AMOC Response to Climate Change: Questions after TRACE21

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TRACE21 collaborators

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……

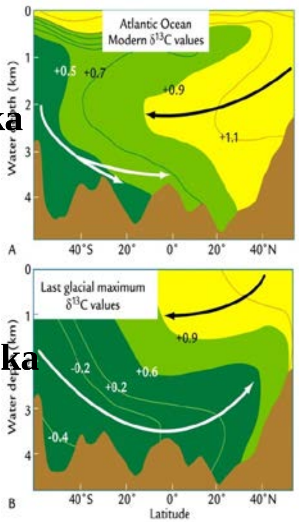
AMOC in TRACE21

Q1:
Why AMOC intensity comparable between glacial and Holocene?

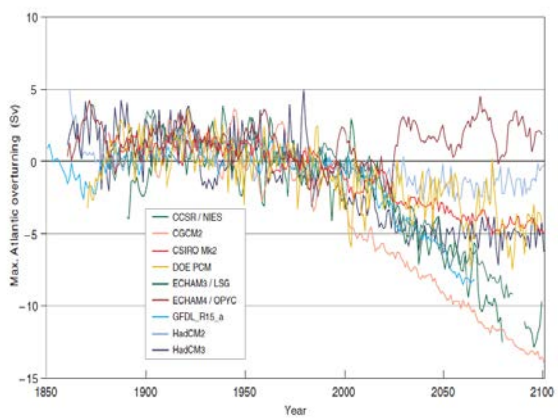
Proxy
Δ 13C

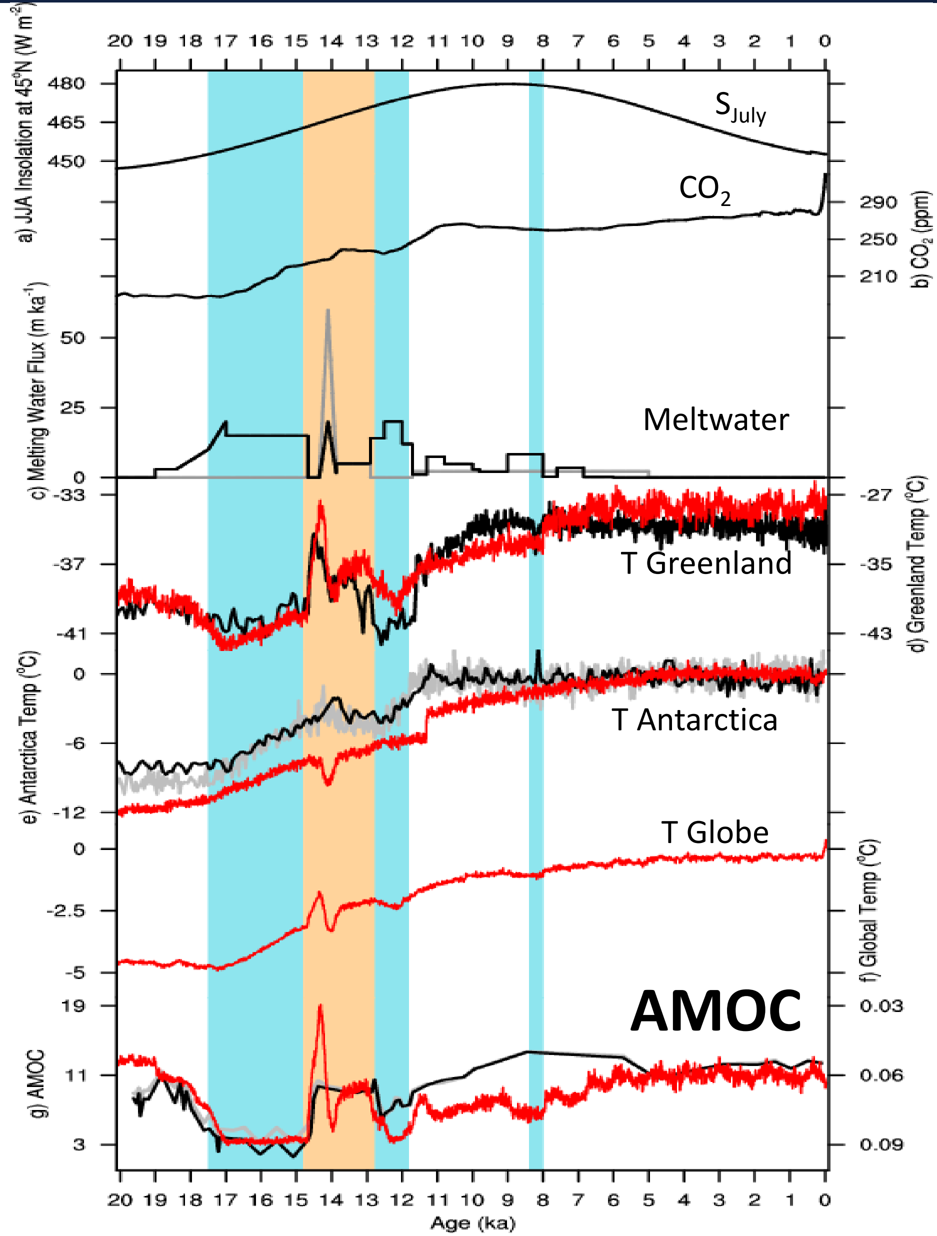
0ka

21ka



IPCC: Transient CO2

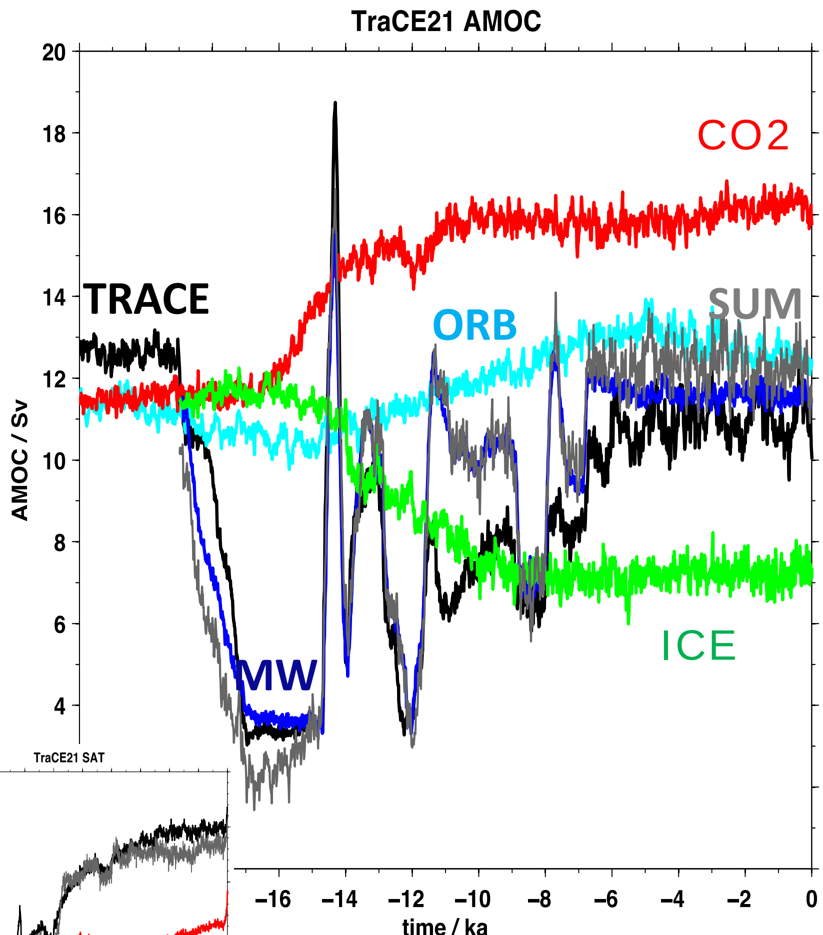


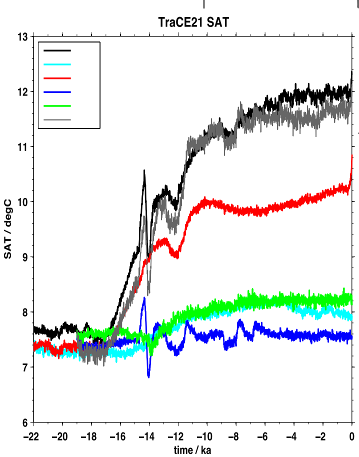


Q2:
What caused abrupt change of AMOC?

Q1: Why AMOC intensity comparable between glacial and Holocene?

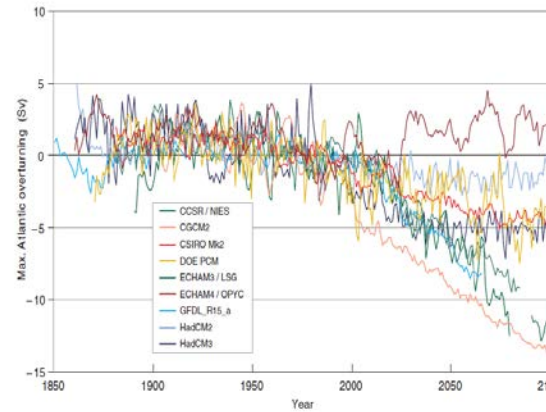
AMOC





T Globe

IPCC: Transient CO2



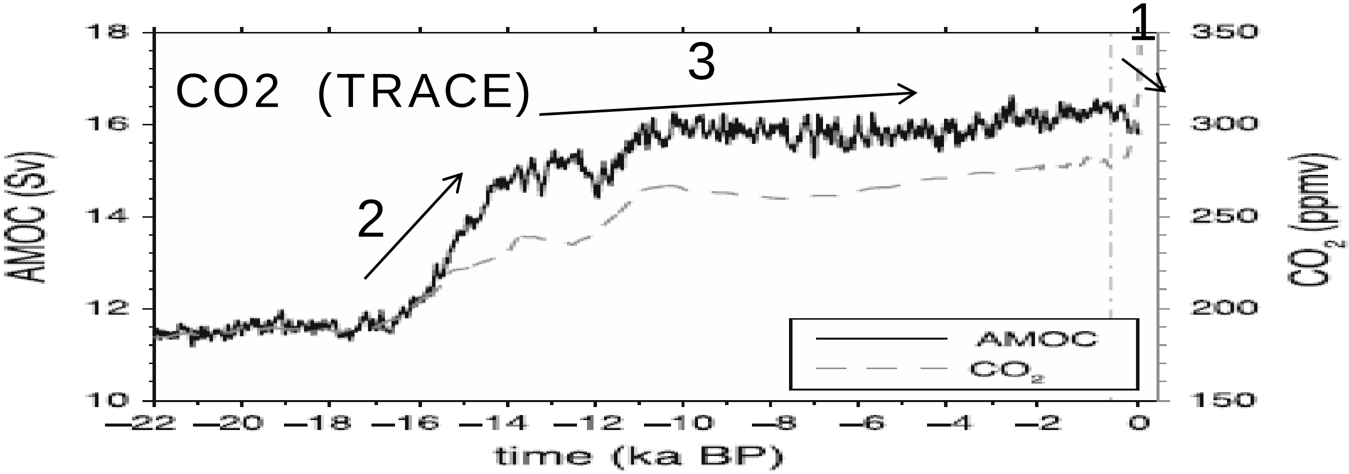
Q1:
Why AMOC intensity is comparable between glacial and Holocene?
➔ Opposite responses to CO2 and Ice sheet

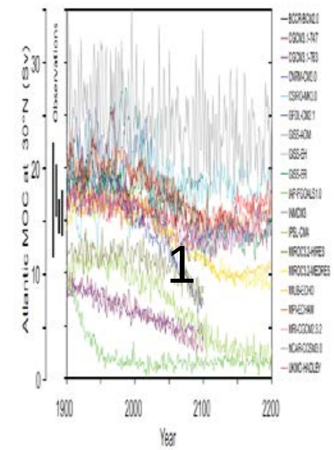
Then:

Q1a: Why AMOC intensifies with rising CO2?

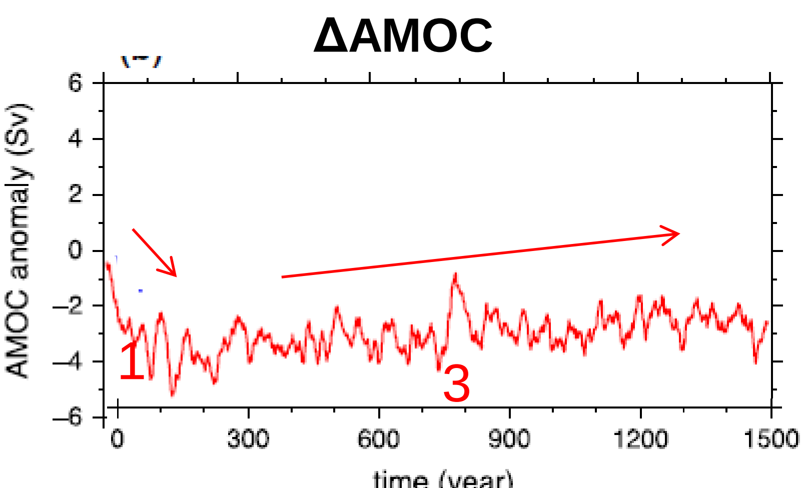
Q1b: Why AMOC decreases with Ice sheet retreat?

