Understanding Multidecadal AMOC Variability

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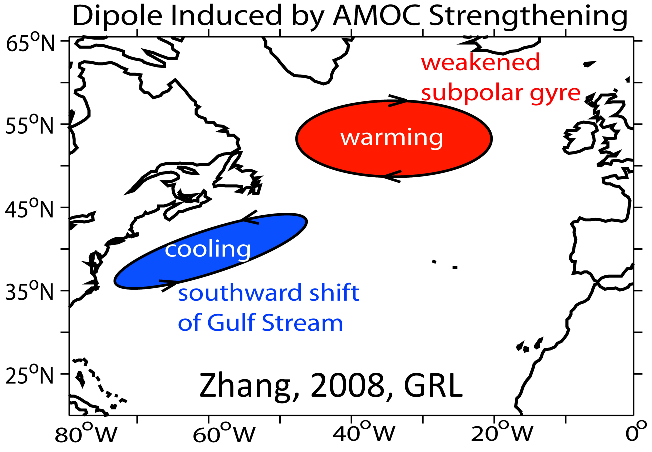
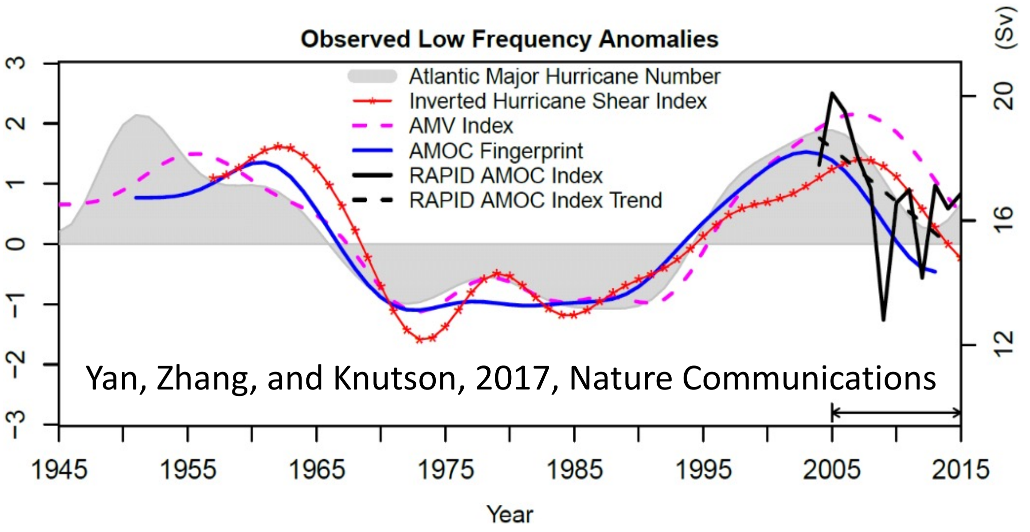
Introduction – Observational Evidence for Multidecadal AMOC Variability

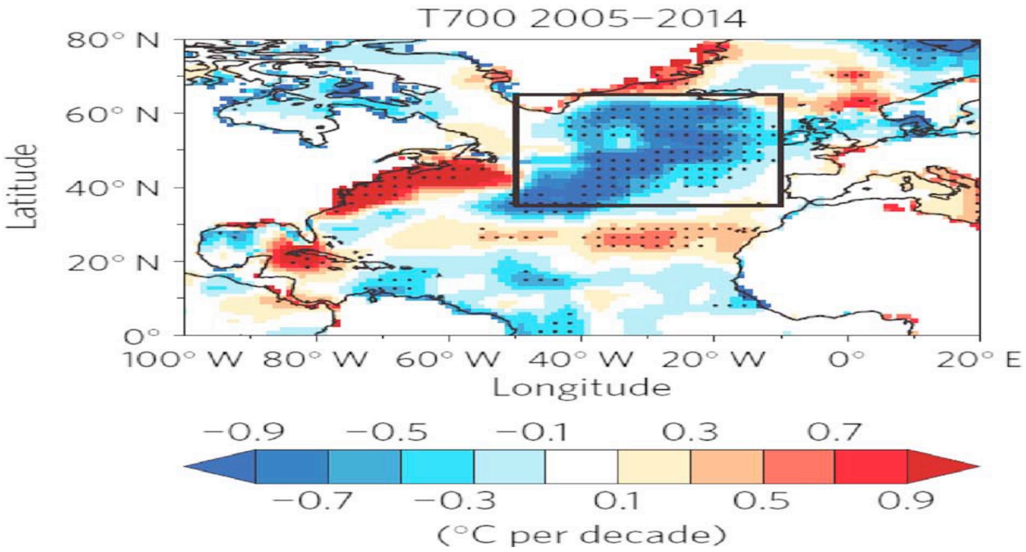
Multidecadal AMOC variability has been reconstructed using observed fingerprints/proxies (e.g. Zhang, 2007, 2008; Yan et al. 2017; Chen & Tung, 2018; Zhang et al. 2019; Rossby et al., 2020; Fraser & Cunningham, 2021)





The leading mode of extratropical NA upper ocean heat content variations (opposite variations in the subpolar gyre and the Gulf Stream region) has been identified as an AMOC fingerprint (Zhang, 2008)

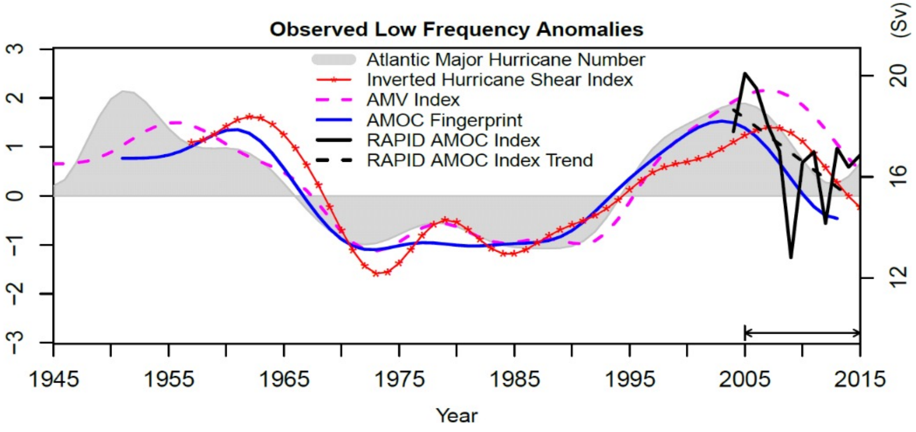
The reconstructed multidecadal AMOC variations are coherent with the observed AMV index, supporting a close AMOC-AMV linkage (Zhang, 2008; Yan et al. 2017)

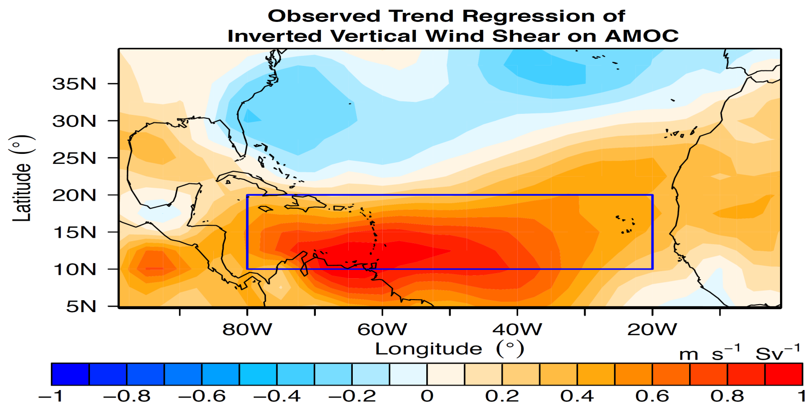


The inferred AMOC decline during 2005-2015 by the fingerprint is consistent the observed cooling trend in the subpolar NA (Robson et al. 2016) and the directly observed AMOC decline from the RAPID program (Frajka-Williams et al. 2016; Smeed et al. 2018)

