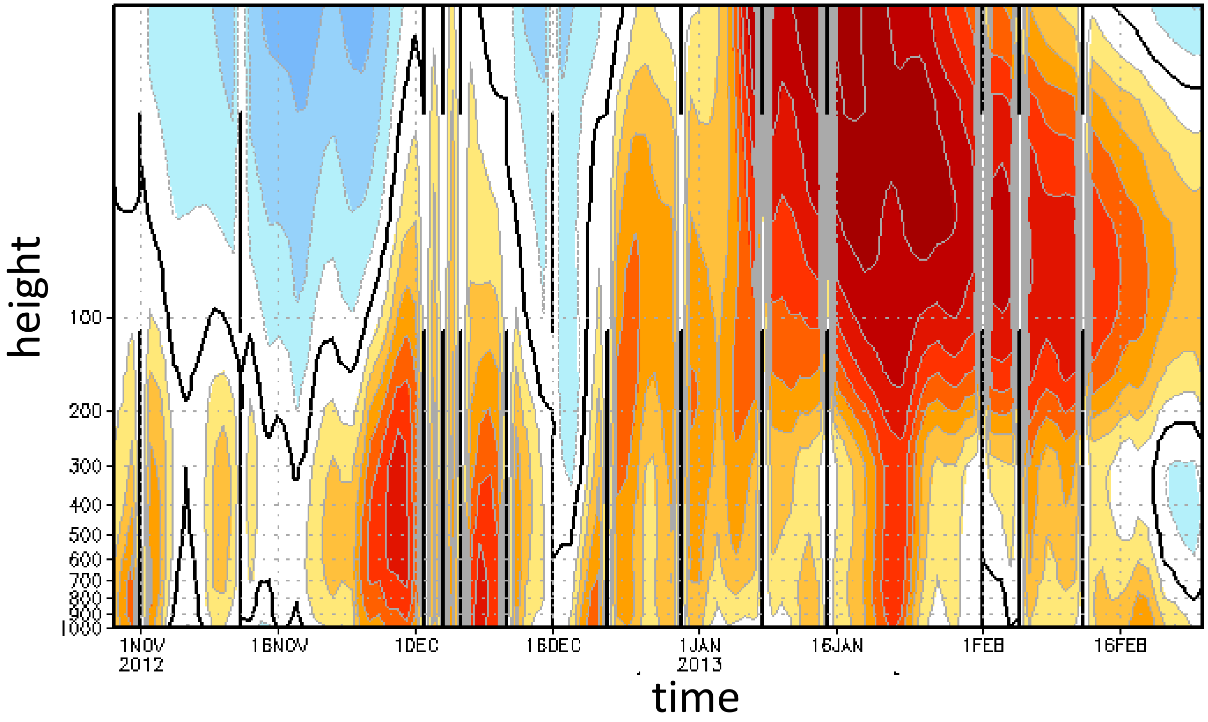
Vertical Coupling in Climate

Thomas Reichler (U. of Utah)

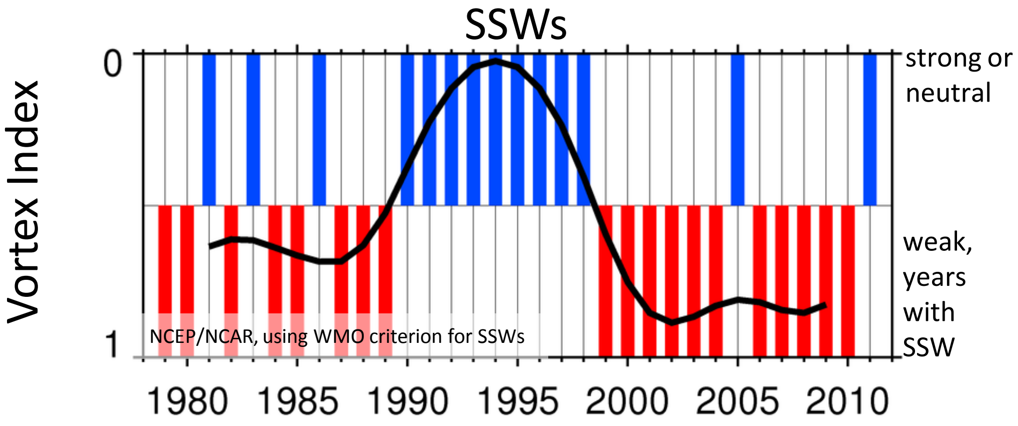
NAM



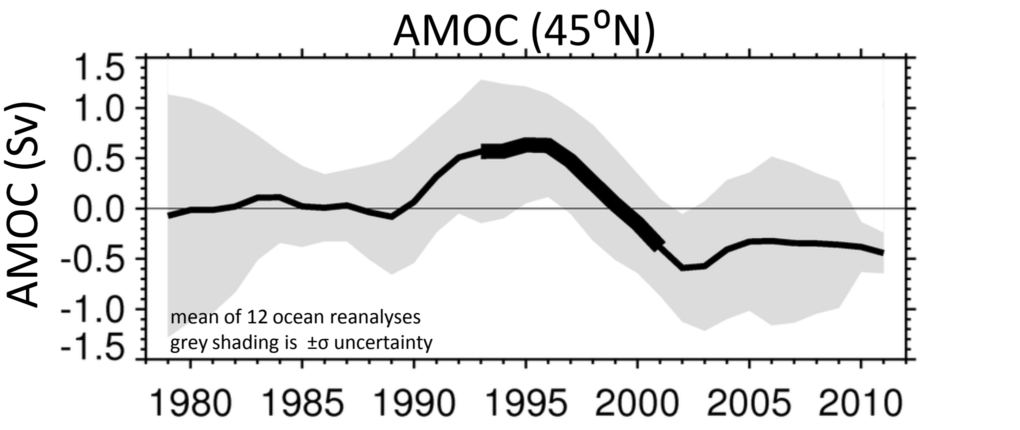
Polar cap averaged geopotential height anomalies

Observations

- Reichler et al. (2012)
- SSWs seem to cluster
- Low-frequency power



- Similar structure in NAM, NAO, and AMOC
- Cause and effect?



Review of Studies With Stratosphere-Resolving Models

Hamilton (1995)

- GFDL SKYHI
- Climatological SSTs and sea ice
- Decadal variability in winter polar vortex

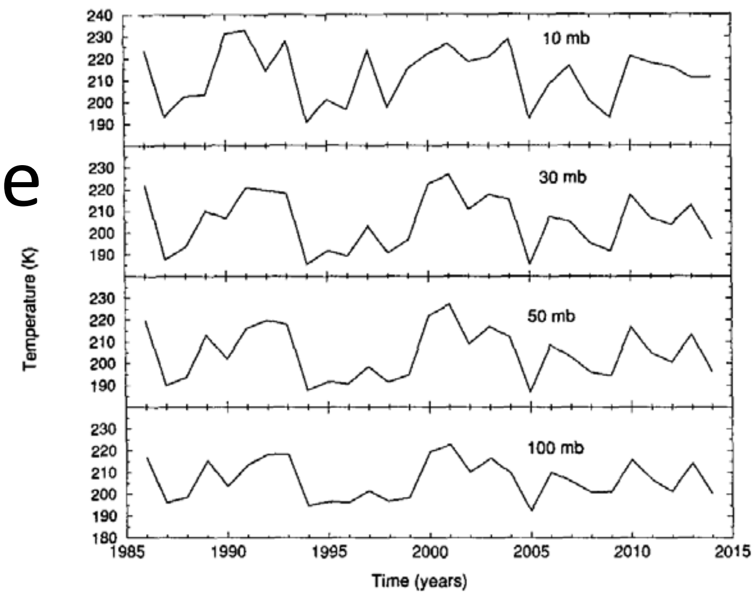


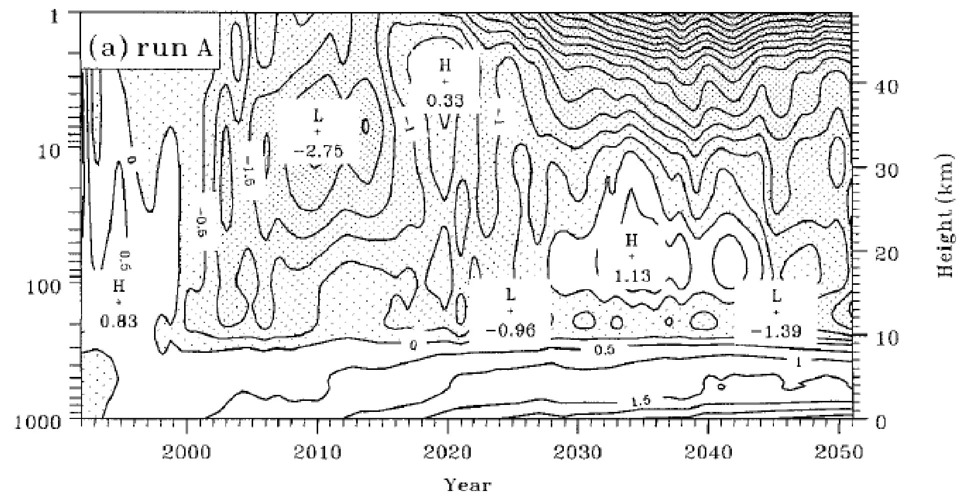
FIG. 9. The December–February mean North Pole temperature in each of 29 consecutive years from the SKYHI control run. Results for 10 mb, 30 mb, 50 mb, and 100 mb.

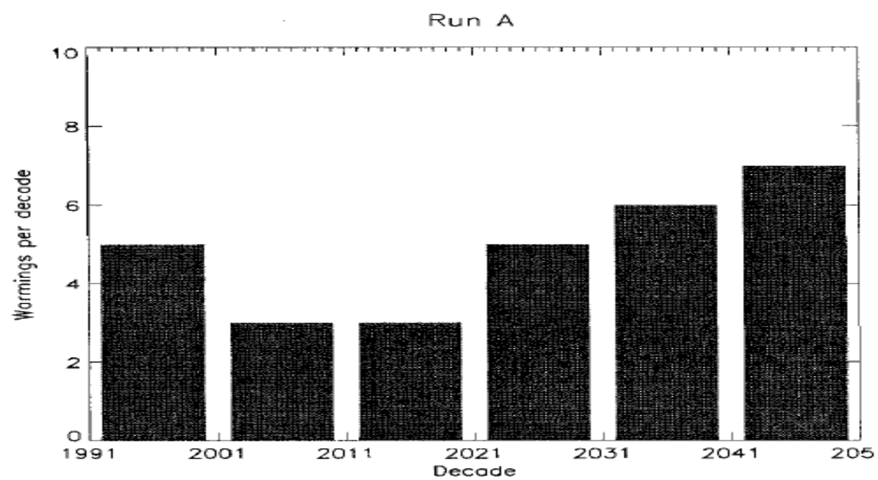
Erlebach et al. (1996)

- Berlin TSM GCM
- SSWs tend to cluster: most SSWs occur centered on two years

Butchart et al. (2000)

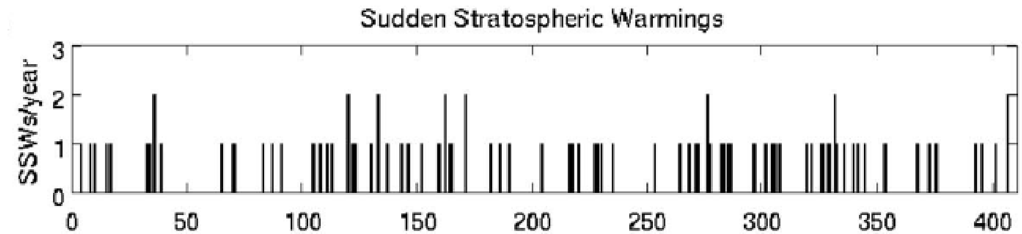
- UKMO ‘‘Unified Model”
- Internally produced decadal variability
- Associated with changes in SSW frequency
- Consistent with variations in EP flux convergence





Schimanke et al. (2011)

- Coupled ECHAM4; constant forcing
- Multi-decadal variability in the number of SSWs
- Connected to variations upward EP flux at 100 hPa



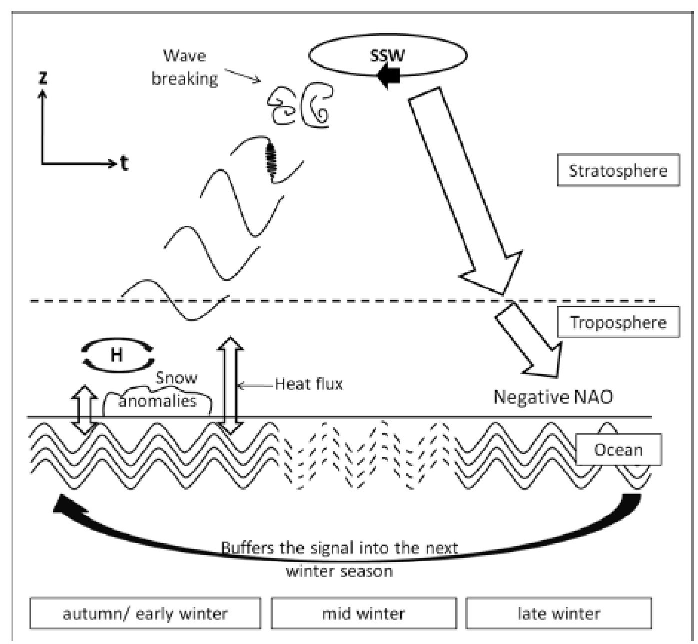
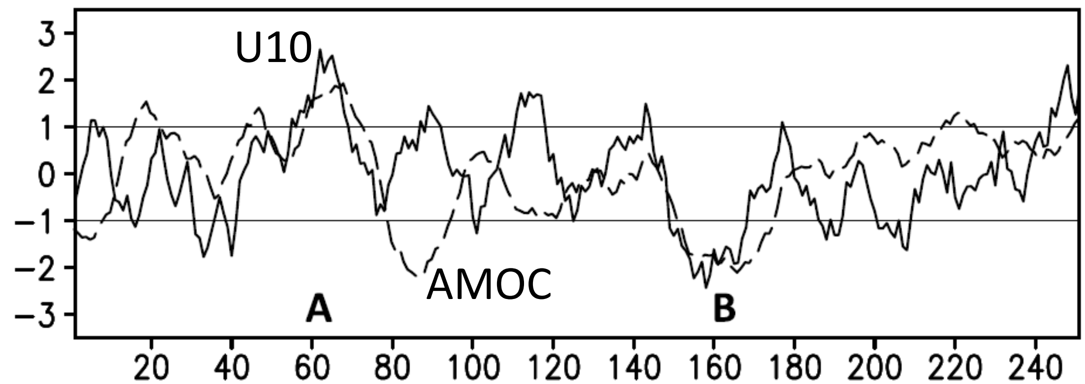


Figure 3. Schematic mechanism for how decadal variability of SSWs is generated. For more detail see text. Based on the works by *Reichler et al.* [2005] and *Cohen et al.* [2007].

