# Low Frequency Variability in the North Atlantic-Arctic Sector

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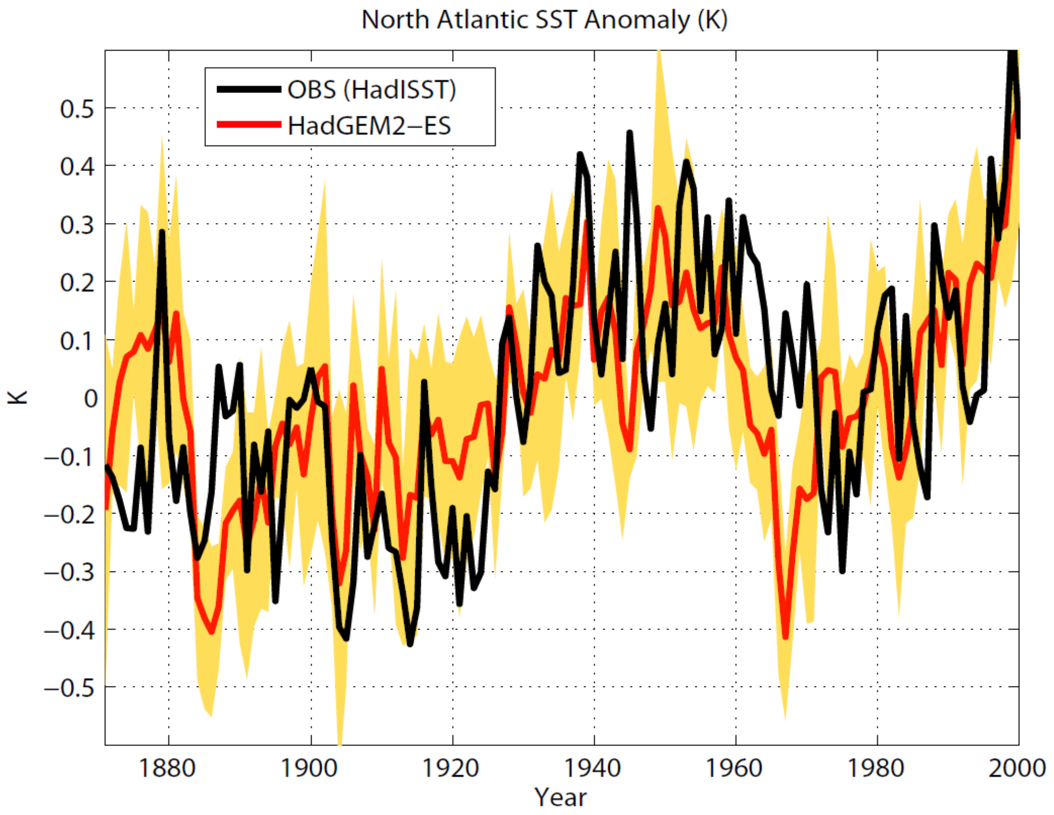
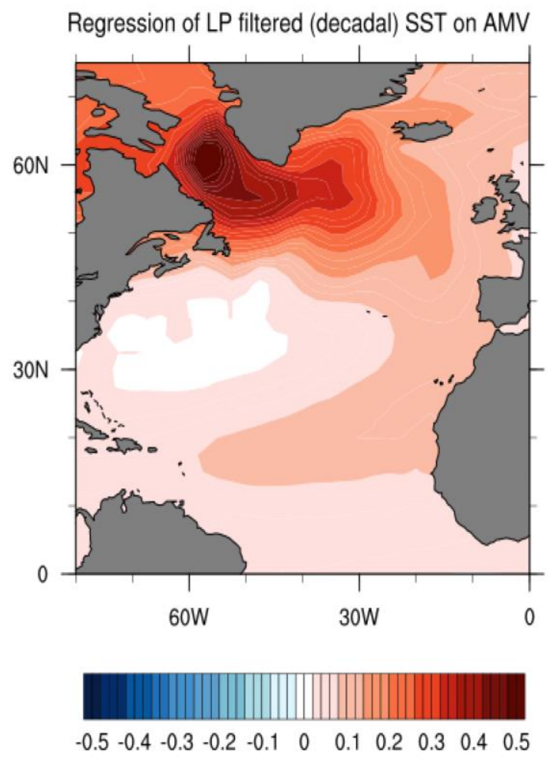
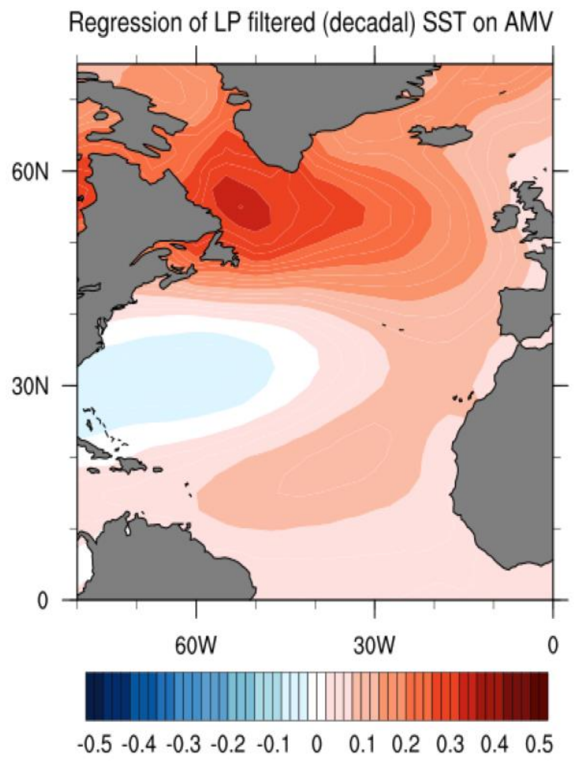
# Recent Debate on Mechanisms of the Atlantic Multidecadal Variability (AMV)




Booth et al., Nature, 2012




Clement et al., 2015, Science

The low frequency AMOC variability is traditionally thought as a leading mechanism for 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)

Recent studies suggest that the AMV is mainly a direct response of the North Atlantic SST to external radiative forcing (Booth et al. 2012) or stochastic atmospheric forcing as found in models coupled with a slab ocean (Clement et al. 2015)