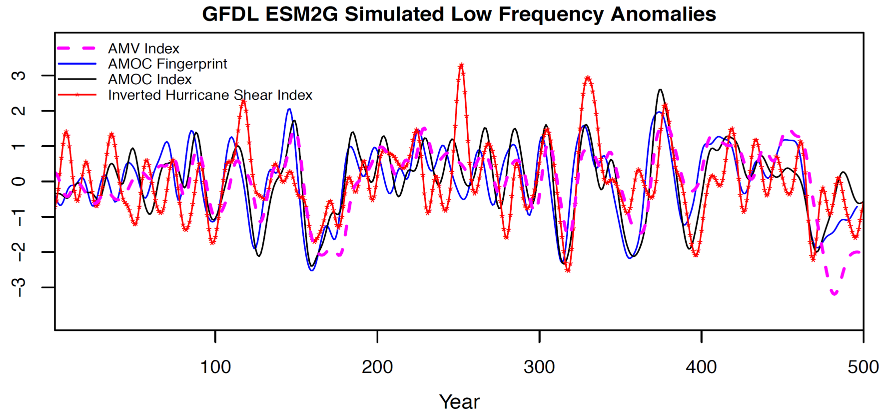
Robson et al. 2016, Nature Geosciences

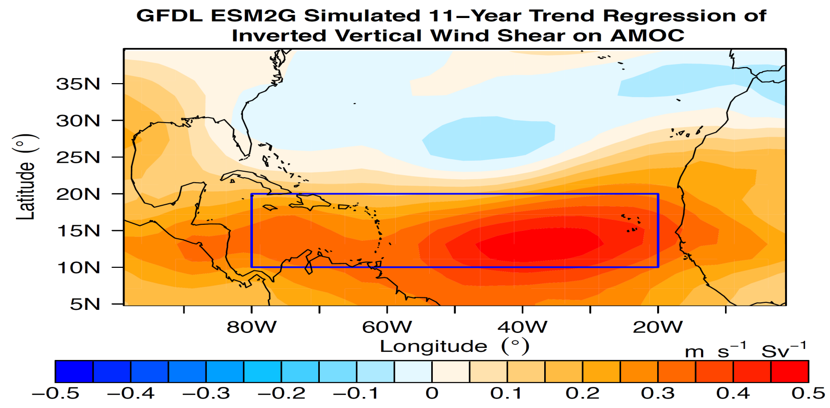
Impacts of the AMOC on Atlantic Major Hurricane Frequency





Observations show coherent multidecadal variations among the Atlantic major hurricane frequency, AMOC fingerprint, AMV index, and inverted vertical wind shear index. The observed decline of the Atlantic major hurricane frequency during 2005–2015 is associated with the directly observed AMOC weakening from the RAPID program



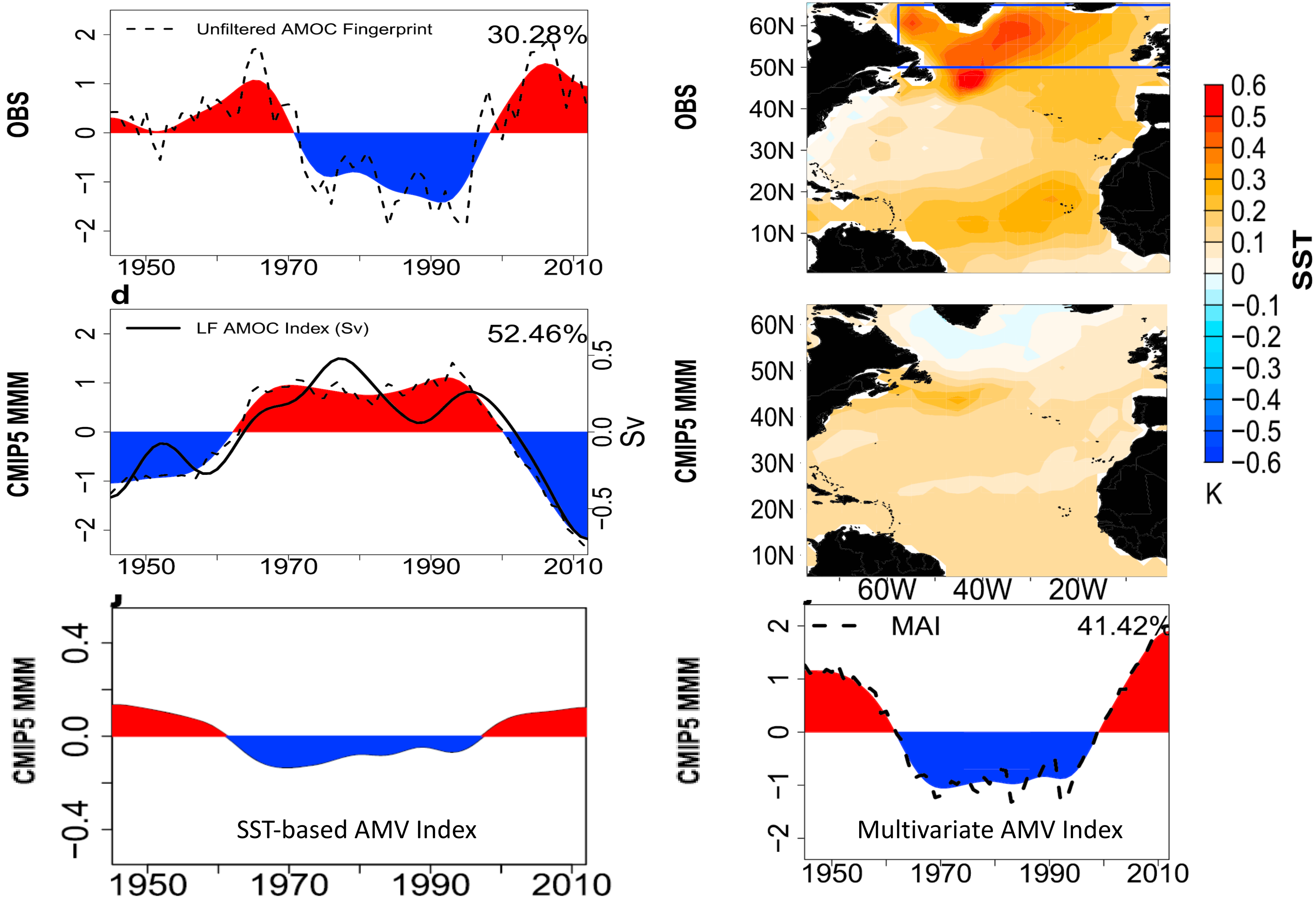


GFDL-ESM2G control simulation has similar coherent variations among AMOC Index/fingerprint, AMV index, and inverted vertical wind hear index, supporting an important role of the AMOC in multidecadal variability of Atlantic major hurricane frequency

Yan, Zhang, and Knutson, 2017, Nature Communications

Extra-tropical AMOC Fingerprint (Observed vs. CMIP5 Externally Forced Response)

Linear Detrending



Externally forced multidecadal AMOC change/AMOC fingerprint is almost opposite to that observed

With linear detrending, the externally forced multidecadal AMOC change is anti-correlated with the externally forced SST-based AMV index