Manzini et al. (2012)

- Coupled ECHAM5; constant forcings
- Low-pass filtered
- 2 periods
  - A: strong vortex (0.6 SSWs/yr)
  - B: weak vortex (1.2 SSWs/yr)
  - AMOC follows along



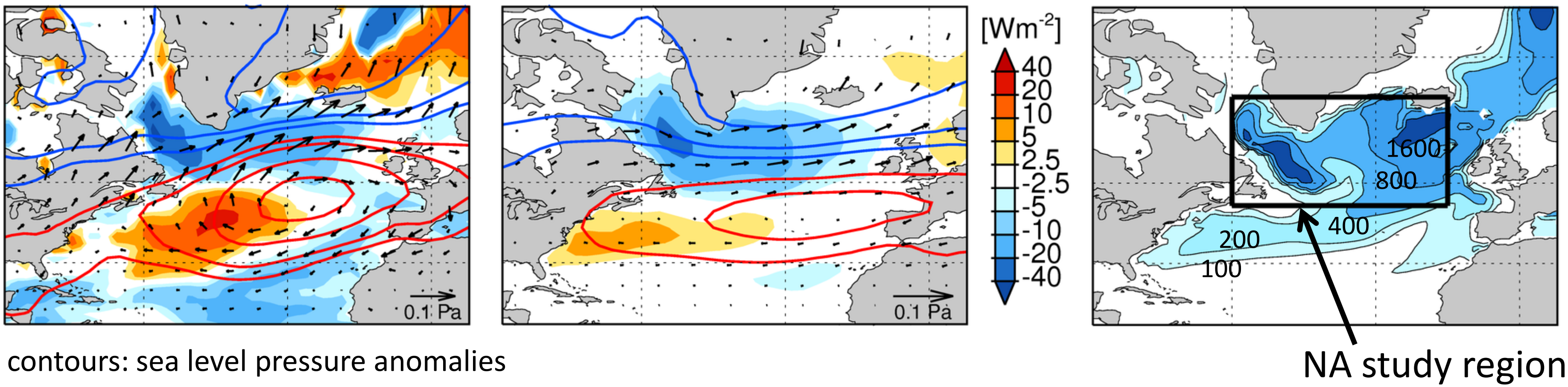
SSWs in CM2.1 and CMIP5

Vortex Composites Atmospheric Response

$NAM10_{daily} > 2.5$, 0-60 days following events

Reanalysis & CM2.1

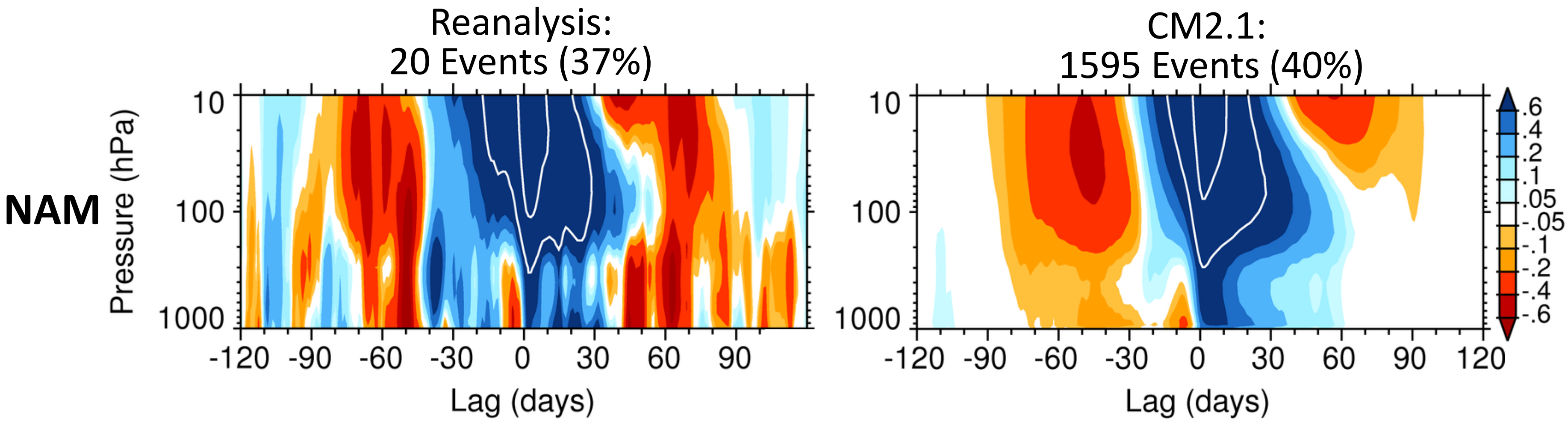
Reanalysis | CM2.1 | CM2.1 Climatological Mixed Layer Depth



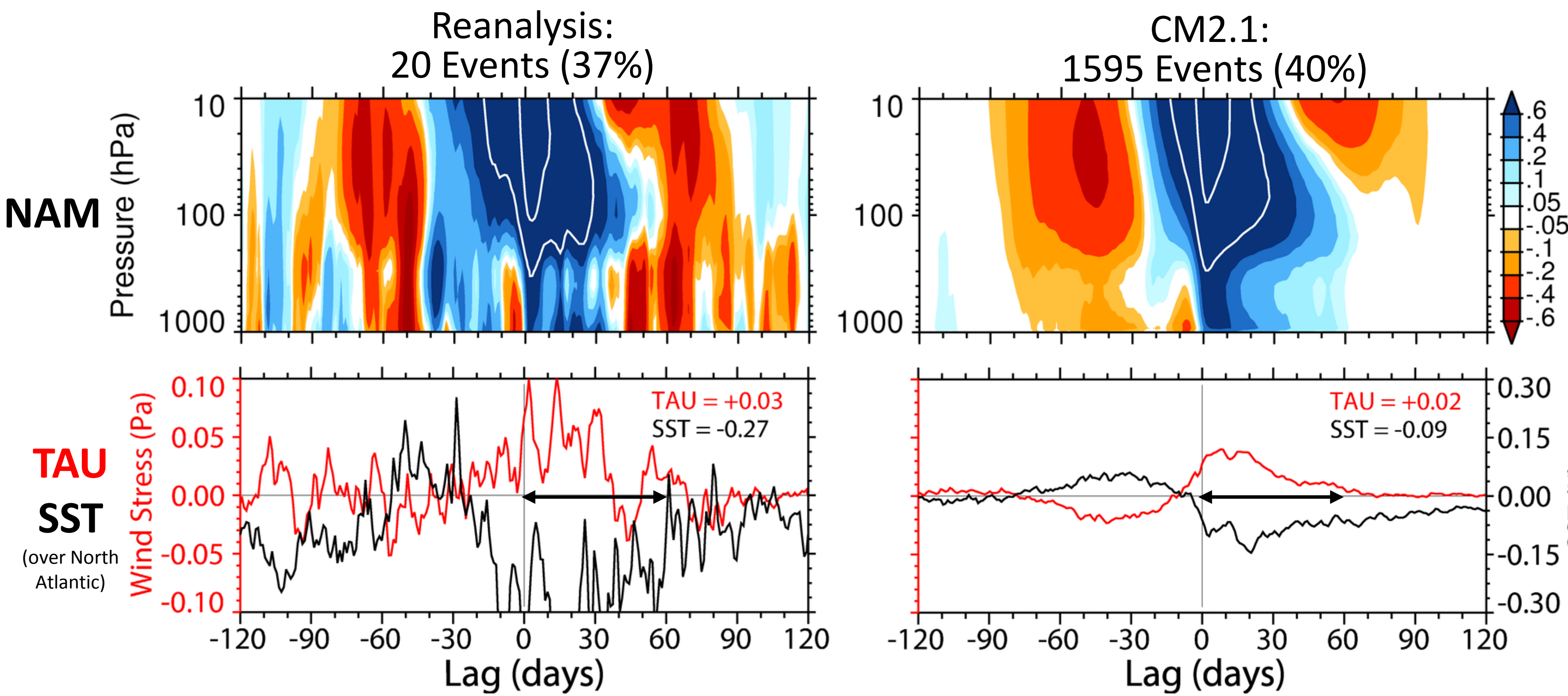
contours: sea level pressure anomalies
vectors: wind stress anomalies
shading: sensible and latent heat flux anomalies

- CM2.1 surface response is too weak
- NAO nodal point coincides with main downwelling region

Reanalysis & CM2.1



Reanalysis & CM2.1

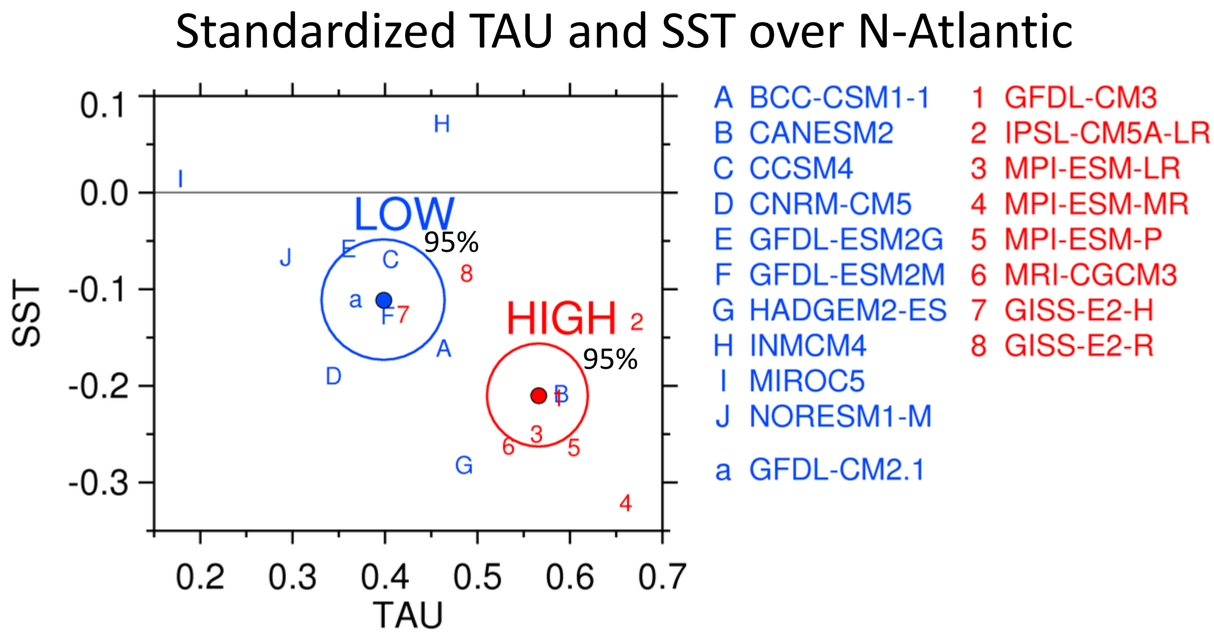


- Surface response to SSWs too weak in CM2.1
- Lack of a good stratosphere?

