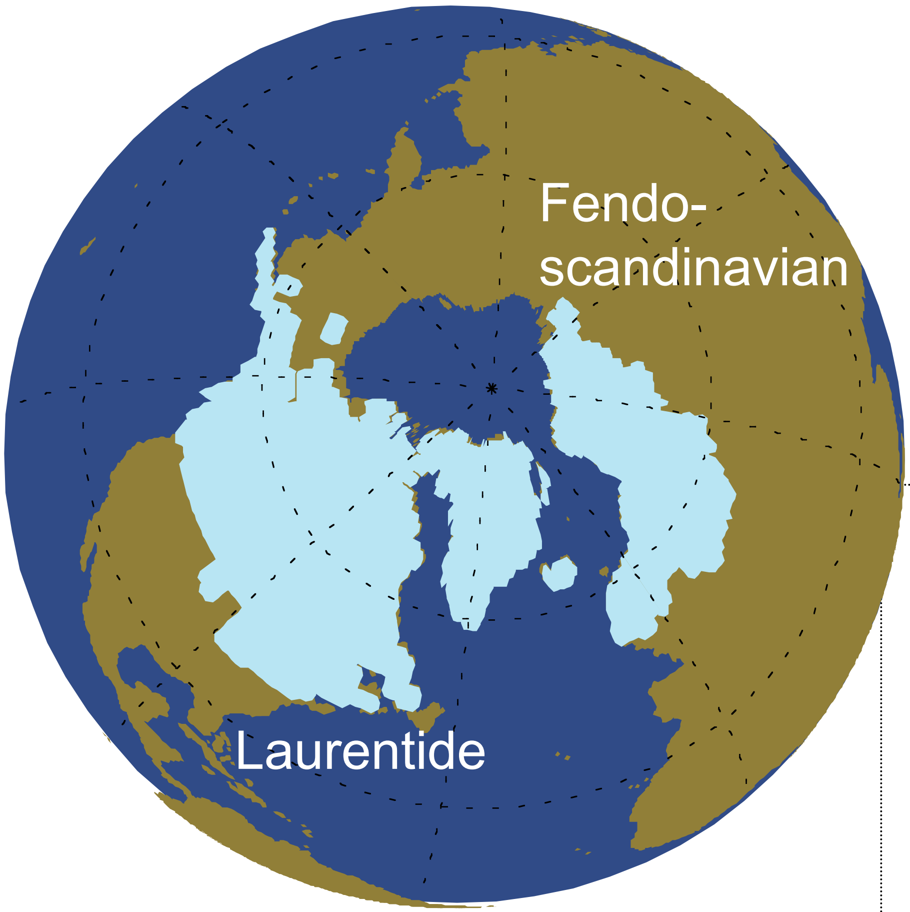
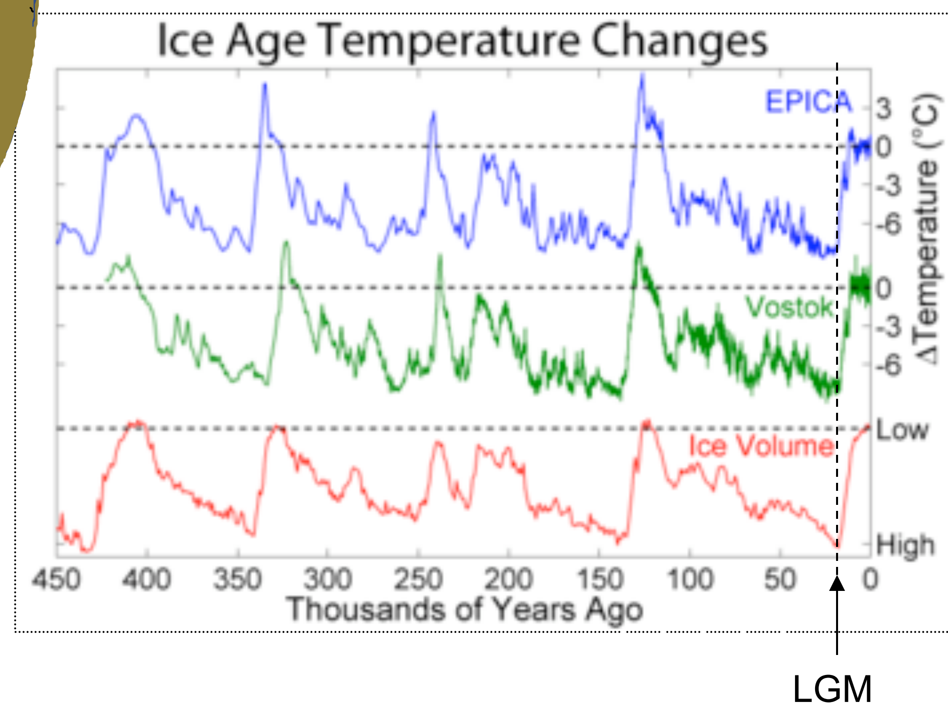
The Last Glacial Maximum (LGM)

the “observations”