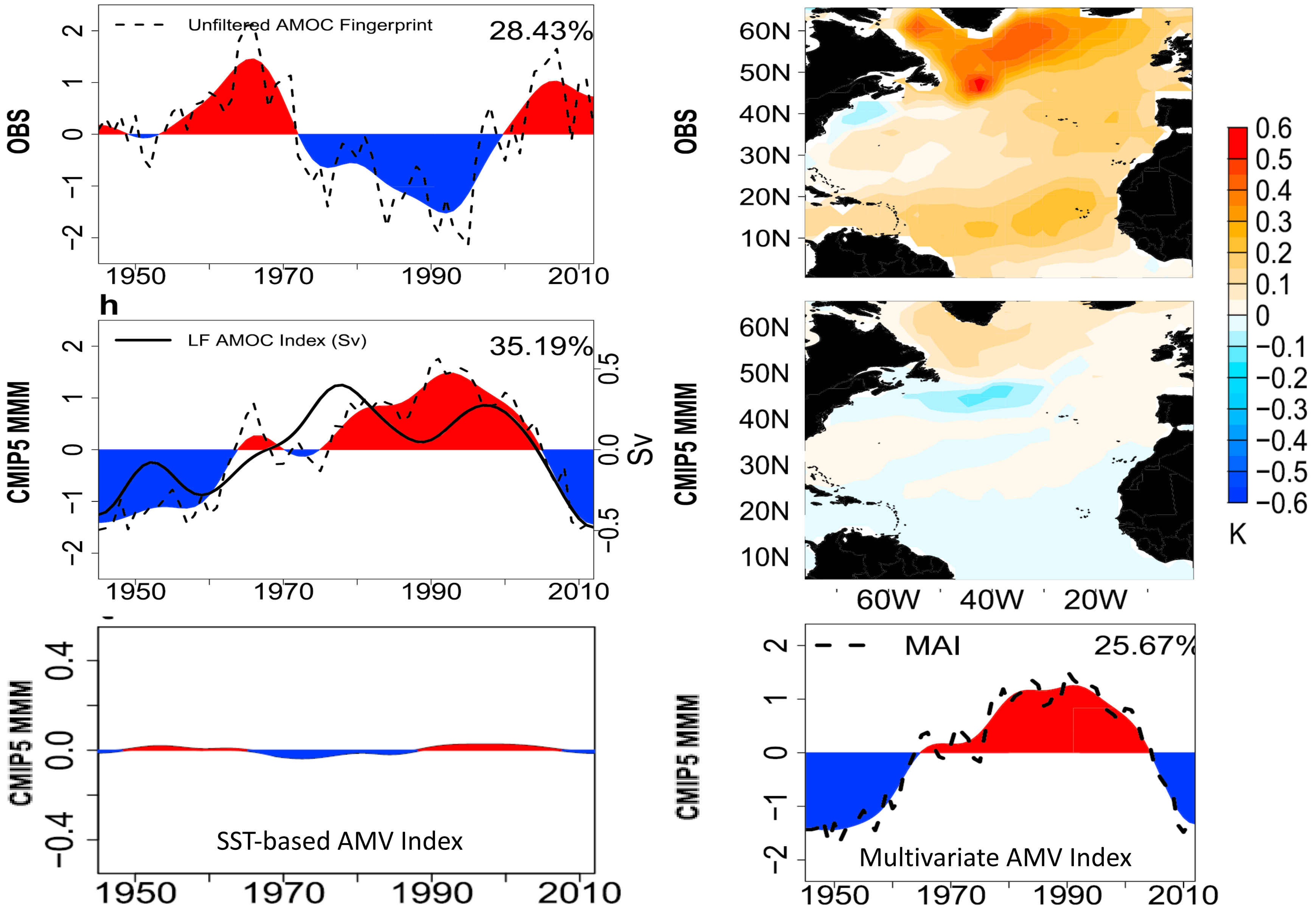
In contrast, the observed AMOC fingerprint is in phase with the observed AMV index

The externally forced AMV SST pattern is very different from that observed

Yan, Zhang, & Knutson, 2019, GRL

Extra-tropical AMOC Fingerprint (Observed vs. CMIP5 Externally Forced Response)

Signal Regressed on Global Mean SST is Removed (Nonlinear Detrending)



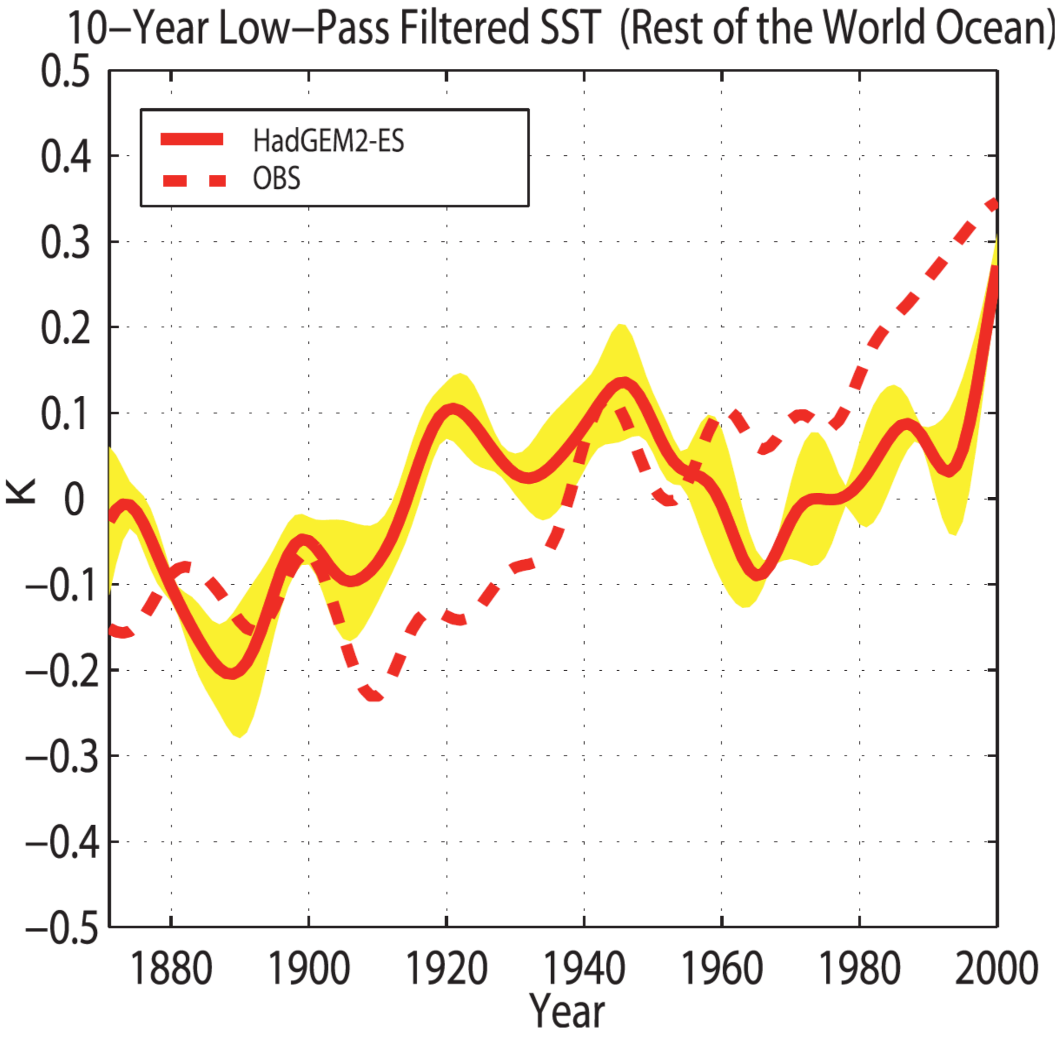
Yan, Zhang, & Knutson, 2019, GRL

When the signal associated with global mean SST is removed, the externally forced multidecadal AMOC change is in phase with the externally forced multivariate AMV index, both are opposite to that observed

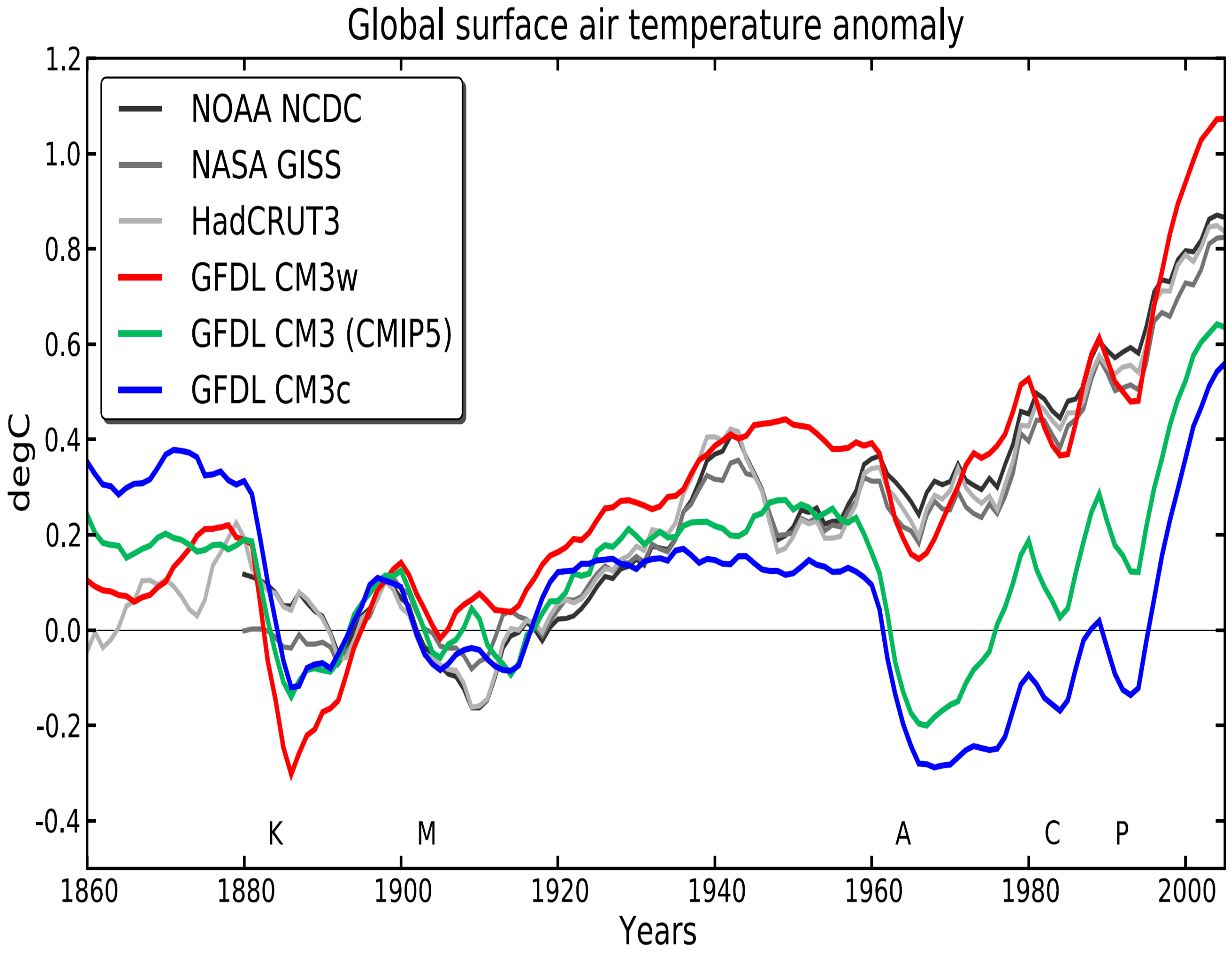
The externally forced SST-based AMV index becomes much weaker