CMIP5

NAM10$_{daily}$ > 2.5 or <-3

Anomalies averaged over months 1–2 (TAU) and 1–3 (SST) following the events:



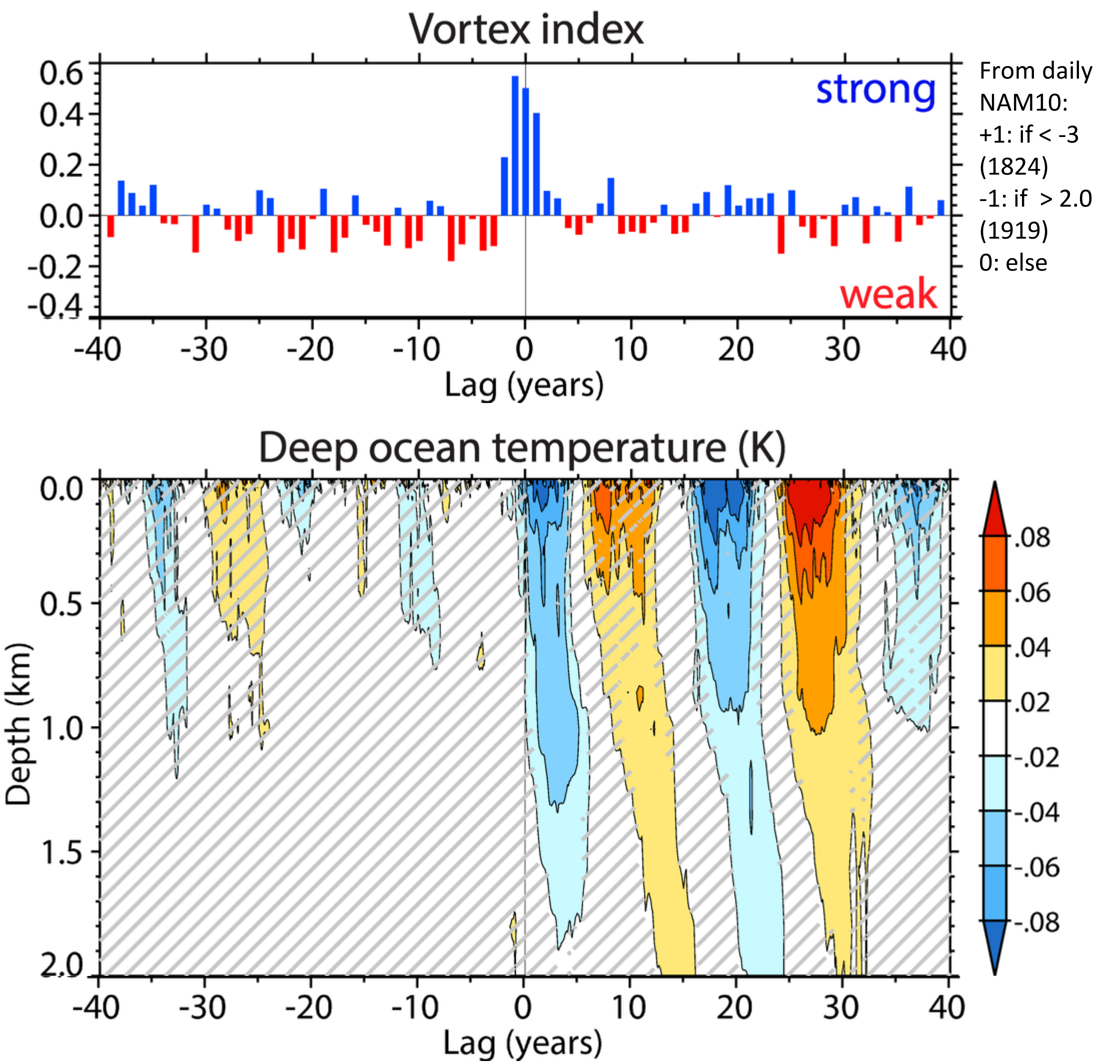
- High-top models show more realistic surface response

Vortex Composites
Ocean Response

Composites on persistent stratospheric events
(low-pass filtered NAM10)

CM2.1

- 96 events
- 50 positive, 46 negative
- every ~42 years

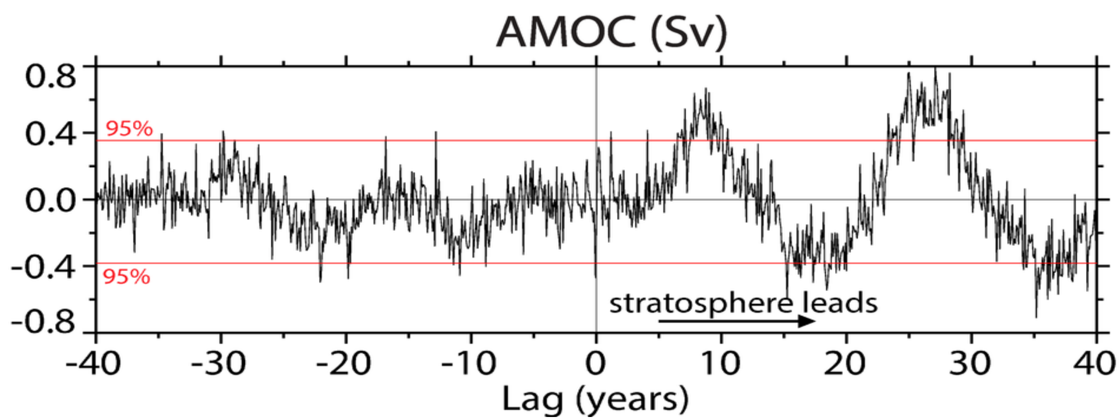


AMOC
monthly data

CM2.1

50 strong and 46 weak events

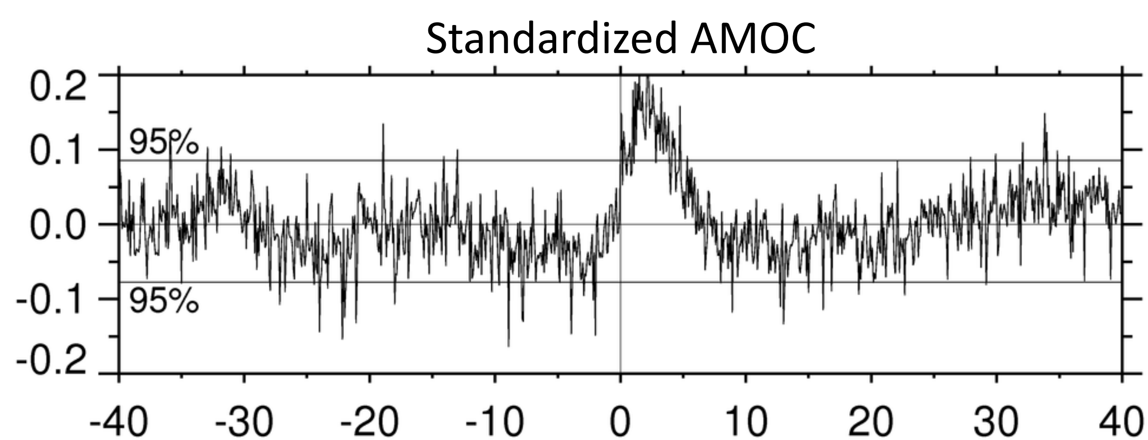
- 4000 years



CMIP5

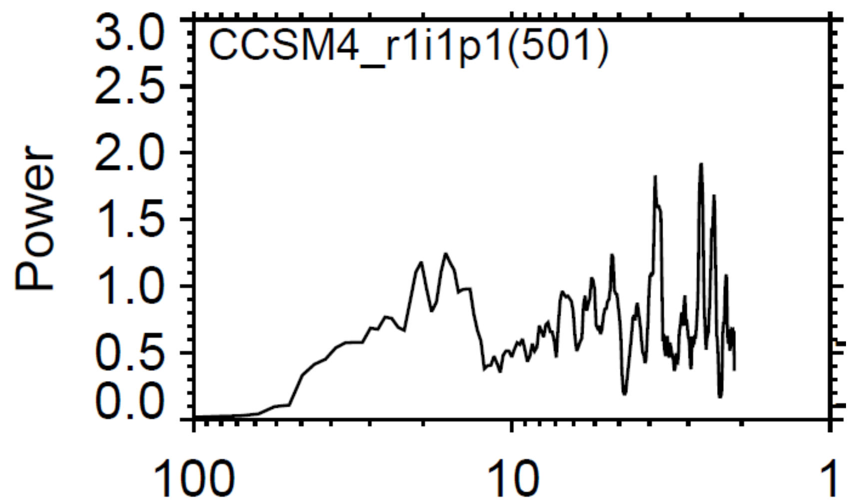
269 strong and 276 weak events

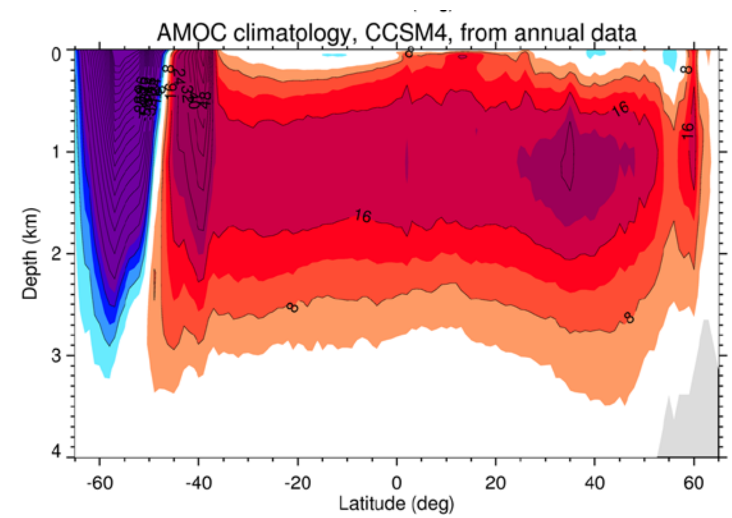
– 18 models (≥ 500 years)
– normalize and concatenate AMOC
– 12,944 years



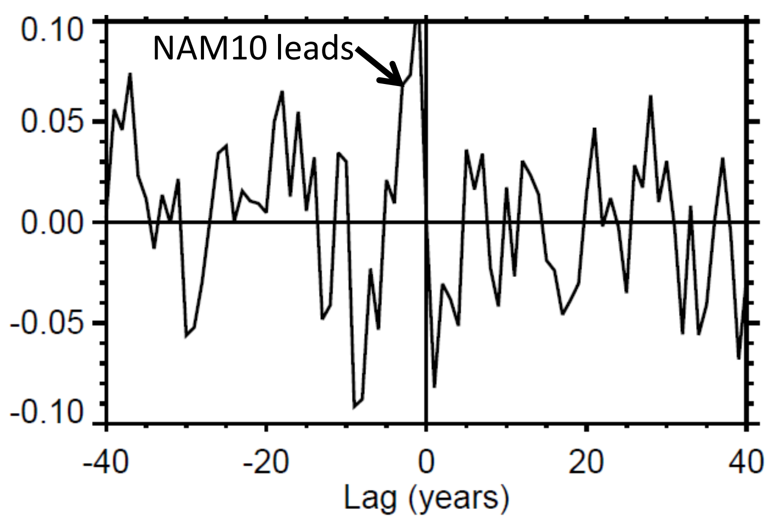
CCSM4 (500 yrs)

NAM10 power spectrum

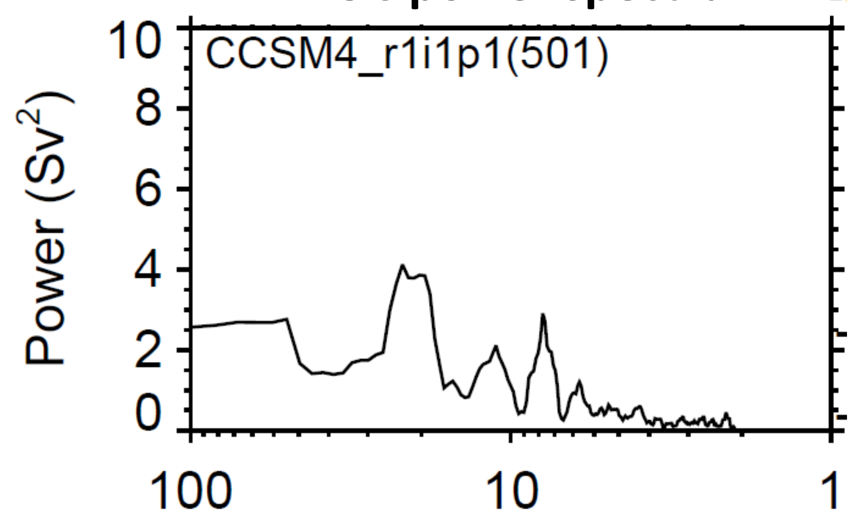




NAM10/AMOC Cross Correlation



AMOC power spectrum

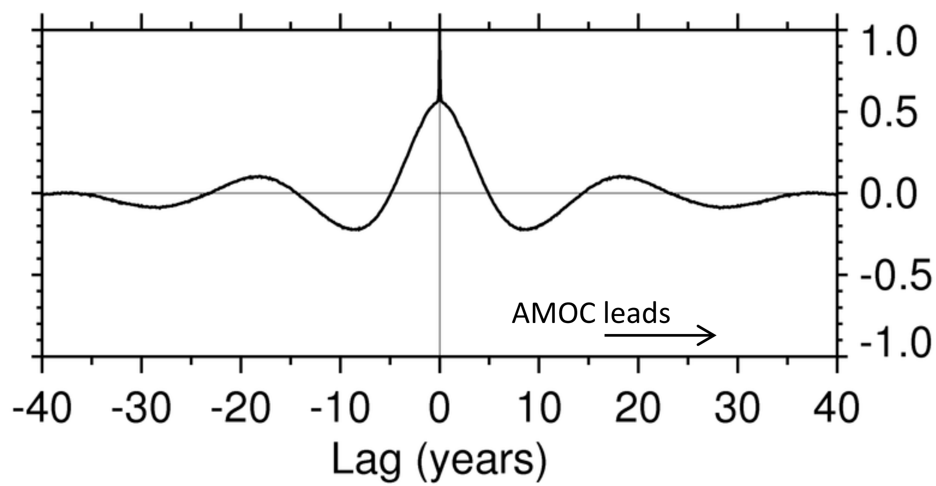


Additional Analysis

- Analysis so far was based on composites on NAM10
- Stratosphere seems to lead AMOC
- What about the troposphere?
  - lagged AMOC regressions
  - spectral coherence analysis
- CM2.1, monthly raw data, no filtering

