# AMOC Variability and Abrupt Change in the Future


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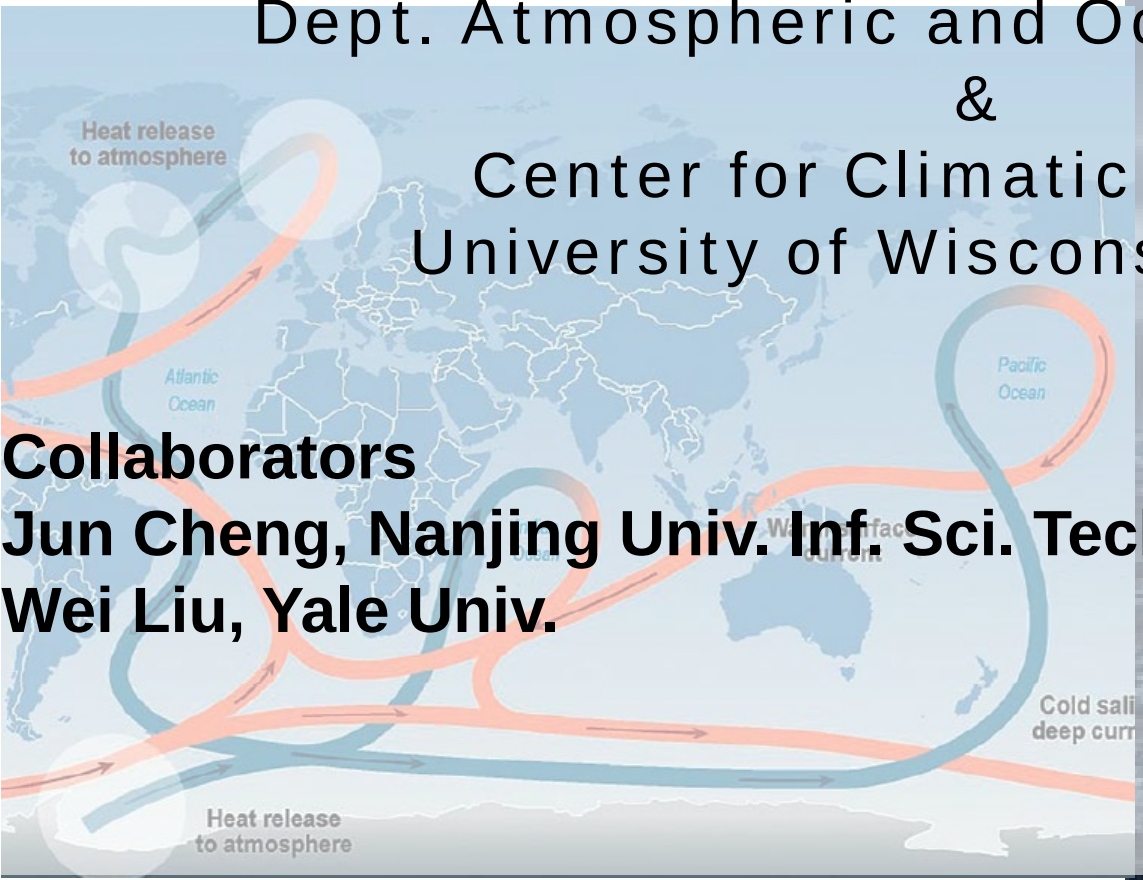




**Collaborators**
**Jun Cheng, Nanjing Univ. Inf. Sci. Tech.**
**Wei Liu, Yale Univ.**

1. How does AMOC interdecadal variability change under global warming?

Weaker and Shorter,

**Cheng et al., 2016, PNAS**

2. Will AMOC collapse under global warming?

More likely than predicted by IPCC,

**Liu et al., 2017, AS, 2014, JC**

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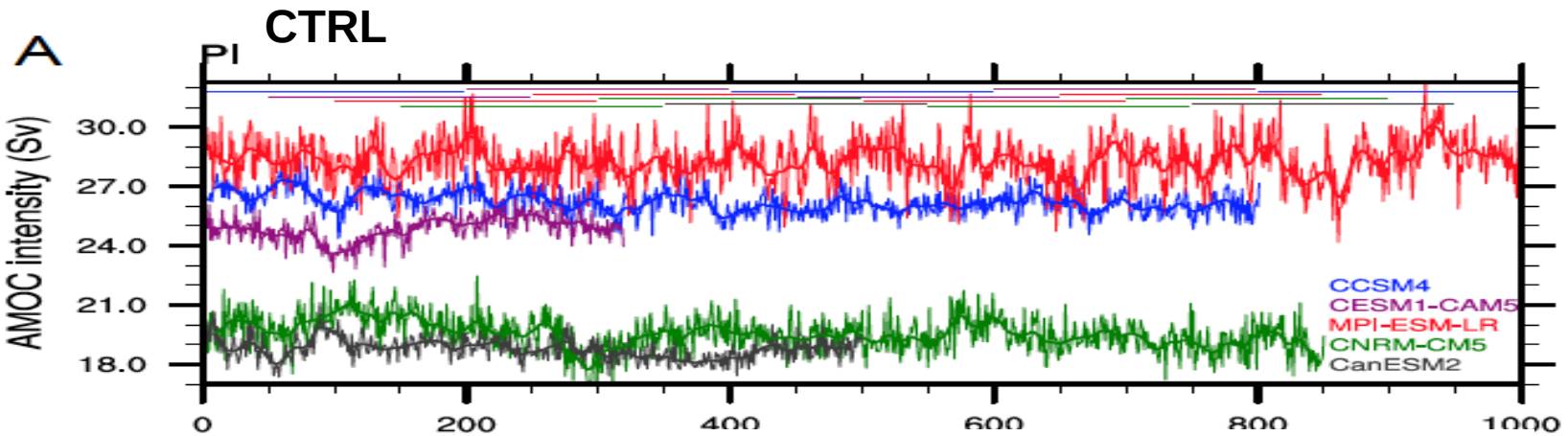
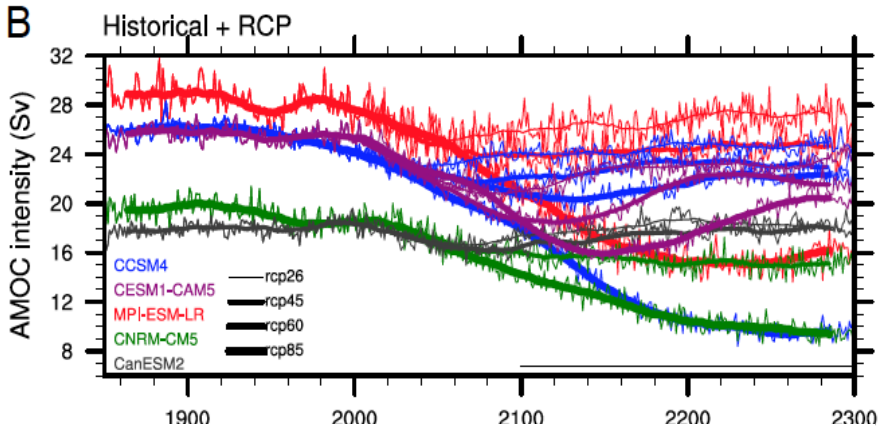
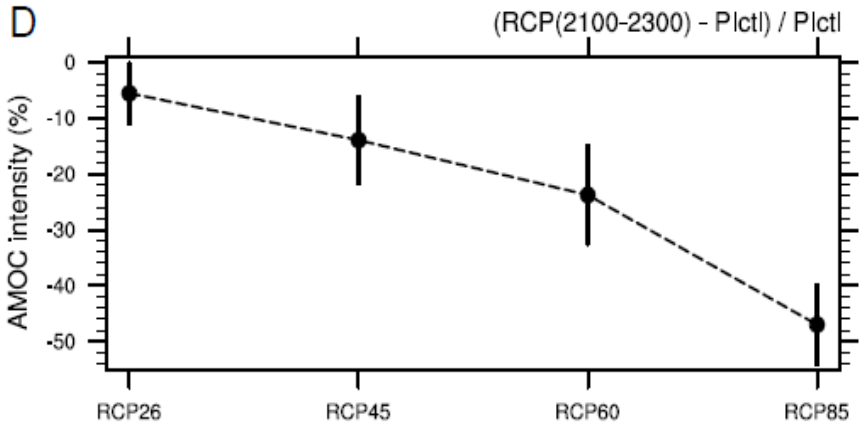
# CMIP5 Long Simulations