Q1a: AMOC response to CO2: across Different Time Scales

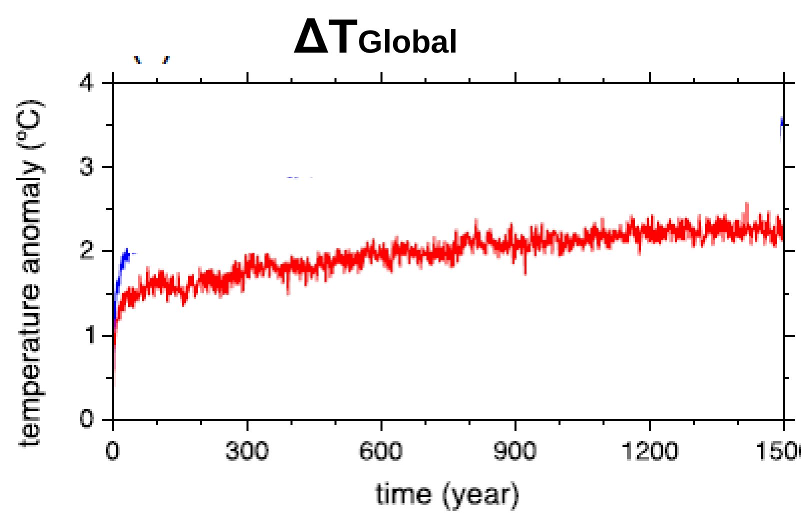




Sensitivity Exp: 2xCO2 – CTRL at 0ka



0ka



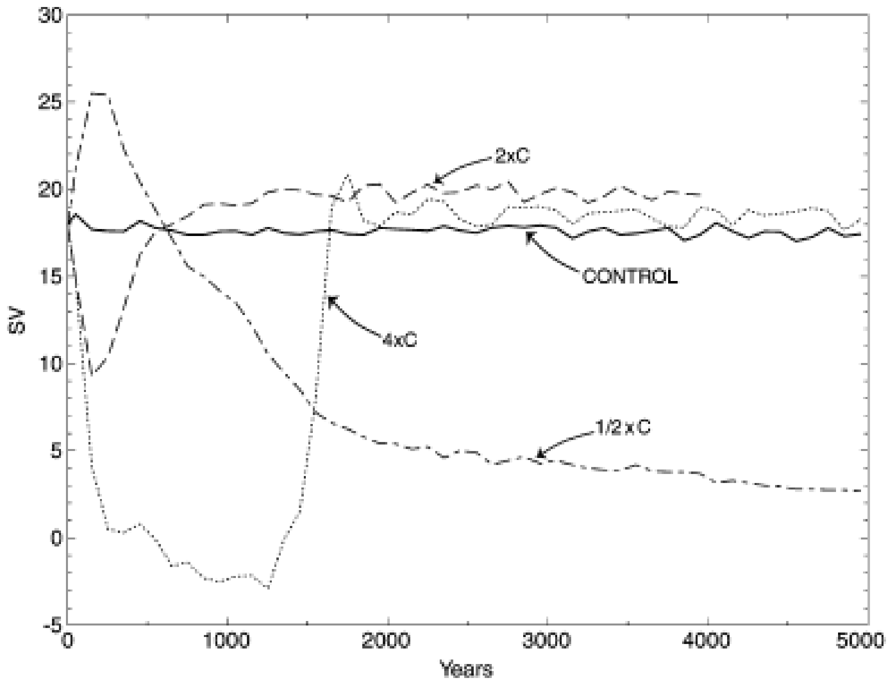
Stage 1: **stronger heat flux in NA => weaker AMOC (Gregory et al., 2005)**

Stage 3: **less SO sea ice => less (local) brine injection => less AABW => stronger AMOC (Shin et al., 2003)**

Zhu et al., 2014, CD

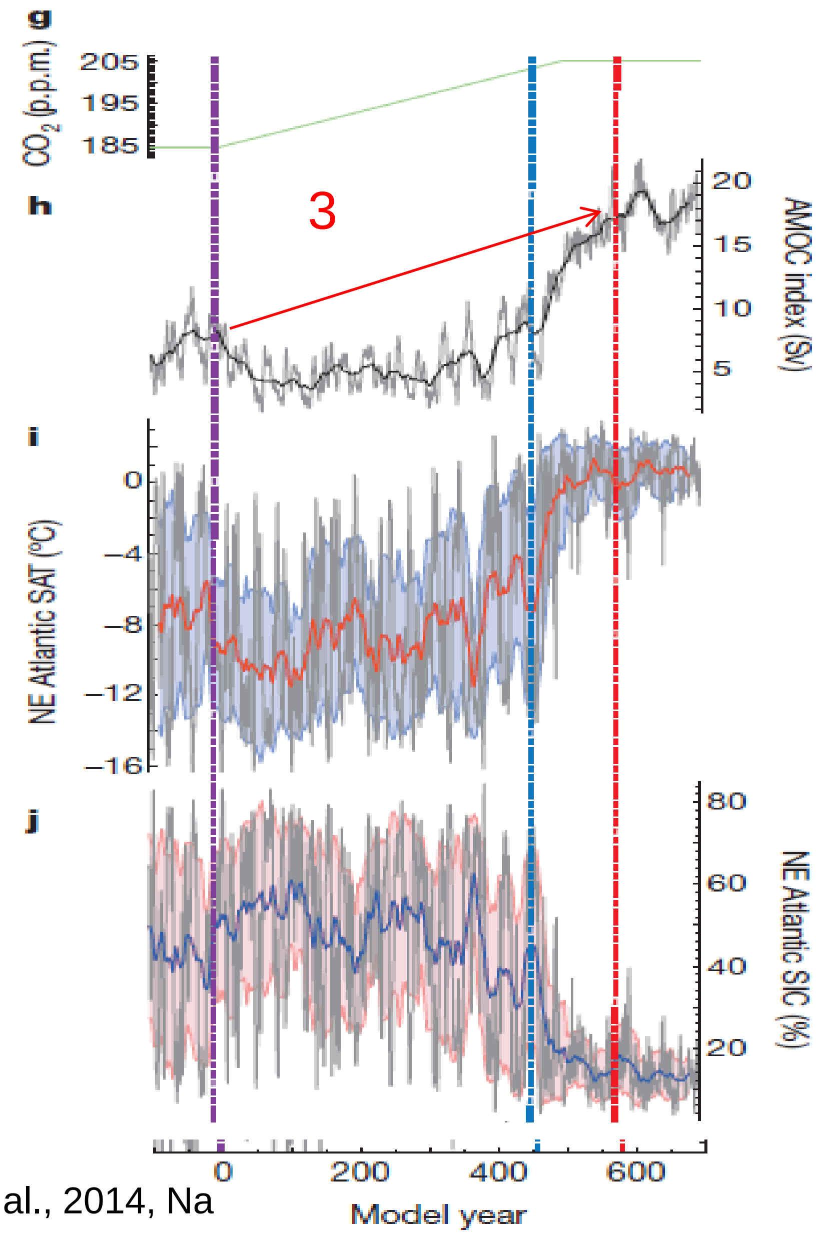
AMOC response to CO2: across time scales, sensitivity

GFDL R30



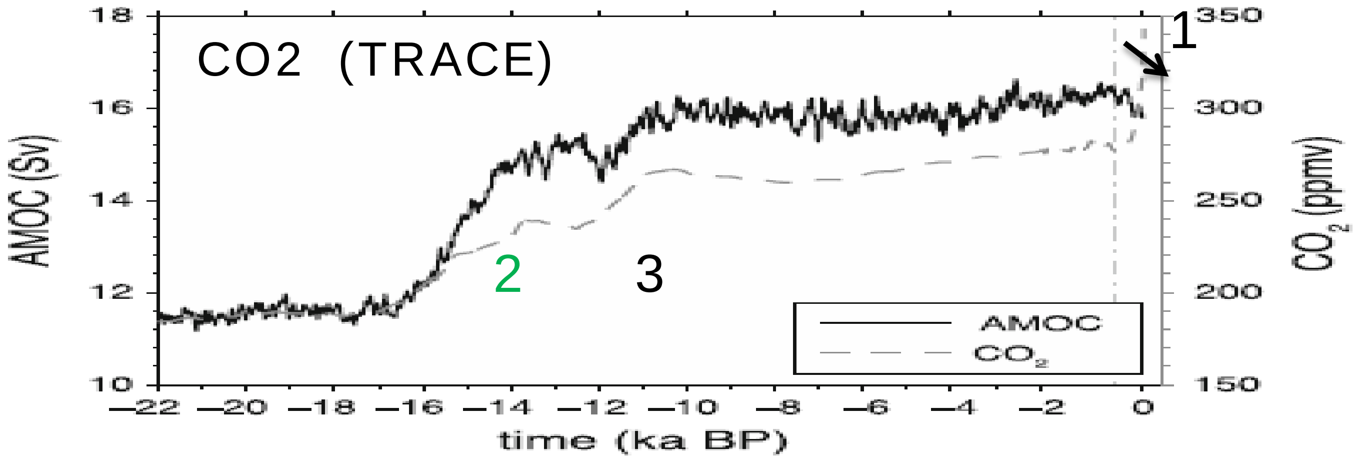
Stouffer et al., 2003, CD

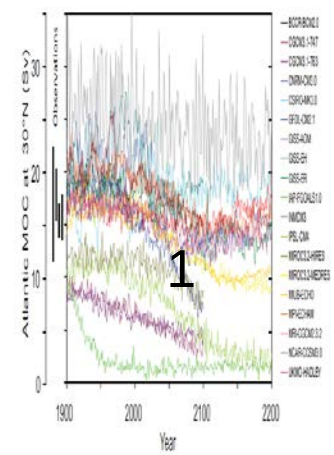
ECHAM5-JSBACH-MPIOM



Zhang et al., 2014, Na

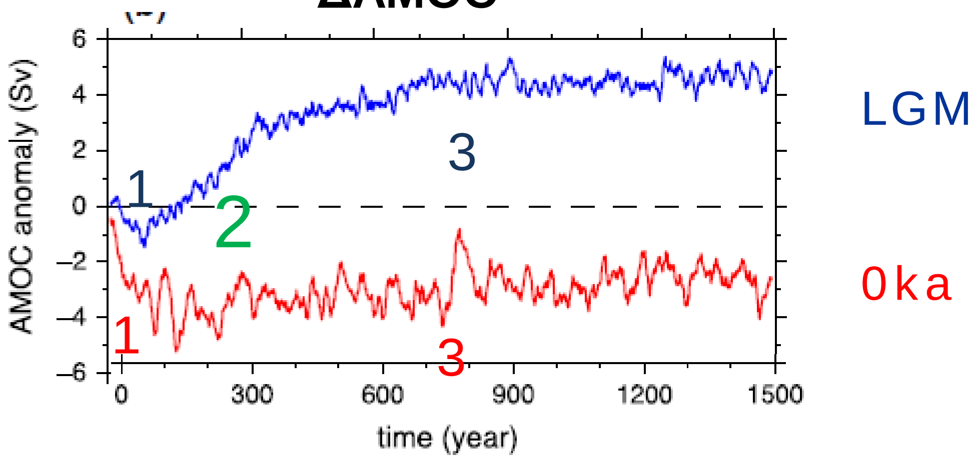
AMOC response to CO2: Different States/Time Scales



