Paleoclimatic constraints on climate sensivity

learning from paleoclimate modelling:
last glacial maximum
mid-Holocene

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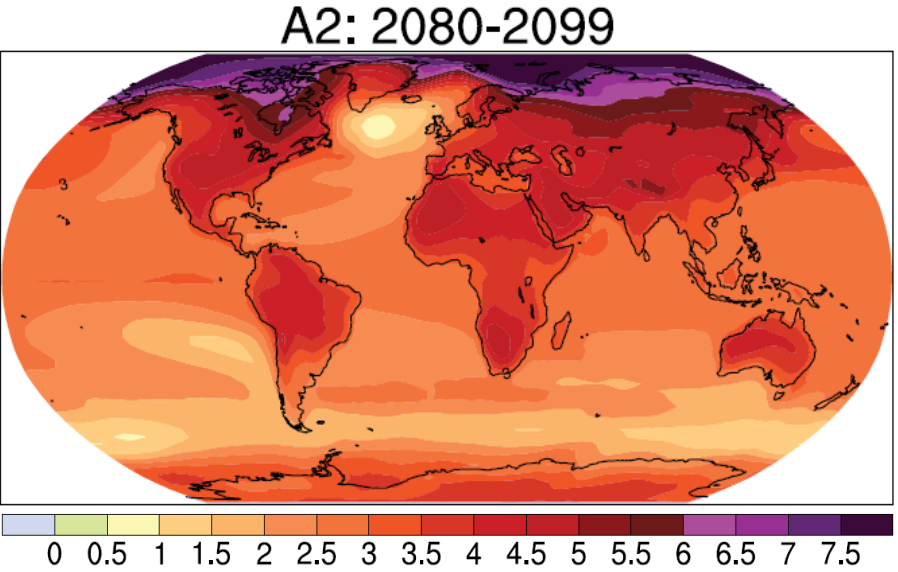
http://www.gisclimat.fr

Projections of future global warming

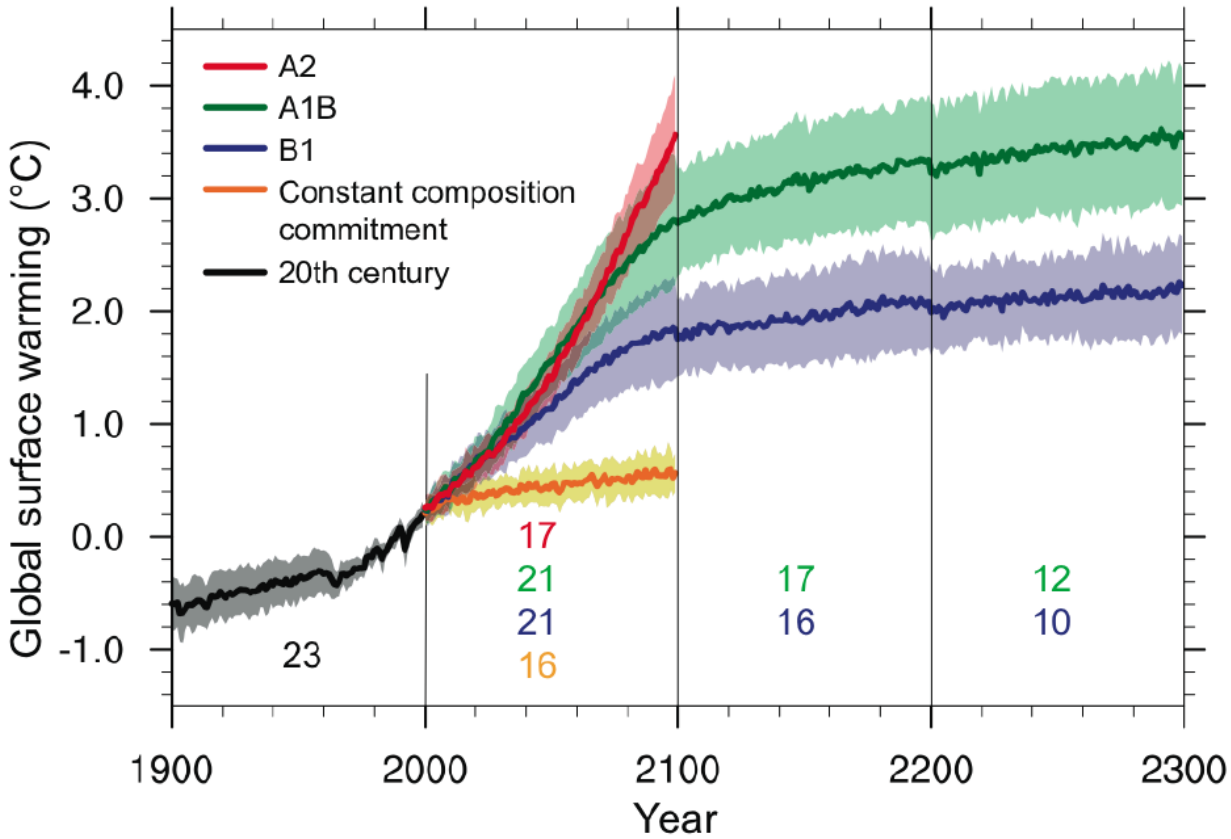


CO_2 in 2100

- ~ 850 ppm
- ~ 700 ppm
- ~ 550 ppm

CO_2 constant

- ~ 370 ppm



Paleoclimate Modelling

PMIP

Intercomparison Project

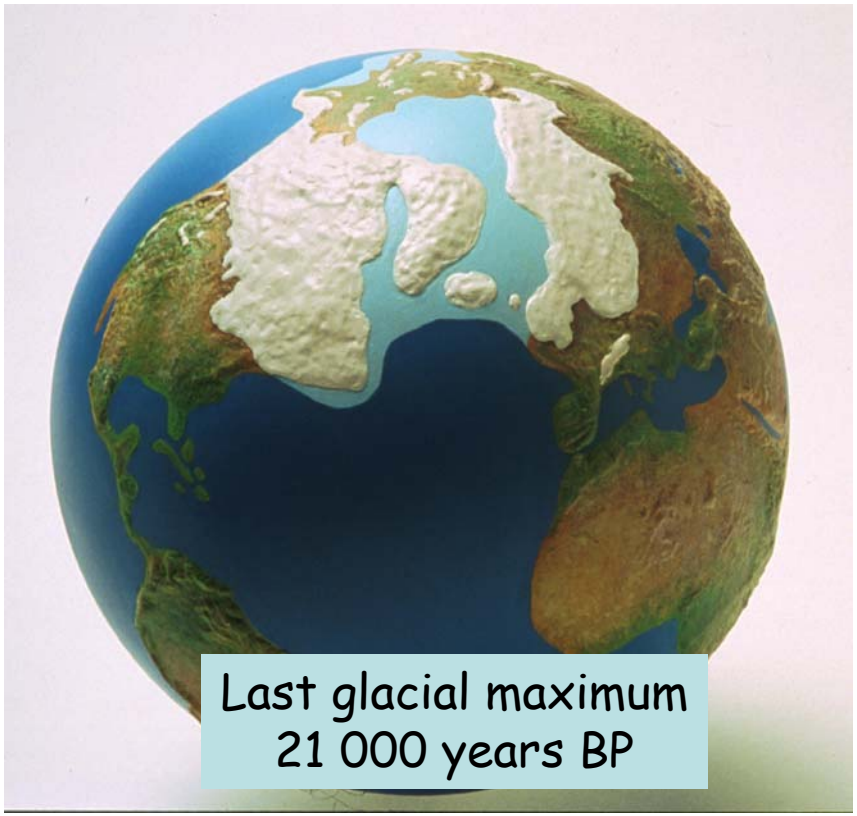
Phase II

WCRP/CLIVAR & IGBP/PAGES

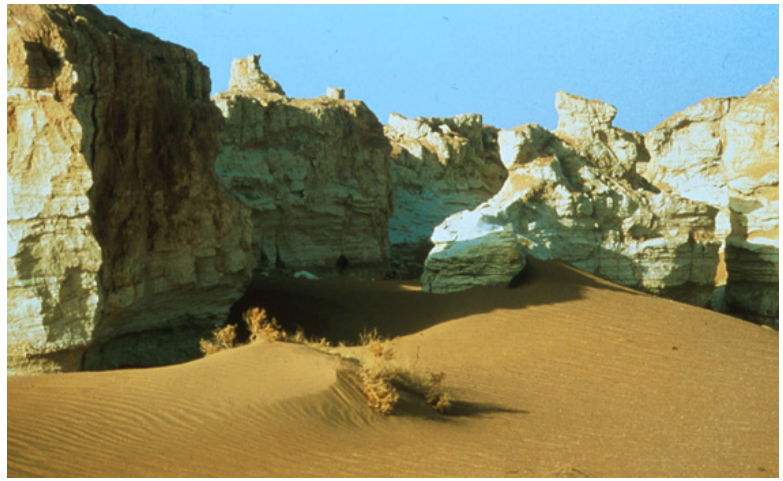
http://pmip2.lsce.ipsl.fr/

Evaluate climate models

Understand past climates

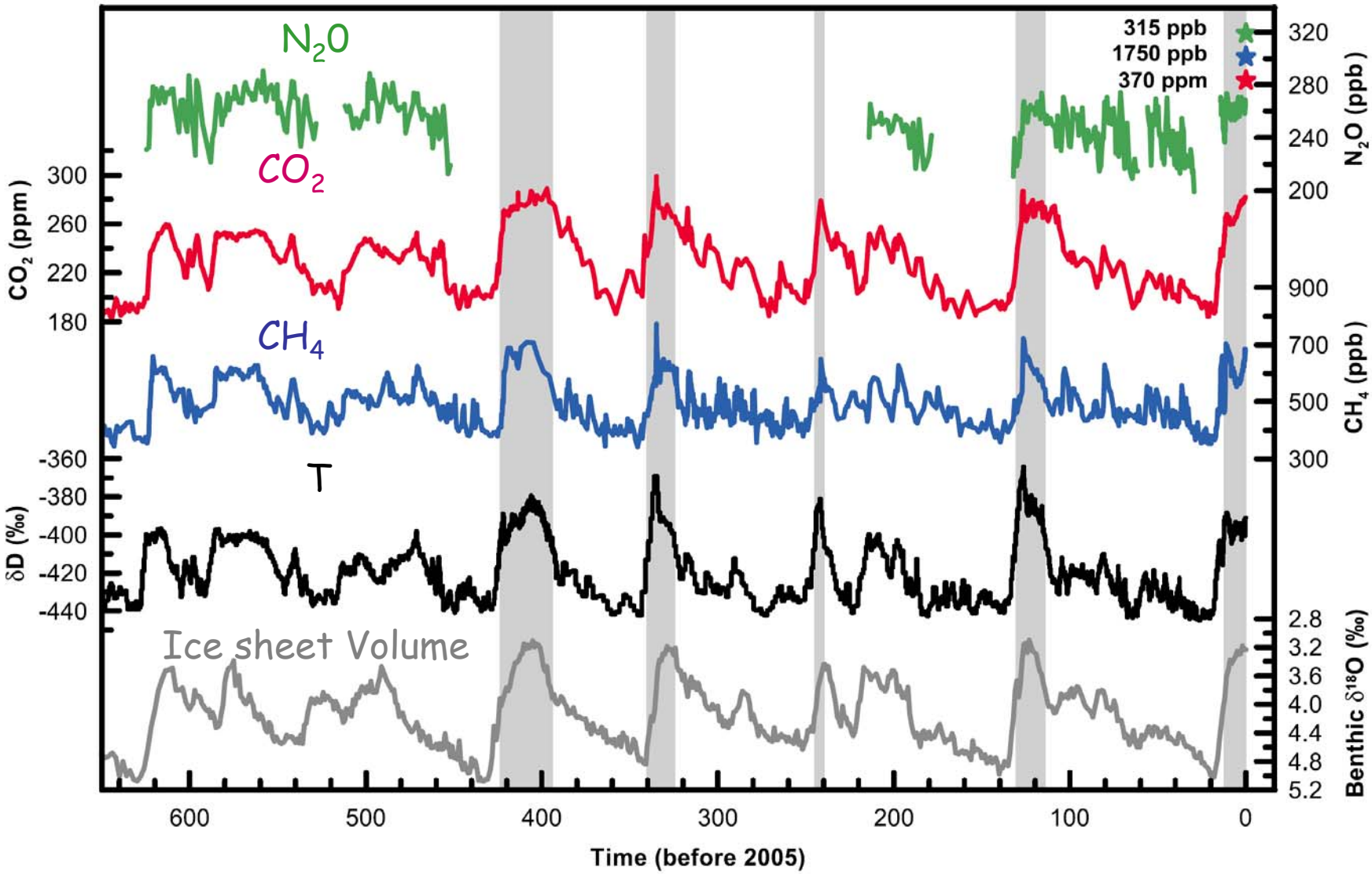


Last glacial maximum
21 000 years BP

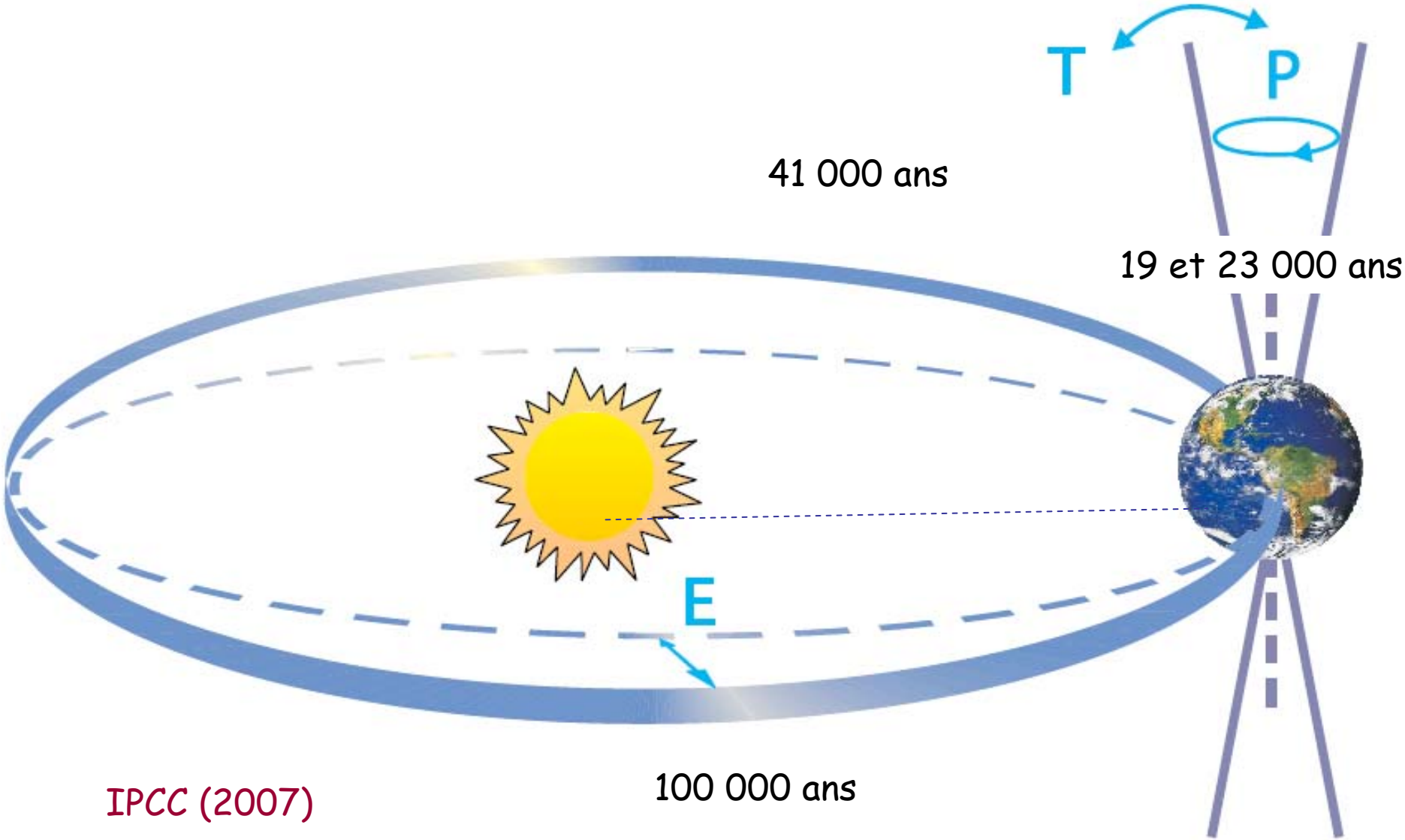


Mid-Holocene
6000 years BP

Source : EPICA community members, Nature 2004



Astronomy theory of glacial-interglacial cycles (Milankovitch)



IPCC (2007)

Paleoclimate Modelling

- Prescribe « boundary conditions »

Last Glacial Maximum : ice sheets, atmospheric composition, insolation

- First experiments :

AGCMs : prescribed SSTs Williams et al. (1974);

SST from CLIMAP (1976) : Gates (1976); Manabe and Hahn (1977)

- CLIMAP (1981) : reconstruction of LGM SST, ice sheets, vegetation albedo

Hansen et al. (1984); Manabe and Broccoli (1985); Rind (1987); Joussaume (1993) …

COHMAP (1987) : Kutzbach et al.

Model-data comparison every 3000 years

PMIP:
Paleoclimate Modelling Intercomparison Project

Coordinated numerical experiments : same "boundary conditions"

- **Objectives:**
  - Understand mechanisms of past climate change
  - Evaluate the ability of climate models to simulate different climates
  - Evaluate roles of feedbacks from the different climate subsystems

- **How :**
  - Simulations with climate models for key periods in the past
  - Data syntheses
  - Model-data comparisons

- PMIP1 : 1991-2001 / Atmosphere models or atmosphere + slab ocean

IPCC TAR (2001)

- PMIP2 : 2002-2007 / Coupled atmosphere-ocean model or atmosphere-ocean-vegetation models

IPCC AR4 (2007)

http://pmip2.lsce.ipsl.fr/

Paleoclimate Modelling PMIP Intercomparison Project Phase II

Status of PMIP2 database

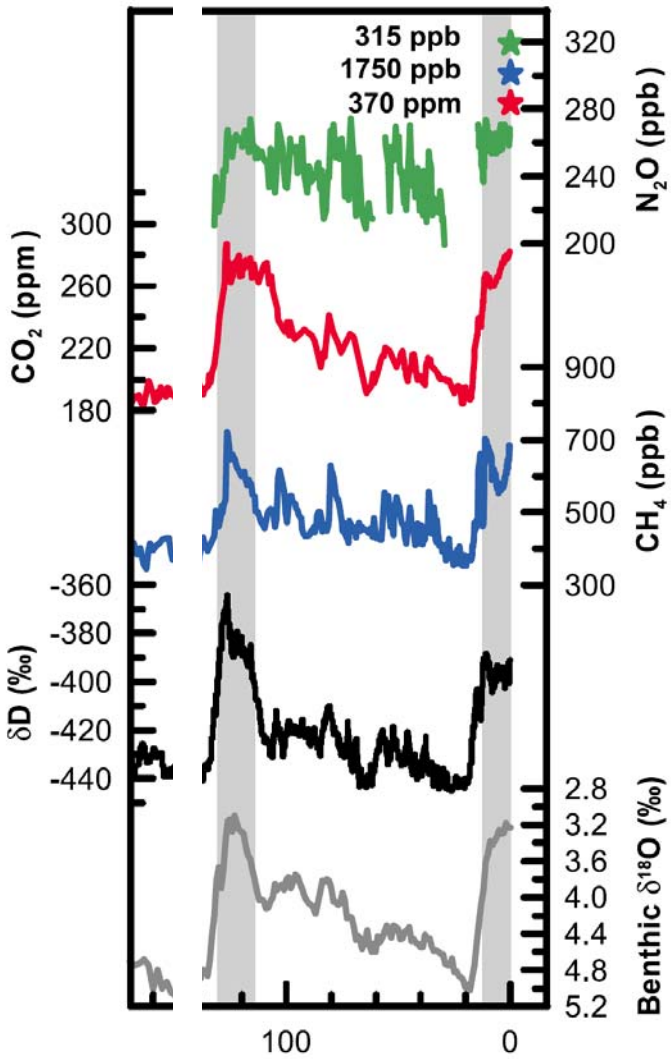
Model	Updated	OA			OAV		
		0	6	21	0	6	21
CCSM	09/20/2006	X	X	X			
CNRM-CM33	09/05/2008	X		X			
CSIRO-Mk3L-1.0	07/21/2008	X	X				
CSIRO-Mk3L-1.1	07/21/2008	X	X				
ECBILTCLIO	04/12/2007	X		X			
ECBILTCLIOVECODE	02/08/2006	X	X		X	X	
ECHAM5-MPIOM1	03/06/2006	X	X				
ECHAM53-MPIOM127-LPJ	09/05/2008	X	X	X	X	X	X
FGOALS-1.0g	09/01/2008	X	X	X			
FOAM	04/27/2005	X	X		X	X	
GISSmodelE	04/17/2008	X	X				
HadCM3M2	07/27/2006	X		X	X		X
IPSL-CM4-V1-MR	09/04/2008	X	X	X			
MIROC3.2	04/28/2005	X	X	X			
MIROC3.2.2	03/07/2007	X		X			
MRI-CGCM2.3.4fa	09/03/2008	X	X		X	X	
MRI-CGCM2.3.4nfa	09/03/2008	X	X		X	X	
UBRIS-HadCM3M2	08/08/2005	X	X		X	X	