The linear detrended SST-based AMV index is dominated by the signal associated with the global mean SST response

The modeled pronounced externally forced multidecadal changes in the global mean SST and surface air temperature (mostly due to strong indirect aerosol effect) do not match the observed global mean signal

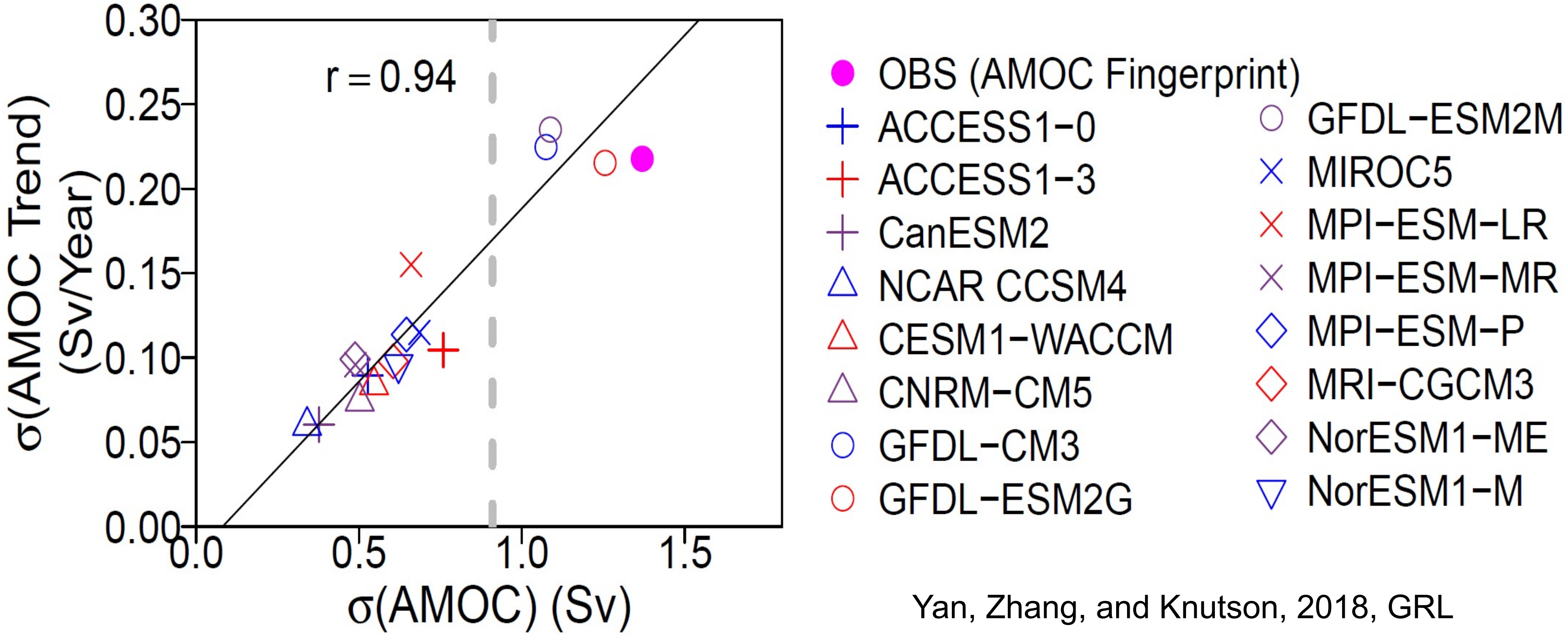


Zhang et al. 2013, JAS



Golaz et al. 2013, GRL

Underestimated Internal Multidecadal AMOC Variability in Most CMIP5 Models



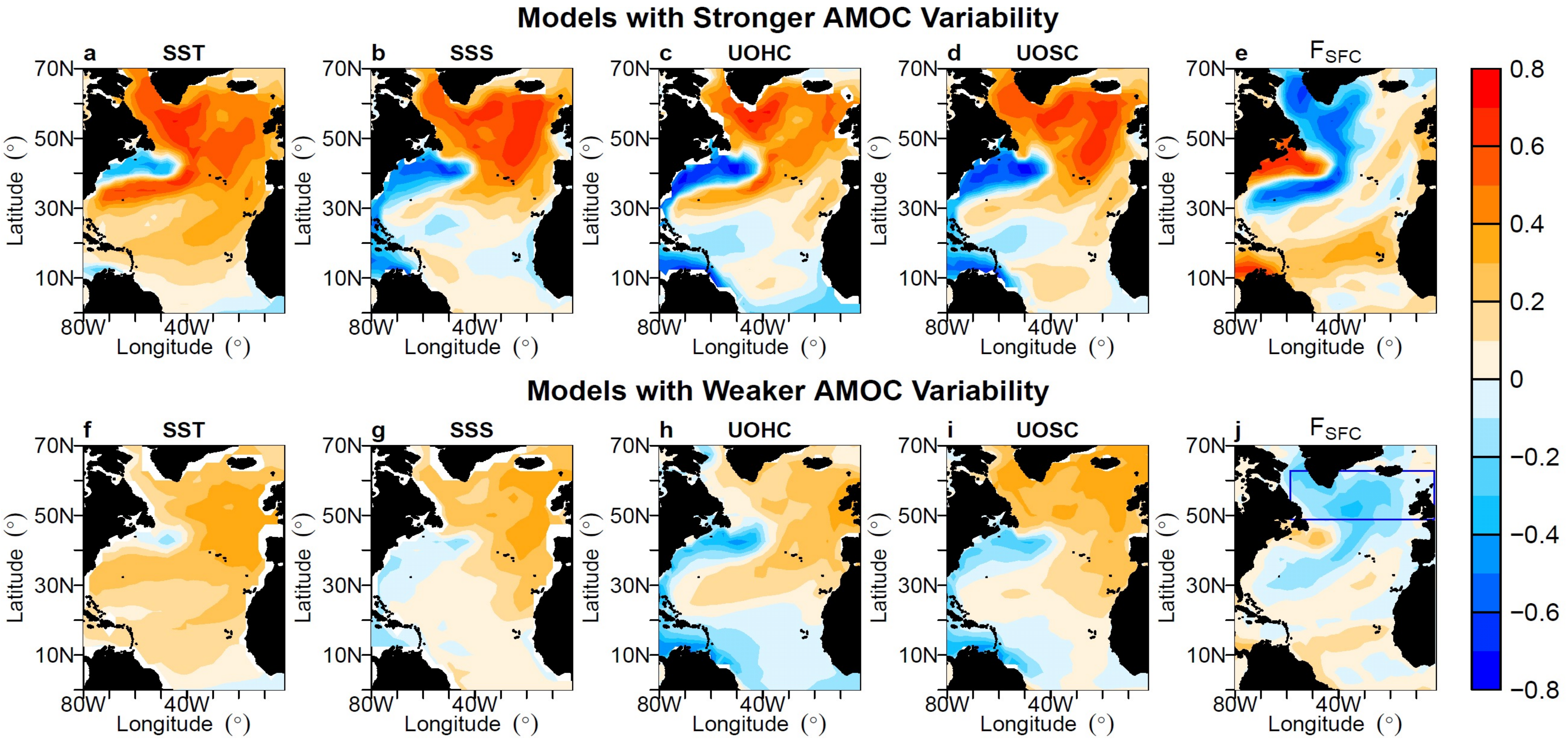
Yan, Zhang, and Knutson, 2018, GRL

Scatterplot of standard deviations of decadal AMOC trends vs. amplitudes of low-frequency AMOC variability (i.e. standard deviations of the 10-year low-pass filtered AMOC anomalies) across CMIP5 control simulations