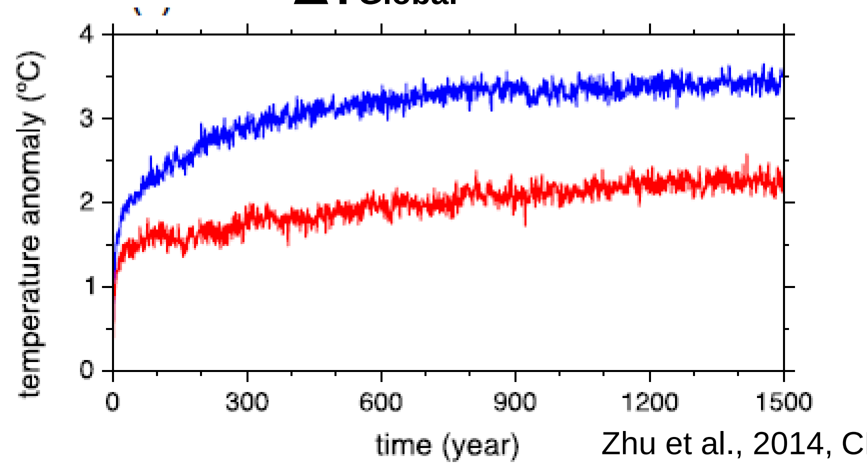


Sensitivity Exp: 2xCO2 – CTRL at 0ka and LGM

ΔAMOC



ΔT Global



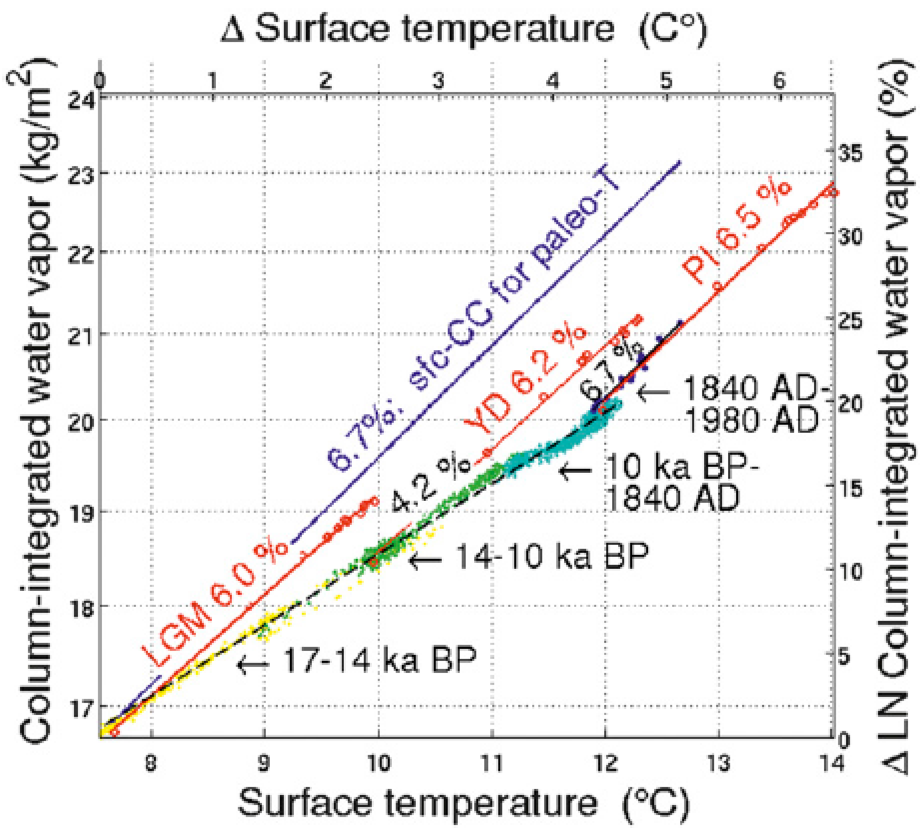
Zhu et al., 2014, CD

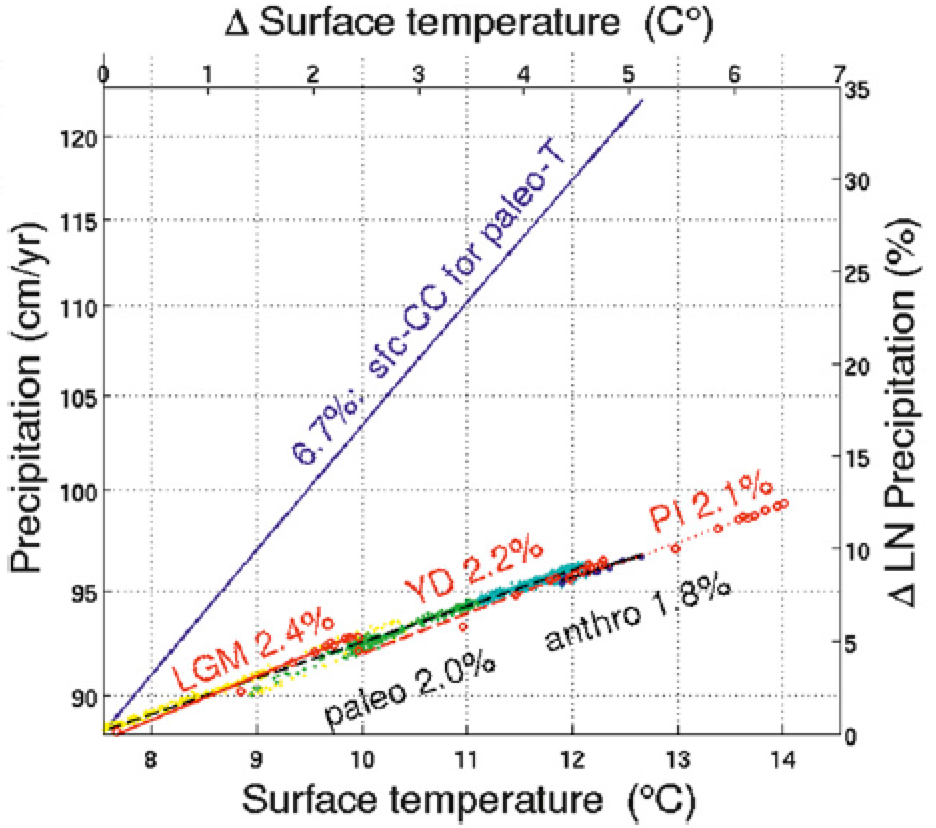
Stage 1: **stronger heat flux in NA => weaker AMOC (Gregory et al., 2005)**

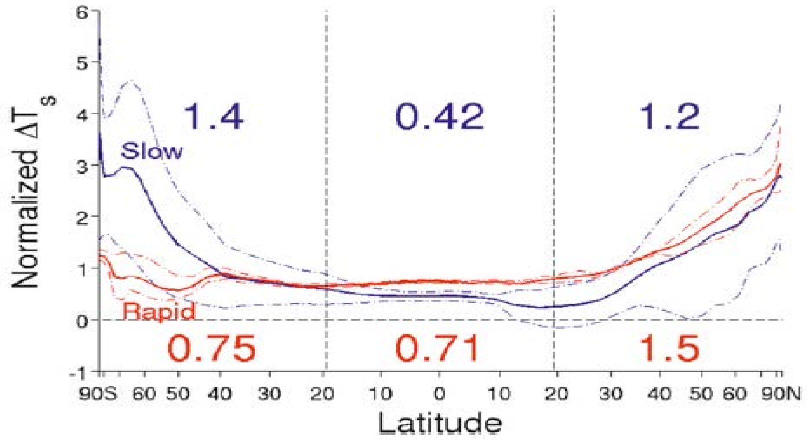
Stage 3**: less SO sea ice => less (local) brine injection => less AABW => stronger AMOC (Shin et al., 2003)**

Stage 2: **LGM large sea-ice retreat => surface heat loss => stronger AMOC (e.g. Oda et al., 2012)**
(=>heat transport =>more sea ice melt => more surface heat loss, positive feedback)

Hydrological Response to slow and fast global warming



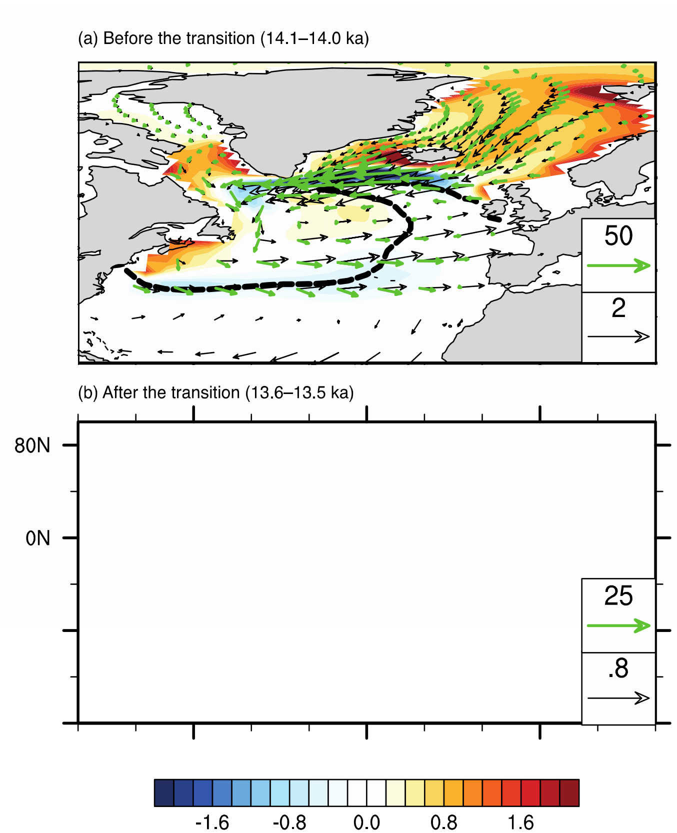


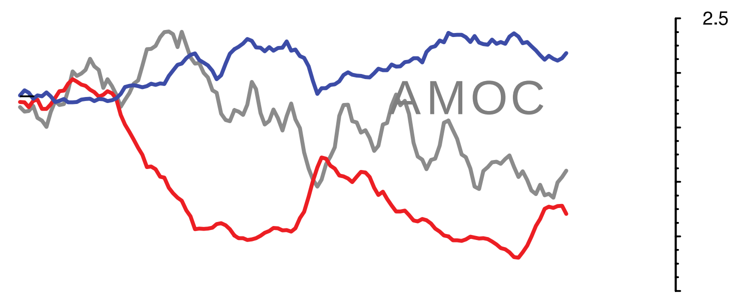


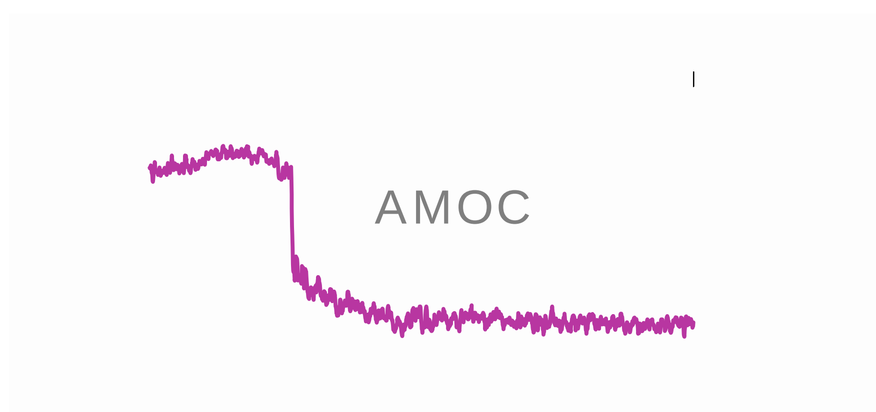
Back et al., 2013, JC

Q1b: AMOC response to ice sheet retreat

Ice sheet lowing => jet northward migration => sea ice expansion => heat loss (and density flux) cut off => AMOC reduced





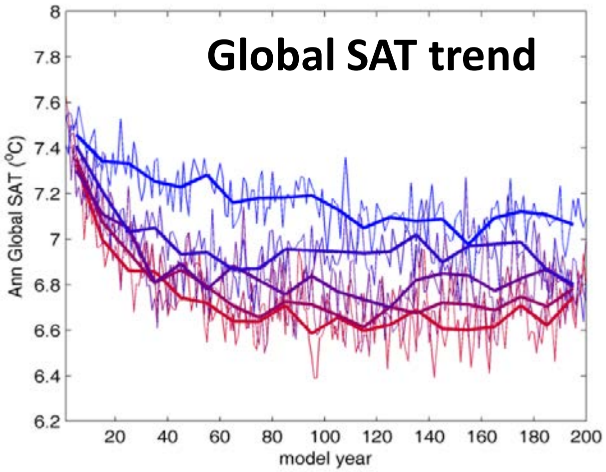


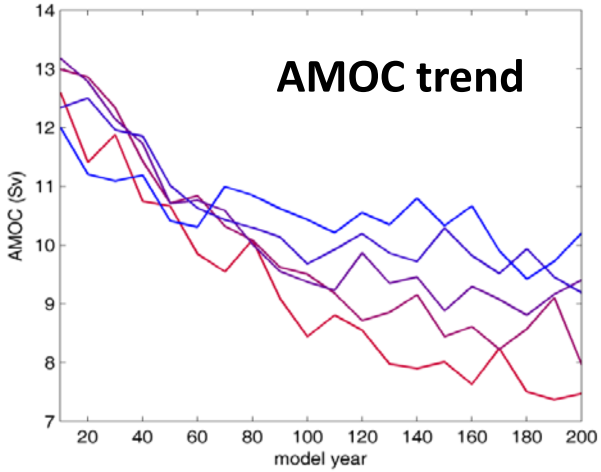
Zhu et al., 2014, GRL

AMOC response to ice sheet sensitivity

Ice sheet topography sensitive runs

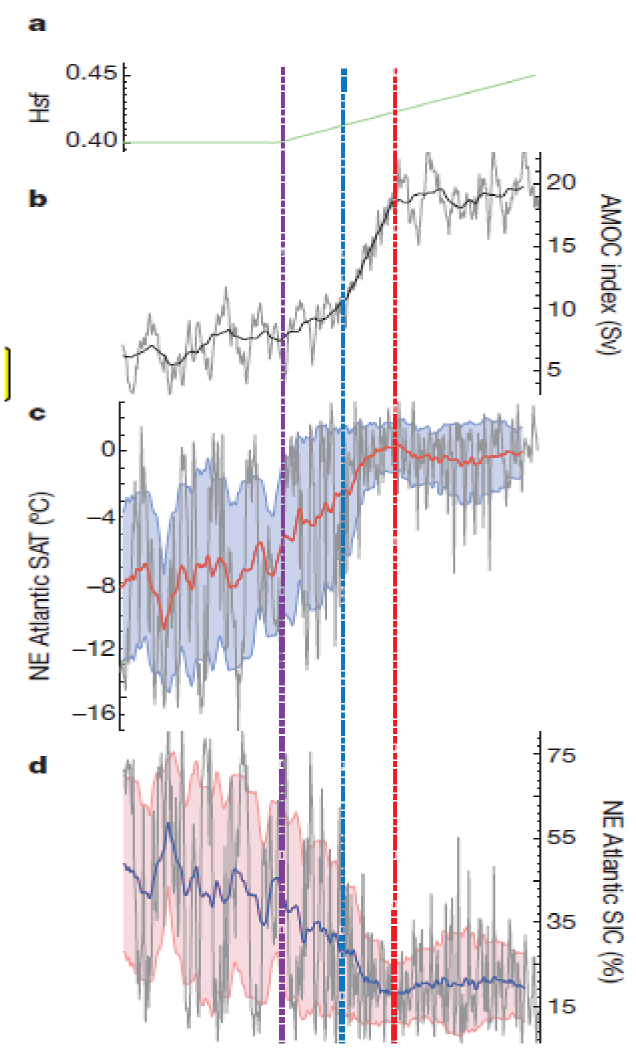
NH ice sheets thickness, % of LGM: 0, 20, 40, 60, 80
each runs for **200** years (red ---------> blue)





Lu Z., 2017.