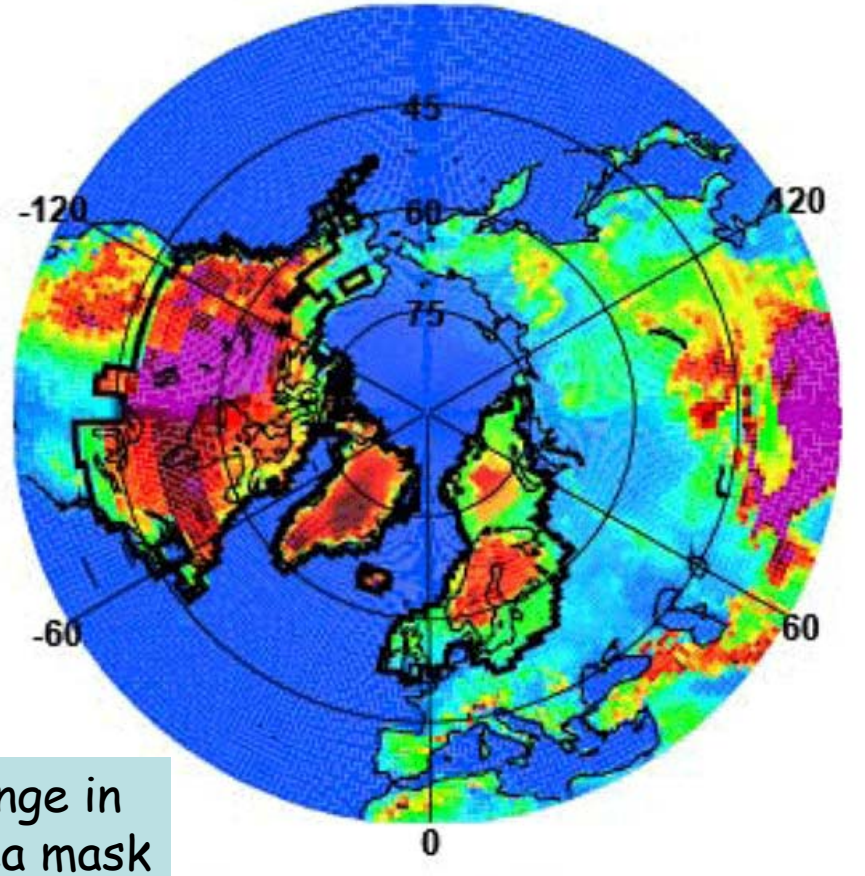
Model	Updated	OA			OAV		
		0	6	21	0	6	21

PMIP2 LGM Forcings and Boundary Conditions

Paleoclimate Modelling PMIP Intercomparison Project Phase II

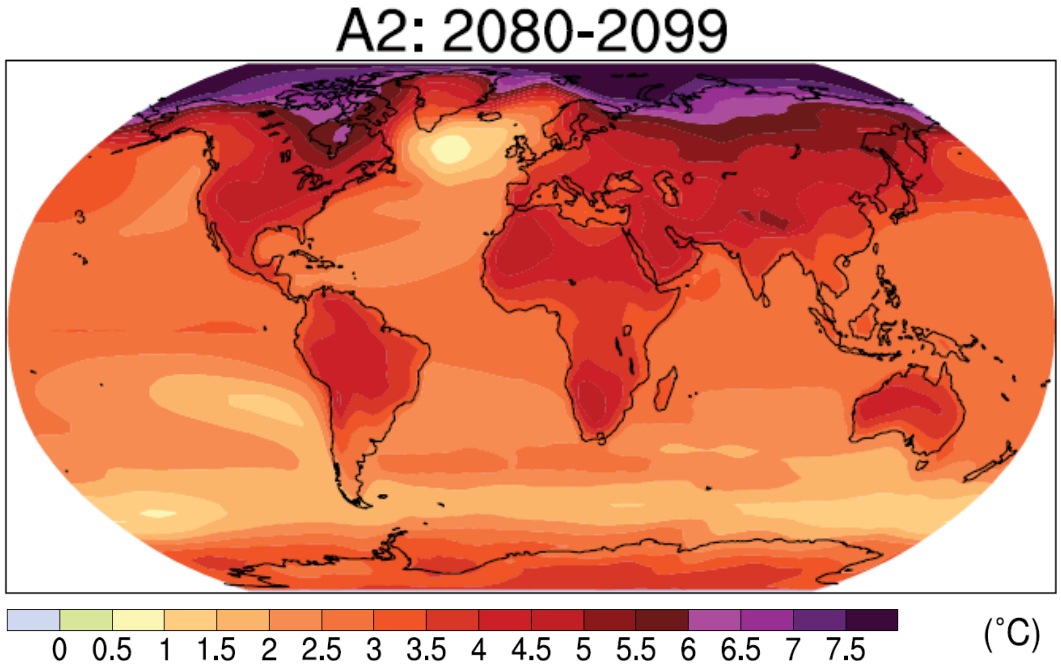
Last Glacial Maximum (LGM, ca. 21 ky ago):
climate response to low greenhouse gas concentrations and large ice sheets





& change in land-sea mask

Peltier et al., 1994

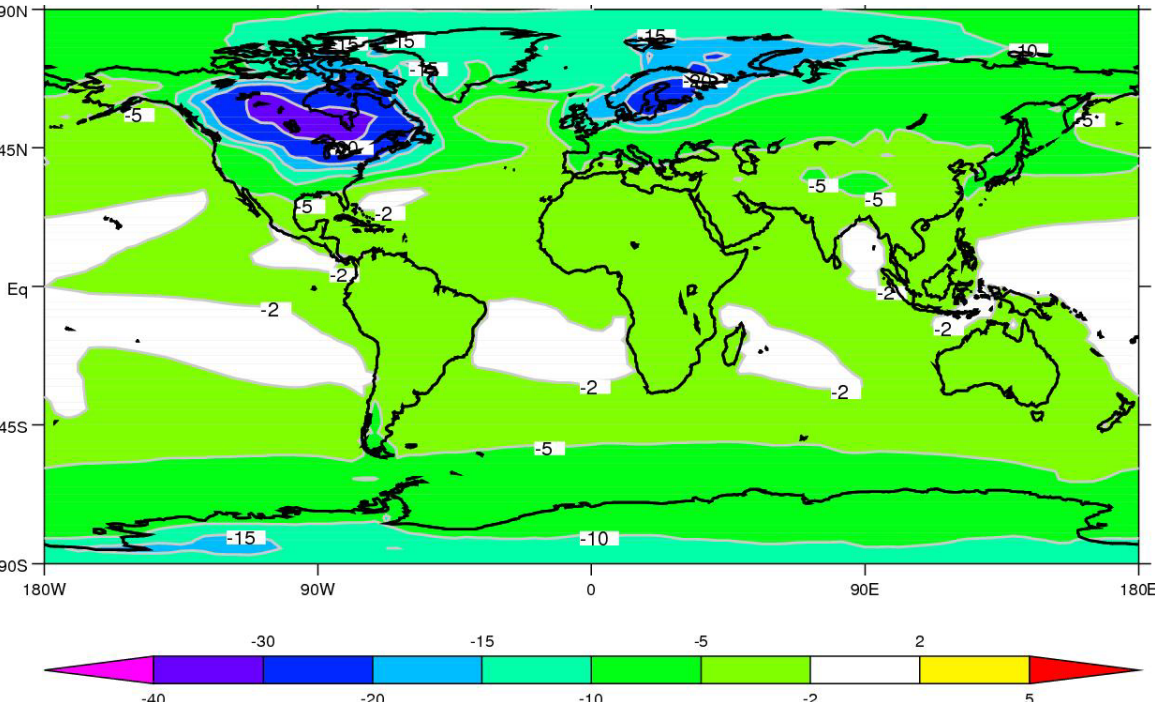


Annual mean change in temperature

CMIP3 OA multimodel

+3° to 4°C

IPCC (2007)



PMIP2 OA multimodel

LGM minus present

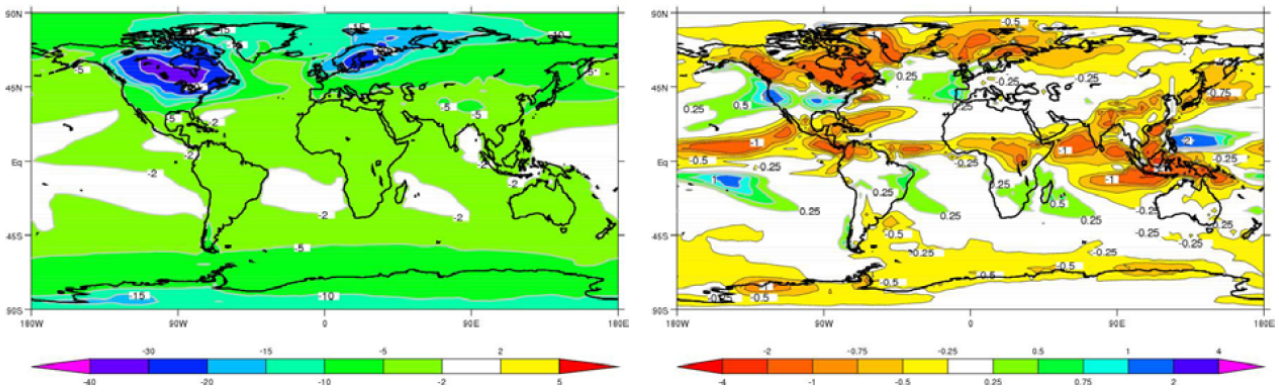
-3,6°C to -5,7°C

5 coupled models

Braconnot et al (CP, 2007a)

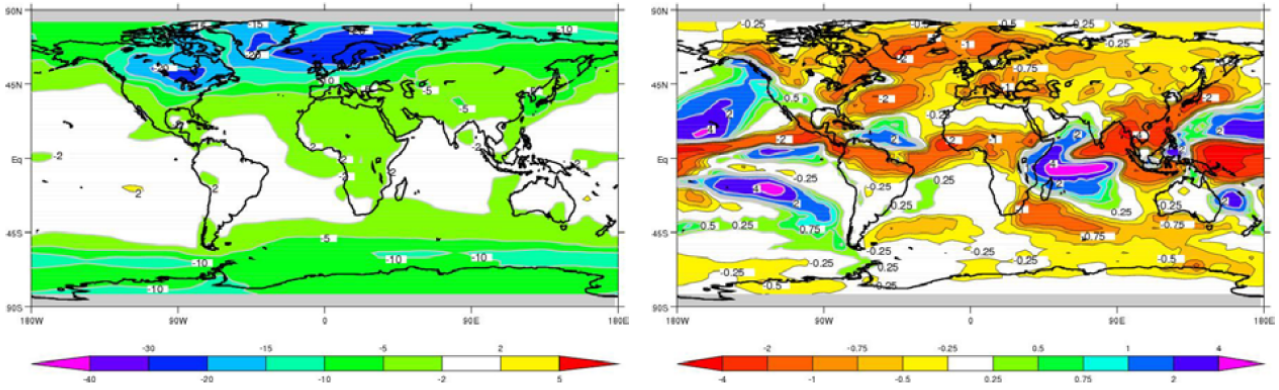
(a) PMIP2 OA mean model

-3.6 °C
to
-5.7 °C



(b) PMIP1 SSTf mean model

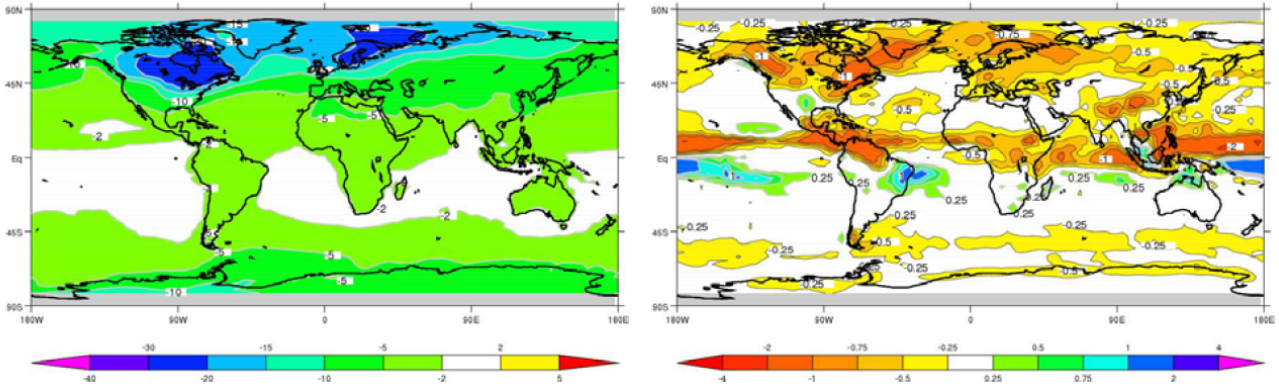
-3.3 °C
to
-4.7 °C



(c) PMIP1 SSTc mean model

Braconnot et al (CP, 2007a)

-2 °C
to
-6 °C



« Climate sensitivity »

- Can we infer climate sensitivity using the past ?

  Is climate sensitivity the same for past and future ?

- Can we evaluate/constrain model climate sensitivity using the past ?

or

Can we evaluate model capabilities for the past ?

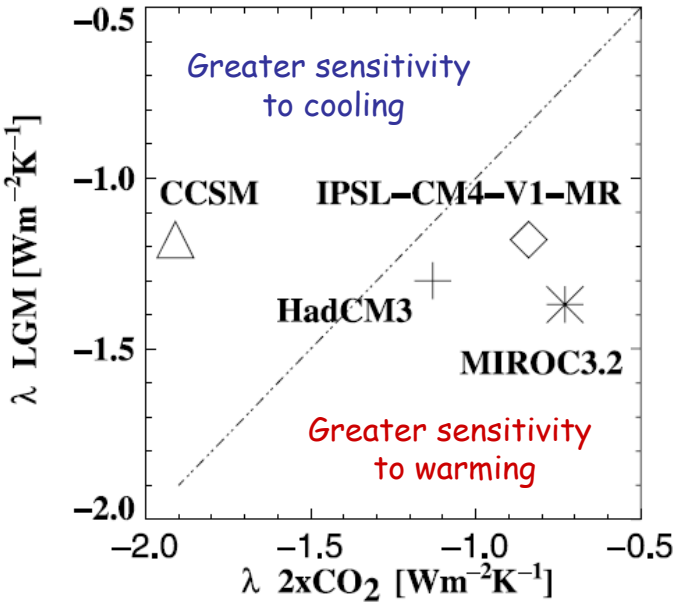
Climate sensitivity at LGM – Comparison with 2x CO2

- $\lambda_{LGM} = 0.85\ \lambda_{2XCO2}$ Hewitt and Mitchell, Clim Dyn (1987) with HADSM2 slab ocean

Greater sensitivity to cooling

- Crucifix (GRL, 2006) with PMIP2 AOGCMs

$\lambda = - \Delta F / \Delta T$

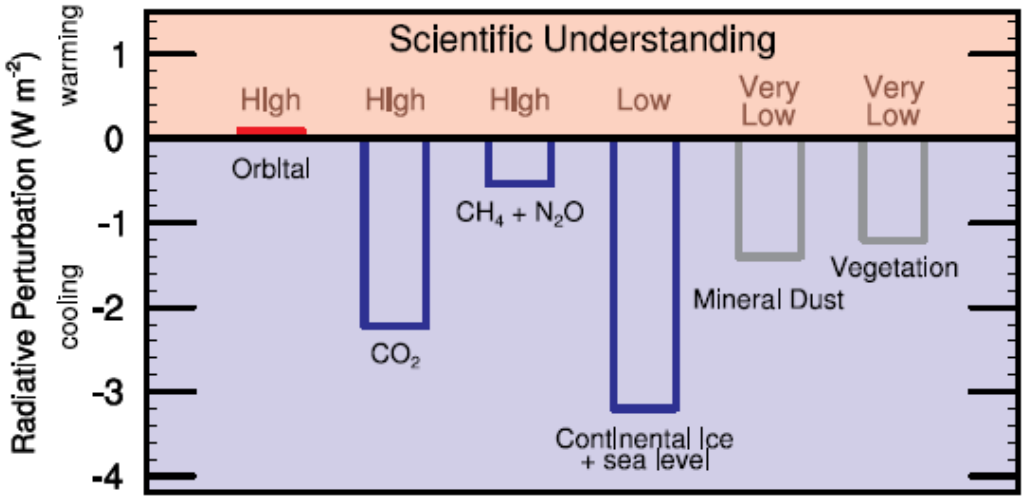


LGM : ΔF albedo forcing from approximate PRP (Taylor et al., J clim, 2007)

M. Crucifix :
« Climate sensitivity cannot be directly estimated from LGM »

Q_{LGM} greenhouse gases = -2.8 Wm^{-2}
Q_{LGM} insolation orbital = +0.1 Wm^{-2}

IPCC WG1 Chapter 6, 2007



$\Delta TS_{LGM} / Q_{LGM} = 1/\lambda$ $\quad 1/\lambda \times Q_{2xCO2} = \Delta TS_{2xCO2}$ (3.7 W/m^2)

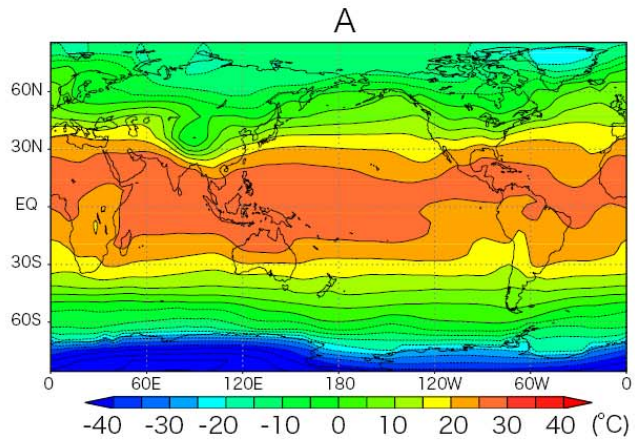
	ΔTS (°C) LGM - PI Global	Q (W/m^2) Ice sheet + sea level	Q (W/m^2) Total	1/λ (°C per W/m^2)	ΔTS $2xCO_2$ Global LGM est.	ΔTS $2xCO_2$ Global Slab ocean
ECBilt-CLIO	-3.1	-1.8	-4.5	0.69	2.6	---
CCSM	-4.5	-2.7	-5.4	0.83	3.1	2.5
FGOALS	-5.1	-3.5	-6.2	0.82	3.0	---
HadCM	-5.1	-4.0	-6.7	0.76	2.8	3.3
IPSL	-3.3	-1.5	-4.2	0.78	2.9	4.4
MIROC	-3.7	-2.3	-5.0	0.74	2.7	4.0

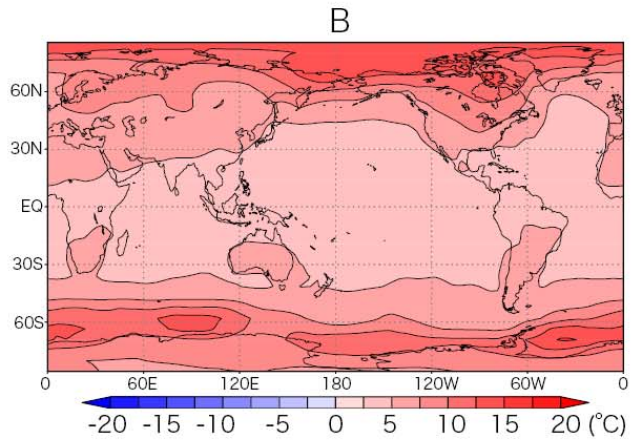
Otto-Bliesner et al., Clim.Dyn., 2008

Perturbed physics experiments

MIROC AGCM & slab ocean – 119 exp
change of model parameters both LGM & 2x CO2

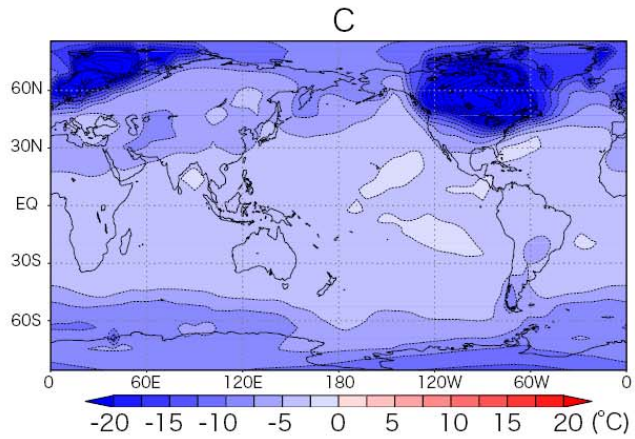
Hargreaves et al. (CP, 2007)