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

Southward propagation of AMOC anomaly

↓

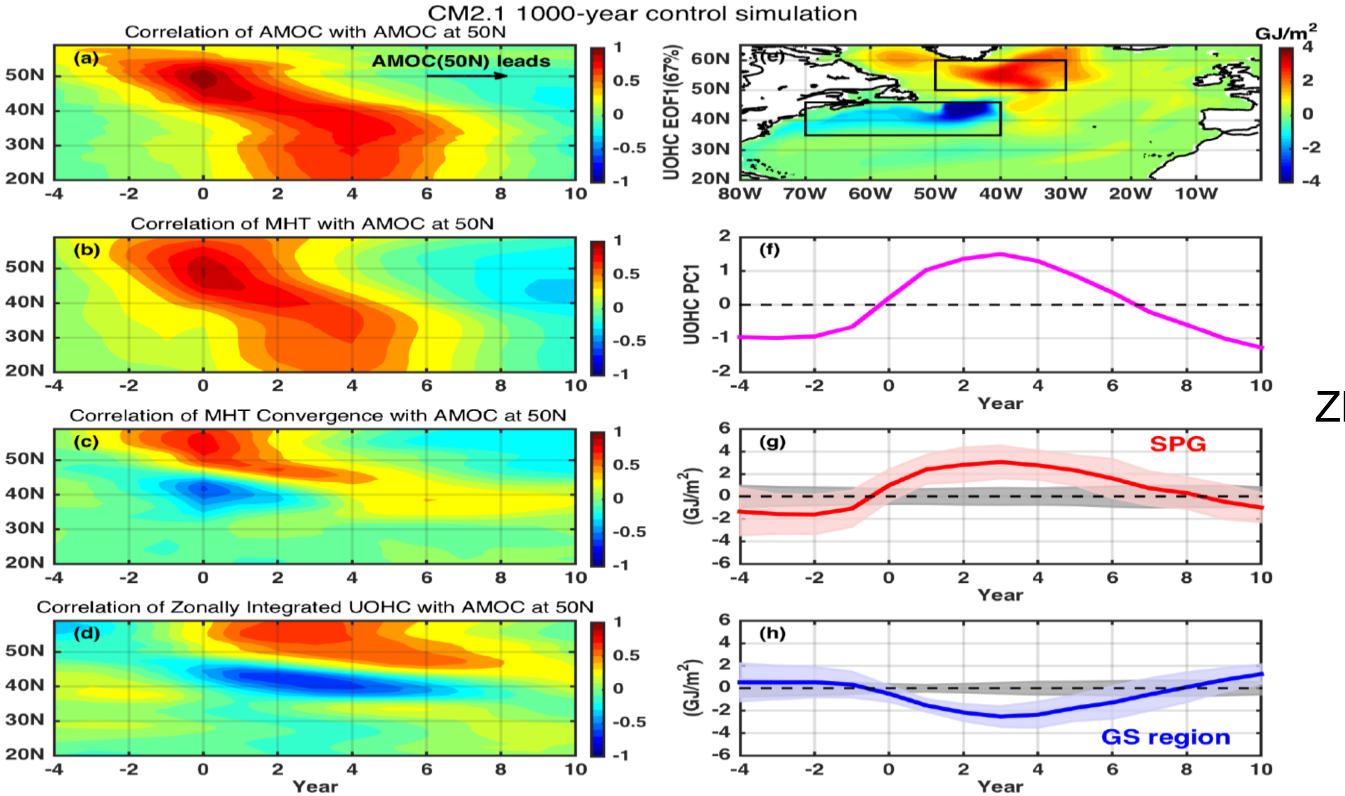
Southward propagation of MHT anomaly

↓

MHT convergence in SPG and divergence in GS

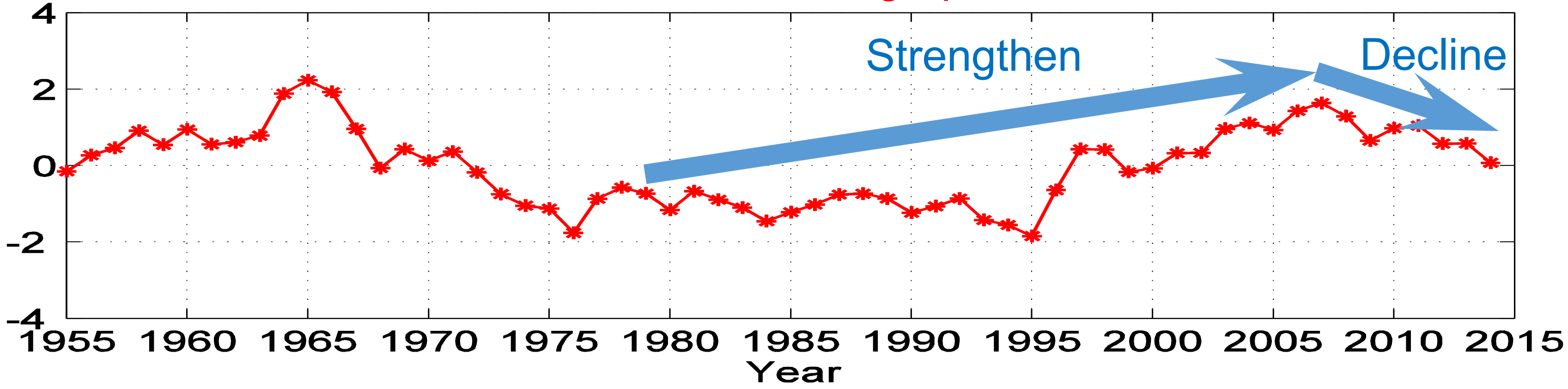
↓

Warming in SPG and cooling in GS



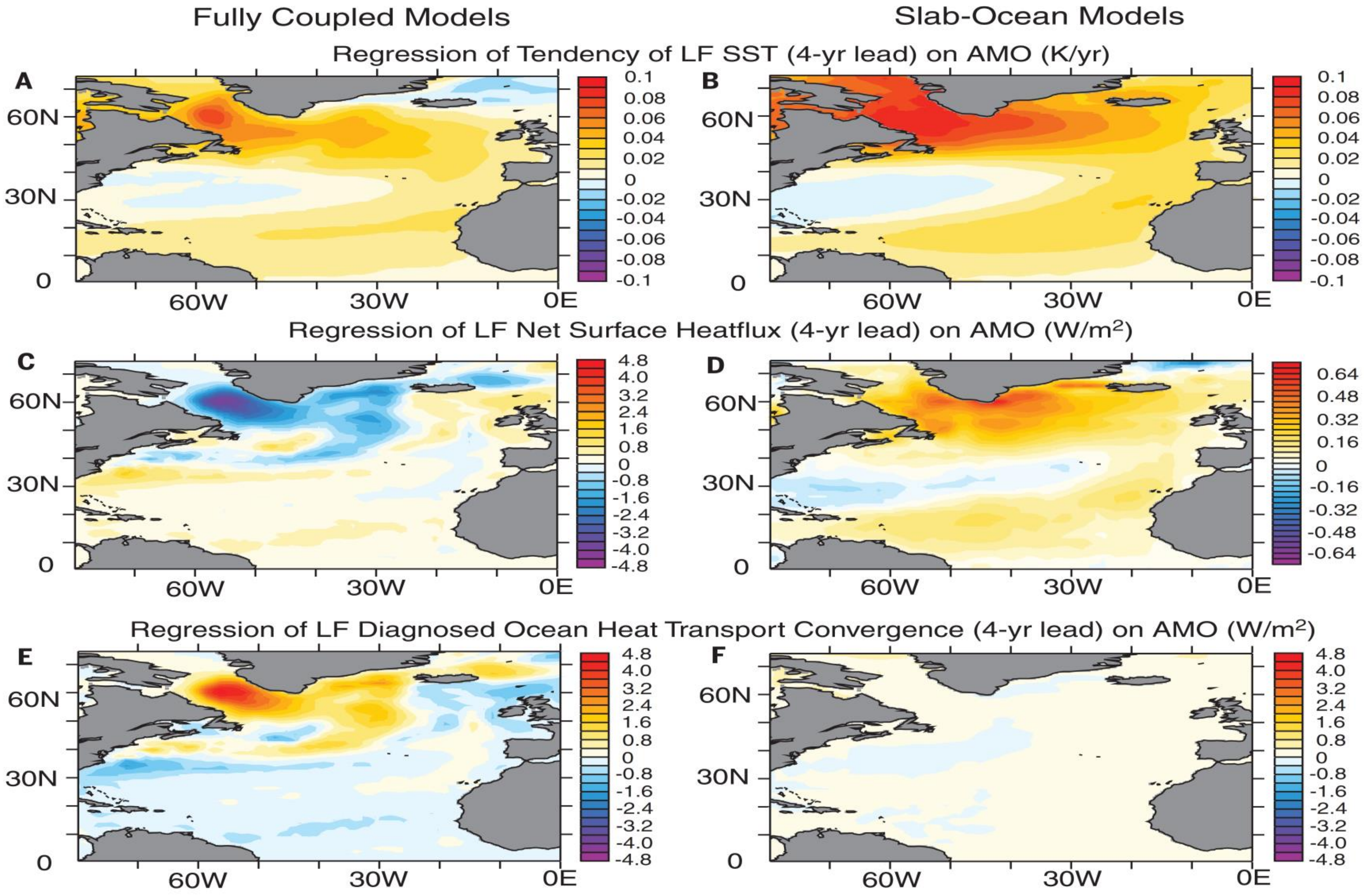

Zhang and Zhang, 2015, GRL

## Observed AMOC Fingerprint



## 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 equations/mechanisms for SST anomalies associate with the AMV are clearly distinguishable 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 indicates the important role of ocean dynamics in the AMV, consistent with many other recent studies (Gulev et al. 2013; O'Reilly et al. 2016; Drews and Greatbatch, 2016; 2017)
- Using a red noise model with no oceanic damping, Clement et al. (2016) interpreted such negative correlation as a result of negligible oceanic forcing, with stochastic atmospheric forcing being the main driver for the AMV