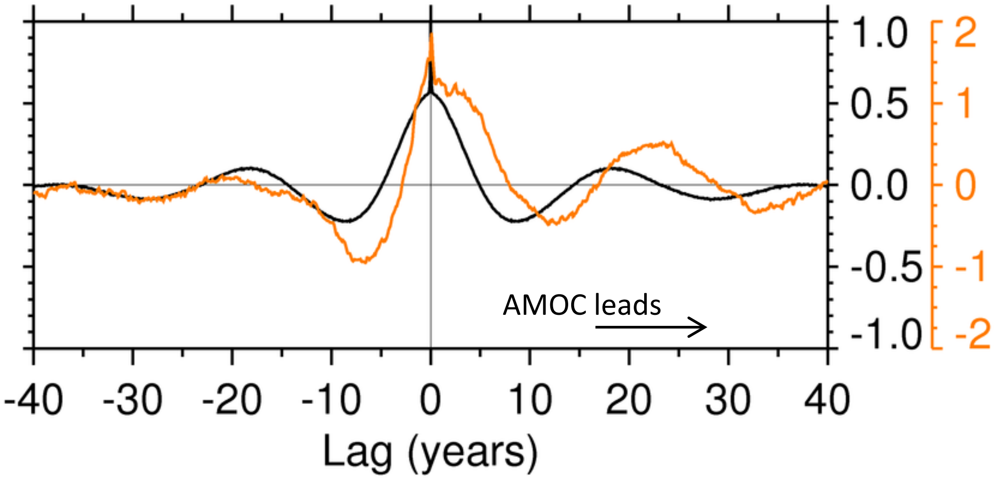
Lagged AMOC Regressions

AMOC



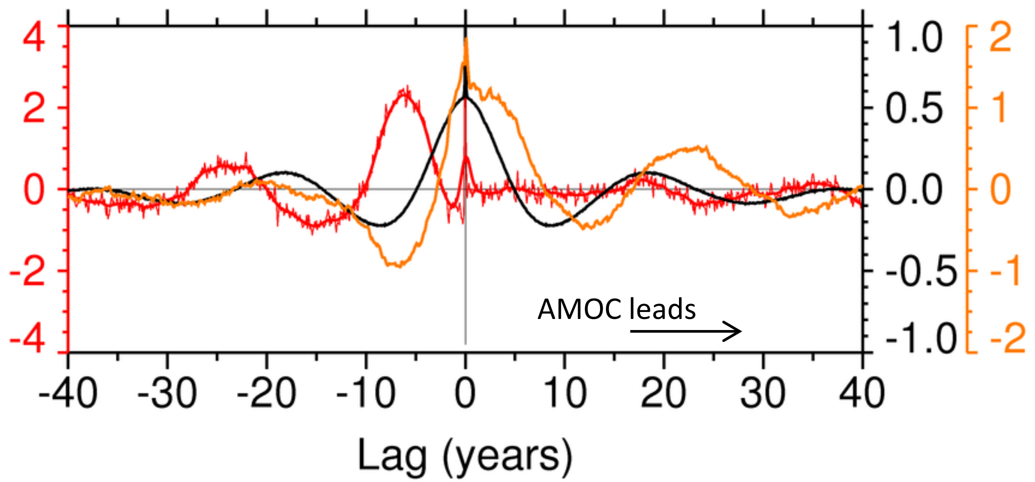
Lagged AMOC Regressions

AMOC
AMO

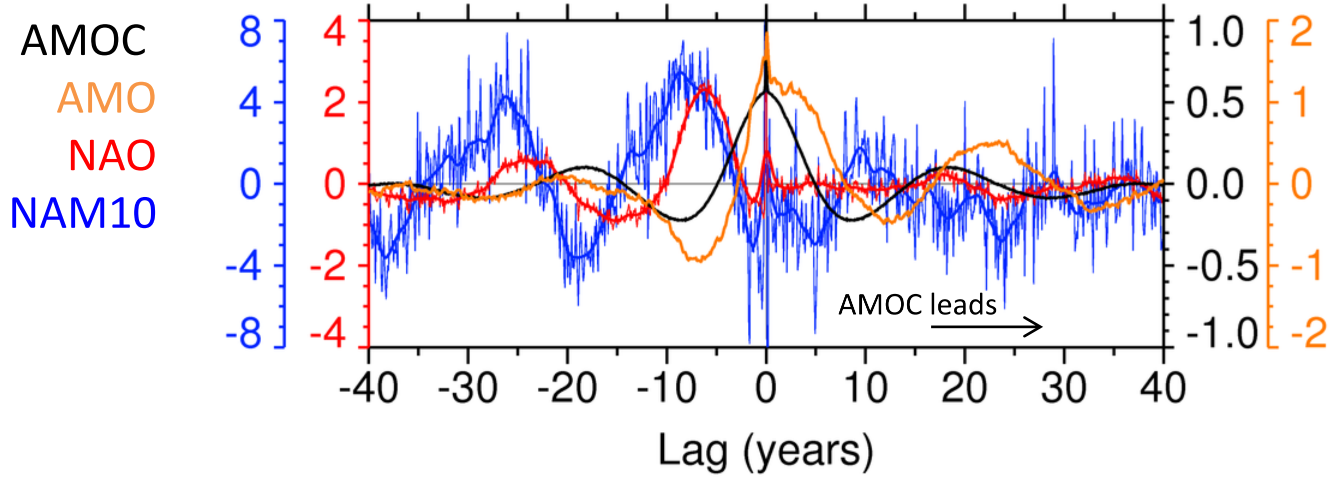


Lagged AMOC Regressions

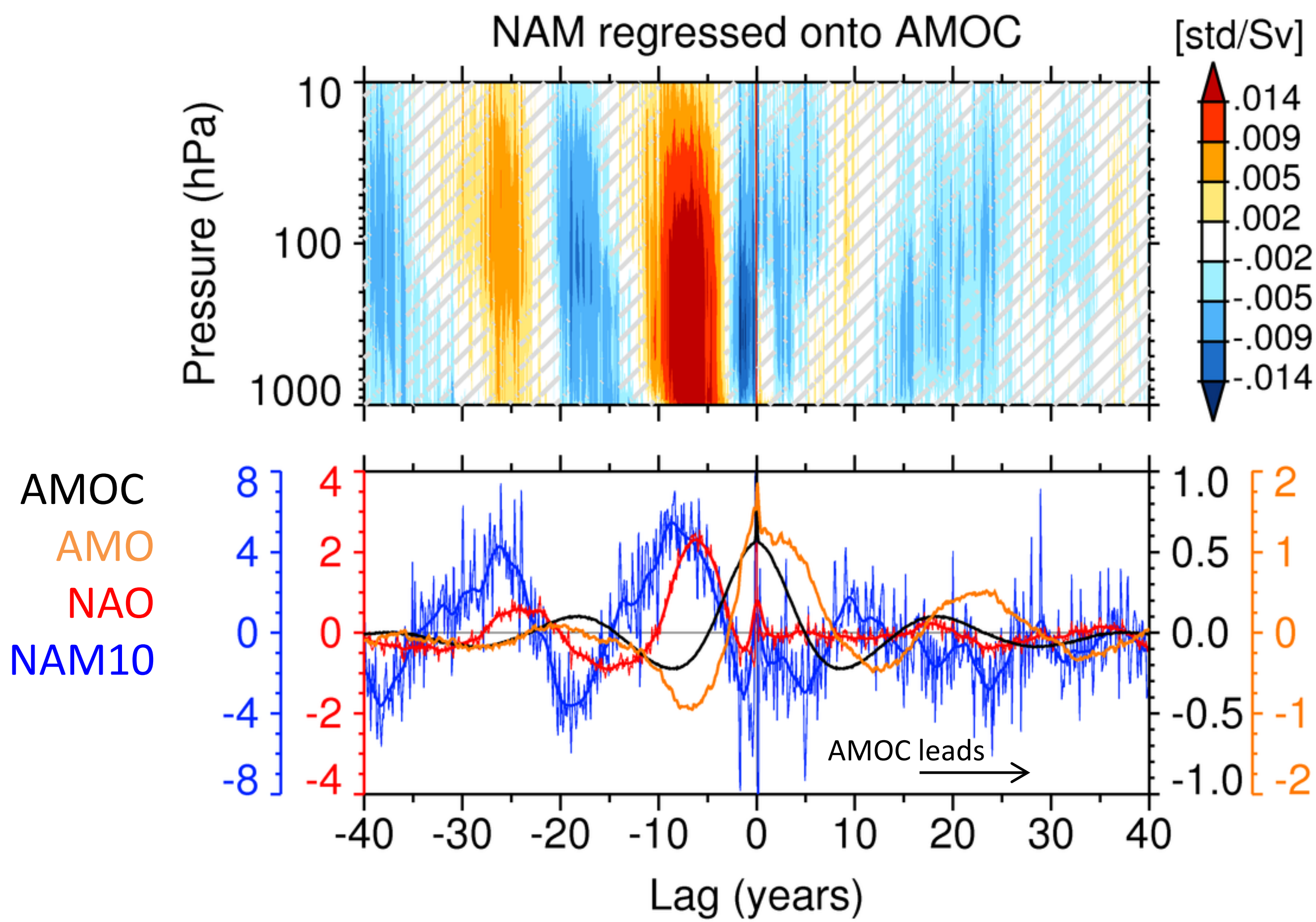
AMOC
AMO
NAO



Lagged AMOC Regressions



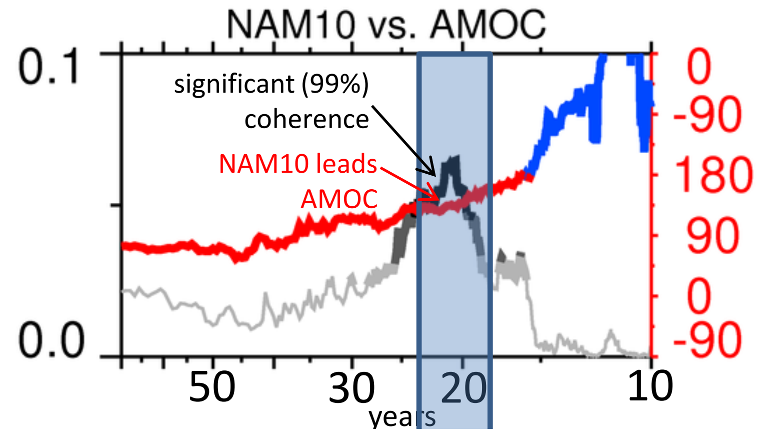
Lagged AMOC Regressions



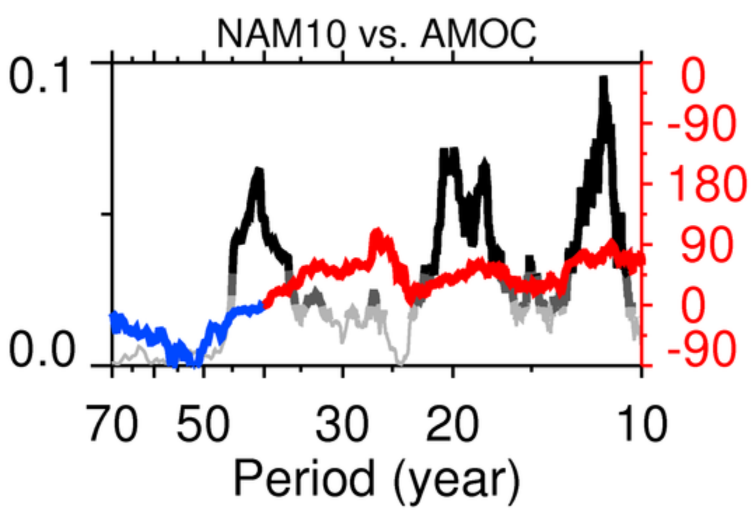
- NAM10 leads NAO by ~2 and AMOC by ~5 years
- Only weak feedback from ocean into atmosphere

Spectral Coherence

Mann and Park (1993)
CM2.1



- Similar outcomes in CMIP5:



Drivers of Stratospheric Variability

1. **Stochastic forcing**
   - stratosphere is dynamically stable, troposphere is source of variability
   - unable to explain clustering of SSWs
2. **External influences**
   - 11-year solar cycle (Ineson et al. 2011), volcanoes (Ottera et al. 2010)
   - unable to explain constant forcing experiments

Drivers of Stratospheric Variability

3. **Internal effects -** requires memory
   - lower boundaries
     - ocean, snow and ice: Ineson and Scaife (2009), Taguchi and Hartmann (2006), Schimanke et al. (2011), Cohen et al. (2007), Ogi et al. (2003)
     - requires feedback into stratosphere, which seems very weak
     - unable to explain atmosphere-only experiments
   - lower stratosphere
     - long radiative damping time scale (30 days) (Baldwin et al. 2003)
     - tropical lower stratosphere (Hamilton 1995)
       - long radiative damping time scale, small Coriolis parameter, strong static stability insulates flow from troposphere
       - missing QBO in models may increase memory
     - ozone memory in lowermost stratosphere (Kuroda and Yamazaki 2010)
   - decadal variations in QBO phase transitions (Anstey and Shepherd 2008)
   - positive dynamical feedbacks, involving chemistry (Hartmann et al. 2001)

Summary

- Key for the stratospheric influence are
  - persistence and decadal power of vortex events
  - vortex events project on NAO
  - NAO nodal point coincides with downwelling region
  - downwelling region is AMOC’s “Achilles heel”
  - AMOC is intrinsically unstable

How Important?