- Most coupled models underestimate amplitudes of internal multidecadal AMOC variability, leading to the underestimation of the AMOC-related climate impacts and Atlantic decadal predictability

- The underestimated internal multidecadal AMOC variability amplifies the relative role of external radiative forcing or stochastic atmospheric forcing in AMV (Kim et al. 2018)

AMOC-AMV Linkage is Underestimated in Many CMIP5 Models



Correlations with AMOC

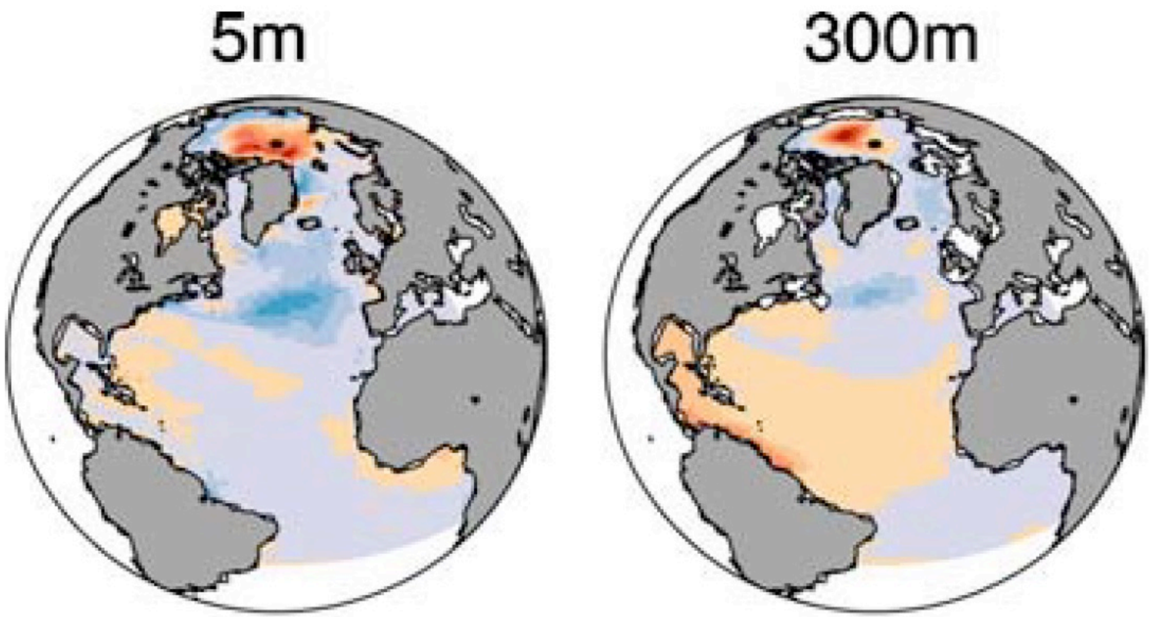
Yan, Zhang, and Knutson, 2018, GRL

The correlation between the AMOC and AMV-related subpolar signal in SST, SSS, upper ocean heat/salt content, and net downward surface heat flux is much stronger (weaker) in models with relatively stronger (weaker) multidecadal AMOC variability

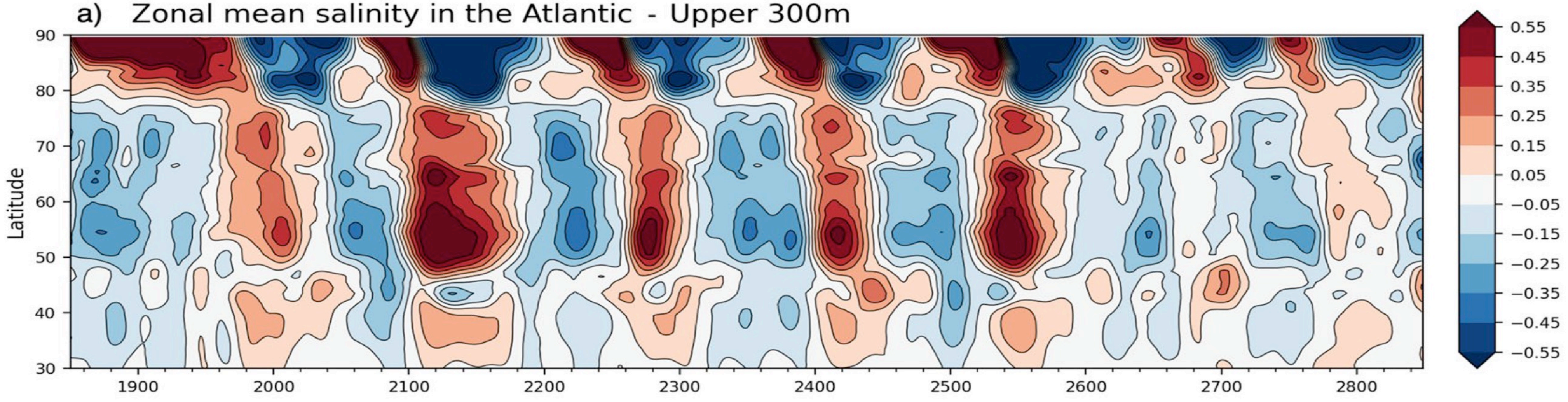
Most climate models underestimate amplitudes of multidecadal AMOC variability, leading to the underestimation of the AMOC-AMV linkage

Multidecadal AMOC variations lag Arctic salinity anomalies (HadCM3)

Low-frequency AMOC variations simulated in different climate models have very different periods (from multidecadal to centennial) (Keenlyside et al. 2016) and often lag Arctic salinity anomalies (e.g. Delworth et al. 1997; Jungclaus et al. 2005; Hawkins & Sutton, 2007; Jackson & Vellinga, 2013; Jiang et al. 2021; Lai et al. 2022; Mehling et al. 2023; Meccia et al. 2023)



