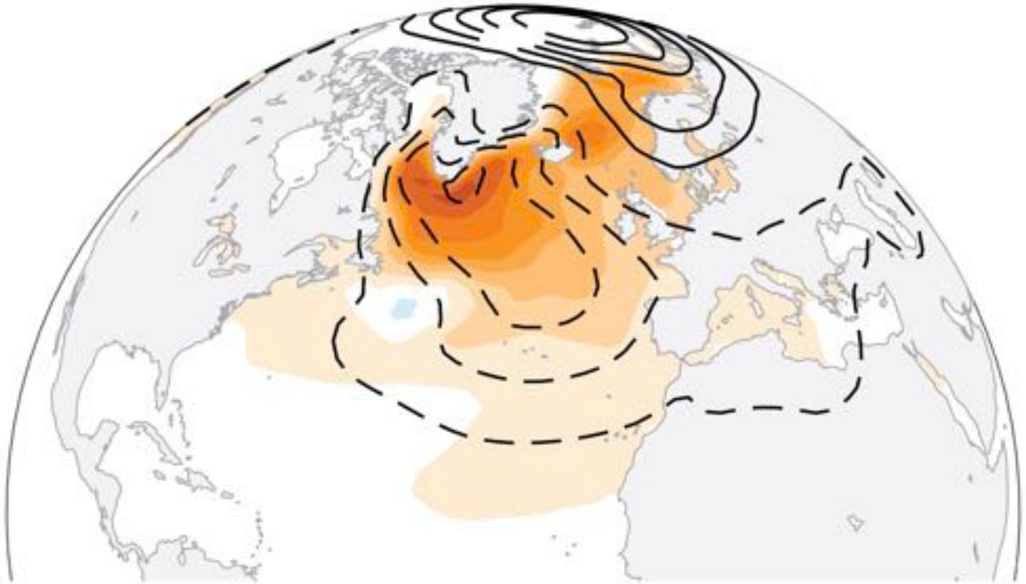
AMOC and ocean-atmosphere dynamical coupling fundamental to the AMO

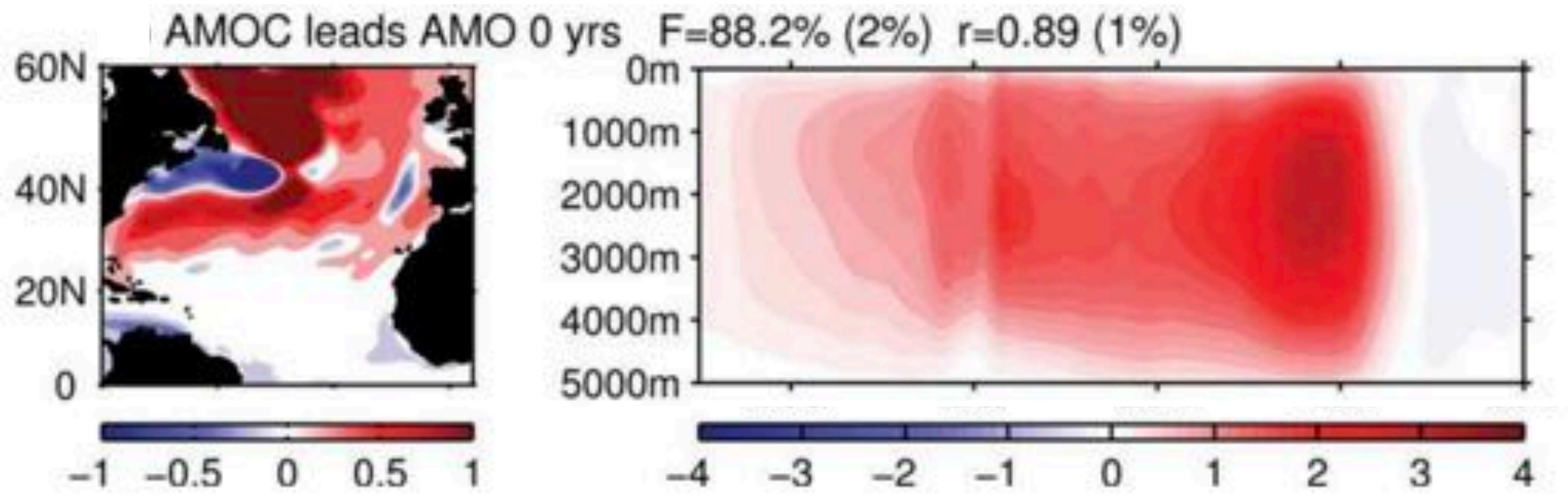


Robert Jnglin Wills, Kyle Armour, David Battisti, Dennis Hartmann, and LuAnne Thompson

University of Washington

International AMOC Science Meeting, July 24, 2018

AMO Linked to AMOC



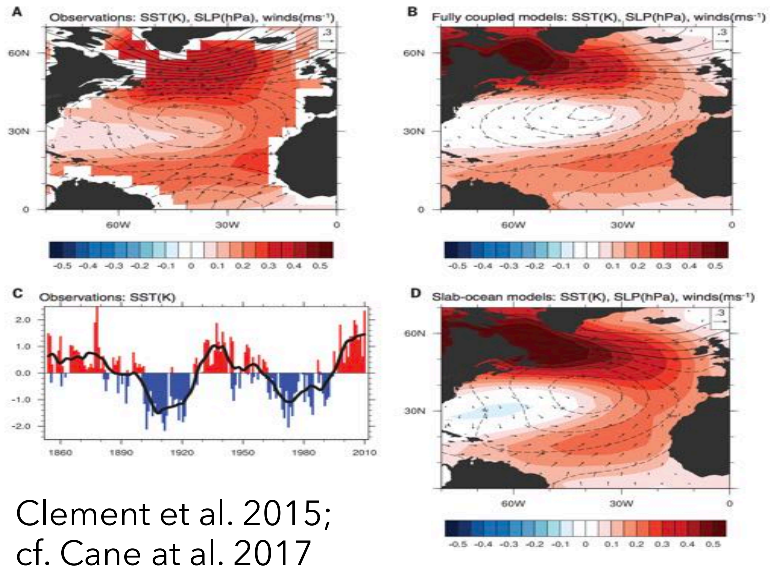
Most studies suggest that the AMO is linked to variability of AMOC

(Delworth et al. 1993; Knight et al. 2005; Latif et al. 2004; Delworth and Mann 2000; Medhaug and Furevik 2011; Wang and Zhang 2013; **Zhang and Wang 2013**; Ba et al. 2014, etc.)

Debate on AMO Mechanisms

The Atlantic Multidecadal Oscillation without a role for ocean circulation

Amy Clement,[1*] Katinka Bellomo,[1] Lisa N. Murphy,[1] Mark A. Cane,[2] Thorsten Mauritsen,[3] Gaby Rädel,[3] Bjorn Stevens[3]

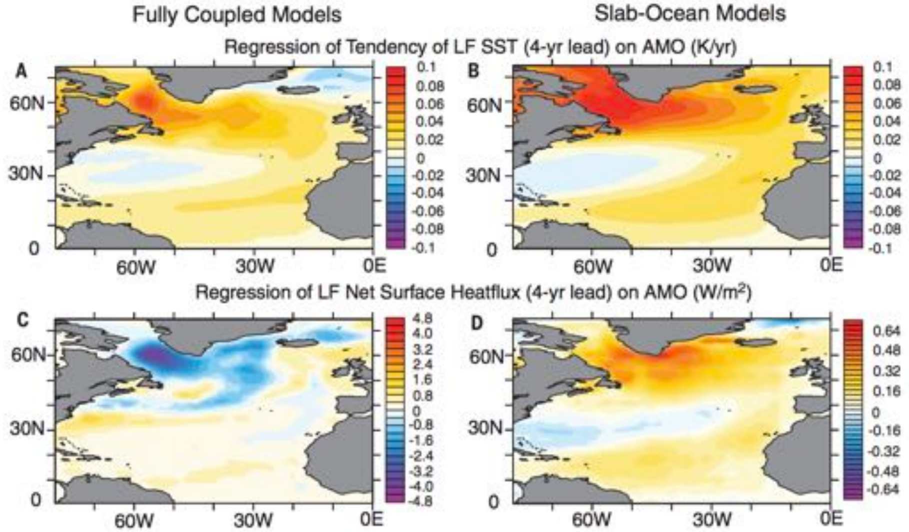


Clement et al. 2015;
cf. Cane at al. 2017

- Slab-ocean models have similar patterns and timescales of AMO variability to coupled models and observations
- Filtering obscures lead-lag relationships

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

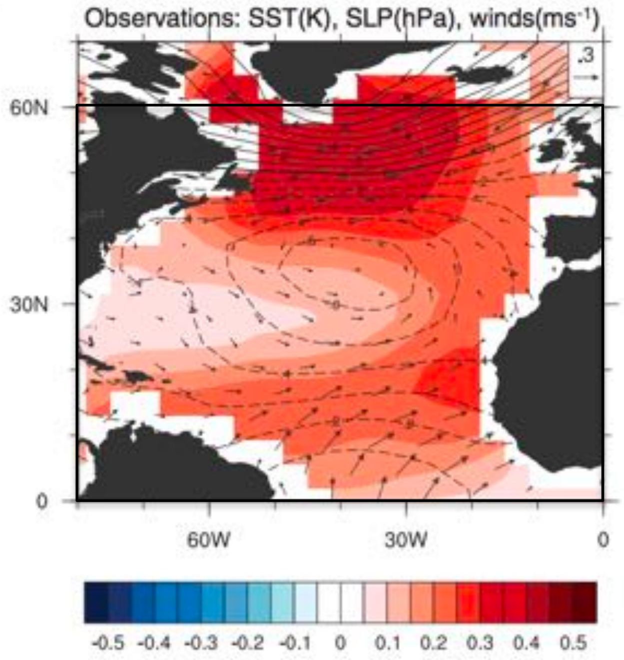
Rong Zhang,[1*] Rowan Sutton,[2] Gokhan Danabasoglu,[3] Thomas L. Delworth,[1] Who M. Kim,[3] Jon Robson,[2] Stephen G. Yeager[3]



Zhang et al. 2016; O'Reilly et al. 2016

- Slab-ocean models have wrong sign of surface heat fluxes during warm events
- Heat loss during warm phases requires active ocean

THE TRADITIONAL DEFINITION OF THE AMO

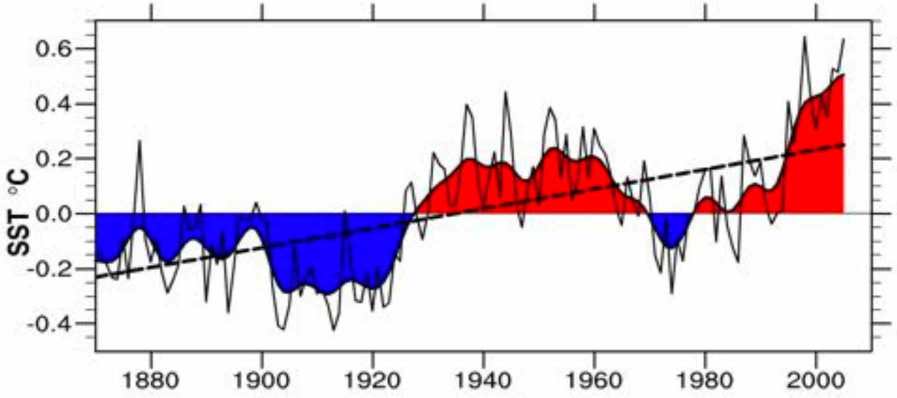


The traditional index: the North Atlantic SST Index (NASSTI)

- Atlantic basin (0-60°N, 0-80°W) SST average minus linear trend (or global-mean SST)

No physical reason why multidecadal variability should be confined to 0-60°N

- Is this really a single mode of variability?



Enfield et al. 2001; Clement et al. 2015; Trenberth and Shae 2006

Motivation

Determine the regions and mechanisms most responsible for multidecadal variability of Atlantic SSTs without *a priori* assumptions about the spatial or temporal structure

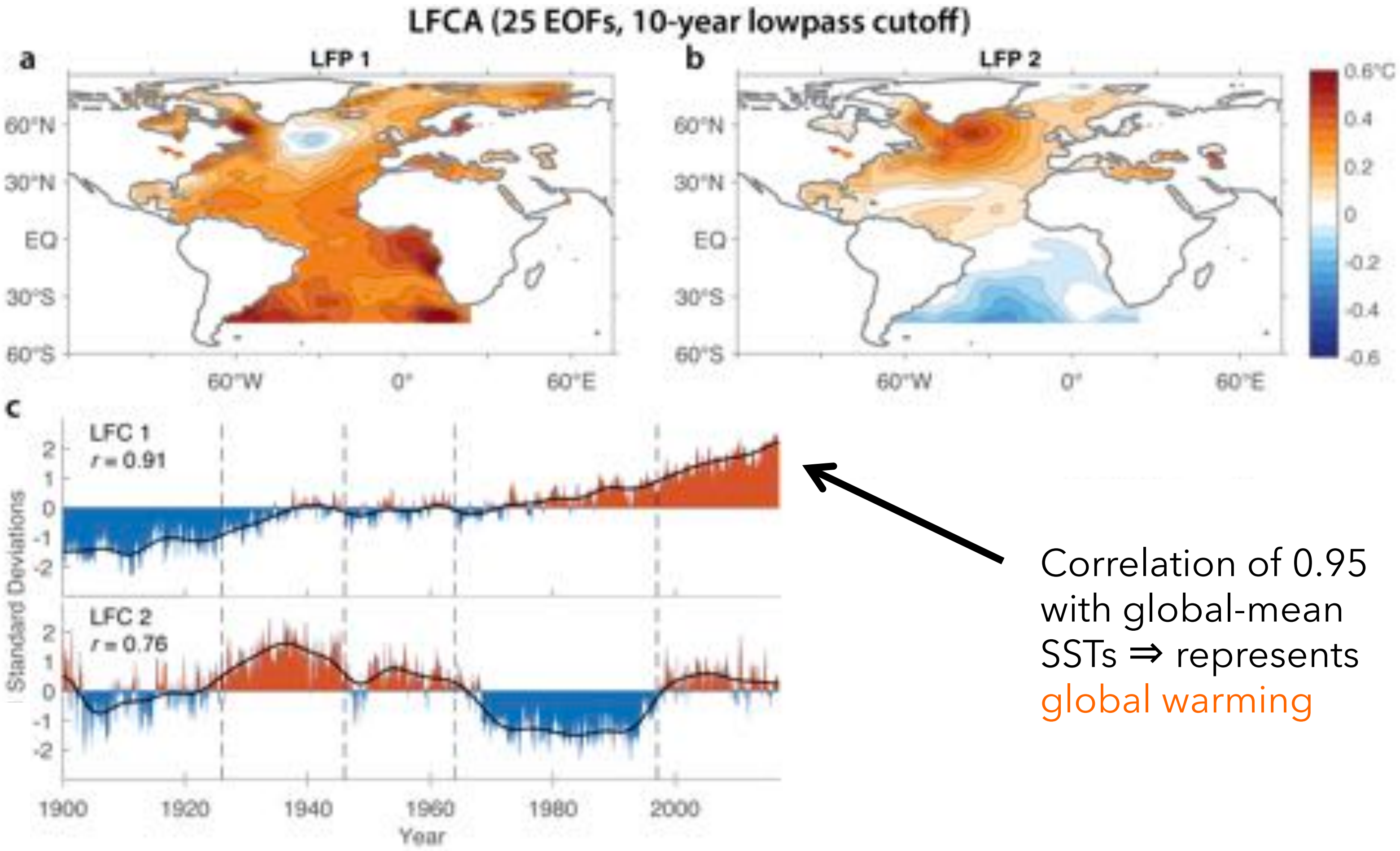
A New Tool: Low-Frequency Component Analysis (LFCA)

- Finds the linear combination of a set of empirical orthogonal functions (EOFs) with the maximum ratio of low-frequency to total variance, *r* – based on application of a lowpass filter (Wills et al. 2018a, GRL)

- Yields mutually uncorrelated ***low-frequency components (LFCs)***, and their associated spatial patterns, ordered by *r*

- Related to a broader class of ***signal-to-noise maximizing EOF analyses*** *that maximize:*
  - Variance that is robust across models (Venzke et al. 1999, Ting et al. 2009, DelSole et al. 2011)
  - Variance between decades (Schneider and Held 2001, Camp and Tung 2007)
  - Predictability or persistence (Schneider and Griffies 1999; DelSole 2001, 2006)