**Hist+RCP**

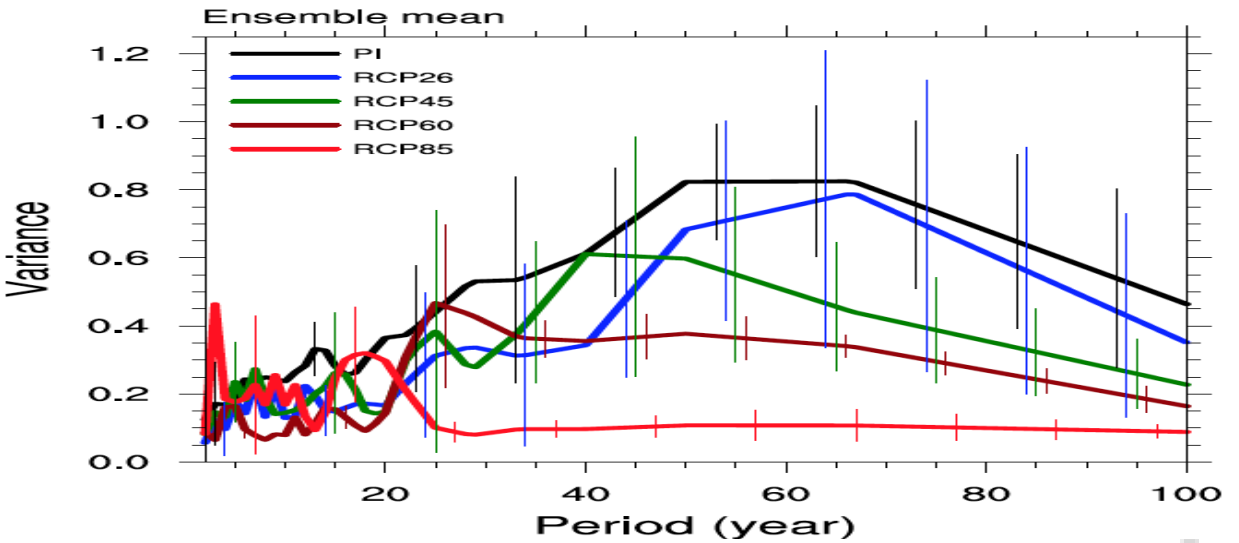



**Change of Mean AMOC**

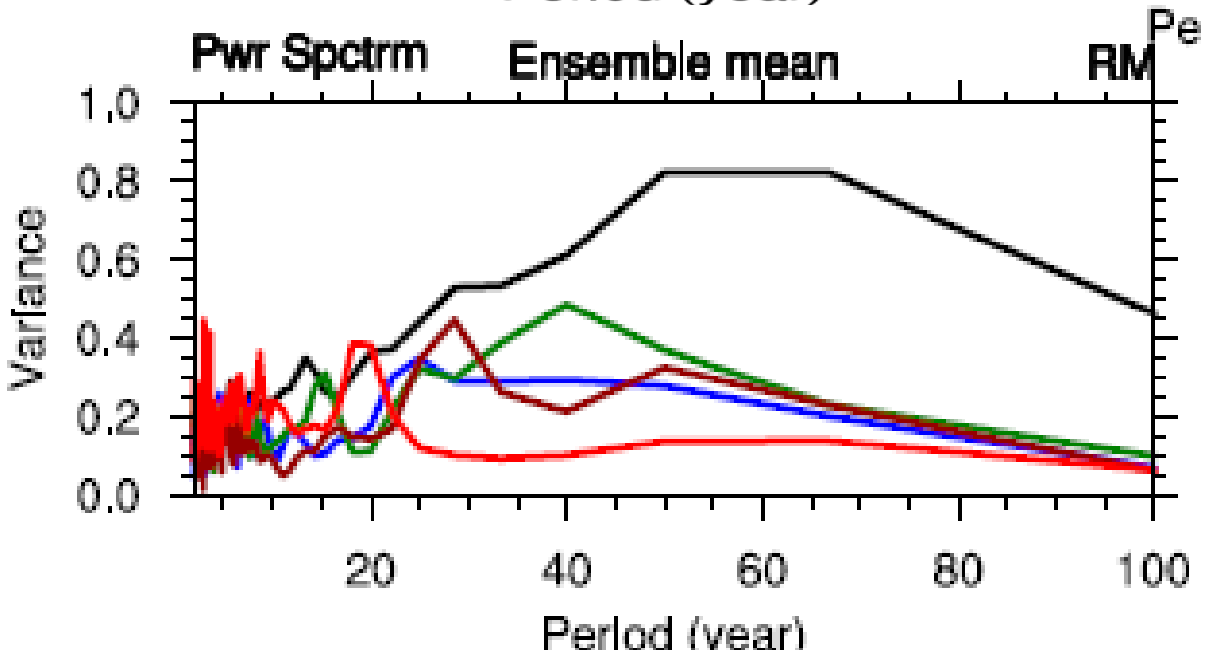


# Response of Power Spectrum to Global Warming

**Ensemble mean of the spectrum of AMOC AMV**




**Filtering 1st EMD mode**

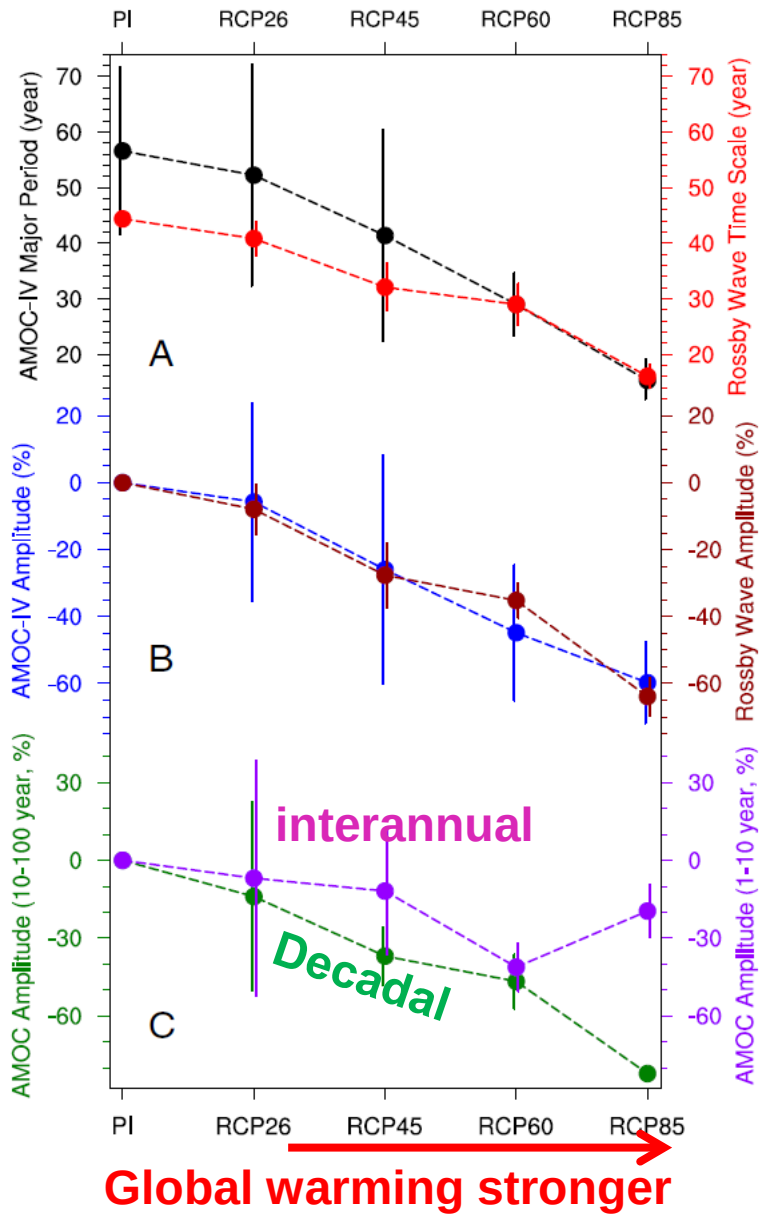



**100-yr running mean**

# Response of period and amplitude

Period

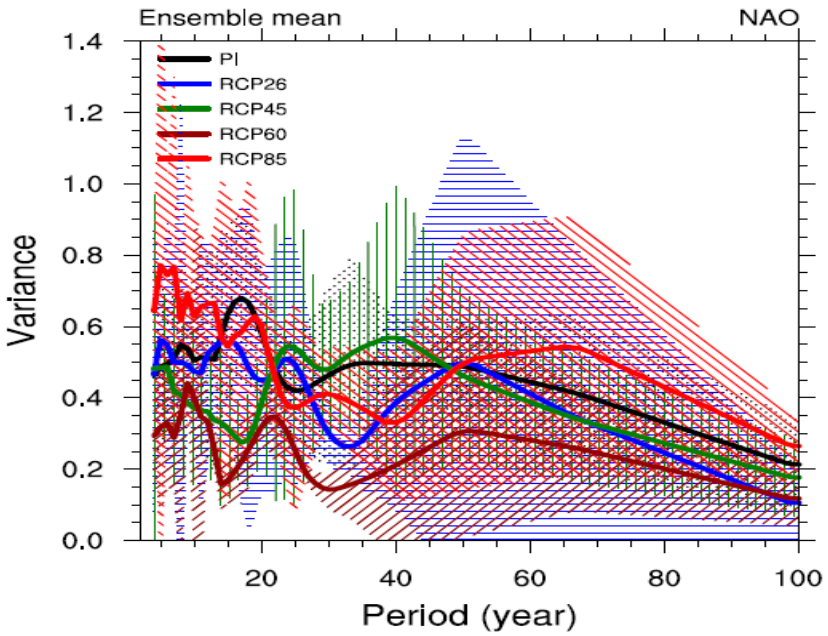
Amplitude




Faster

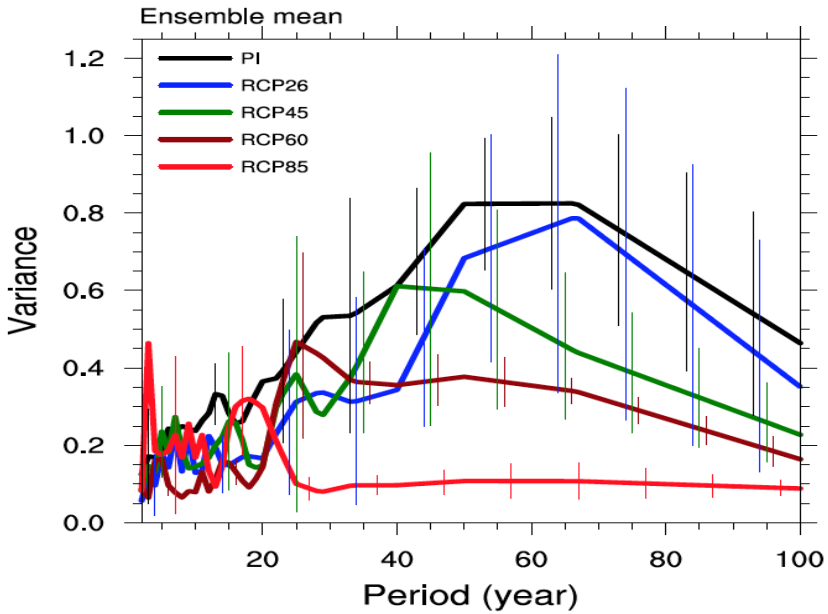
Weaker

# Response of atmosphere and AMOC




SLP

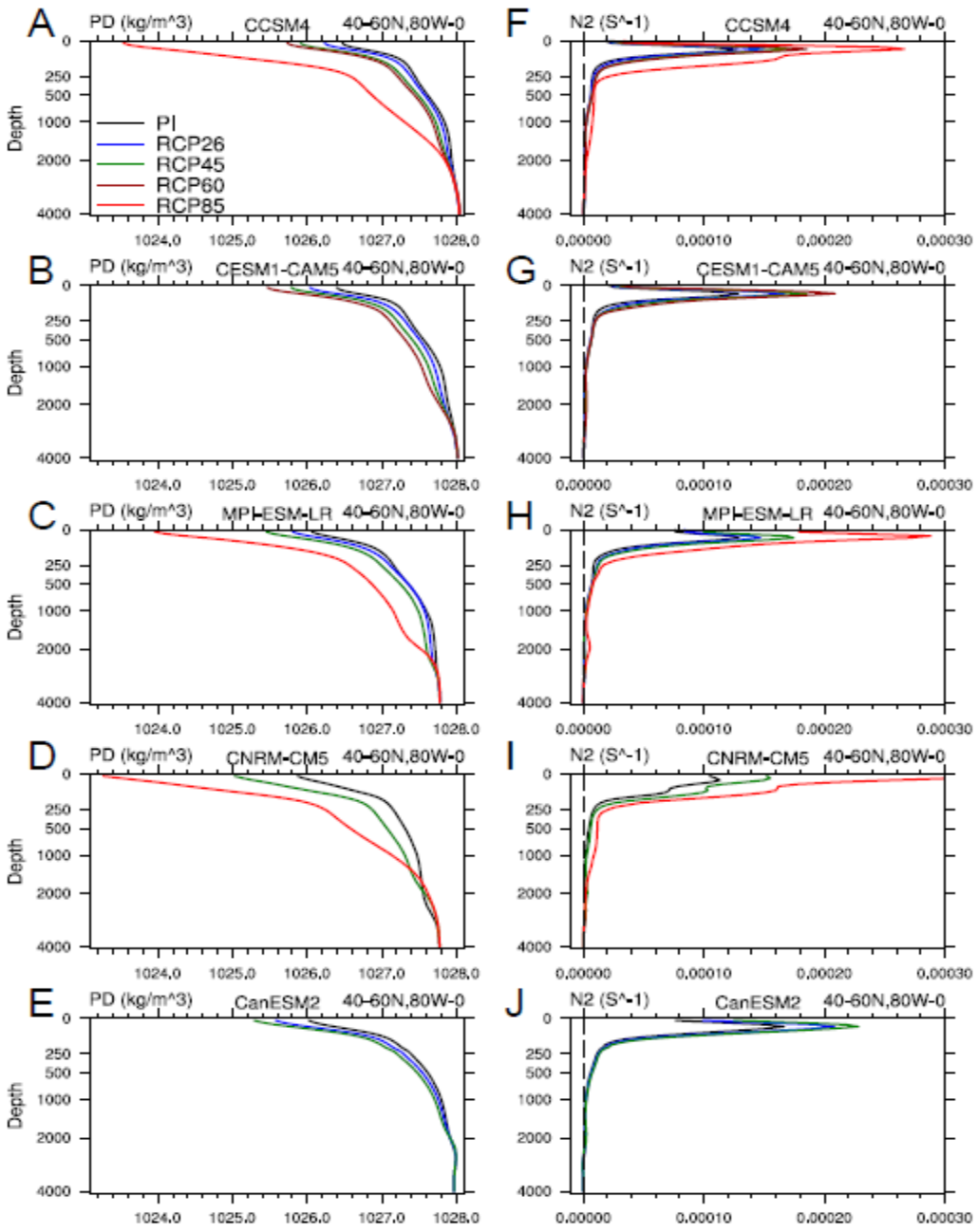
No significant change



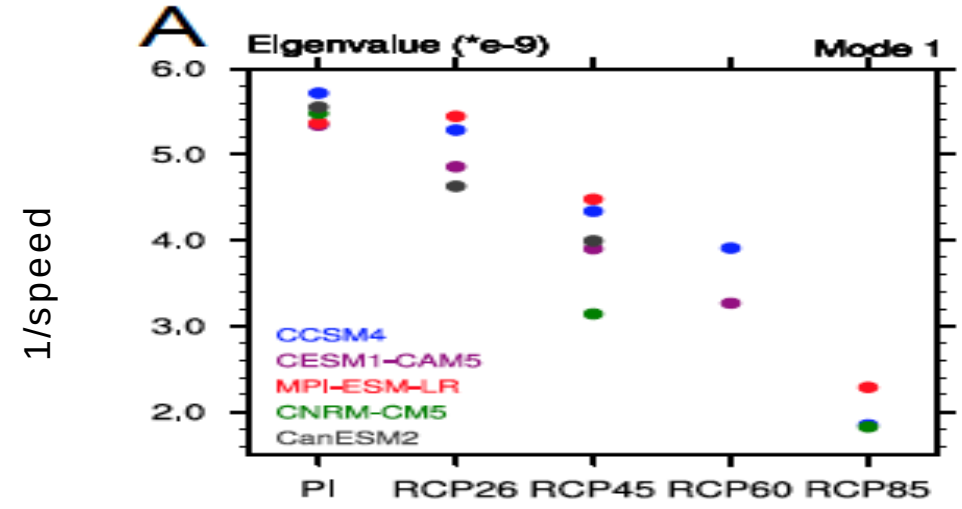

AMOC

Faster and weaker

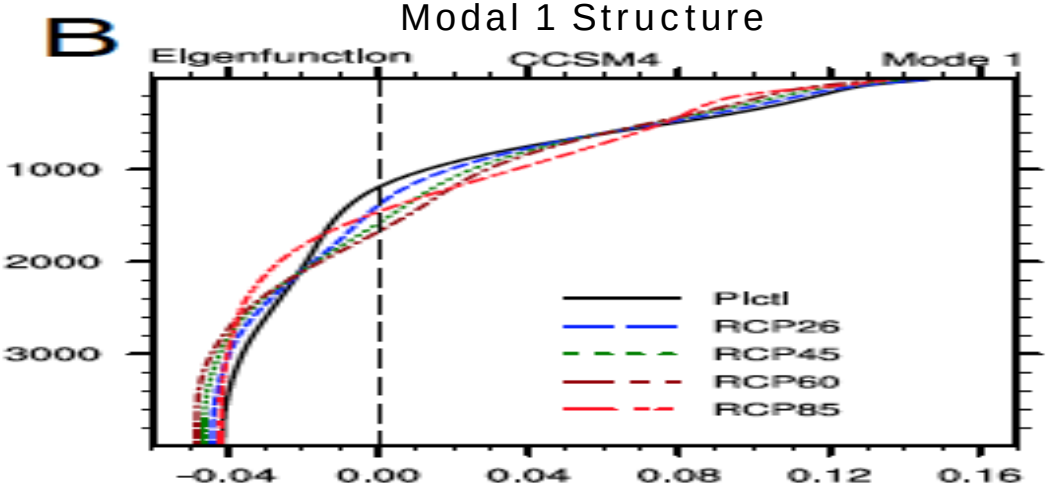
# Stronger Stratification forced by global warming