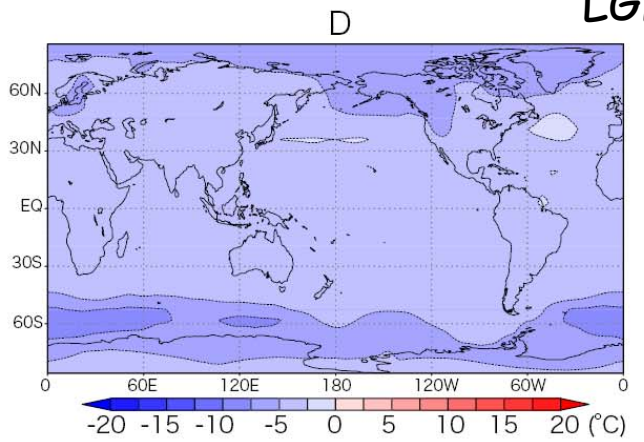


2 x CO2

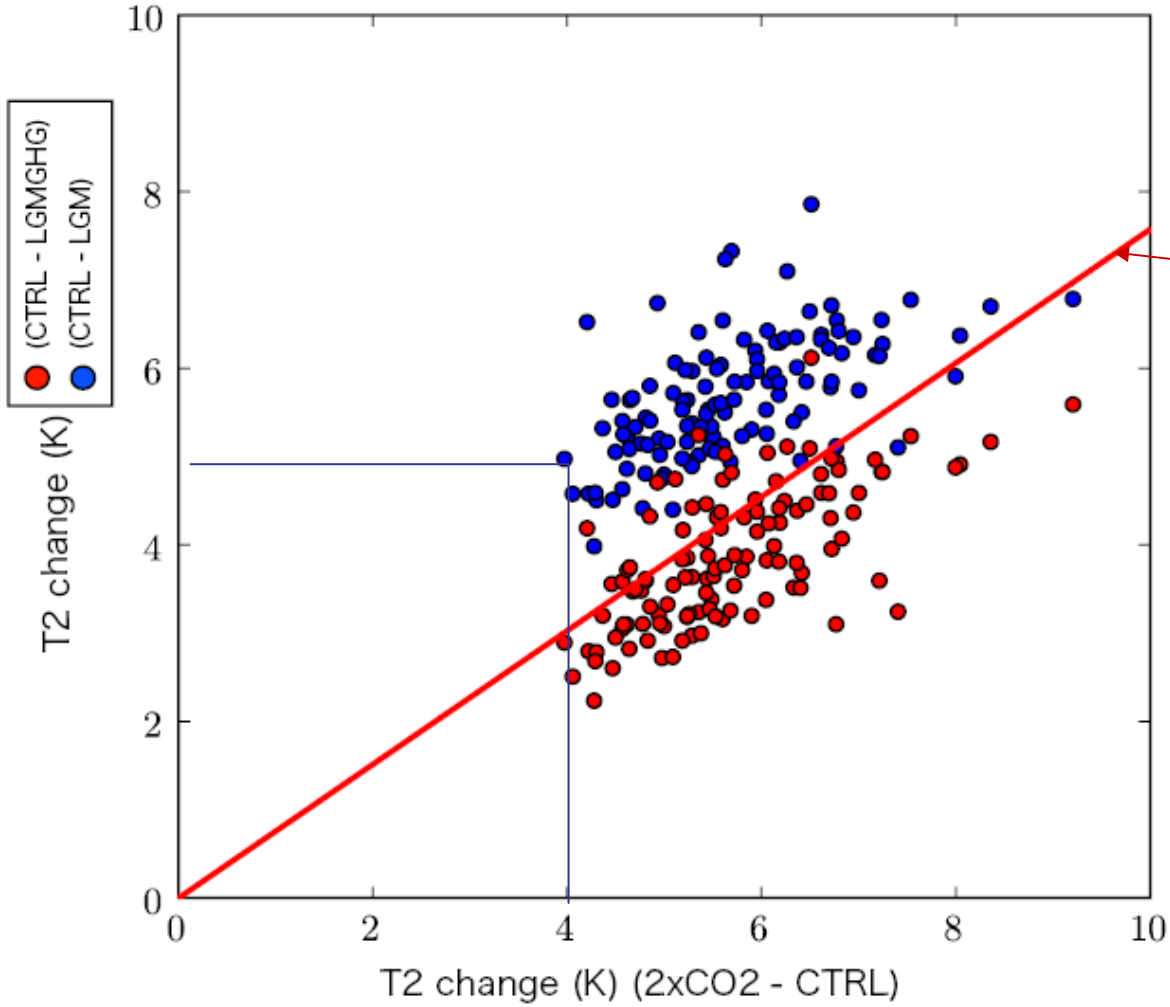
LGM



LGM GHG only



NH : ice sheets ; SH : mainly CO2
Also shown by Manabe and Broccoli (1985)



Linear response to CO2 forcing 2.8 vs 3.7 Wm^{-2}

CO2 only at LGM

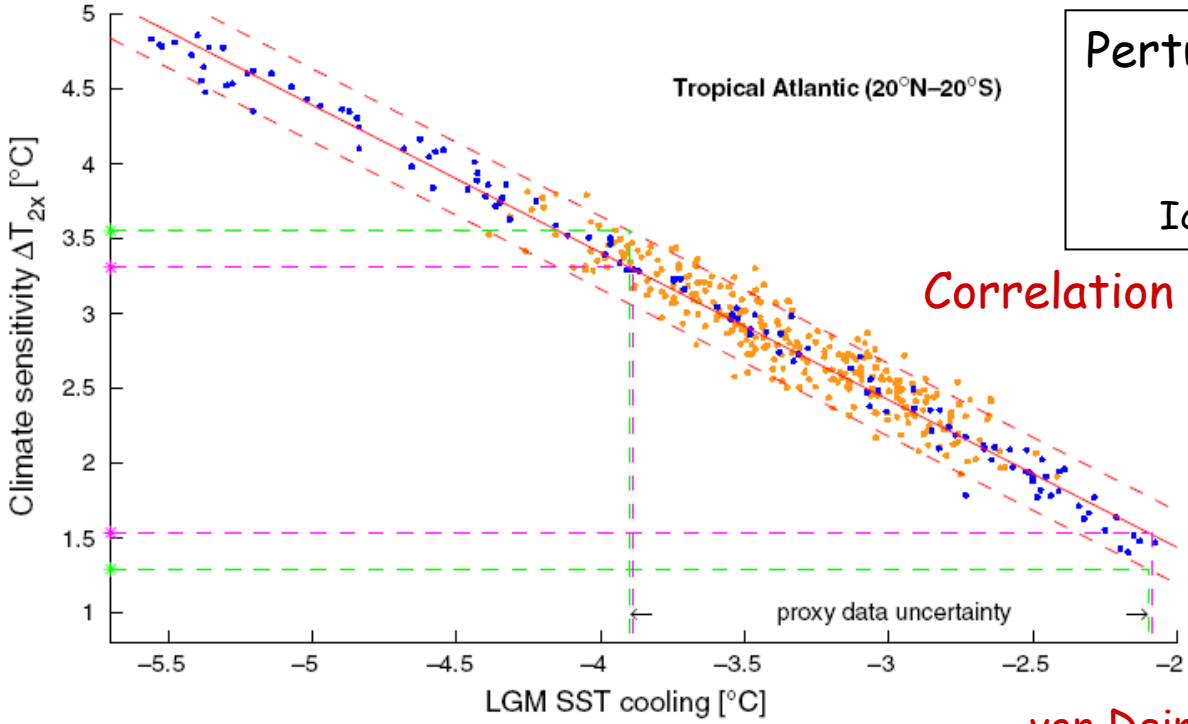
Full LGM

Hargreaves et al. (CP, 2007)

LGM (CO2 only) vs 2x CO2 :
80% show a greater sensitivity to warming than cooling

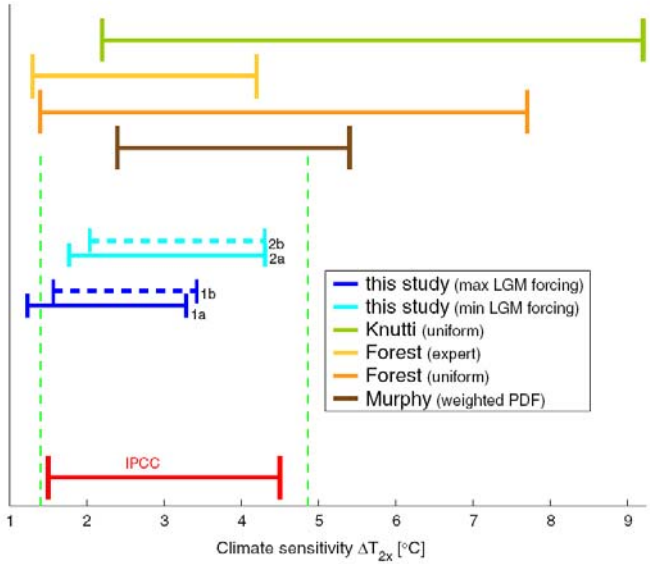
Are there key regions to constrain model climate sensitivity ?

Perturbed physics experiments
With an EMIC
CLIMBER
Ice sheet + CO2 eq + dust + veg

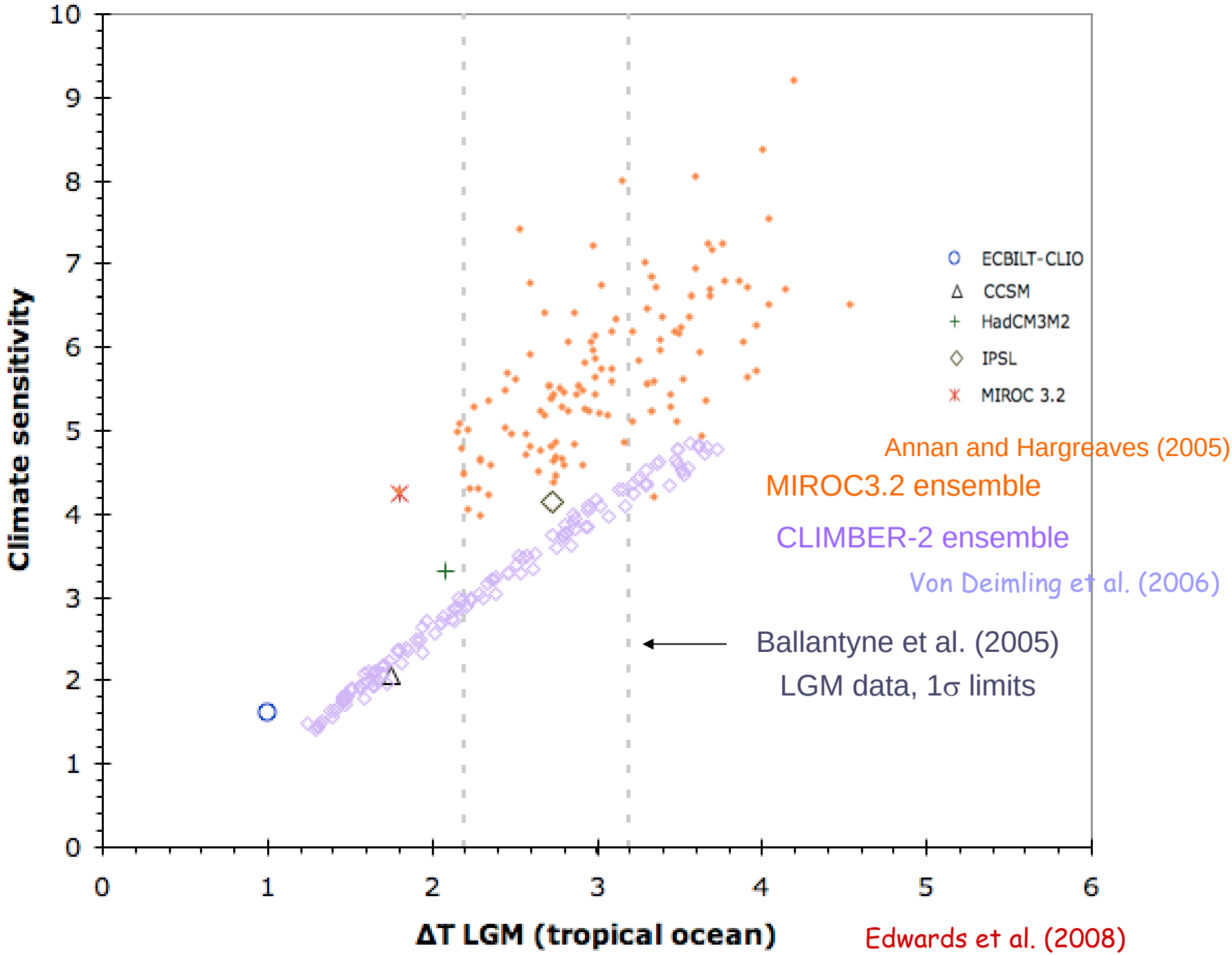


Correlation with LGM tropical SSTs

von Deimling et al., Clim Dyn (2006)

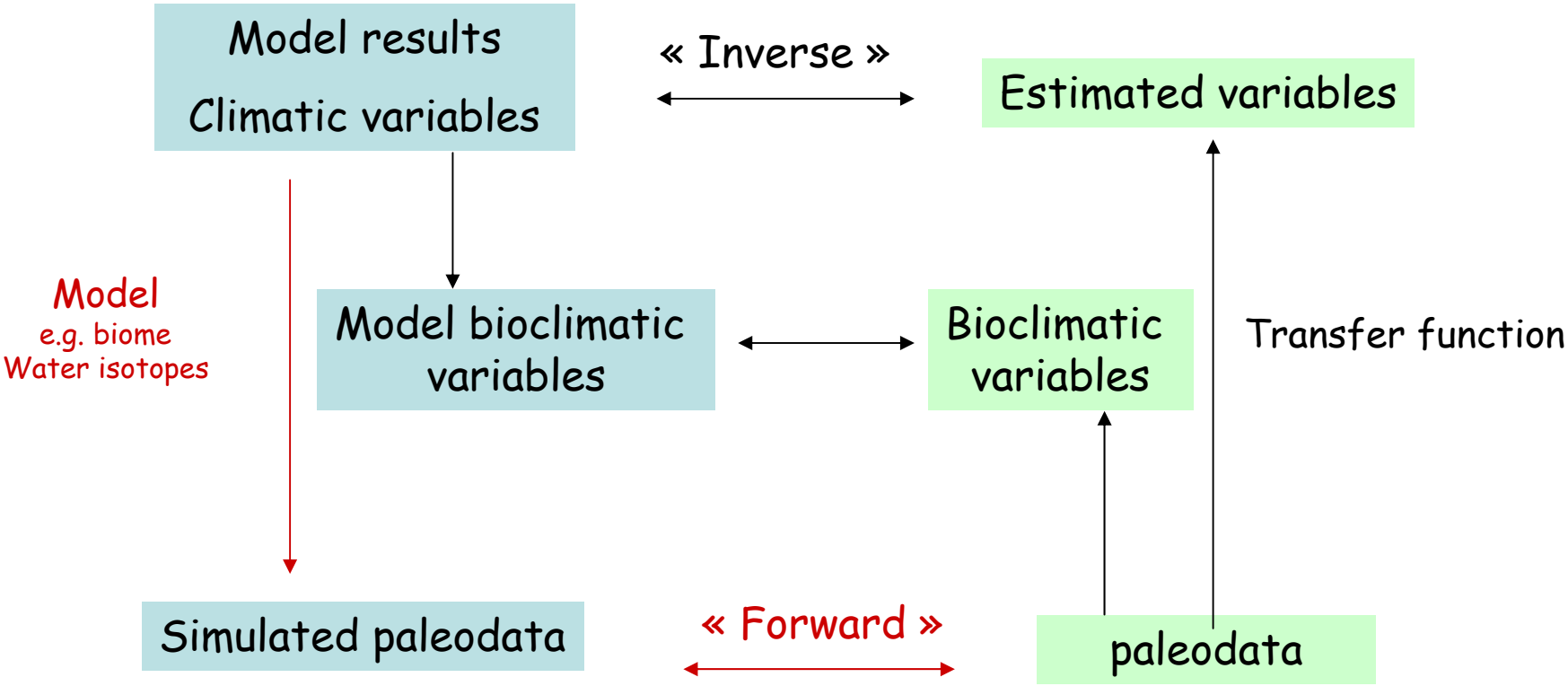


with sensitivity to uncertainty in forcings


Climate sensitivity
ΔT LGM (tropical ocean)
0
1
2
3
4
5
6
7
8
9
10
ECBILT-CLIO
CCSM
HadCM3M2
IPSL
MIROC 3.2
Annan and Hargreaves (2005)
MIROC3.2 ensemble
CLIMBER-2 ensemble
Von Deimling et al. (2006)
Ballantyne et al. (2005)
LGM data, 1σ limits
Edwards et al. (2008)

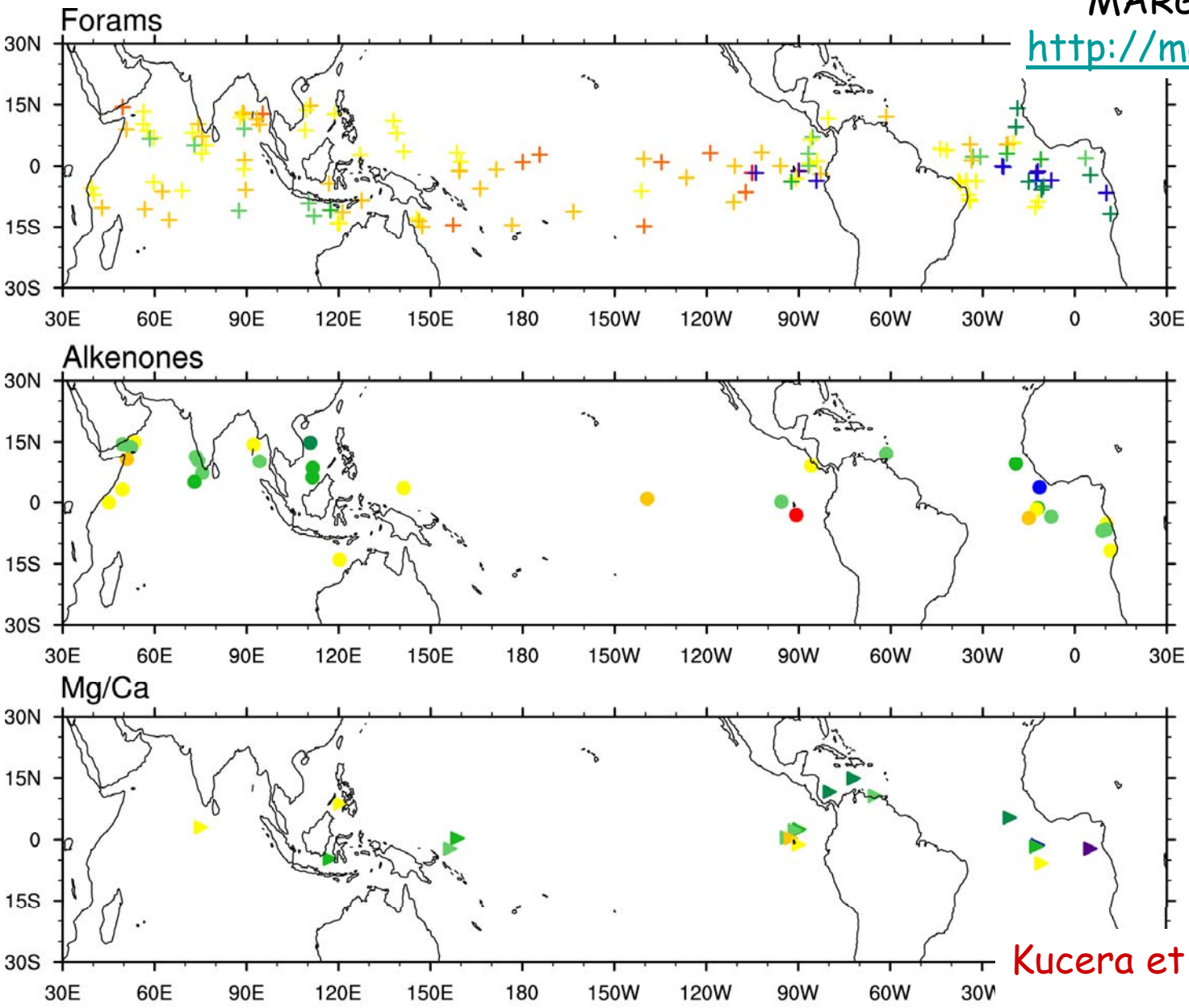
Can we evaluate climate models at LGM ?