## A Simple Conceptual Model for SST Anomalies

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

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

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

$\lambda_A$: net surface heat flux damping rate, $\lambda_O$: 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) 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)

Zhang, 2017

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 $T'$:

$$cov(f_O', T') - cov(f_A', T') \approx \left(\lambda_O - \lambda_A - 2\frac{r(F_{Net}', T')\sigma_{F_{Net}'}}{\sigma_{T'}}\right)\sigma_{T'}^2$$

$$\frac{cov(f_O', T')}{cov(f_A', T')} \approx \frac{\lambda_O - \frac{r(F_{Net}', T')\sigma_{F_{Net}'}}{\sigma_{T'}}}{\lambda_A + \frac{r(F_{Net}', T')\sigma_{F_{Net}'}}{\sigma_{T'}}}$$

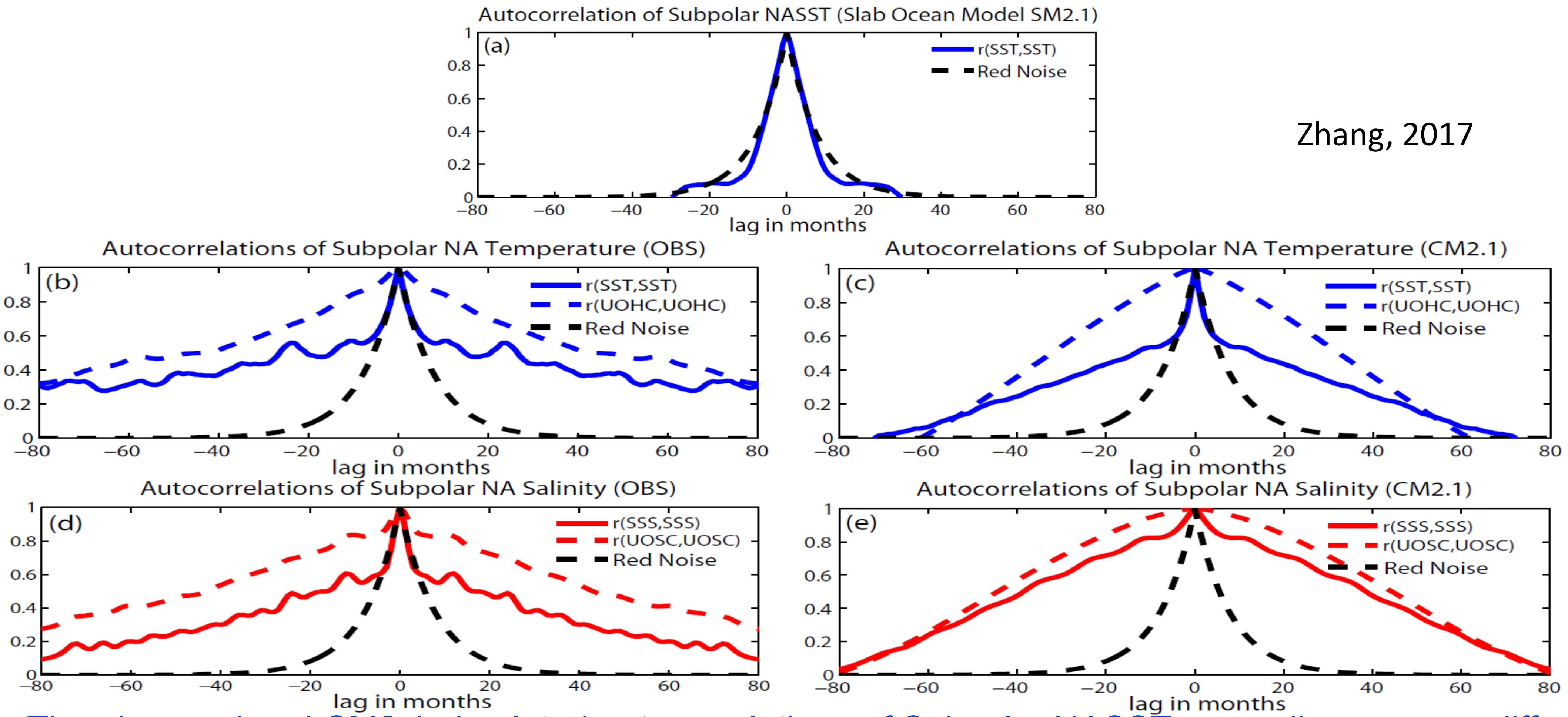
- For both observations and GFDL CM2.1 control simulation, $\frac{cov(f_O', T')}{cov(f_A', T')} \gg 1$, $f_O'$ has a dominant role for low frequency Subpolar NASST anomalies associated with the AMV

- In the red noise model (Clement et al. 2016), the lack of oceanic damping ($\lambda_O = 0$, i.e. $f_O' = F_O'$) leads to the unrealistic conclusion:

$$\frac{cov(f_O', T')}{cov(f_A', T')} \ll 1$$

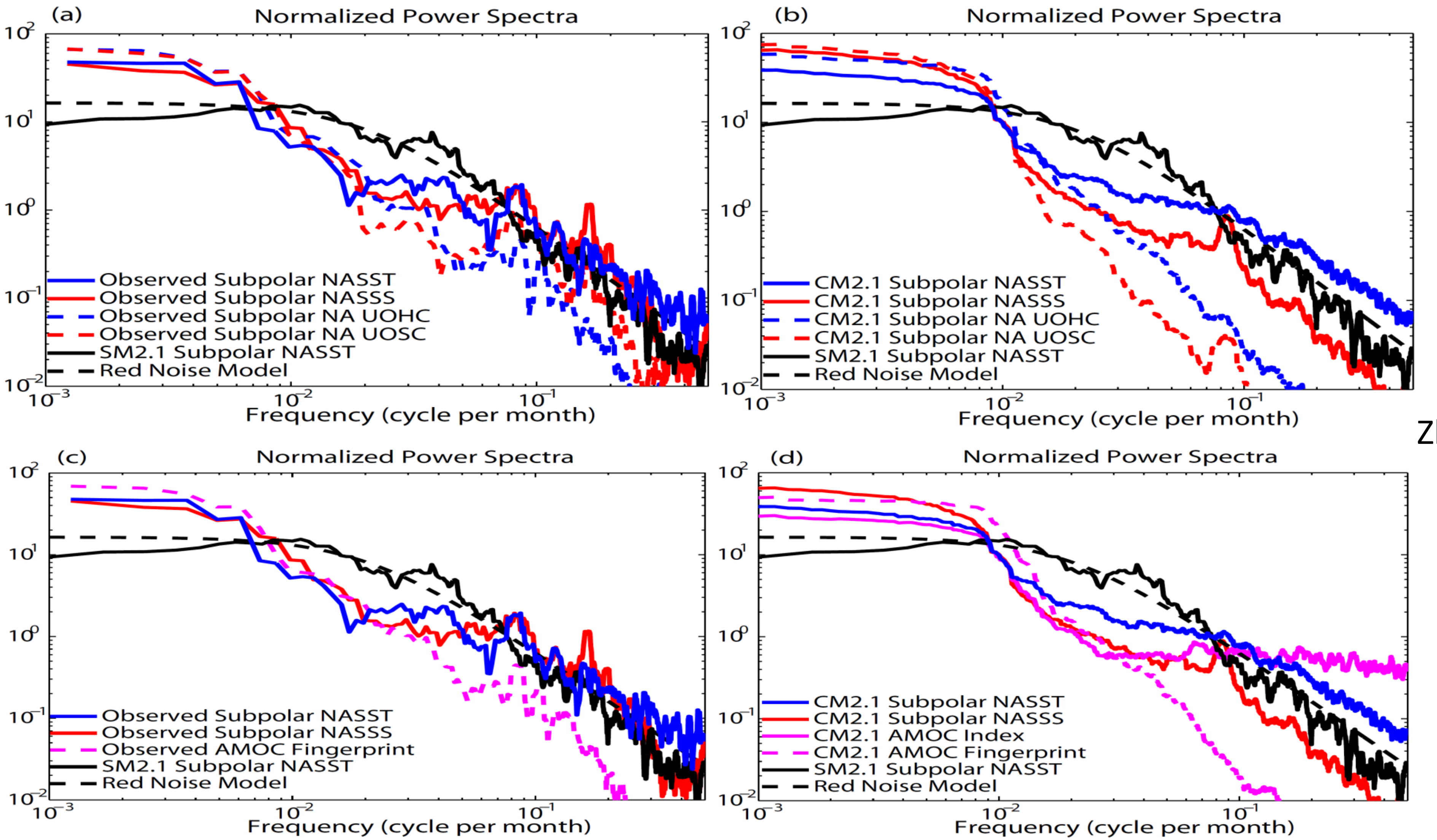
i.e. $f_O'$ has a negligible role and $f_A'$ is the main driver of the AMV to interpret the result $r(F_{Net}', T') < 0$ at low frequency (Gulev et al. 2013; O'Reilly et al. 2016; Zhang et al. 2016; Drews and Greatbatch, 2016)