# 1st baroclinic mode



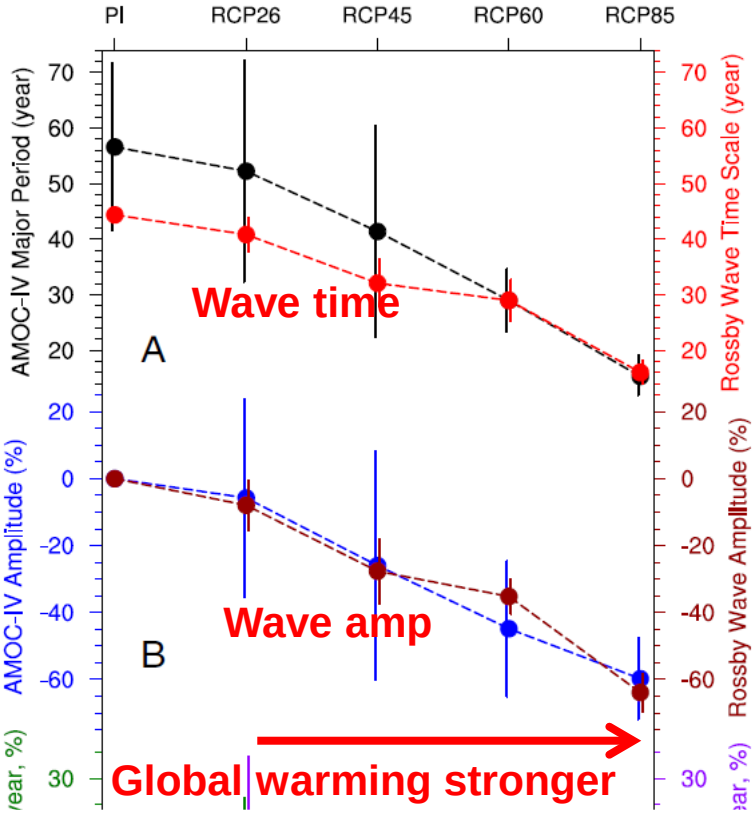

Modal 1 Structure



# The Amplitude: Rossby Wave Viewpoint

Period

Amplitude




Faster

Weaker

$$\partial_t \varphi - C\partial_x \varphi = G$$

$$-C\partial_x \varphi = G$$

$$\partial_x \varphi \sim G/C$$

$$\partial_t \left[ \partial_z \left( \frac{f^2}{N^2} \partial_z \varphi \right) \right] \varphi + \beta \partial_x \varphi = \frac{curl(F)}{\rho} + \partial_z \left( \frac{f \rho Q}{N^2} \right)$$

$$\beta \partial_x \varphi = \frac{curl(F)}{\rho} + \partial_z \left( \frac{f \rho Q}{N^2} \right)$$

Q forcing? Subpolar?

Thermal Rossby? Non-Doppler?

# The Amplitude: Delayed Oscillator Viewpoint

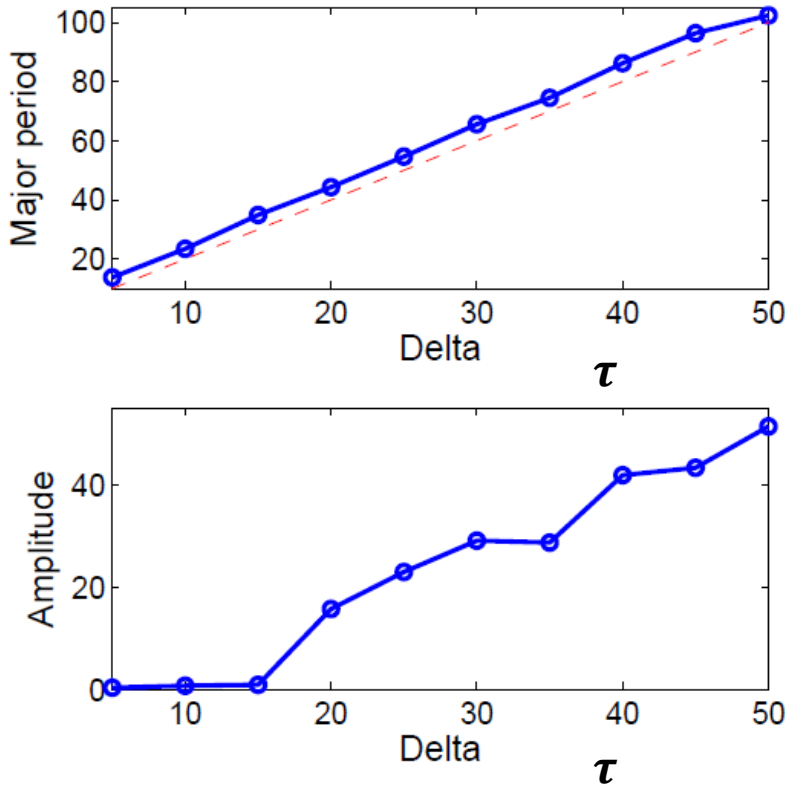



**Fig. S11.** Changes of major period and amplitude of circulation with respect to different delay times in a four-box ocean model with white noise forcing (34).

$$\partial_t M = aM(t) - bM(t-\tau) - \varepsilon M^3 + W(t)$$

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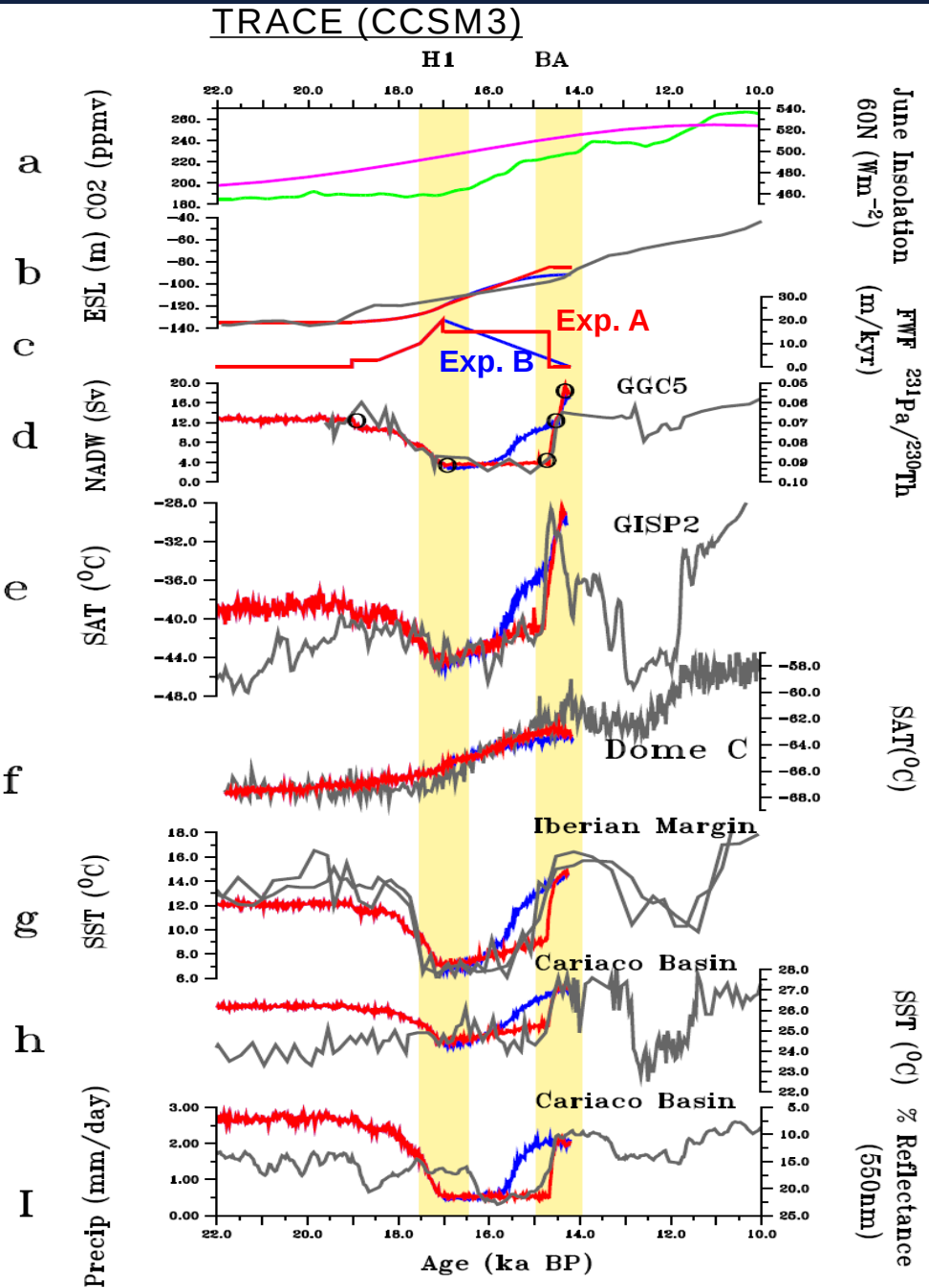
2. Will AMOC collapse under global warming?

More likely than predicted by IPCC,

**Liu et al., 2017, AS, 2014, JC**

# AMOC Instability or Ice Sheet Instability?




Is AMOC bistable in real world:

Paleo obs:

meltwater chronology ?

Liu et al., 2009, Sci

# Thermohaline Instability and Abrupt Climate Change
## A Historical Perspective

1960 1980 1990 2000 2010

**Theory**

**Stommel**
Box Model

**Bryan**
OGCM

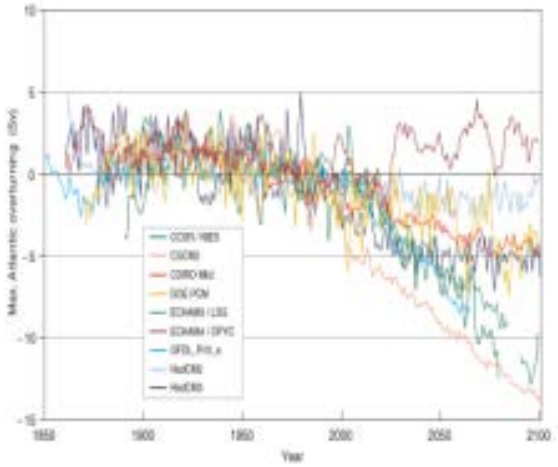
**Manabe**
**Stouffer**
CGCM+**ADJ**

**Rahmstorf**
Propose
Fov

**IPCC 3,4..**
CGCM
2CO2
Hosing
**No ADJ**

**DeVries**
**Weber**
Test
Fov

**Liu**
Mov
**ADJ(?)**



**Obs**

**Ice core**
Abrupt Change

**Broecker**
AMOC role

**AMOC instability**

**Instability criterion**

**Stable AMOC**

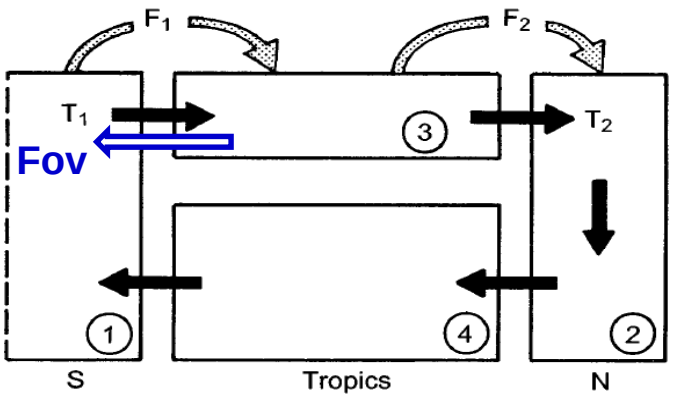
?