Model-data comparisons



MARGO synthesis

http://margo.pangaea.de



Kucera et al., QSR, 2005;

MARGO, Nature, in press

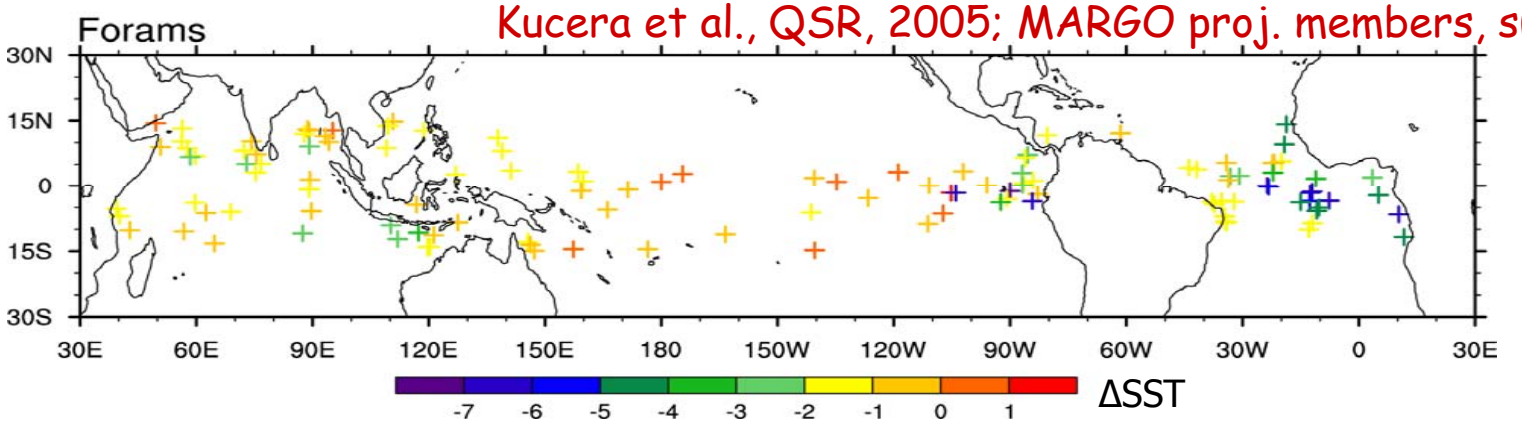
LGM Tropical Sea Surface Temperatures

Paleoclimate Modelling PMIP Intercomparison Project Phase II

MARGO Proxy Reconstruction

Otto-Bliesner et al., Clim.Dyn., 2008

Kucera et al., QSR, 2005; MARGO proj. members, subm.



PMIP2 Model Simulations

	ΔSST LGM 15S-15N All basins	ΔSST LGM 15S-15N Indian[1]	ΔSST LGM 15S-15N Pacific[2]	ΔSST LGM 15S-15N Atlantic[3]
MARGO data	**-1.7±1**	**-1.4±0.7**	**-1.2±1.1**	**-2.9±1.3**
ECBilt-CLIO	-1.0	-1.1	-0.8	-1.5
CCSM	-1.7	-1.8	-1.6	-1.8
FGOALS	-2.2	-1.9	-2.3	-2.4
HadCM	-2.0	-2.2	-1.7	-2.0
IPSL	-2.3	-2.2	-2.2	-2.3
MIROC	-2.4	-2.5	-2.2	-2.6

LGM Tropical Sea Surface Temperatures

models are too zonal

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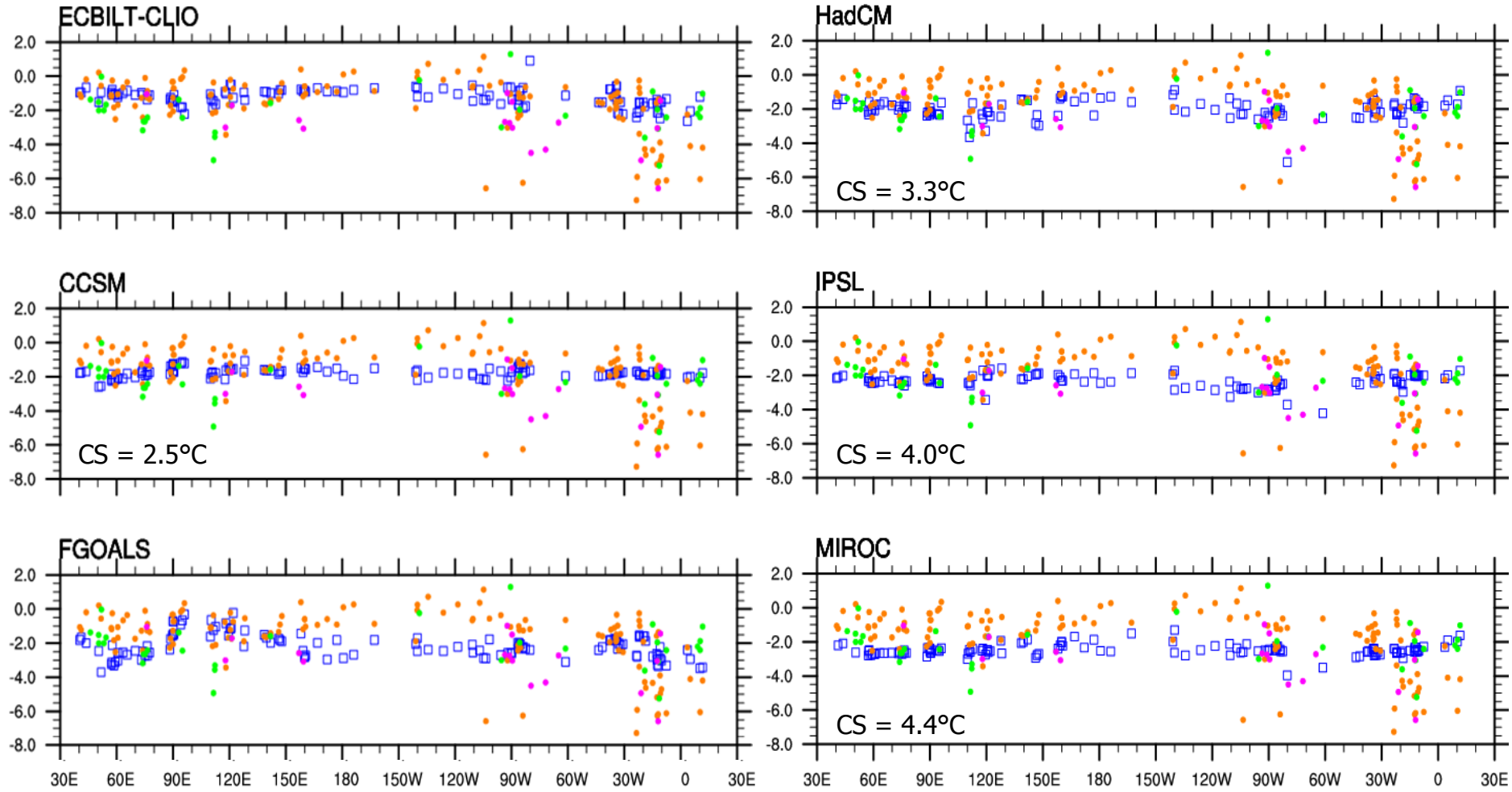
Proxy Evidence (dots) versus PMIP2 Model Simulations (squares)



Climate sensitivity (global) of these models ranges from 2.5 to 4.4°C

Otto-Bliesner et al., Clim.Dyn., 2008

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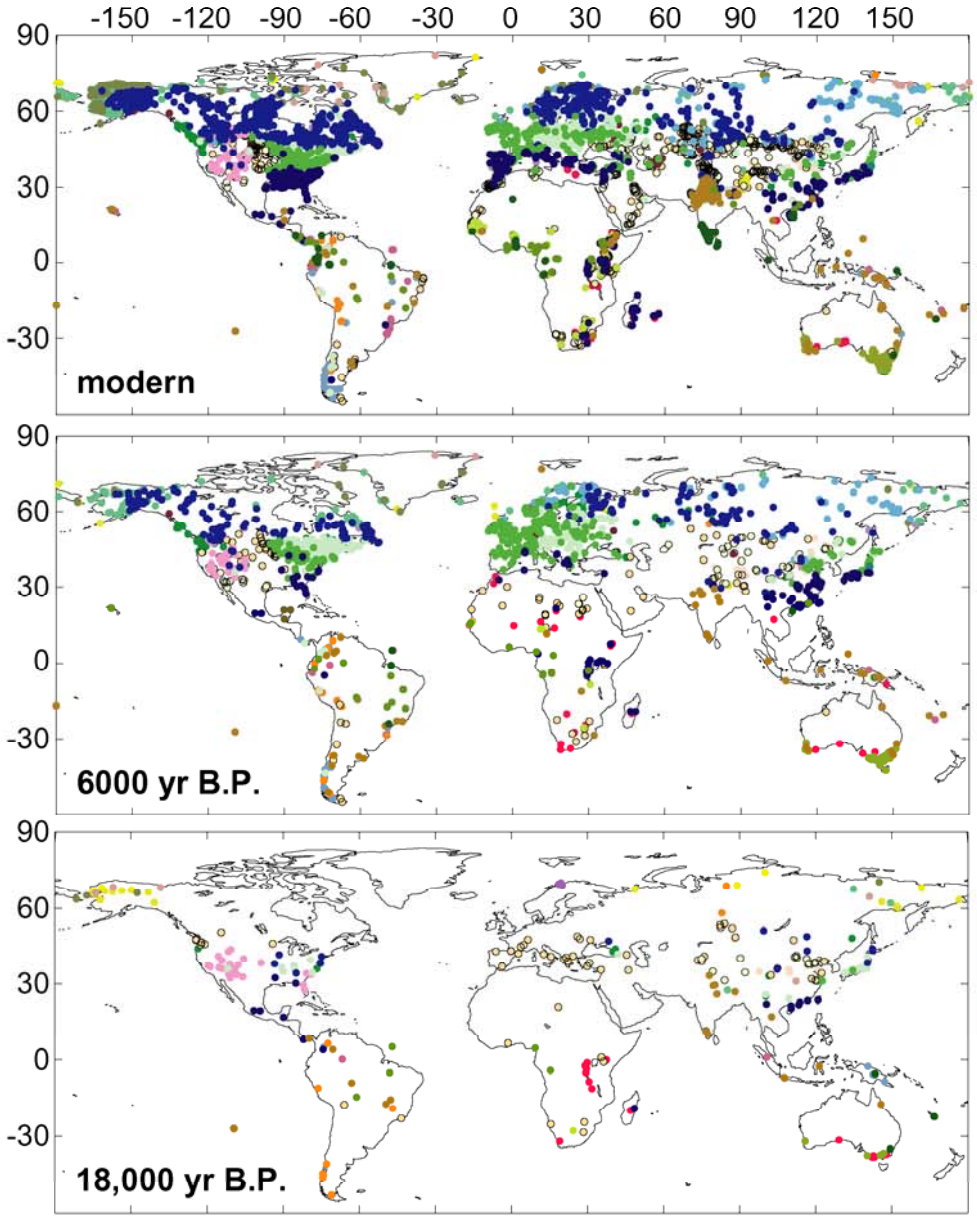
PMIP
Intercomparison Project
Phase II



tropical evergreen broadleaf forest
tropical semi-evergreen broadleaf forest
tropical deciduous broadleaf forest & woodland
temperate deciduous broadleaf forest
temperate evergreen needleleaf forest
warm-temperate evergreen broadleaf & mixed forest
cool mixed forest
cool evergreen needleleaf forest
cool-temperate evergreen needleleaf & mixed forest
cold evergreen needleleaf forest
cold deciduous forest
tropical savanna
tropical xerophytic shrubland
temperate xerophytic shrubland
temperate sclerophyll woodland and shrubland
temperate deciduous broadleaf savanna
temperate evergreen needleleaf open woodland
cold parkland
tropical grassland
temperate grassland

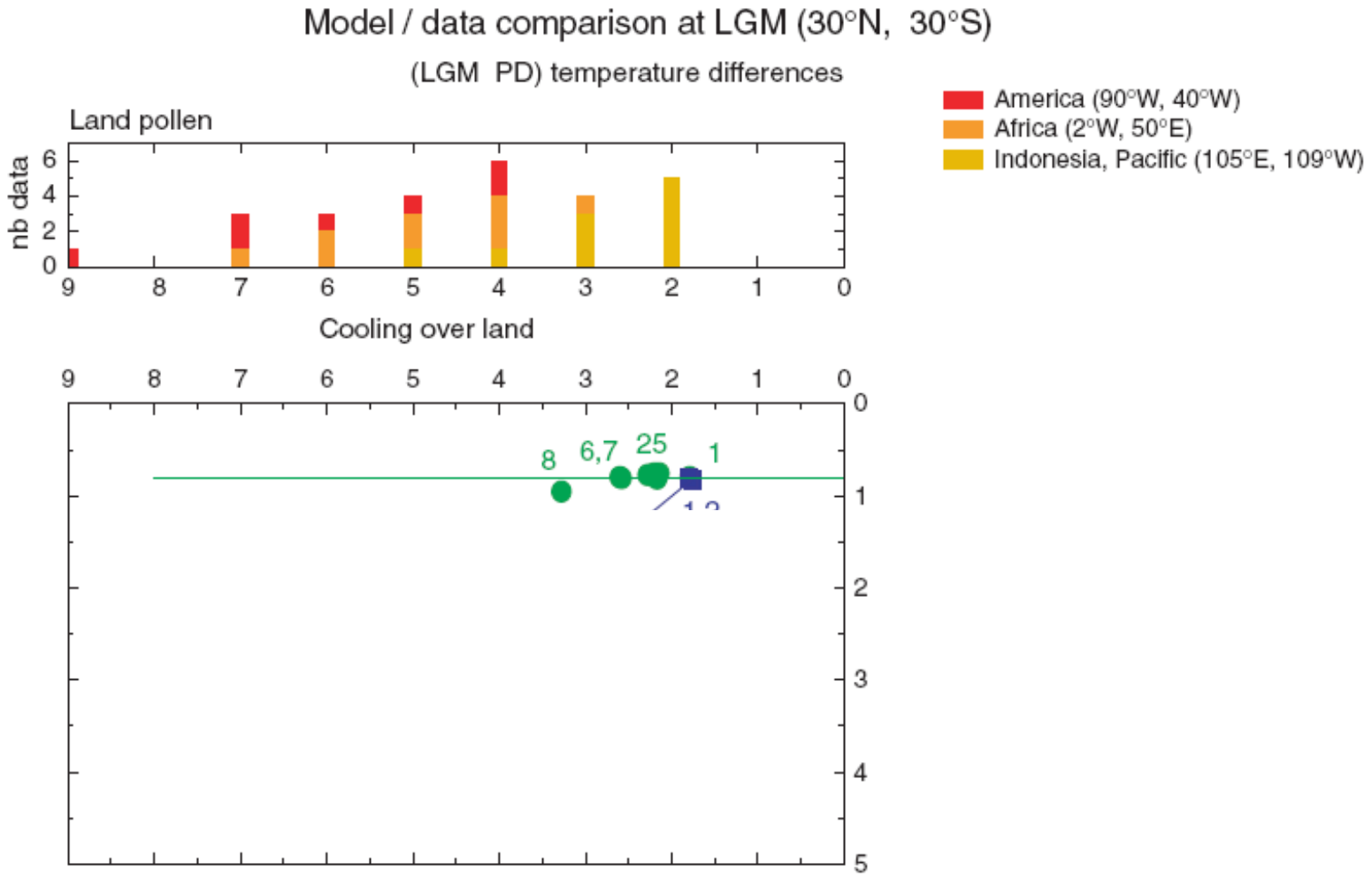
desert
graminoid and forb tundra
low and high shrub tundra
erect dwarf-shrub tundra
prostrate dwarf-shrub tundra
cushion-forb tundra
barren
ice
tundra
warm-temperate evergreen broadleaf forest
steppe
xerophytic woods/scrub
warm temperate rainforest
wet sclerophyll forest
cool temperate rainforest
semi-arid woodland scrub
heathland
alpine grassland
moor
temperate grassland and xerophytic shrubland

BIOME 6000

Prentice et al., 2000; Bigelow et al., 2003; Pickett et al., 2004; Marchant et al., in prep; Sutra et al., in prep.

Tropical cooling at Last Glacial Maximum

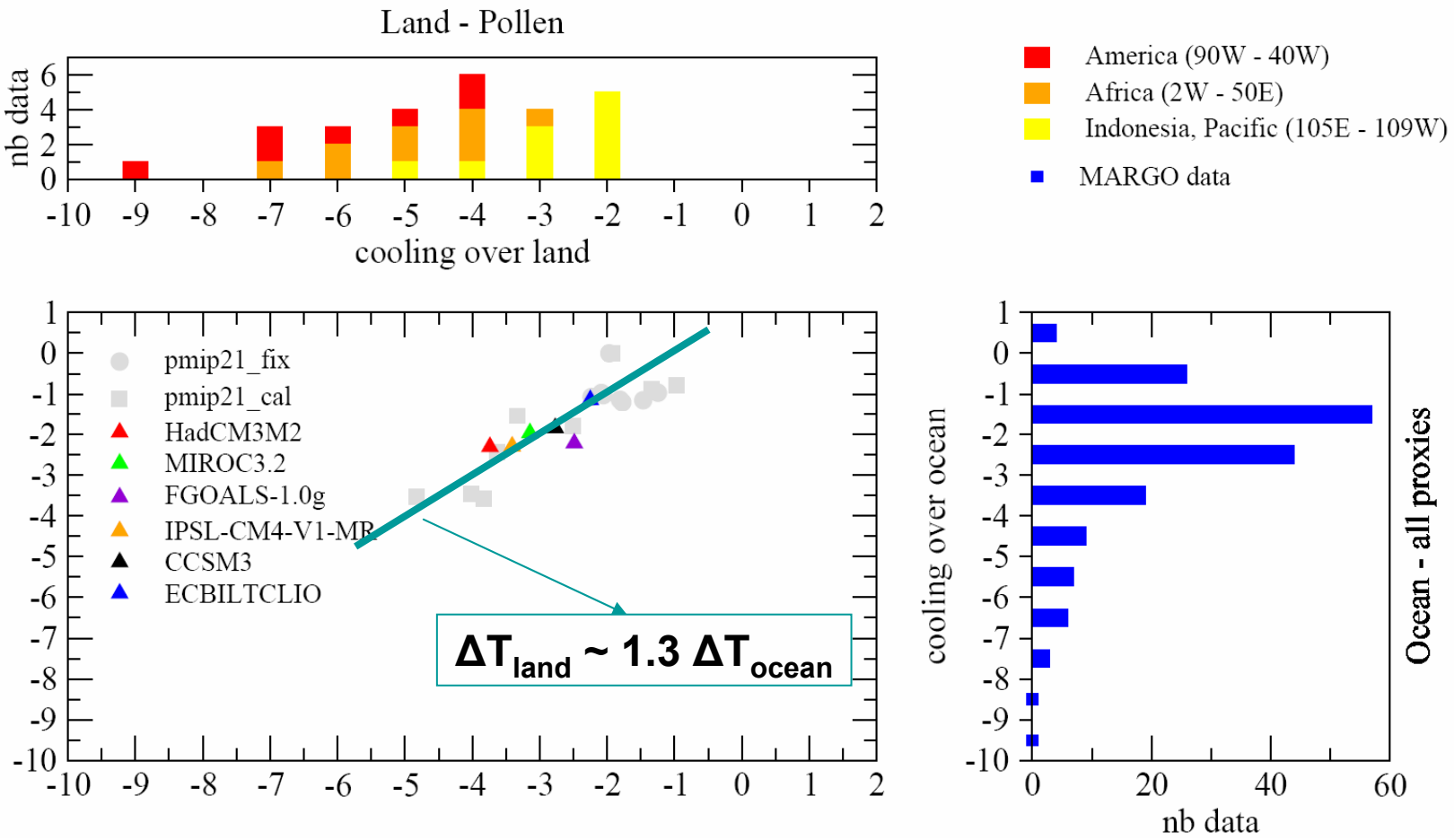
Mc Avaney et al., IPCC (2001)



Tropical cooling at Last Glacial Maximum

Paleoclimate Modelling PMIP Intercomparison Project Phase II

AOGCMs



Masa Kageyama, pers. Com. (2008)