Zhang, 2017



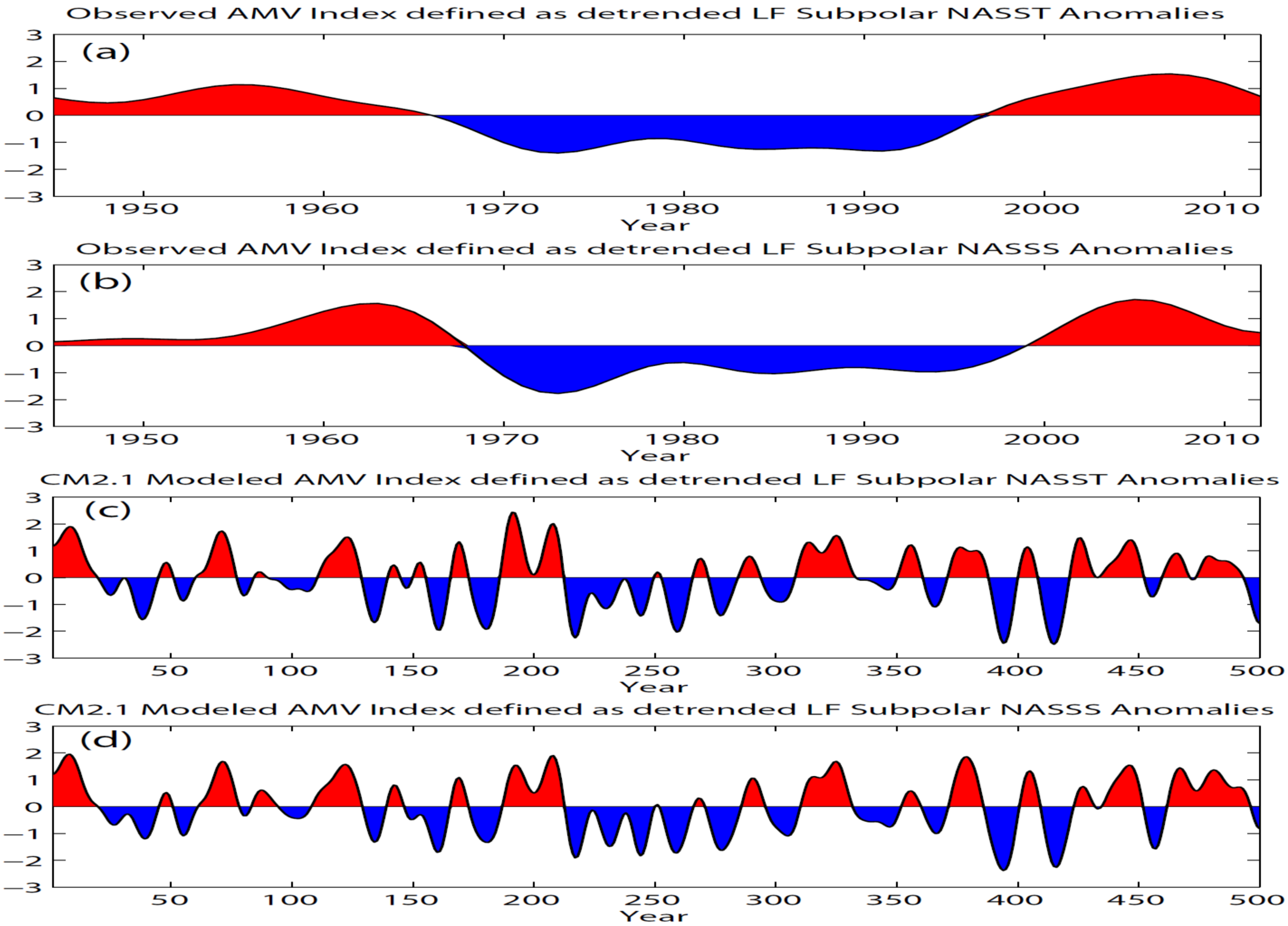

Zhang, 2017

- The observed and CM2.1 simulated autocorrelations of Subpolar NASST anomalies are very different from the slab ocean model results or a red noise process
- Subpolar NASSS and Subpolar NA UOHC/UOSC exhibit similar decadal persistence
- Decadal persistence of Subpolar NASST anomalies in observations and CM2.1 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 NA by initializing observed ocean states in fully coupled models (Robson et al., 2012b; Yeager et al., 2012;Yang et al., 2013; Msadek et al., 2014)