**CGCM too stable**

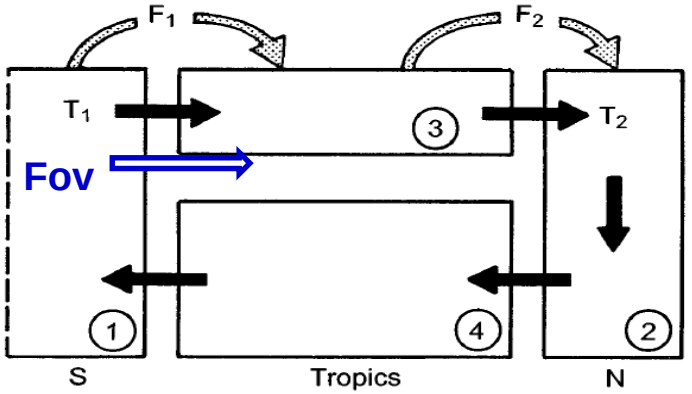
# Thermohaline instability and abrupt climate change

**Fov: Freshwater transport by AMOC (overturning)**

**Bi-stable**




**Mono-stable**

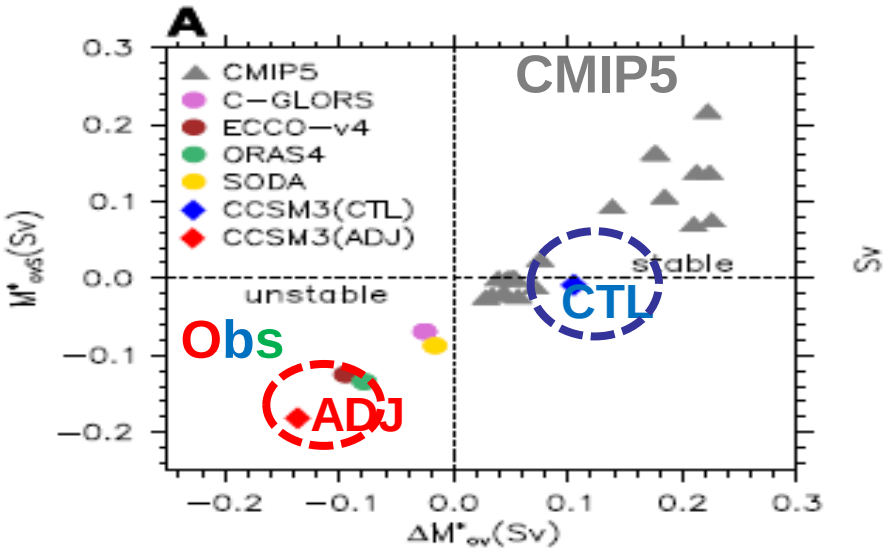



Rahmstorf, 1996

**Observation**

**State of Art Models**

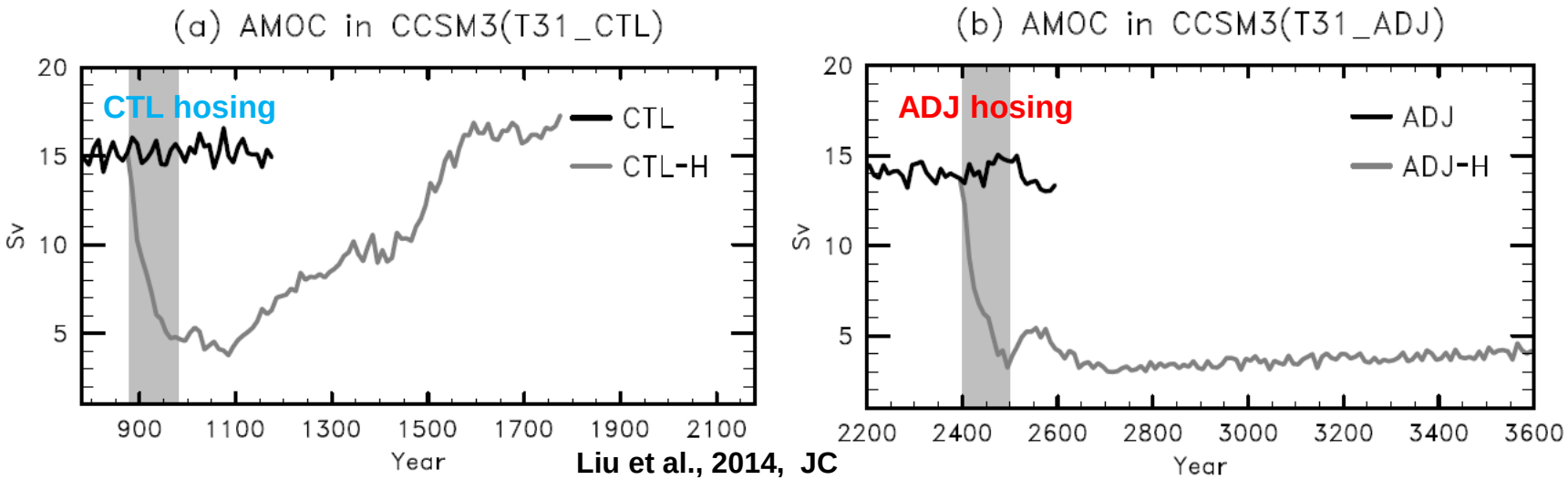
Fov




**Mov=FovS-FovN**

# Future AMOC Response: Before and After Bias Correction

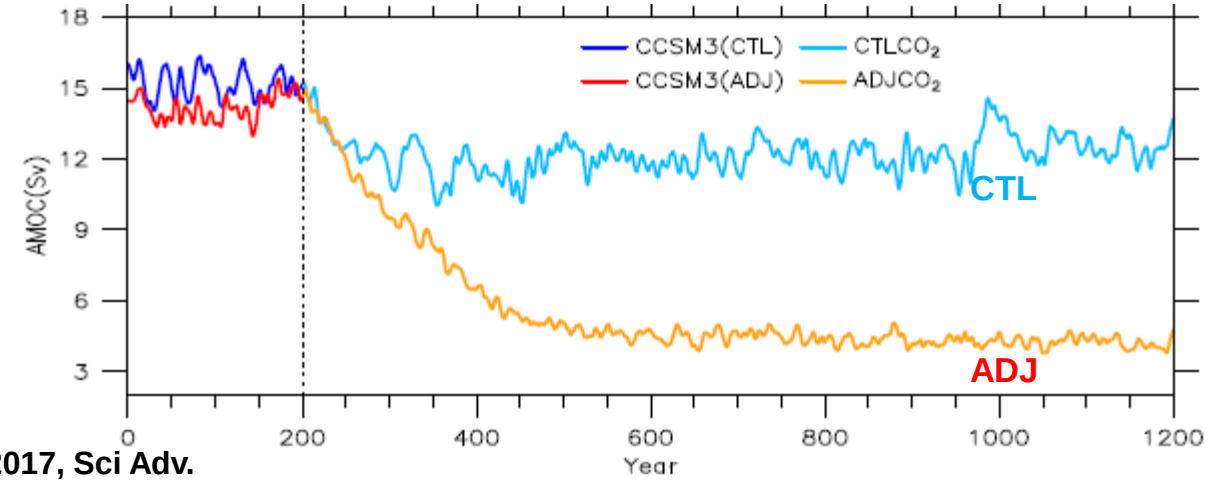
## AMOC response to North Atlantic Melting Water Pulse (such as Greenland melting)



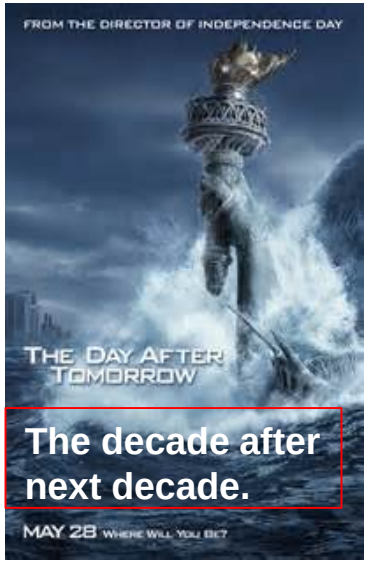

Liu et al., 2014, JC

May not be a fantasy!

## AMOC response to 2xCO2




Liu et al., 2017, Sci Adv.



# The Danger of Flux Adjustment !?

**Imperfections of the Thermohaline Circulation: Multiple Equilibria and Flux Correction***

HENK A. DIJKSTRA

*Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Utrecht, the Netherlands*

J. DAVID NEELIN

*Department of Atmospheric Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, California*

(Manuscript received 20 June 1997,

**Ocean–Atmosphere Interaction and the Tropical Climatology. Part I: The Dangers of Flux Correction**

J. DAVID NEELIN

*Department of Atmospheric Sciences, University of California Los Angeles, Los Angeles, California*

HENK A. DIJKSTRA

*Institute for Marine and Atmospheric Research Utrecht, University of Utrecht, Utrecht, the Netherlands*

(Manuscript received 8 February 1994, in final form 5 October 1994)

**Atmospheric Transports, the Thermohaline Circulation, and Flux Adjustments in a Simple Coupled Model**

JOCHEM MAROTZKE AND PETER H. STONE

*Center for Global Change Science, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts*

(Manuscript received 29 March 1994, in final form 18 October 1994)

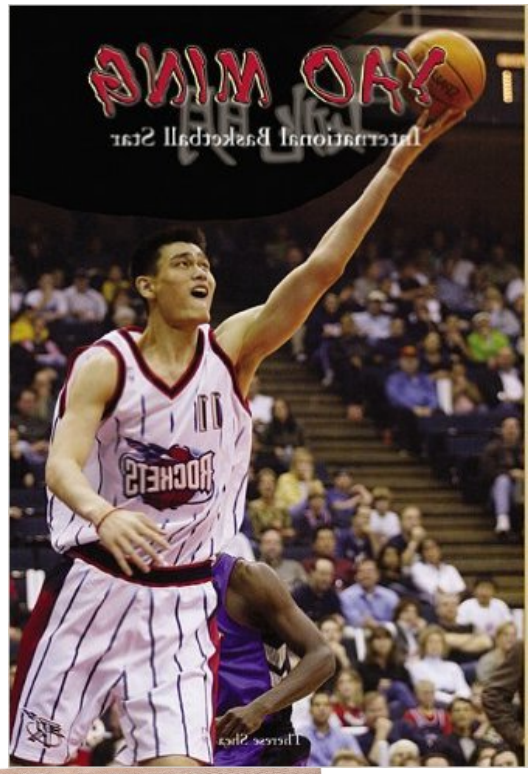
Current Options:

A: A model without flux adjustment but with the wrong AMOC stability?

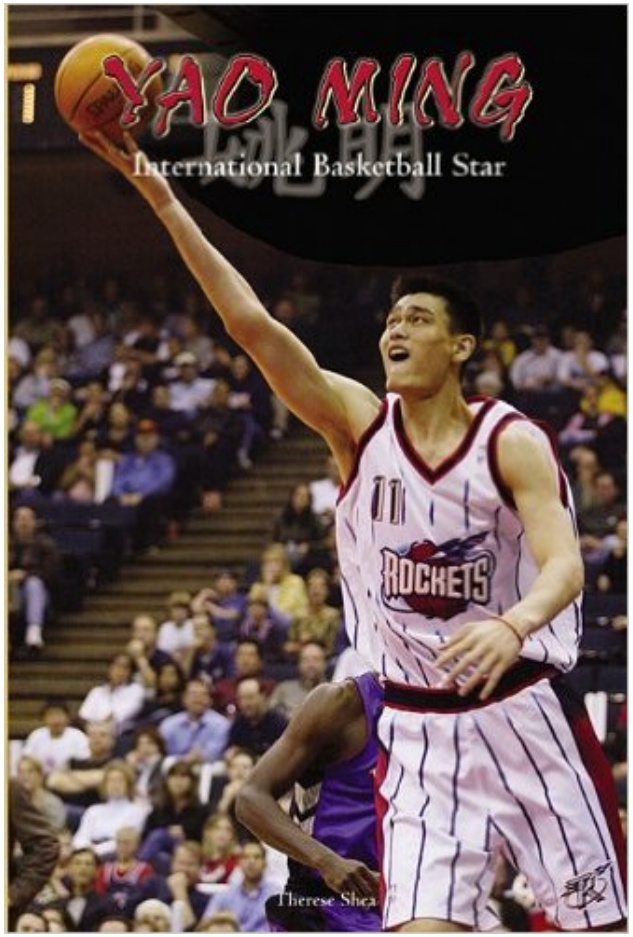
Or

B: A model with flux adjustment (and therefore related uncertainty) and a likely correct AMOC stability?

