The Atlantic Multidecadal Variability: Mechanism, Predictability, and Associated Impact on Hurricane Activity

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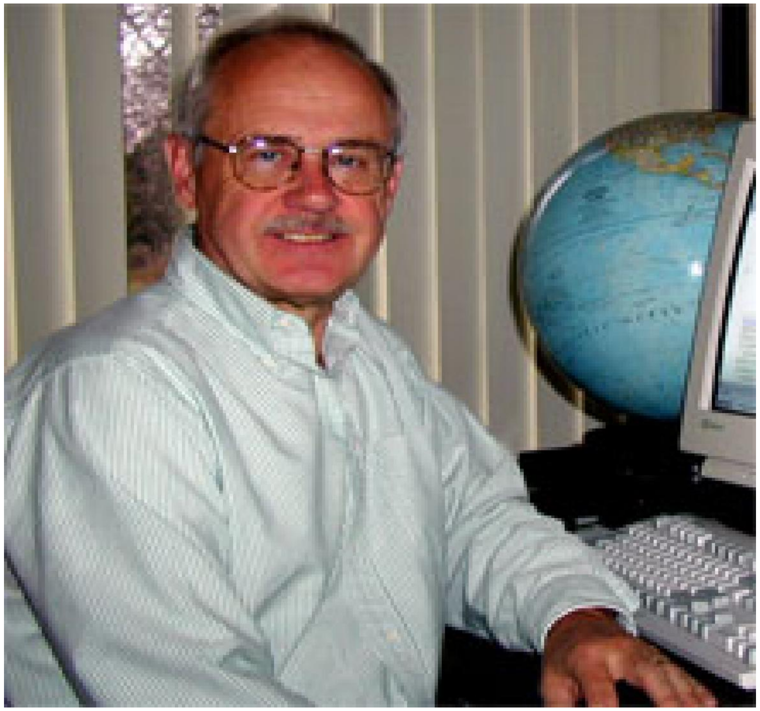
NOAA/GFDL

Workshop on Atlantic Climate Variability – Dynamics, Prediction and Hurricane Risk
Columbia University, September 8, 2017

Dedicated to Ants Leetmaa

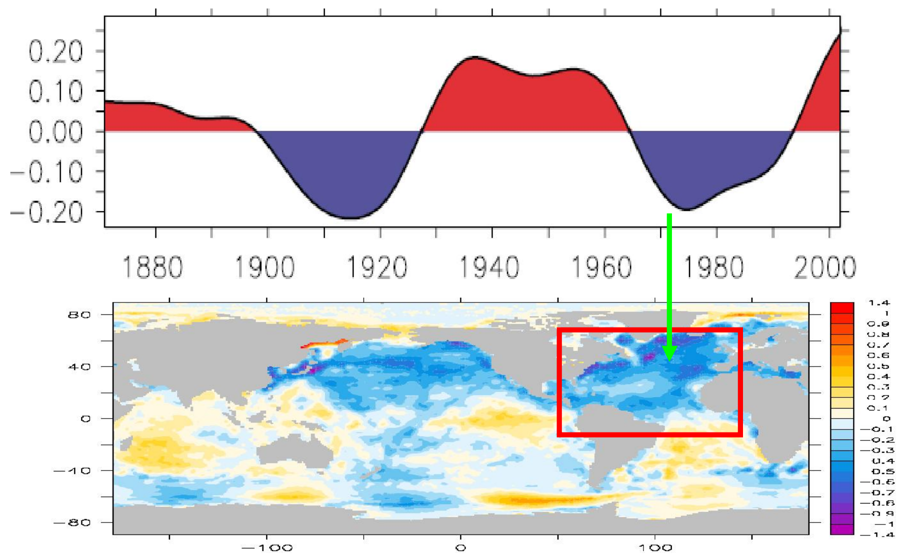
GFDL's Third Director



Atlantic Multidecadal Variability (AMV)

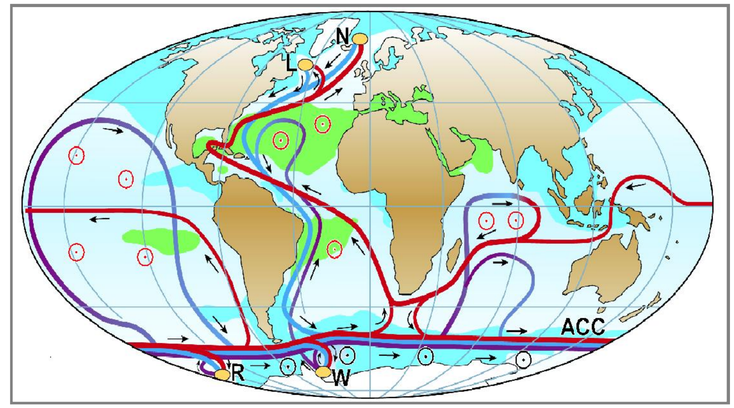
Large-scale low frequency variability in the Atlantic has been observed during the 20th century - Atlantic Multidecadal Variability (AMV)

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



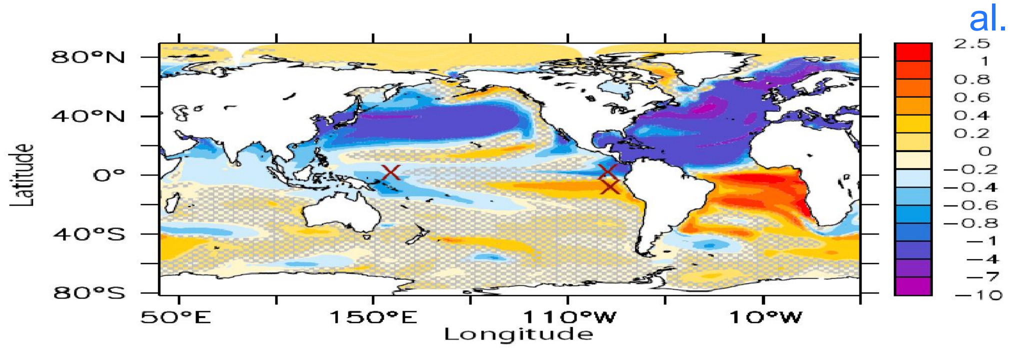
Observed Multidecadal SST Difference (1971-1990) – (1941-1960) (HadISST, detrended)

Atlantic Meridional Overturning Circulation (AMOC)



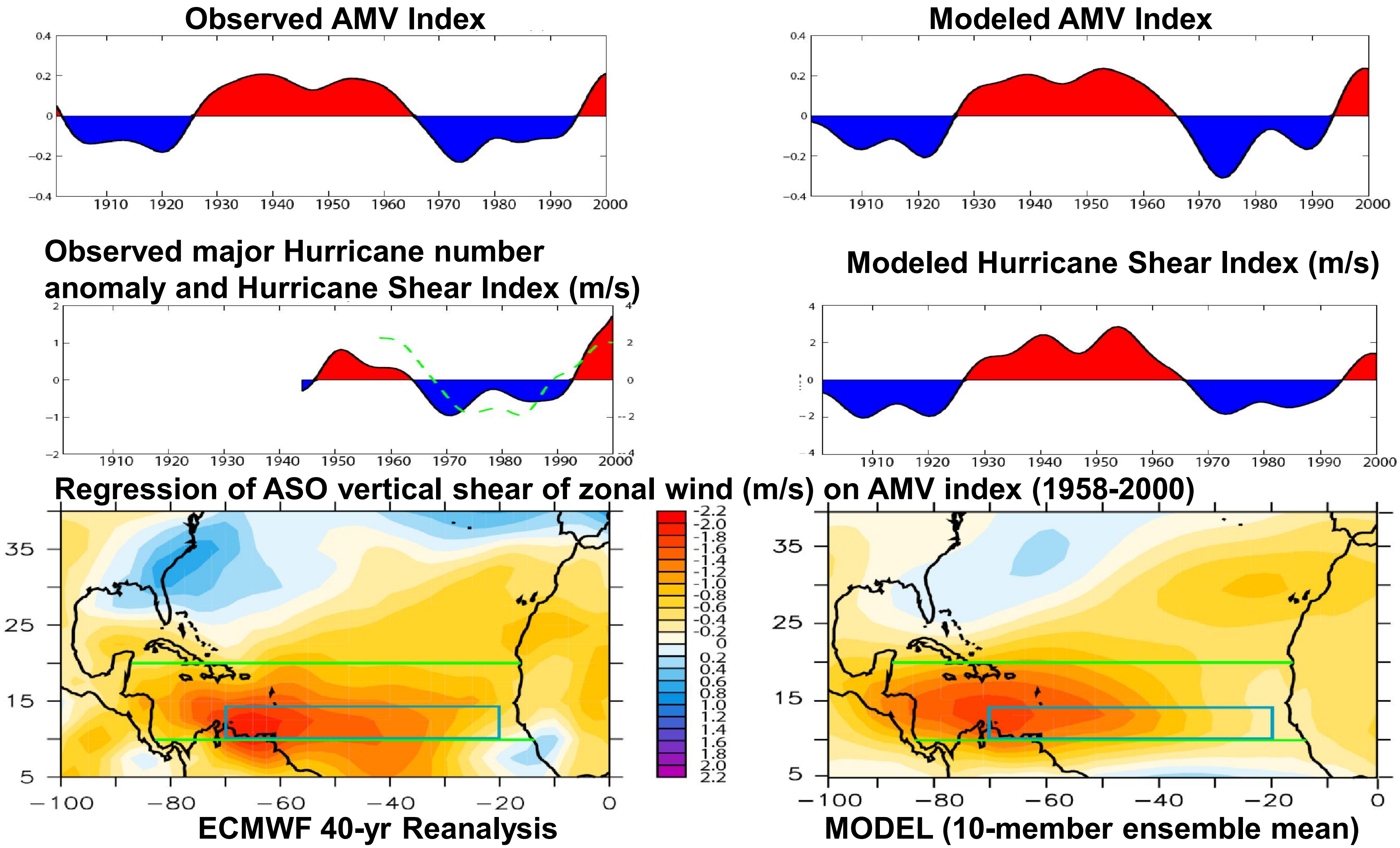
Kuklbrodt et al. 2007, Reviews of Geophysics

Many observational and modeling studies suggest that the low frequency AMOC variability is a leading mechanism of the observed AMV (Kushnir, 1994; Delworth and Mann, 2000; Knight et al., 2005; Latif et al., 2006; Zhang et al. 2013; Ba et al. 2013)



Simulated SST anomaly induced by AMOC weakening in the water-hosing experiment (Zhang and Delworth, 2005, JOC)

Impact of AMV on Atlantic Hurricane Activity



Zhang and Delworth, 2006, GRL

Positive AMV phase leads to a reduction of the vertical shear over the tropical North Atlantic Main Development Region (MDR)