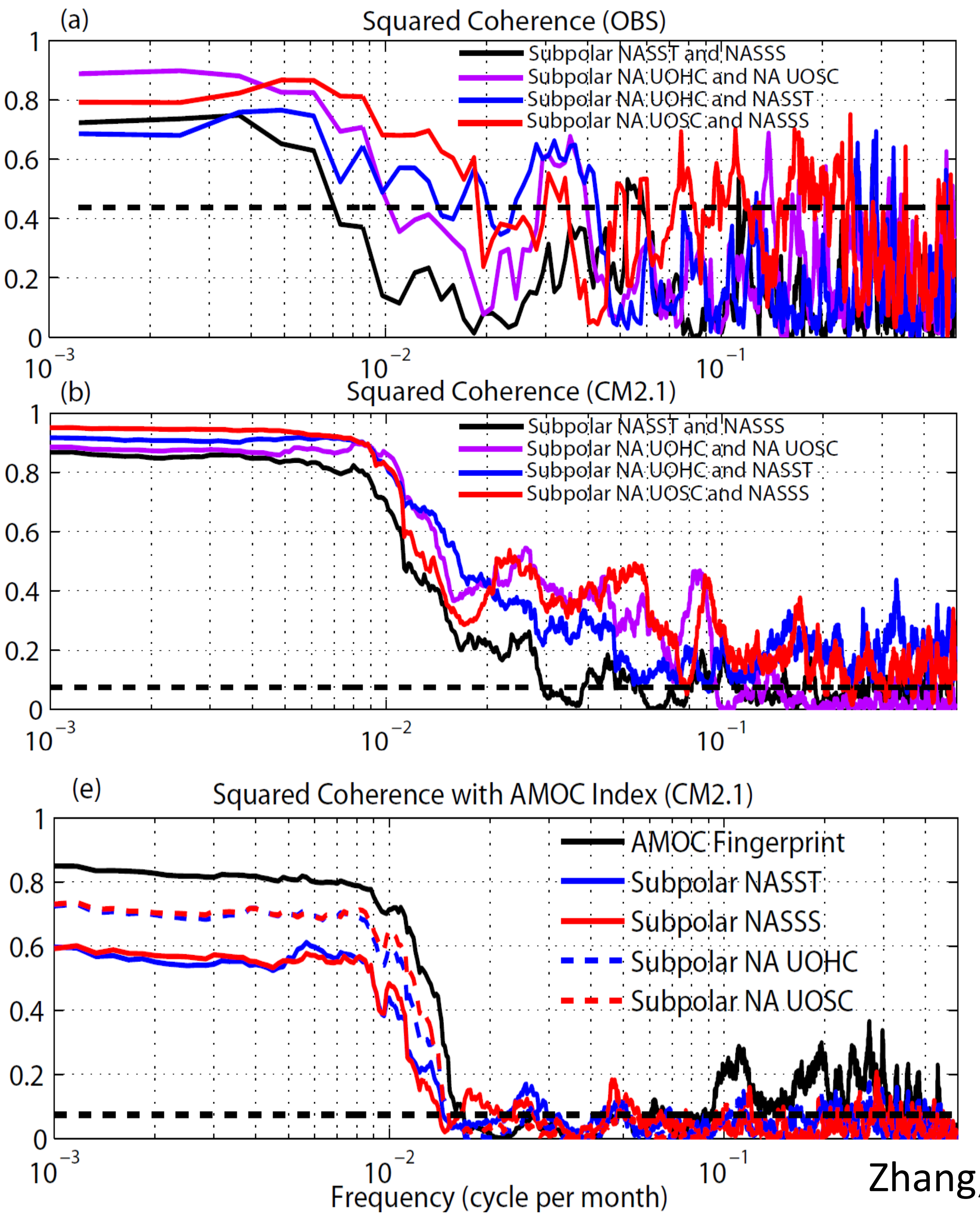

Zhang, 2017

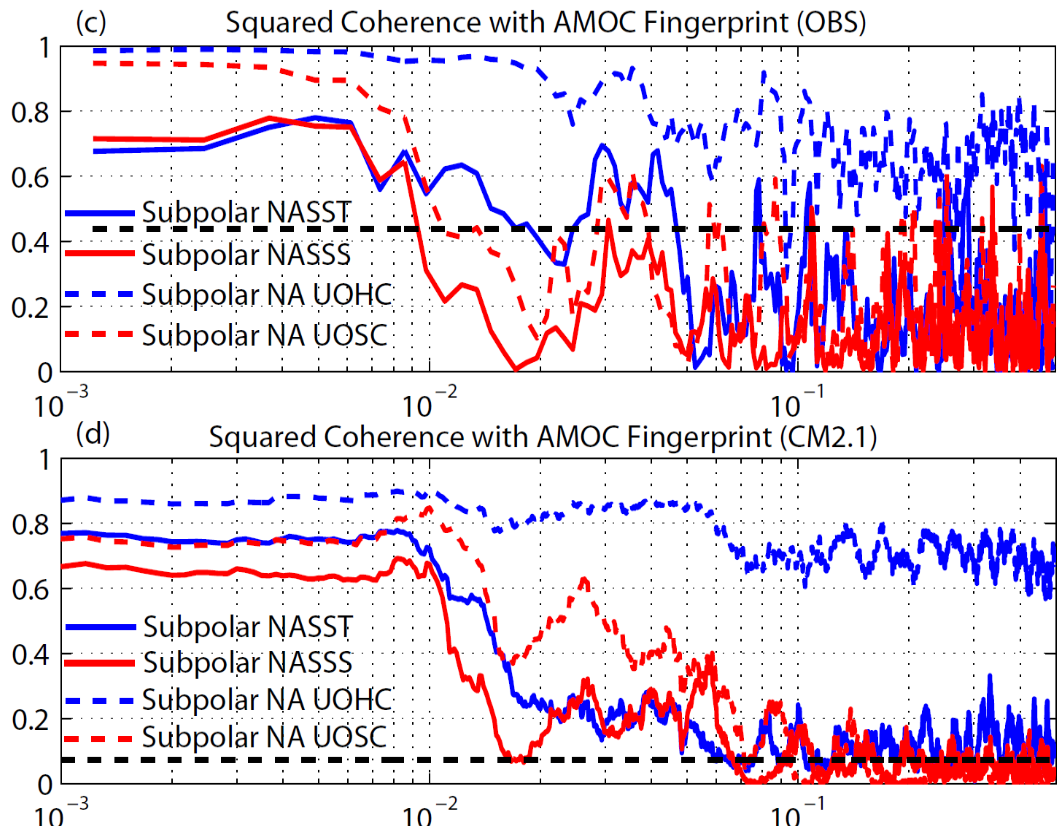
The observed and CM2.1 simulated two-step bending in the Subpolar NASST power spectra cannot be explained by the slab ocean model results or a red noise process, but consistent with AMOC variability being a major oceanic forcing at low frequency




Zhang, 2017

In both observations and the CM2.1 control simulation, the AMV is associated with coherent maultidecadal variations in subpolar NA SST and SSS

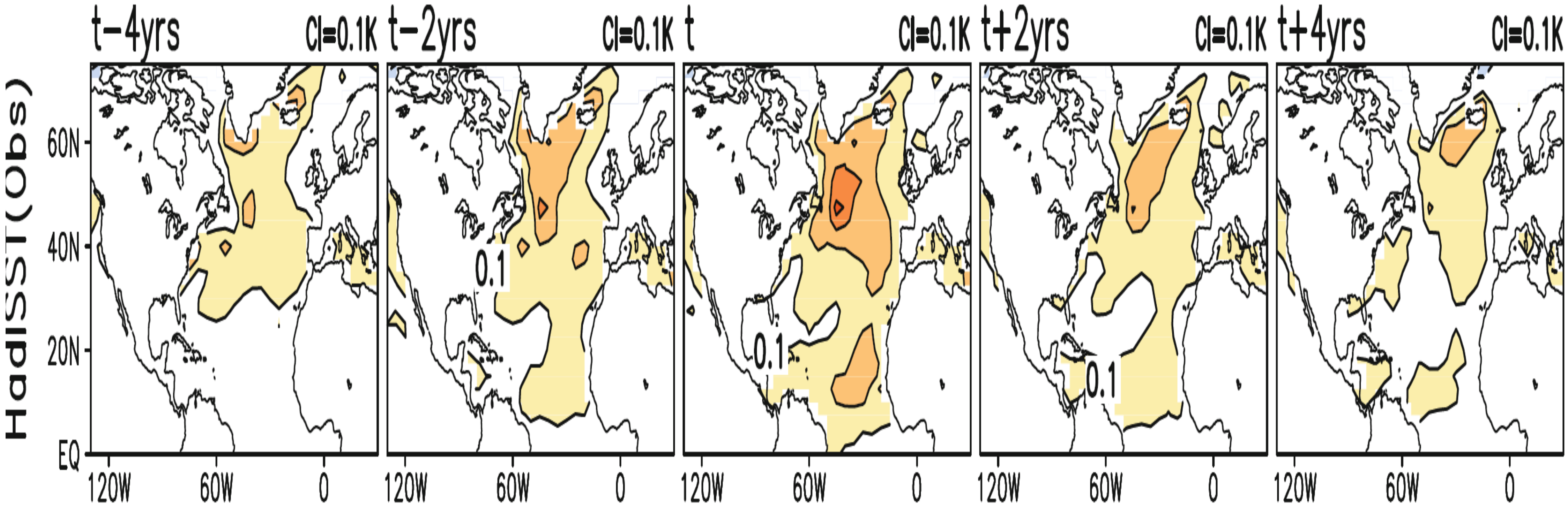



Zhang, 2017

High coherence among Subpolar SST/NASSS, 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 (e.g. low frequency AMOC variability)