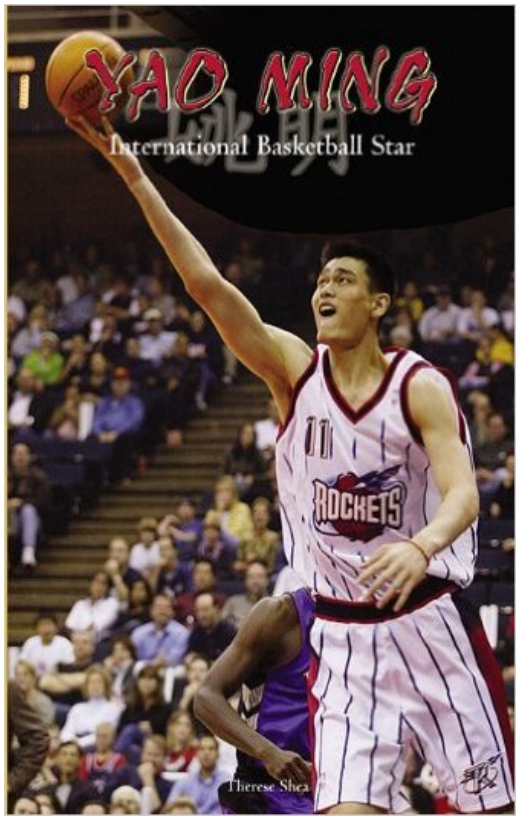
**Adjusted Model**




**Perfect Model**



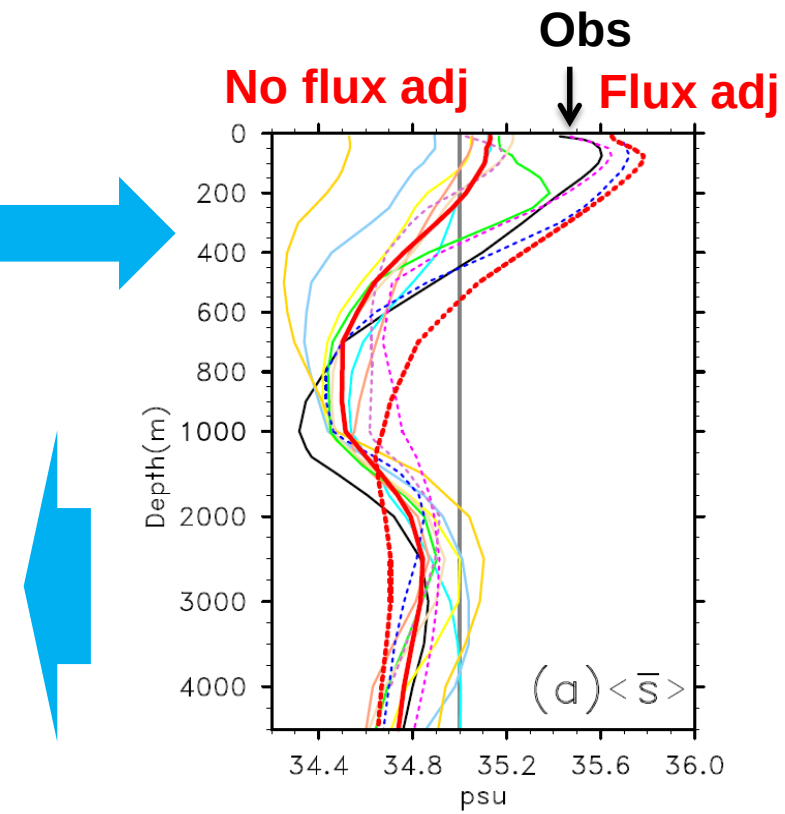

**Biased Model**




**Flux Adjustment**

# The End

# Freshwater Transport and Tropical Bias (in AR4 CGCMs)



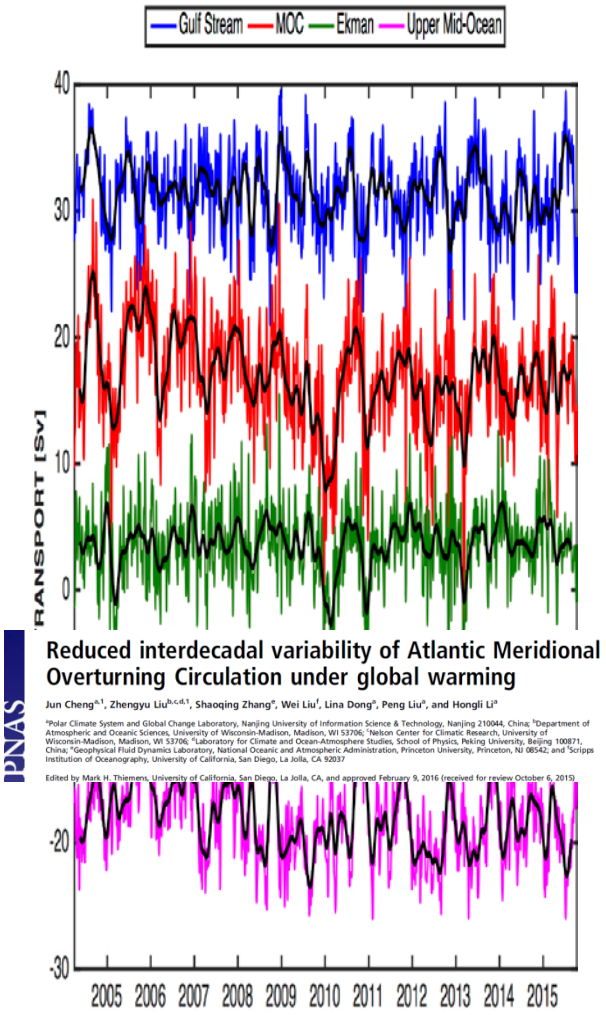

Liu et al., ,2014, JC

# Future Work....

## Future

**AmocStabilityMIP**

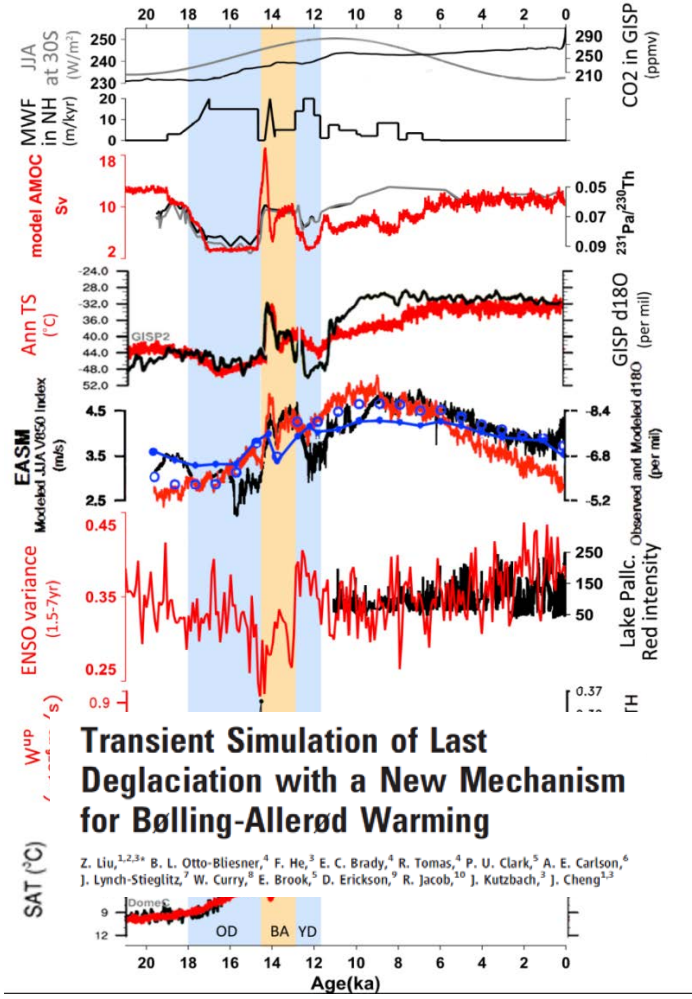

## Present




**RAPID Array 26N**

## Past

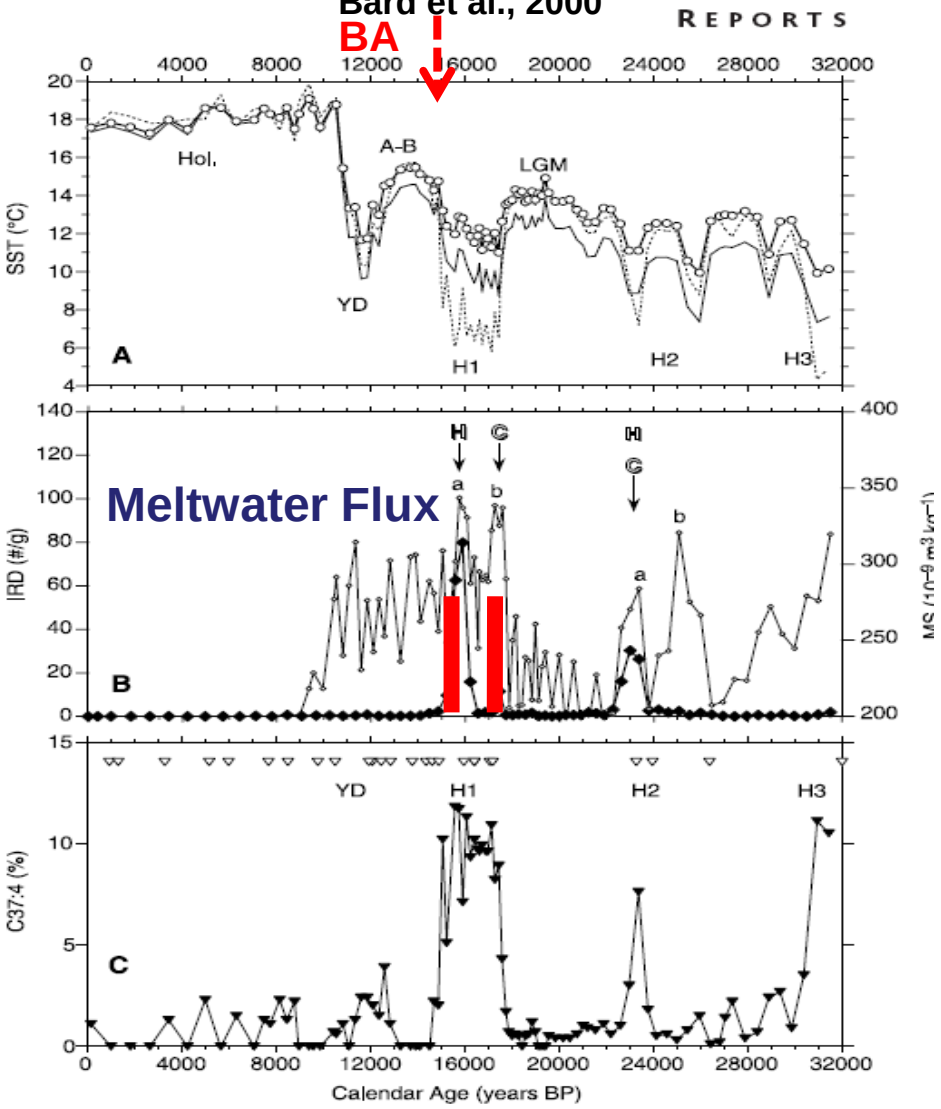
**TRACE21, iTRACE21**



# Paleo perspective: Meltwater History Prior to BA

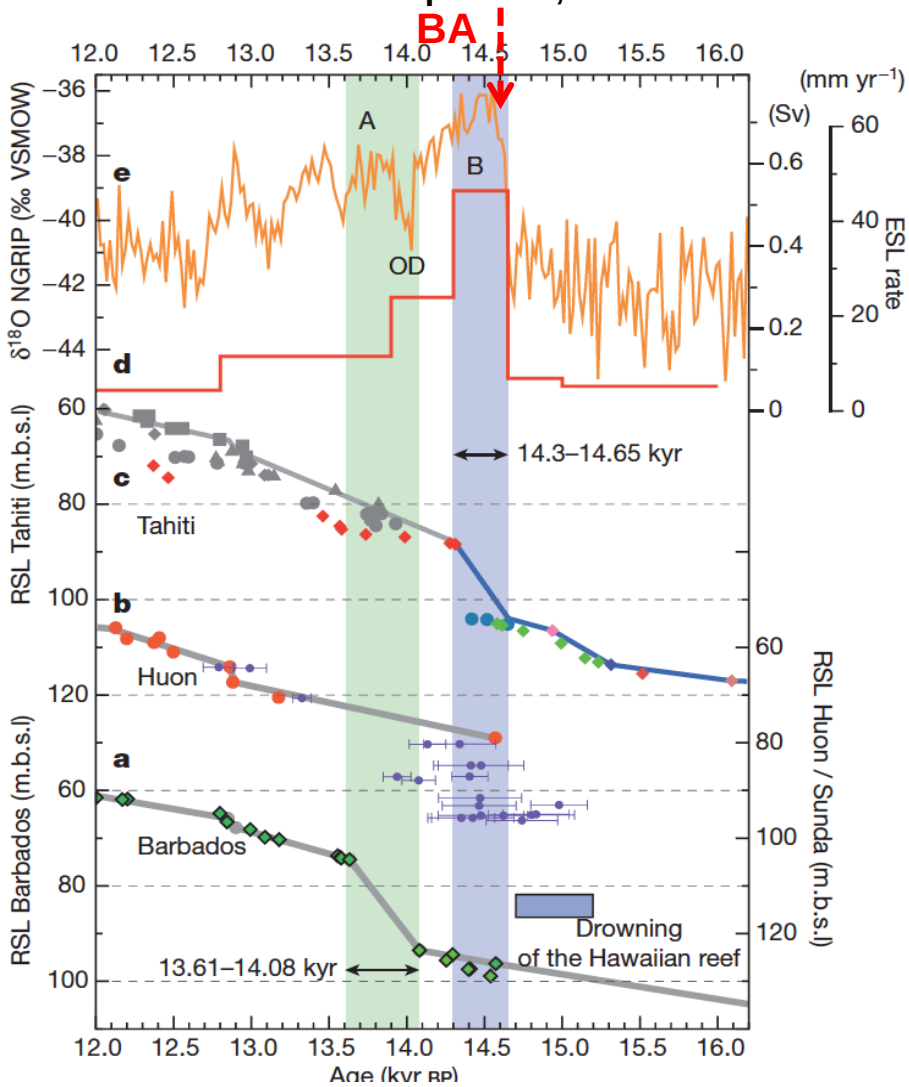
## NH meltwater

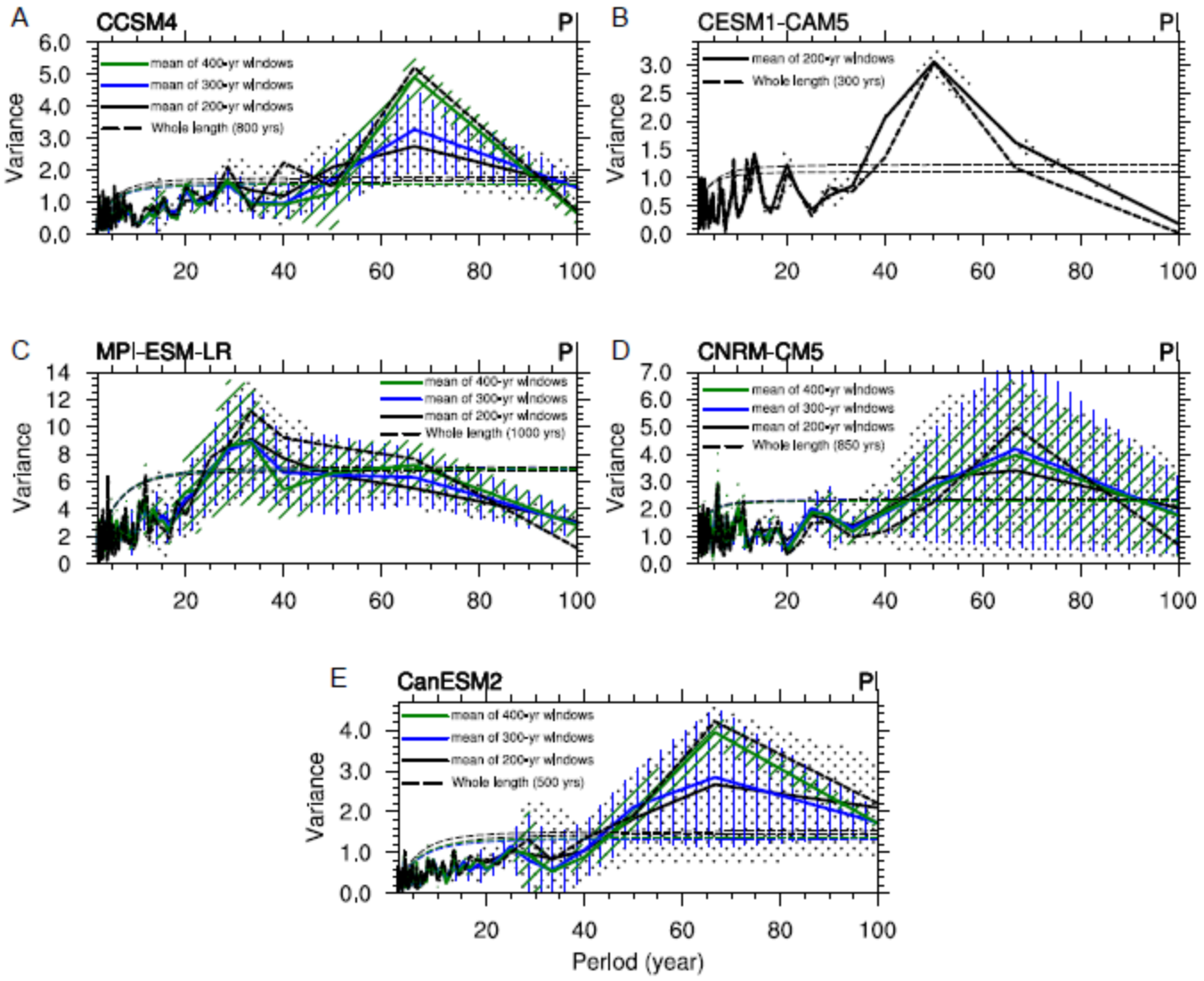
Bard et al., 2000

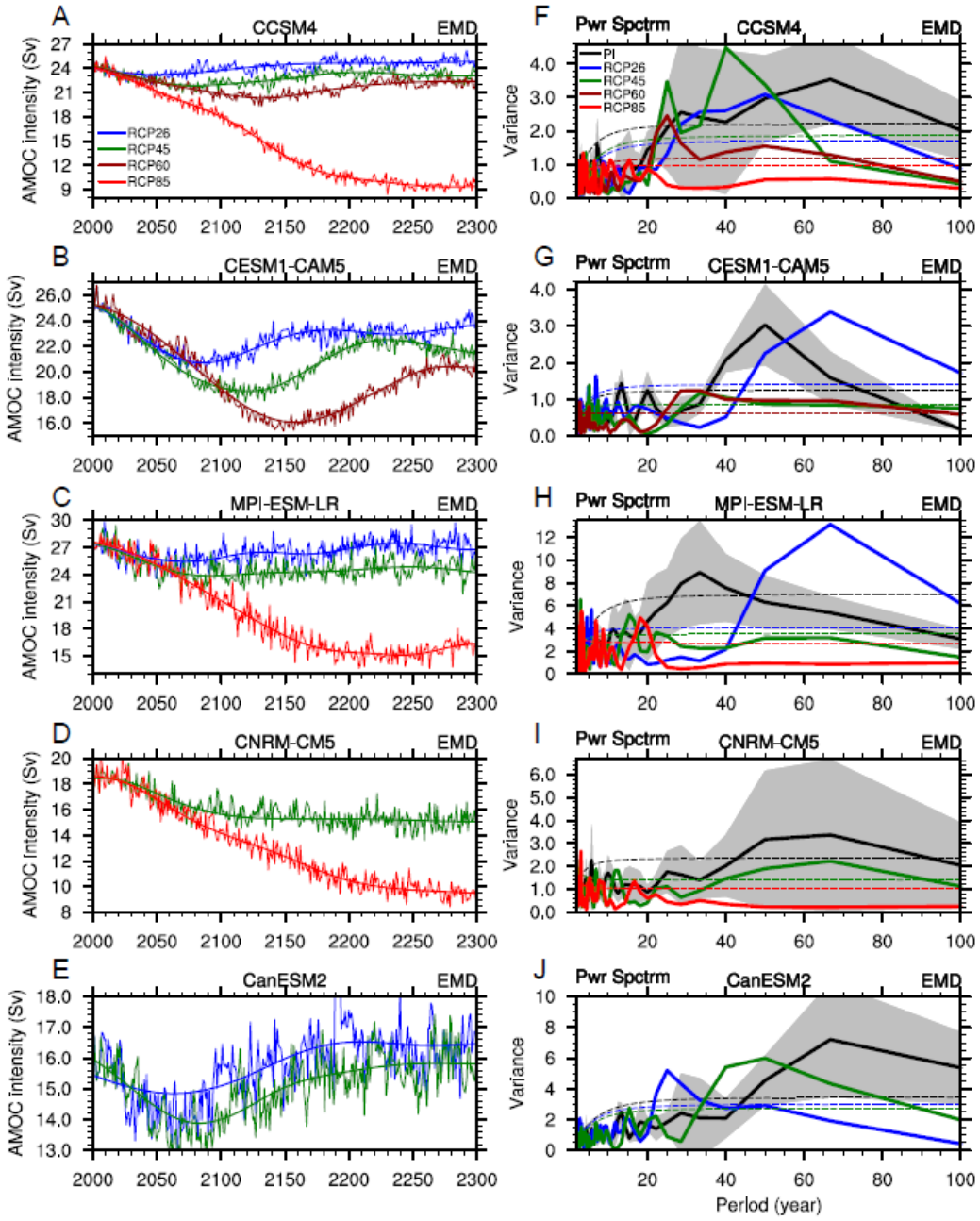


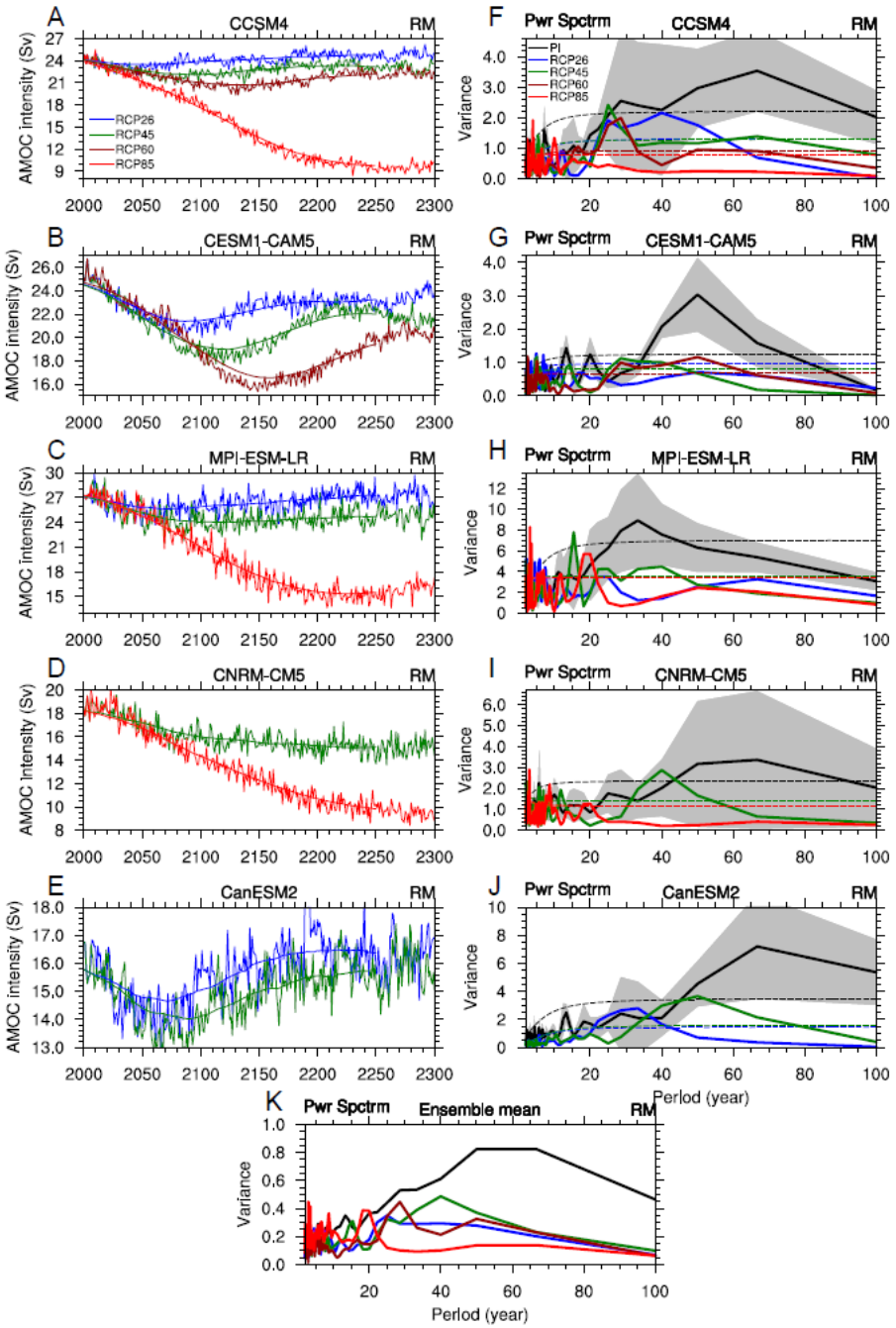

## SH meltwater (MWP1A, Clark et al., 1996

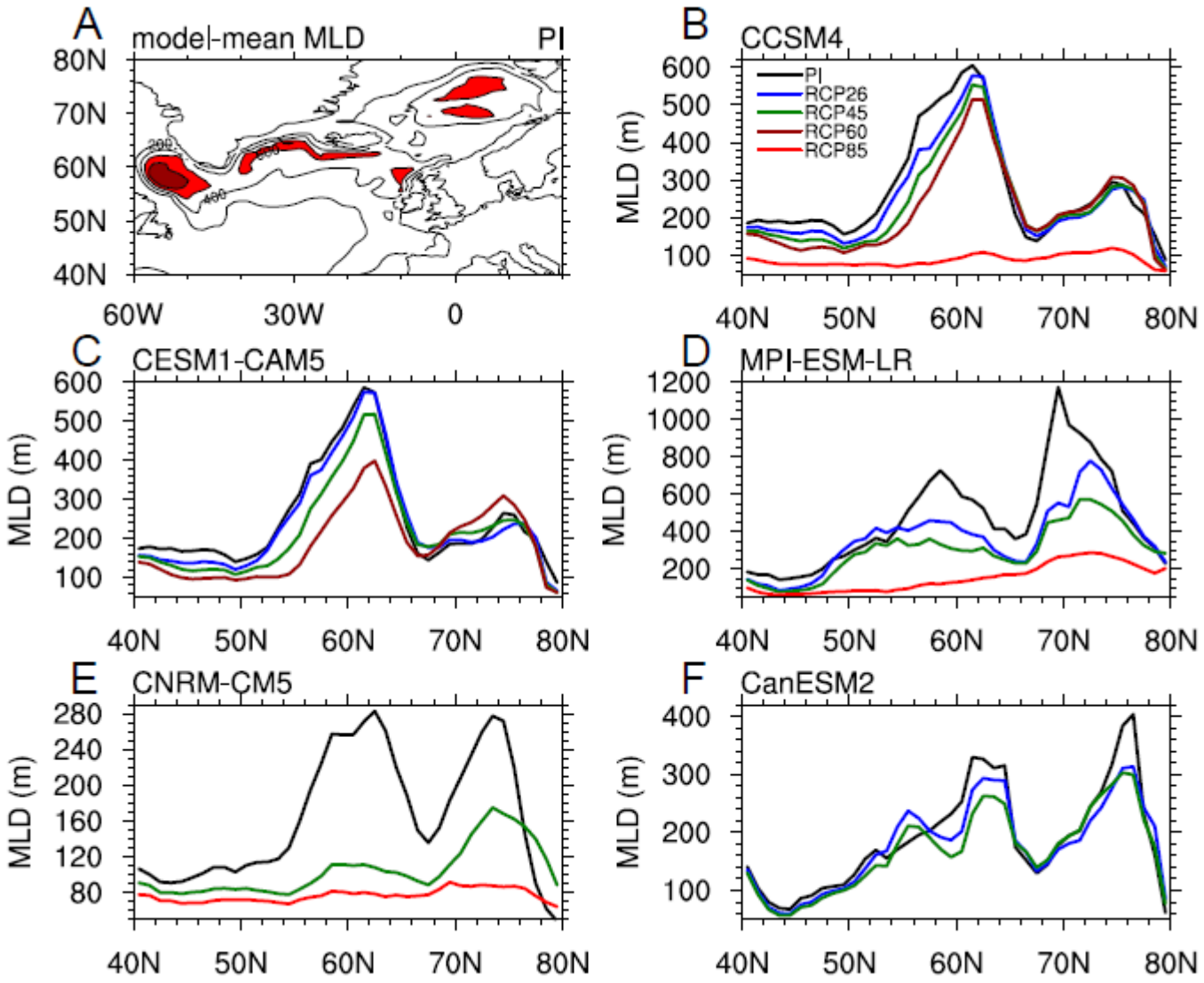
Deschamps et al., 2012

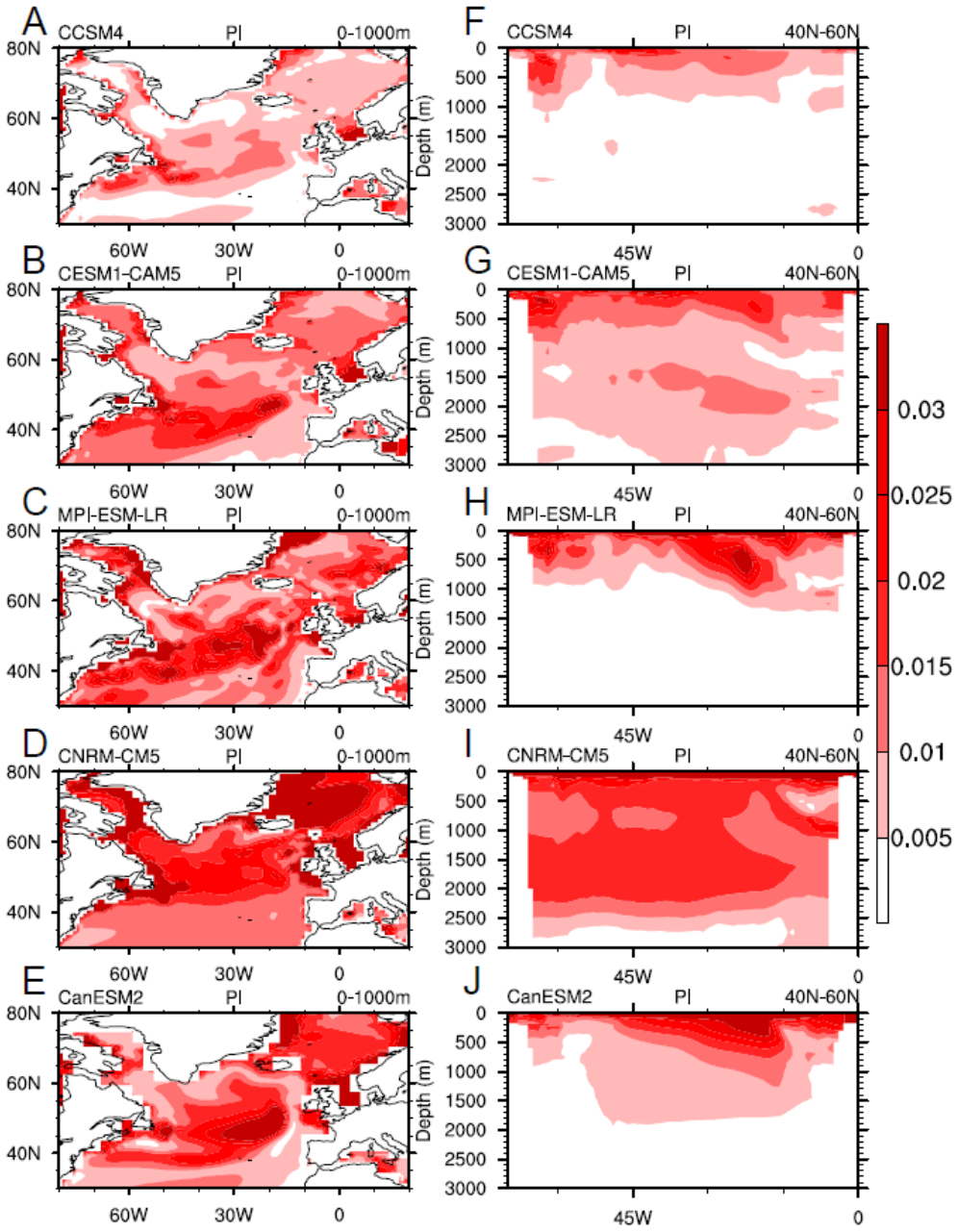



A
CCSM4
P
mean of 400-yr windows
mean of 300-yr windows
