state SST in tropical North Atlantic can simulate better linkage between the AMOC variability/subpolar AMV signal and the tropical AMV signal/ITCZ shift
- The AMOC/AMV has predictable impact on low frequency winter Arctic sea ice variability, but the amplitude of low frequency Atlantic variability is underestimated in coupled models
- It's crucial to improve climate models' mean state for a better simulation of the impacts of AMOC on AMV and associated global and regional scale variability
- The AMOC fingerprint has high coherence with subpolar AMV signal in temperature and salinity, and provides more evidence for AMOC variability being a key driver for the AMV