Hawkins & Sutton, 2007, Climate Dynamics

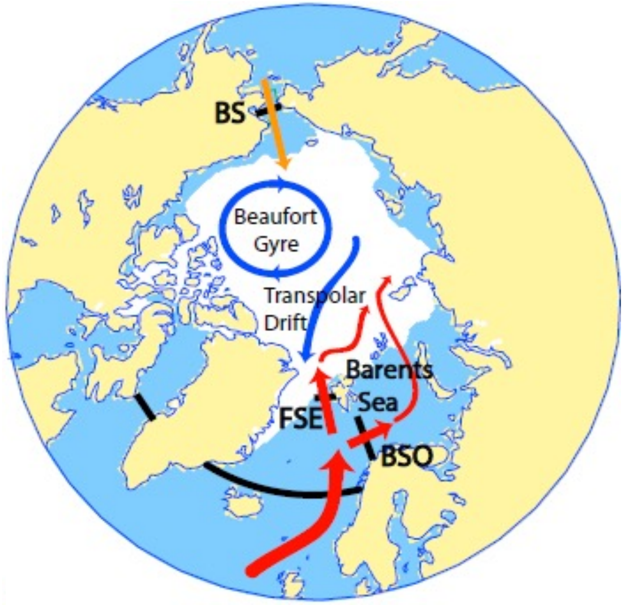


Meccia et al. 2023, Climate Dynamics

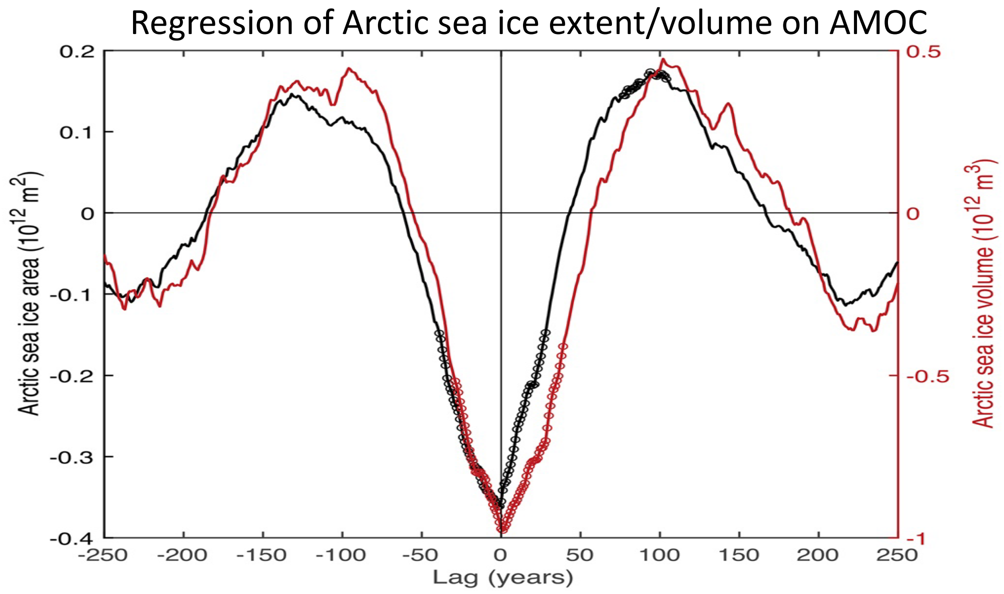
Multi-centennial AMOC variations lag Arctic salinity anomalies (EC-Earth3)

Multidecadal AMOC Variability and Associated Two-Way Interactions with the Arctic

- Multidecadal AMOC variability and associated Atlantic heat transport entering the Arctic also affect multidecadal Arctic sea ice variability



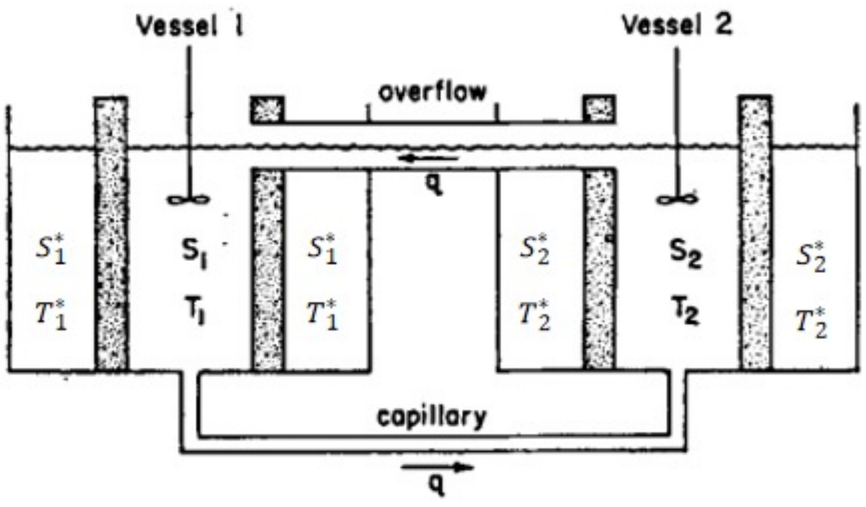
Zhang, 2015, PNAS



Jiang et al. 2021, JAMES   IPSL-CM6-LR

- Unlike ENSO variability that has been explained through simple conceptual models, multidecadal AMOC variability, its two-way interactions with the Arctic, and factors affecting its periods are not well understood from the theoretical perspective using simple conceptual models

AMOC Conceptual Model



Stommel, 1961

Stommel's Two-Box Model (1961) provides a pioneering and powerful theoretical framework to study steady AMOC states and abrupt AMOC changes

However, it does not include multidecadal AMOC oscillation solutions. What physical processes are missing in the original Stommel's Two-Box Model?

How to construct a conceptual model that is as simple as possible but can explain the reconstructed/simulated multidecadal AMOC variability and its two-way interactions with the Arctic?

T: Temperature
S: Salinity
ρ: Density
T*: Temperature of the reservoir (atmosphere)
S*: Salinity of the reservoir (freshwater forcing)
c: Temperature damping coefficient
d: Salinity damping coefficient
q: AMOC strength
k: Coefficient linking AMOC with high- and low-latitude density contrast

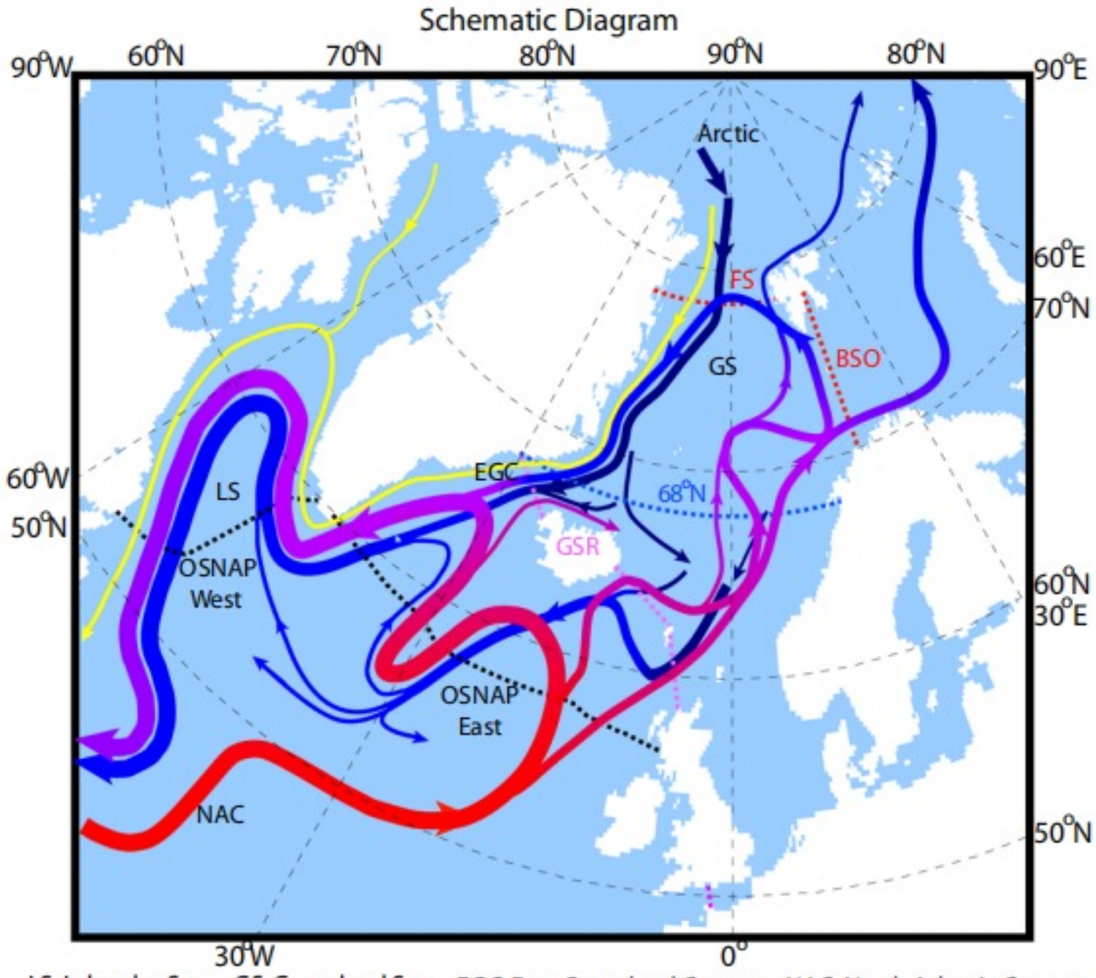
$$\begin{cases} \dfrac{dT_1}{dt} = c(T_1^* - T_1) - |q|(T_1 - T_2) \\ \dfrac{dT_2}{dt} = c(T_2^* - T_2) - |q|(T_2 - T_1) \end{cases}$$

$$kq = \rho_1 - \rho_2$$

$$\begin{cases} \dfrac{dS_1}{dt} = c(S_1^* - S_1) - |q|(S_1 - S_2) \\ \dfrac{dS_2}{dt} = c(S_2^* - S_2) - |q|(S_2 - S_1) \end{cases}$$

$$\rho = \rho_0(1 - \alpha T + \beta S)$$

Reconstruction of the Long-term Mean AMOC Structure Suggests that the Arctic Ocean is the Northern Terminus of the AMOC