mean of 200-yr windows
Whole length (800 yrs)
Variance
B
CESM1-CAM5
P
mean of 200-yr windows
Whole length (300 yrs)
Variance
C
MPI-ESM-LR
P
mean of 400-yr windows
mean of 300-yr windows
mean of 200-yr windows
Whole length (1000 yrs)
Variance
D
CNRM-CM5
P
mean of 400-yr windows
mean of 300-yr windows
mean of 200-yr windows
Whole length (850 yrs)
Variance
E
CanESM2
P
mean of 400-yr windows
mean of 300-yr windows
mean of 200-yr windows
Whole length (500 yrs)
Variance
Period (year)


A
CCSM4
EMD
AMOC intensity (Sv)
RCP26
RCP45
RCP60
RCP85
B
CESM1-CAM5
EMD
C
MPI-ESM-LR
EMD
D
CNRM-CM5
EMD
E
CanESM2
EMD
F
Pwr Spctrm
CCSM4
EMD
PI
RCP26
RCP45
RCP60
RCP85
Variance
G
Pwr Spctrm
CESM1-CAM5
EMD
H
Pwr Spctrm
MPI-ESM-LR
EMD
I
Pwr Spctrm
CNRM-CM5
EMD
J
Pwr Spctrm
CanESM2
EMD
Perlod (year)


A
CCSM4
RM
AMOC intensity (Sv)
RCP26
RCP45
RCP60
RCP85
B
CESM1-CAM5
C
MPI-ESM-LR
D
CNRM-CM5
E
CanESM2
F
Pwr Spctrm
PI
Variance
G
H
I
J
K
Ensemble mean
Period (year)


A
model-mean MLD