- AMOC is important for decadal climate variations

- AMOC changes by
  - CM2.1: ±0.4 Sv (0.2 std)
  - CMIP5: 0.15 std

- CM2.1 underestimates effect of vortex events
  - stratosphere resolving models are needed

- Effect in real atmosphere is likely more important

Decadal Predictability

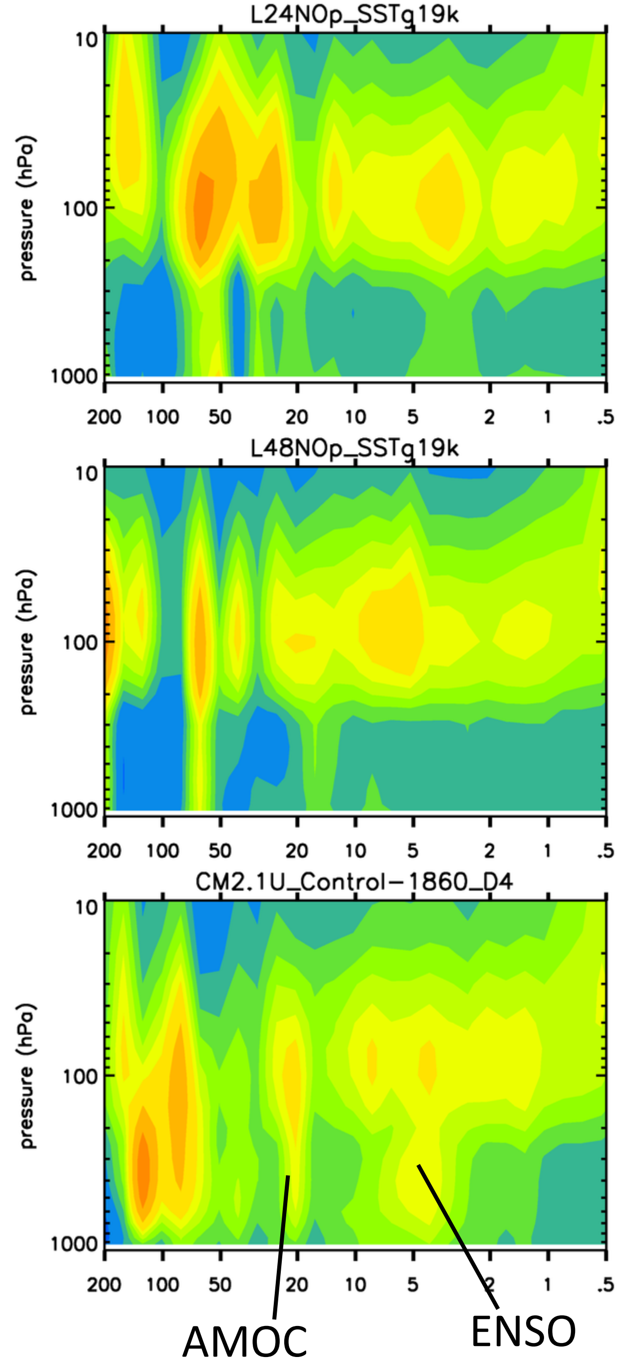
- Individual vortex events are unpredictable, which may limit the success of decadal predictions (AR5)
- Perhaps decadal rhythm of SSWs is real and predictable

Thank You

Extra figures

NAM Spectra

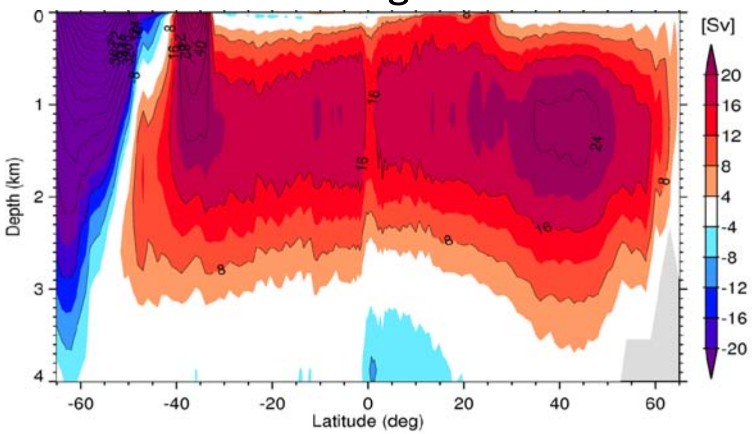
- NAM is polar cap averaged Z
- 50 frequency bands
- CM2.1: 1001-4000
- L24: 2001-4000
- L48:



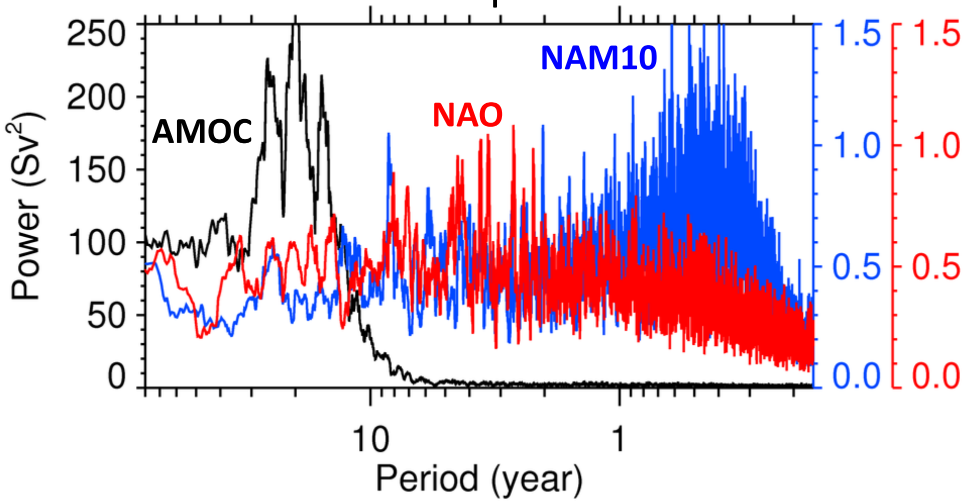
CM2.1 Control Run

- 24 levels, not stratosphere resolving, no QBO, …
- 4000 years, constant (1860) forcings

Atlantic Overturning Streamfunction

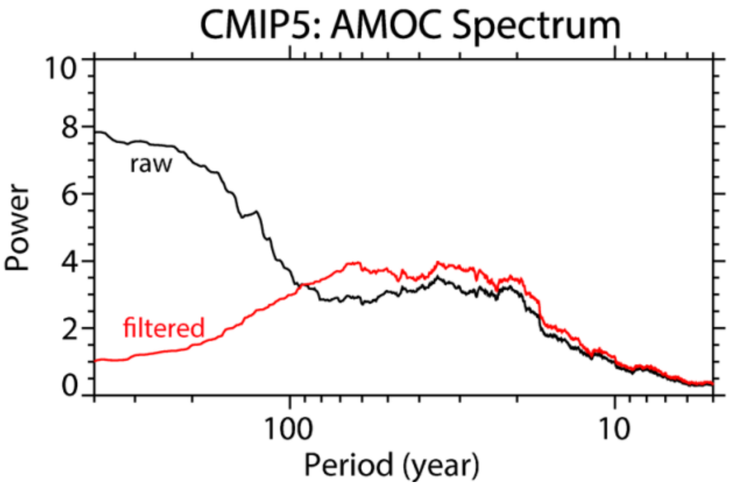


Power Spectra



CMIP5 Control Runs

- CMIP5
  - 18 models (≥ 500 years)
  - normalize and concatenate AMOC
  - ca. 50% high-top models
  - 12,944 years



Stratosphere

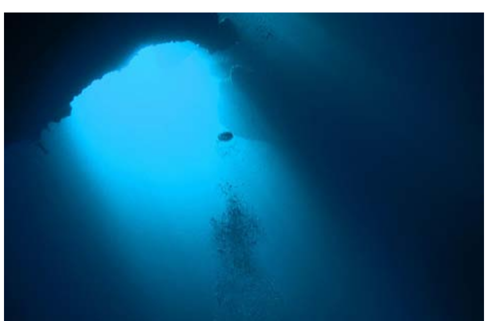
Stratospheric Sudden Warmings (SSWs)

Troposphere

Northern Annular Mode (NAM)

Ocean Surface

North Atlantic Oscillation (NAO)



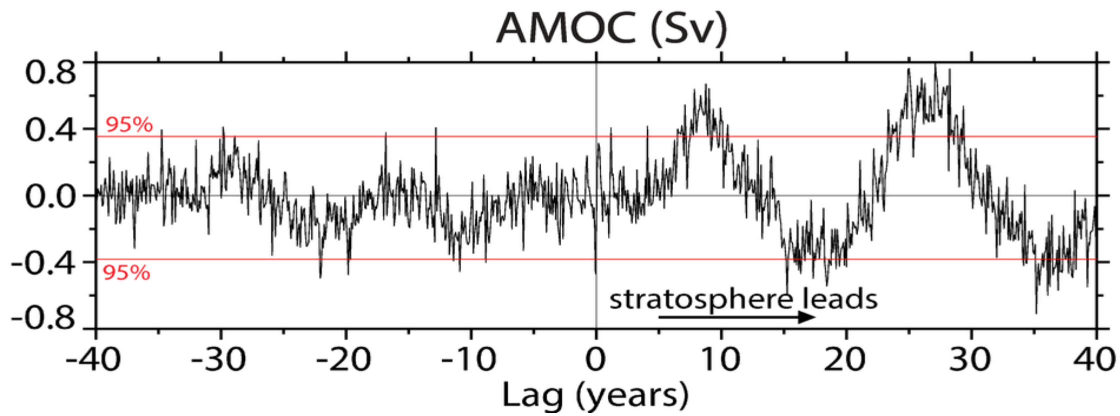
Deep Ocean

Atlantic Meridional Overturning Circulation (AMOC)

AMOC

CM2.1

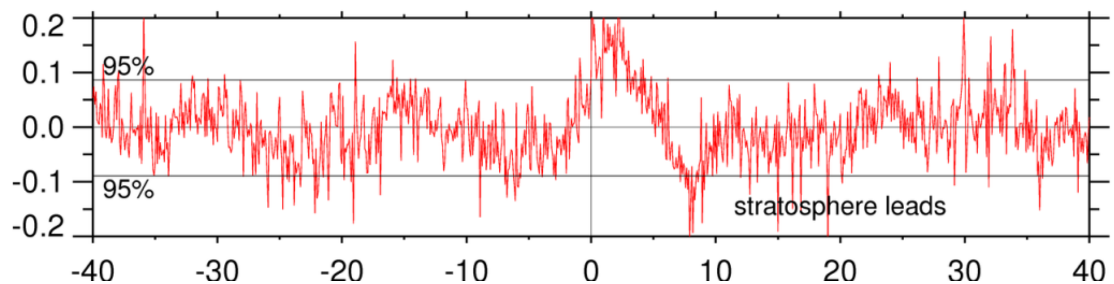
50 strong and 46 weak events



CMIP5 – HIGH

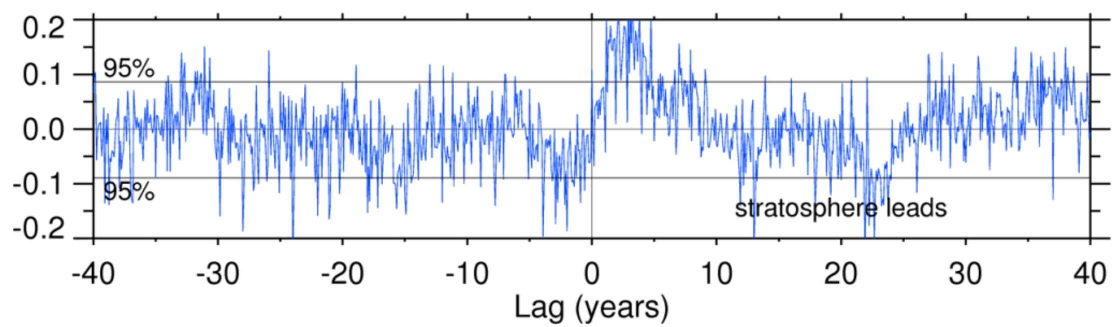
143 strong and 144 weak events

Standardized AMOC



CMIP5 – LOW

127 strong and 133 weak events



Proposed Mechanism

Vortex events may trigger AMOC oscillations

strong vortex

+NAO

+wind stress

-SST

+density

+downwelling

+AMOC

τ~20yrs

-AMOC

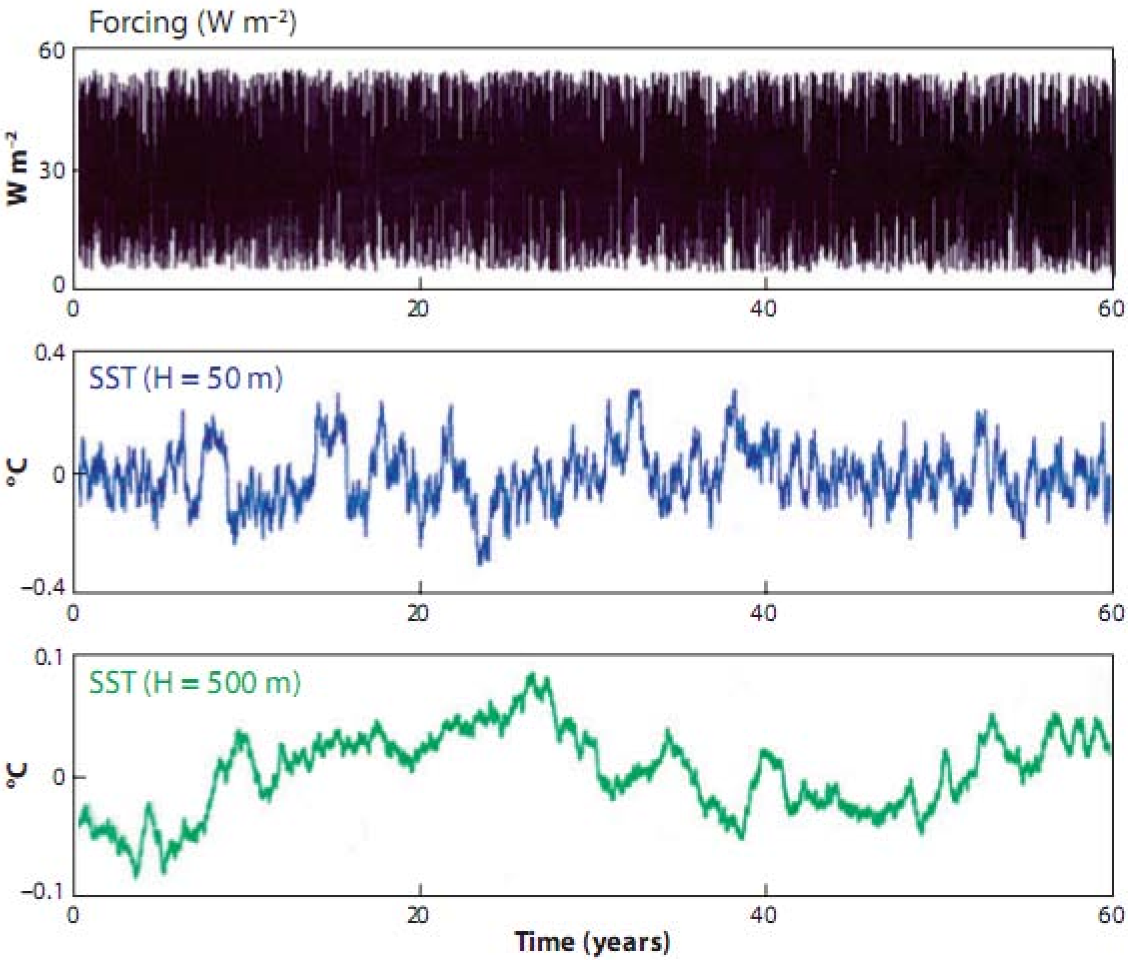
-downwelling

-density

+SST

AMOC is intrinsically unstable; self-sustained oscillations

Stochastic Climate Model Paradigm



Atmosphere

Random atmospheric heat flux forcing (white noise)