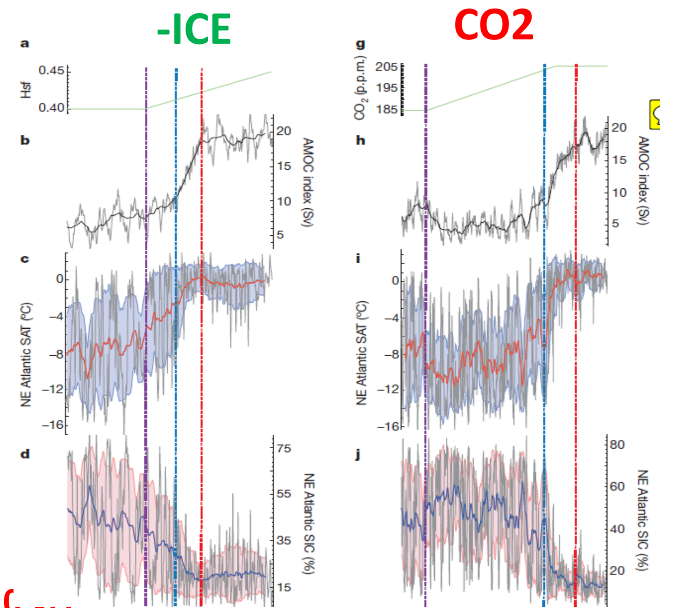
ECHAM5-JSBACH-MPIOM



Zhang et al., 2014, Na

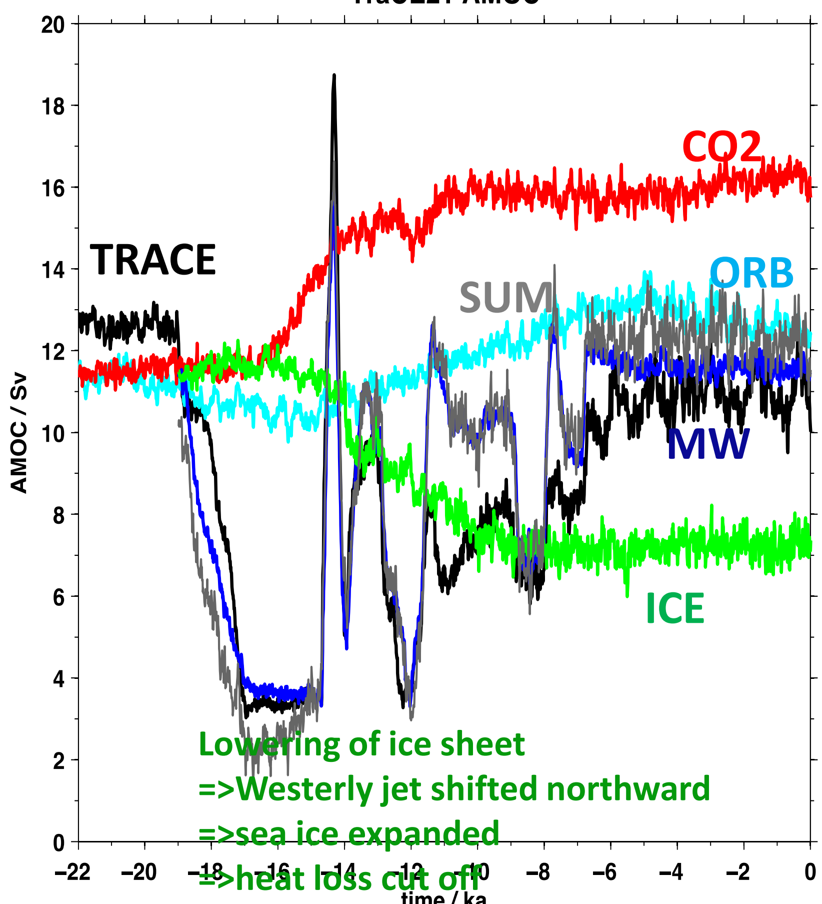
Summary of AMOC response mechanisms

ECHAM5-JSBACH-MPIOM



Zhang et al., 2014, Na

AMOC



Lowering of ice sheet
=>Westerly jet shifted northward
=>sea ice expanded
=>heat loss cut off
=>AMOC reduced

Zhu et al., 2014, GRL

CO_2 increase

I: NA heat flux decrease
⇒ AMOC decrease (~ 1C

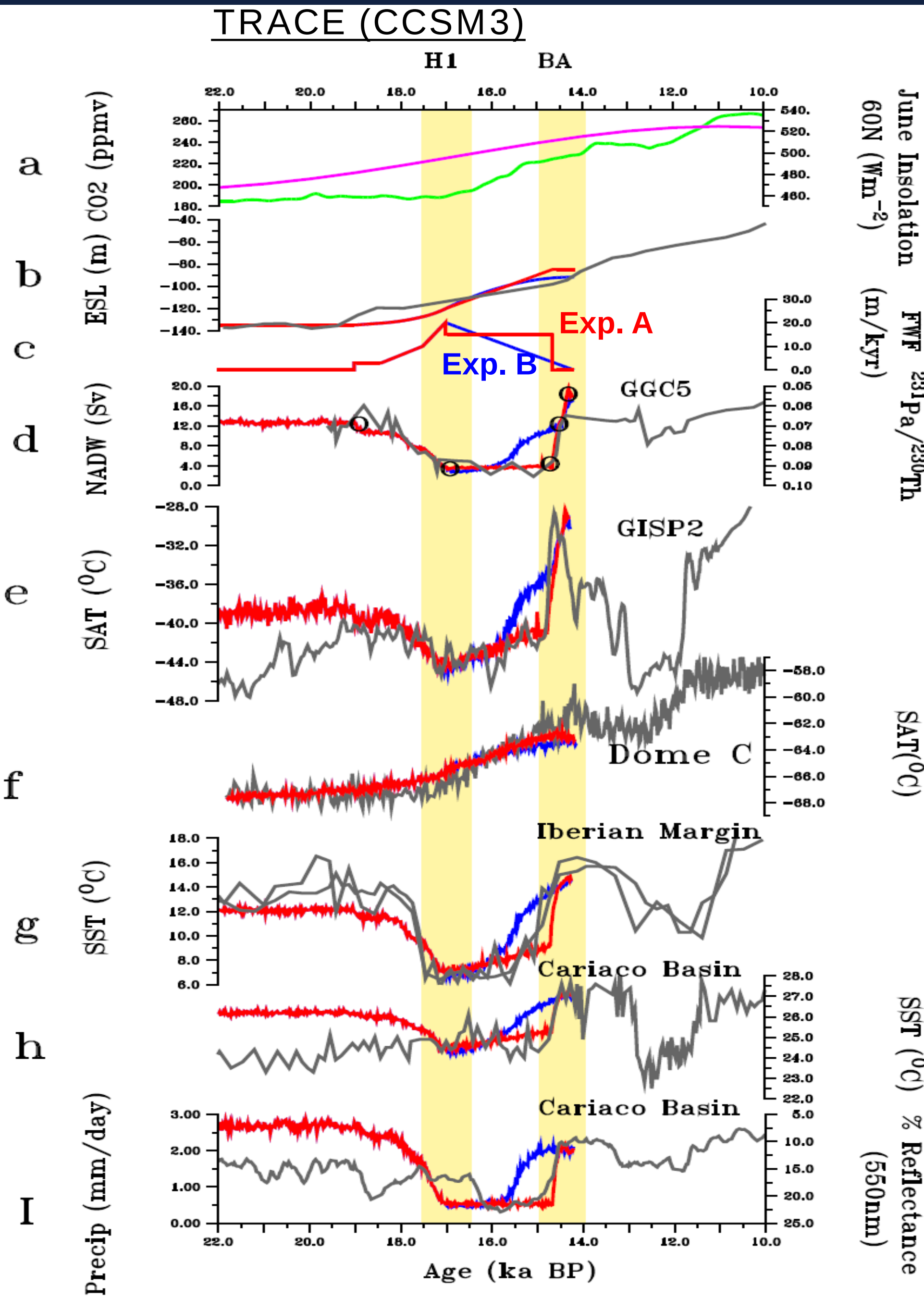
II: NA sea ice decrease
=>Arctic meltwater import decrease
=>AMOC increased(~100 yr)

III: SO sea ice decrease
=> Local brine injection decrease
⇒ AABW decrease
=> AMOC increase (~1000 yr)

Time scale dependent
State dependent
II, III: dominant in glacial climate

Zhu et al., 2014, CD

Q2: AMOC Instability and Abrupt Climate Change?



Q2: Is AMOC bistable in real world

Paleo obs:

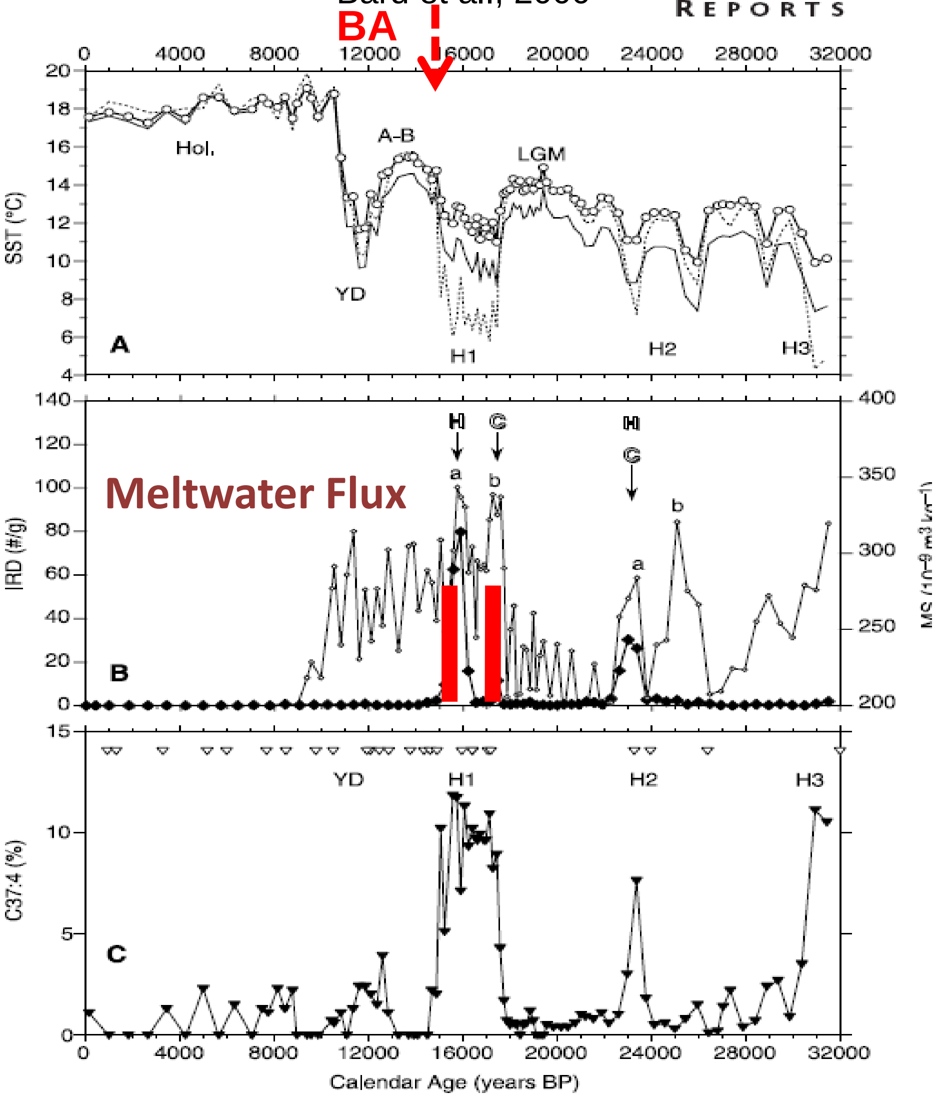
meltwater chronology ?