PI
80N
70N
60N
50N
40N
60W
30W
0
B
CCSM4
PI
RCP26
RCP45
RCP60
RCP85
MLD (m)
600
500
400
300
200
100
40N
50N
60N
70N
80N
C
CESM1-CAM5
MLD (m)
600
500
400
300
200
100
40N
50N
60N
70N
80N
D
MPI-ESM-LR
MLD (m)
1200
1000
800
600
400
200
40N
50N
60N
70N
80N
E
CNRM-CM5
MLD (m)
280
240
200
160
120
80
40N
50N
60N
70N
80N
F
CanESM2
MLD (m)
400
300
200
100
40N
50N
60N
70N
80N


A
CCSM4
PI
0-1000m
B
CESM1-CAM5
PI
0-1000m
C
MPI-ESM-LR
PI
0-1000m
D
CNRM-CM5
PI
0-1000m
E
CanESM2
PI
0-1000m
80N
60N
40N
60W
30W
0
Depth (m)
F
CCSM4
PI
40N-60N
G
CESM1-CAM5
PI
40N-60N
H
MPI-ESM-LR
PI
40N-60N
I
CNRM-CM5
PI
40N-60N
J
CanESM2
PI
40N-60N
0
500
1000
1500
2000
2500
3000
45W
0.03
0.025
0.02
0.015
0.01
0.005

# Thermal Rossby wave?

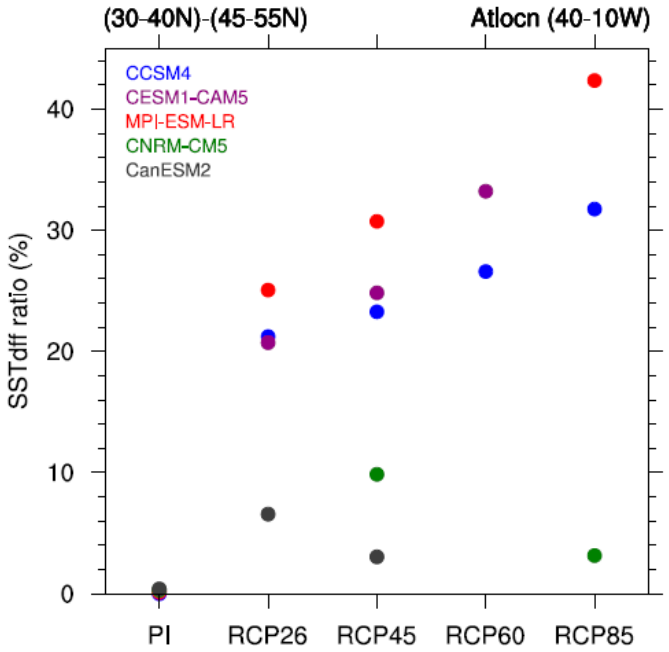
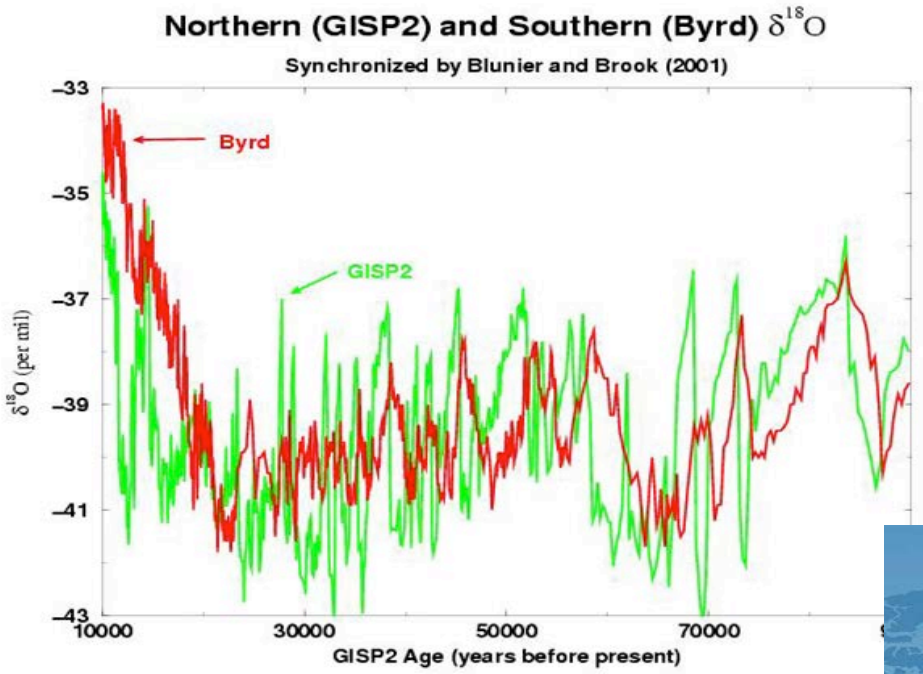



Fig. S6. Change ratio of meridional SST gradient (SST dff ratio) in the Atlantic of the RCP simulations compared with the value of the PI simulation for each model.