# Evolution of the Observed AMV

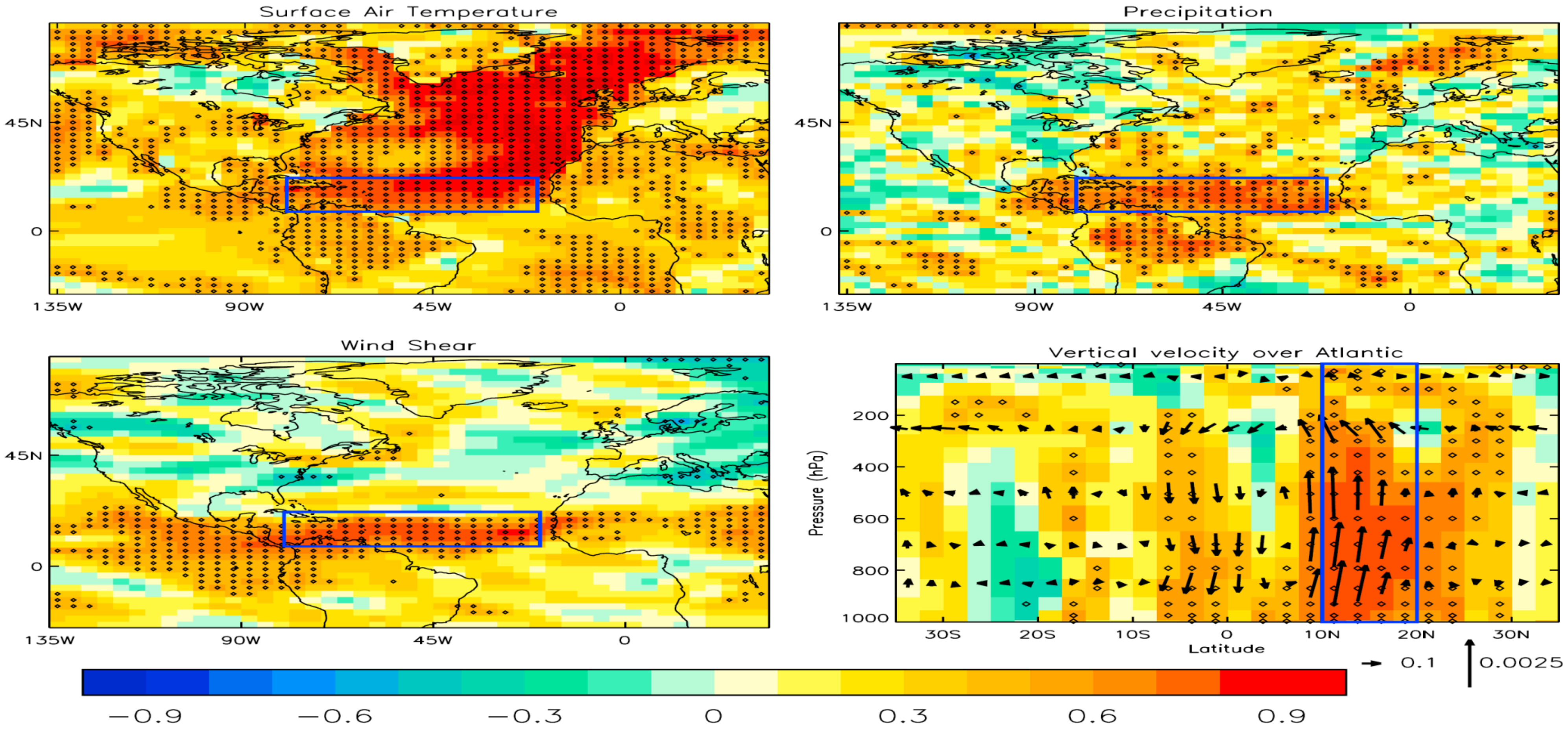



Ruiz-Barradas et al. 2013, Climate Dynamics

The weaker low-latitude AMV signal responds to the stronger subpolar AMV signal through combined oceanic and atmospheric teleconnections, 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

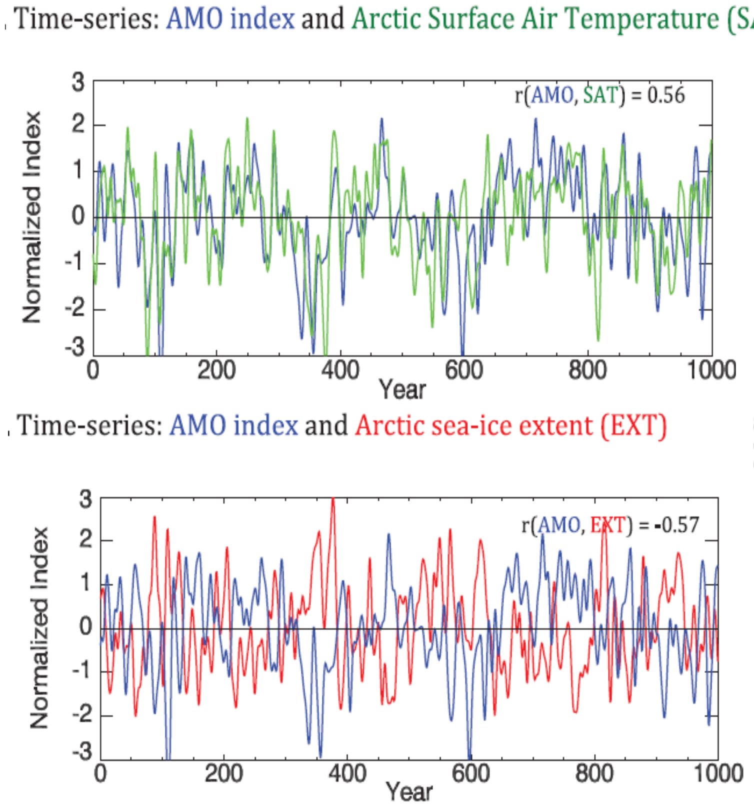
The North Atlantic Subpolar Gyre (SPG) is identified as a key driver of skills in predicting the tropical Atlantic atmosphere, including tropical precipitation, wind shear, vertical velocity, and storm numbers

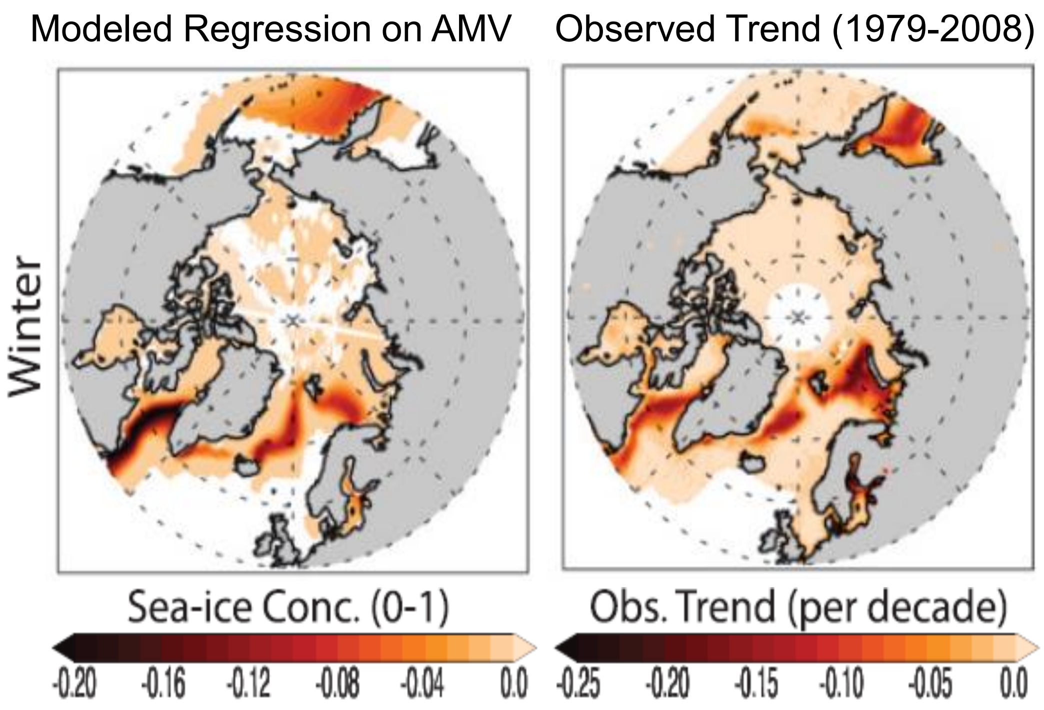



Anomaly correlations for Years 2-6 ensemble means of the perfect and the initialized forecast experiments using HadCM3