The LGM was 19-23 kyr BP

200ppm CO_2
Land ice in NH



The Last Glacial Maximum: Forcing

Similar insolation as today

Table 2. Orbital parameters for the control (present day) and LGM (21 kBP) experiments derived from Berger (1978)

	0 kBP	21 kBP
Longitude of perihelion (relative to the vernal equinox)	102.5°	114.4°
Obliquity	23.44°	22.95°
Eccentricity	0.0167	0.0190

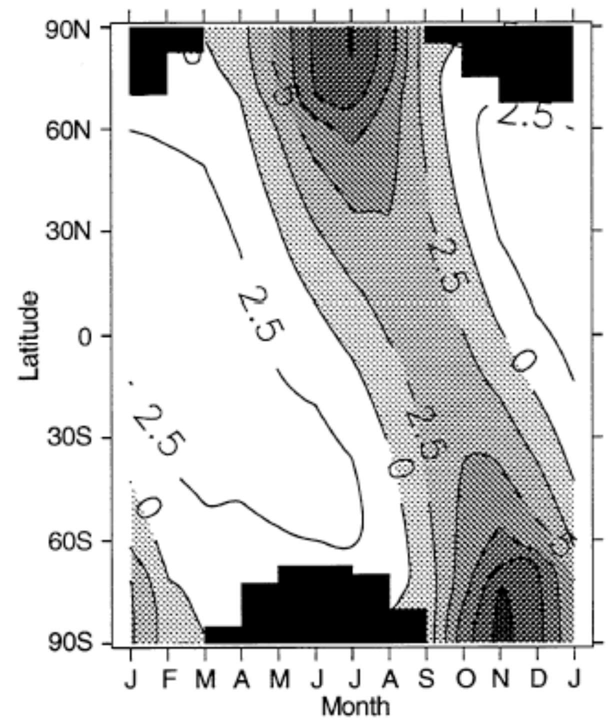
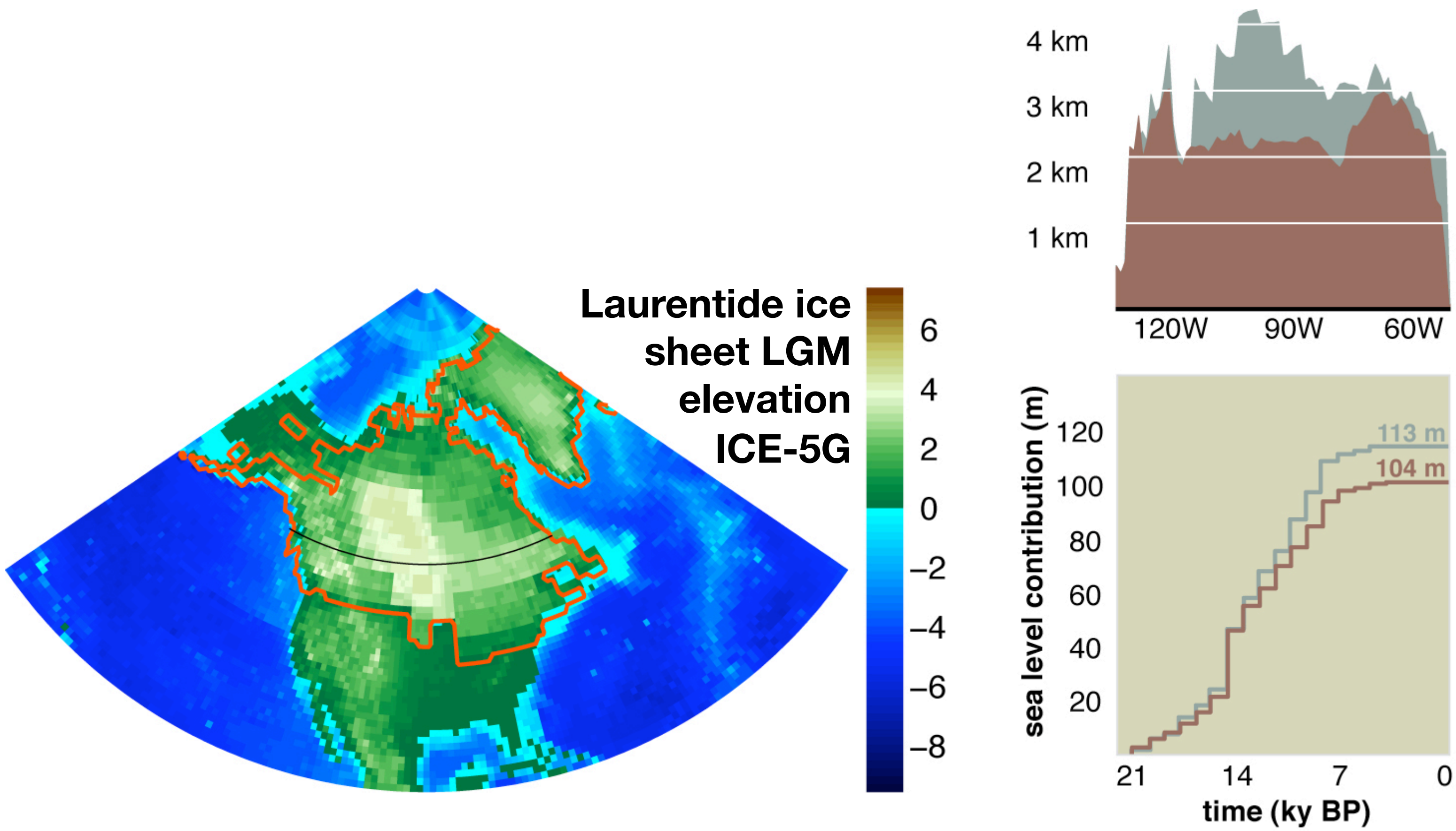