AMV and Multidecadal Atlantic Hurricane Activity

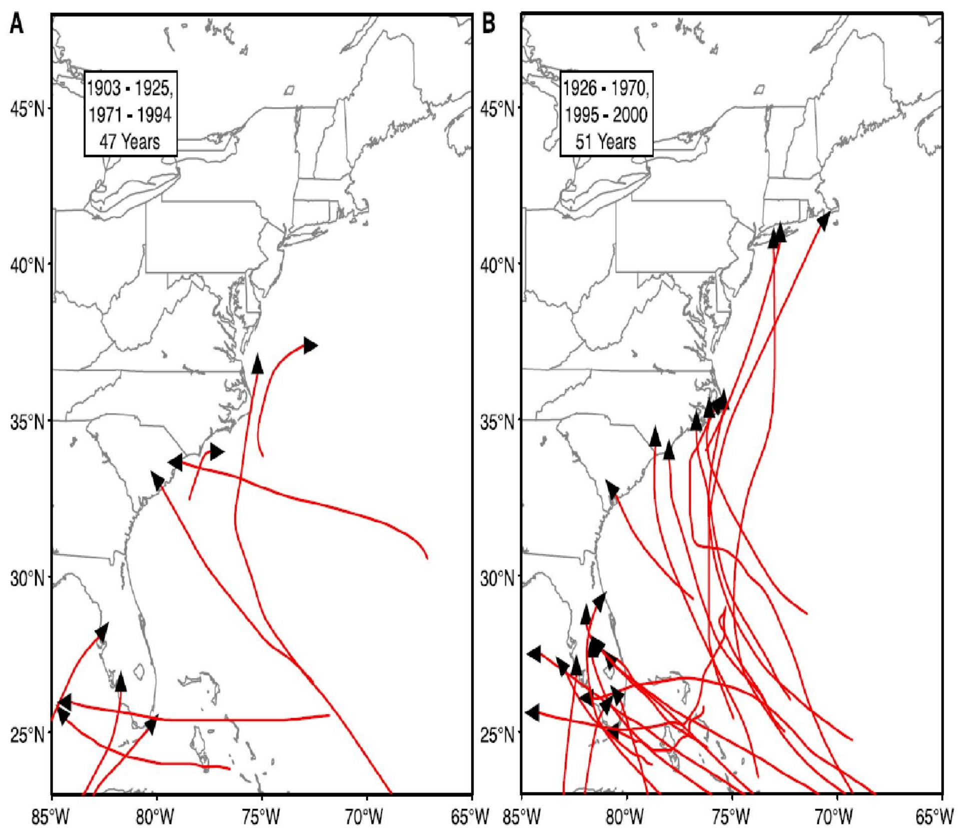
Negative AMV Phase

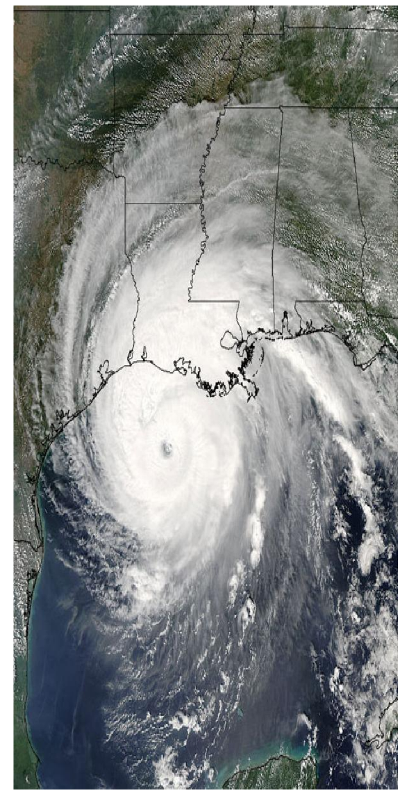
Cold North Atlantic

Positive AMV Phase

Warm North Atlantic

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

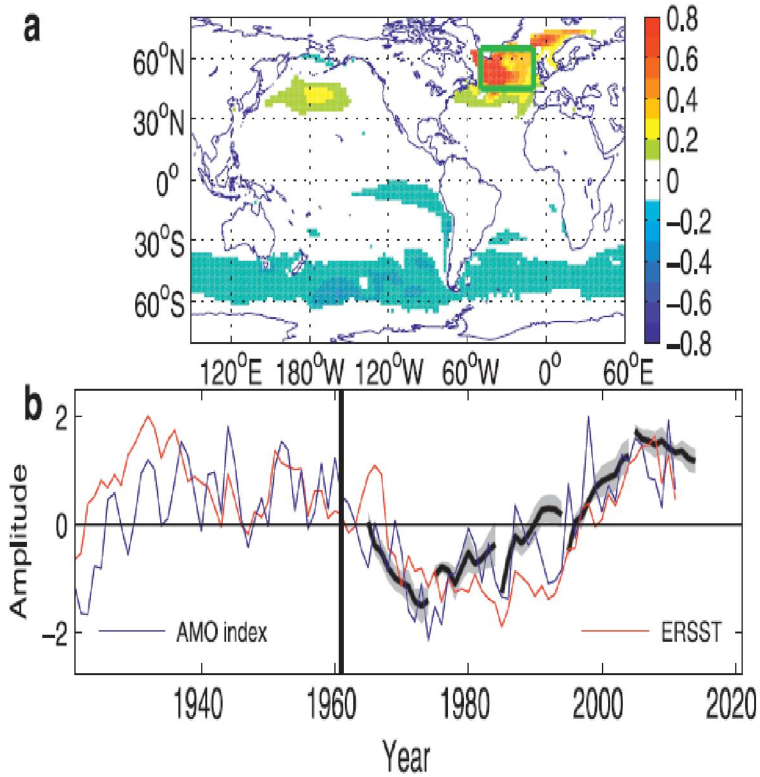




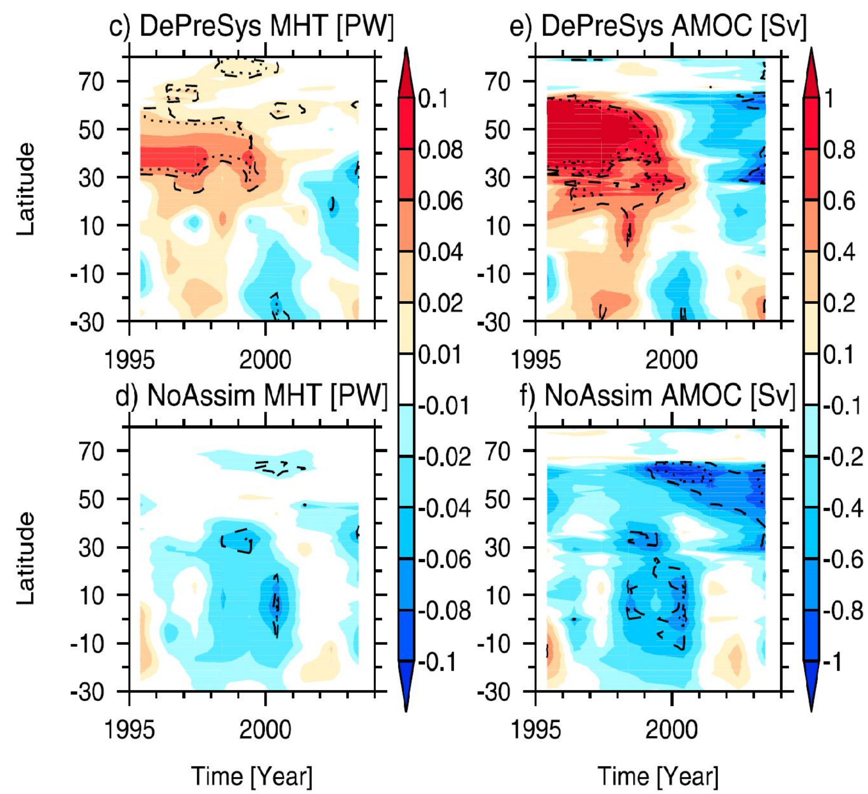
Goldenberg et al. 2001, Science

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

Decadal Prediction of the Observed Atlantic Multidecadal Variability (AMV)



Yang et al. 2013, JOC

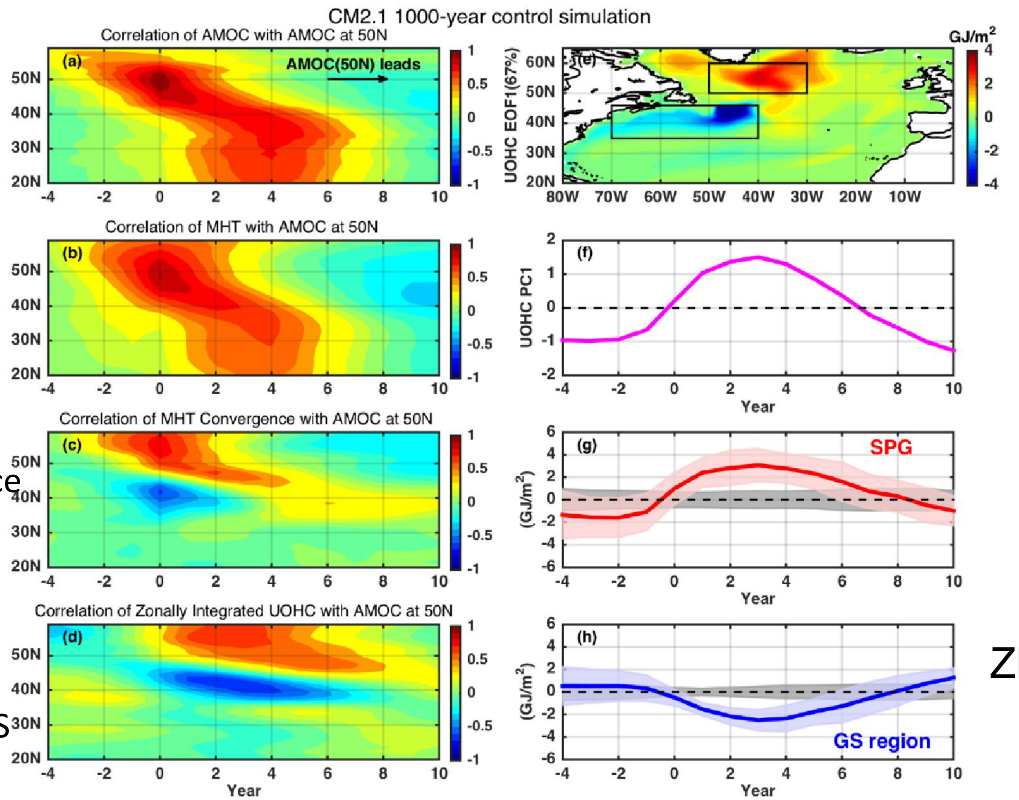


Robson et al. 2012, GRL

- Recent decadal prediction studies (Yeager et al. 2012; Robson et al. 2012; Yang et al., 2013; Msadek et al. 2014) successfully predicted the decadal warming shift in the mid 90's in the NA SPG with initialized ocean states
- Initializing a strong AMOC at northern high latitudes is the key for the successful predictions
- Hindcasts with no initialization in the ocean states are not able to predict the decadal warming shift

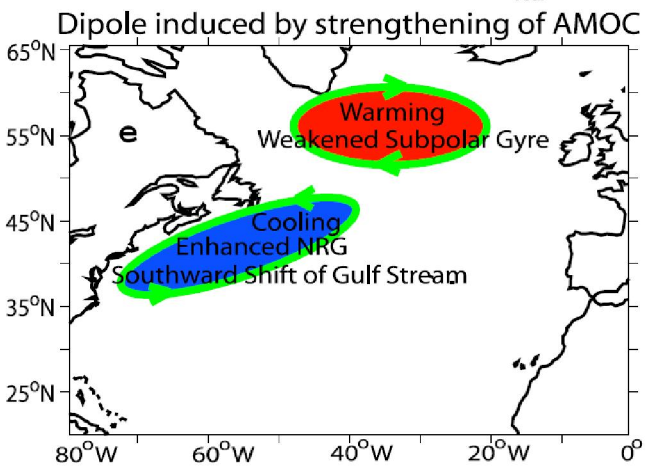
Extra-tropical AMOC Fingerprint – Leading Mode of Upper Ocean Heat Content

Southward propagation of AMOC anomaly
↓
Southward propagation of MHT anomaly
↓
MHT convergence in SPG and divergence in GS
↓
Warming in SPG and cooling in GS



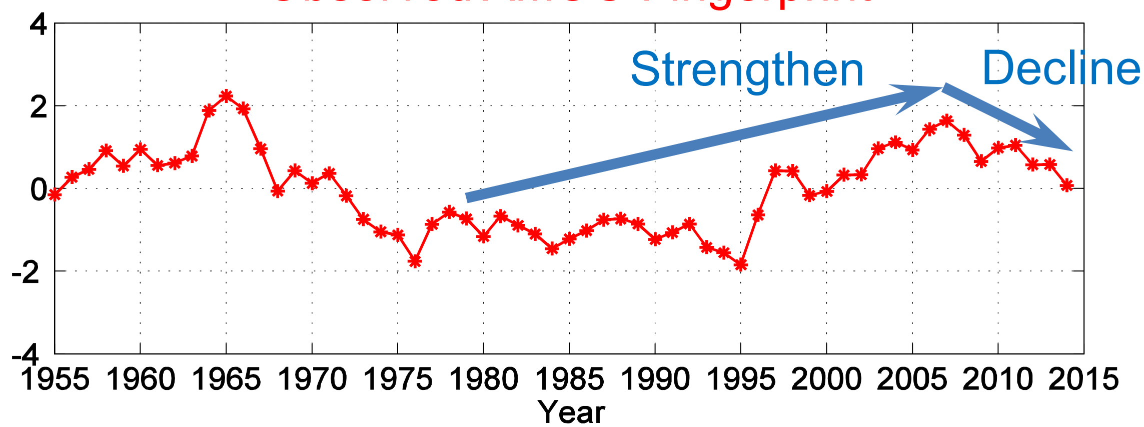
The slow southward propagation of AMOC anomaly is crucial for the evolution and enhanced decadal predictability of the AMOC fingerprint