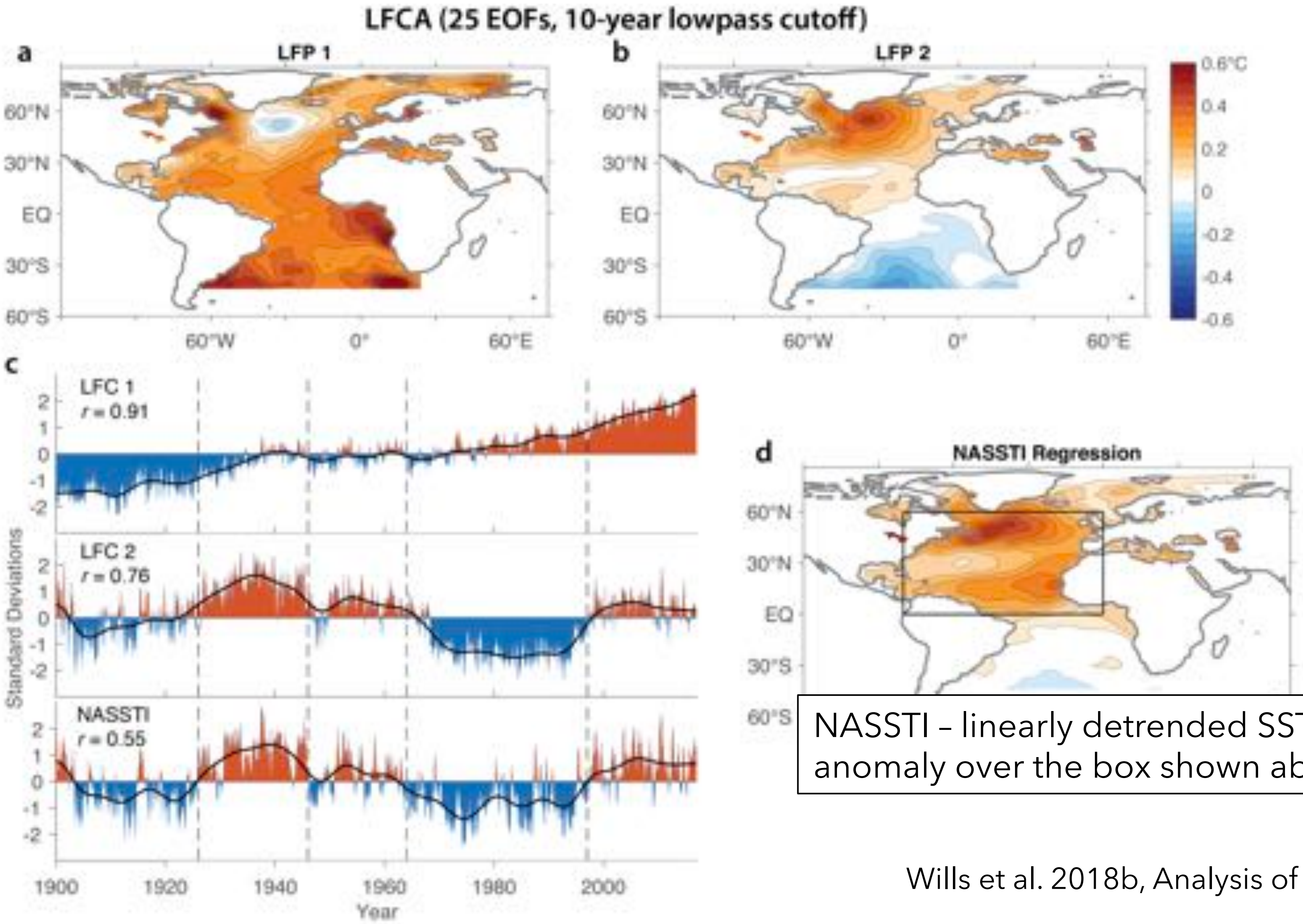
Low-Frequency Components of Atlantic SST



Correlation of 0.95 with global-mean SSTs ⇒ represents global warming

Wills et al. 2018b, Analysis of ERSST

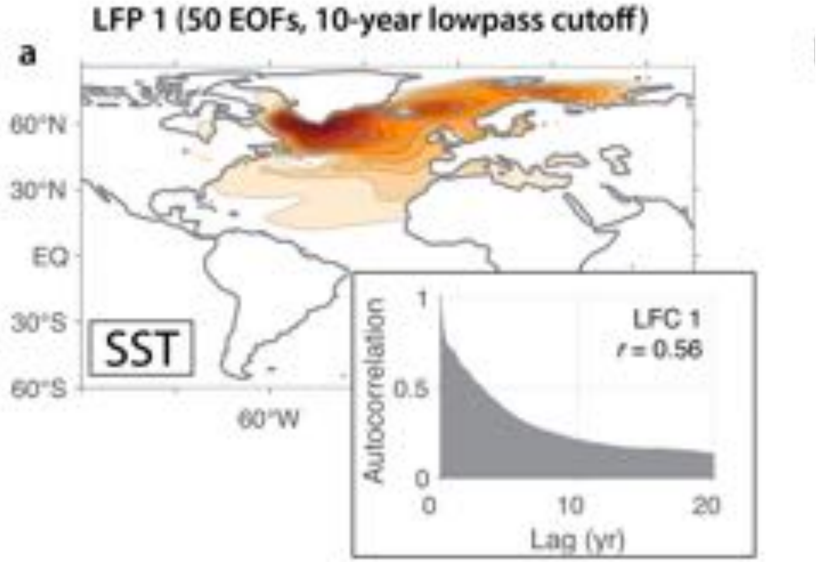
Low-Frequency Components of Atlantic SST



NASSTI – linearly detrended SST anomaly over the box shown above

Wills et al. 2018b, Analysis of ERSST

AMO in CMIP5 Models (Pre-Industrial)

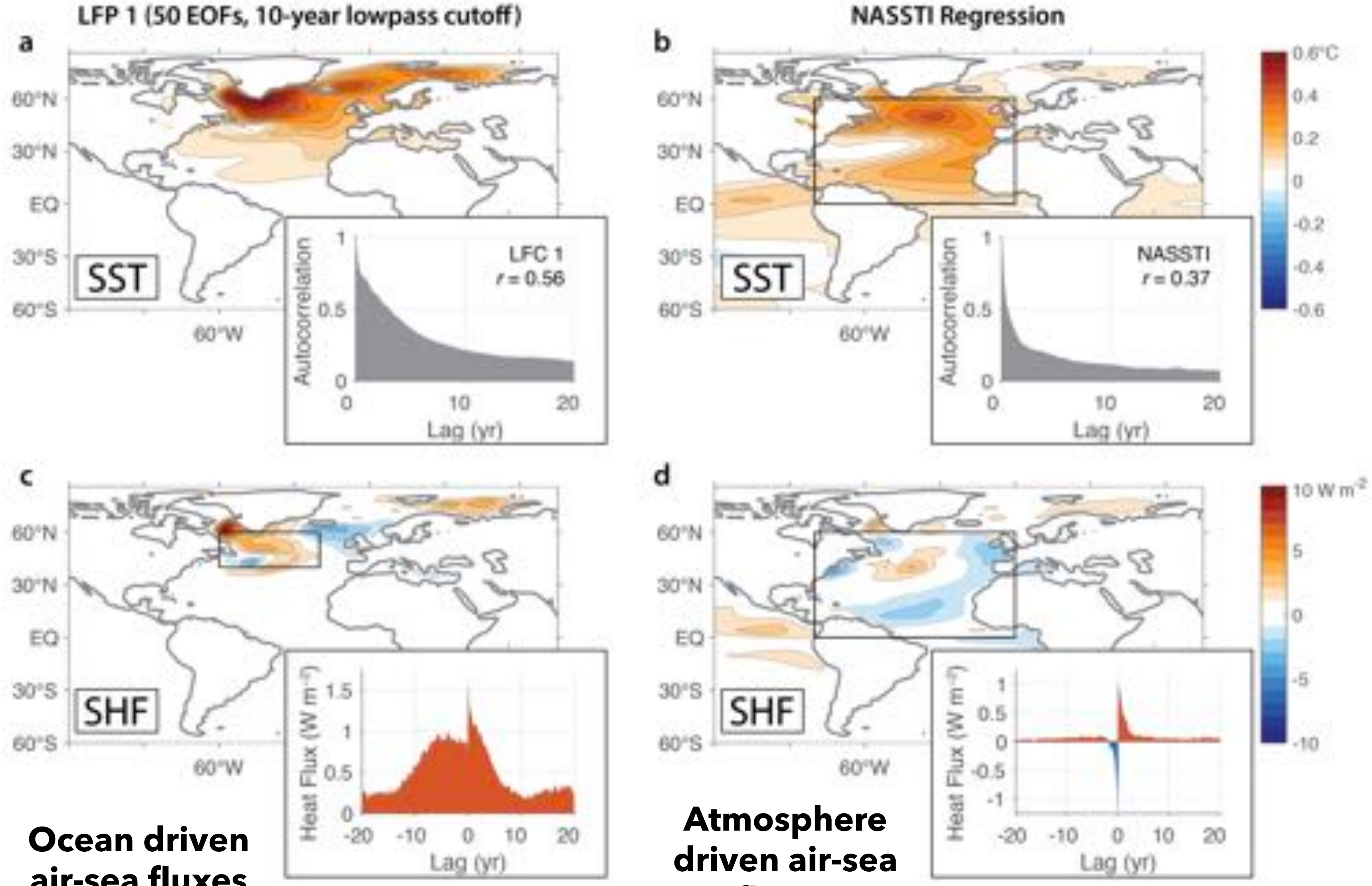


Pre-industrial control simulations from 26 CMIP5 models (500 years from each, 13,000 years of data)

- Ignore climatological differences between models
- Apply LFCA

Wills et al. (2018b, submitted)
Analysis of 26 CMIP5 models

AMO in CMIP5 Models (Pre-Industrial)

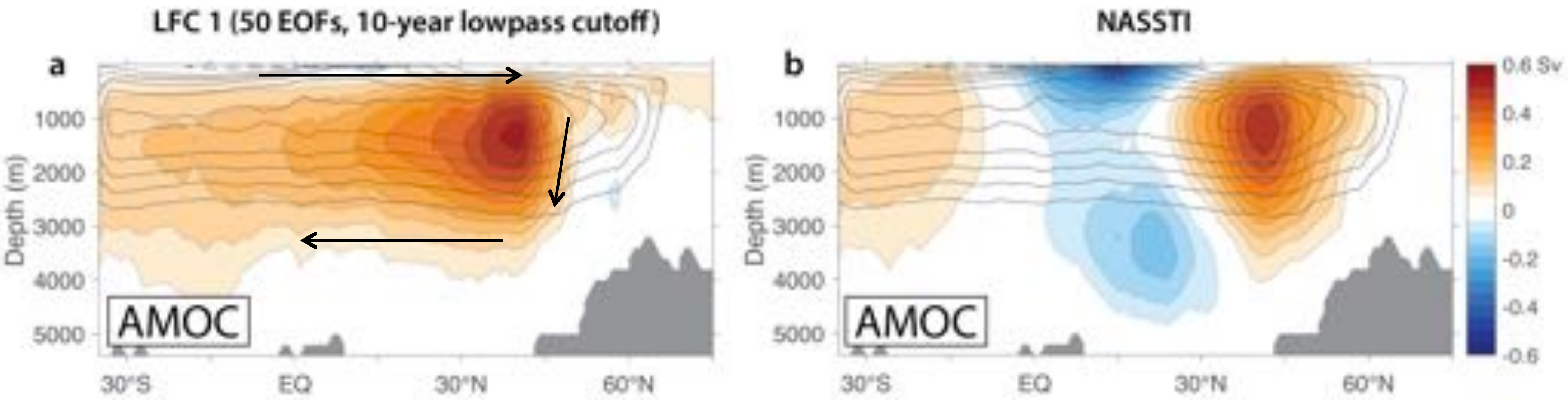


Ocean driven air-sea fluxes

Atmosphere driven air-sea fluxes

Wills et al. (2018b, submitted)
Analysis of 26 CMIP5 models

Ocean-Driven AMO in CMIP5 Models (Pre-Industrial)



Interhemispheric AMOC Anomaly

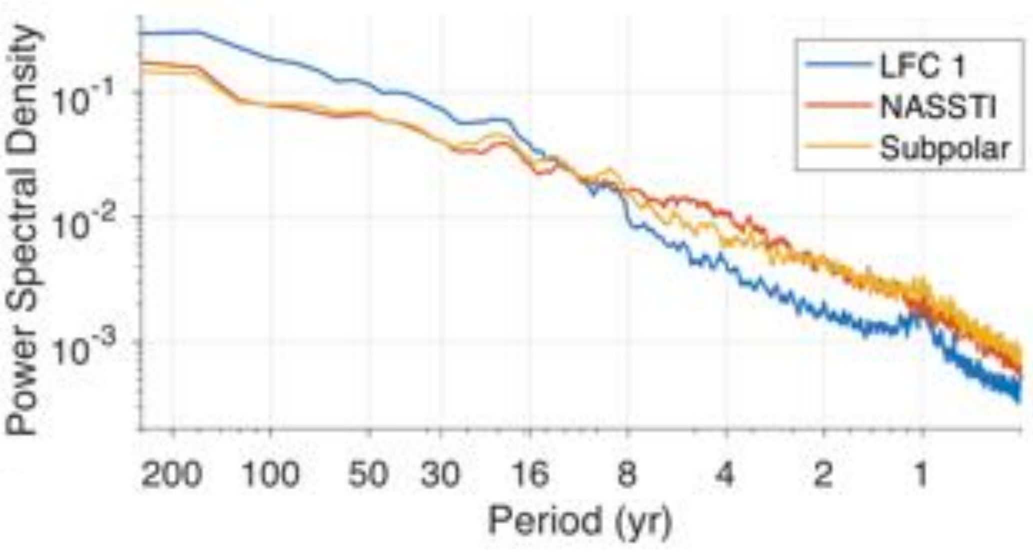
**Ocean Gyre Shift
(and interhemispheric AMOC anomaly)**

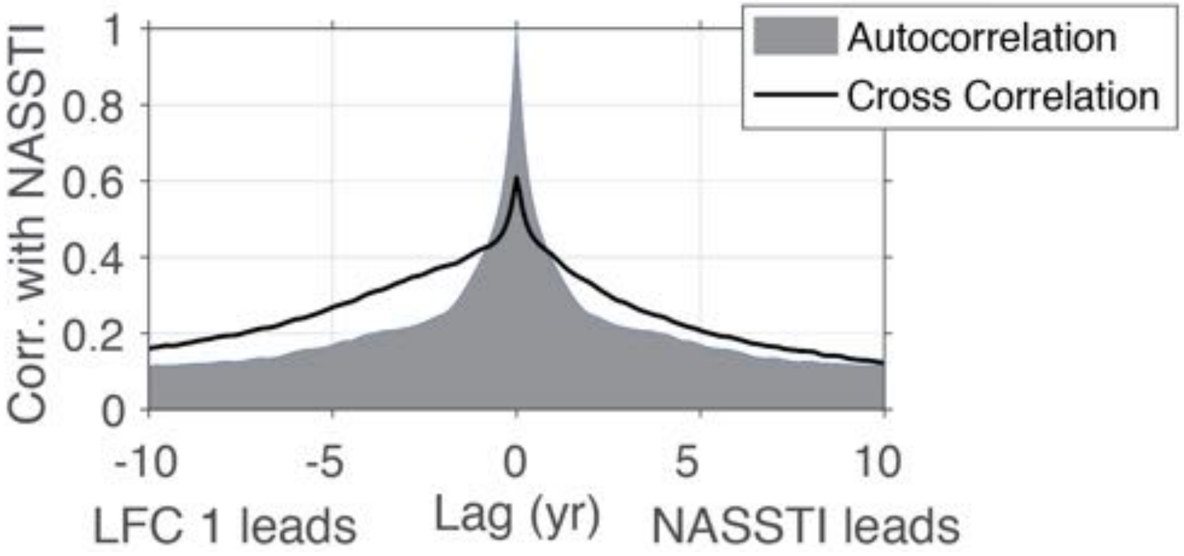
Contours – AMOC climatology

Shading – AMOC anomalies

Wills et al. (2018b, submitted) – Analysis of 26 CMIP5 models

LFC–AMO vs. NASSTI





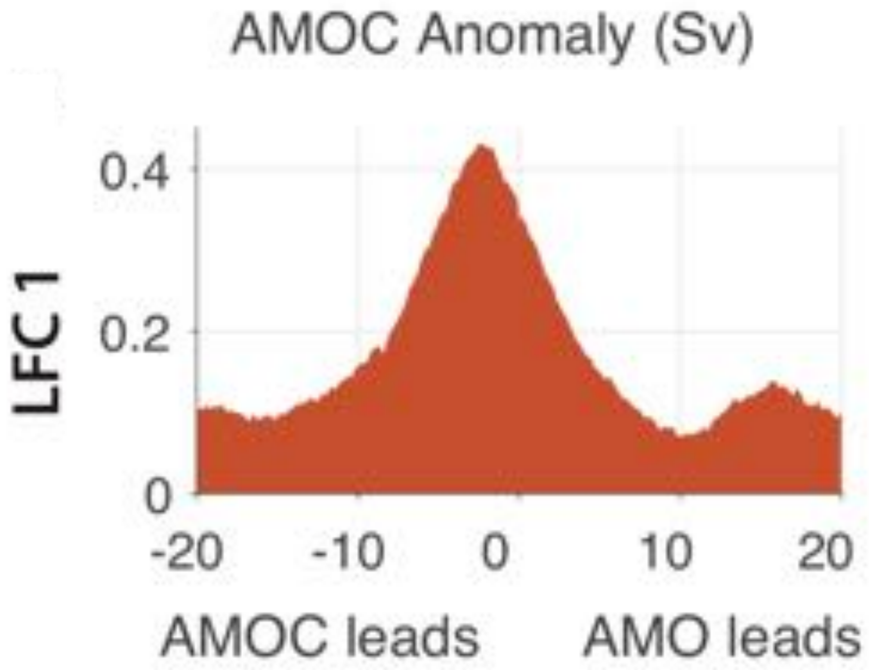
LFC 1 has double the power of NASSTI at multidecadal timescales