"Polar amplification" LGM & future

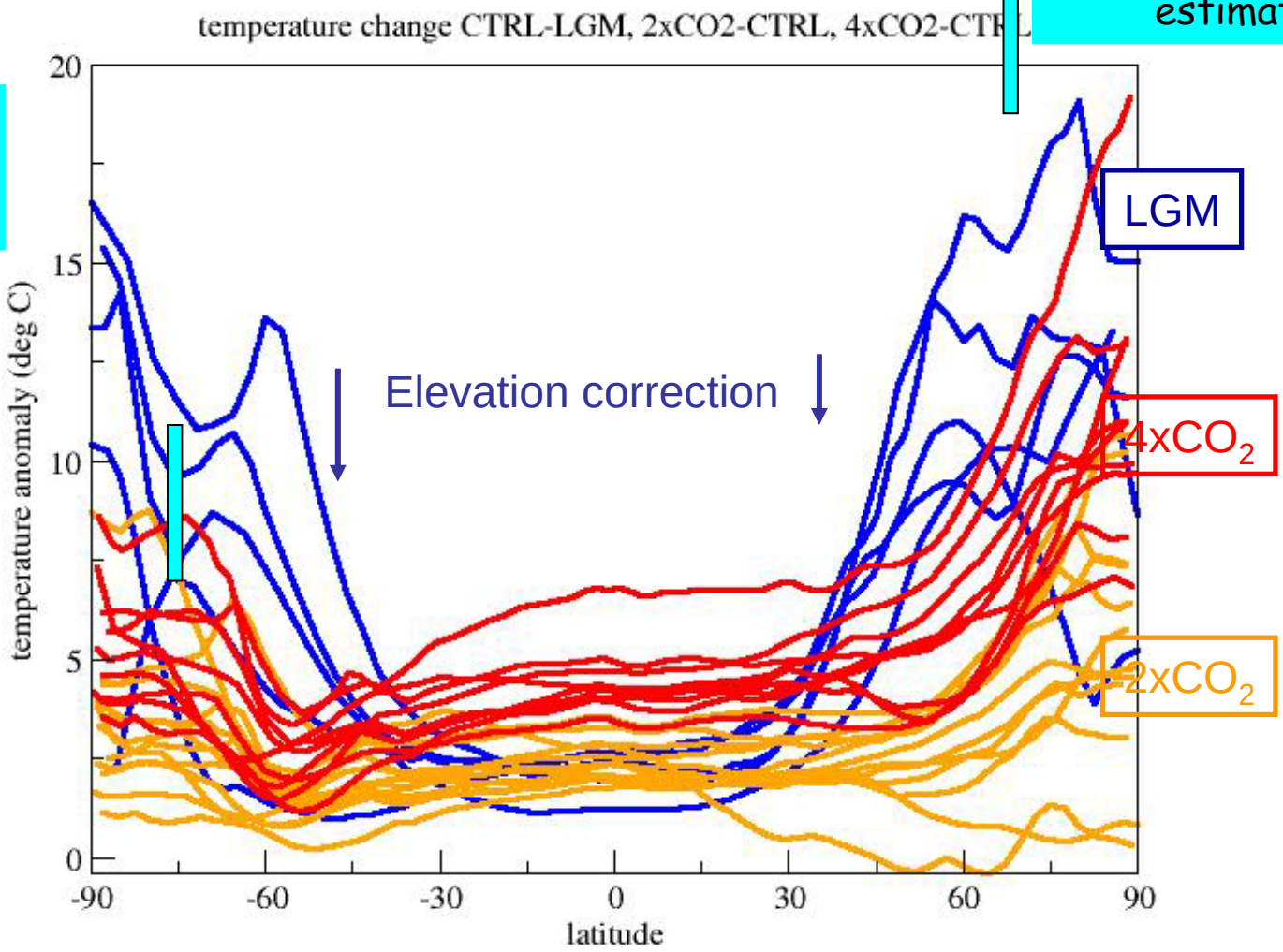
Paleoclimate Modelling PMIP Intercomparison Project Phase II

Masson-Delmotte et al, CP 2006

Underestimation of the polar amplification at LGM

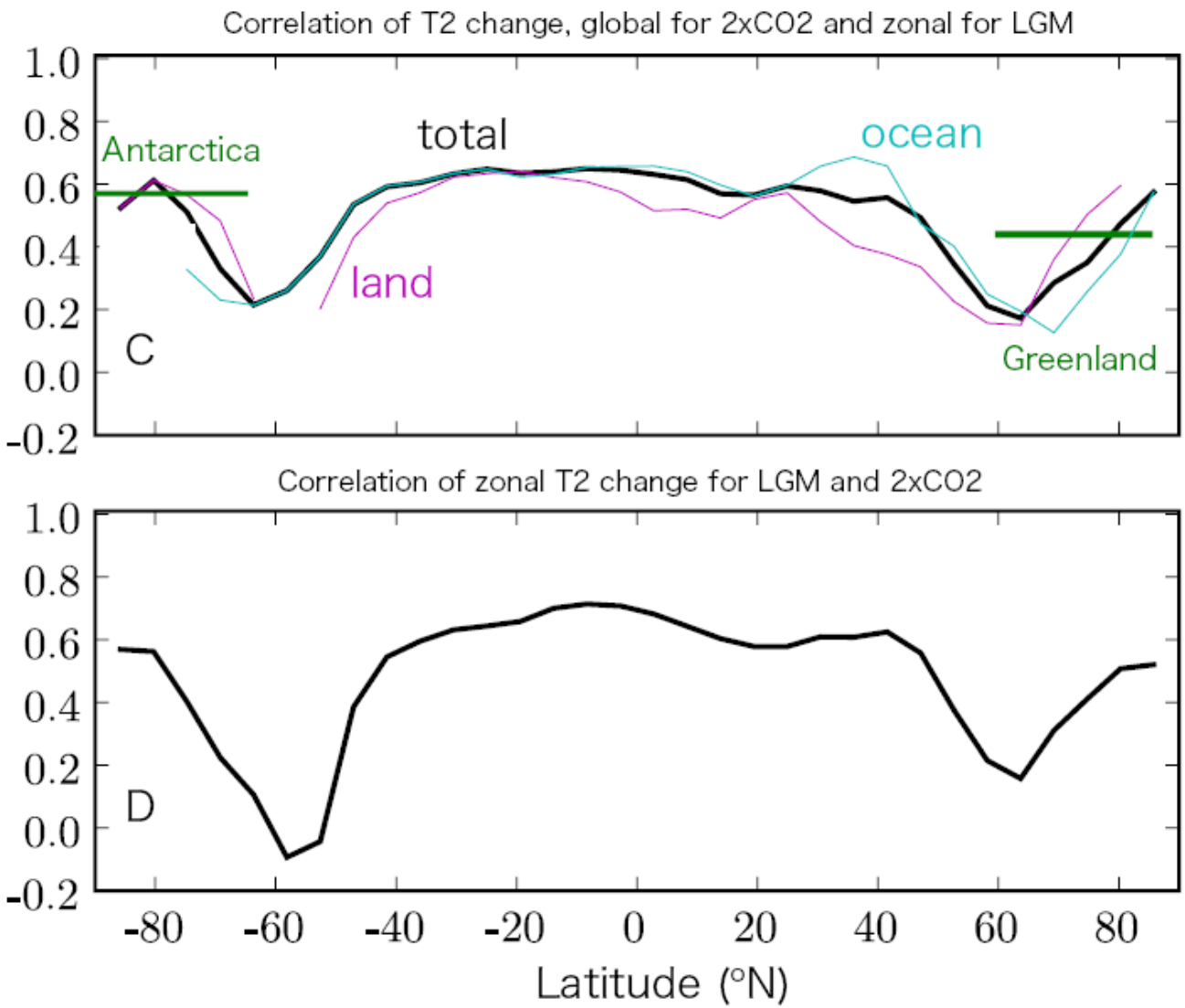
Greenland ice core estimates

Antarctic ice core estimates

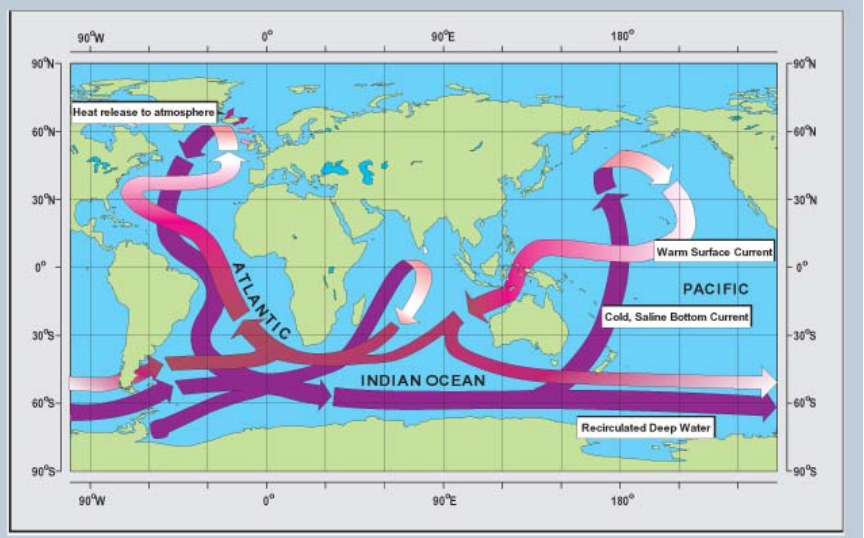


Hargreaves et al., Clim. Past (2008) MIROC ensemble

LGM vs 2xCO2 : higher correlation in tropics and high latitudes

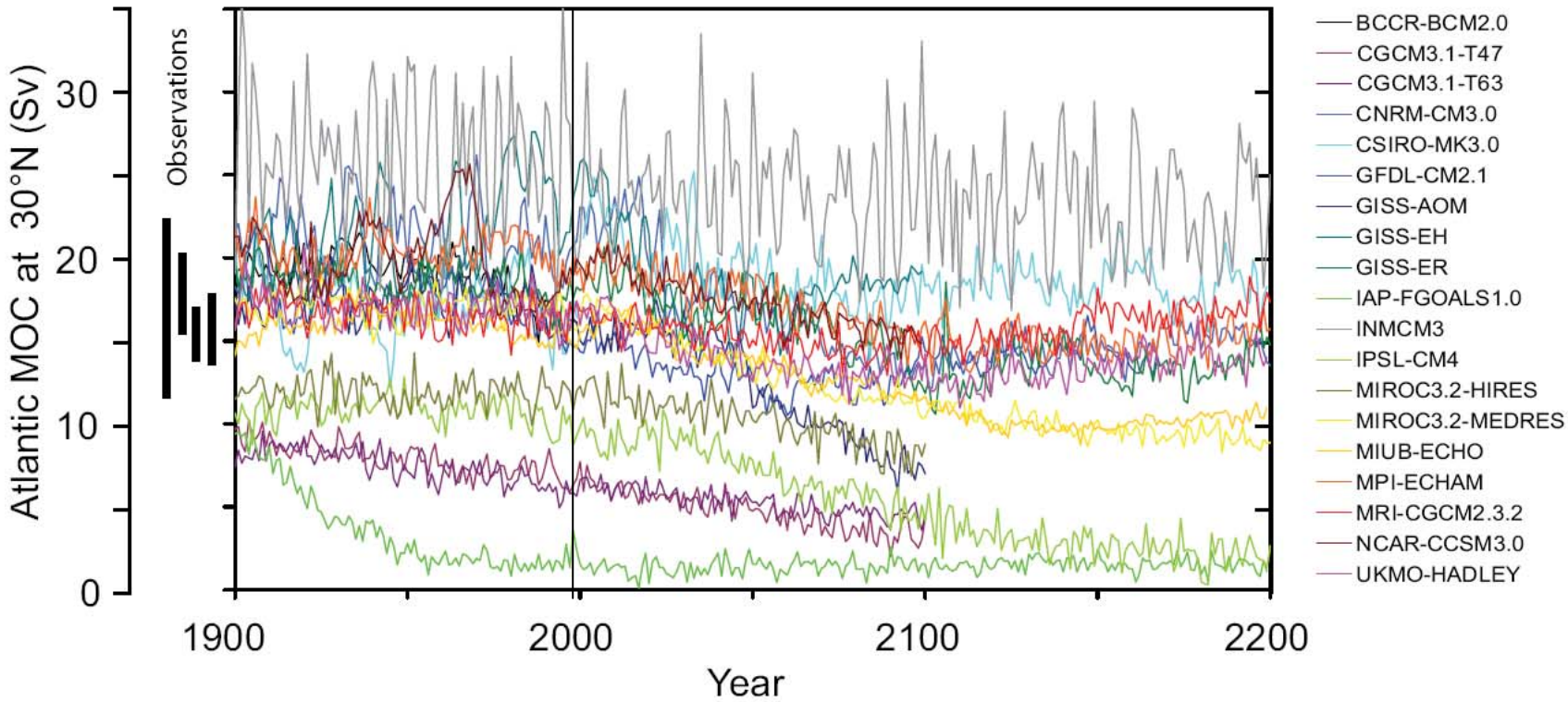


Thermohaline circulation



Schematic diagram of the global ocean circulation pathways, the 'conveyer' belt (after W. Broecker, modified by E. Maier-Reimer).

IPCC (2007) WGI, ch 10

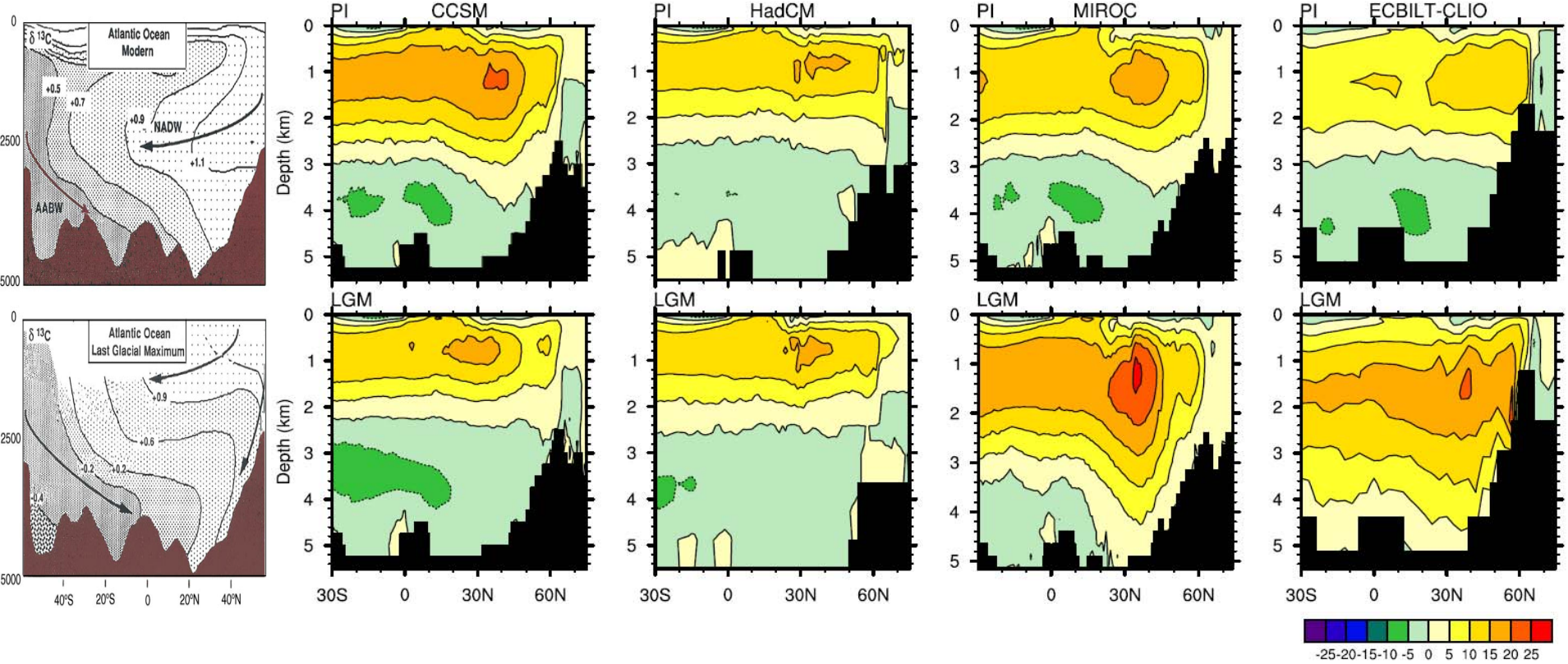


LGM Atlantic - Thermohaline and Deep Ocean

Paleoclimate Modelling PMIP Intercomparison Project Phase II

Atlantic MOC (Sv)

Modern



Duplessy et al (1988)

Otto-Bliesner et al., GRL, 2007

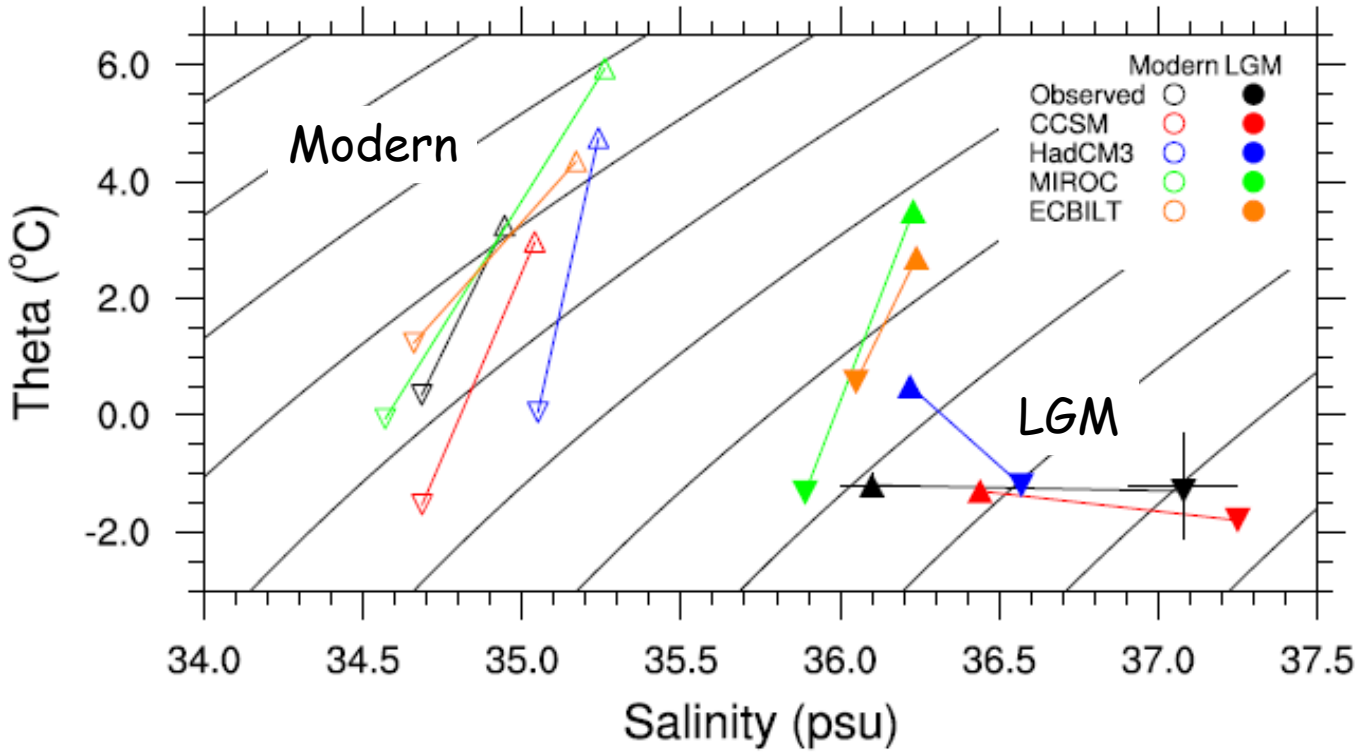
LGM Atlantic - Thermohaline and Deep Ocean

Paleoclimate Modelling PMIP Intercomparison Project Phase II

North Atlantic

South Atlantic

Deep Ocean Temperature – Salinity at ODP sites



Otto-Bliesner et al., GRL, 2007 : importance of sea ice

Weber et al., CP (2007)
difference of density between NADW and AABW
is the main control of AMOC differences