Zhang and Zhang, 2015, GRL

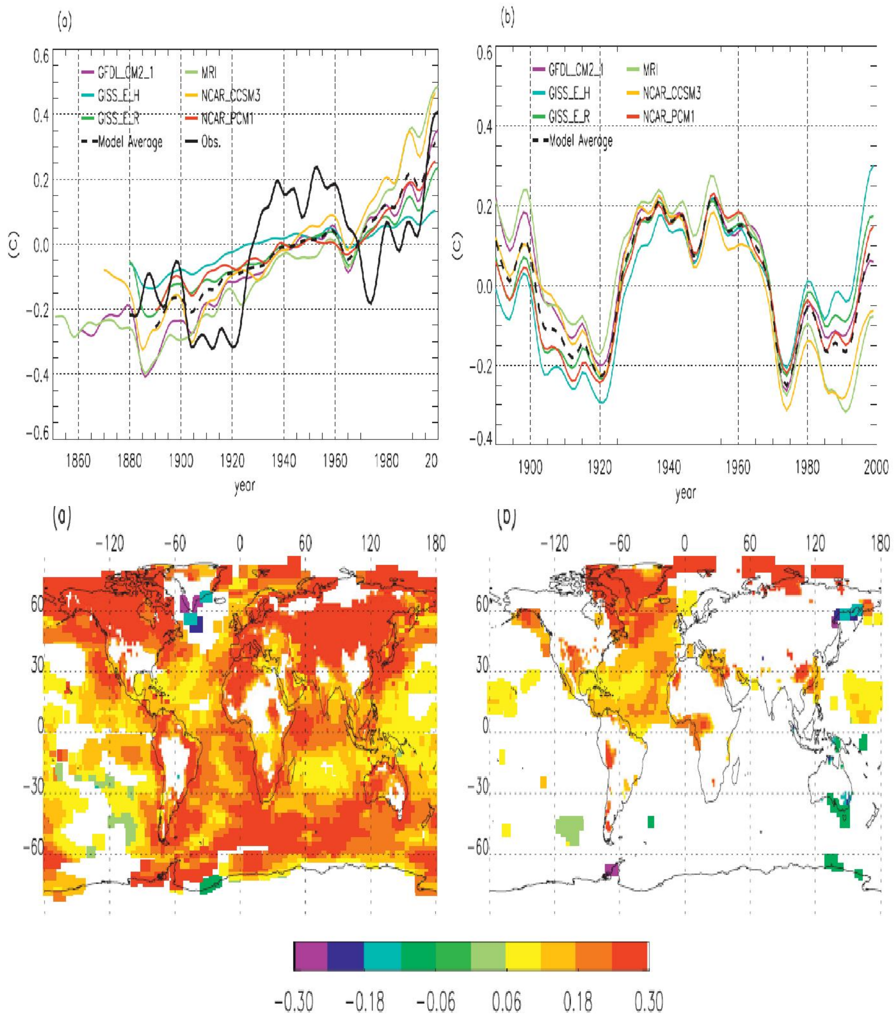


Zhang, 2008, GRL

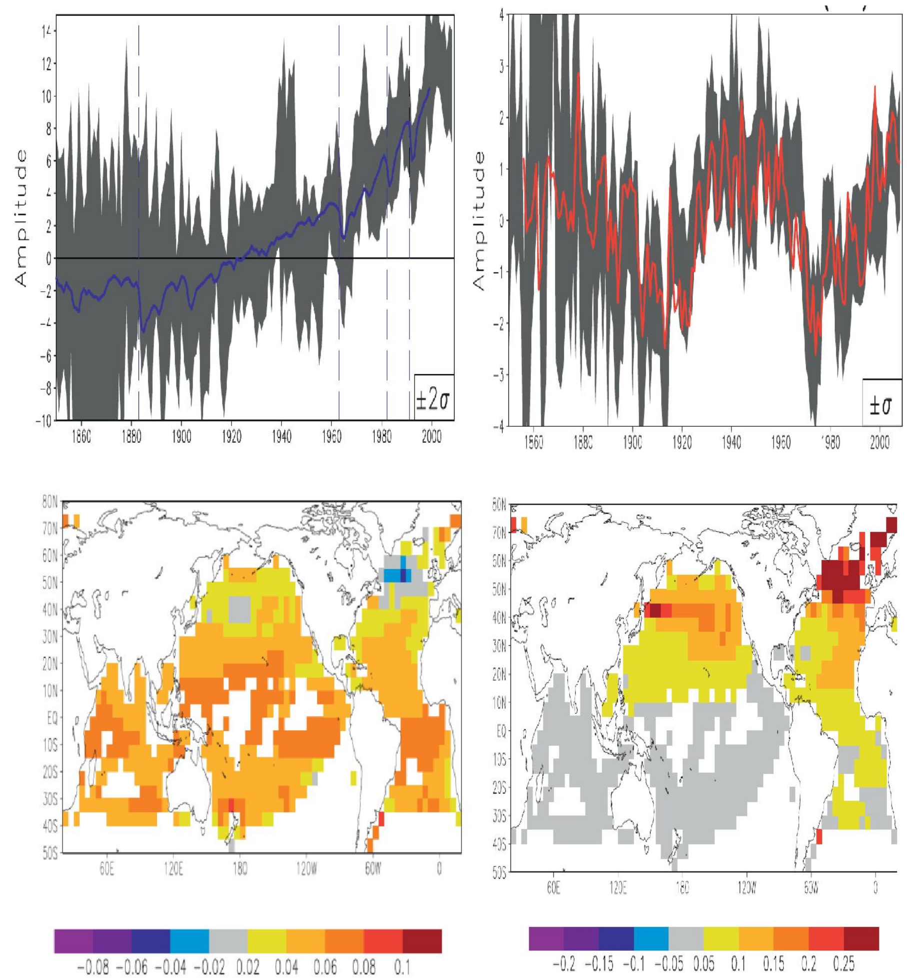
Observed AMOC Fingerprint



Forced and Natural Atlantic Variability



Forced Response   Natural Variability

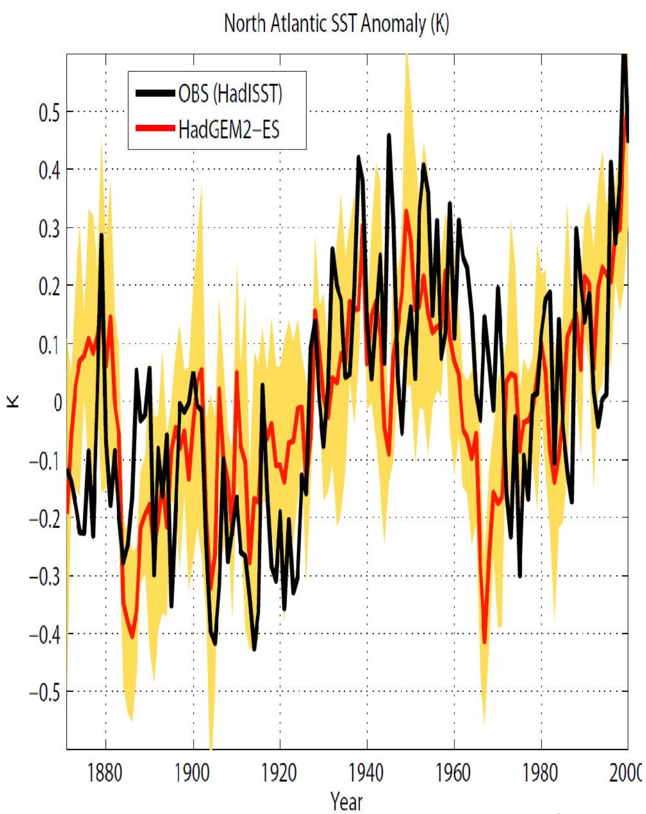


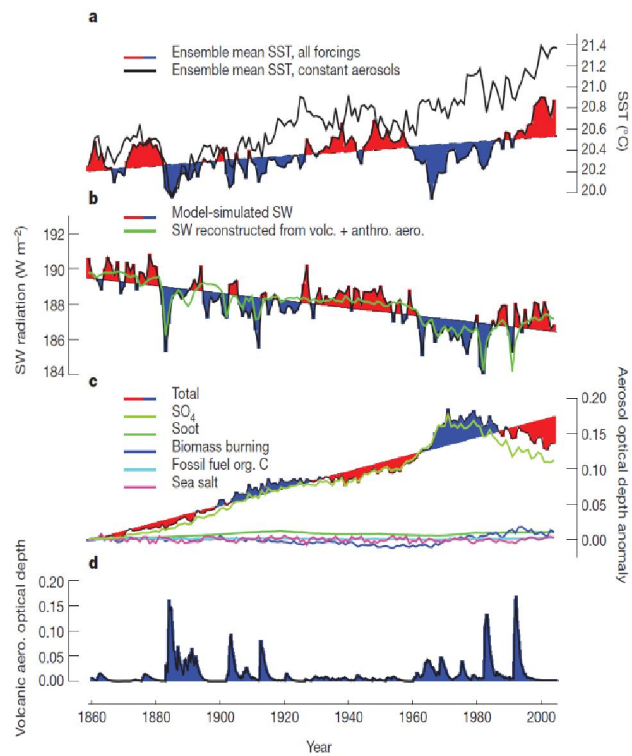
Forced Response   Internal Multidecadal Pattern

Ting et al. 2009, JOC

Delsole et al 2011, JOC

Recent Debate on Mechanisms of the AMV

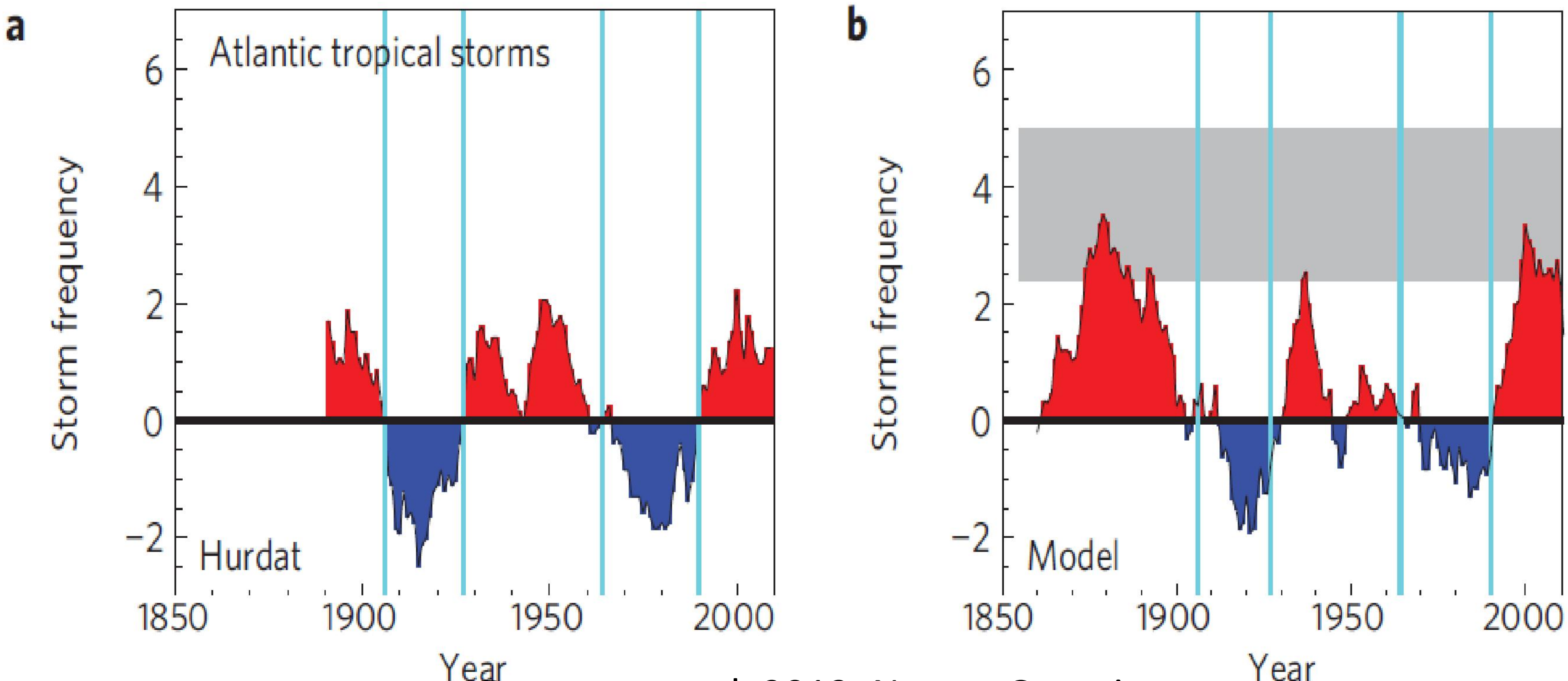




Booth et al., 2012, Nature

A recent study using the latest UK Met Office Earth System Model (HadGEM2-ES) closely reproduces the observed SST-based AMV Index, which is forced by aerosol indirect effects that modify net surface shortwave radiation. Hence the study claimed aerosols as a prime driver of observed AMV