At decadal timescales, LFC 1 is a better predictor of NASSTI than NASSTI itself

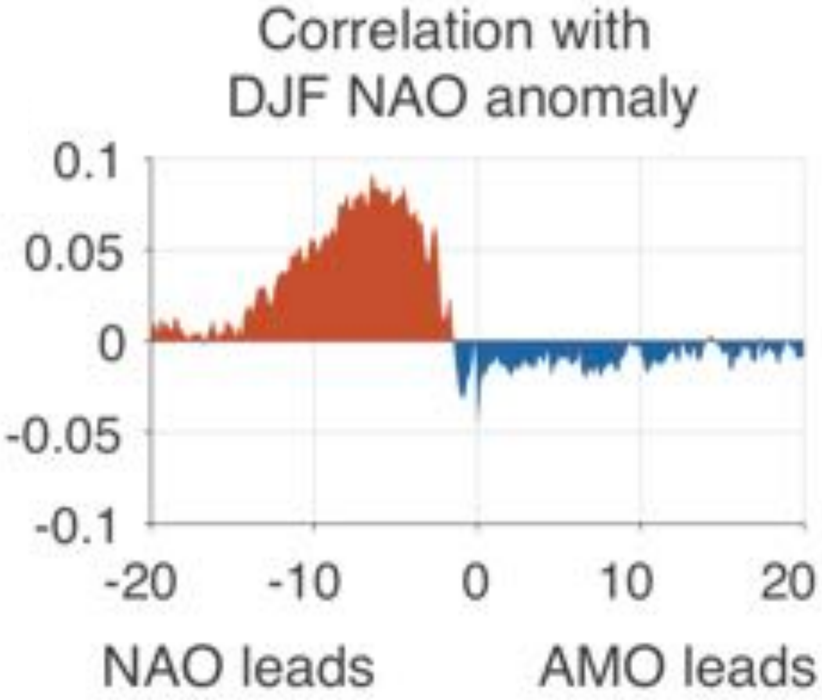
→ **Study AMO mechanisms based on LFC 1**

Wills et al. (2018b, submitted)
Analysis of 26 CMIP5 models

AMOC – AMO – NAO Interactions



- AMOC maximum 2 years before maximum North Atlantic warming

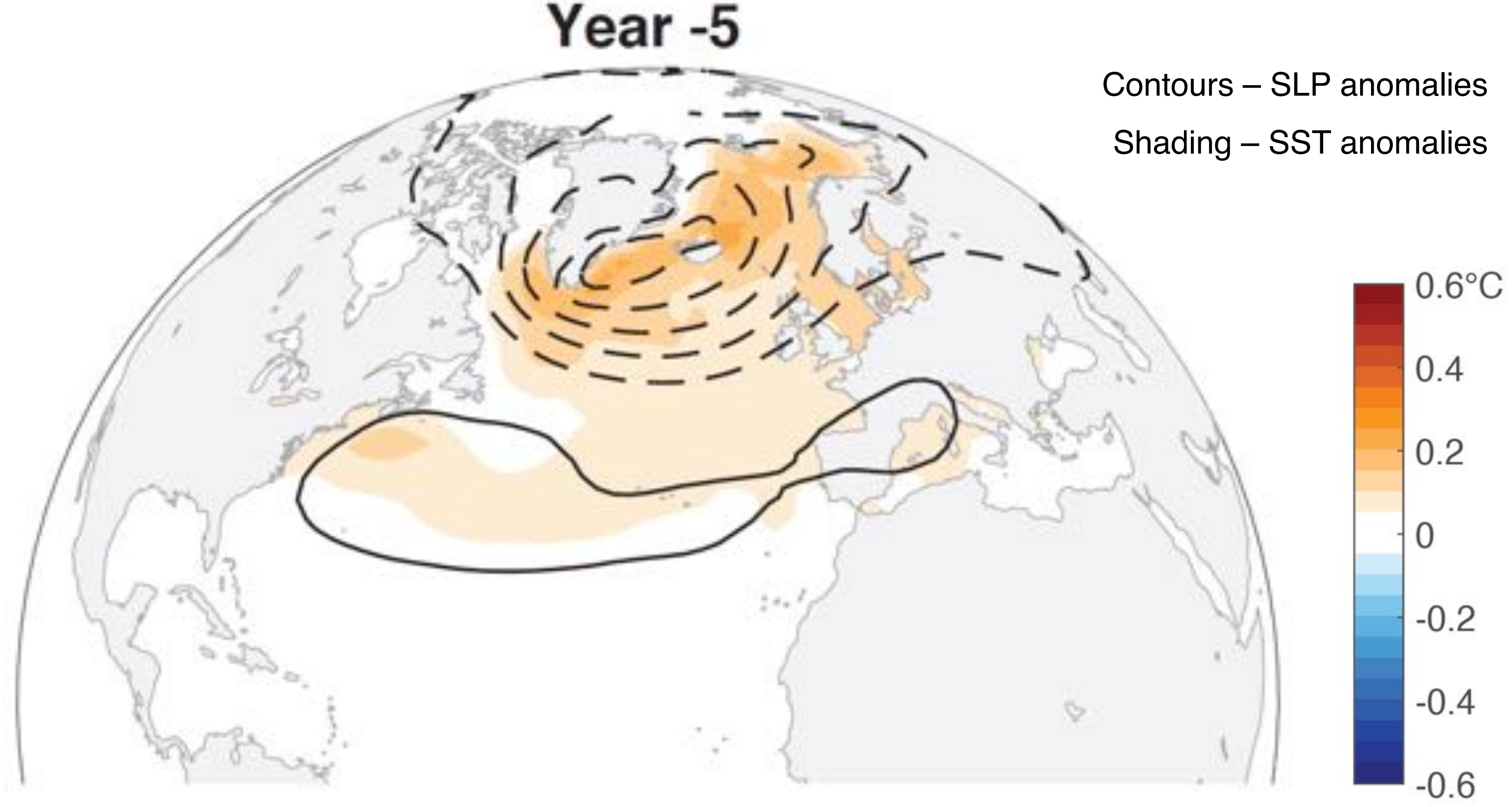


- NAO+ leads to increase in AMOC
- Weak NAO– during and after maximum warming

cf. Delworth and Zeng 2016, Delworth et al., 2016, 2017

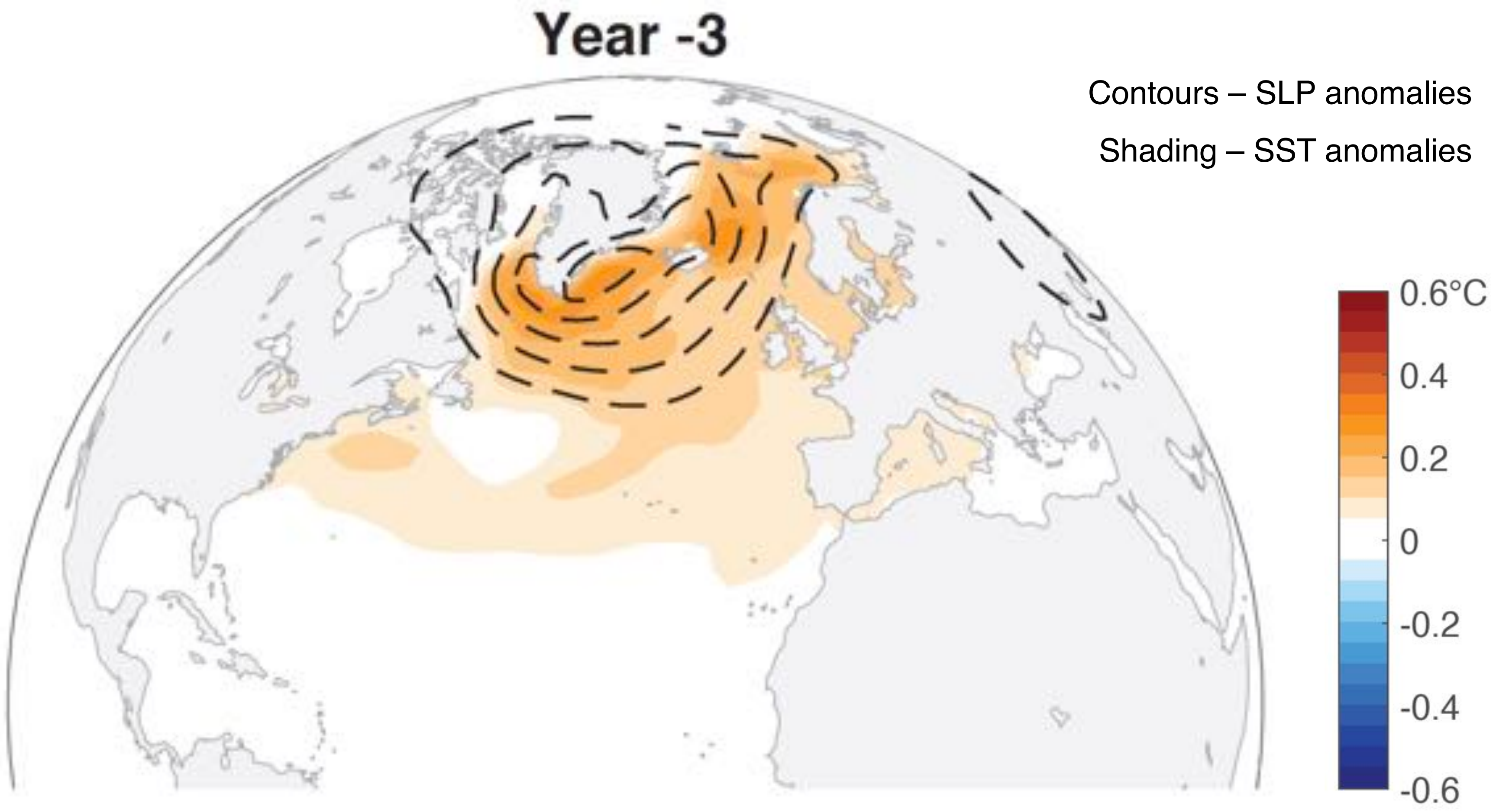
Wills et al. (2018b, submitted) – Analysis of 26 CMIP5 models