Paleoclimate Modelling
PMIP
Intercomparison Project
Phase II

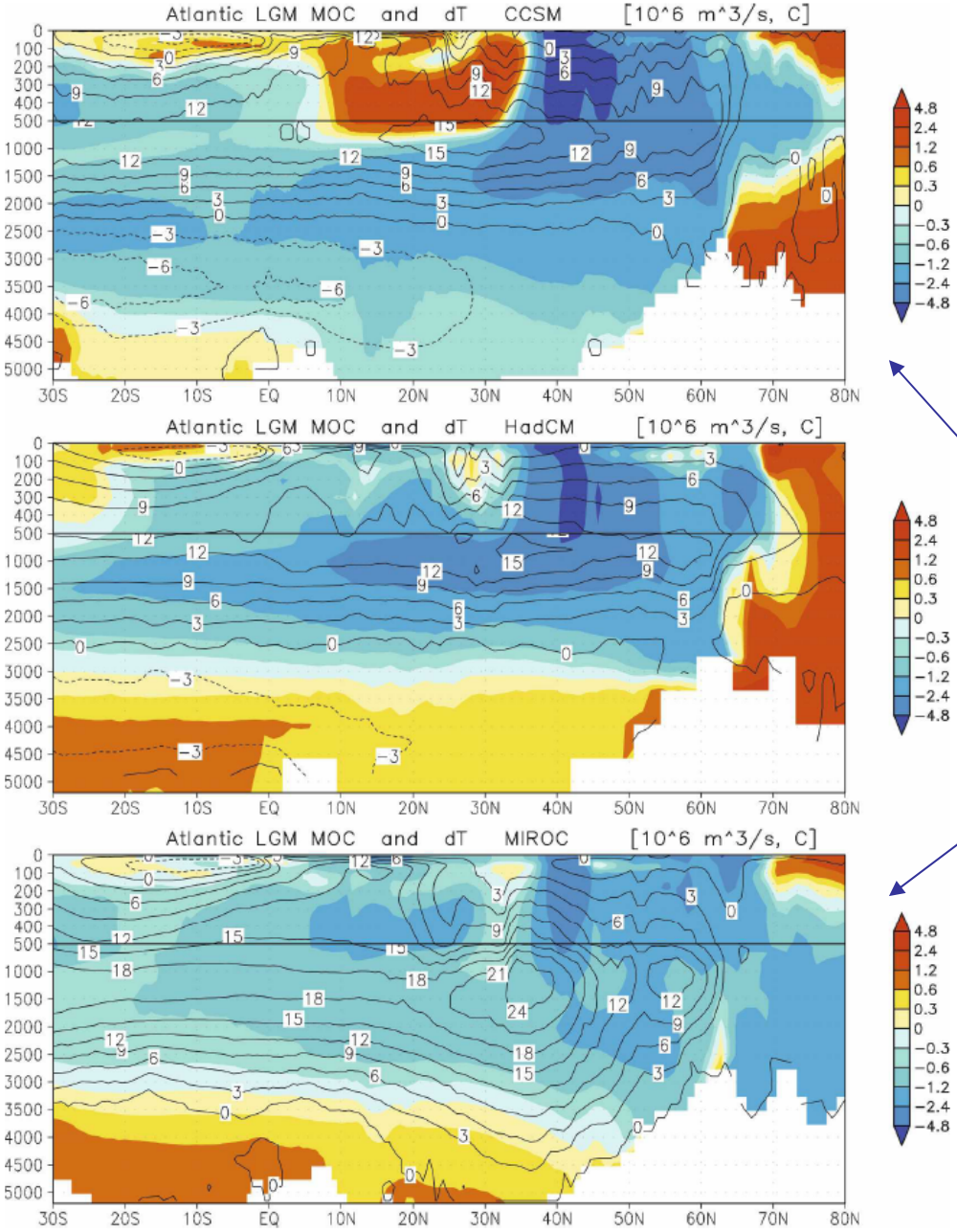


FIG. 14. Streamfunctions of the Atlantic MOC during the LGM (contour) and temperature differences between the LGM and CTL excluding entire ocean volume mean changes (shaded): (top) CCSM, (middle) HadCM, and (bottom) MIROC simulation results. Contour interval is 5 × 10^6 m^3 s^{-1}.

Murakami et al., J. Clim. (2008)
different MOC responses
BUT :
Oceanic heat transport increases

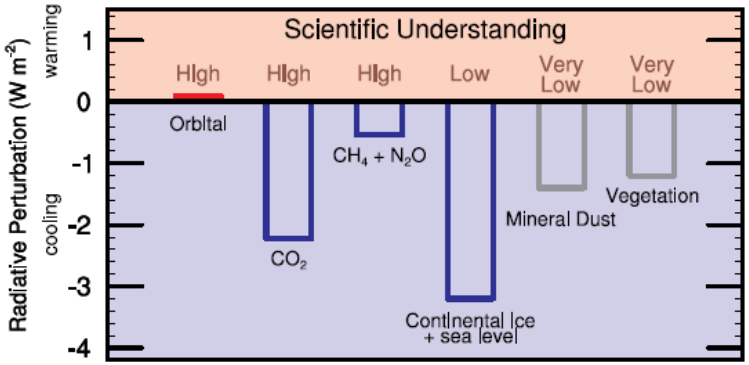
Decreased volume transport
BUT stronger temperature contrast
(upper/lower)

Or

Enhanced volume transport
BUT smaller temperature contrast

Accounting for Uncertainties

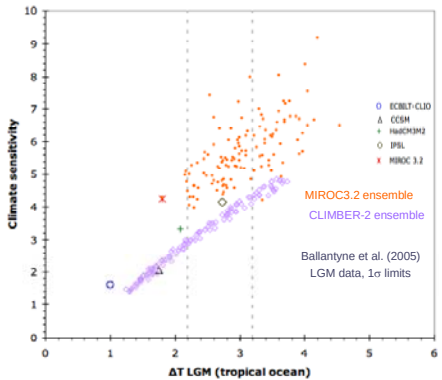
Paleodata estimates



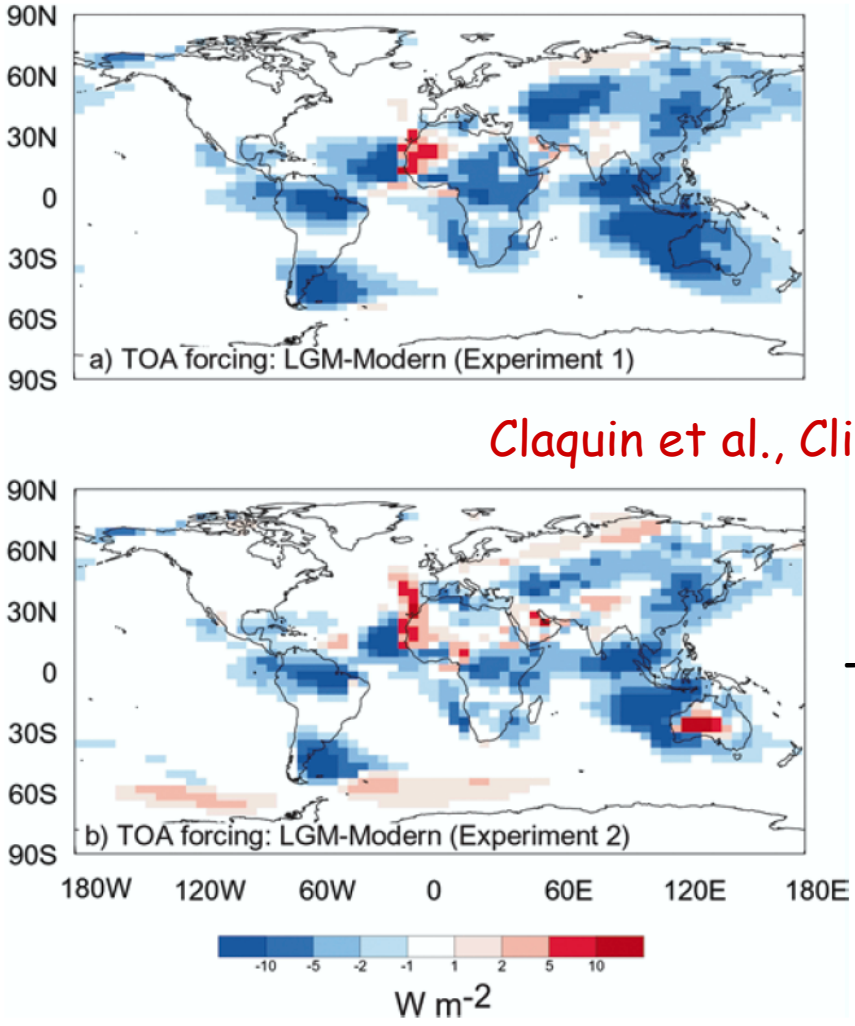
Ice sheets
Dust
Vegetation

Boundary conditions

Models/
model parameters



Uncertainty in dust forcing



-1 Wm^{-2}

Claquin et al., Clim Dyn (2003)

-2 Wm^{-2}

Uncertainties :
in dust cycle
In aerosol properties
& indirect effect

Fig. 3 Modelled annual mean difference in radiative forcing at the top of the atmosphere (TOA), LGM minus modern, based on the optical depth fields in Fig.2. **a** experiment 1, assuming external mixing of minerals in the aerosol. **b** Experiment 2, assuming internal mixing of haematite

LGM North Atlantic and Europe

Kageyama et al. QSR, 2006

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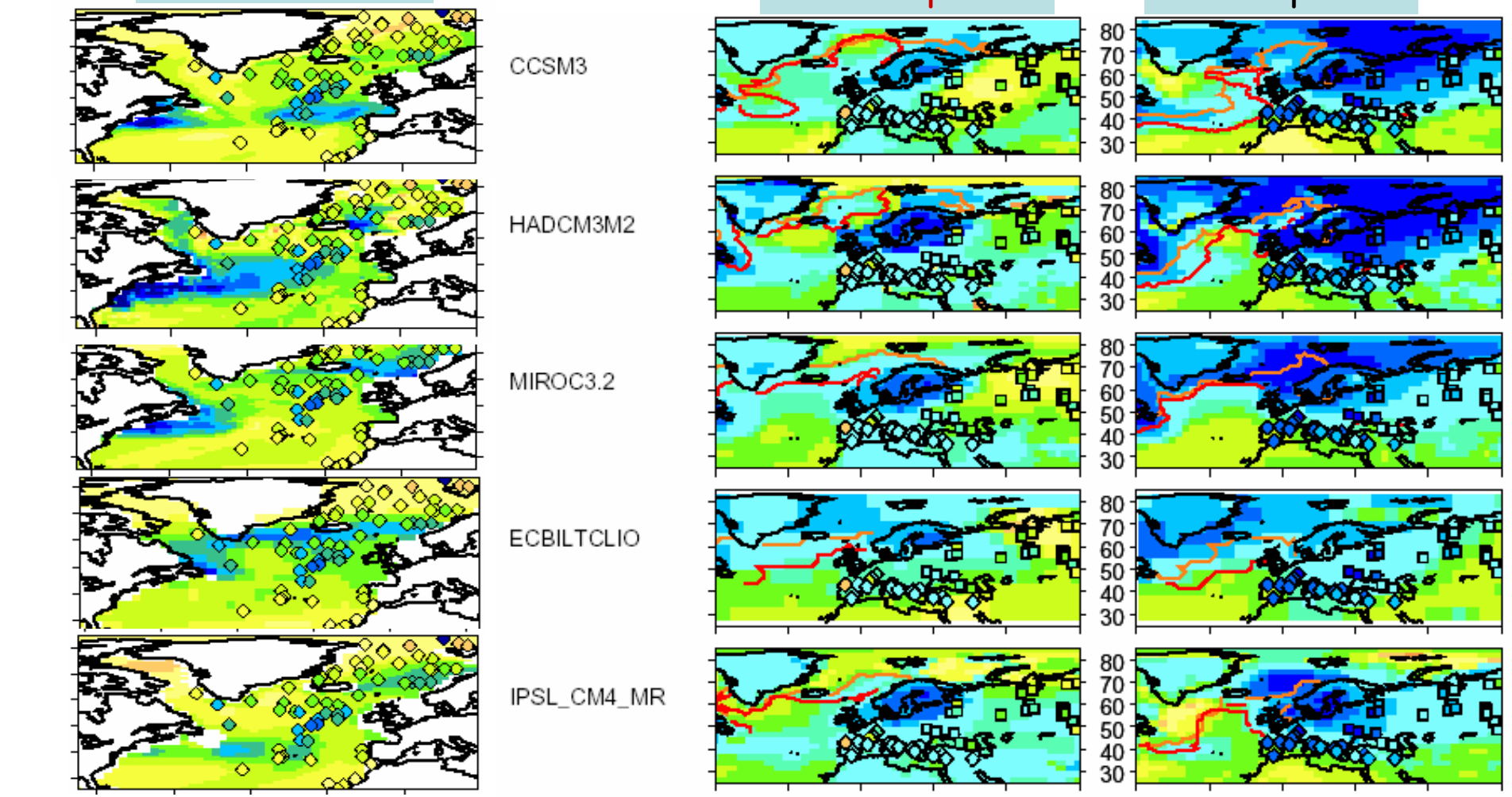
Ocean/ forams

Twarm/ pollen

Tcold/ pollen



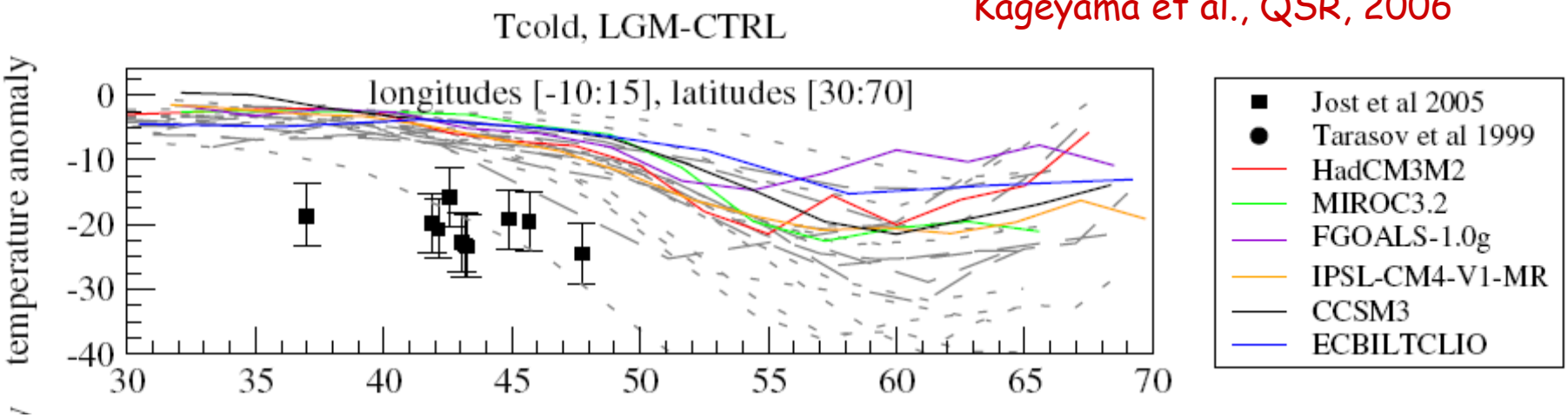
In the range of data

In the range of data/ not cold enough

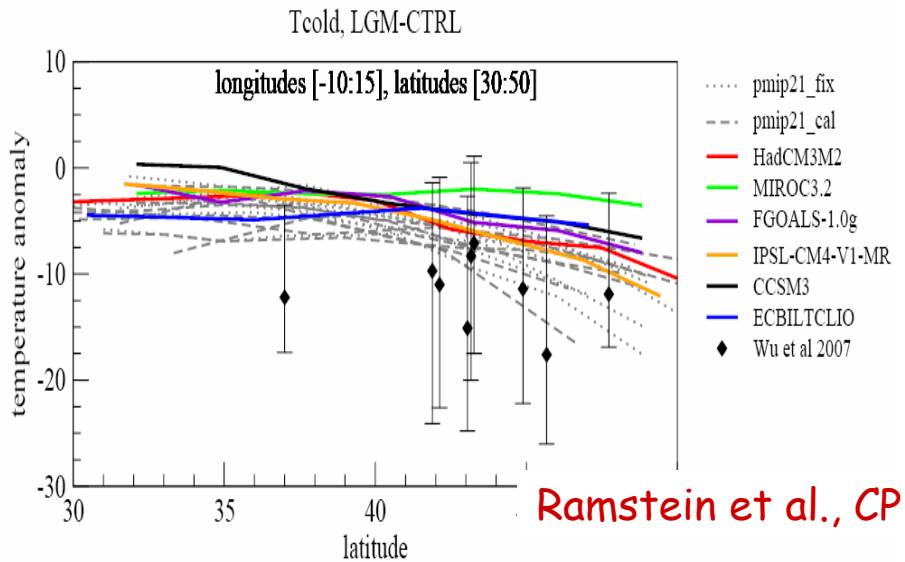
LGM European climate (PMIP2)

Paleoclimate Modelling PMIP Intercomparison Project Phase II

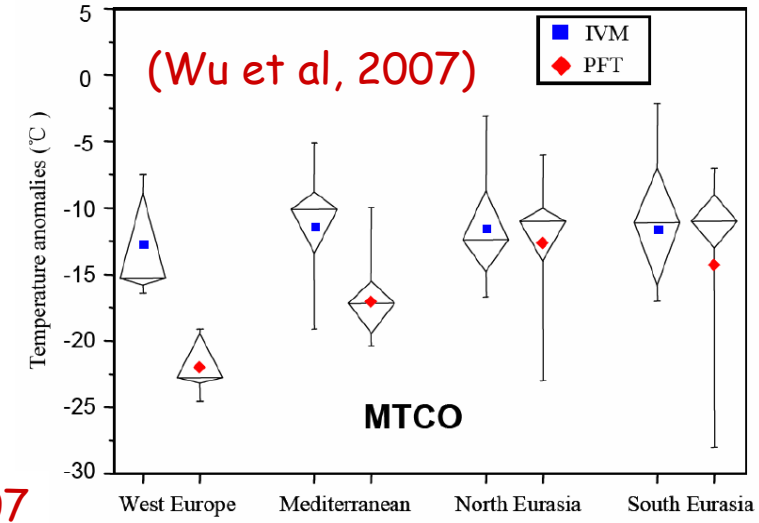
Kageyama et al., QSR, 2006



New reconstructions of Tcold using Inverse Vegetation Modelling



Ramstein et al., CP, 2007



Last Glacial Maximum Conclusions

- LGM vs warming : Different climate sensitivity
- Key regions to help constrain sensitivity of models using the past: tropics and high latitudes
- LGM, compared to paleodata:
  - Reasonable response of coupled models in the tropics
  - Underestimation of high latitude cooling
- Uncertainties :
  - Uncertainties in forcing : dust, vegetation
  - Uncertainties in paleodata : need close interaction between communities

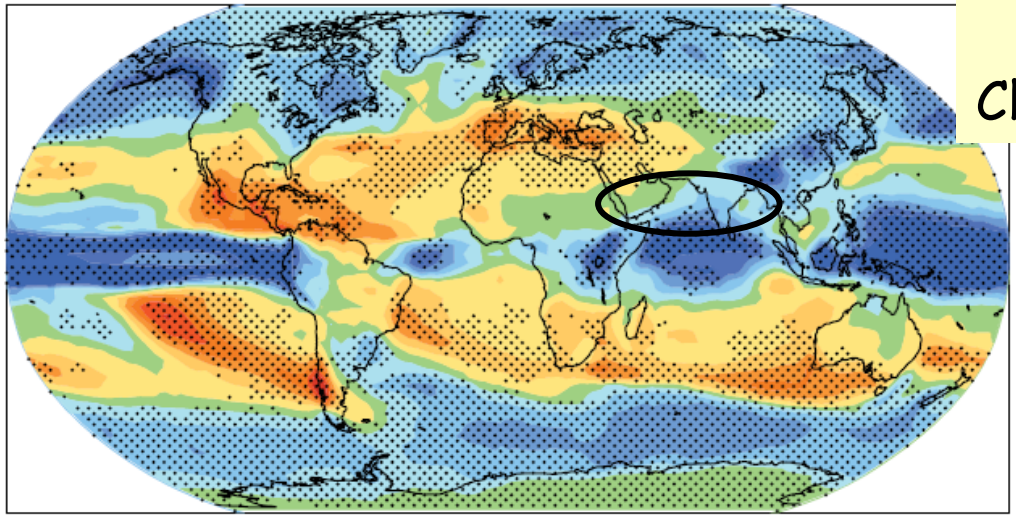
Evaluation at the mid-Holocene ?