Liu et al., 2009, Sci

Paleo perspective: Meltwater History Prior to BA

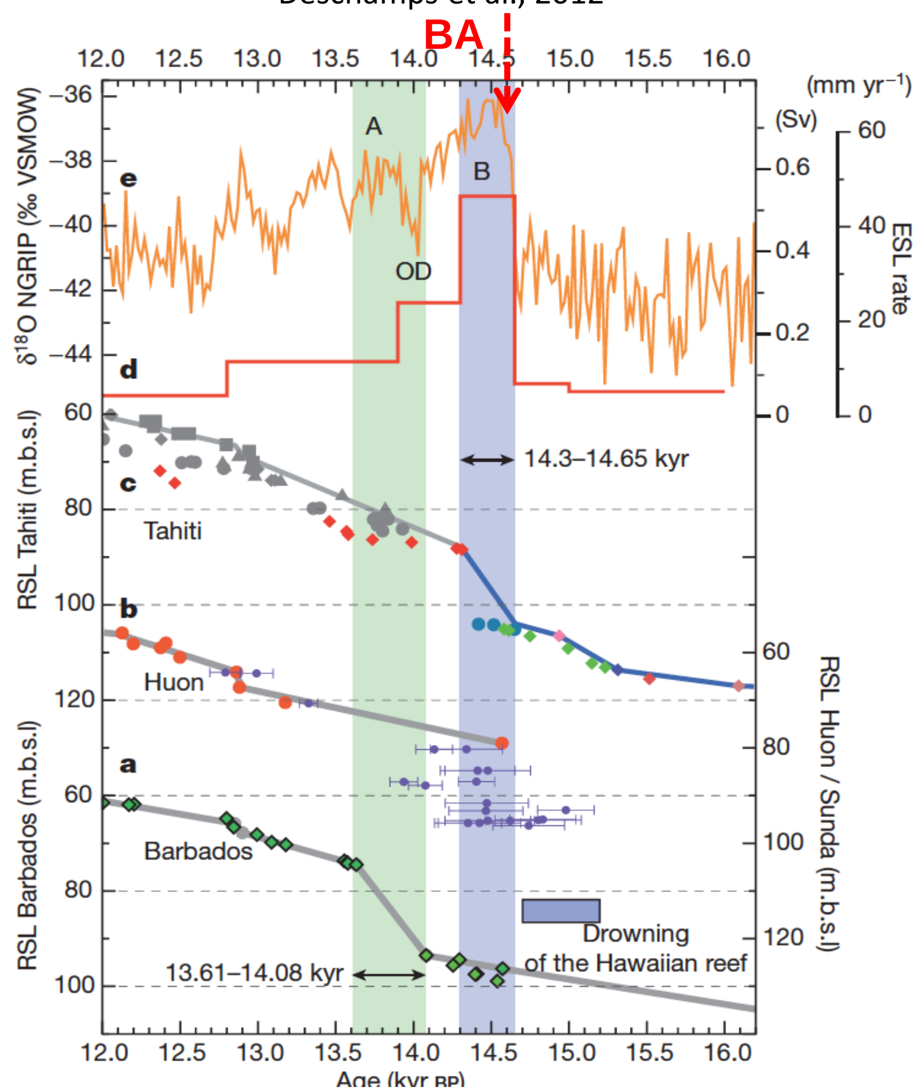
NH meltwater

Bard et al., 2000



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

Deschamps et al., 2012



Thermohaline Instability and Abrupt Climate Change
A Historical Perspective

1960 | 1980 | 1990 | 2000 | 2010

Theory

Stommel
Box Model

Bryan
OGCM

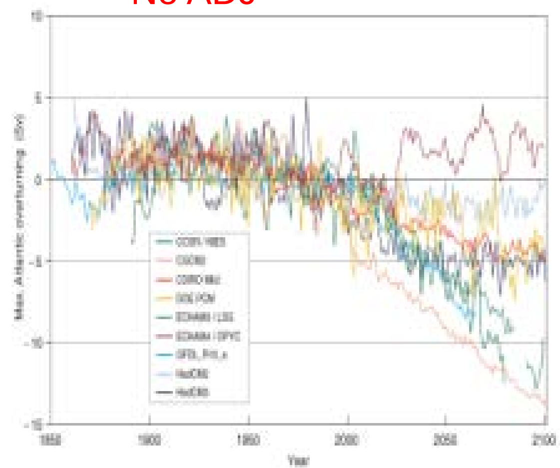
Manabe
Stouffer
CGCM+ADJ

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

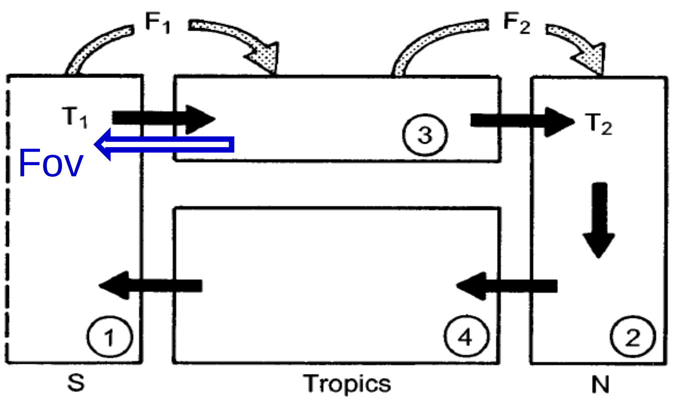
?

CGCM too
stable

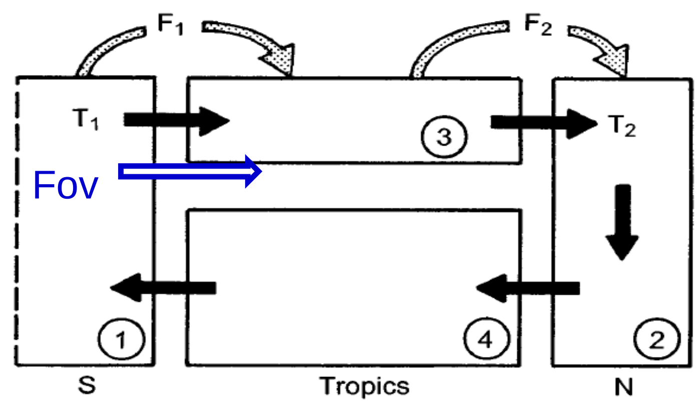
Thermohaline instability and abrupt climate change

Fov: Freshwater transport by AMOC (overturning)

Bi-stable



Mono-stable

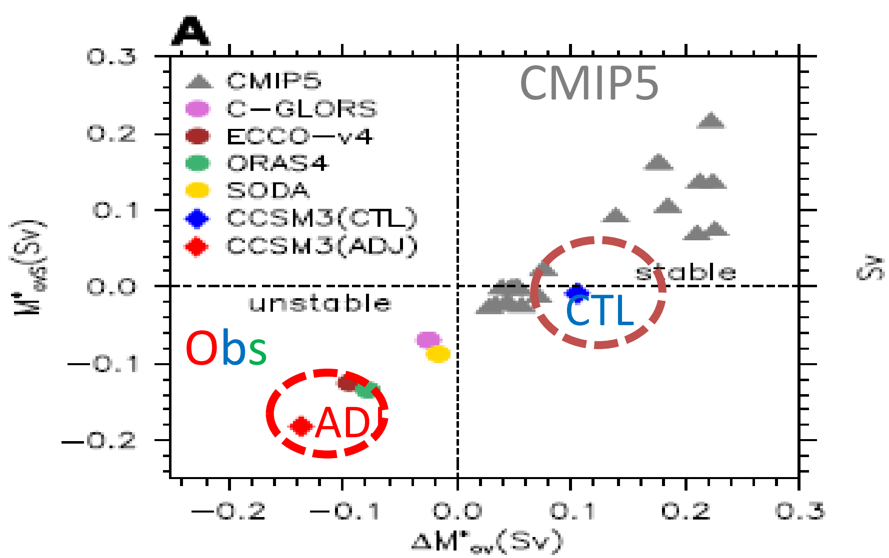


Rahmstorf, 1996

Observation

State of Art Models

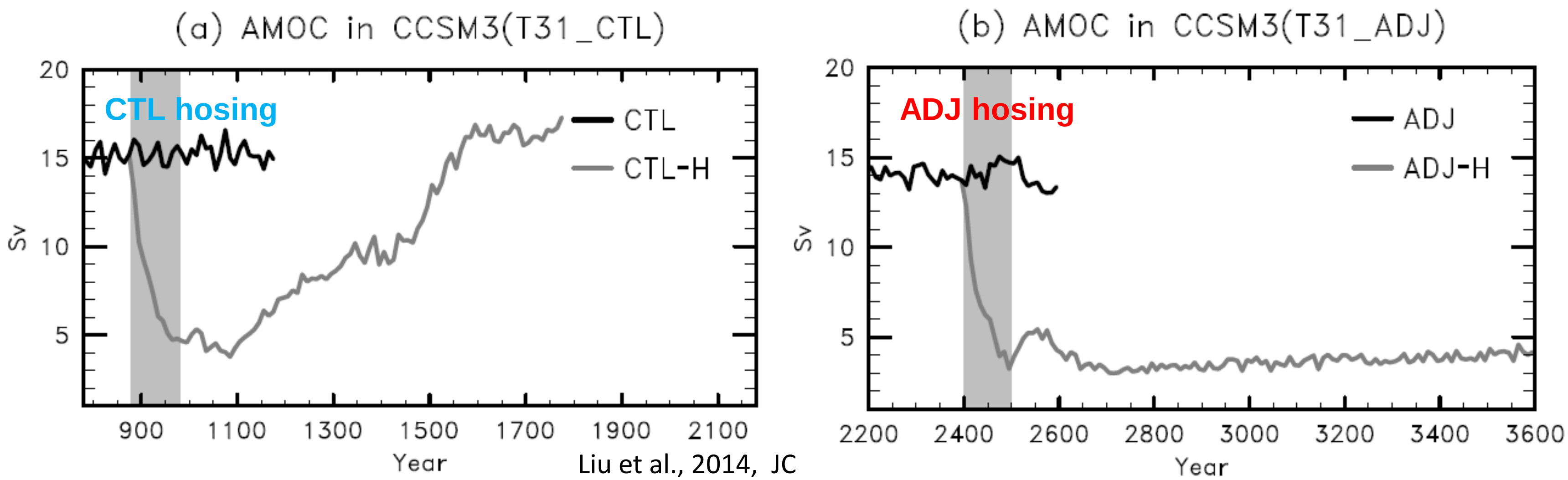
Fov



Mov=FovS-FovN

Future AMOC Response: Before and After Bias Correction

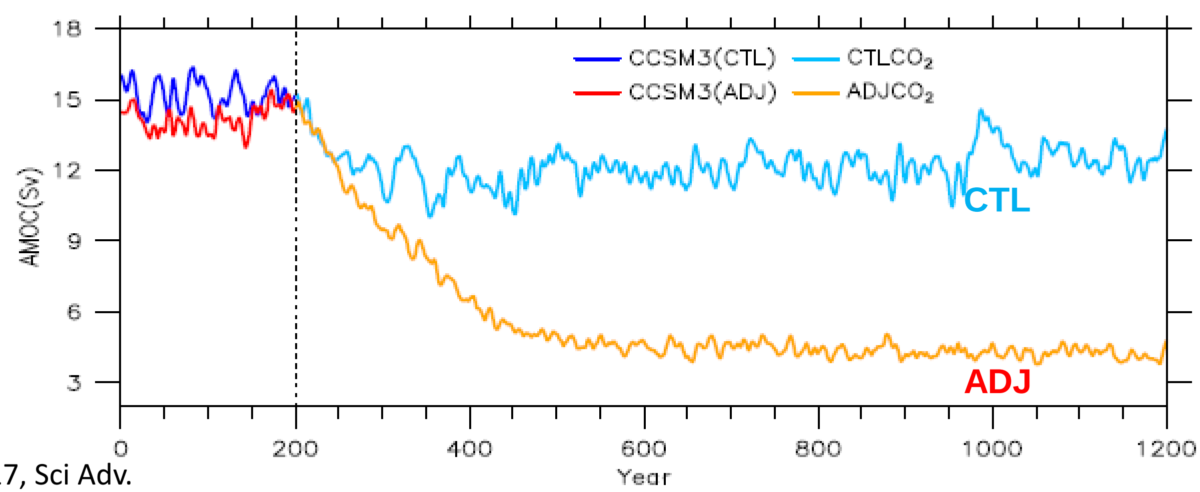
AMOC response to North Atlantic Melting Water Pulse (such as Greenland melting)



Liu et al., 2014, JC

May not be a fantasy!

AMOC response to 2xCO2



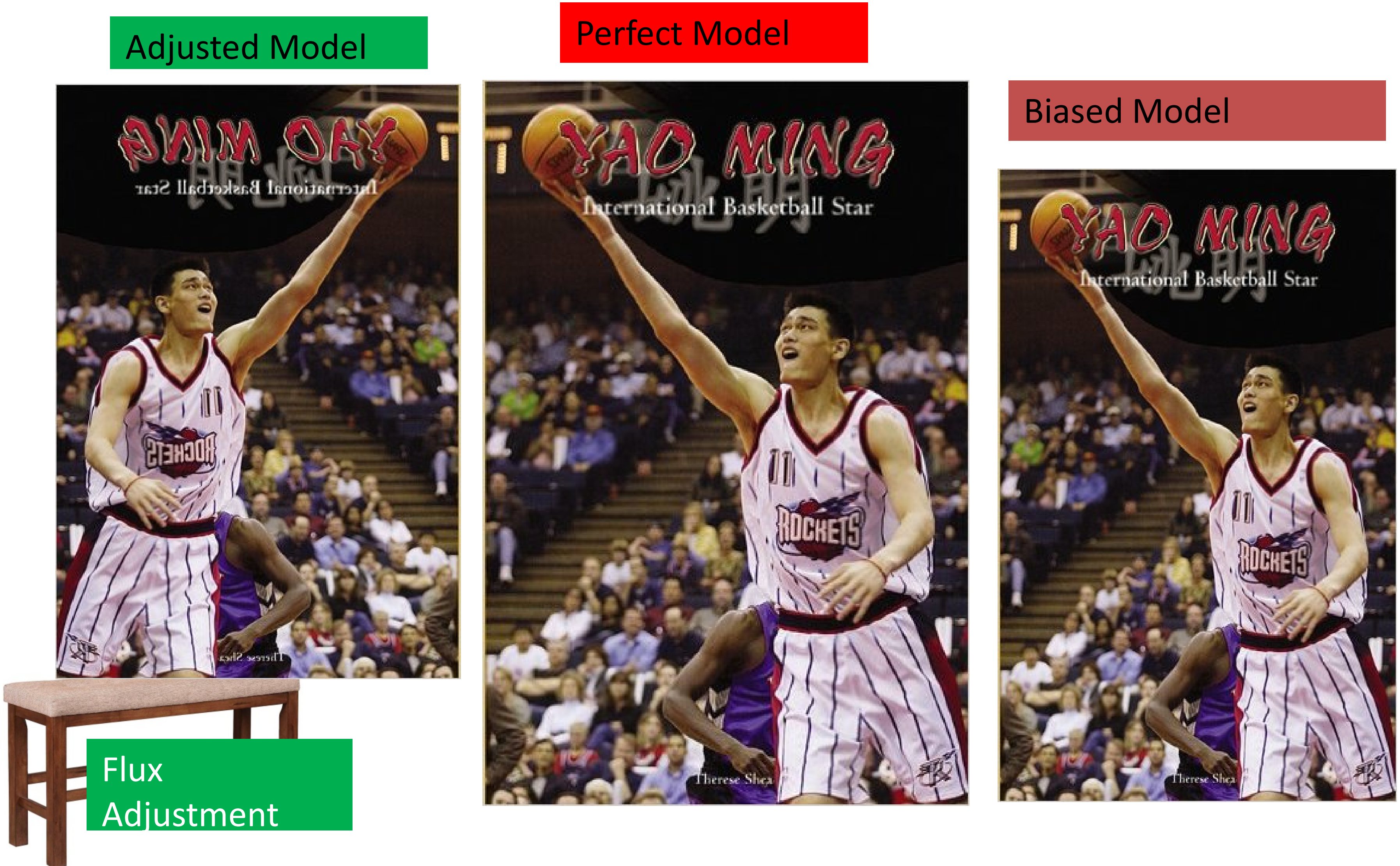
Liu et al., 2017, Sci Adv.