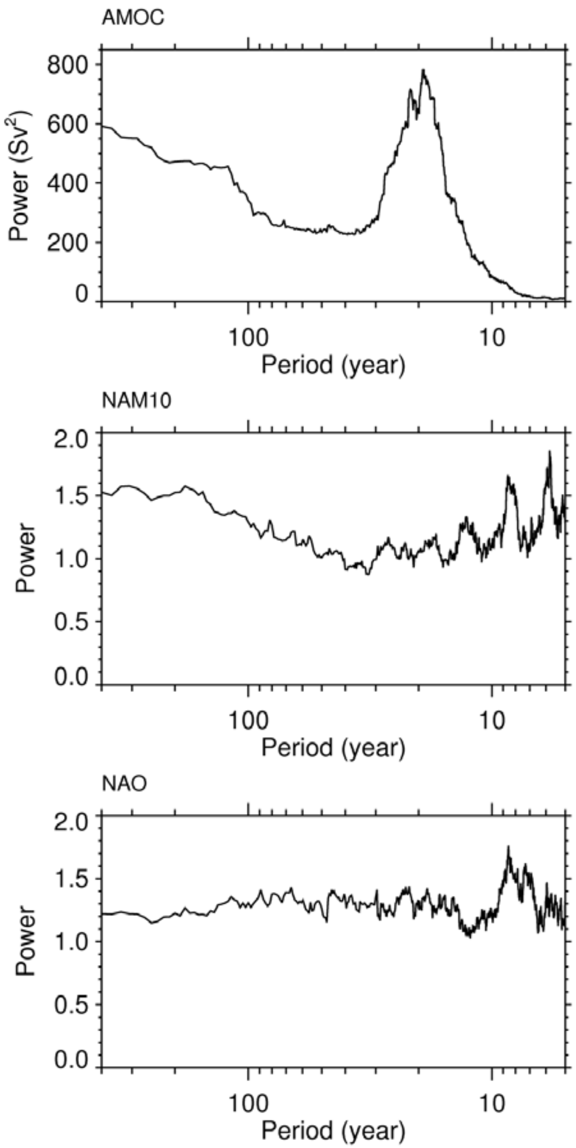
Ocean

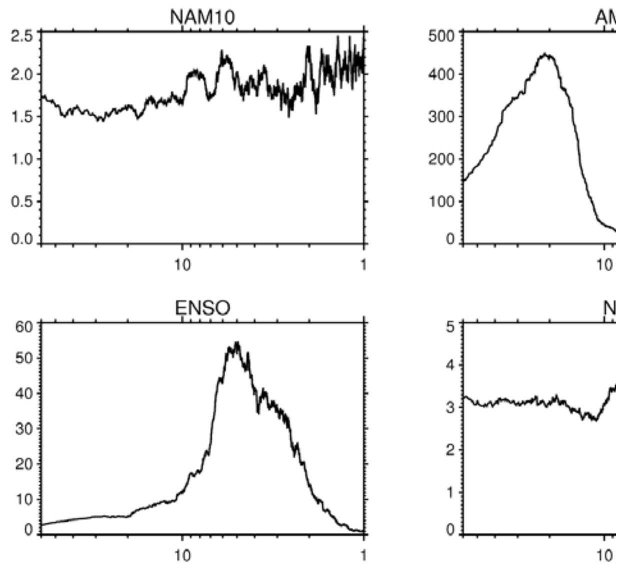
The mixed layer temperature response (red noise)

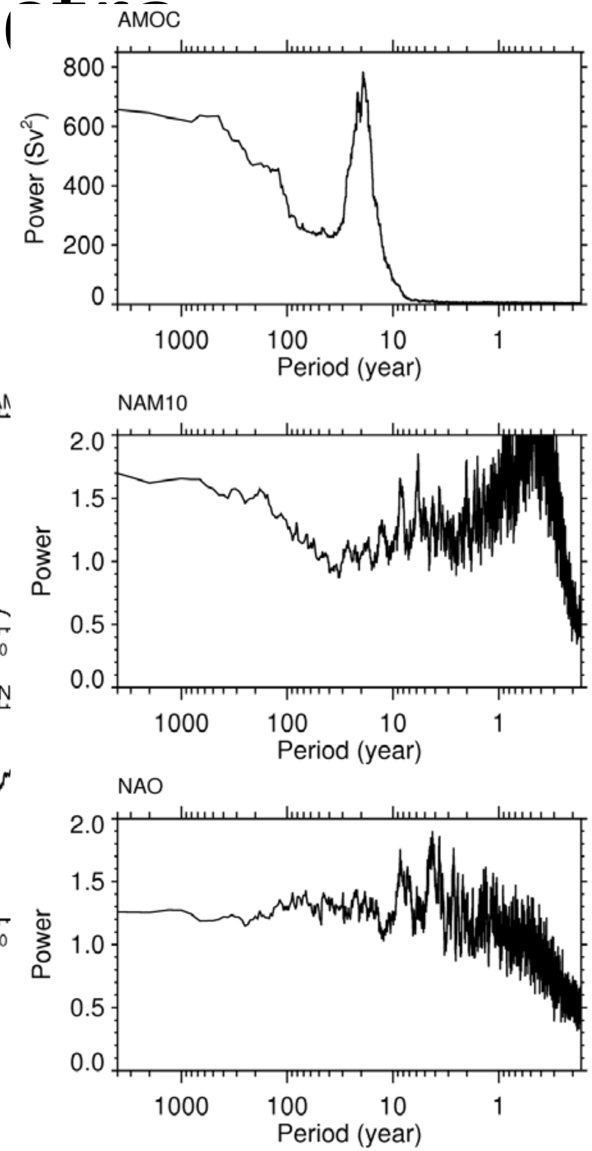
Slow variations induced by random (e.g., unpredictable) atmospheric forcing simply due to thermal inertia associated with a deep mixed layer

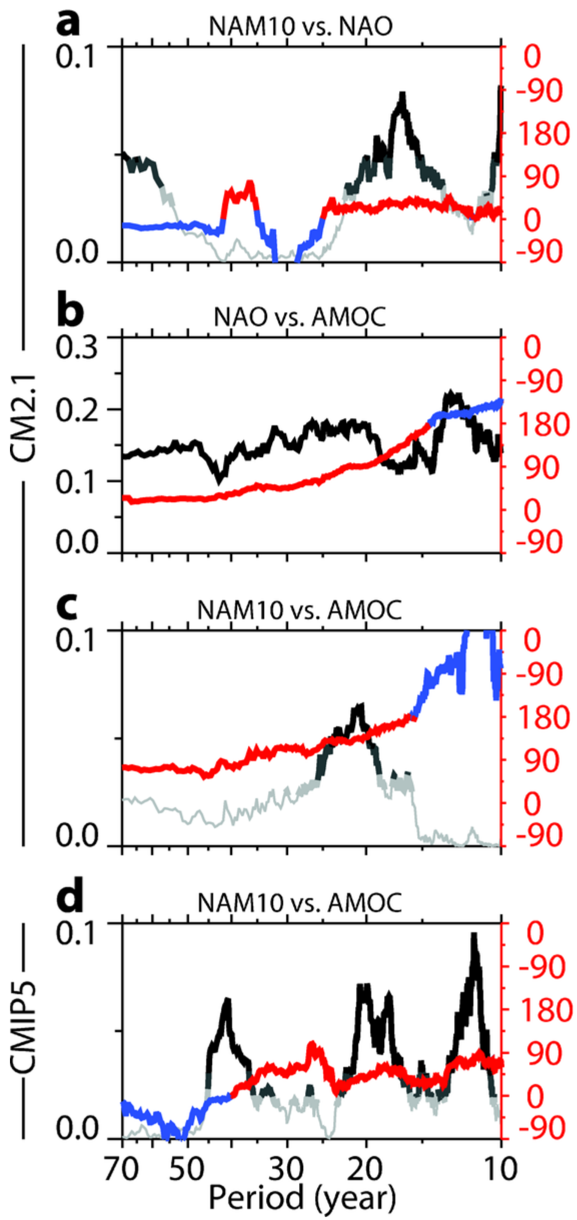
Deser et al., *Annu. Rev. Mar. Sci.* 2010

CM2.1 Power Spectra



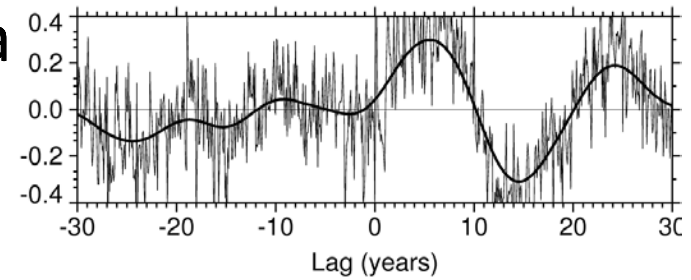




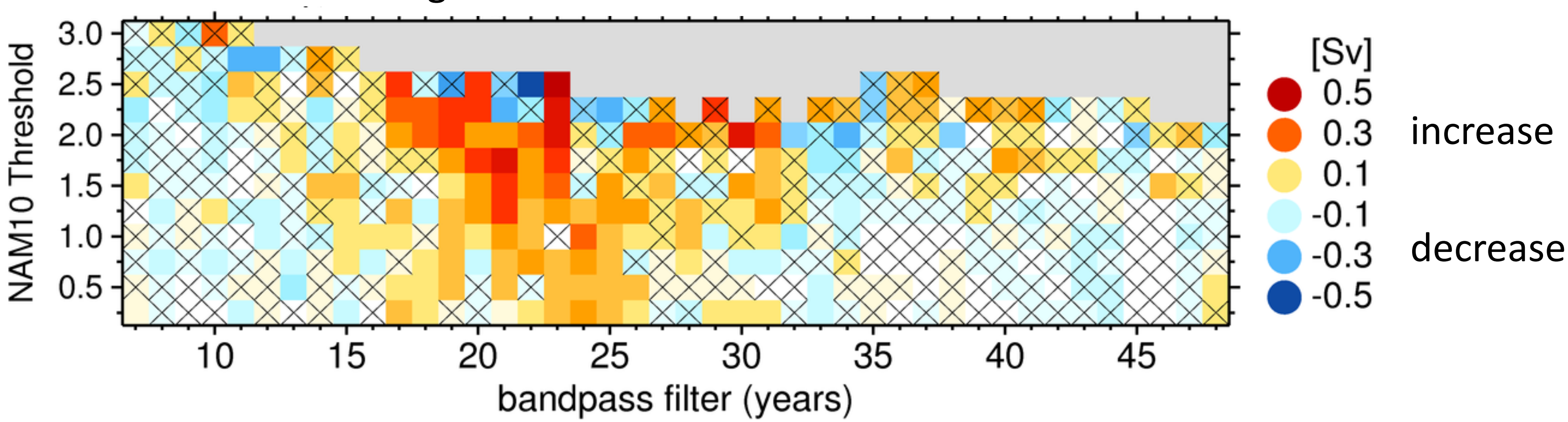

a
NAM10 vs. NAO
0.1
0.0
0
-90
180
90
0
-90
b
NAO vs. AMOC
0.3
0.2
0.1
0.0
c
NAM10 vs. AMOC
d
NAM10 vs. AMOC
CM2.1
CMIP5
70
50
30
20
10
Period (year)

What Controls AMOC Response?