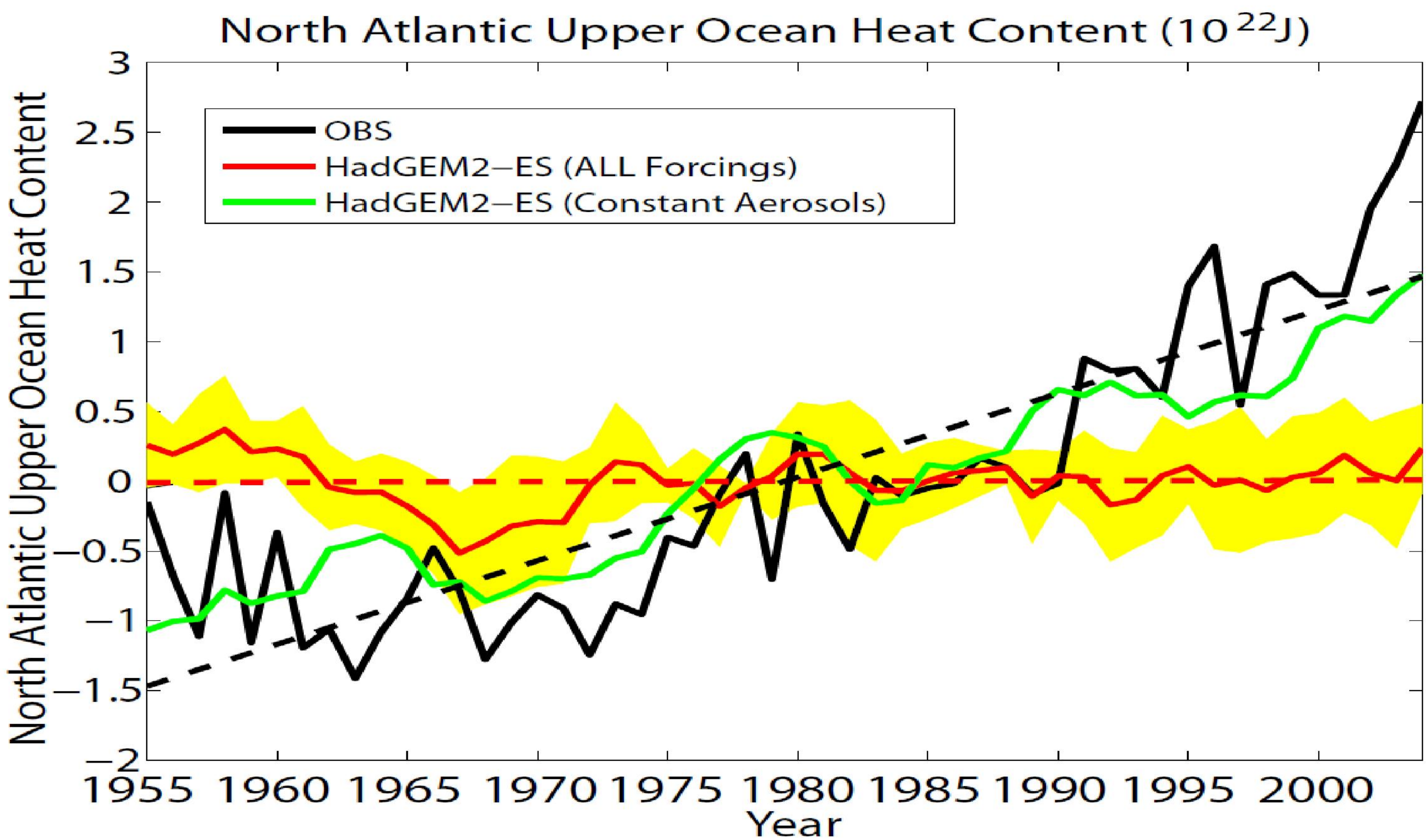
Anthropogenic Aerosol Forcing of Atlantic Tropical Storms



Dunstone et al. 2013, Nature Geoscience

Similarly, a very recent study using the same HadGEM2-ES historical ensemble simulation well reproduces the observed multidecadal variations of Atlantic tropical storms frequency, mainly due to simulated aerosol indirect effects. This study concludes that anthropogenic aerosols may have dominated the historical tropical storm variability

Key Discrepancies between HadGEM2-ES Simulations and Observations

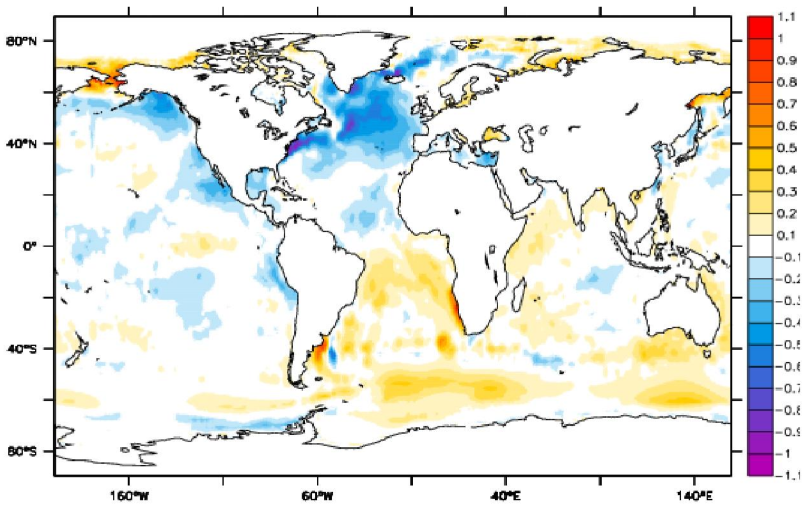


Zhang et al. 2013, JAS

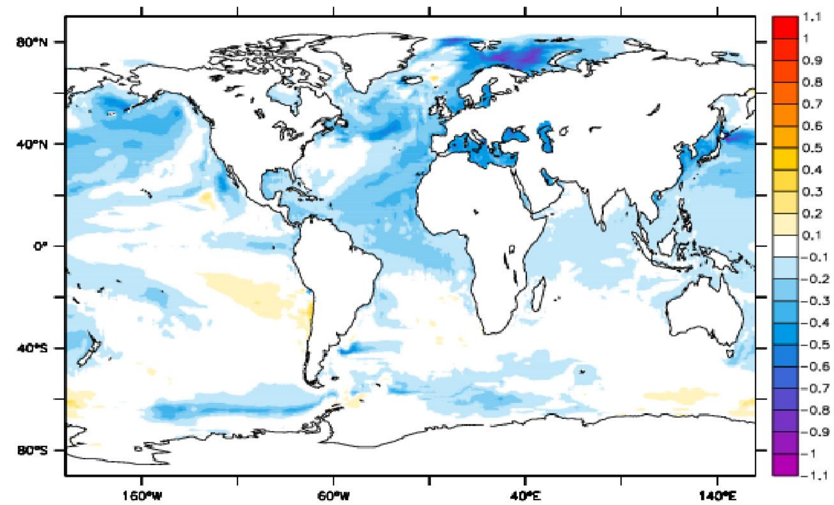
Observations show substantial warming trend in the North Atlantic upper ocean heat content, in contrast, the All-forcing simulations in HadGEM2-ES show no warming trend. The discrepancy is mainly due to anthropogenic aerosols and suggests that aerosol effects are strongly overestimated

Key Discrepancies between HadGEM2-ES Simulations and Observations

OBS



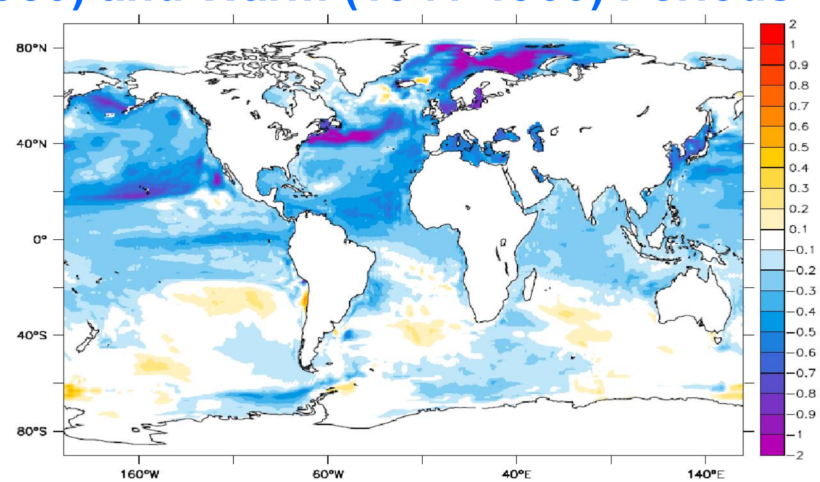
HadGEM2-ES (All Forcings)



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

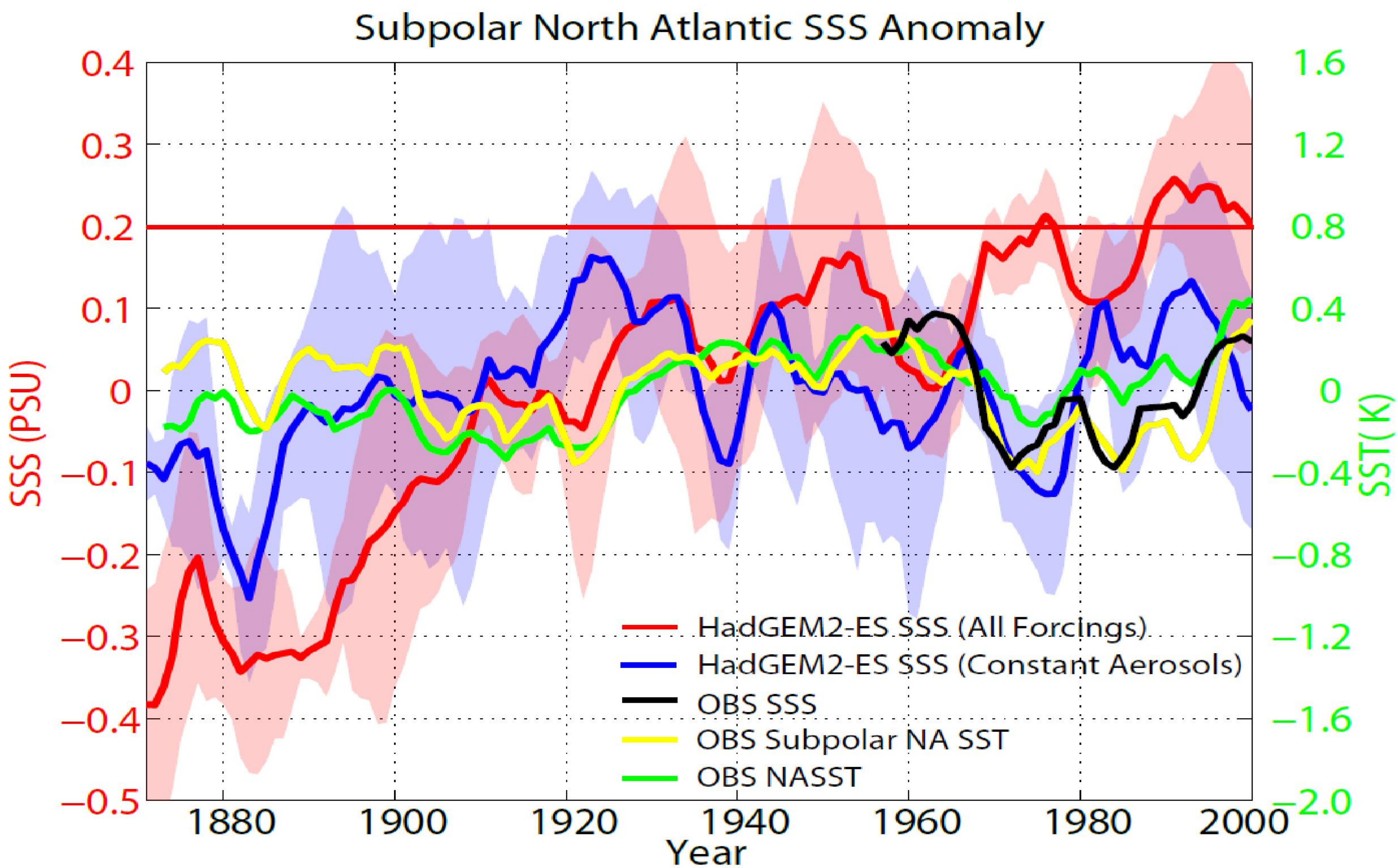
HadGEM2-ES
(All Forcings)-(Constant Aerosols)
net aerosol response

Zhang et al. 2013, JAS



The observed pattern is suggestive of an important role for AMOC variations, and related variations in Atlantic heat transport (Robson et al. 2012). The net aerosol response in HadGEM2-ES shows excess cooling in most ocean basins, and can not explain the observed pattern