AMO Evolution



Wills et al. (2018b, submitted), Analysis of 26 CMIP5 Models

AMO Evolution

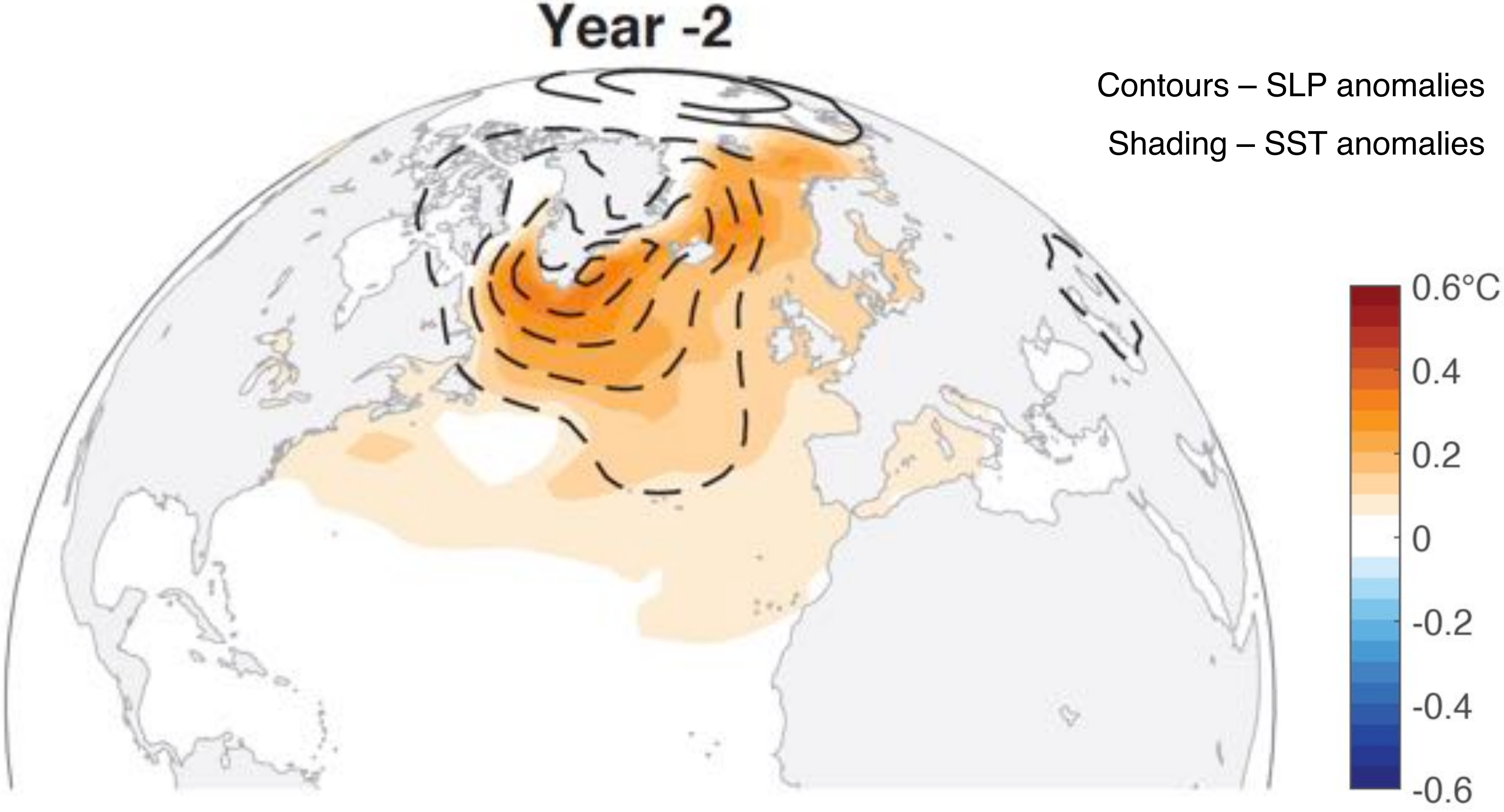


Contours – SLP anomalies

Shading – SST anomalies

Wills et al. (2018b, submitted), Analysis of 26 CMIP5 Models

AMO Evolution



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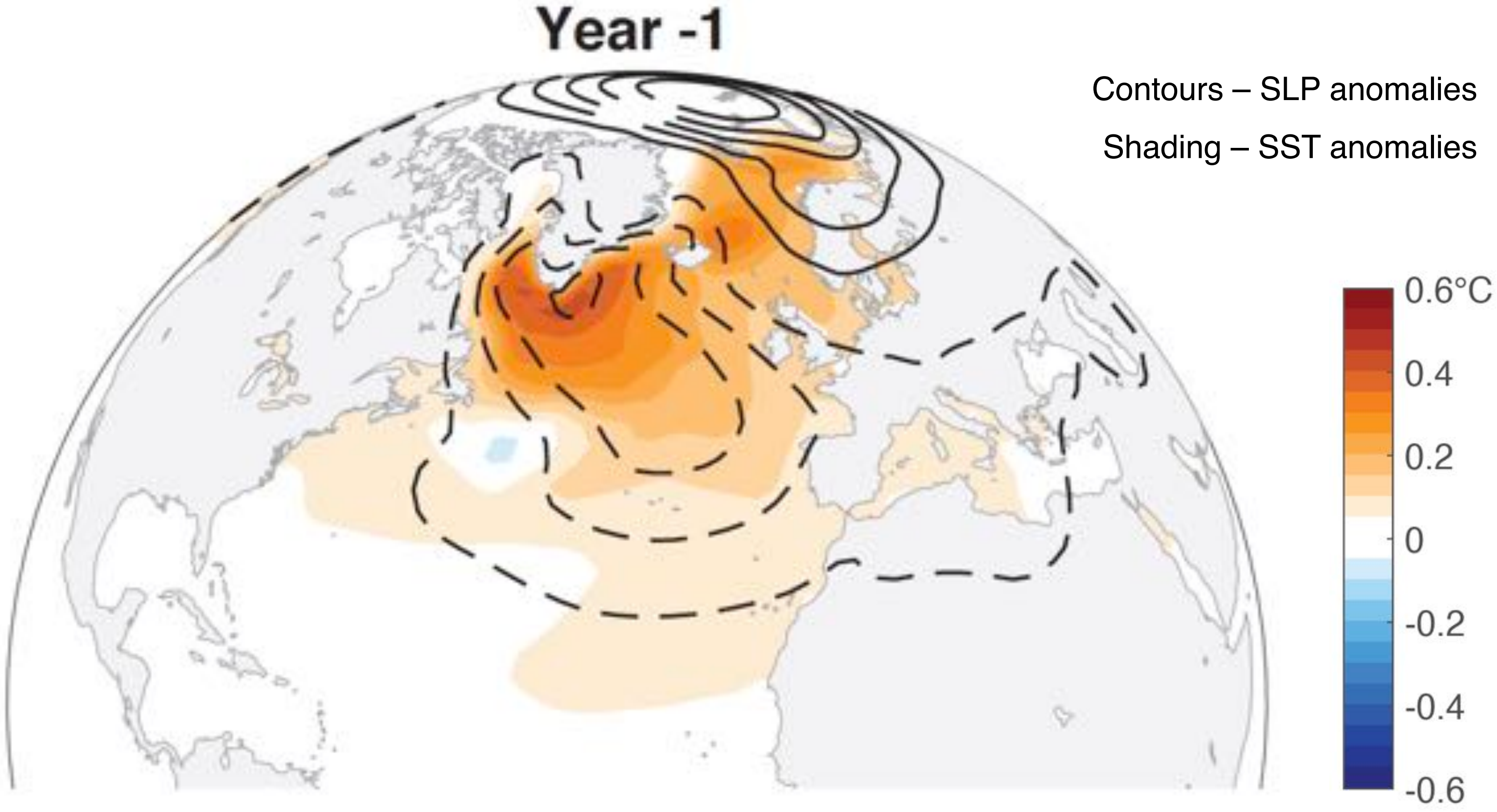
Wills et al. (2018b, submitted), Analysis of 26 CMIP5 Models

AMO Evolution



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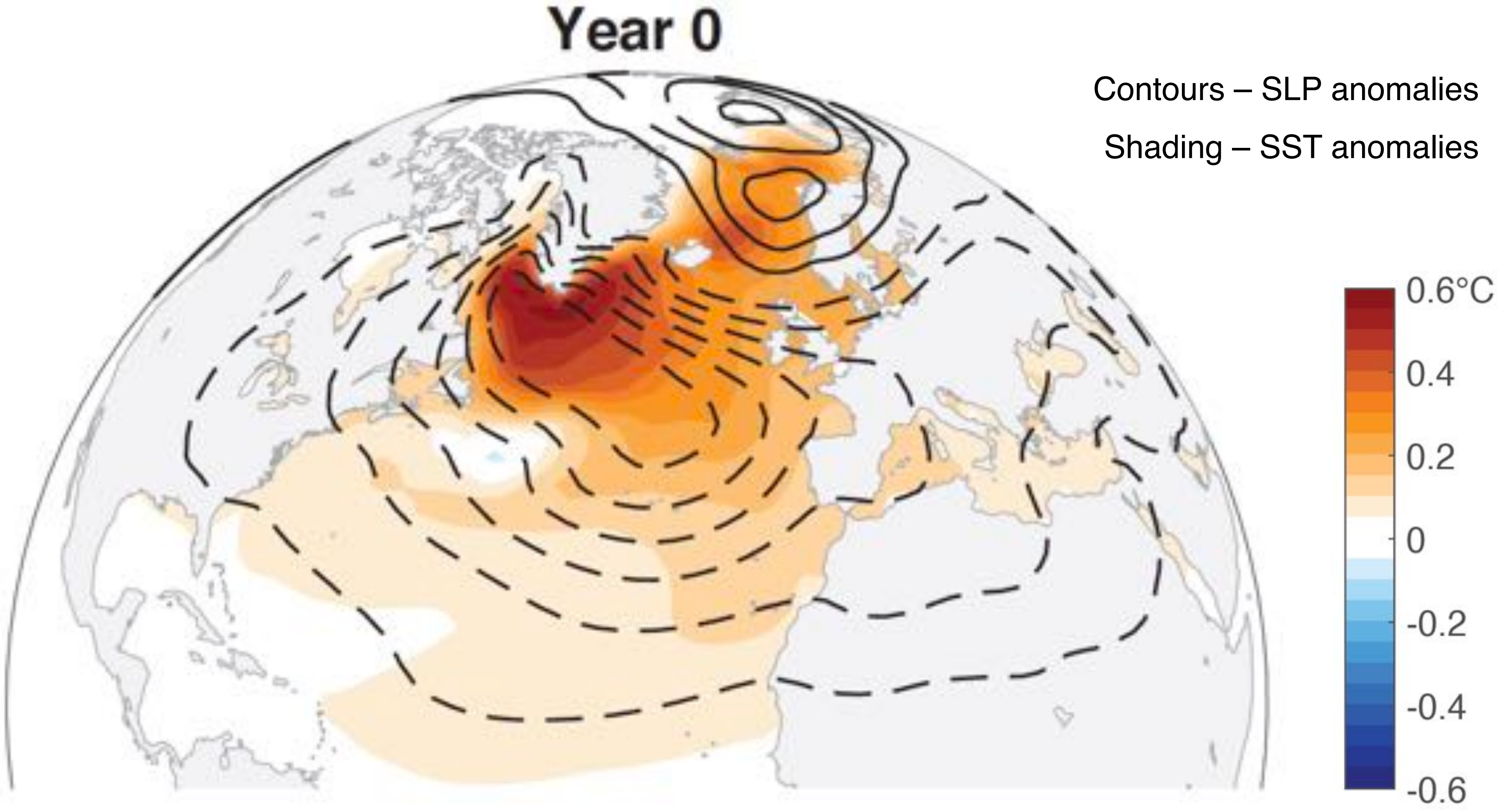

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Wills et al. (2018b, submitted), Analysis of 26 CMIP5 Models

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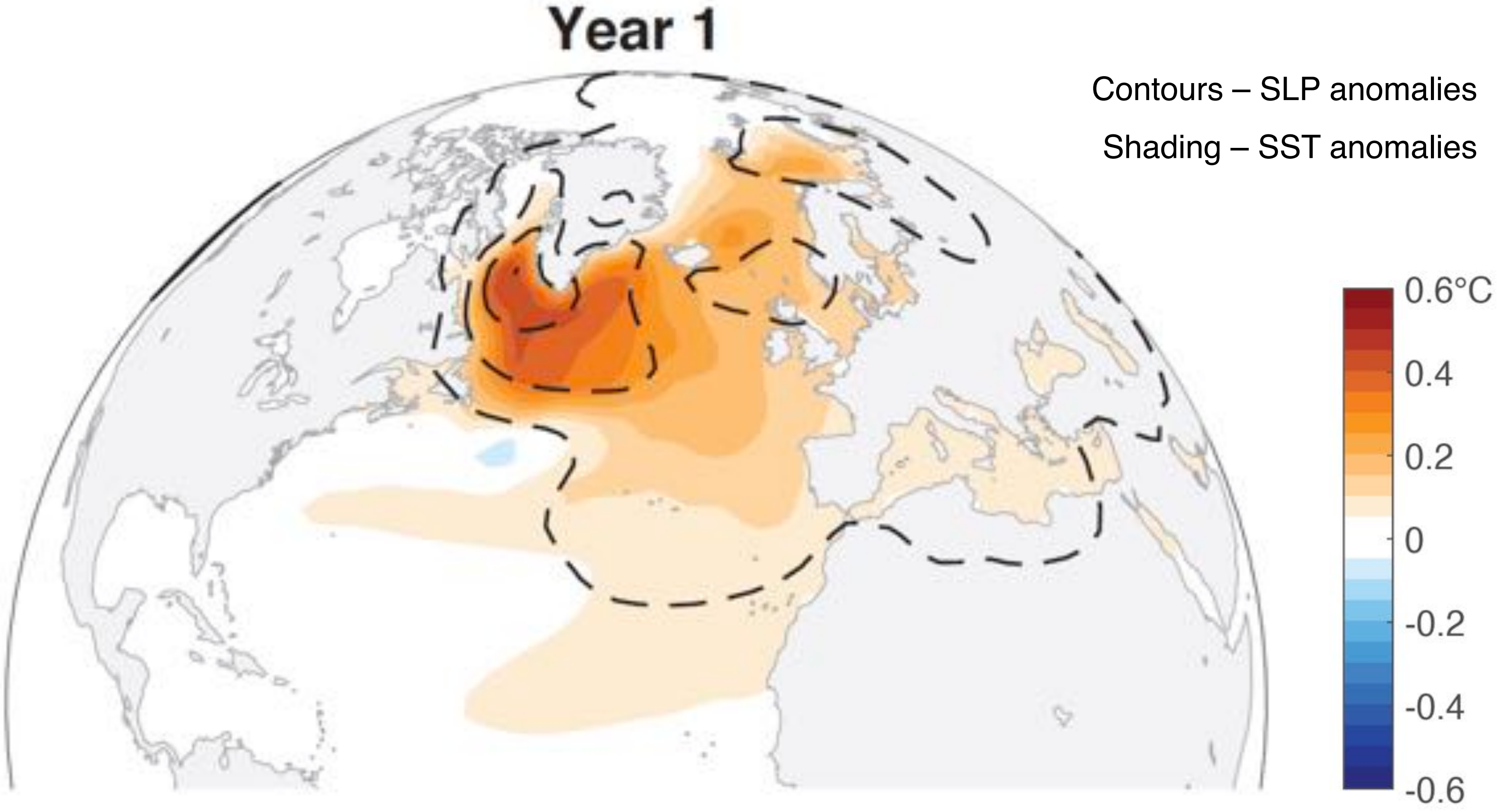

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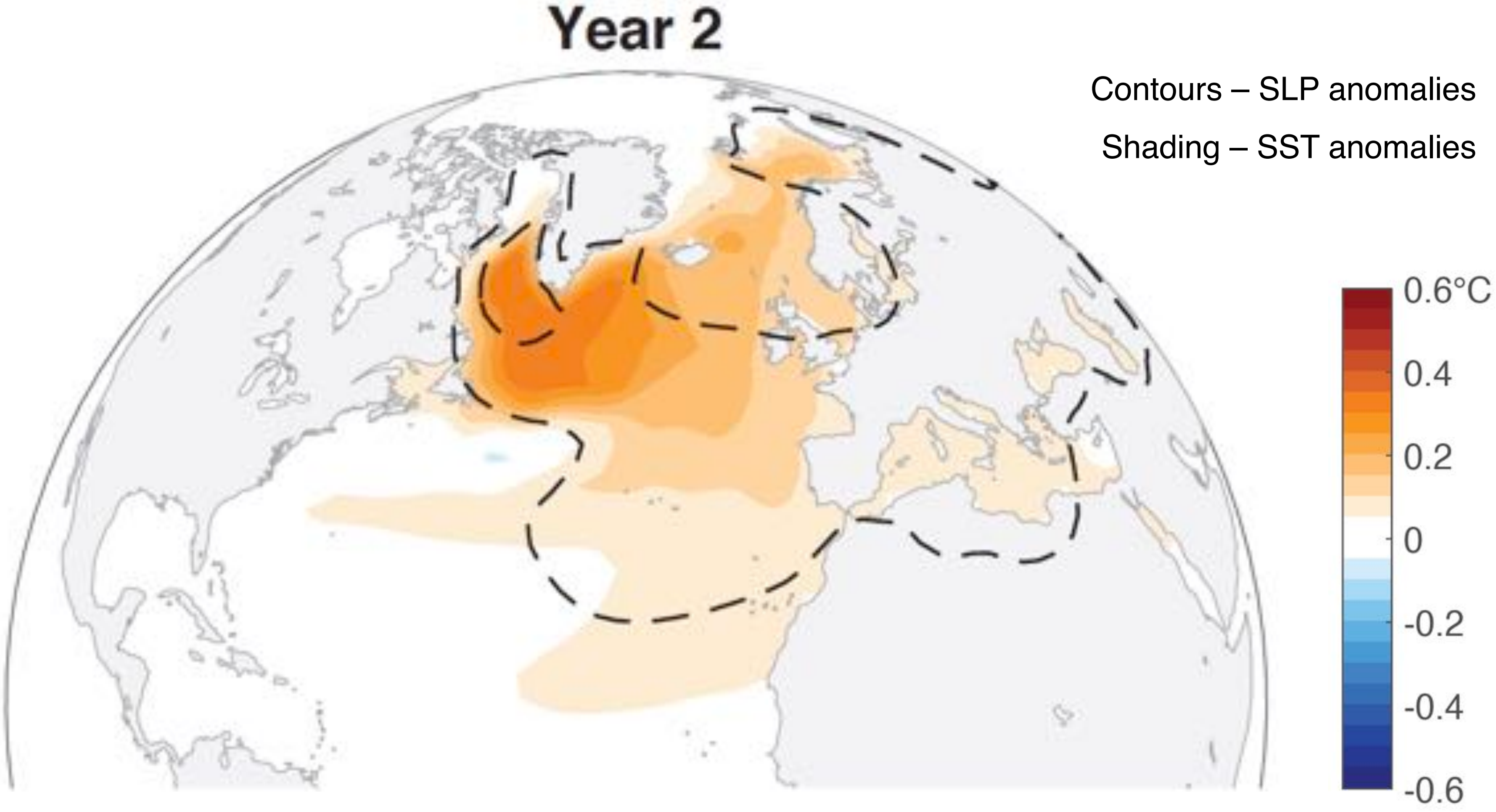