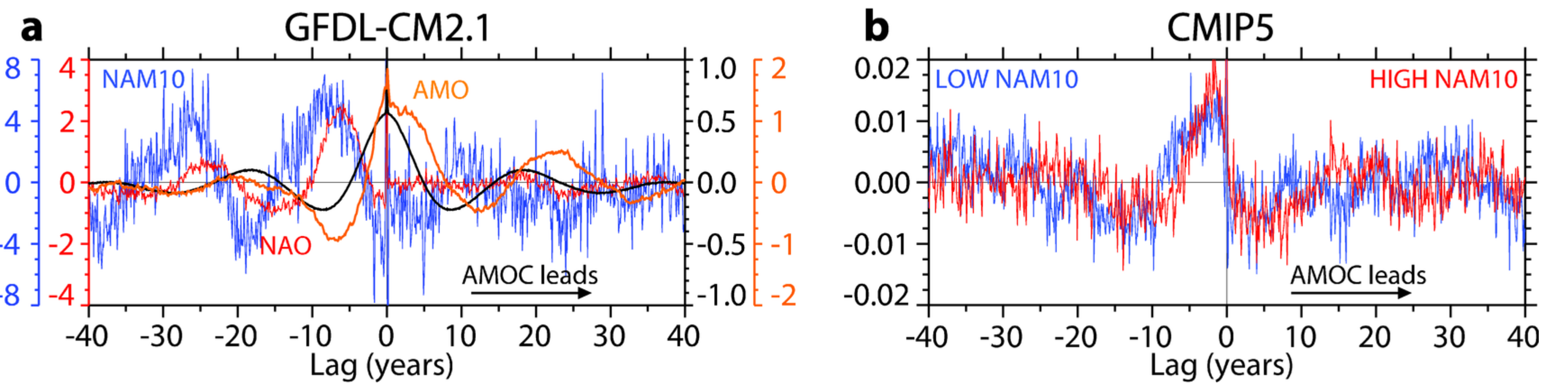
- Examine different NAM10 criteria
  - increasing strength: 0.25 … 3 SDEV
  - at discrete periods: 7 … 48 years

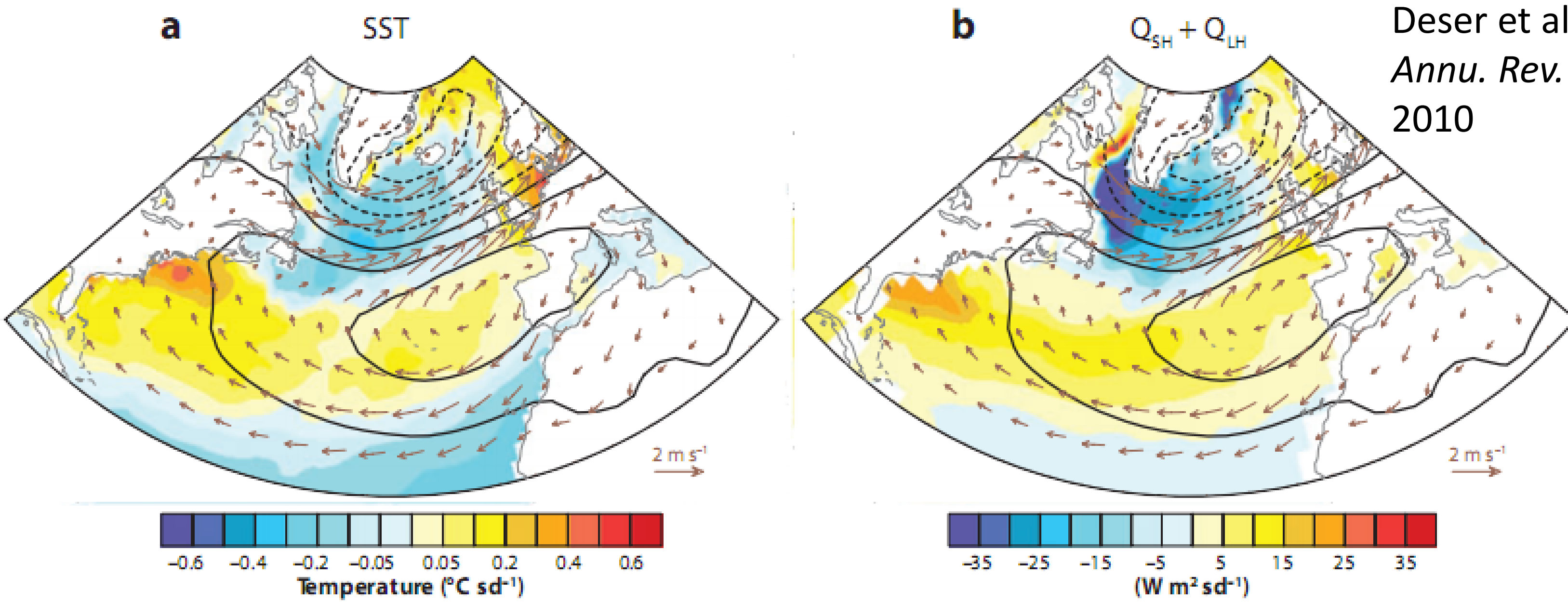


Change in AMOC variance: after - before



- As expected, strong NAM10 variations with power at intrinsic AMOC frequency (~20 years) are most capable of driving AMOC

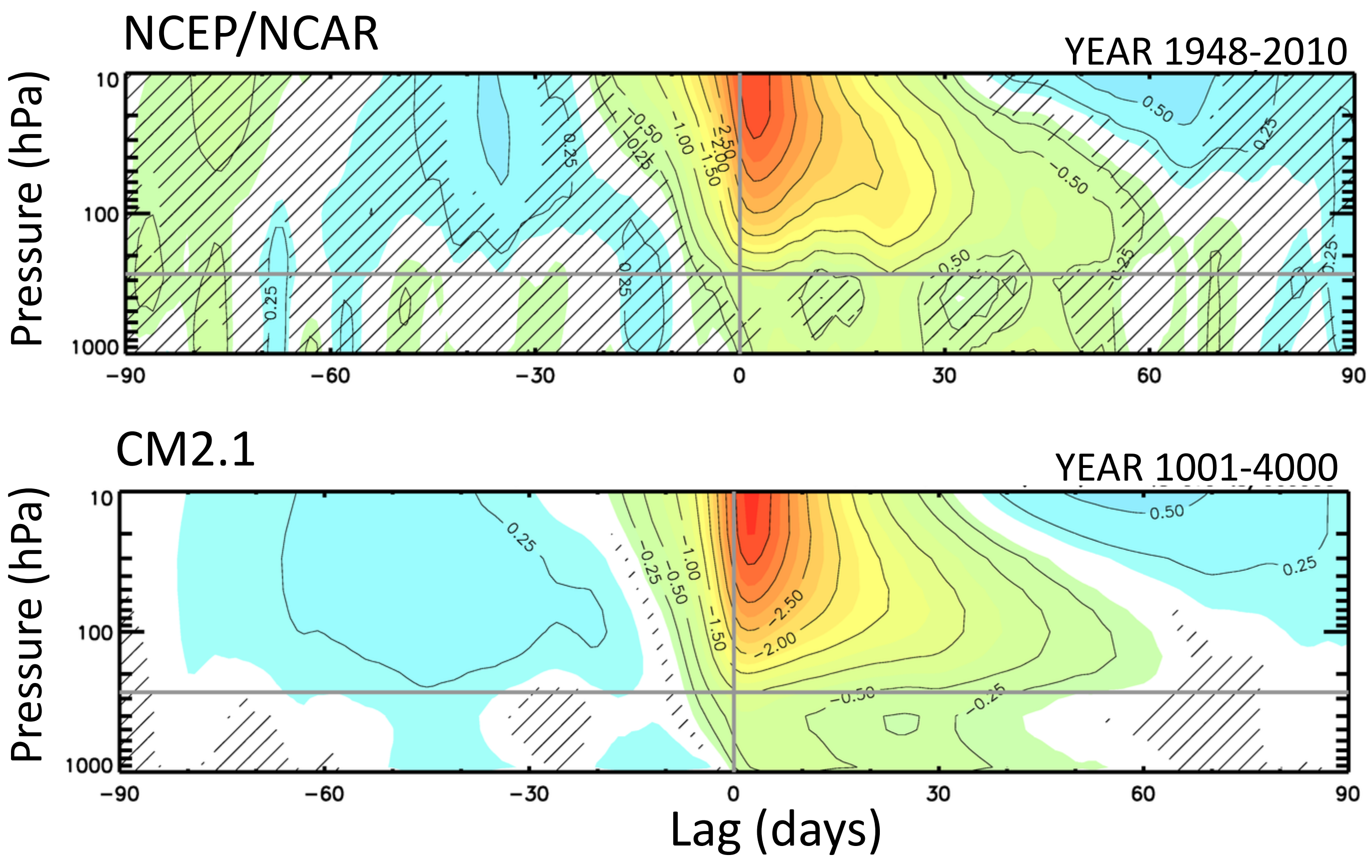

a
GFDL-CM2.1
NAM10
NAO
AMO
AMOC leads
Lag (years)
b
CMIP5
LOW NAM10
HIGH NAM10
AMOC leads
Lag (years)



Deser et al.
Annu. Rev. Mar. Sci.
2010

“Baldwin and Dunkerton” Composites

Normalized NAM at each level composited on NAM at 30 hPa ($NAM_{30} < -3$)



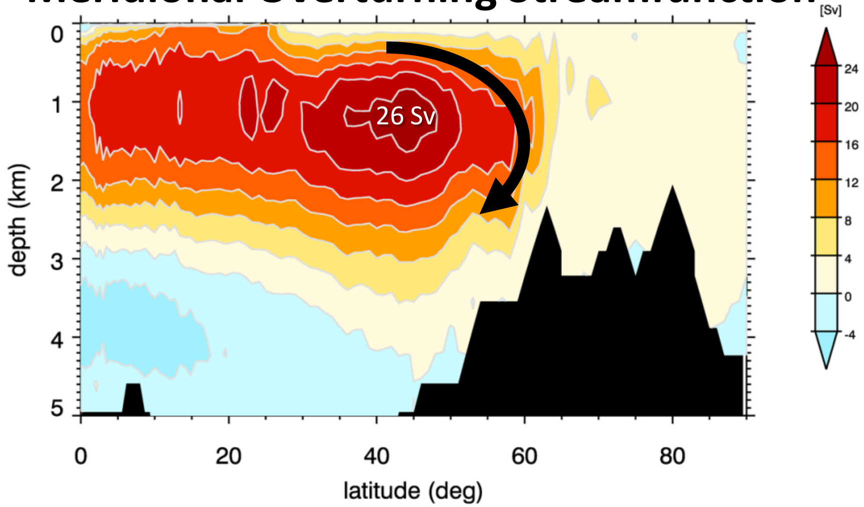
SSW events per decade

4.8

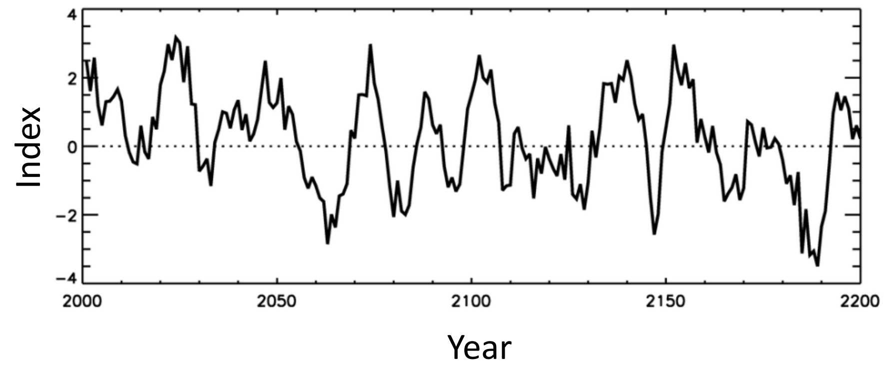
4.3

AMOC in CM2.1

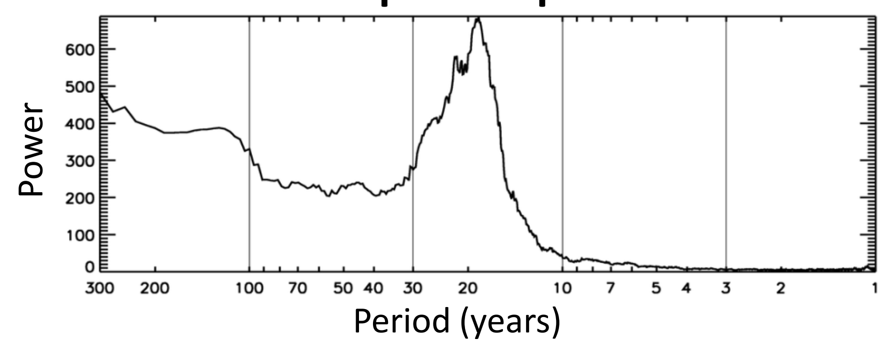
North Atlantic
Meridional Overturning Streamfunction