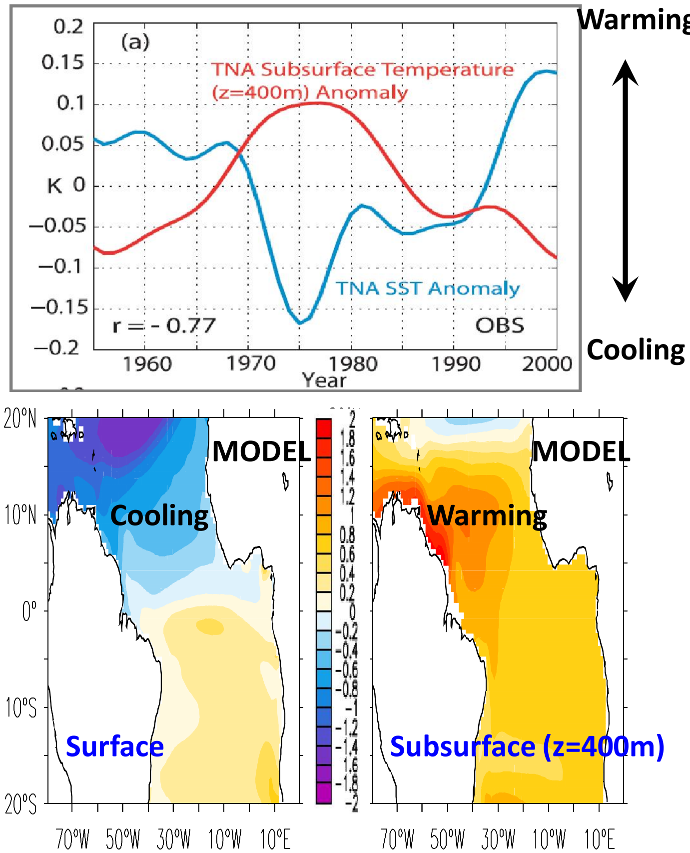
Key Discrepancies between HadGEM2-ES Simulations and Observations



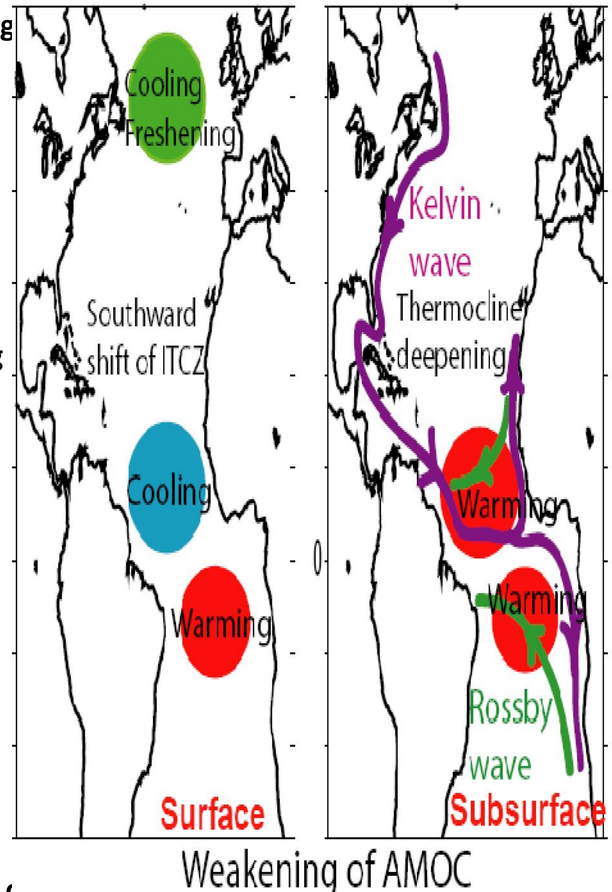
Zhang et al. 2013, JAS

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

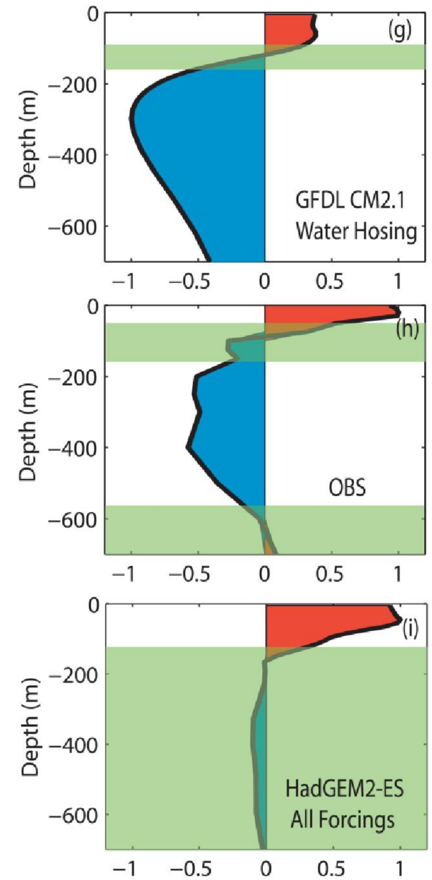
The observed anti-correlated variations between TNA surface and subsurface temperature



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



Zhang, 2007, GRL



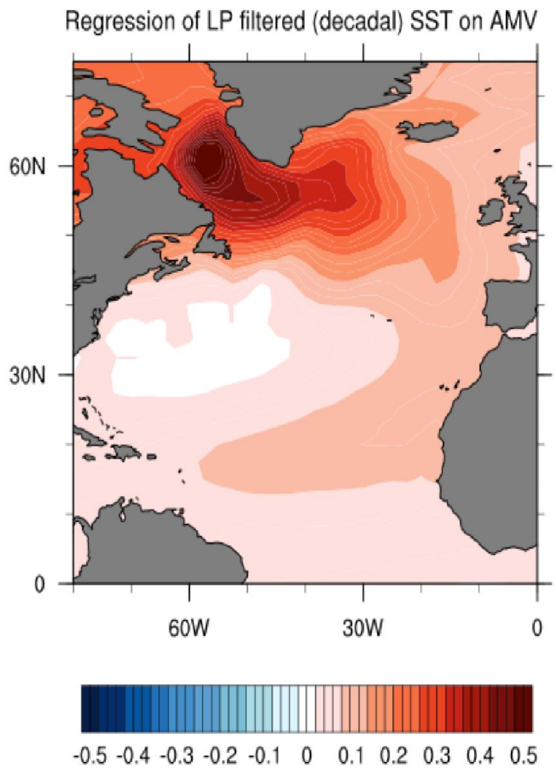
Zhang et al. 2013, JAS

- The anticorrelation between TNA surface and subsurface temperature is a fingerprint of AMOC variations, indicating the important role of AMOC in observed tropical AMV signal

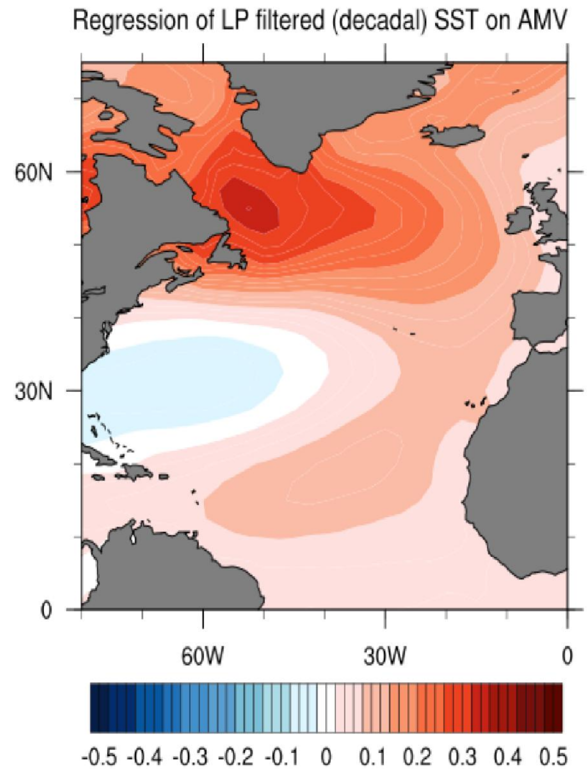
- The aerosol mechanism cannot account for the observed anticorrelated multidecadal TNA SST and subsurface temperature variations, inconsistent with the interpretation that aerosol forcing drives the bulk of the observed AMV

Recent Debate on Mechanisms of the AMV

Fully Coupled Models



Slab-ocean Models



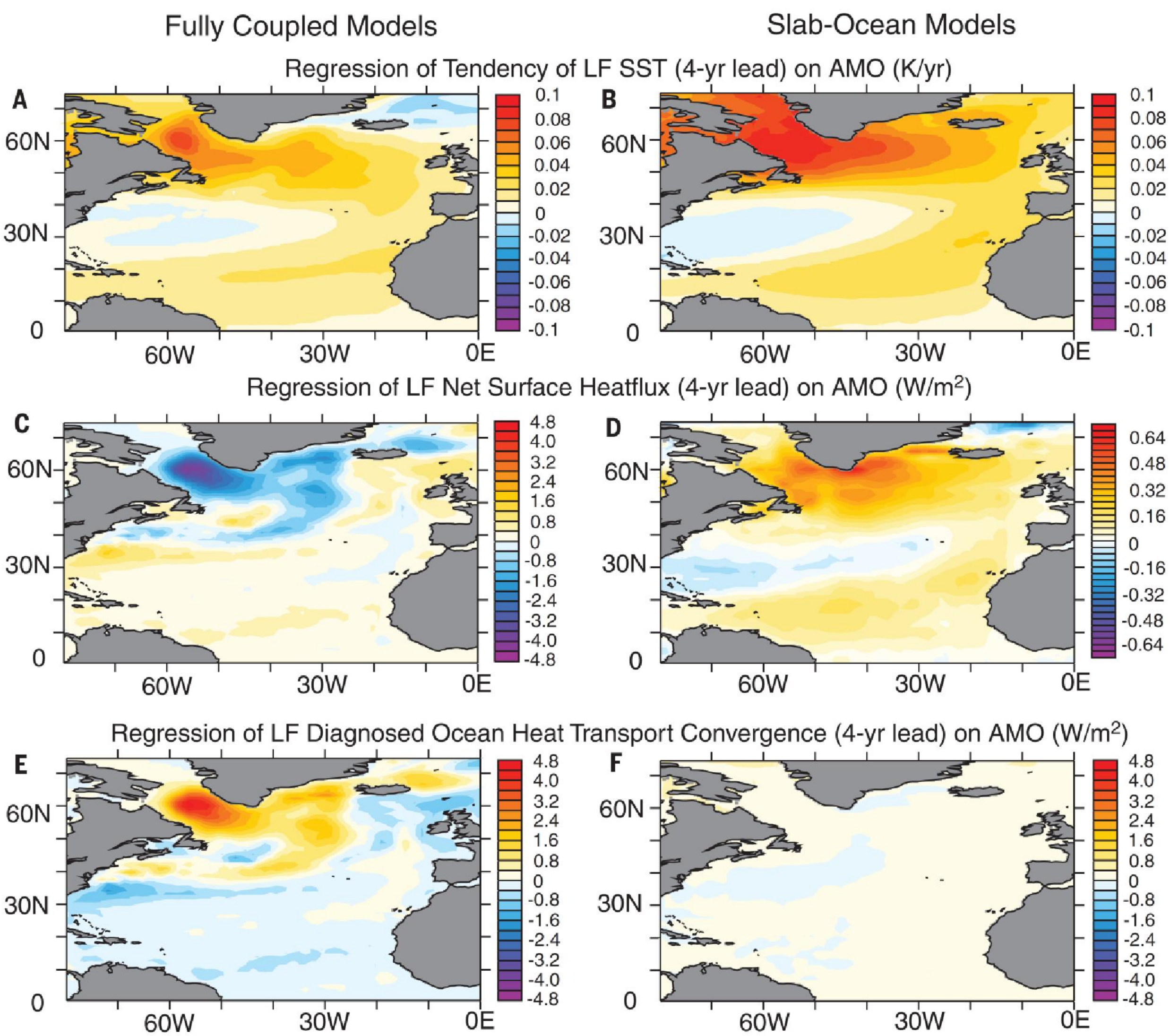
Clement et al., 2015, Science

Based on the similarity of AMV pattern and power spectra, Clement et al. 2015 conclude that the AMV in fully coupled general circulation models is generated by the same mechanism as in slab-ocean models without ocean dynamics:

The AMV is a direct response of the ocean mixed layer to stochastic surface heat fluxes without a role for ocean heat transport/circulation changes

Comment on “The Atlantic Multidecadal Oscillation without a role for ocean circulation”

Rong Zhang[1*], Rowan Sutton[2], Gokhan Danabasoglu[3], Thomas L. Delworth[1], Who M. Kim[3], Jon Robson[2], Stephen G. Yeager[3]



Zhang et al. 2016, Science

Zhang et al., 2016 shows that fundamental equation and mechanisms for the AMV are quite different between fully coupled models and slab-ocean models

The negative regression between net downward surface heat flux and SST in subpolar NA in fully coupled models indicate the important role of ocean dynamics in the AMV, consistent with many recent studies (Gulev et al. 2013; O’Reilly et al. 2016; Drews and Greatbatch, 2016; 2017)