Dunstone et al. 2011, GRL

# Impact of AMOC/AMV on Winter Arctic Sea Ice Variability



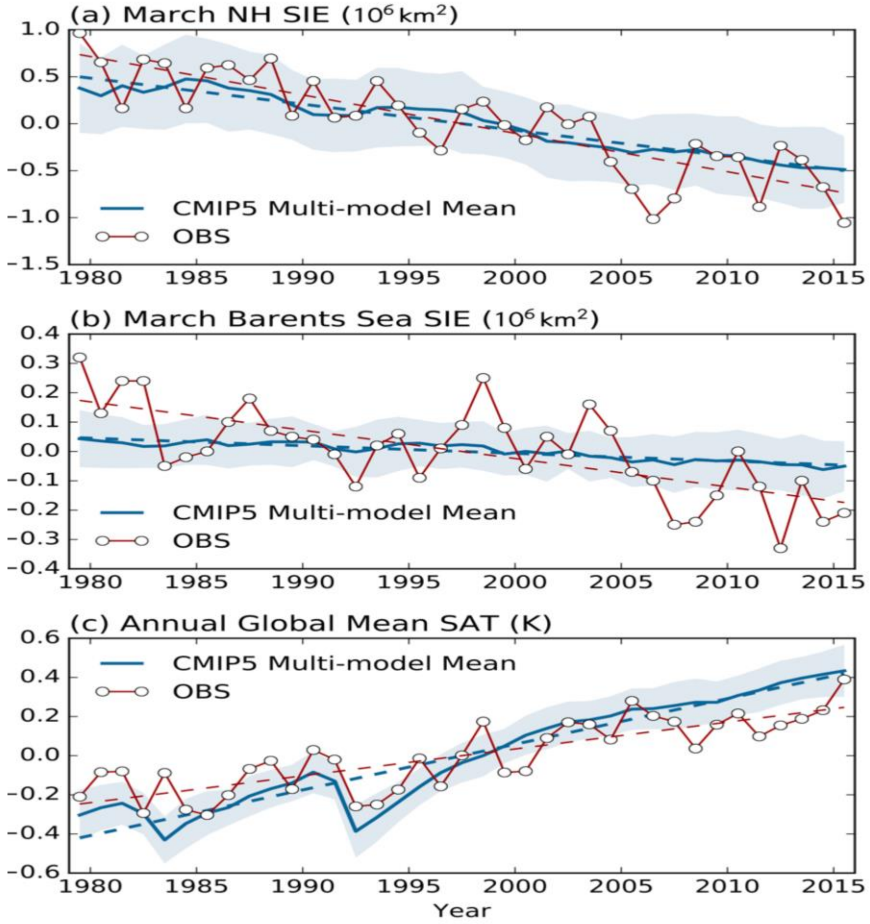



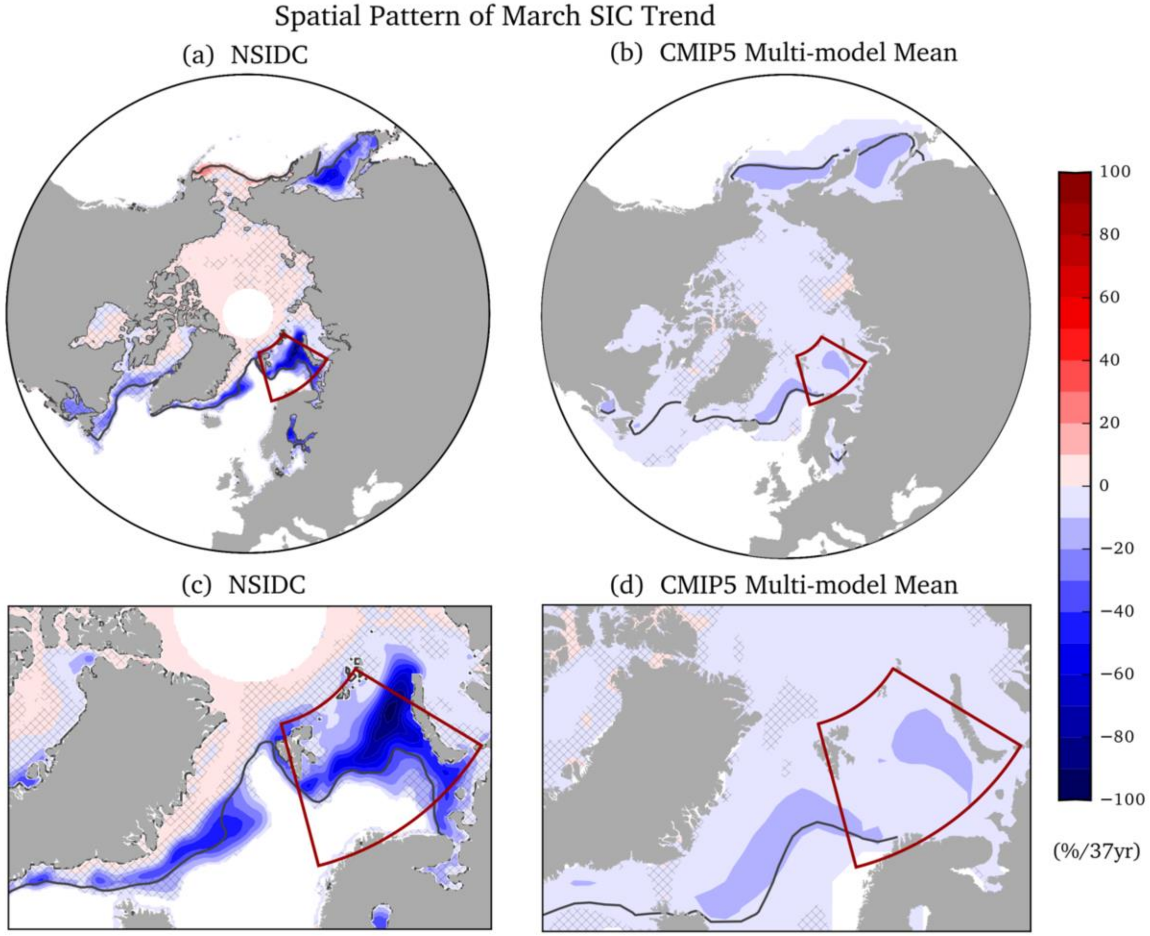

GFDL CM2.1 1000-year control simulation

(Mahajan, Zhang, and Delworth, 2011, JOC)

- Winter Arctic sea ice in the Atlantic side declines with an intensified AMOC/AMV
- Similar spatial patterns suggest a possible role of the AMOC/AMV in the observed winter sea ice decline
- The anti-correlation between AMV and winter Arctic sea ice is also found in other climate models (Day et al. 2012), paleo records (Miles et al. 2014), and decadal prediction experiments (Yeager et al. 2015)