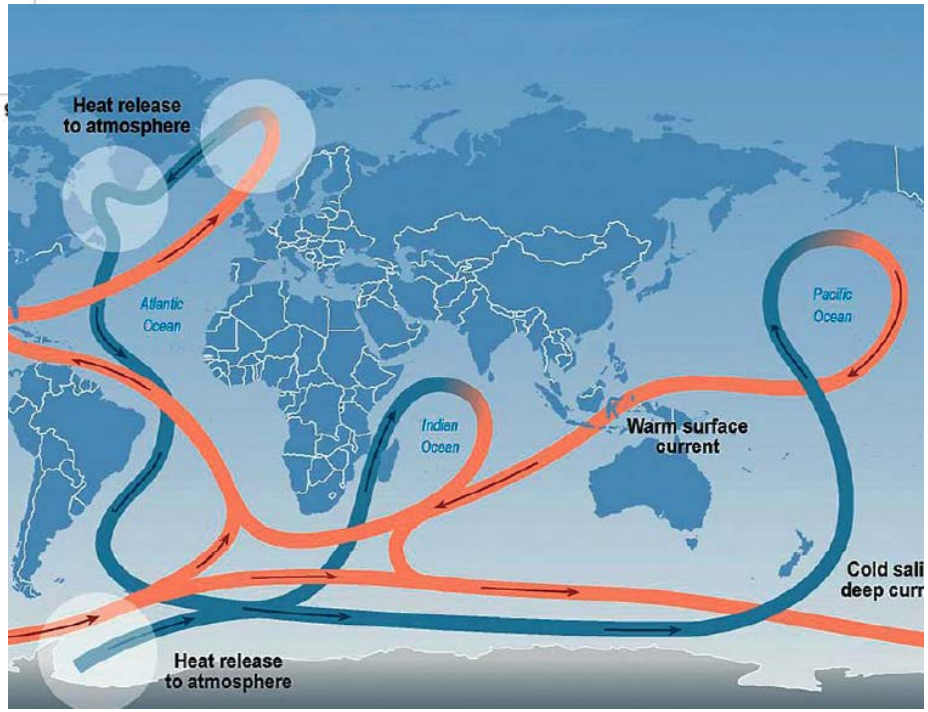
Meridional Gradient Change?
Non-Doppler cancelation?

# AMOC and Abrupt Climate Change

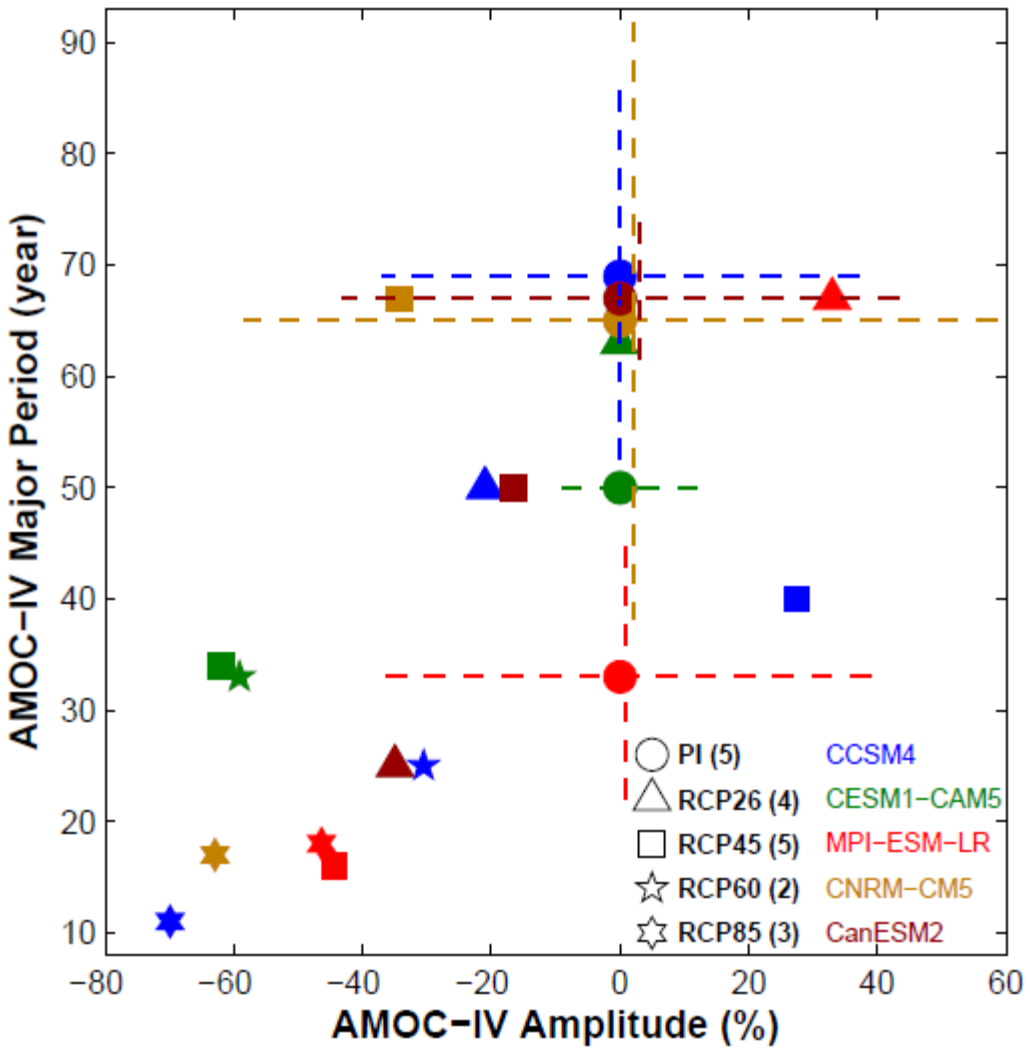



Greenland Ice Core

Atlantic Meridional Overturning Circulation (AMOC)

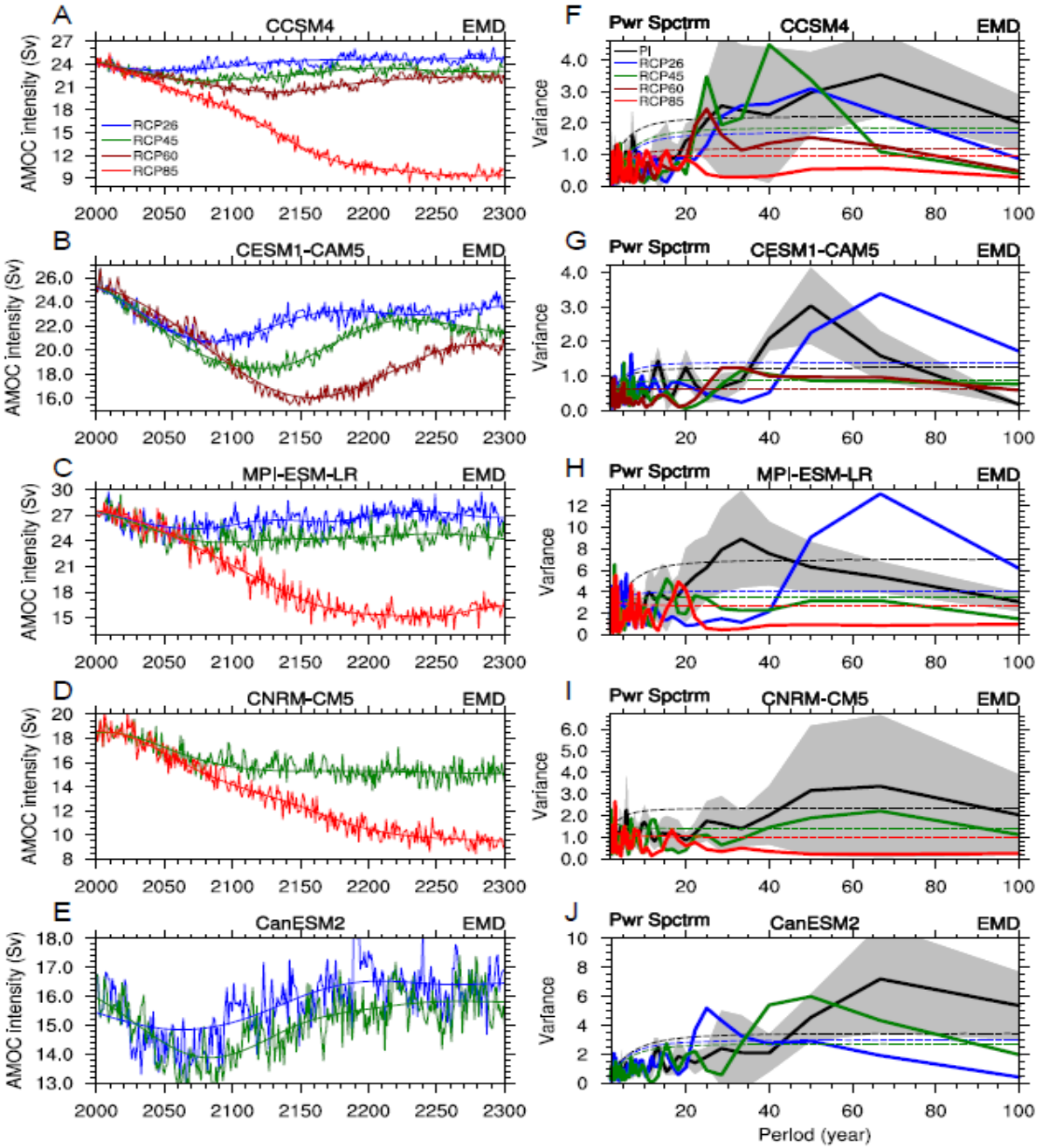


# Individual Model Response



# Response of Power Spectrum to Global Warming

**Individual model**



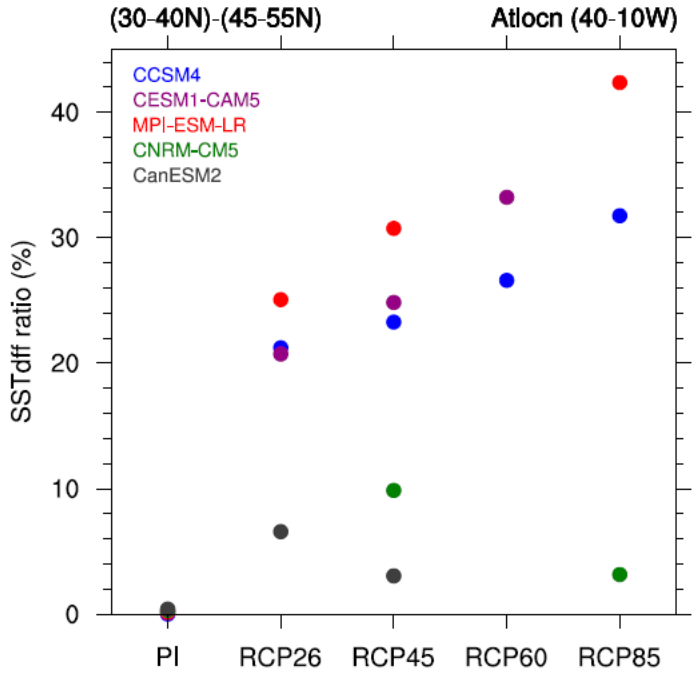



**Fig. S6.** Change ratio of meridional SST gradient (SST dff ratio) in the Atlantic of the RCP simulations compared with the value of the PI simulation for each model.