Zhang & Thomas, 2021, Communications Earth & Environment

The AMOC across the OSNAP section depends on the west-east density contrast across the section through both thermal wind and horizontal gyre contributions

A Simple Conceptual Model for Multidecadal AMOC Variability

Wei and Zhang, 2022, GRL

- The high and low latitude boxes are separated at the OSNAP section
- OSNAP observations of AMOC volume, heat, and salt transport (Lozier et al. 2019; Li et al. 2021) are used to calibrate the revised Stommel's Two-Box Model
- The original Stommel's Two-Box Model relates the AMOC with instantaneous density contrast between high- and low-latitude boxes
- The density at OSNAP western boundary is affected by the AMOC outflow from the Arctic (Zhang & Thomas, 2021), and the density at OSNAP eastern boundary is affected by the AMOC inflow along the North Atlantic Current from the subtropics (Sutton & Allen, 1997)
- Hence it takes a mean advective time delay τ_H (τ_L) for water properties in high (low) latitude to reach OSNAP western (eastern) boundary to affect the AMOC q across the OSNAP section

$$q = k\big(\rho_H(t-\tau_H) - \rho_L(t-\tau_L)\big)$$

A Simple Conceptual Model for Multidecadal AMOC Variability

Coupled freshwater feedback

- A stronger AMOC leads to enhanced poleward ocean heat transport (OHT) and heat/moisture released from the ocean into high-latitude atmosphere, resulting in stronger river runoff into the Arctic, which increases linearly with the AMOC with a few-year time lag (Jungclaus et al. 2005)
- The intensified AMOC and associated warmer high latitude temperature increases the high-latitude atmospheric blocking and reduces the Arctic freshwater export (Peings & Magnusdottir, 2014; Lonita et al. 2016)
- The AMOC-induced enhanced poleward OHT causes more Arctic sea ice melting and less Arctic sea ice export (Zhang, 2015; Li et al. 2018; Jiang et al. 2021)
- These processes are represented simply as an Arctic freshwater flux anomaly lagging the AMOC anomaly with a simplified time delay τ_C, whereas the freshwater flux is uncoupled to the AMOC in the original Stommel's Two-Box Model

Coupled freshwater feedback

$$F' = cq'(t - \tau_C)$$

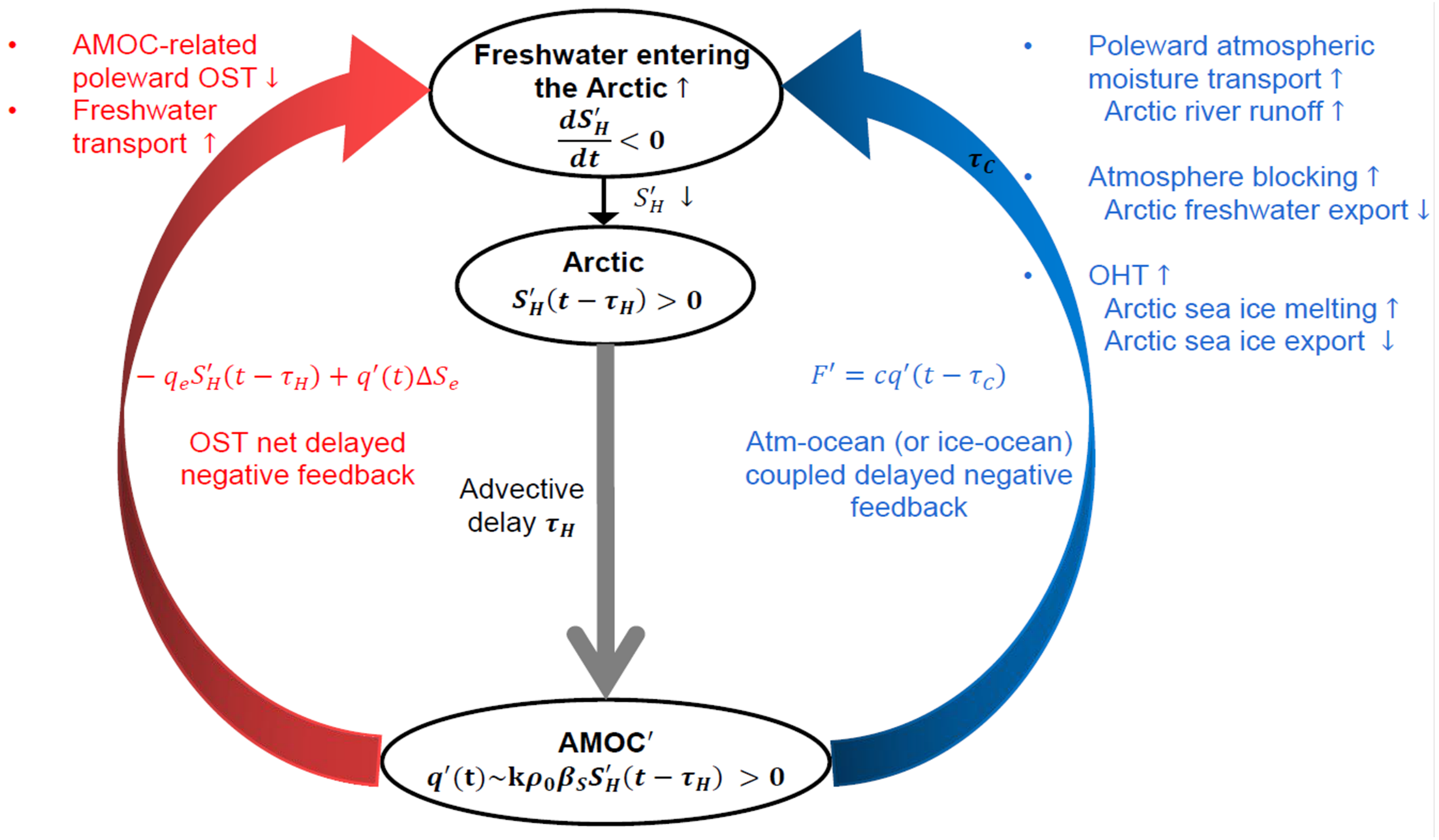
Multidecadal AMOC Variability and Associated Two-Way Interactions with the Arctic

Simplified/linearized delay differential equation (DDE) for Arctic salinity anomalies:

$$\frac{dS'_H}{dt} = -\lambda S'_H\,(t - \tau_H)$$

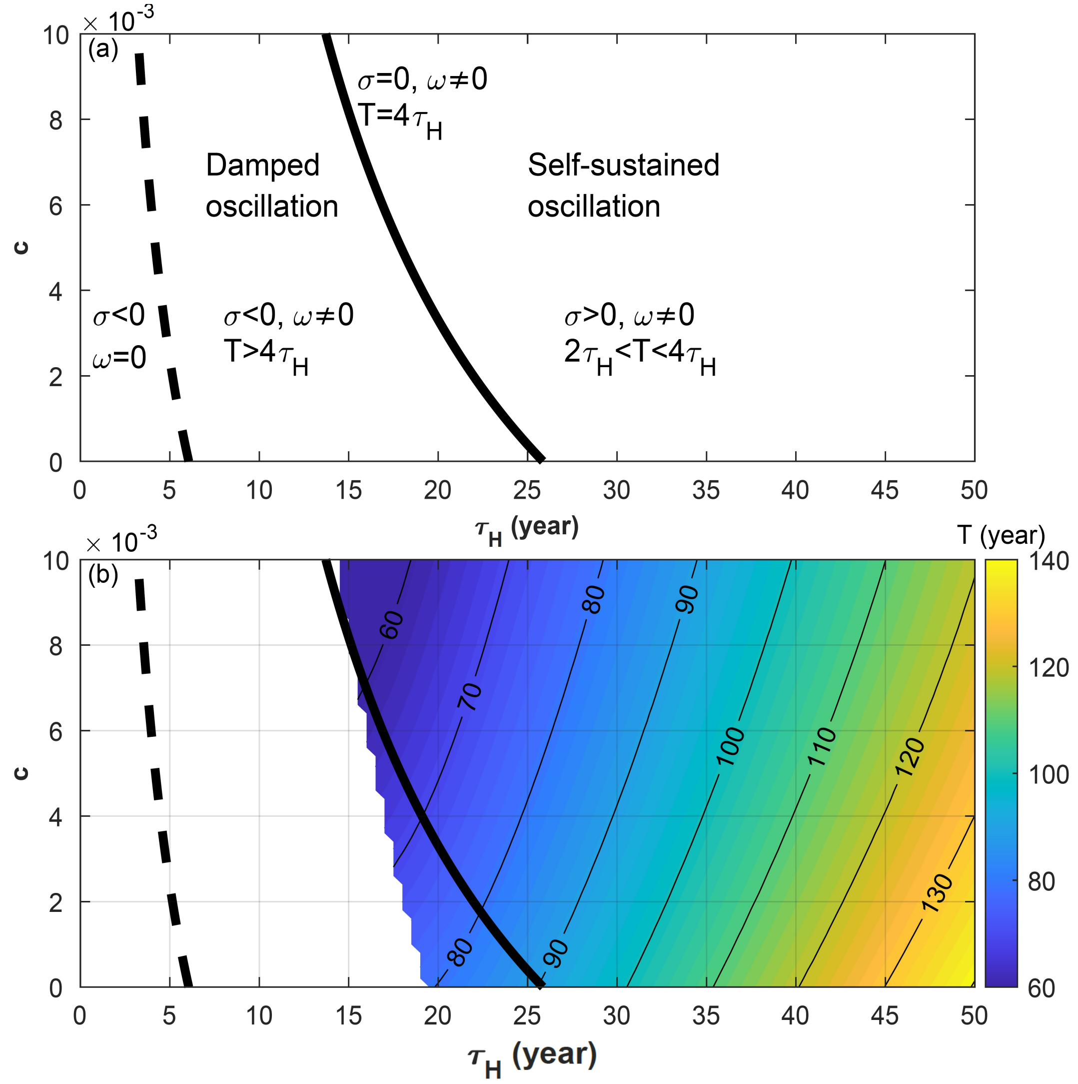
- Without the advective time delay, the system will only have steady state solutions like the original Stommel's model
- With the advective time delay, multidecadal AMOC oscillation solutions also exist