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?



Summary of AMOC response mechanisms

Q1: AMOC Deglacial Evolution

- Strengthened by slow CO_2 increase

  due to melting of sea ice increases surface heat loss

  time scale dependent! state dependent!
- Weakened by ice sheet retreat

  due to stronger wind sea ice expansion

➔ Opposing each other to generate an AMOC of comparable strength at LGM and Holocene

Q3: What are the relative magnitudes?

Q2: AMOC Instability

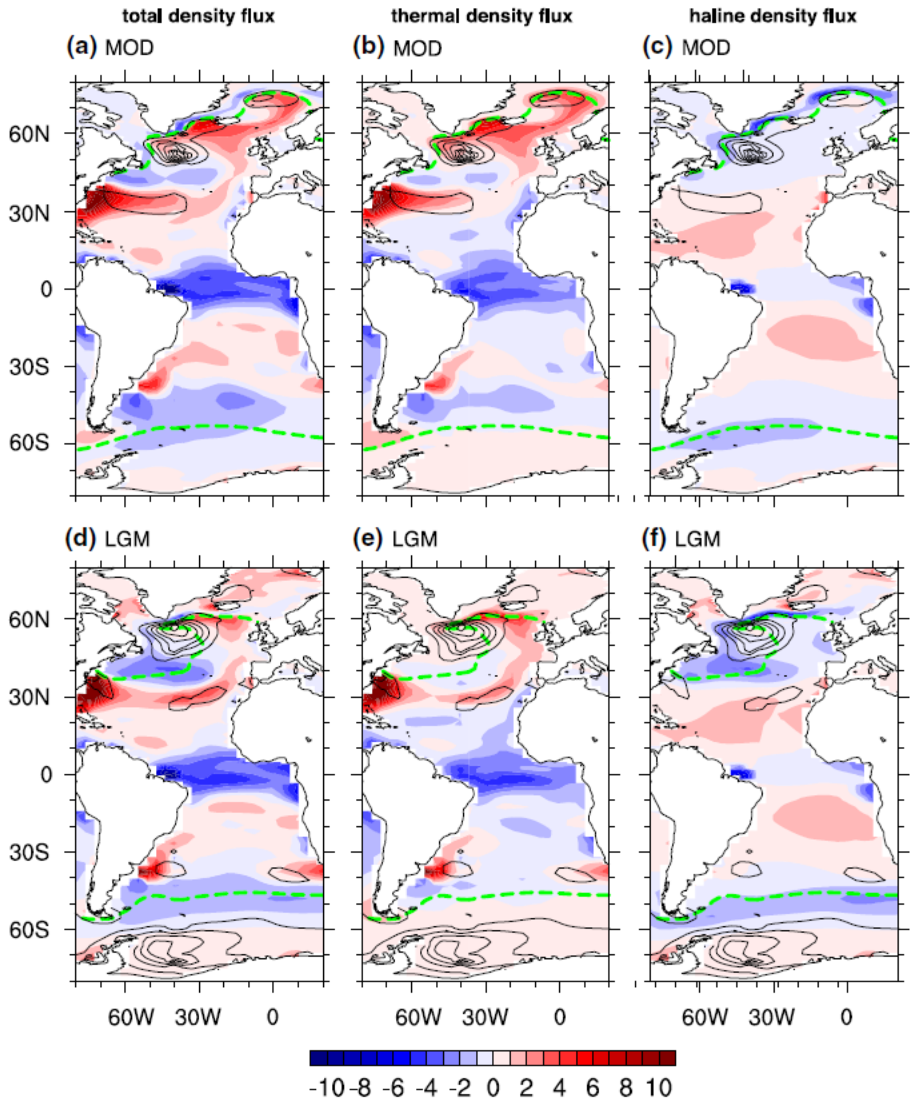
- AMOC may be more unstable than projected by current CGCMs!?

Q4: Can paleo help clarify AMOC stability?
What to do for the future, Now!?

The End

The Role of North Atlantic Sea Ice, Heat Loss

Fig. 4 *Shading* represents the Atlantic surface density flux in the control experiments, **a** the total density flux, **b** the thermal density flux and **c** the haline density flux in the modern climate (units: 10^{-6} kg m^{-2} s^{-1}). The *black contours* are the March and September mixed layer depth for the Northern and Southern Hemisphere, respectively, and the contour interval is 200 m. The *green contours* depict the annual mean sea-ice margin (defined as 15 % sea-ice coverage). **d**, **e** and **f** are the same, but for the LGM. Note that data of the last 100 years from each control simulation is used to generate its climatology, and the results do not depend on the choice of time period, because the trend in the surface state variables is very small



---Sea ice margin
----mixed layer depth
Shade: buoyancy flux

Zhu et al., 2014, CD

The Danger of Flux Adjustment !?

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

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(Manuscript received 20 June 1997,

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

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

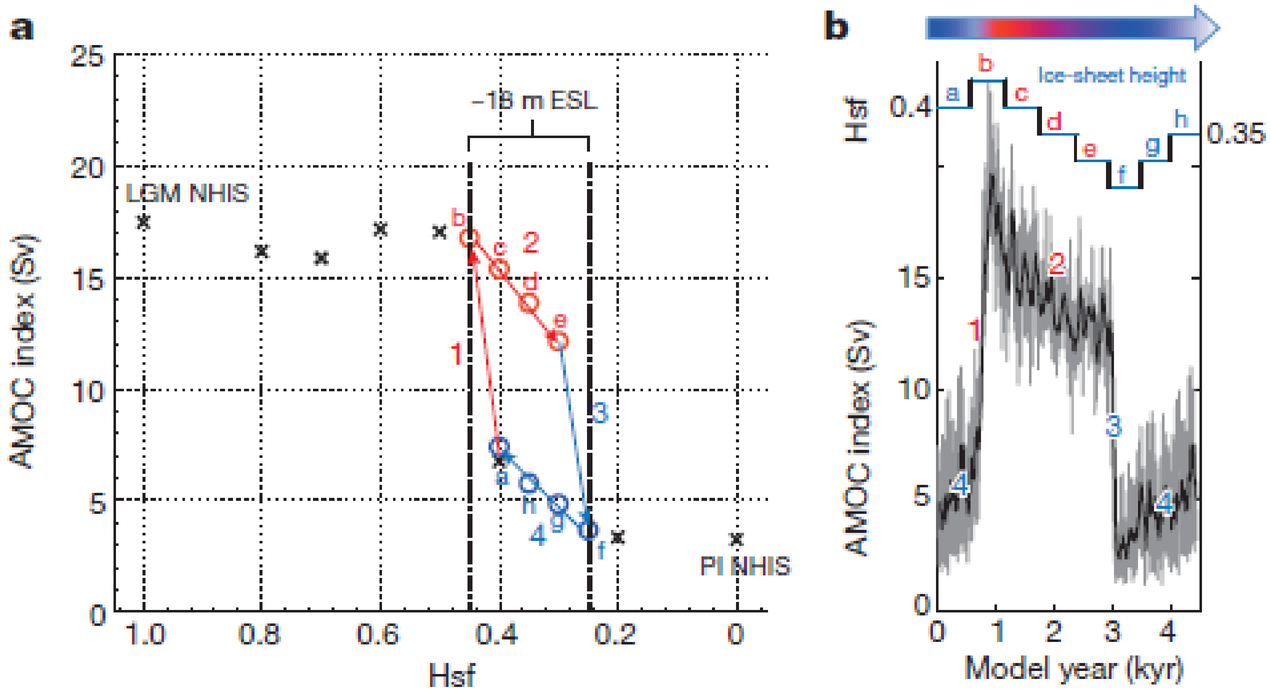
Atmospheric Transports, the Thermohaline Circulation, and Flux Adjustments in a Simple Coupled Model

JOCHEM MAROTZKE AND PETER H. STONE

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

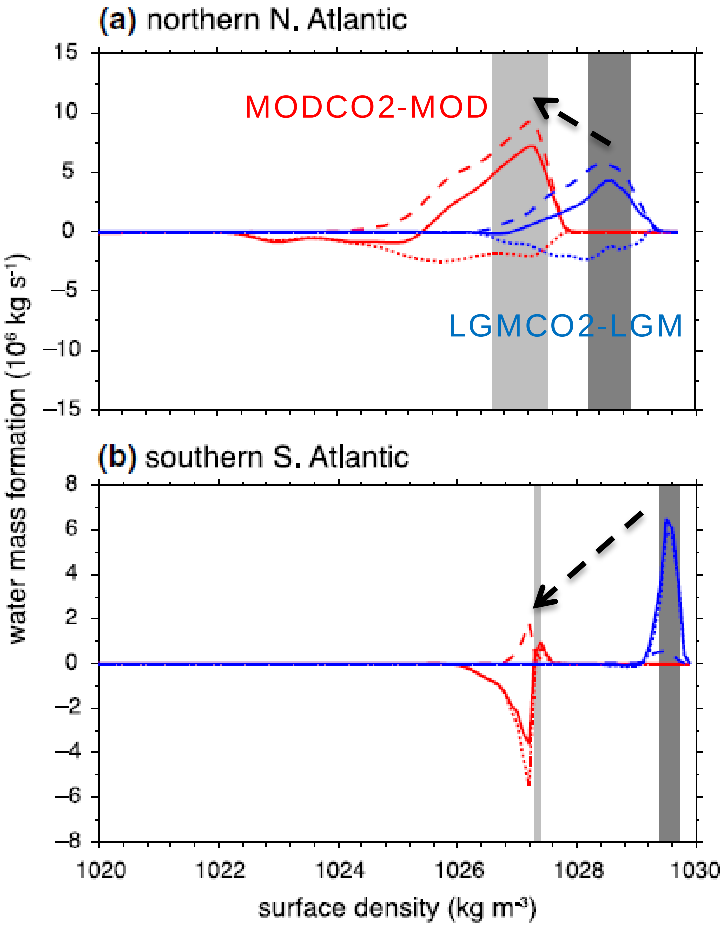
(Manuscript received 29 March 1994, in final form 18 October 1994)

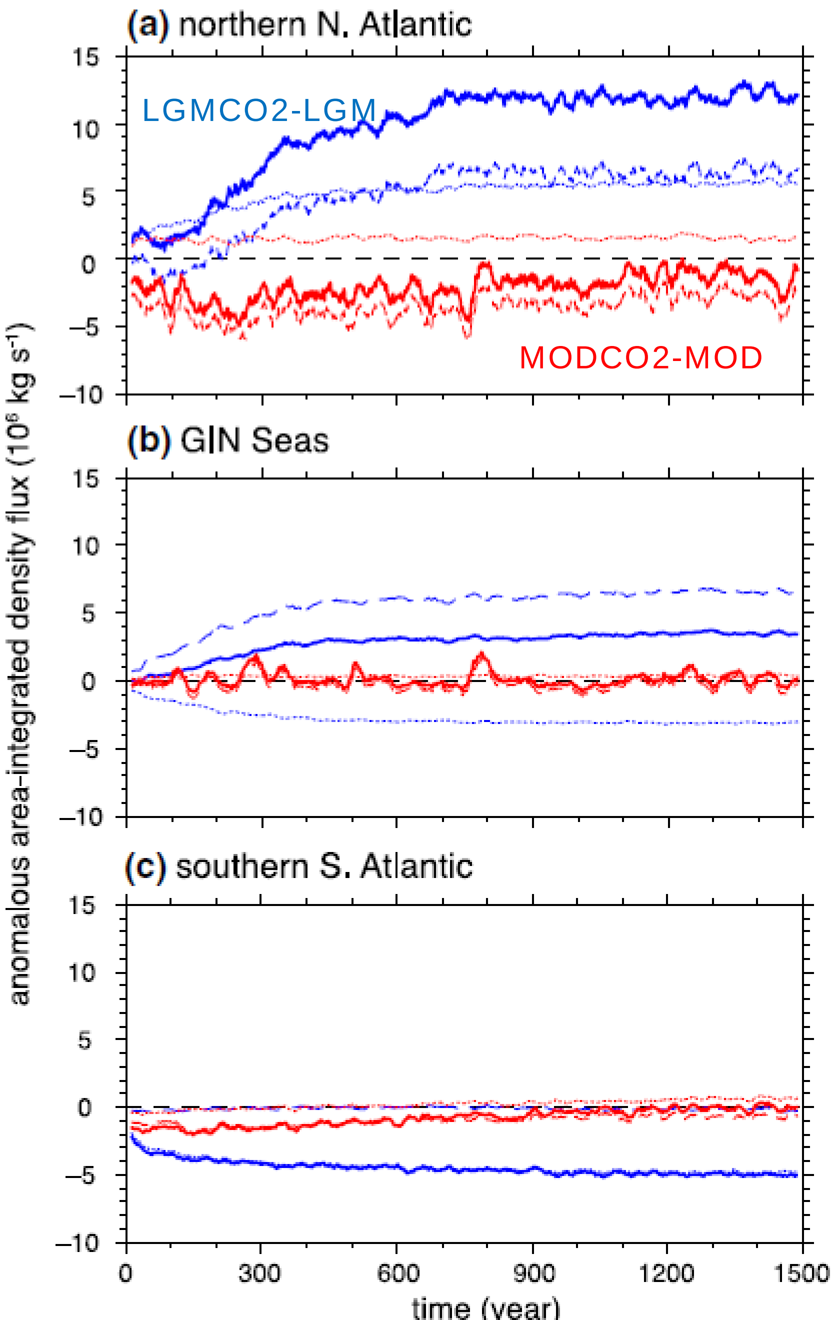
Implication to the Hysteresis response to ice sheet: Would it be reduced by CO2?