A Simple Conceptual Model for SST Anomalies

$$\rho c_p h \frac{\partial T'}{\partial t} \approx F'_{Net} + F'_O \approx -\lambda_A T' + f'_A - \lambda_O T' + f'_O$$

$$F'_{Net} \approx -\lambda_A T' + f'_A$$

$$F'_O \approx -\lambda_O T' + f'_O$$

λ_A: net surface heat flux damping rate, λ_O: oceanic damping rate

- Oceanic damping is crucial in reality and fully coupled models. If $\lambda_O = 0$, SSS would have unrealistic unbounded growth
- One major source for oceanic damping in SST/SSS is vertical entrainment from subsurface water. Observations suggest $\lambda_O \sim \lambda_A$ in most mid-latitude oceans (Frankignoul 1985; Goodman and Marshall, 1999), and $\lambda_O \gg \lambda_A$ in subpolar North Atlantic (Hall and Manabe, 1997)
- The red noise model with no oceanic damping ($\lambda_O = 0$) (Clement et al. 2016; Cane et al. 2017) leads to unrealistic interpretation of the relative roles of atmospheric vs. oceanic forcing in T', e.g. the negative correlation $r(F'_{Net}, T') < 0$ at low frequency is explained with negligible f'_O (assumed to be the same as F'_O). However, f'_A should be compared with $f'_O = F'_O + \lambda_O T'$, not compared with F'_O as in Clement et al. 2016 and Cane et al. 2017

Zhang, 2017, GRL

Relative Roles of Atmospheric (f'_A) vs. Oceanic (f'_O) Forcing in Low Frequency Subpolar NASST anomalies (T') are revealed by their cross covariances with T':

$$\frac{cov(f'_O, T')}{cov(f'_A, T')} \approx \frac{\lambda_O - \dfrac{r(F'_{Net}, T')\sigma_{F'_{Net}}}{\sigma_{T'}}}{\lambda_A + \dfrac{r(F'_{Net}, T')\sigma_{F'_{Net}}}{\sigma_{T'}}}$$

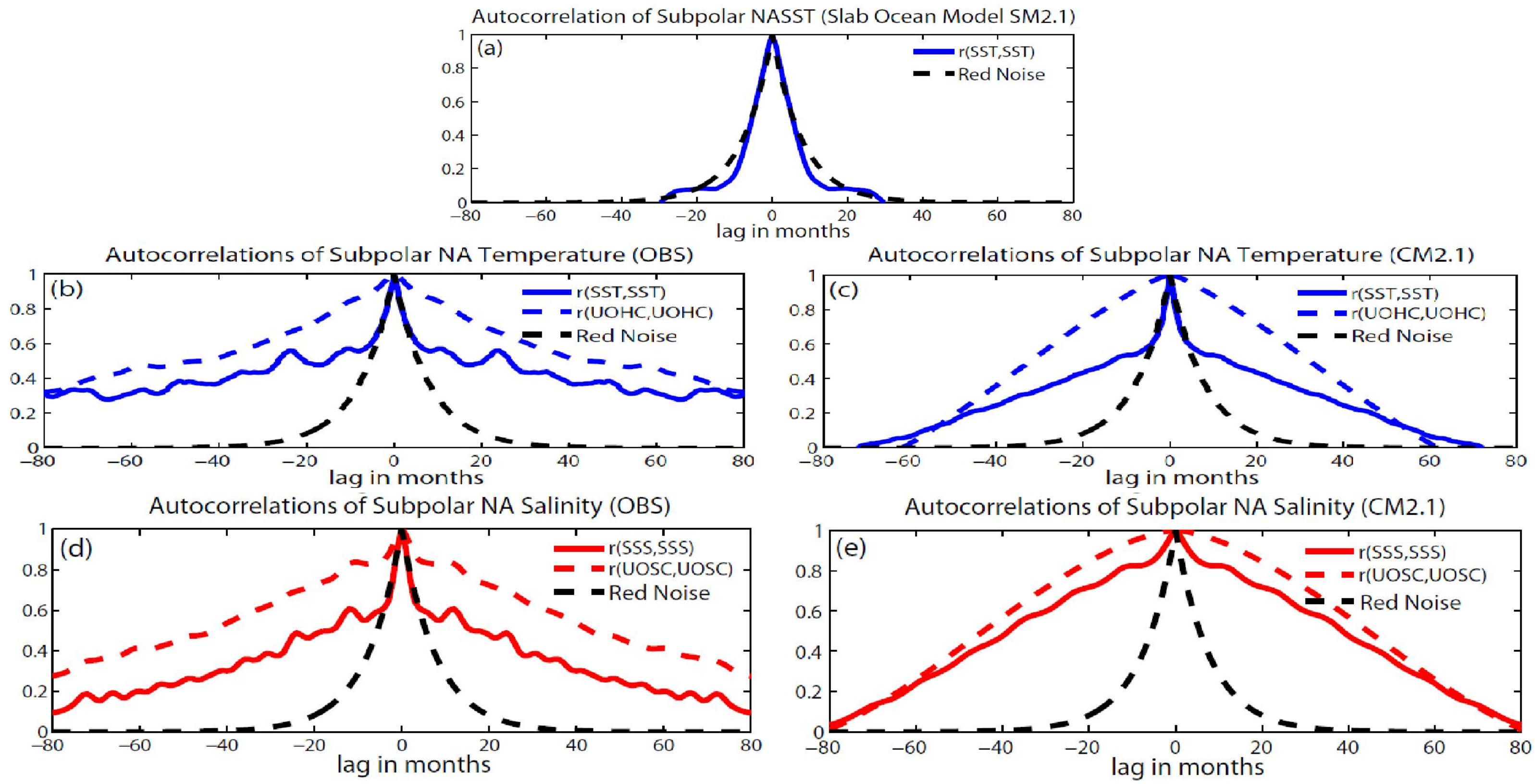
The correlation/regression between net surface heat flux and SST at low frequency are key indicators for the relative roles of oceanic vs. atmospheric forcing

- For both observations and GFDL CM2.1 control simulation, $\frac{cov(f'_O,T')}{cov(f'_A,T')} \gg 1$, f'_O has a dominant role for low frequency Subpolar NASST anomalies associated with the AMV
- In the red noise model (Clement et al. 2016; Cane et al. 2017), the lack of oceanic damping ($\lambda_O = 0$, i.e. $f'_O = F'_O$) leads to the unrealistic conclusion:

$$\frac{cov(f'_O, T')}{cov(f'_A, T')} \ll 1$$

i.e. f'_O has a negligible role, and f'_A is the main driver of the AMV to interpret the result $r(F'_{Net}, T') < 0$ at low frequency (Gulev et al. 2013; O'Reilly et al. 2016; Zhang et al. 2016; Drews and Greatbatch, 2016)

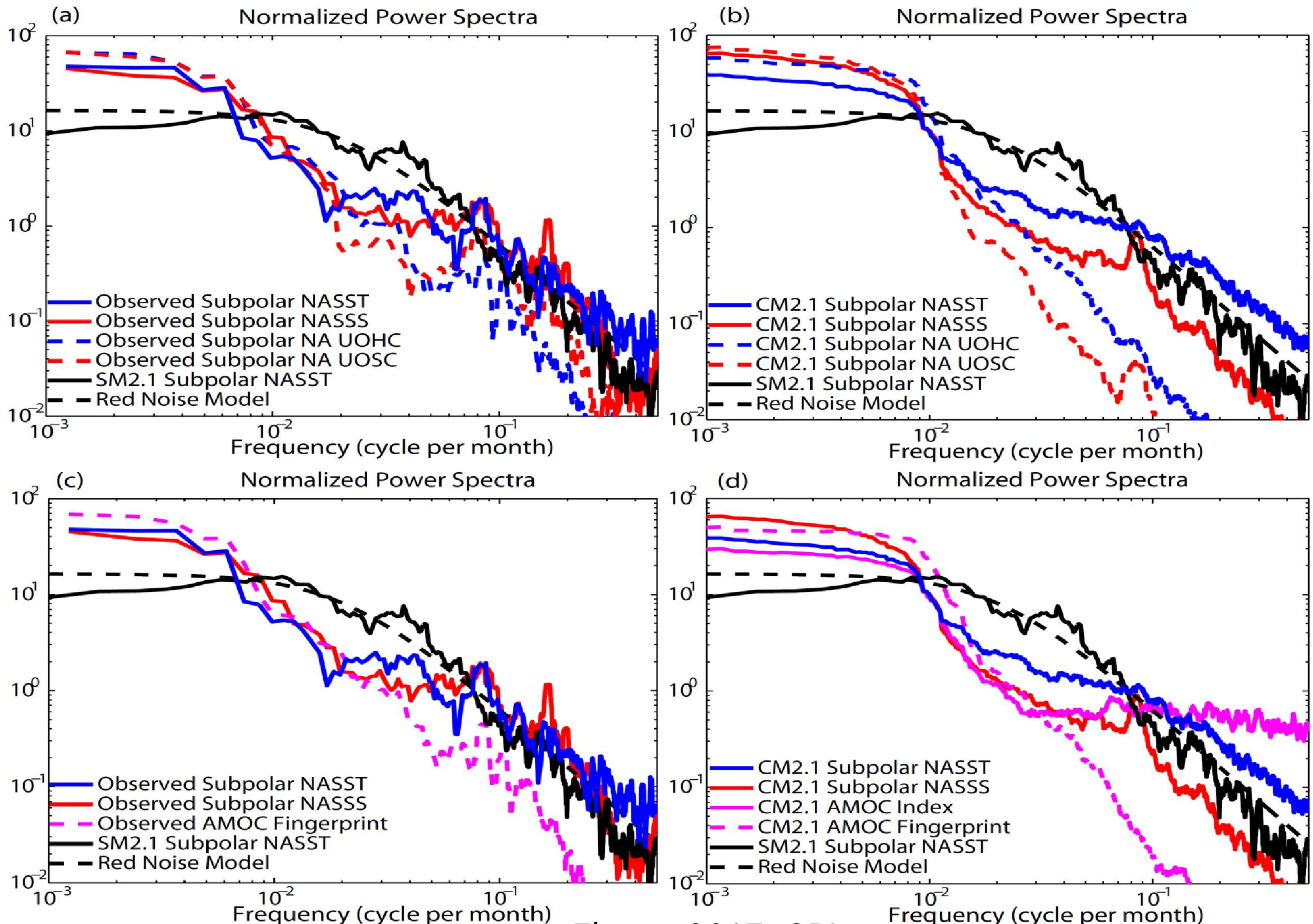
Zhang, 2017, GRL



Zhang, 2017, GRL

- The observed and CM2.1 simulated autocorrelations of Subpolar NASST anomalies with two different persistent time scales (decadal and intermonth) are very different from the slab ocean model results or the red noise process

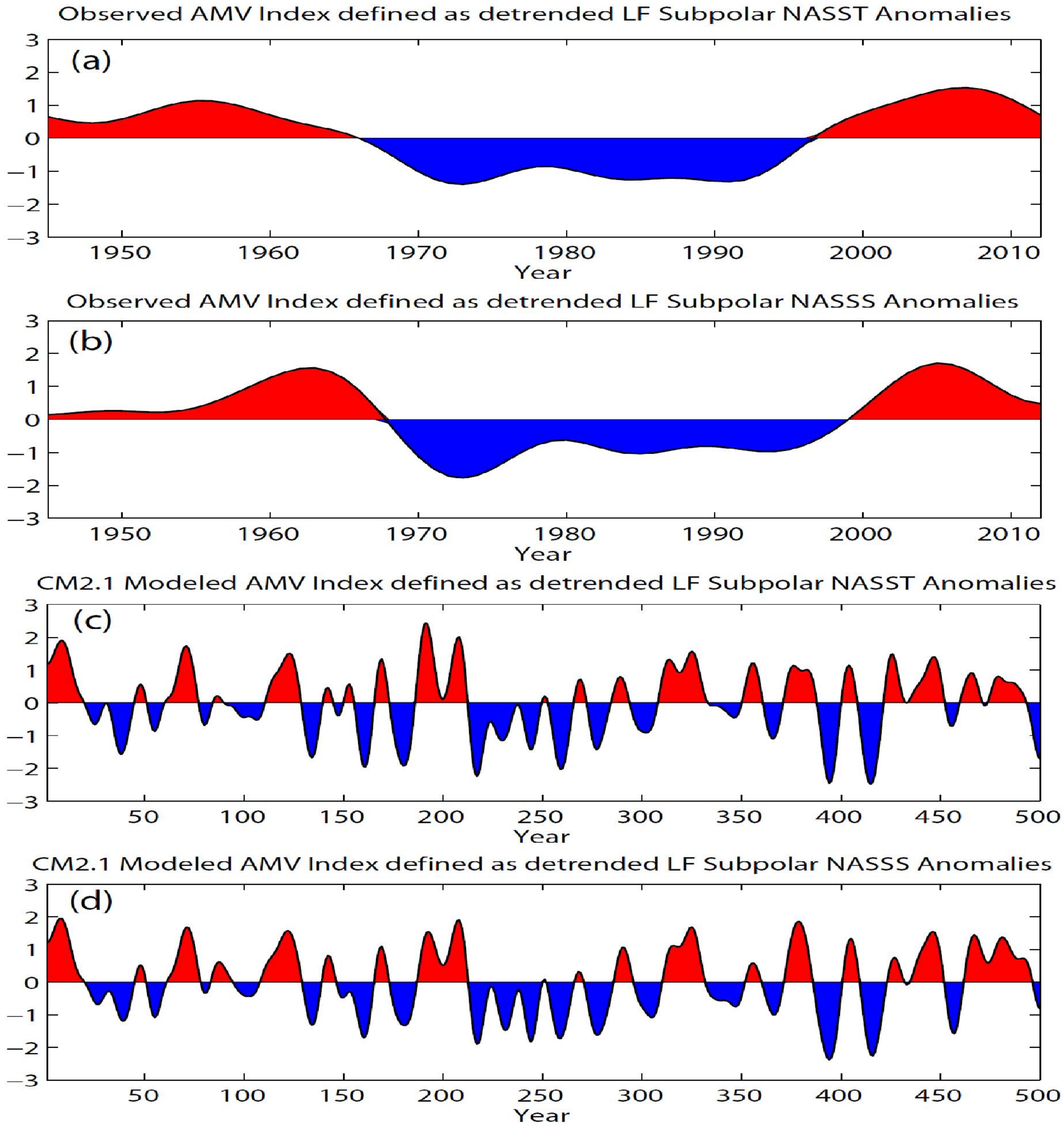
- The observed and CM2.1 simulated decadal persistence of Subpolar NASST anomalies associated with the AMV will lead to much higher decadal prediction skill than that obtained from the slab ocean models or the fitted red noise model, consistent with successful decadal predictions in subpolar North Atlantic by initializing observed ocean states in fully coupled models