AMOC Delayed Oscillator



The simple conceptual model illustrates the AMOC delayed oscillator mechanism and reveals the important role of the Arctic salinity anomaly in multidecadal AMOC variability

Analytical vs. Numerical Solutions of the Simple Conceptual Model



Self-sustained oscillation threshold:

$$\tau_H = \frac{\pi}{2\lambda} = \frac{\pi V_H}{2(q_e - k\rho_0\beta_S\Delta S_e + k\rho_0\beta_S S_0 c)}$$

$$\frac{dS'_H}{dt} = -\lambda S'_H(t-\tau_H)$$

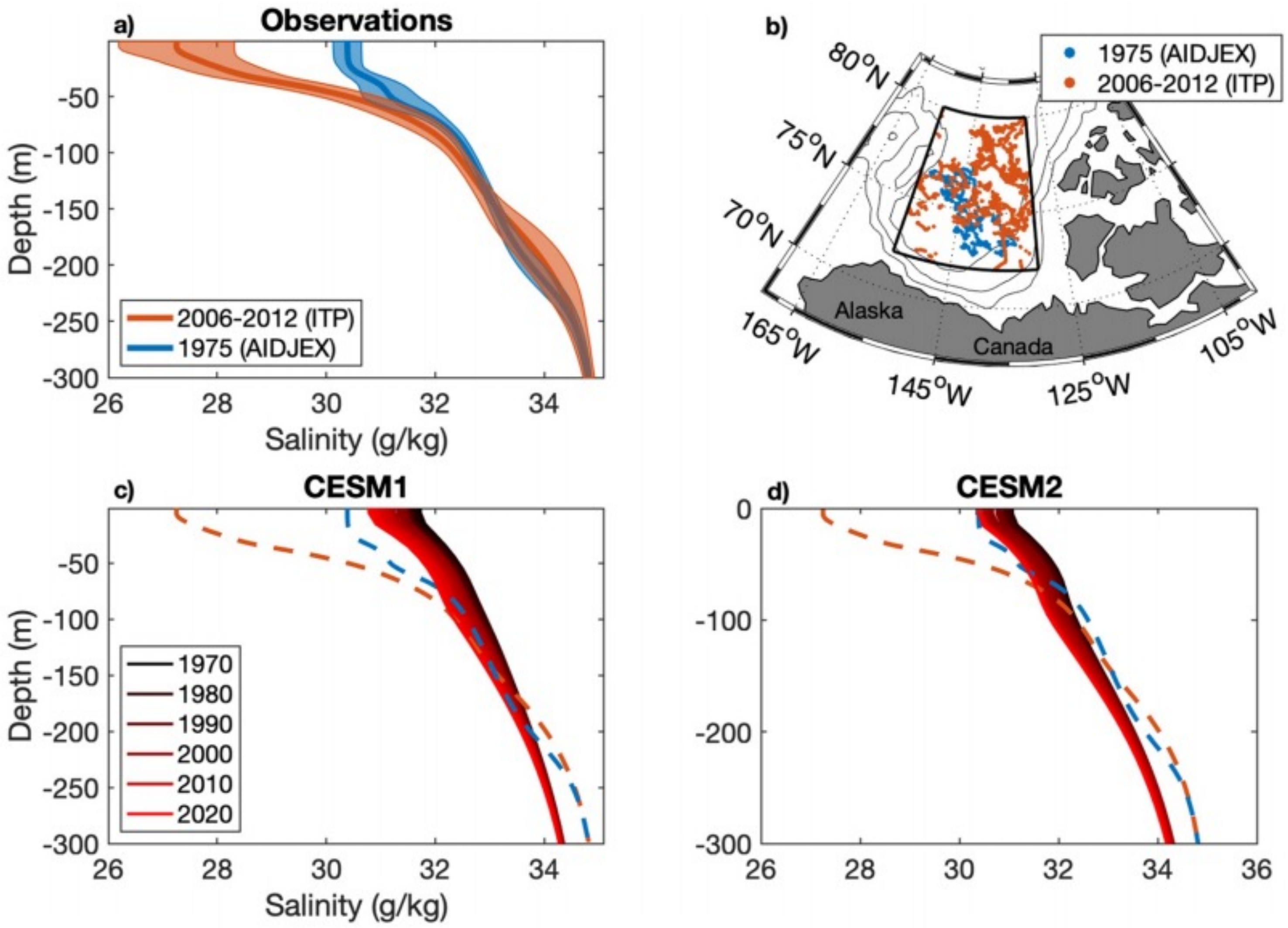
The key factors affecting the AMOC delayed oscillator are the advective time delay τ_H for the Arctic density/salinity anomalies to reach the subpolar NA and the net coupled freshwater feedback strength c

A longer advective time delay leads to a longer AMOC variability period, consistent with climate model results (e.g. Delworth et al. 1997; Jungclaus et al. 2005; Hawkins & Sutton, 2007; Jackson & Vellinga, 2013; Jiang et al., 2021; Meccia et al. 2023; Mehling et al. 2023)

Differences in simulated advective time delay and coupled freshwater feedback strength may contribute to different AMOC variability periods across climate models

The simple conceptual model provides a theoretical framework to understand multidecadal AMOC variability, its two-way interactions with the Arctic, and the diverse periods simulated in climate models

Modeling Biases in Arctic Salinity Anomalies



Rosenblum et al. 2021, GRL

Multidecadal variability has also been observed in the Arctic salinity (Polyakov et al. 2008)

However, climate models have difficulties to simulate observed multidecadal Arctic salinity anomalies (Rosenblum et al. 2021)

The underestimation of Arctic salinity anomalies may contribute to the underestimation of multidecadal AMOC variability in climate models

Summary and Discussion

- The correlations between the AMOC and AMV-related variables are stronger in models with relatively stronger multidecadal AMOC variability
- Many climate models underestimate internal multidecadal AMOC variability, thus underestimate the AMOC-AMV linkage
- When the signal associated with global mean SST is removed, the modeled externally forced multidecadal AMOC fingerprint is in phase with the modeled externally forced multivariate AMV index, both are almost opposite to that observed
- A simple conceptual model is constructed to illustrate the two-way Atlantic-Arctic interactions and associated AMOC delayed oscillator mechanism, suggesting an important role of Arctic salinity anomalies in multidecadal AMOC variability
- When the advective time delay and coupled freshwater feedback are included, multidecadal AMOC oscillations are possible solutions in the revised Stommel's Two-Box Model
- The regimes and multidecadal periods of the AMOC delayed oscillator depend crucially on the delay time scale for the Arctic salinity signal propagating into the subpolar North Atlantic
- Monitoring the potential propagations of Arctic salinity anomalies along the boundary outflow would be valuable for predicting the timing and amplitude of future AMOC changes