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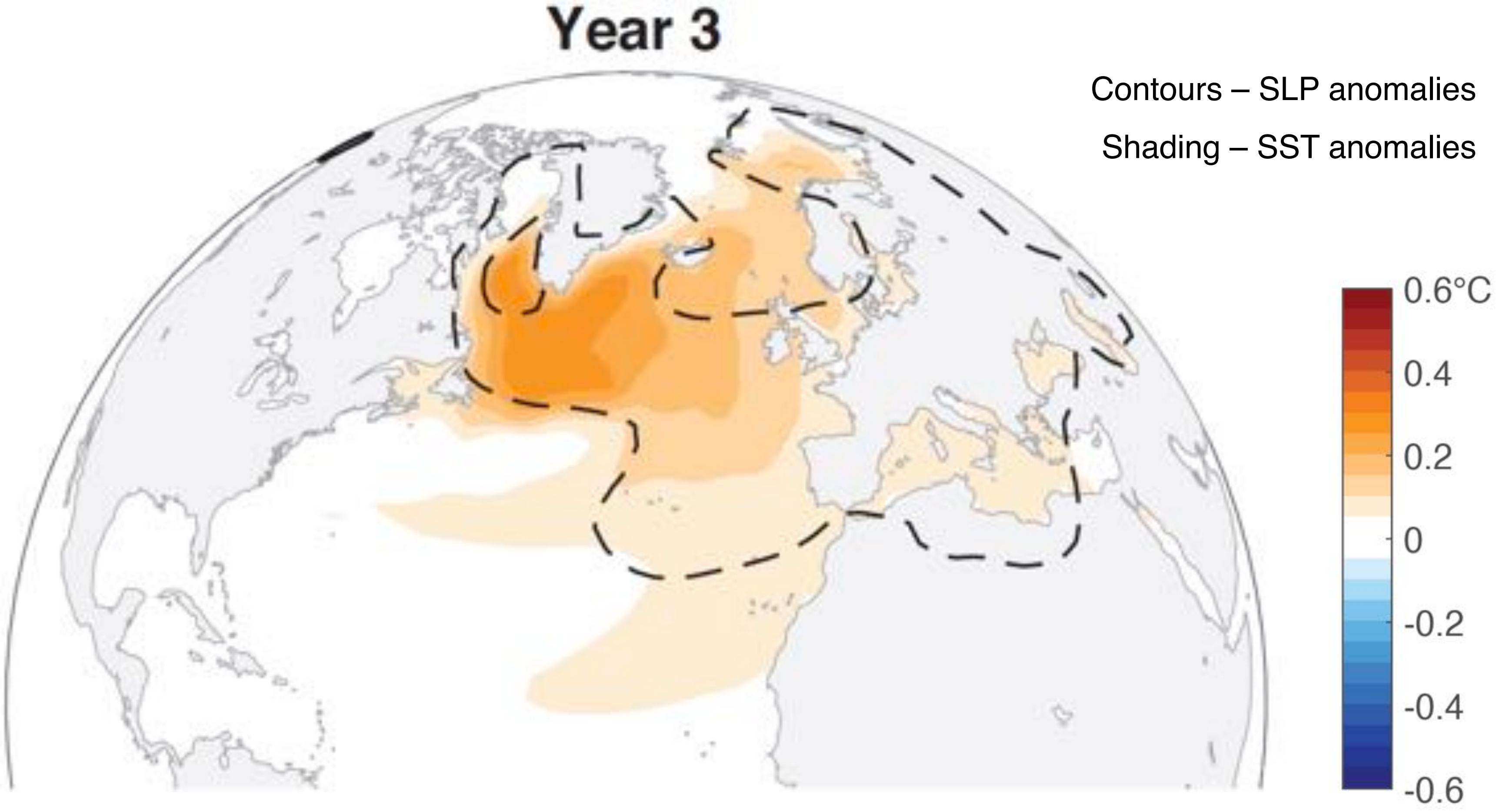

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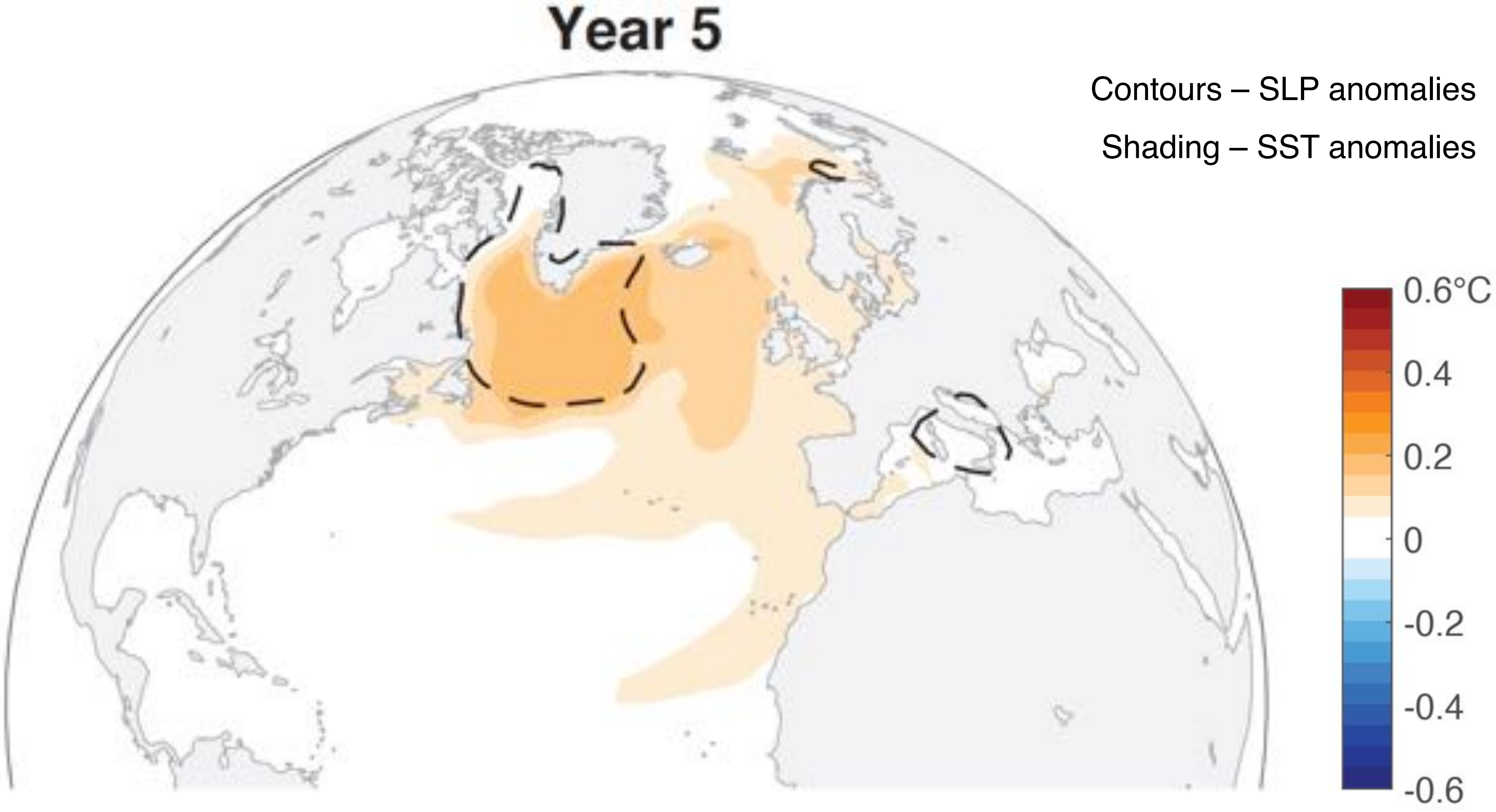
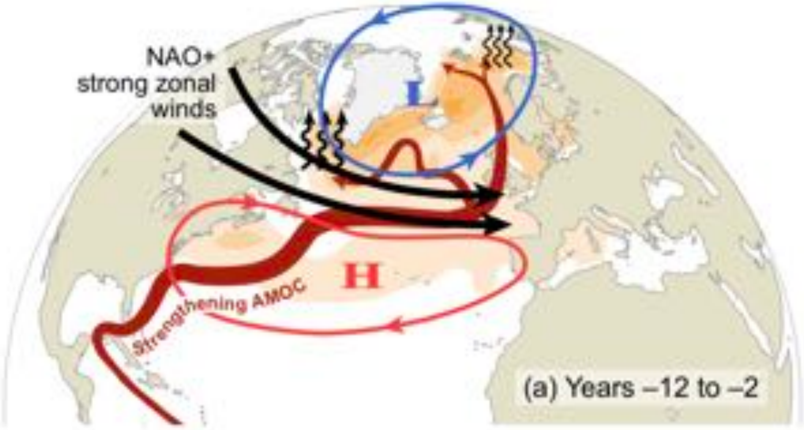
AMO Evolution



Wills et al. (2018b, submitted), Analysis of 26 CMIP5 Models

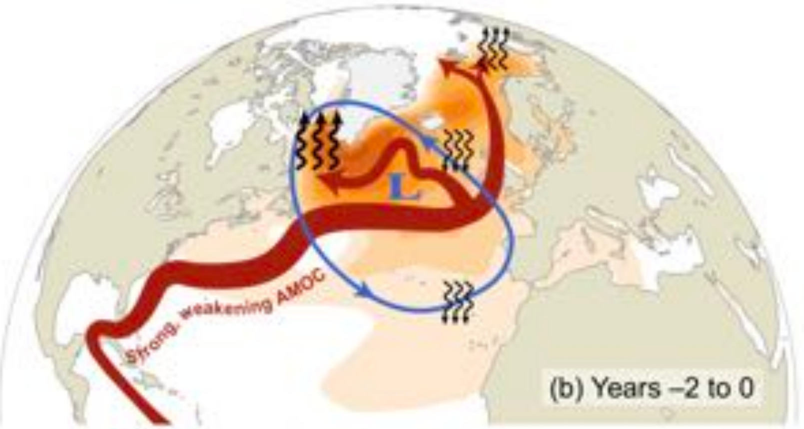
Anatomy of the AMO

Years -12 to -2 (build-up)



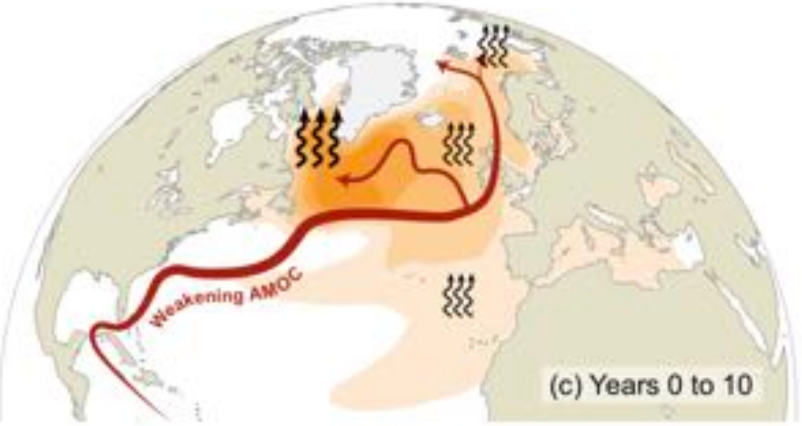
- NAO+, strong zonal winds lead to heat loss from the Labrador sea, strengthening deep convection and AMOC
- AMOC-induced warming overcompensates for heat loss

Years -2 to 0
(expansion and shutoff)



- Cyclonic atmospheric response to warm SSTs in the subpolar gyre
- Atmospheric circulation anomaly warms ocean to the east and south
- Buoyancy gain upstream weakens deep convection and AMOC

Years 0 to 10 (decay)



- SST anomalies decay through turbulent and radiative heat fluxes, ocean loses energy to the atmosphere

Wills et al. (2018b, submitted)

Debate on AMO Mechanisms

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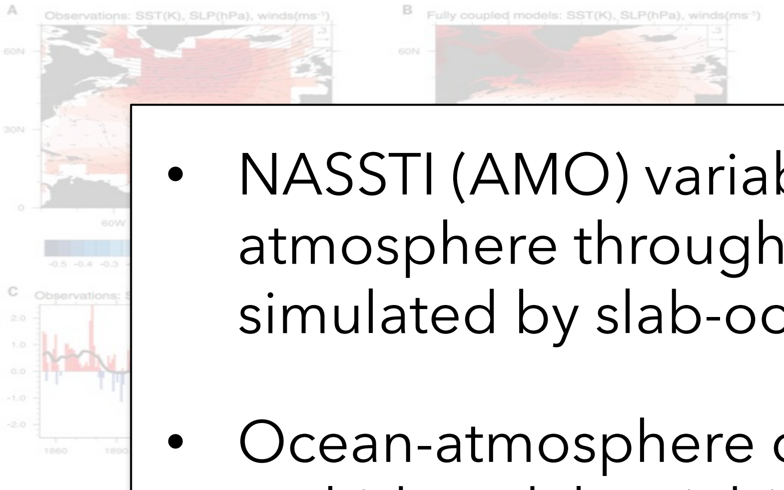

Clemen
cf. Cane

- Slab-oc
  and timescales of AMO variability to coupled models and observations
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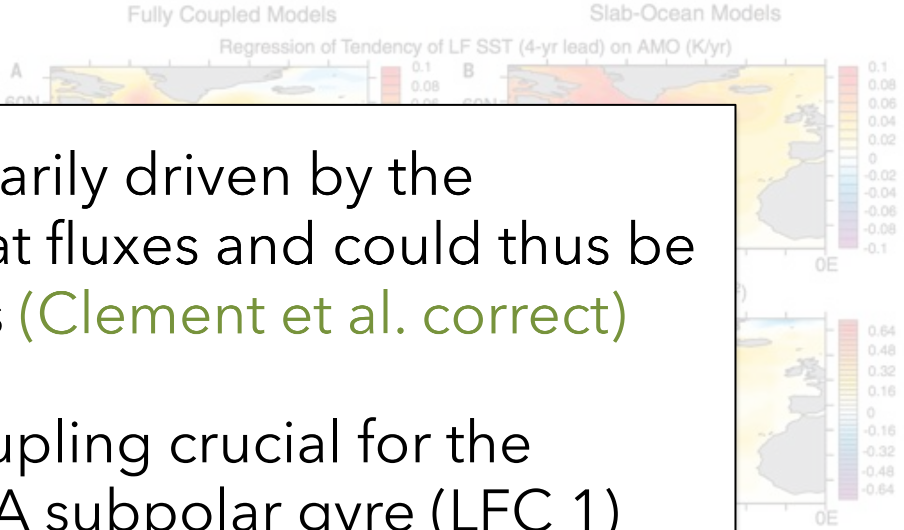
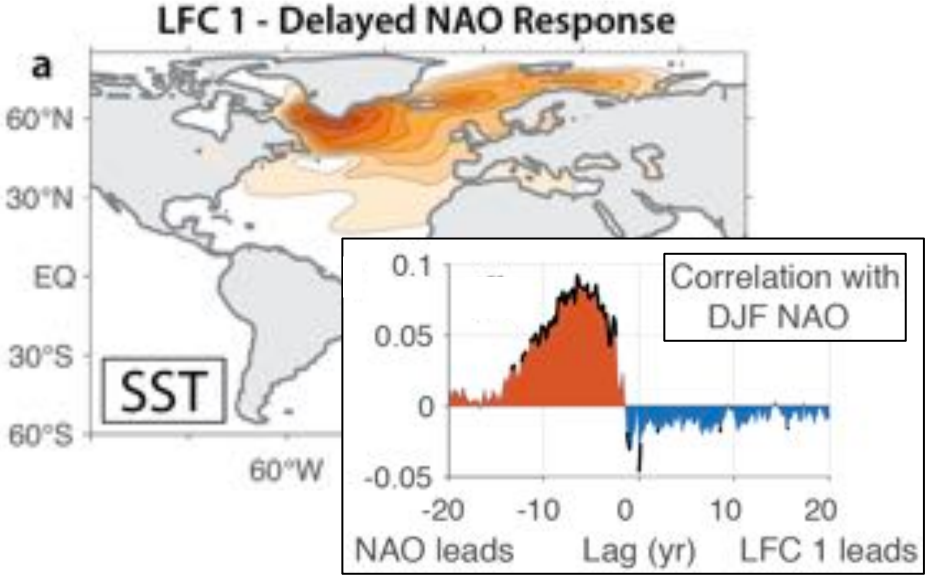


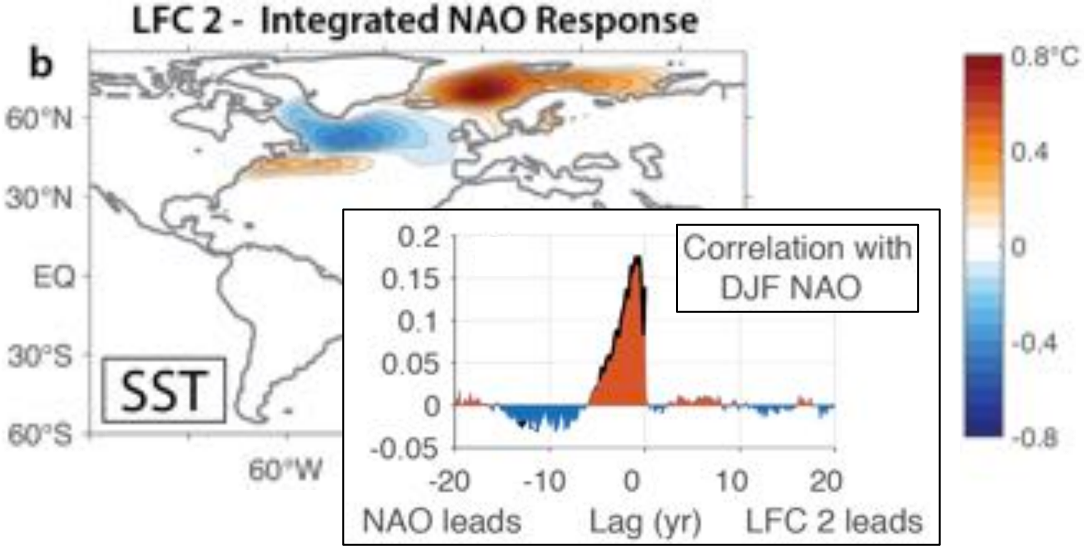
…lly et al. 2016

- …g sign of surface heat fluxes during warm events
- Heat loss during warm phases requires active ocean