Zhang, 2017, GRL

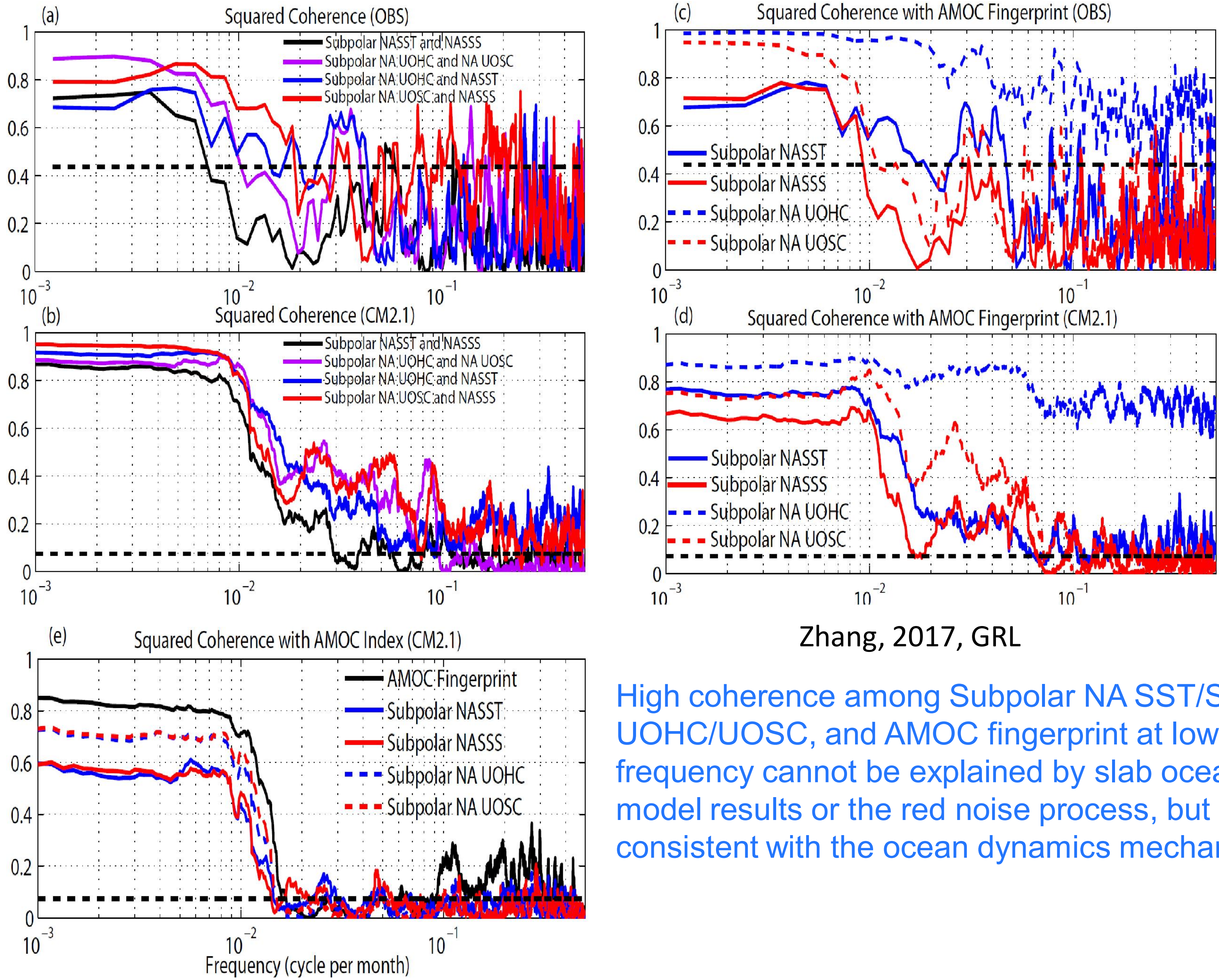
The observed and CM2.1 simulated two-step bending in the Subpolar NASST power spectrum cannot be explained by the slab ocean model or a red noise process, but is consistent with AMOC variability as a major oceanic forcing at low frequency

Coherent multidecadal variations of Subpolar NASST and NASSS anomalies



Zhang, 2017, GRL

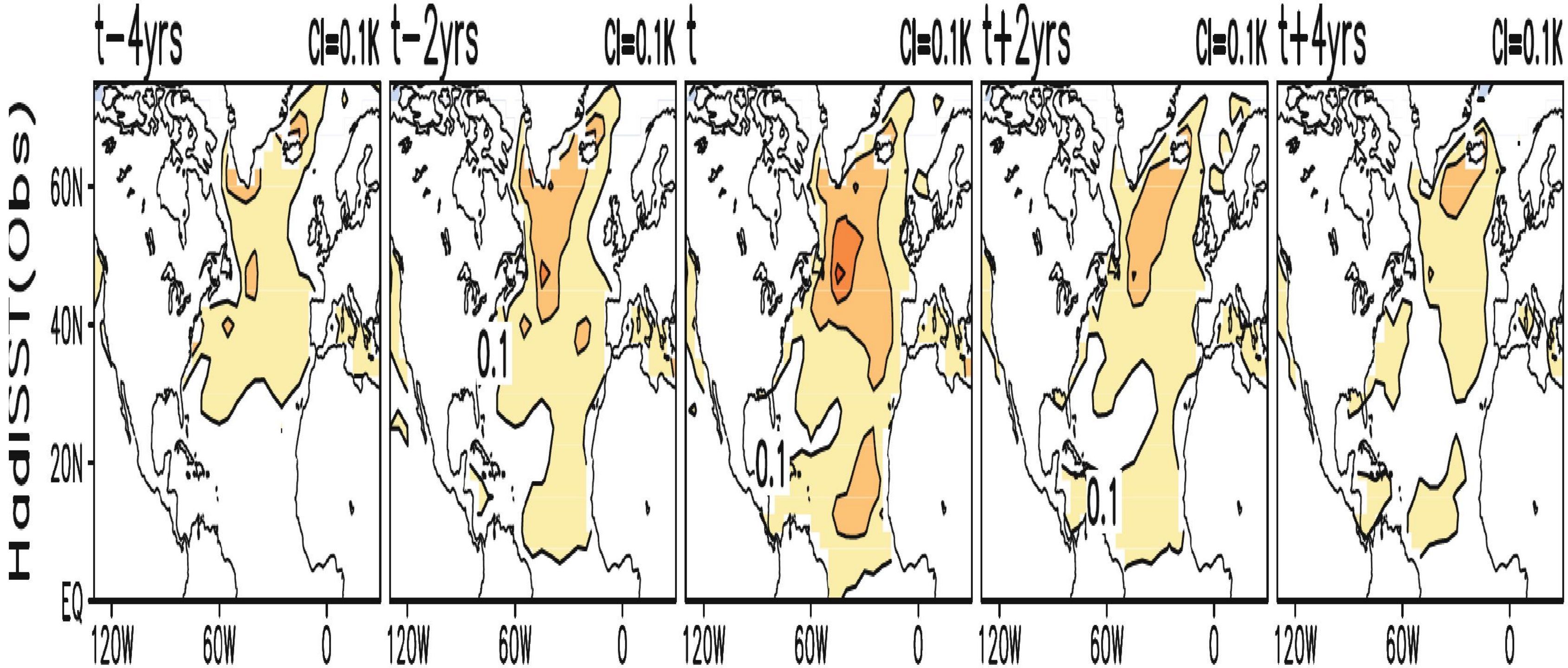
The alternative AMV indices using subpolar NASST and NASSS are almost indistinguishable



Zhang, 2017, GRL

High coherence among Subpolar NA SST/SSS, UOHC/UOSC, and AMOC fingerprint at low frequency cannot be explained by slab ocean model results or the red noise process, but is consistent with the ocean dynamics mechanism

Evolution of the Observed AMV

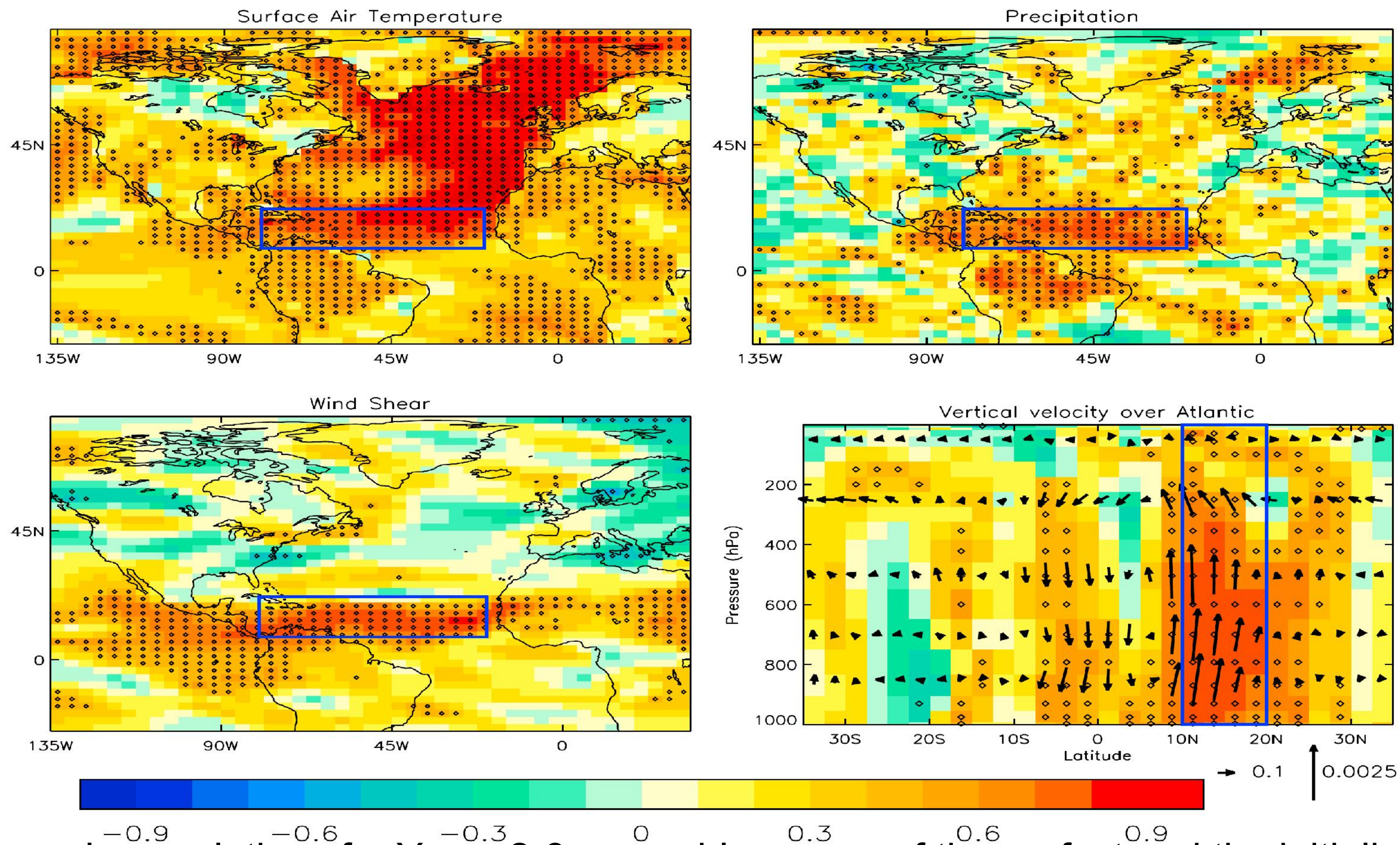


Ruiz-Barradas et al. 2013, Climate Dynamics

The weaker tropical AMV signal responds to the stronger subpolar AMV signal through combined oceanic and atmospheric teleconnections, including changes in the Hadley circulation, WES feedback, and cloud and dust feedback (Zhang, 2007; Dunstone et al. 2011; Wang et al. 2012; Hodson et al. 2014, Yuan, et al. 2016; Brown et al. 2016)