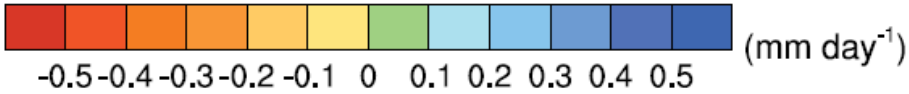
Future climate

Change in annual mean precipitation

A1B

a) Precipitation — Multi-model

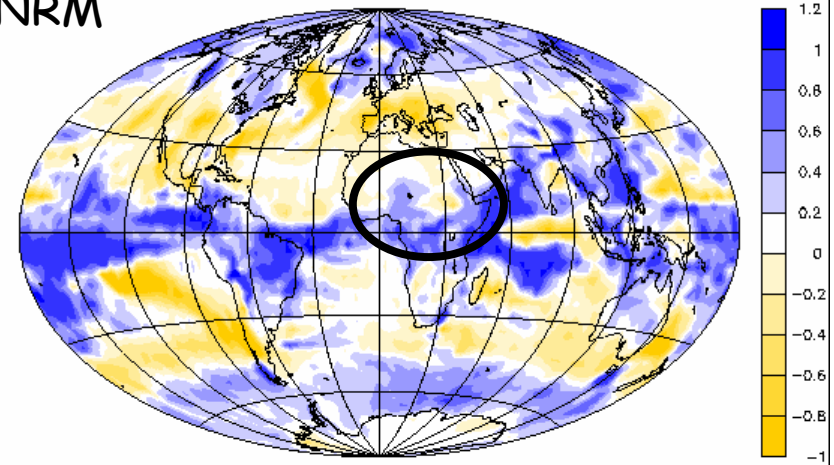




Difference exceeds inter-model standard deviation

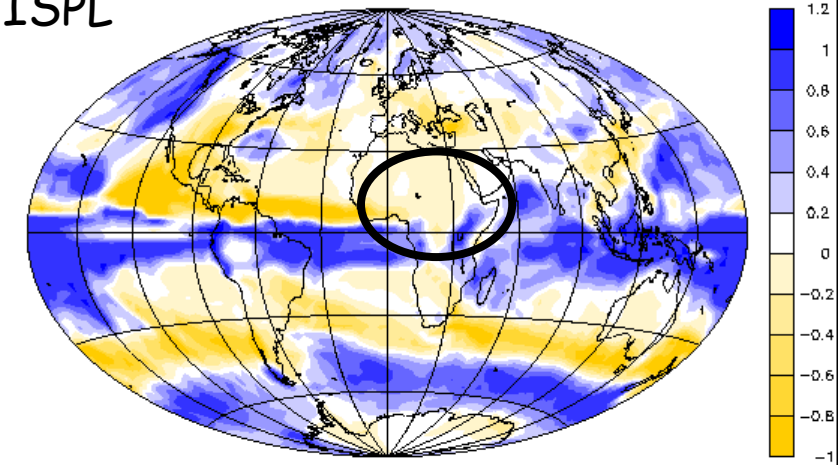
IPCC (2007)

CNRM



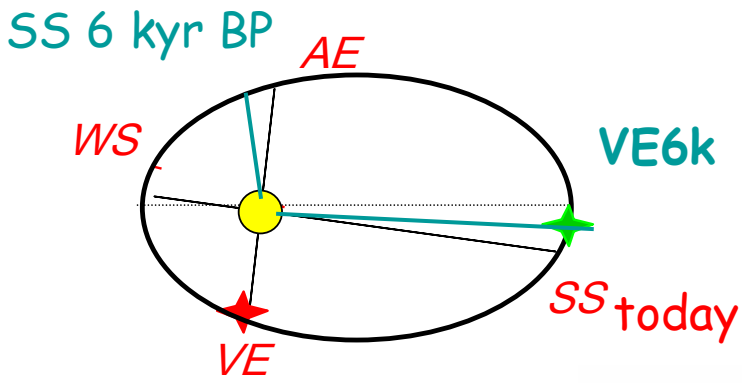
IPCC / CNRM – SRESA2 scenario – Anomalies de la precipitation (mm/jour)
(2090–2099) comparee a (2000–2009)

ISPL

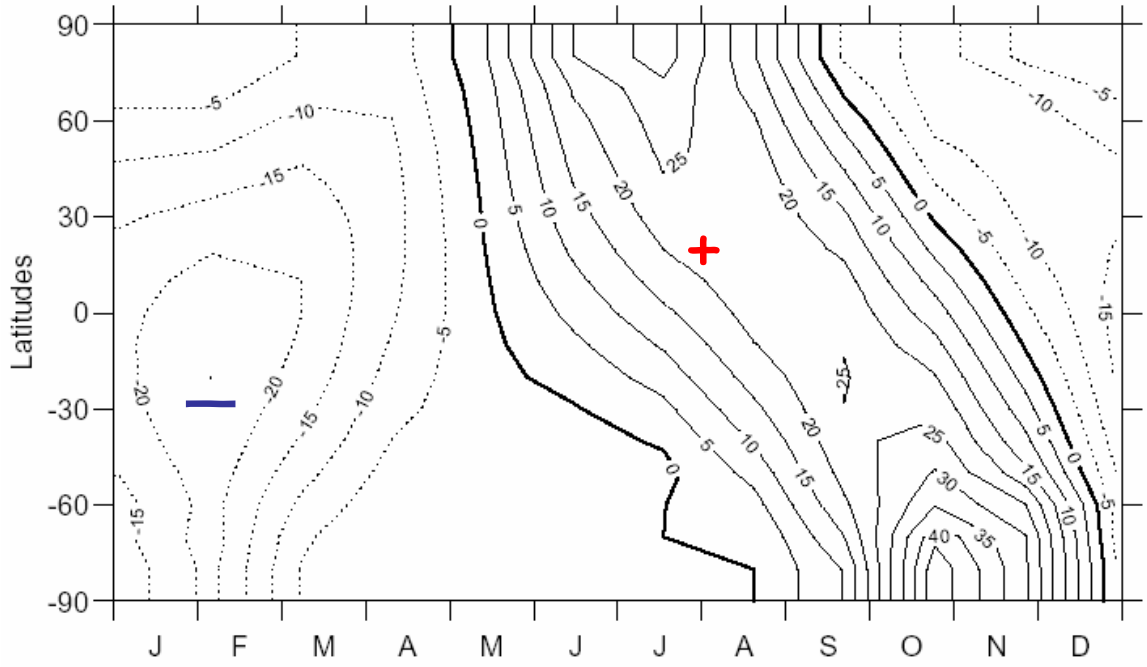


IPCC / IPSL – SRESA2 scenario – Anomalies de la precipitation (mm/jour)
(2090–2099) comparee a (2000–2009)

The mid-Holocene climate



Northern Hemisphere : increased seasonal cycle



Changes in insolation forcing
(6000 yrs BP – present)

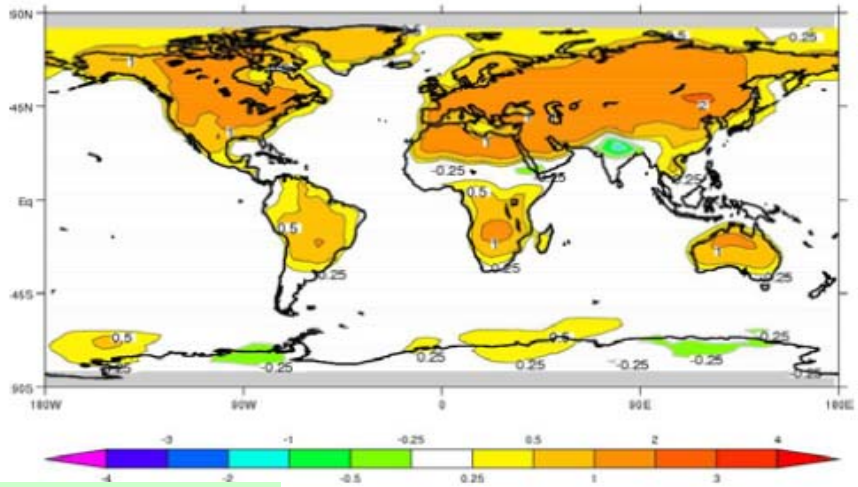
The global response to 6ka BP insolation

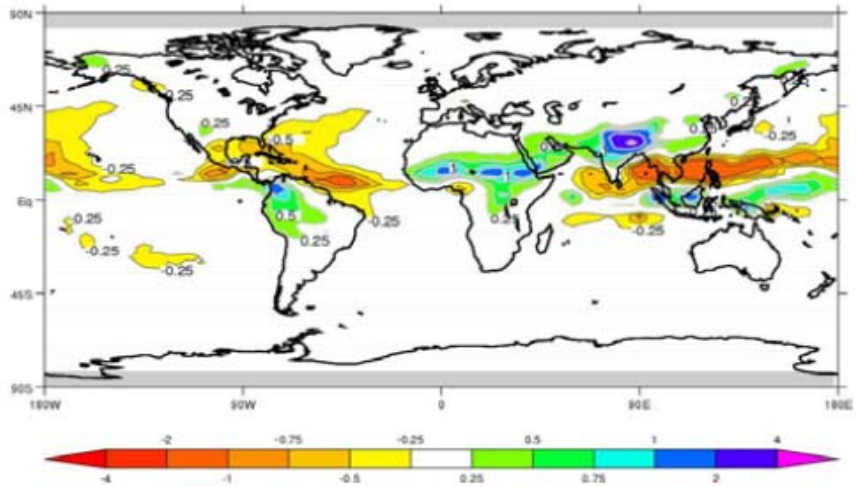
Paleoclimate Modelling PMIP Intercomparison Project Phase II

First models: AGCMs
modern SSTs
modern vegetation cover

PMIP averages

Joussaume et al. GRL (1999)



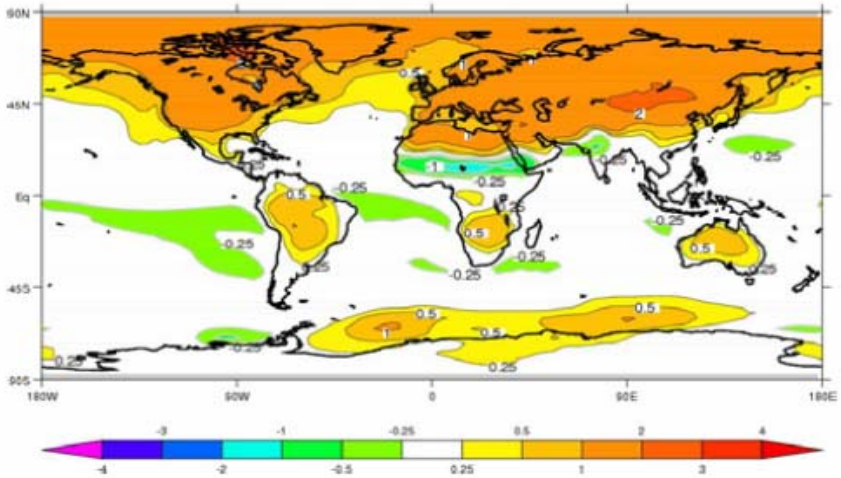


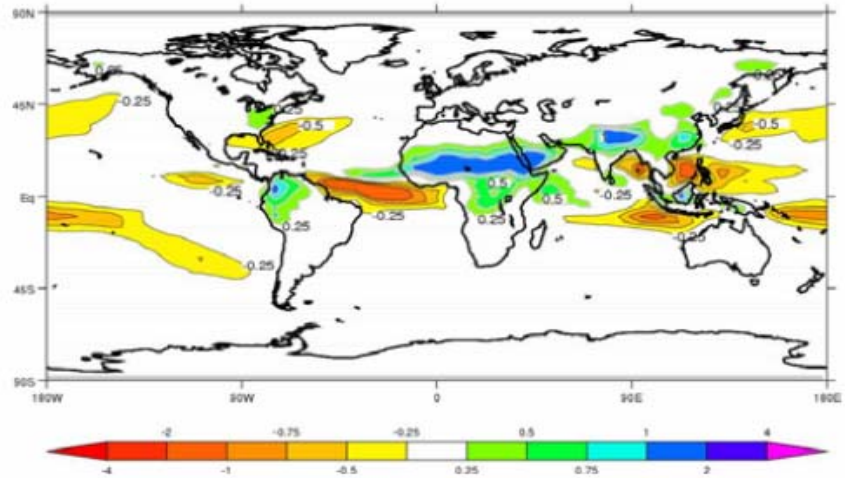
Interactive ocean in AOGCMs

temperature (6k – 0k)

JJAS

precipitation (6k – 0k)

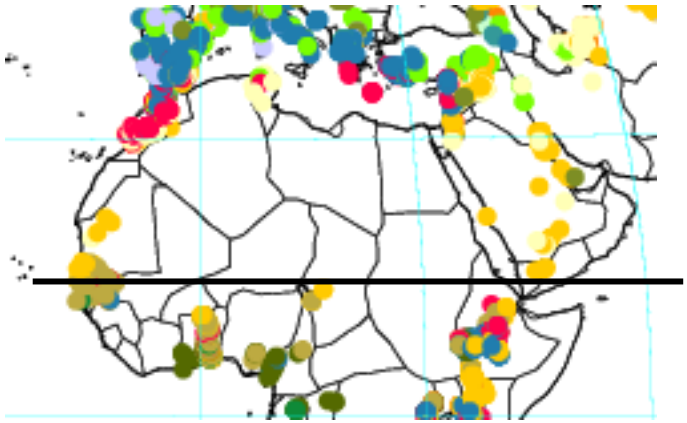




Braconnot et al, CP (2007a)

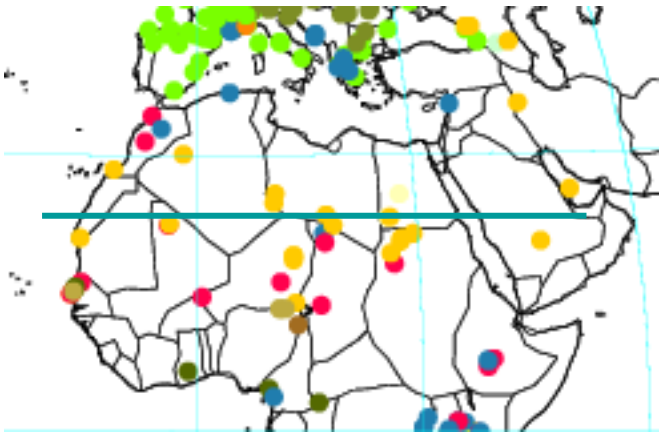
African monsoon changes at Mid-Holocene

Present



steppe

6ka BP

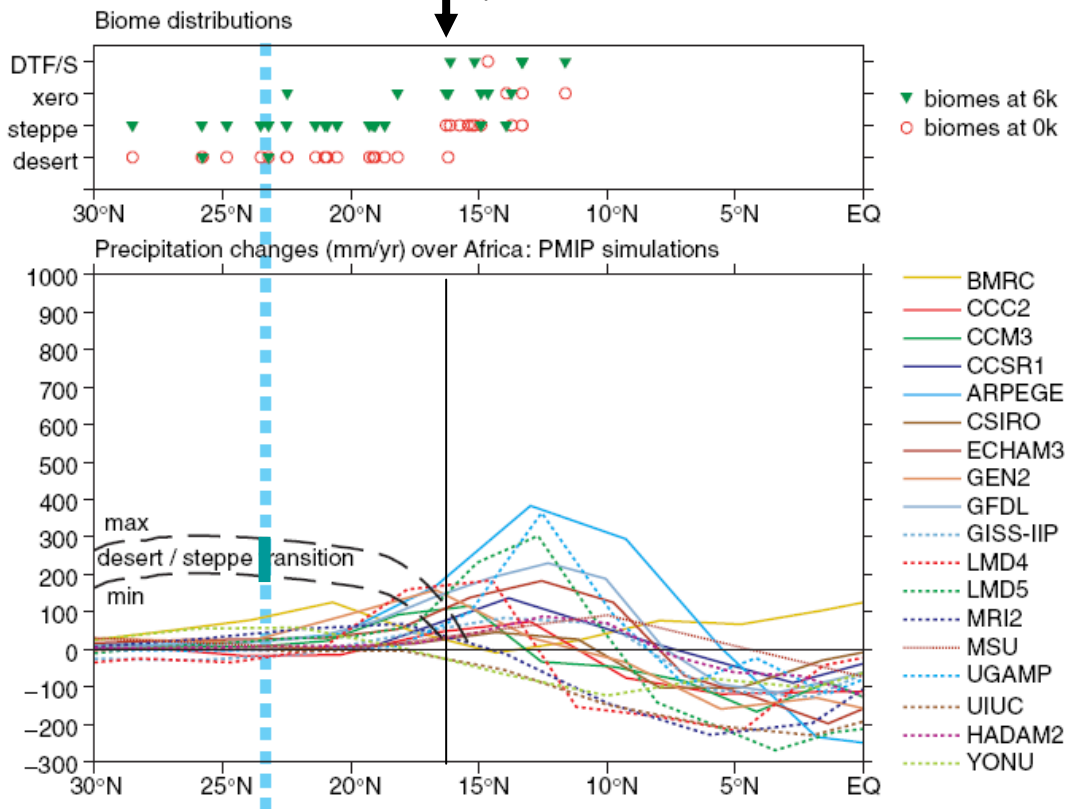


Biomes Jolly et al, 1998

Desert/steppe transition

6 ky

present



Joussaume et al., GRL, 1999

Possibilities for model benchmarking identification and analysis of key feedbacks

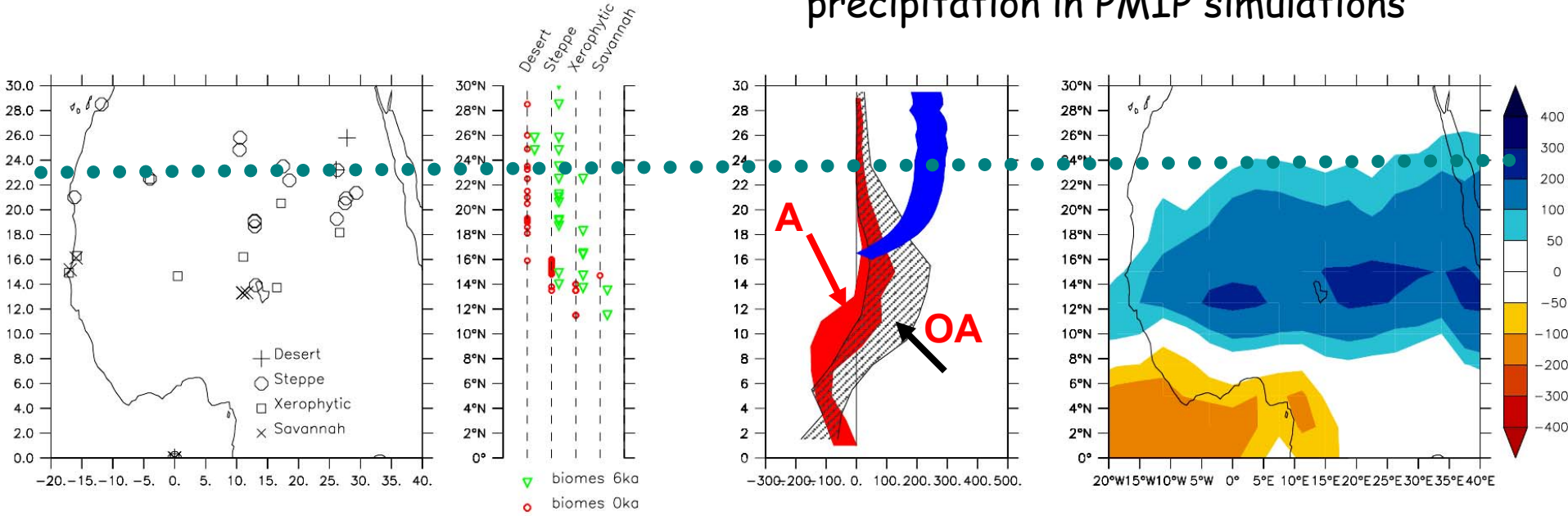
Paleoclimate Modelling PMIP Intercomparison Project Phase II