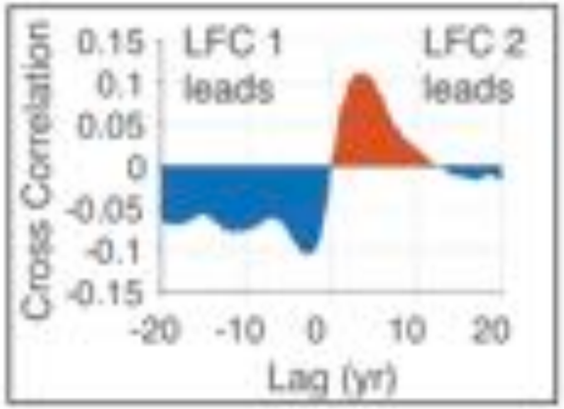
- NASSTI (AMO) variability is primarily driven by the atmosphere through surface heat fluxes and could thus be simulated by slab-ocean models (Clement et al. correct)
- Ocean-atmosphere dynamic coupling crucial for the multidecadal variability of the NA subpolar gyre (LFC 1) (Zhang et al. correct)

Two Timescales of Ocean Response to NAO Forcing



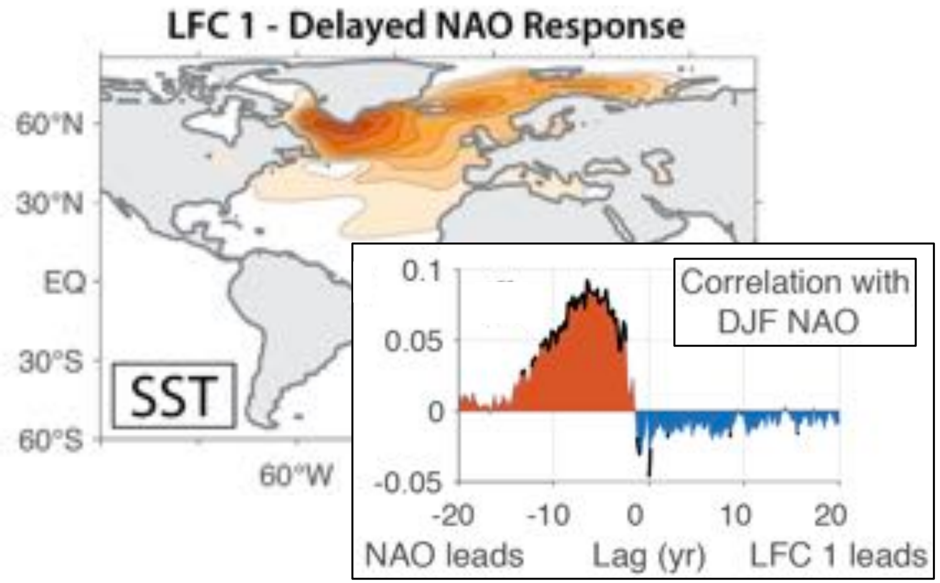


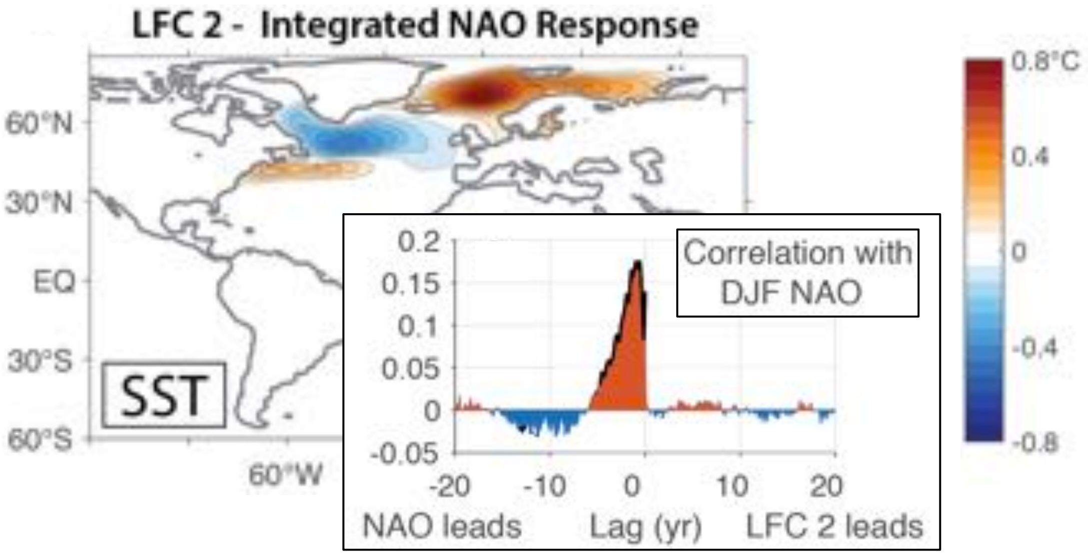
LFC/LFP 2 shows North Atlantic Tripole (cf. Sun et al. 2015)

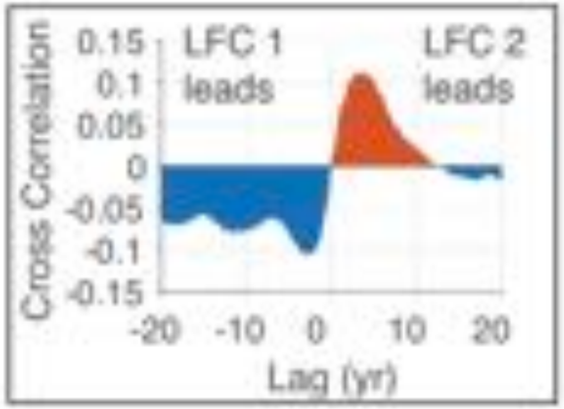


Analysis of 26
CMIP5 Models

Two Timescales of Ocean Response to NAO Forcing

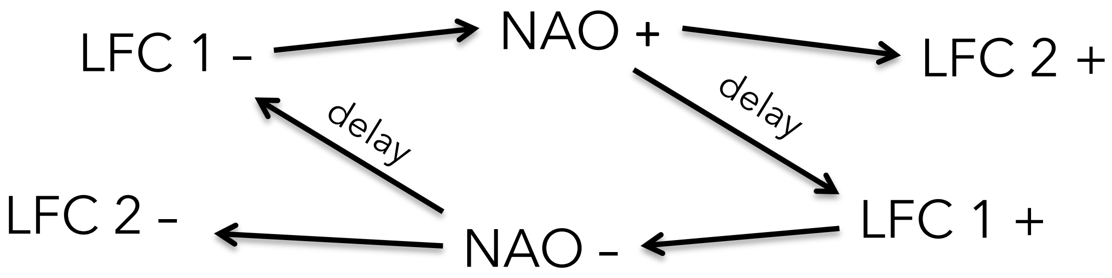






Analysis of 26
CMIP5 Models

Indications of a weak cycle:



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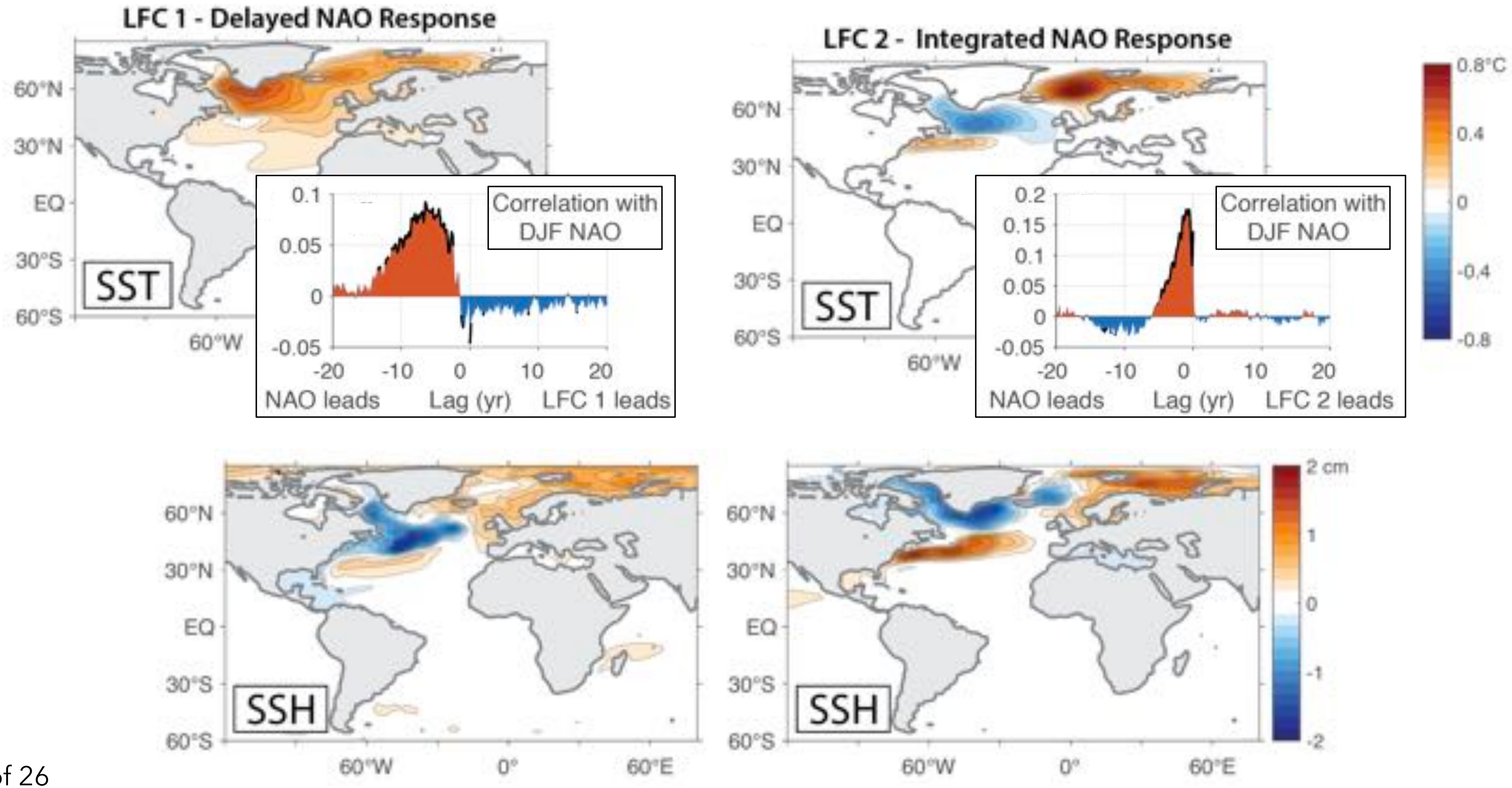
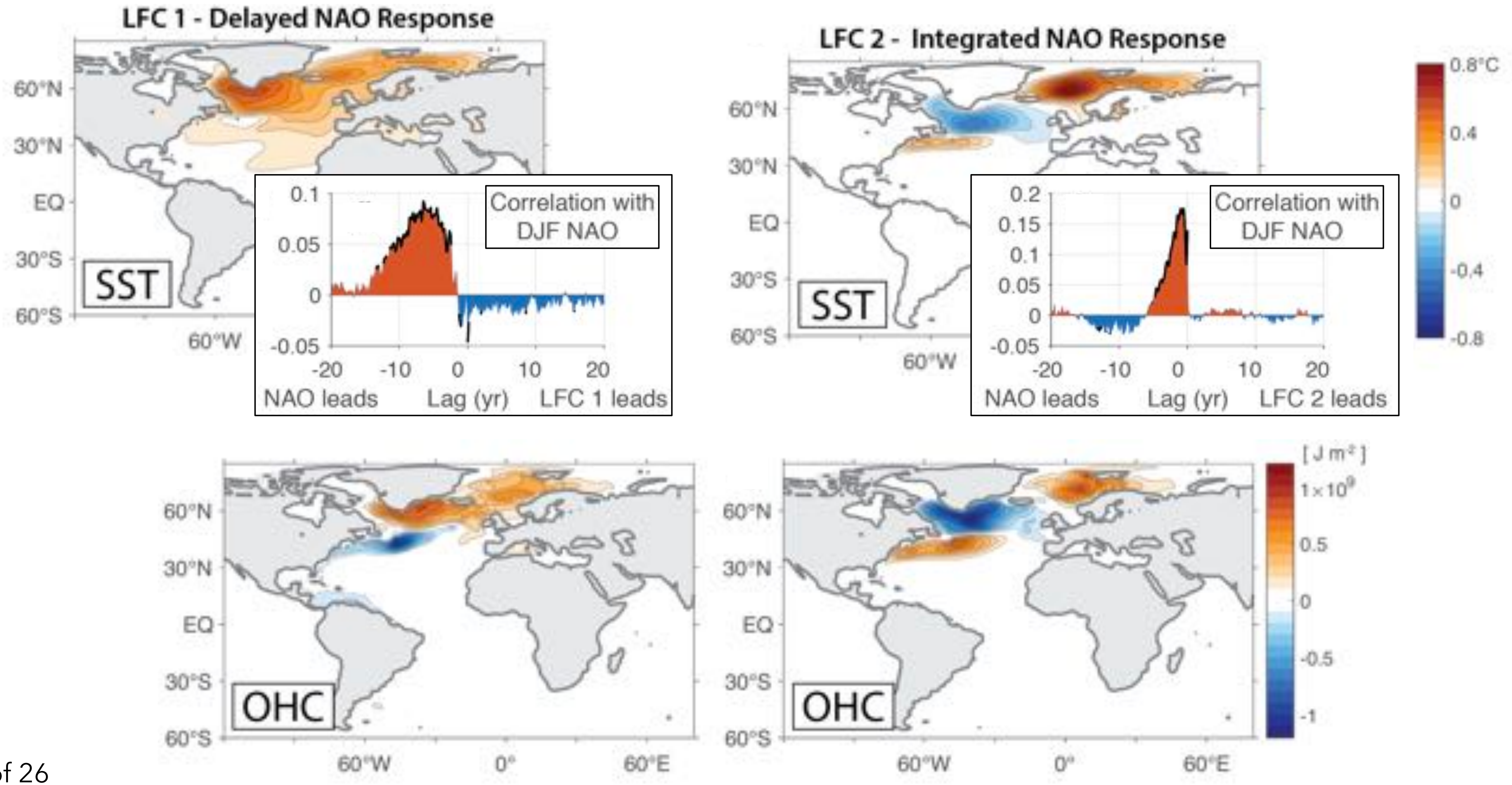


Analysis of 26 CMIP5 Models

Two Timescales of Ocean Response to NAO Forcing



Analysis of 26
CMIP5 Models

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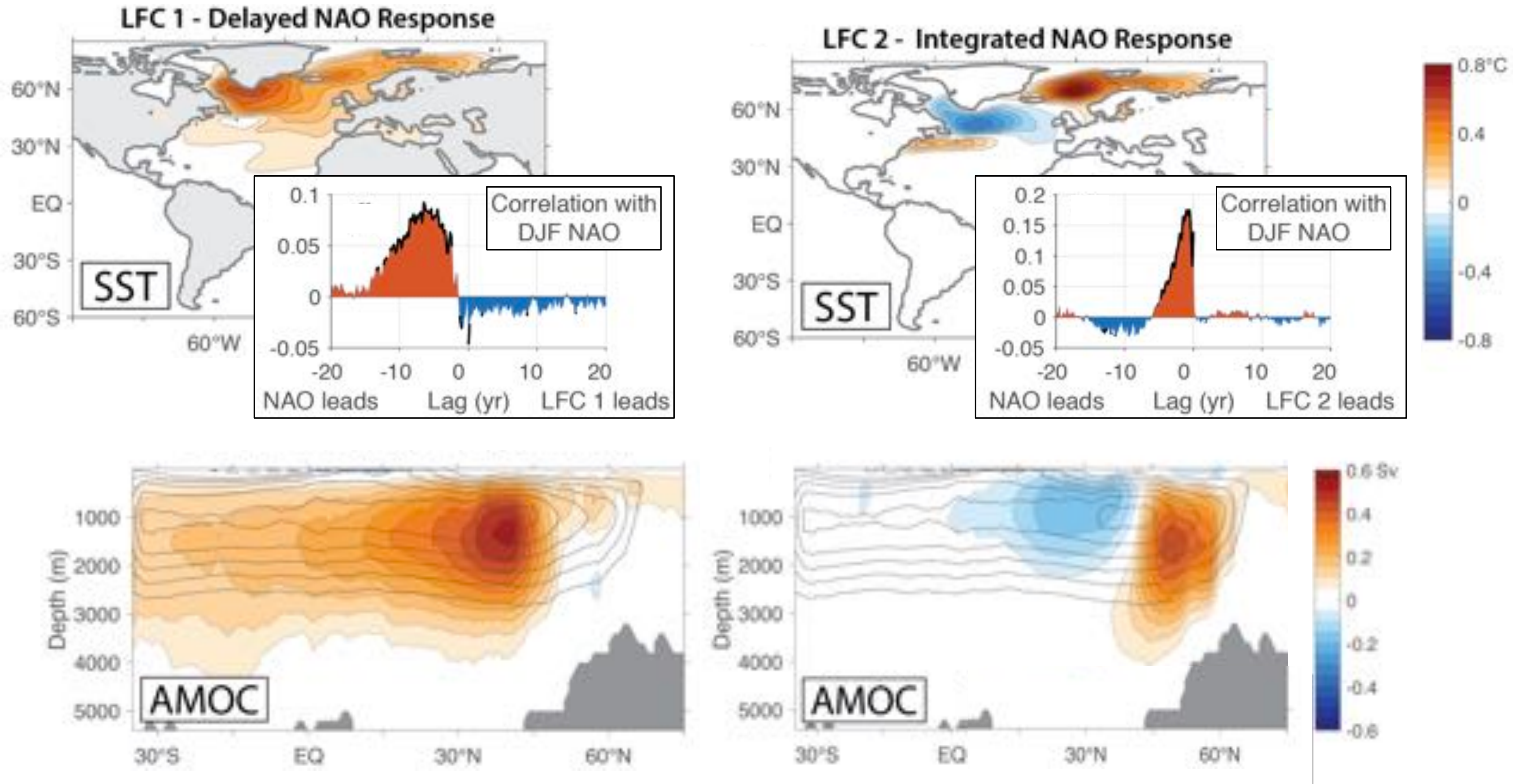