Multi-year Predictability of Tropical Atlantic Atmosphere driven by the Subpolar North Atlantic Ocean

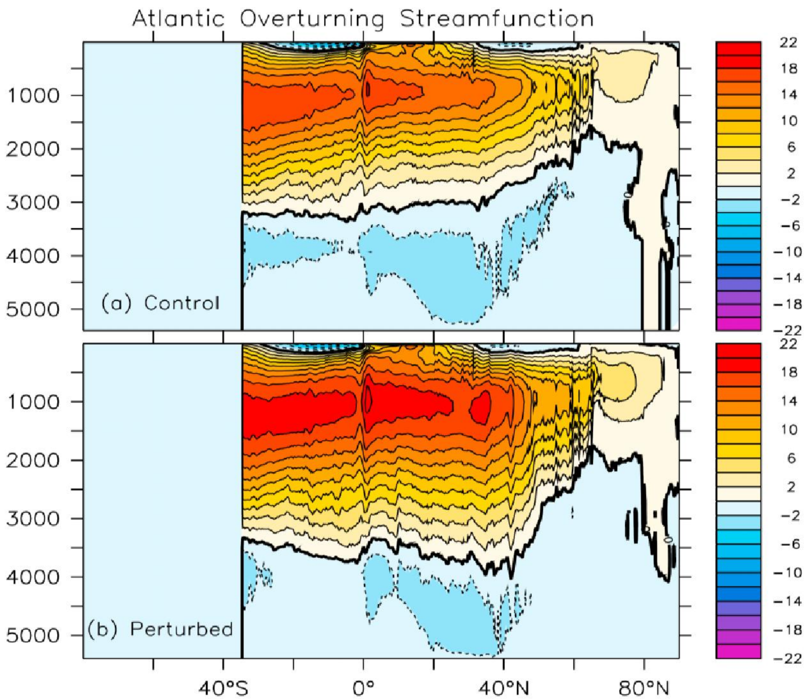
The North Atlantic Subpolar Gyre is identified as a key driver of skills in predicting the tropical Atlantic atmosphere, including tropical precipitation, wind shear, vertical velocity, and storm numbers

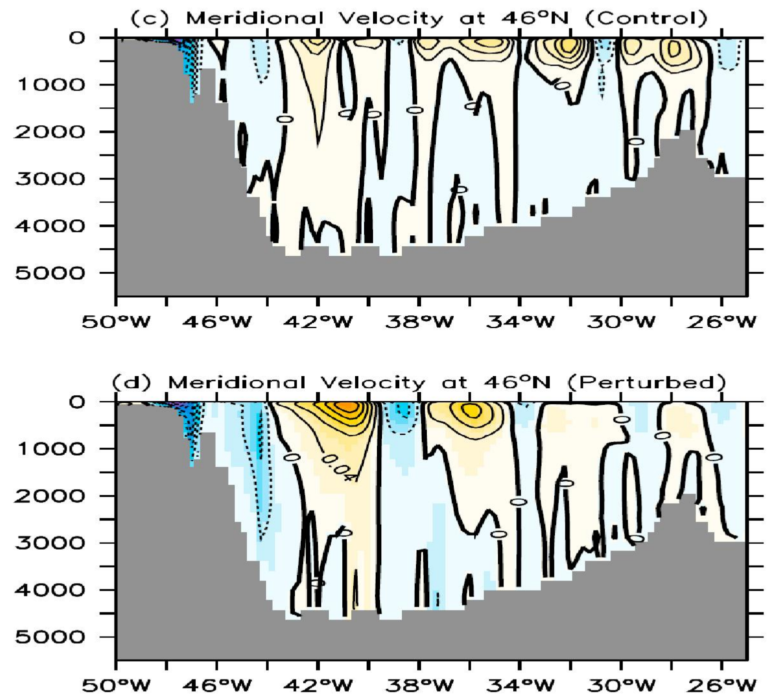


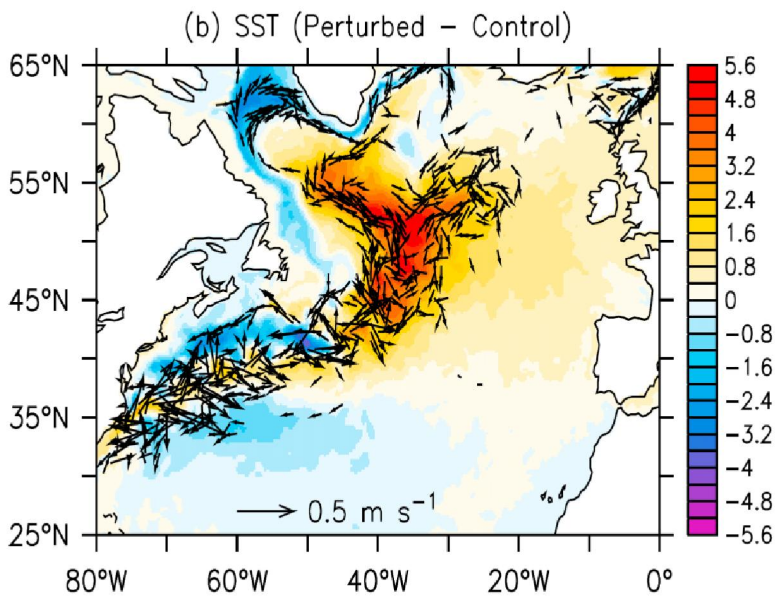
Anomaly correlations for Years 2-6 ensemble means of the perfect and the initialized forecast experiments using HadCM3

Dunstone et al. 2011, GRL

Mean State Modelling Biases in North Atlantic





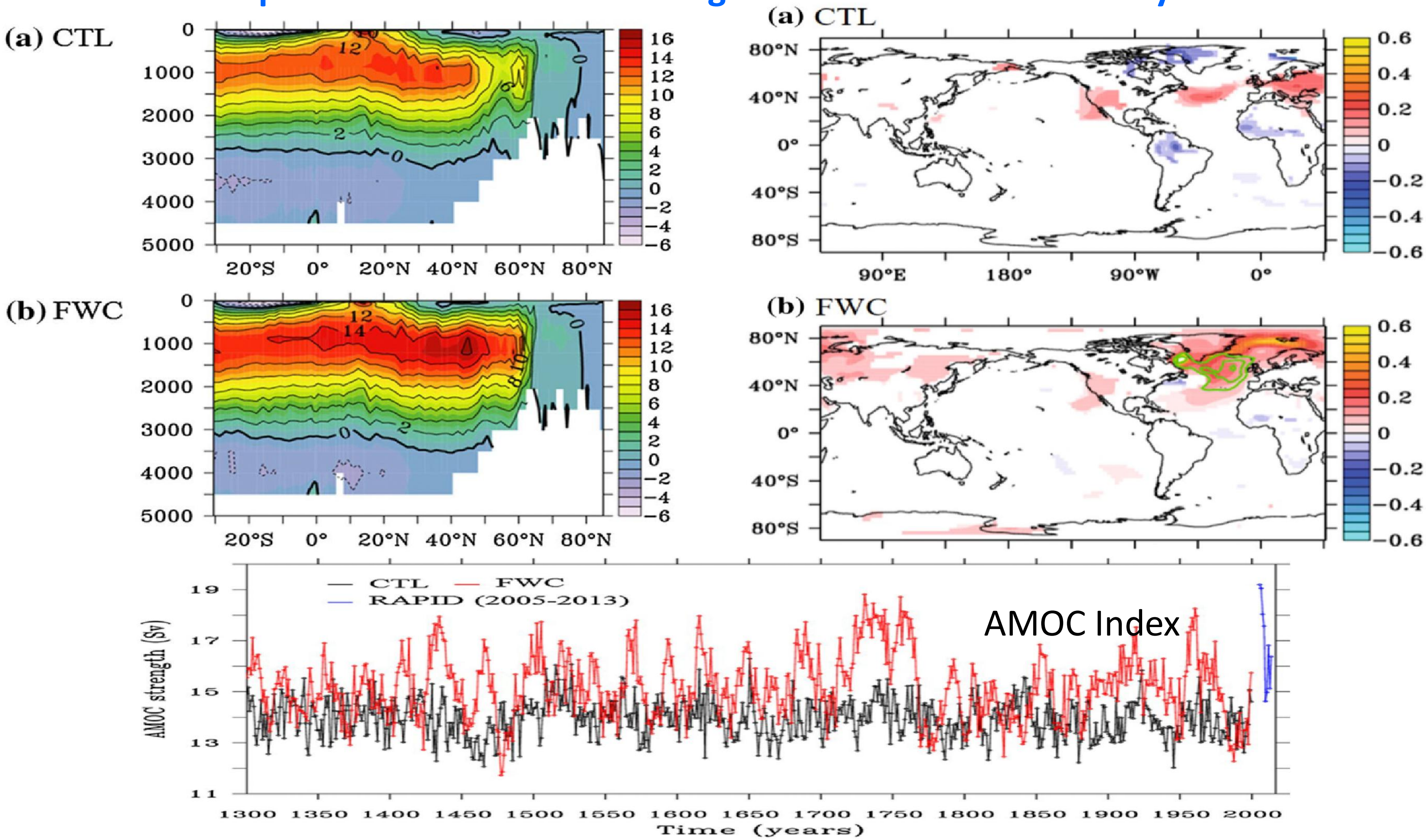


Zhang et al. 2011, JGR-Oceans

Most CMIP5 models simulate a strong SST cold bias in mid-latitude North Atlantic, due to simulated bias in AMOC strength and structure (Wang et al. 2014)

A stronger and more realistic Nordic Sea overflow can lead to stronger/deeper AMOC , more realistic North Atlantic Current (NAC) pathways, thus reduced SST cold bias in mid-latitude North Atlantic

Impact of Mean State Modeling Biases on AMOC Variability and AMV



Park et al. 2016, Climate Dynamics

Climate model with corrected mean state in the North Atlantic can simulate deeper AMOC, reduced SST cold bias in the North Atlantic, stronger and more realistic AMOC variability, thus more realistic pattern/amplitude of AMV induced by AMOC variability

Summary

- The AMV has played a key role in multidecadal variations of vertical wind shear over the main development region (MDR) for Atlantic hurricane activity. Understand the mechanism for the observed AMV is very important for predicting future Atlantic major hurricane frequency

- Many key observed AMV features (e.g. decadal persistence of monthly mean subpolar NA SST/SSS, high coherence among subpolar NA SST/SSS, UOHC/UOSC, AMOC fingerprint at low frequency, anticorrelated multidecadal TNA SST and subsurface temperature) cannot be explained by a direct response to stochastic atmospheric forcing or external radiative forcing, but are consistent with the ocean dynamics mechanism

- The observed decadal persistence of Subpolar NASST anomalies will lead to much higher decadal prediction skill than that obtained from the slab ocean models or the red noise process, consistent with the successful decadal predictions of subpolar AMV signal in recent studies by initializing ocean states

- The SST-based AMV Index often leads to incomplete understanding of the AMV mechanism only in terms of SST anomalies. There are major discrepancies between the HadGEM2-ES simulations and observations in NA upper ocean heat content, subpolar NASSS, and SST pattern within and outside NA, and the aerosol mechanism cannot account for the observed anticorrelated multidecadal TNA SST and subsurface temperature variations, inconsistent with the claim that anthropogenic aerosol forcing is a prime driver of the AMV

- The correlation and regression between net downward surface heat flux and SST at low frequency are key indicators of the relative roles of oceanic vs. atmospheric forcing in SST anomalies. The red noise model without oceanic damping gives unrealistic interpretation of the negative correlation

- The oceanic forcing has a dominant role in low frequency subpolar NASST anomalies, and is closely linked to AMOC variability, which is not a white noise but signal with enhanced low frequency variability and a major source for the decadal persistence in subpolar temperature and salinity

- The subpolar North Atlantic is a key region for generating the AMV and predicting the tropical Atlantic atmosphere

- Most CMIP5 models simulate a strong SST cold bias in mid-latitude North Atlantic, due to simulated biases in AMOC strength and structure in mean state.

- Climate models with corrected mean state in the North Atlantic can simulate stronger and deeper AMOC, more realistic pathways of the North Atlantic Current, reduced SST cold bias in mid-latitude North Atlantic, stronger and more realistic AMOC variability, thus stronger and more realistic AMV