AMOC time series



AMOC power spectrum



CM2.1

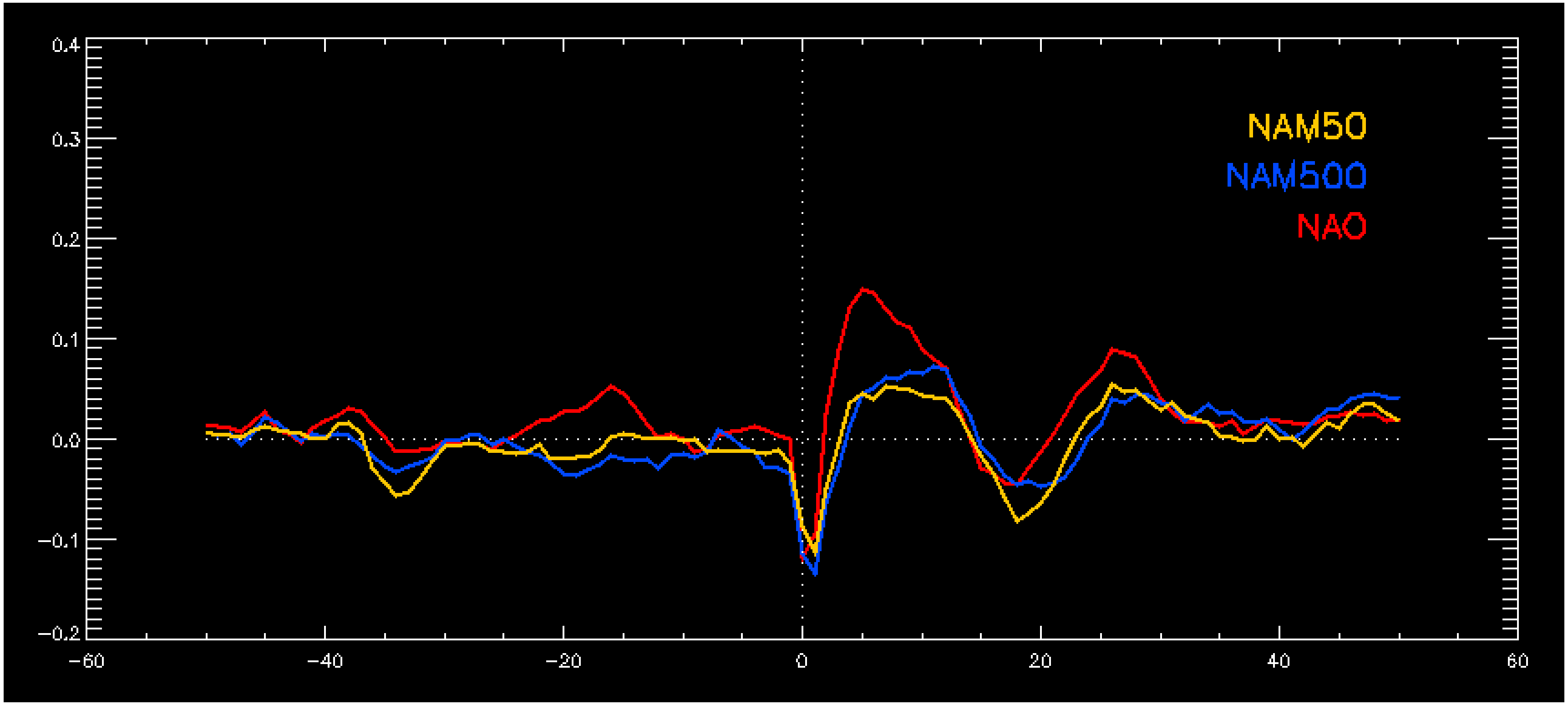
- strength: 26 Sv
- standard deviation: 1.6 Sv
- periodicity: 20 years

Observations

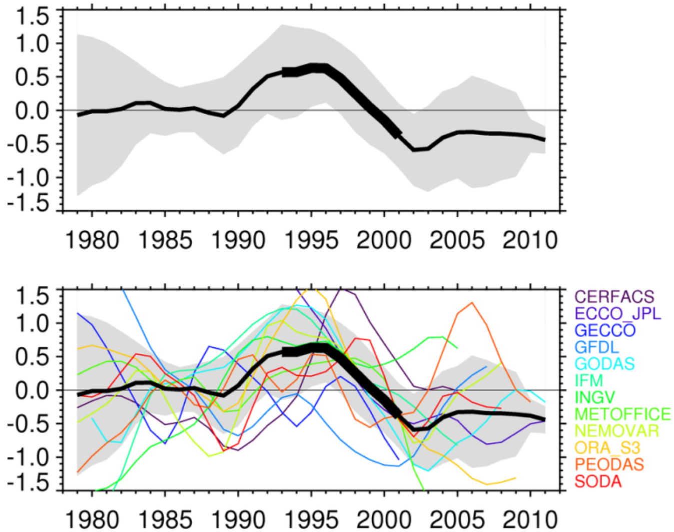
- strength: ~17 Sv
- standard deviation: ?
- periodicity: 60 years (AMO)

Cross-correlation
:NAM50 and NNA-SST (yellow)
:NAM500 and NNA-SST (blue)
:NAO and NNA-SST (red)

Solid: Annual (DJFM)

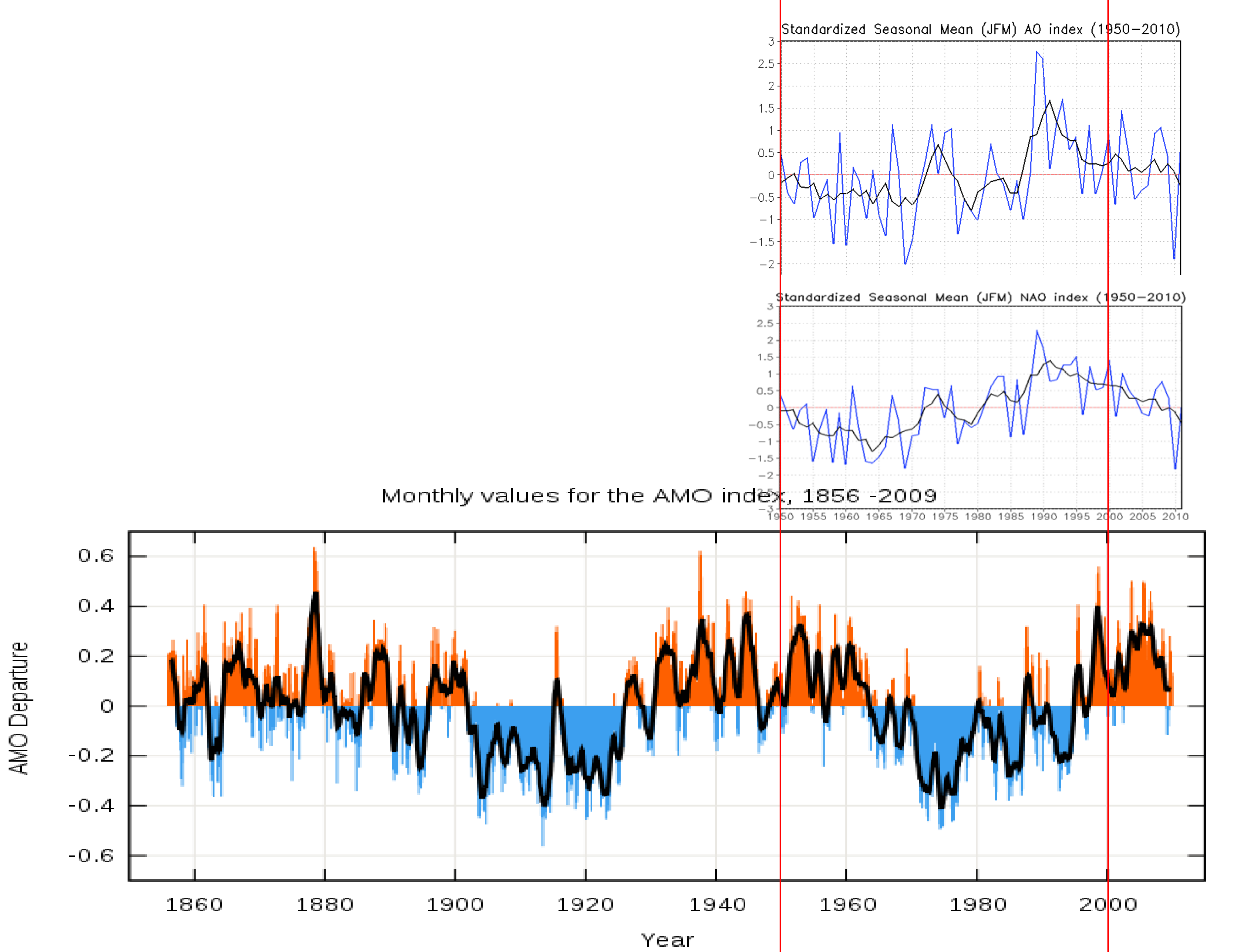


Lag (years)

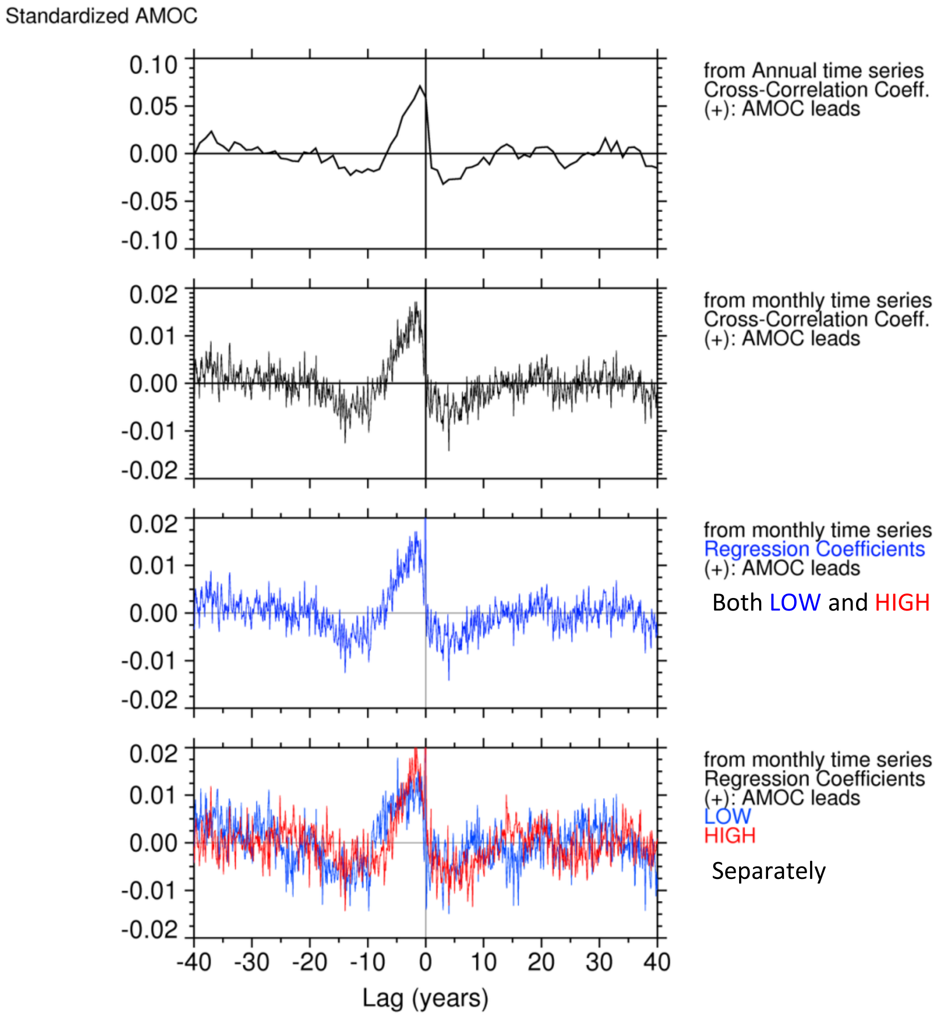


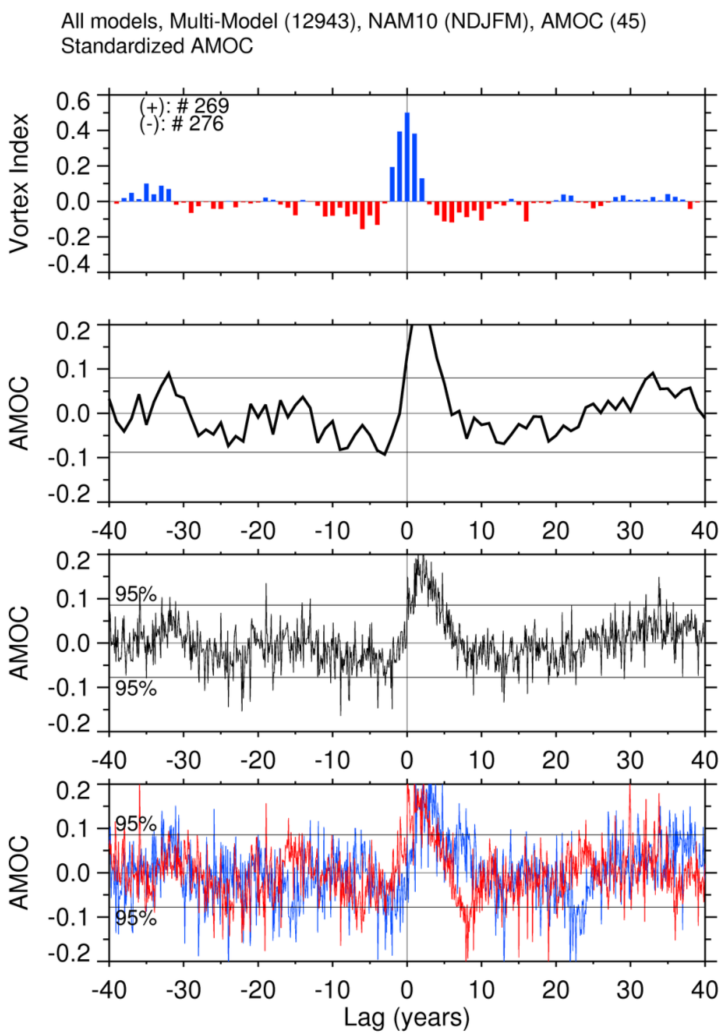
thick black: x1

FWHM= 3 years



Standardized Seasonal Mean (JFM) AO index (1950–2010)
Standardized Seasonal Mean (JFM) NAO index (1950–2010)
1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010
Monthly values for the AMO index, 1856 -2009
AMO Departure
Year
1860 1880 1900 1920 1940 1960 1980 2000


Standardized AMOC
0.10
0.05
0.00
-0.05
-0.10
from Annual time series
Cross-Correlation Coeff.
(+): AMOC leads
0.02
0.01
0.00
-0.01
-0.02
from monthly time series
Cross-Correlation Coeff.
(+): AMOC leads
from monthly time series
Regression Coefficients
(+): AMOC leads
Both LOW and HIGH
from monthly time series
Regression Coefficients
(+): AMOC leads
LOW
HIGH
Separately
-40 -30 -20 -10 0 10 20 30 40
Lag (years)



All models, Multi-Model (12943), NAM10 (NDJFM), AMOC (45)
Standardized AMOC
(+): # 269
(-): # 276
Vortex Index
AMOC
95%
Lag (years)