Zhang et al., 2014, Na

The Role of North Atlantic Heat Loss

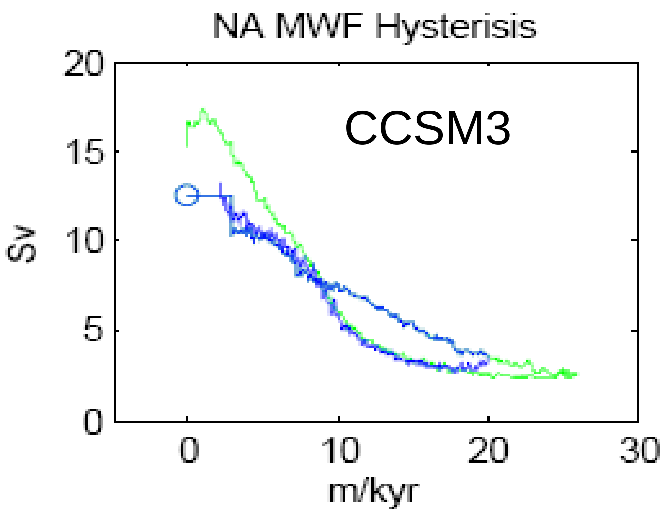




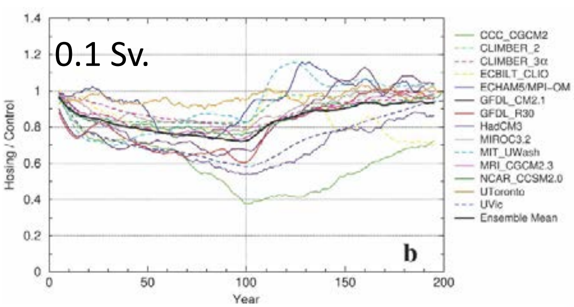
Zhu et al., 2014, CD

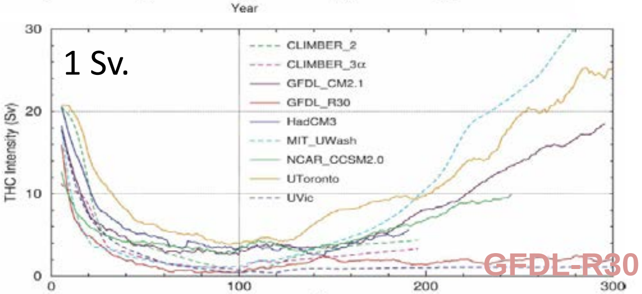
AMOC Instability in Models: Inconsistency

CGCMs



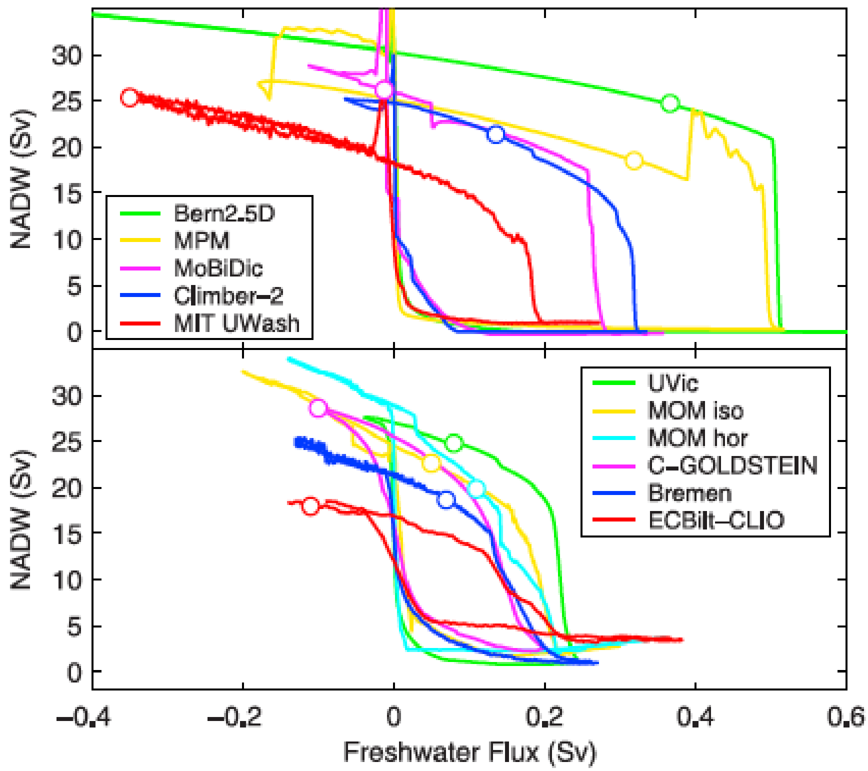
Hosing Exp.





Stouffer et al., 2006, JC

EMICs



Rahmstorf et al. 2005, GRL

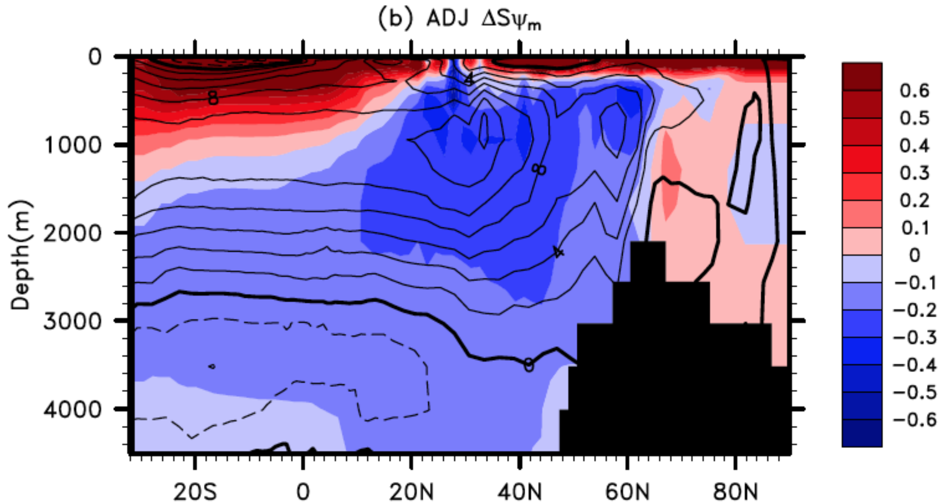
Model-Model inconsistency

Why CGCMs mono-stable, but EMICs bistable?

Attribution of climate bias on MovS

Surface Bias **Ψmean, ΔS**

ADJ-CTL



But, tropical bias is not the whole story….
Tropical adjustment, ….

Liu W. et al., 2014

ΔM_{ov} for CGCM (AR4): Monostable

Stability Indicator

	M_{ovS}	M_{ovN}	ΔM_{ov}
Observation	**-0.3 – -0.1**	**-0.16**	-0.14 – +0.06
No Flux Adjustment			
BCCR-BCM2.0 (Norway)	**0.023**	**-0.127**	**0.150**
CCSM3(T85) (USA)	**0.078**	**-0.185**	**0.263**
CNRM-CM3 (France)	**0.290**	**-0.097**	**0.387**
CSIRO-MK2.0 (Australia)	**-0.030**	**-0.465**	**0.435**
UKMO-HadCM3 (UK)	**0.359**	**-0.013**	**0.372**
IPSL-CM4 (France)	**-0.008**	**-0.128**	**0.120**
MIRCO3.2(medres) (Japan)	**-0.004**	**-0.110**	**0.106**
CCSM3(T31) (USA)	**-0.013**	**-0.127**	**0.114**
Ensemble Mean	**0.1**	**-0.16**	**0.26**
Flux Adjustment			
CGCM3.1(T63) (Canada)	**-0.118**	**-0.082**	-0.036
MRI-CGCM2.3.2 (Japan)	**-0.080**	**-0.160**	**0.080**
ECHO-G (Germany-Korea)	**0.046**	**-0.009**	**0.055**
CCSM3(T31_ADJ) (USA)	**-0.197**	**-0.095**	-0.102
Ensemble Mean	**-0.1**	**-0.086**	-0.01

>0 => Monostable

<0 => Bistable

No Flux Adj: **mono-stable;** Flux Adj**: bi-stable!**

➔ CGCM in AMOC Stability: Overstabilization

Liu , W. et al., 2014, JC

Summary for AMOC Bistability

ΔM_{ov} seems to work best!

AMOC is likely weakly bi-stable in real world;

AMOC is over-stabilized in most CGCMs, because of, at least partly, the tropical bias.

Summary

AMOC Deglacial Evolution

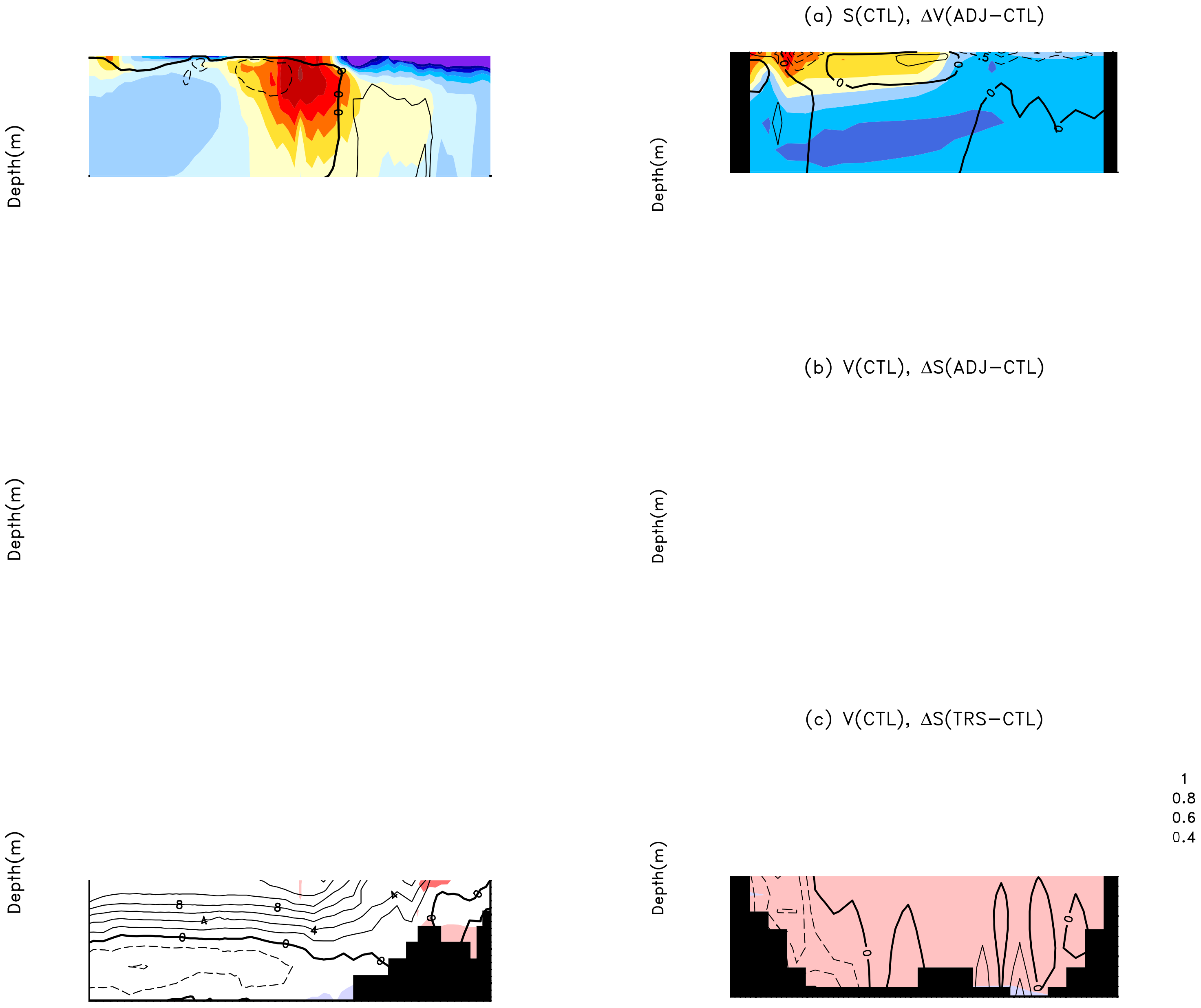
AMOC is intensified by slow CO2 increase (time scale dependent, state dependent), but reduced by ice sheet retreat such that AMOC is of comparable strength at LGM and Holocene

Implications: Future projection can't simply use glaical evolution as analogy, because of different time scales, climate states and different forcings

AMOC Instability

AMOC is likely weakly bi-stable in real world;
AMOC is over-stabilized in most CGCMs, because of, at least partly, the tropical bias.

Implications: Future abrupt change may be underestimated in current CGCMs?