Underestimation of monsoon shift

Positive ocean feedback

Biome distribution

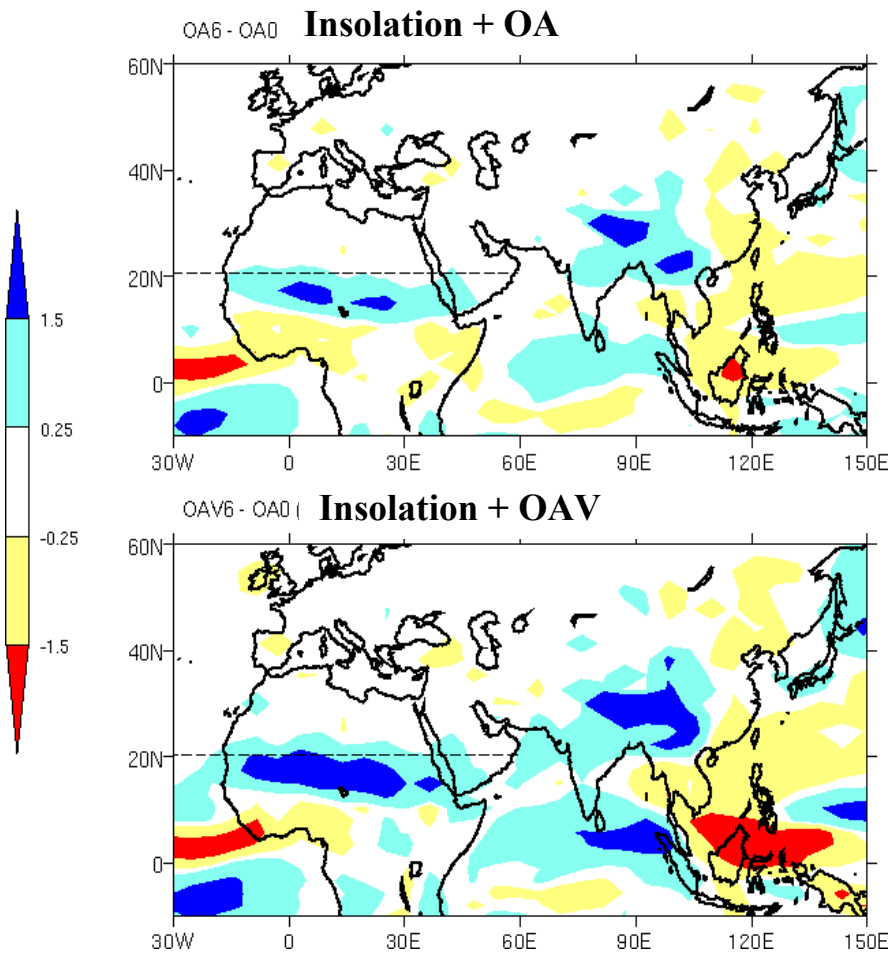
Change in annual mean precipitation in PMIP simulations



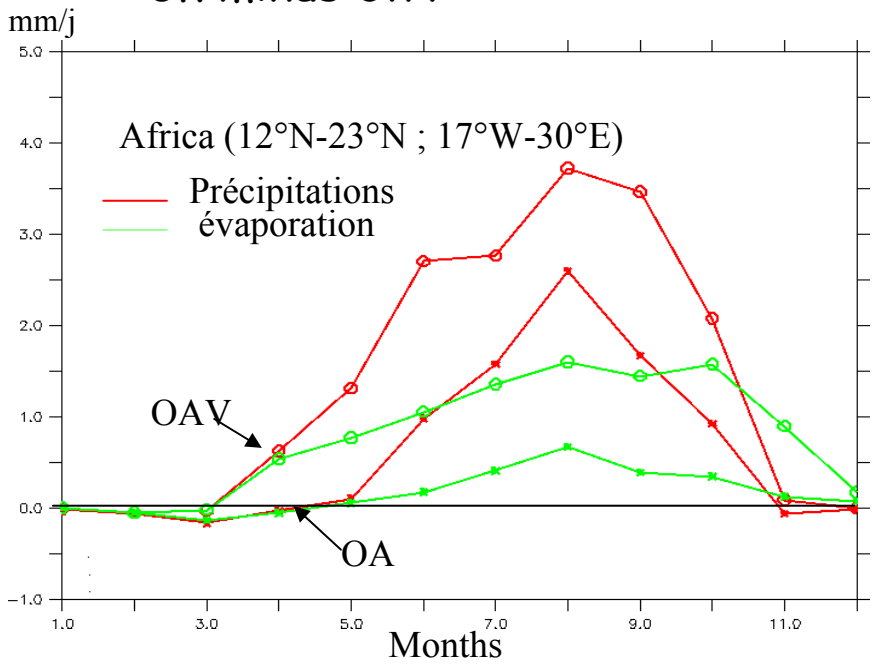
Braconnot and Harrison . PAGES, avril 2008

Synergy with vegetation feedback for mid-Holocene

IPSL model



6k minus ctrl

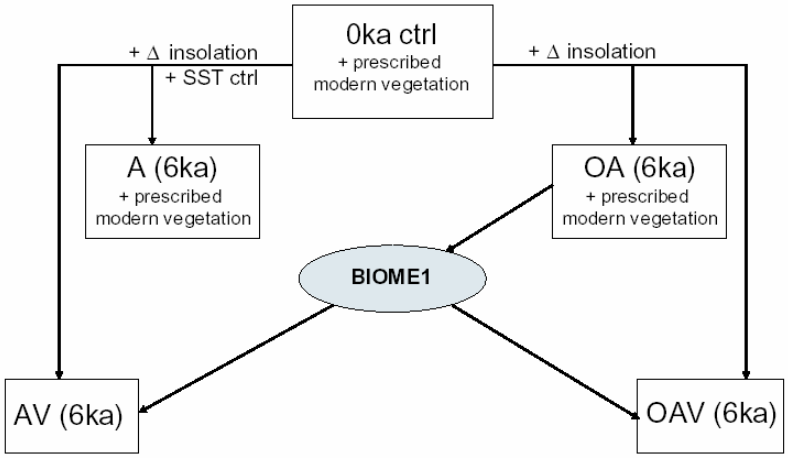


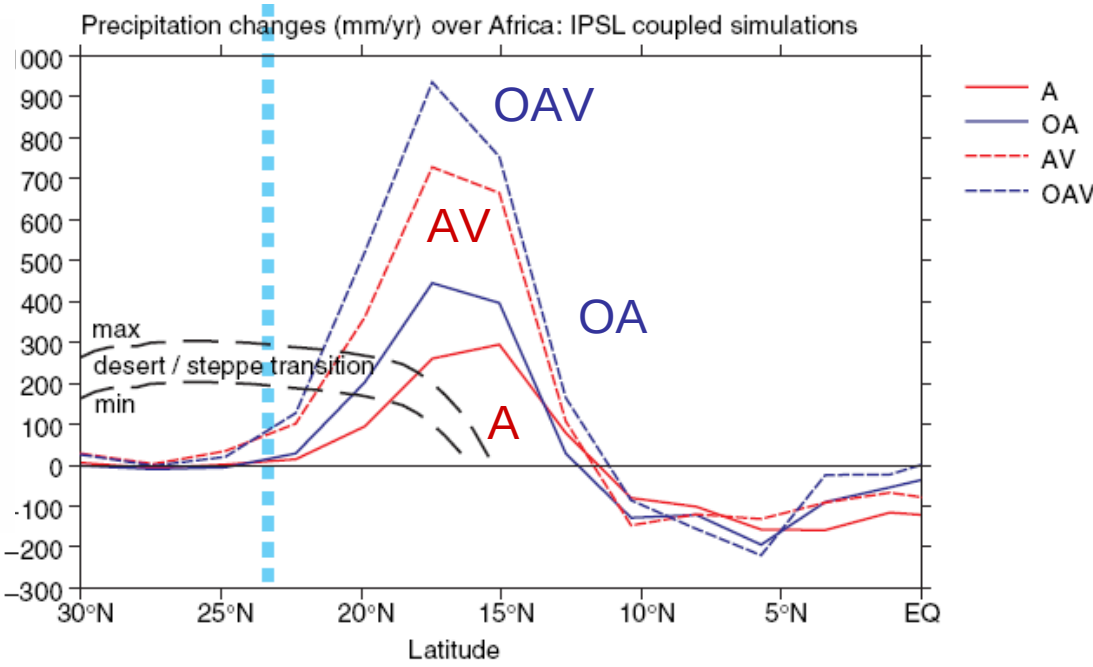
Ocean ---> moisture advection
Vegetation ---> local recycling (evaporation)

Braconnot et al, GRL (1999)

IPCC (2001)
Braconnot et al., 1999

Vegetation :
first results
positive feedback





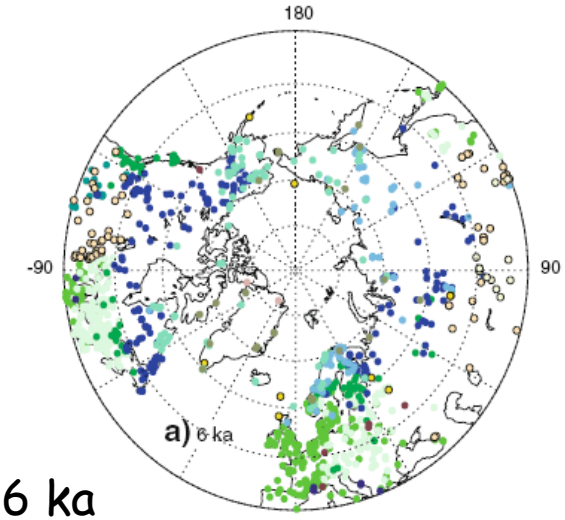
PMIP2 : coupled OAV with dynamic vegetation

Damped response
Dependence on control performance

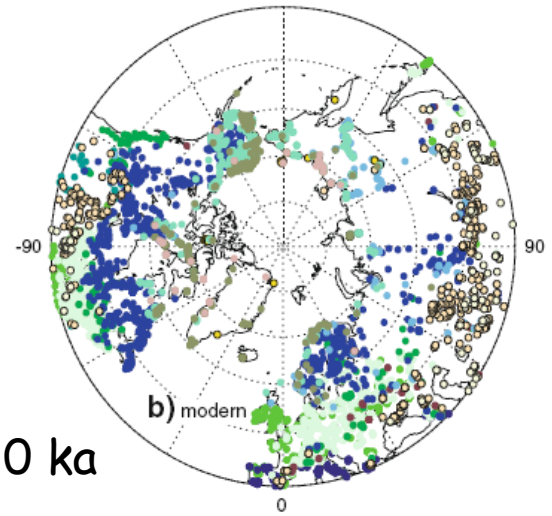
Paleoclimate Modelling
PMIP
Intercomparison Project
Phase II

Boreal extratropics

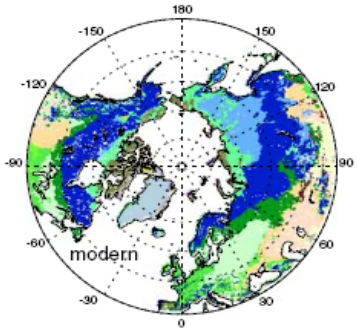
Paleoclimate Modelling
PMIP
Intercomparison Project
Phase II

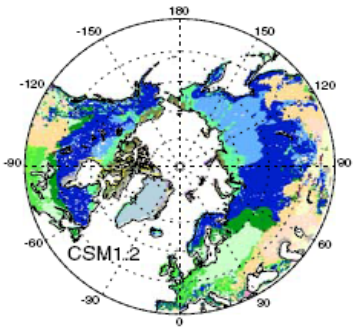


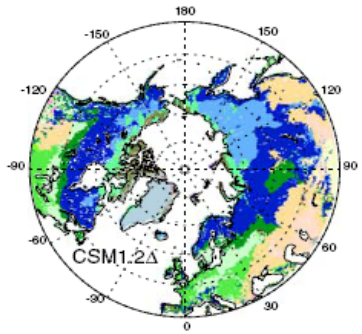
6 ka



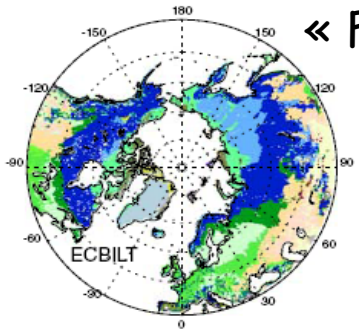
0 ka

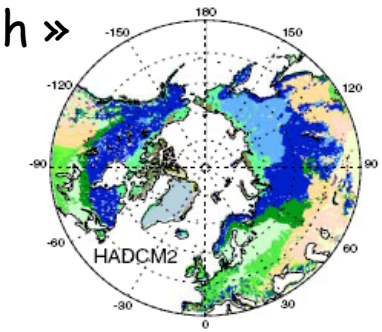


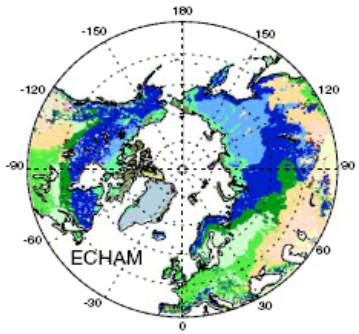


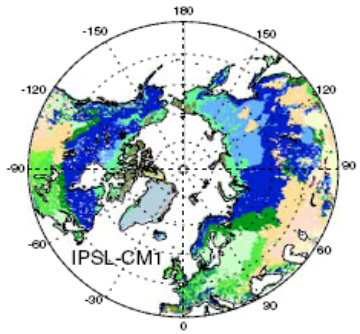


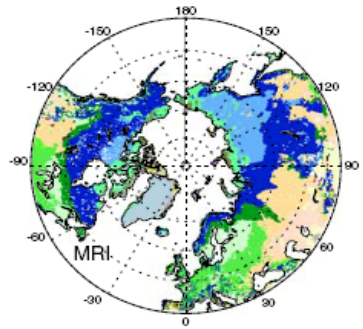
« Forward approach »











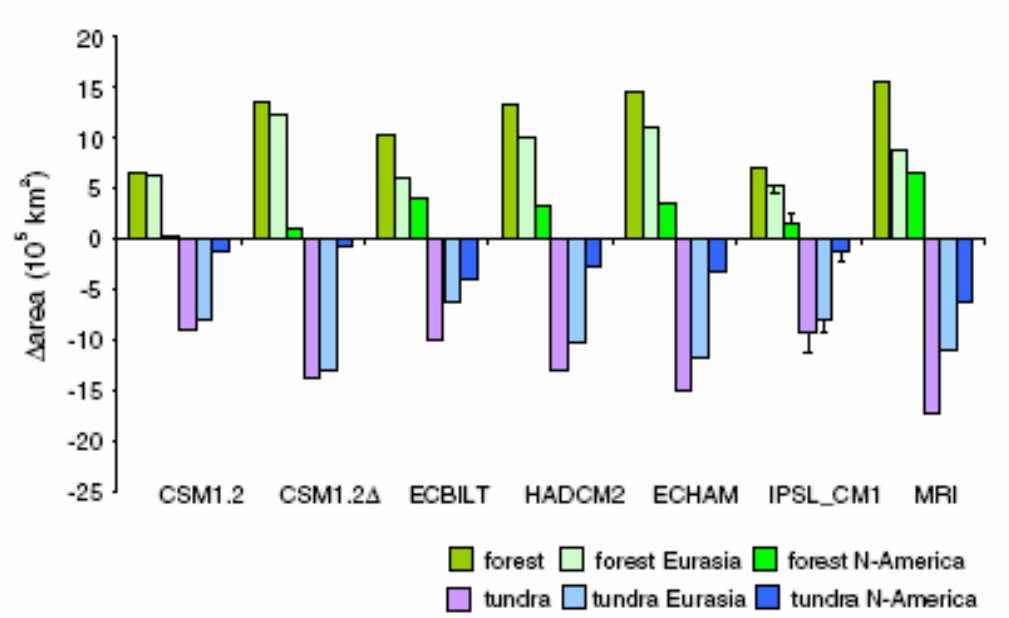
- temperate deciduous broadleaf forest
- temperate evergreen needleleaf forest
- warm-temp. evergreen broadleaf & mixed forest
- cool mixed forest
- cool evergreen needleleaf forest
- cool-temp. evergr. needleleaf & mixed forest
- cold evergreen needleleaf forest
- cold deciduous forest
- temperate xerophytic shrubland
- temperate grassland
- desert
- graminoid and forb tundra
- low and high shrub tundra
- erect dwarf-shrub tundra
- prostrate dwarf-shrub tundra

Wohlfahrt et al, Clim. Dyn. (2008)

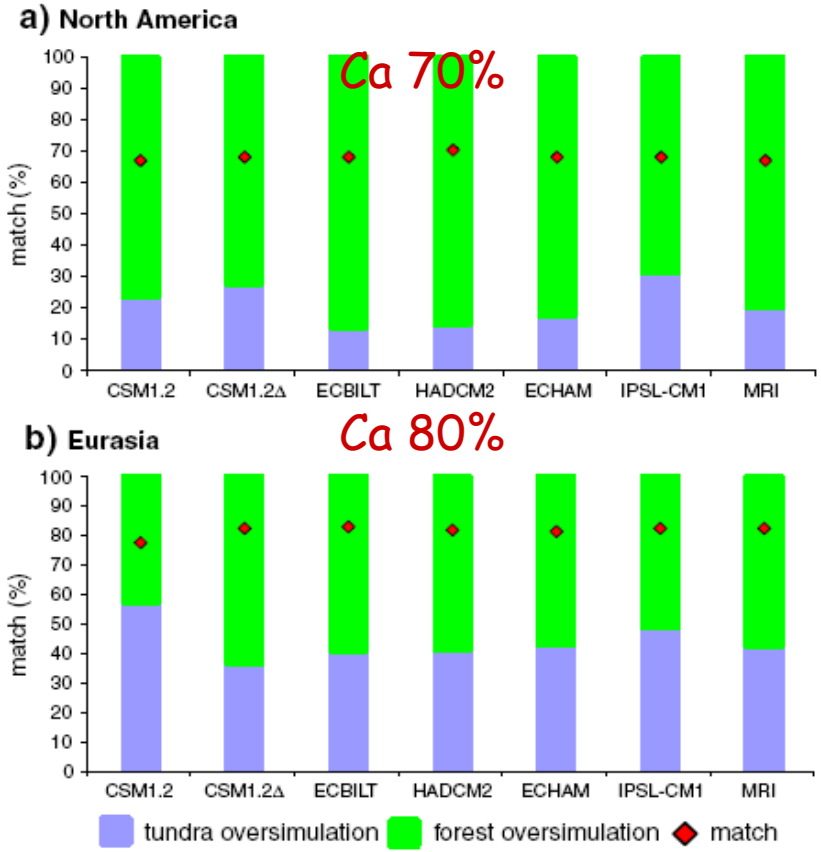
Boreal extratropics

Paleoclimate Modelling PMIP Intercomparison Project Phase II

Wohlfahrt et al, 2008



Model-data match %



Conclusions

Mid-Holocene :
right direction but underestimation
African monsoon ; northern latitudes

Last Glacial Maximum :
Fairly realistic
BUT
Underestimation of the high latitudes changes
Different answers for THC

Paleo: only way to evaluate models used for future projections on a different climate

Continuous process : towards a systematic test

Need investigate uncertainties : forcing, models (param & feedbacks)

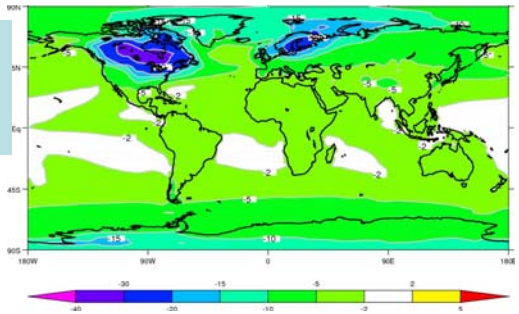
Towards Earth system models

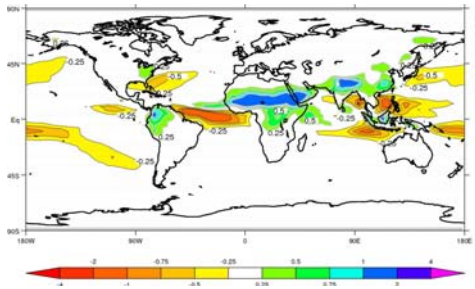
Need close collaboration model-data communities

PMIP 3

6th PMIP workshop, Estes Park 2008 - CLIVAR/WGCM 2008

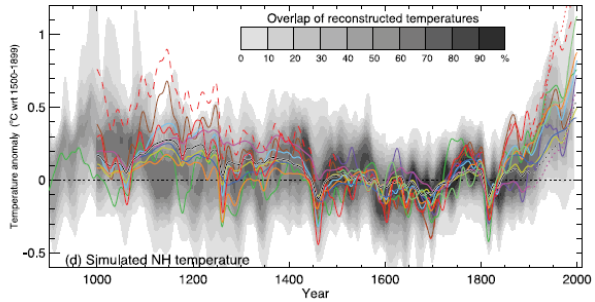
Climate extremes of the past :
LGM & mid-Holocene





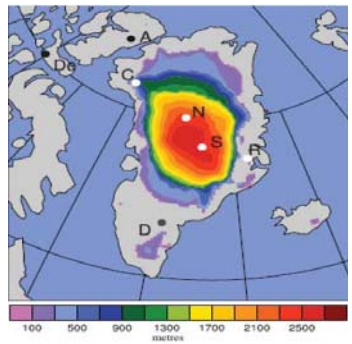
AR5:
very high priority

Climate of the Last Millenium



AR5:
recommended

Warm climates of the past :
Last Interglacial (130 kyr BP)
& Mid-Pliocene (3 Myr)



Deglaciation & fresh-water experiment (8.2 kyr BP)