Analysis of 26 CMIP5 Models

Conclusions

1. AMO temperature anomalies are driven by ocean heat transport associated with AMOC

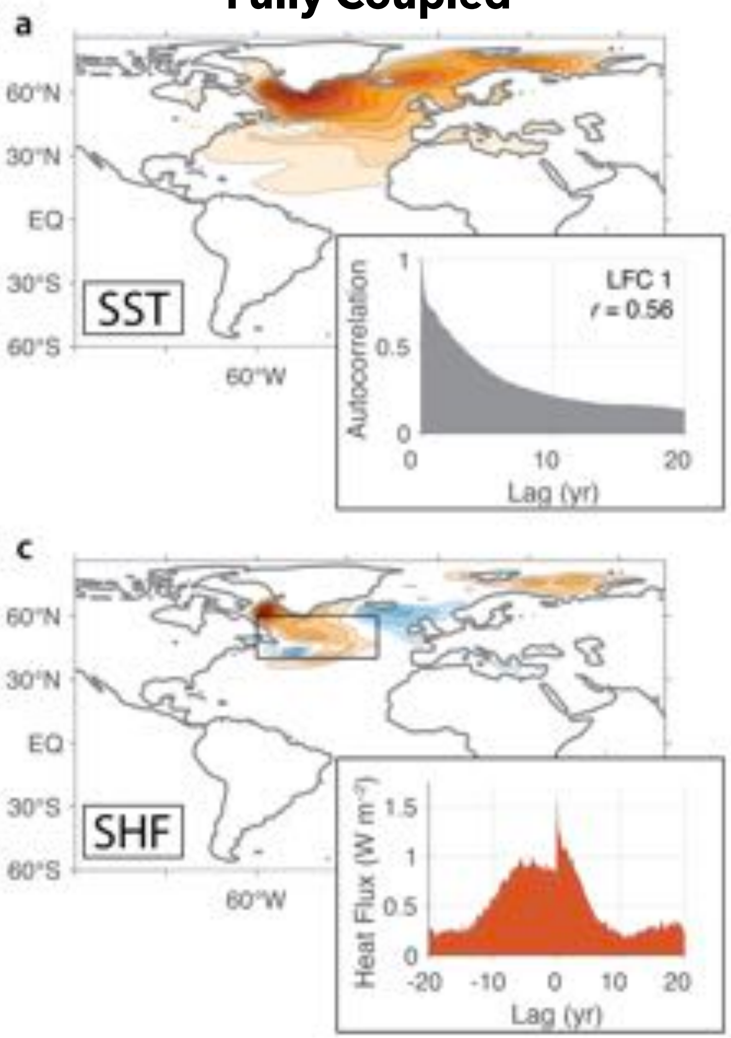
2. Atmospheric circulation anomalies trigger changes in AMOC and act to spread AMO warming throughout the North Atlantic

3. The traditional (NASSTI) definition of the AMO does not isolate the multidecadal variability associated with AMOC

4. There are multiple timescales of ocean response to NAO forcing in CMIP5 models, each with different physics

How would this work with a Slab Ocean?

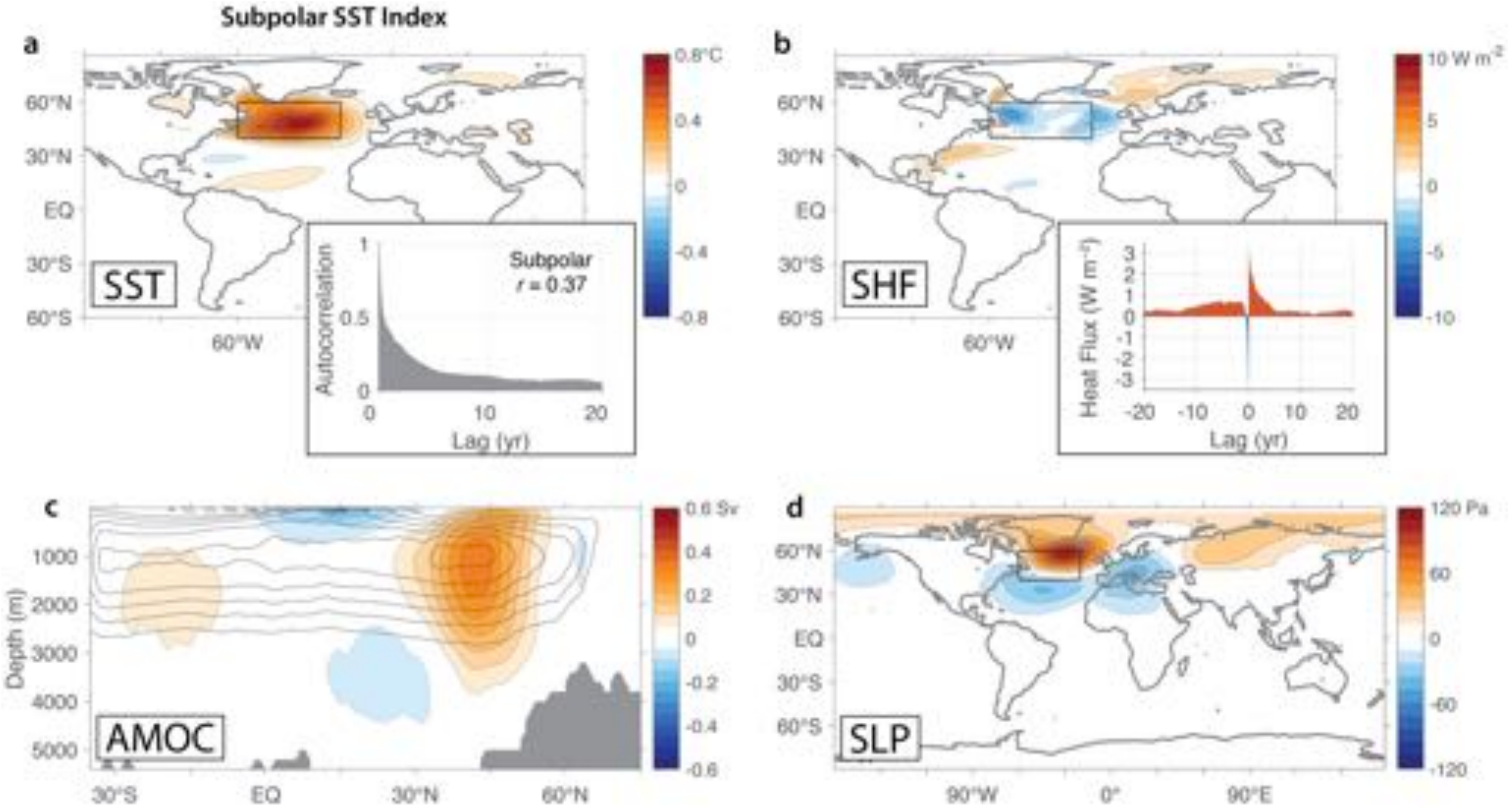
Fully Coupled



Ocean driven air-sea fluxes

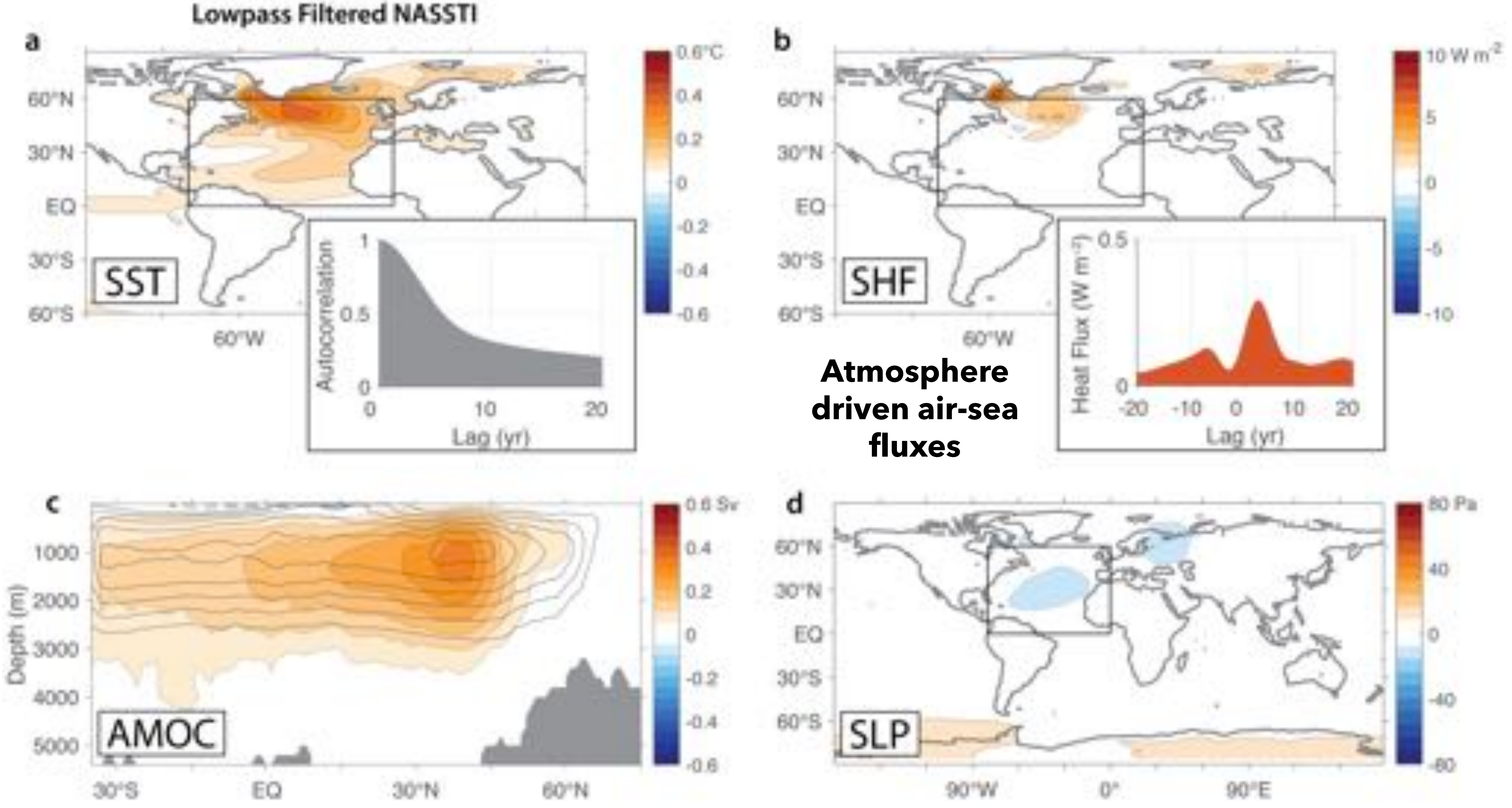
What if we applied the same analysis to a slab-ocean simulation?

Subpolar SST Index



Wills et al. 2018b, Analysis of 26 CMIP5 Models

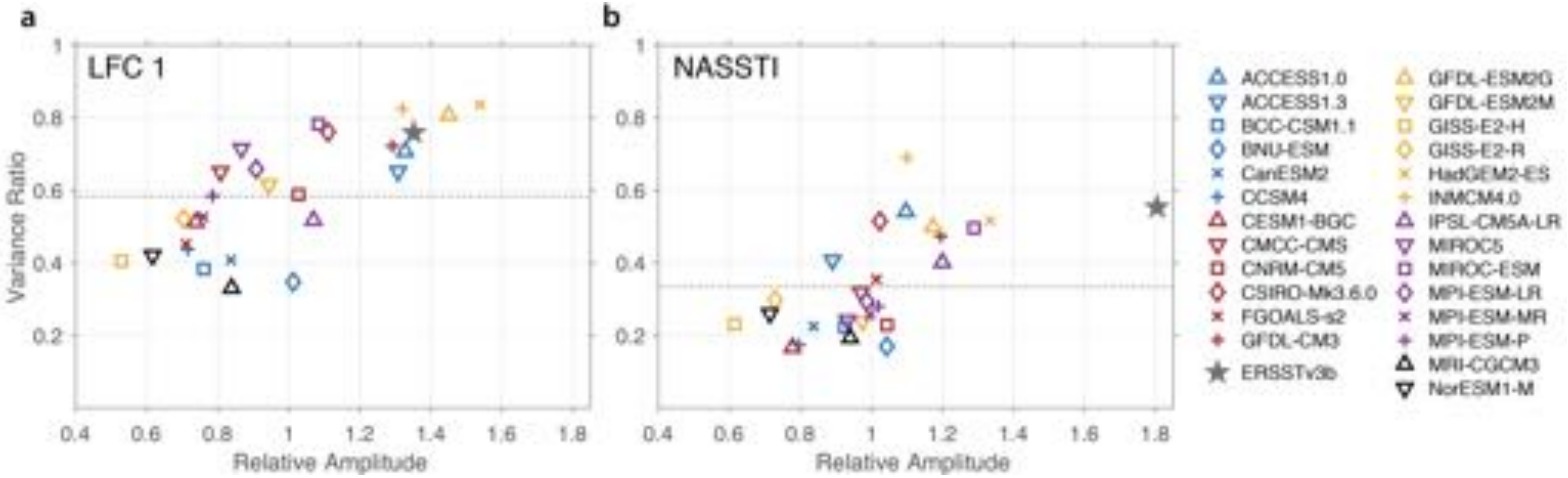
Lowpass Filtered NASSTI



Atmosphere driven air-sea fluxes

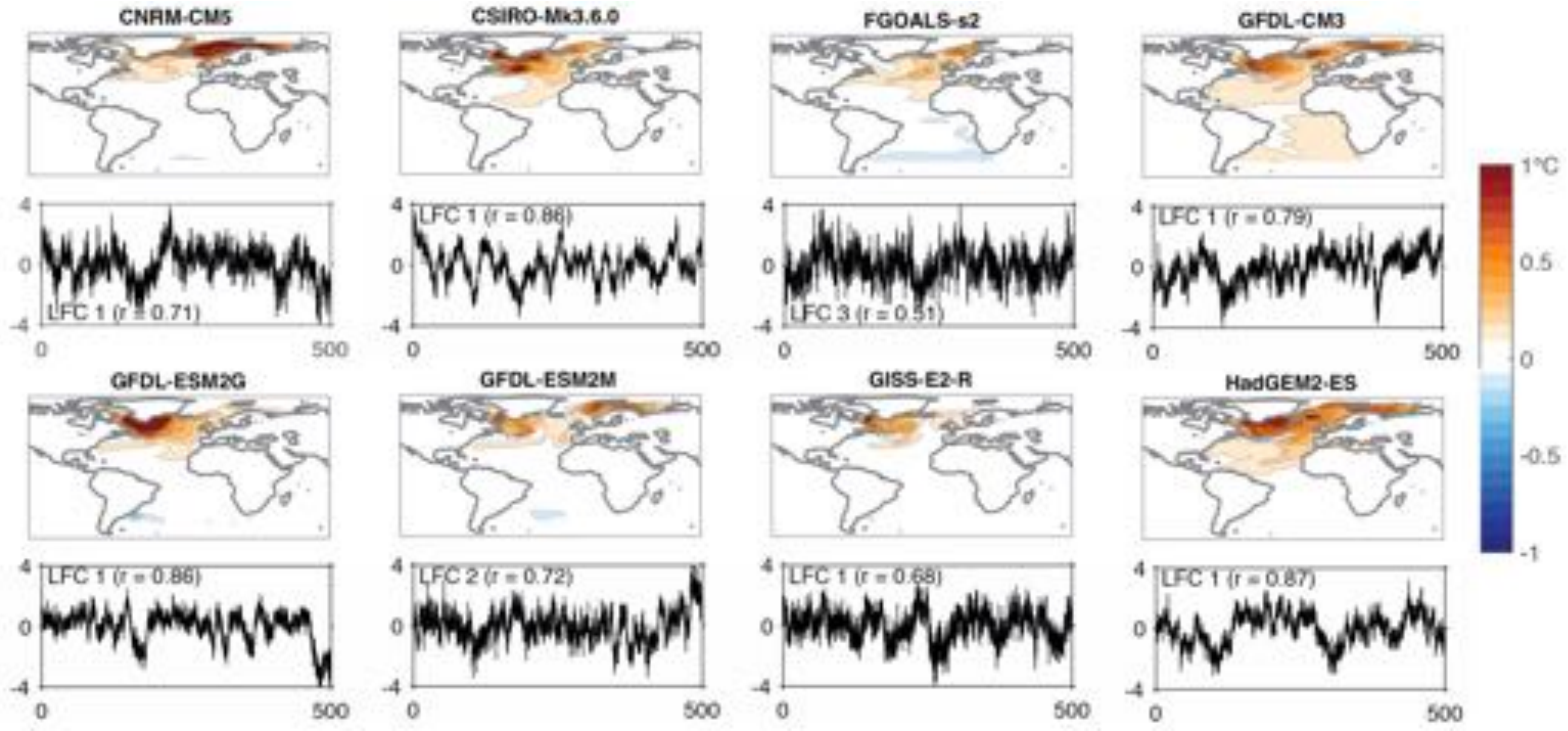
Wills et al. 2018b, Analysis of 26 CMIP5 Models