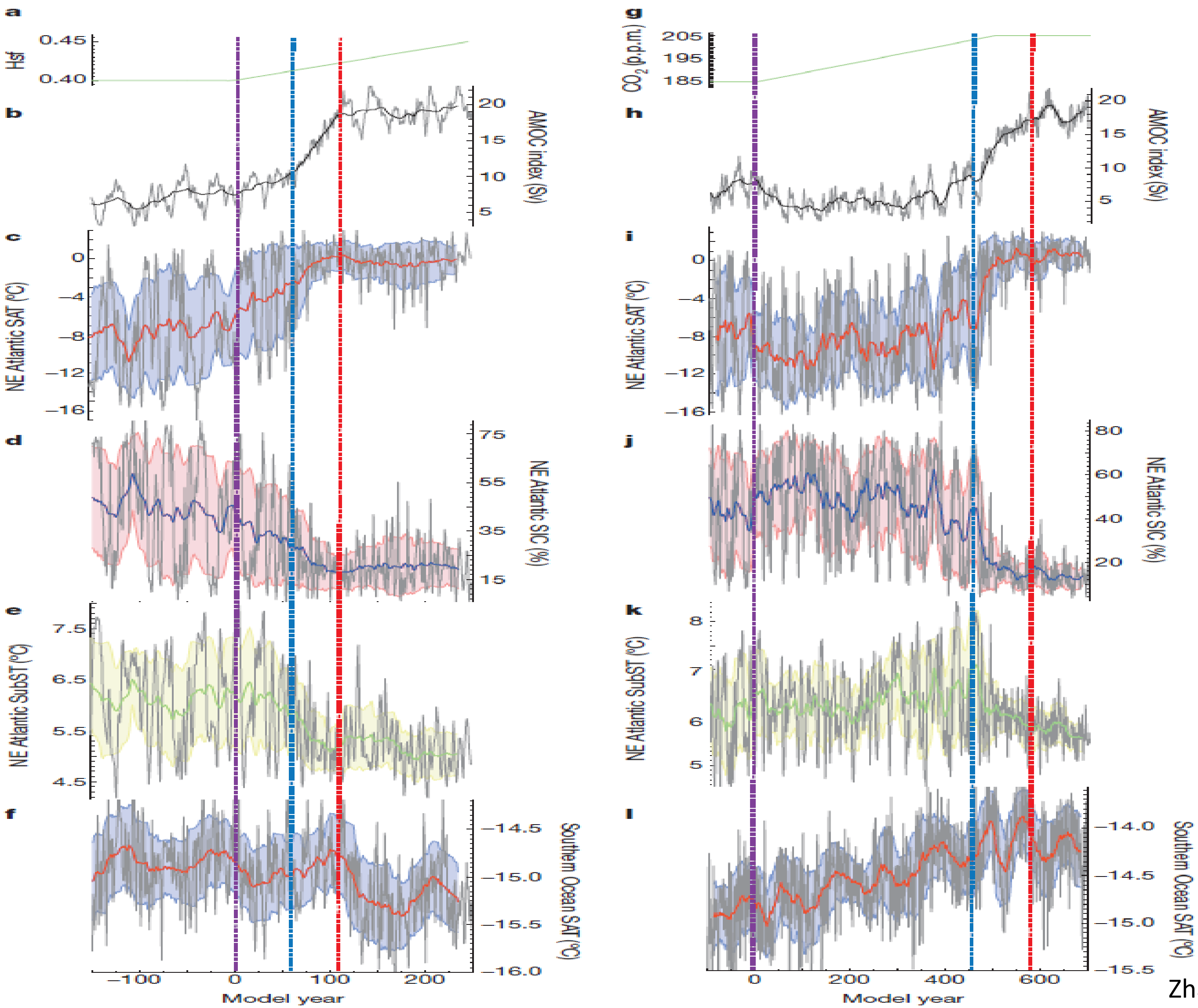


(a) S(CTL), ΔV(ADJ−CTL)
(b) V(CTL), ΔS(ADJ−CTL)
(c) V(CTL), ΔS(TRS−CTL)
Depth(m)
Depth(m)
Depth(m)
Depth(m)
Depth(m)
Depth(m)
1
0.8
0.6
0.4

ECHAM5-
JSBACH-MPIOM

Increasing NHIS

Increasing CO2



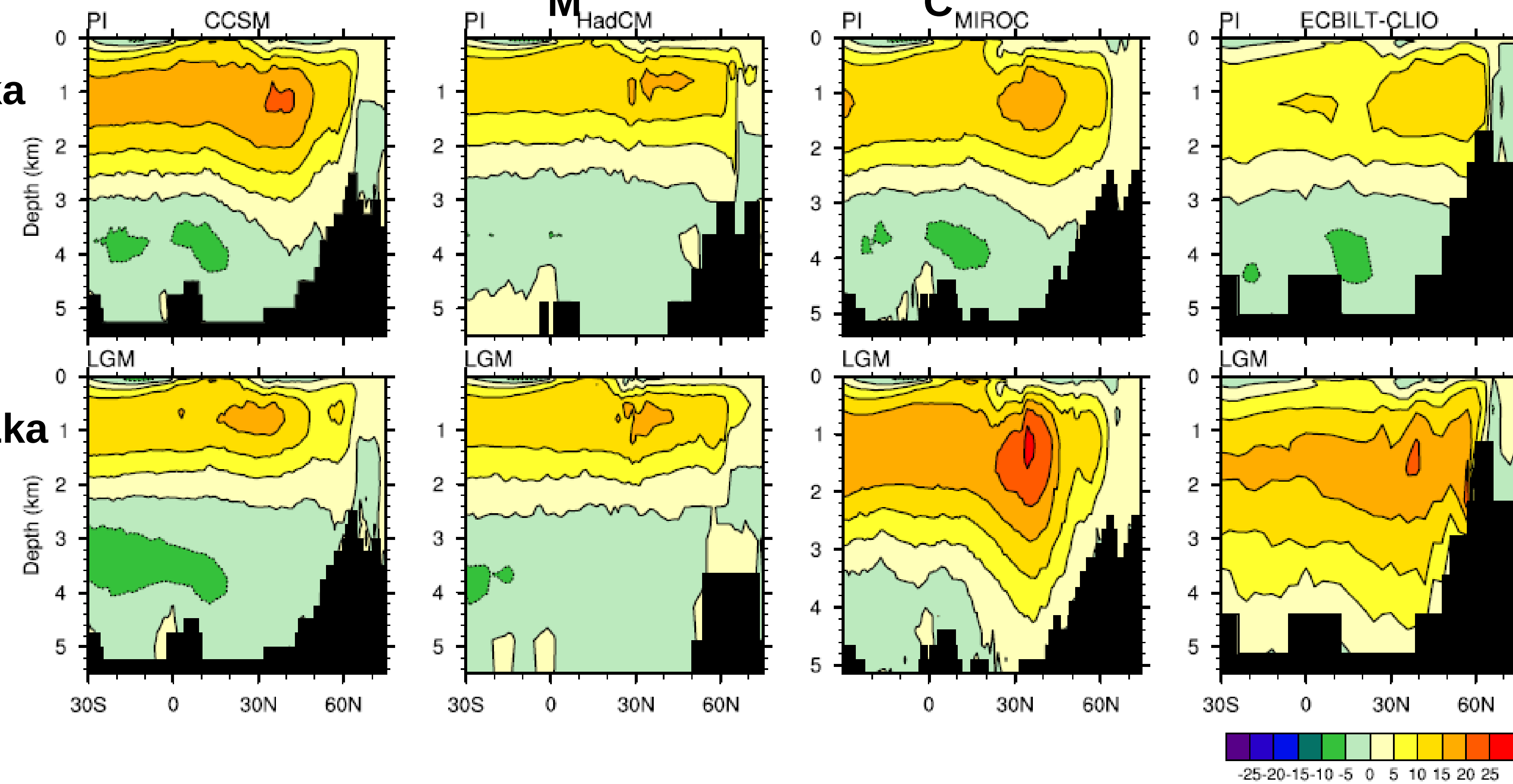
Zhang et al., 2014

LGM Thermohaline: PMIP2

CCSM | **HadCM** | **MIROC** | **ECBILT_CLIO**

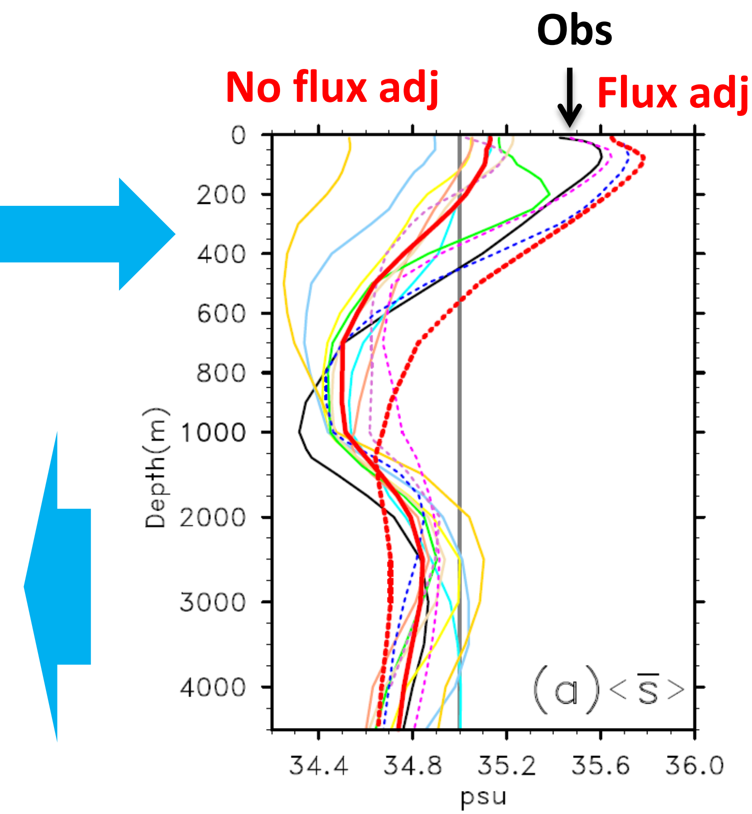
0ka

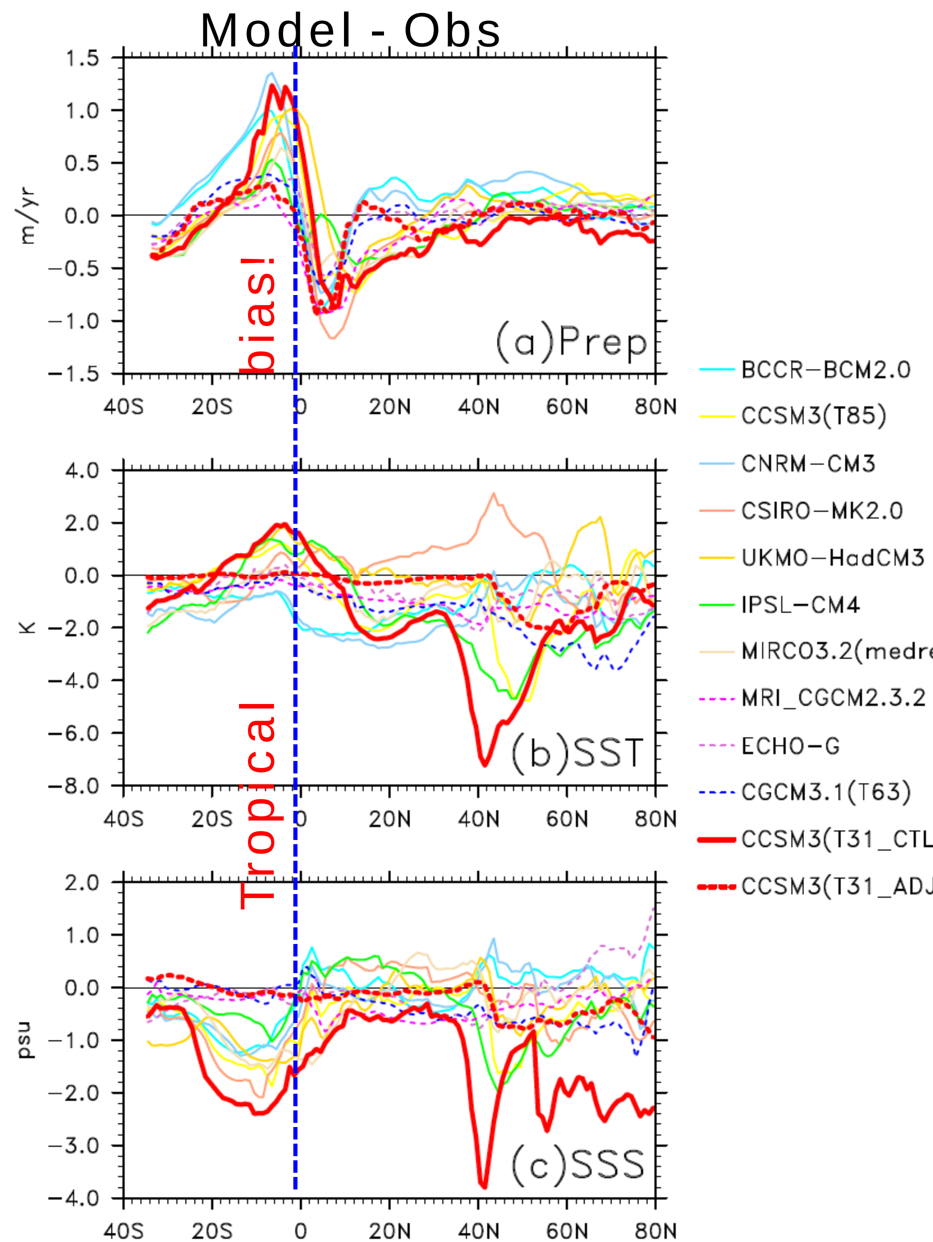
21ka



Otto-Bliesner et al., 2007, GRL

Freshwater Transport and Tropical Bias (in AR4 CGCMs)





Liu et al., ,2014, JC