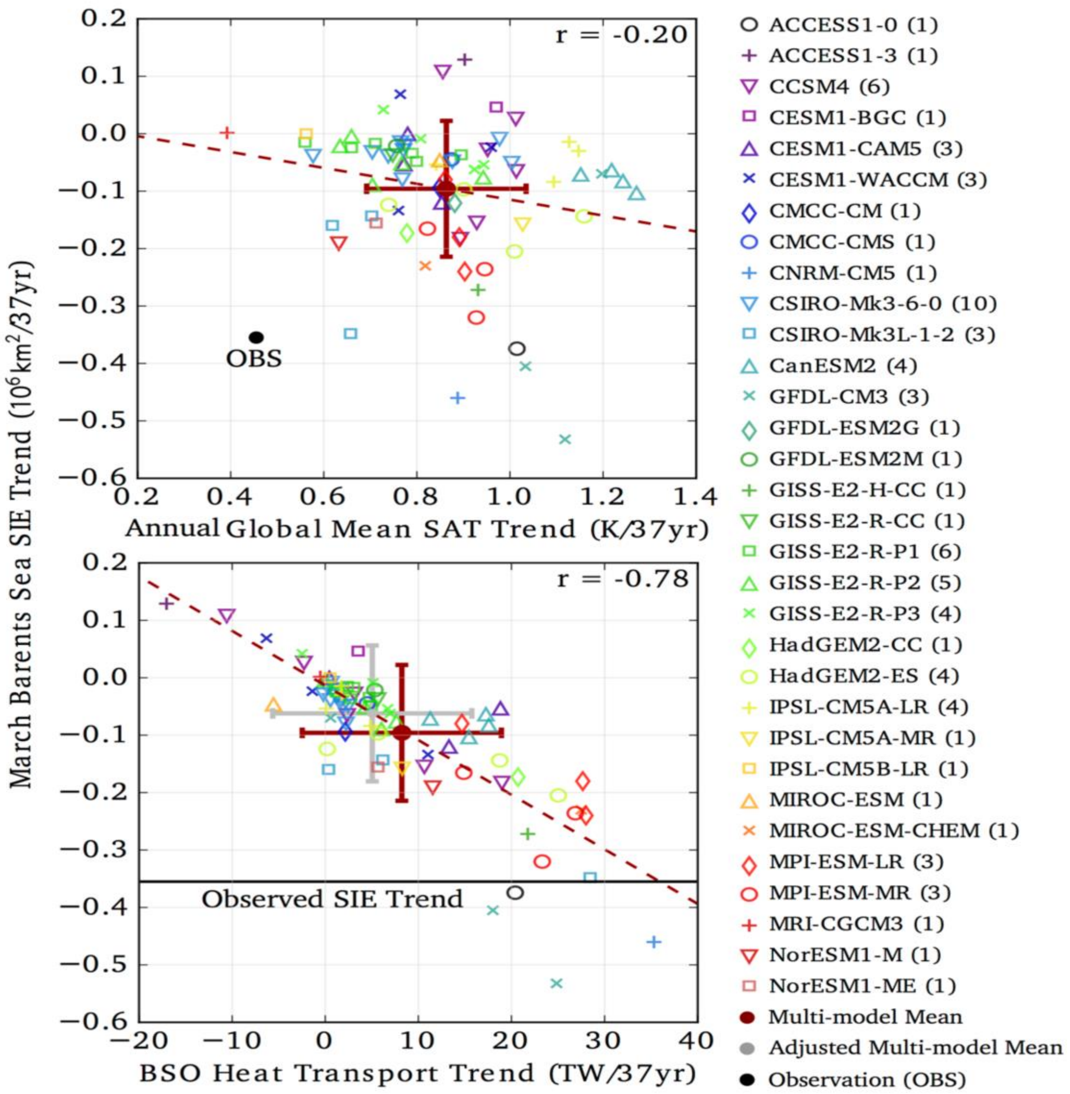
# Discrepancy between Observed and CMIP5 Multi-Model Simulated Barents Sea Winter Sea Ice Decline

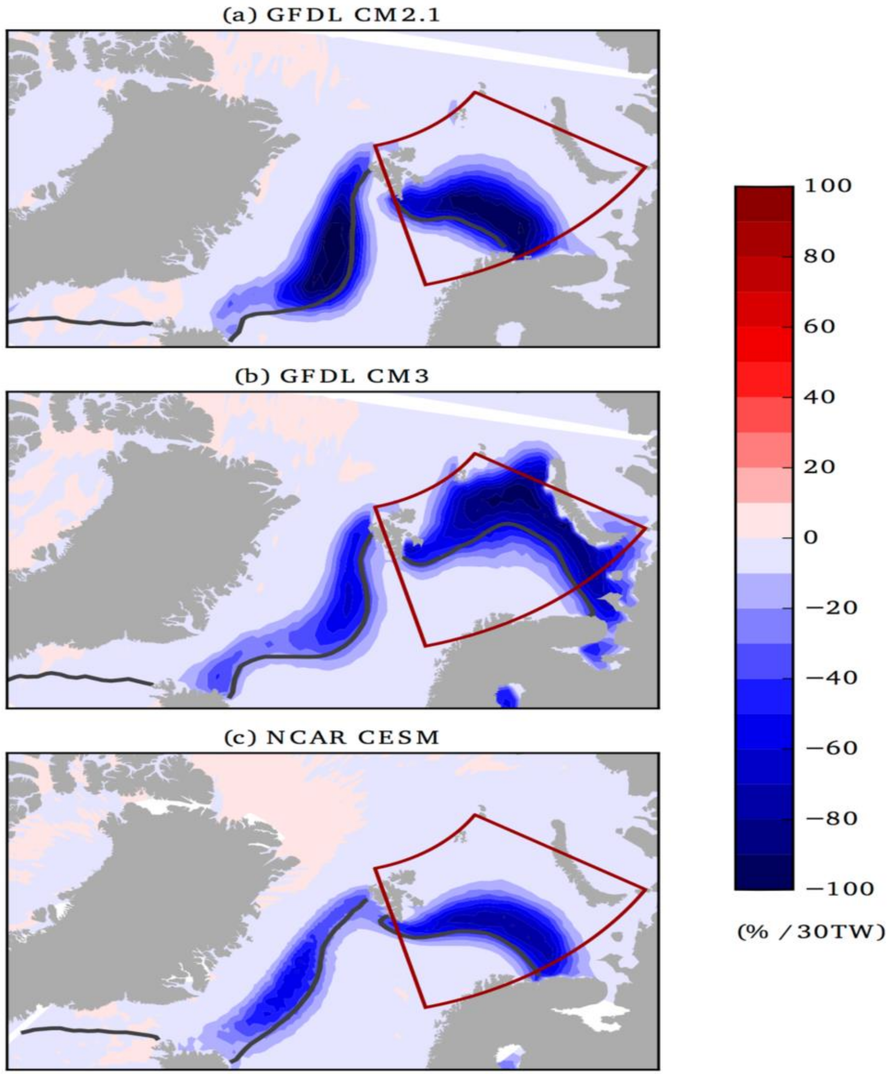



Li, Zhang, and Knutson, 2017, Nature Communications

- Comparing the time series of March NH SIE anomalies alone is insufficient for understanding the cause of the observed winter NH sea ice decline
- Closer inspection of spatial patterns reveals that CMIP5 externally forced March NH SIC trend in individual regions (especially in Barents Sea) differs substantially from that observed




Li, Zhang, and Knutson, 2017, Nature Communications

March Barents Sea SIE trends have little correlation with global mean SAT trends, but are strongly anti-correlated with trends in Atlantic heat transport across the BSO

Comparison with control simulations suggests that the Atlantic heat transport across the BSO associated with internal variability might have been the leading cause for the observed winter sea ice decline in Barents Sea

# Summary

## What is the observed Atlantic Multidecadal Variability (AMV) ?

- The AMV is associated with coherent multivariate low frequency variability observed in the Atlantic, including coherent multidecadal variations in Atlantic SST, SSS, upper ocean heat/salt content, ocean-driven surface heat fluxes (Zhang, 2007; 2008; Wang and Zhang, 2010; Robson et al. 2012a; Zhang et al. 2013; Gulev et al. 2013; Ba et al. 2013; Robson et al. 2016; Zhang et al. 2016)

- These key observed AMV features cannot be explained by a direct response to stochastic atmospheric forcing (Clement et al. 2015;2016) or external radiative forcing (Booth et al. 2012)

- The SST-based definition of the AMV Index often leads to incomplete understanding of the AMV mechanism only in terms of SST anomalies

- The decadal persistence of Subpolar NASST anomalies associated with the AMV in observations and fully coupled model GFDL CM2.1 will lead to much higher decadal prediction skill than that obtained from the slab ocean models or the red noise process

- The correlation and regression between net surface heat flux and SST at low frequency are key indicators for the relative roles of oceanic vs. the atmospheric forcing in SST anomalies. The red noise model with no oceanic damping gives unrealistic interpretation of the negative correlation

- The oceanic forcing has a dominant role in the low frequency Subpolar NASST anomalies associated with the AMV, and is closely linked to AMOC variability, which is a major source for the decadal persistence in Subpolar SST/SSS and UOHC/UOSC

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

- The ocean dynamics associated with the AMV is important for low frequency Arctic sea ice variability