Differences Across Models



Wills et al. 2018b, Analysis of 26 CMIP5 Models

DIFFERENCES ACROSS MODELS



Wills et al. 2018b, Analysis of 26 CMIP5 Models

A New Tool: Low-Frequency Component Analysis (LFCA)

Full data matrix (zero time mean) X

Lowpass filter with cutoff timescale T

Principal Component Analysis

Compute the eigenvectors of the covariance matrix

$$C = \frac{1}{n-1} X^T X$$

$$\text{EOFs} \quad \mathbf{a}_k \qquad C\mathbf{a}_k = \sigma_k^2 \mathbf{a}_k \qquad ||\mathbf{a}_k|| = 1$$

total variance $\sum_{k=1}^{p} \sigma_k^2$

EOFs $\mathbf{a}_k$

Low-Frequency Component Analysis

Filtered data matrix $\widetilde{X}$

Find linear combinations of EOFs

$$\mathbf{u}_k = \begin{bmatrix} \frac{\mathbf{a}_1}{\sigma_1} & \frac{\mathbf{a}_2}{\sigma_2} & \dots & \frac{\mathbf{a}_N}{\sigma_N} \end{bmatrix} \mathbf{e}_k$$

that maximize the **ratio of low-frequency to total variance** (exactly solvable)

$$r_k = \frac{\left(\widetilde{X}\mathbf{u}_k\right)^T \widetilde{X}\mathbf{u}_k}{\left(X\mathbf{u}_k\right)^T X\mathbf{u}_k}$$

$\mathbf{u}_k$

Full data matrix (zero time mean) X

low-frequency components $\quad \mathrm{LFC}_k = X\mathbf{u}_k$

low-frequency patterns $\quad \mathbf{v}_k = X^T \mathrm{LFC}_k$

Wills et al. (2018a, GRL)

A New Tool: Low-Frequency Component Analysis (LFCA)

Full data matrix (zero time mean) X → Discard all information about high-frequency variability

$$r_k = \frac{\left(\widetilde{X}\mathbf{u}_k\right)^T \widetilde{X}\mathbf{u}_k}{\left(X\mathbf{u}_k\right)^T X\mathbf{u}_k}$$

Lowpass filter with cutoff timescale T

Filtered data matrix $\widetilde{X}$ →

Principal Component Analysis

Compute the eigenvectors of the filtered covariance matrix

$$\widetilde{C} = \frac{1}{n-1}\widetilde{X}^T\widetilde{X}$$

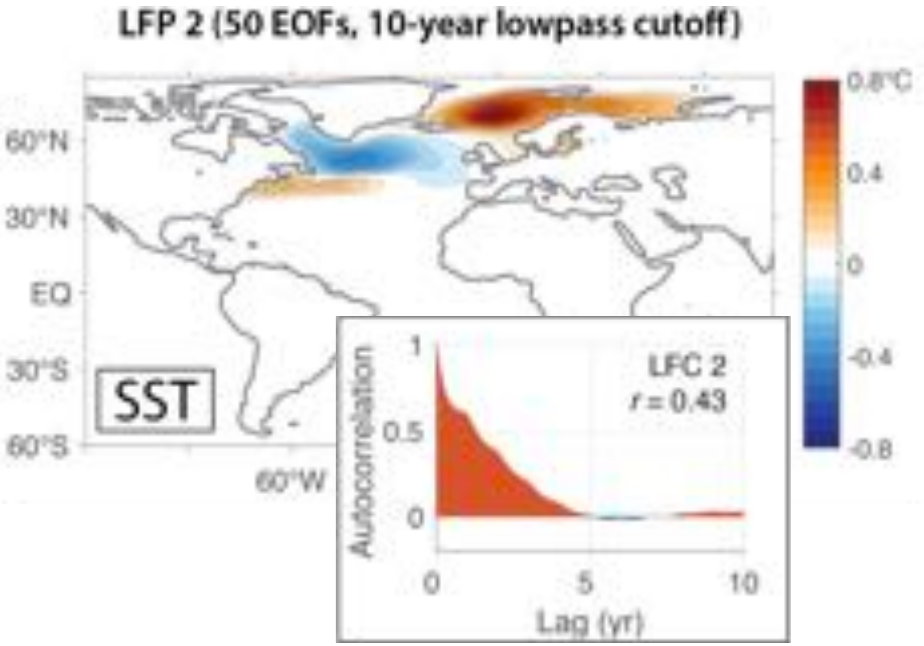
EOFs $\mathbf{a}_k$ $\quad \widetilde{C}\mathbf{a}_k = \sigma_k^2\mathbf{a}_k$

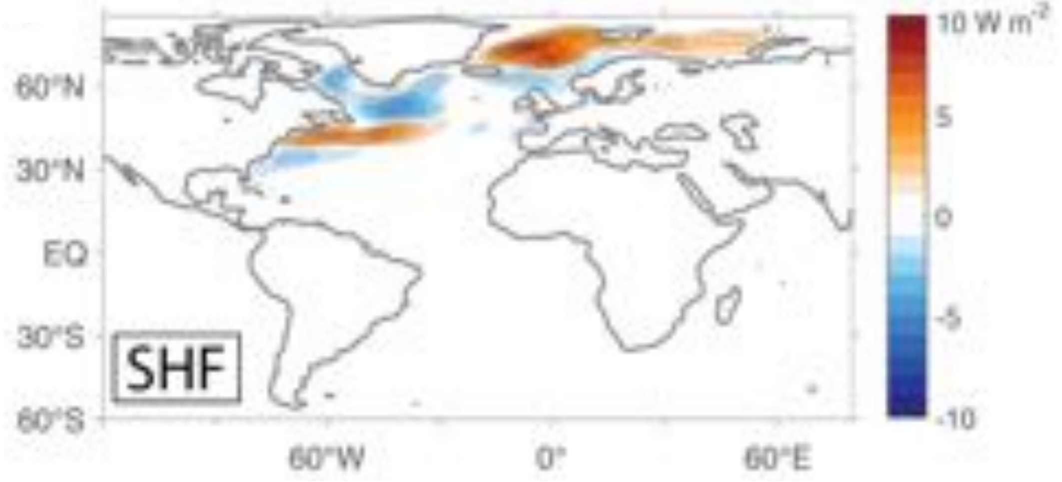
$$||\mathbf{a}_k|| = 1$$

total variance $\Sigma_{k=1}^{p}\sigma_k^2$

↓ EOFs $\mathbf{a}_k$

Second Low-Frequency Component





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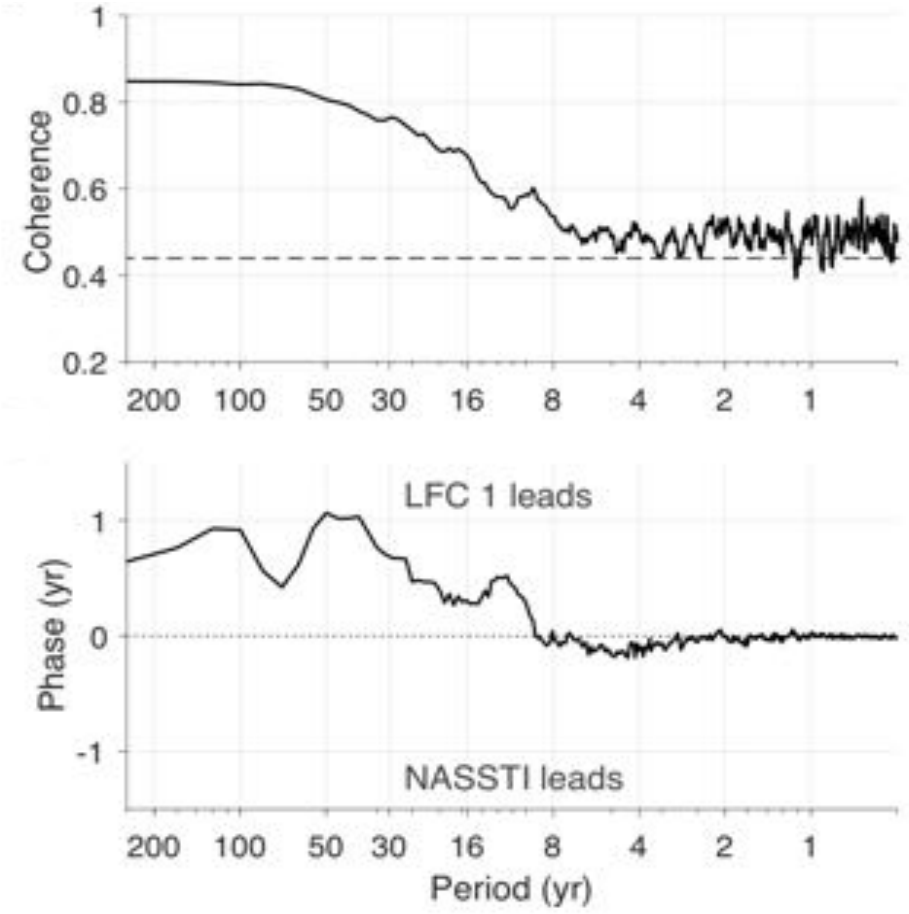
LFC/LFP 2 shows North Atlantic Tripole (cf. Sun et al. 2015)

Wills et al. 2018b, Analysis of 26 CMIP5 Models

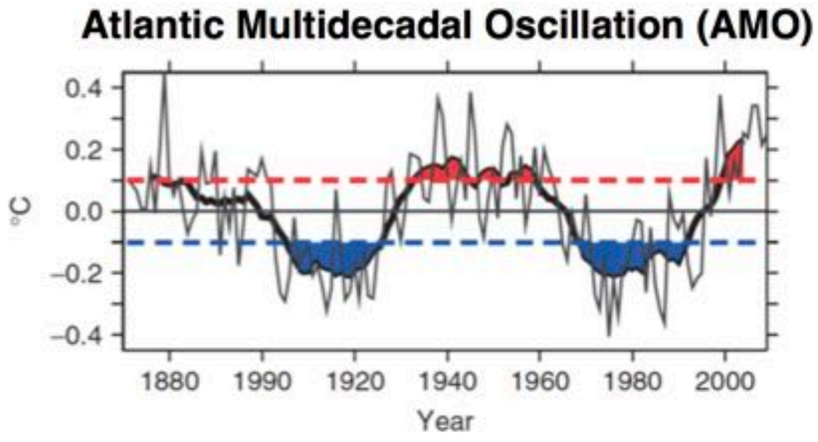
LFC–AMO vs. NASSTI

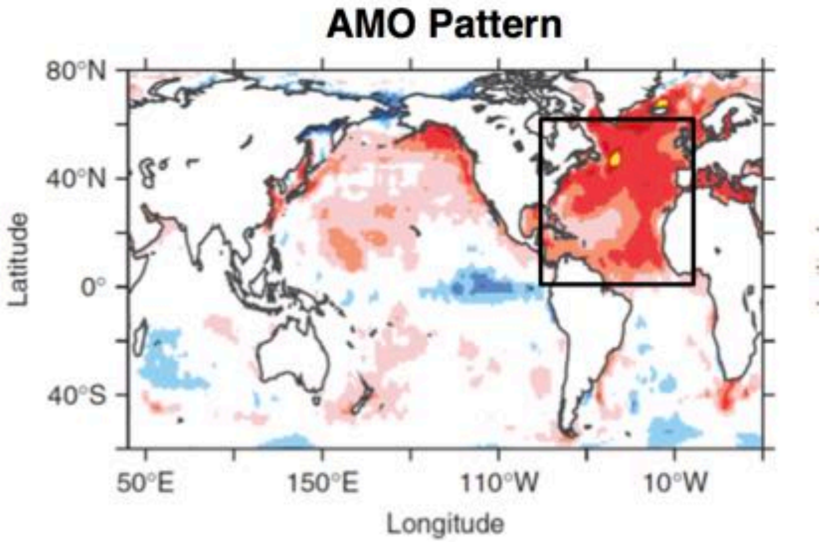


LFC 1 still capturing the same multidecadal variability as NASSTI

Wills et al. (2018b, submitted)
Analysis of 26 CMIP5 models

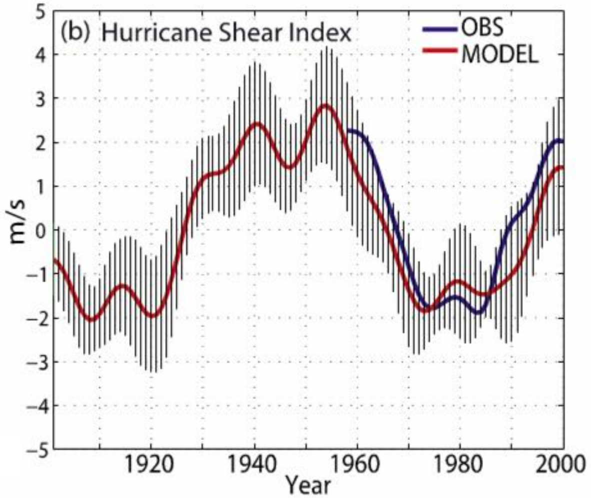
AMO and its Impacts





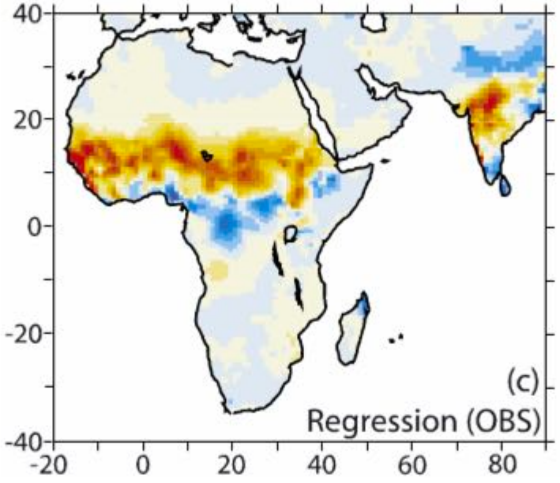
Enfield et al., 2001;
Keenlyside and Ba, 2010

Atlantic Hurricane Frequency



McCabe et al., 2004;
Zhang and Delworth, 2006

Sahel Rainfall



US Drought