Fig. 1. Time-latitude diagram (zonal average of monthly mean values) of change in incoming shortwave radiation at the top of the atmosphere between 21 kBP and 0 kBP with *areas of decrease shaded.* The polar night has been masked out. Contours every 2.5 Wm^{-2}

Hewitt et al 1987

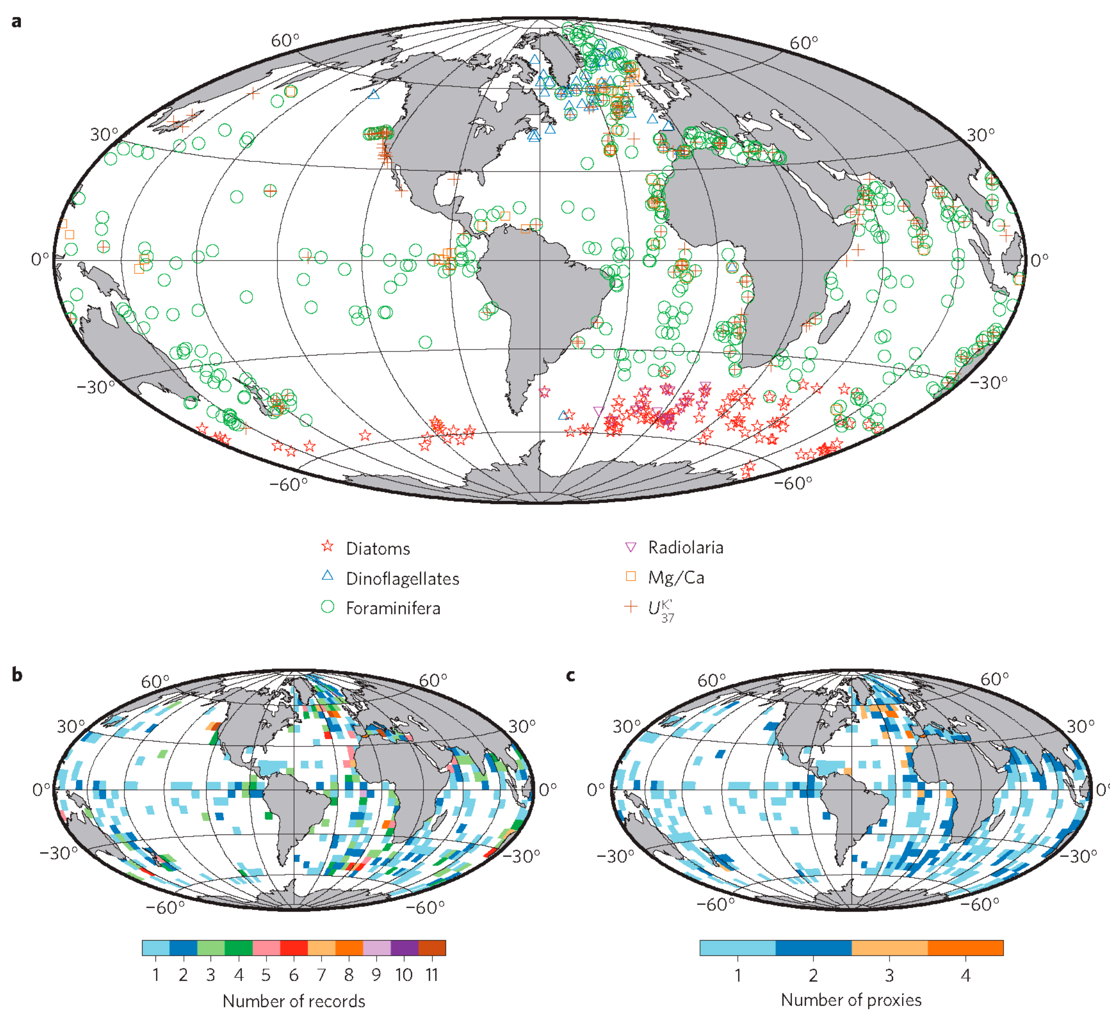
LGM Ice Sheet Reconstructions



Peltier 2004 AREPS

The Last Glacial Maximum:

the sites where SST is reconstructed using proxy data



Location of data

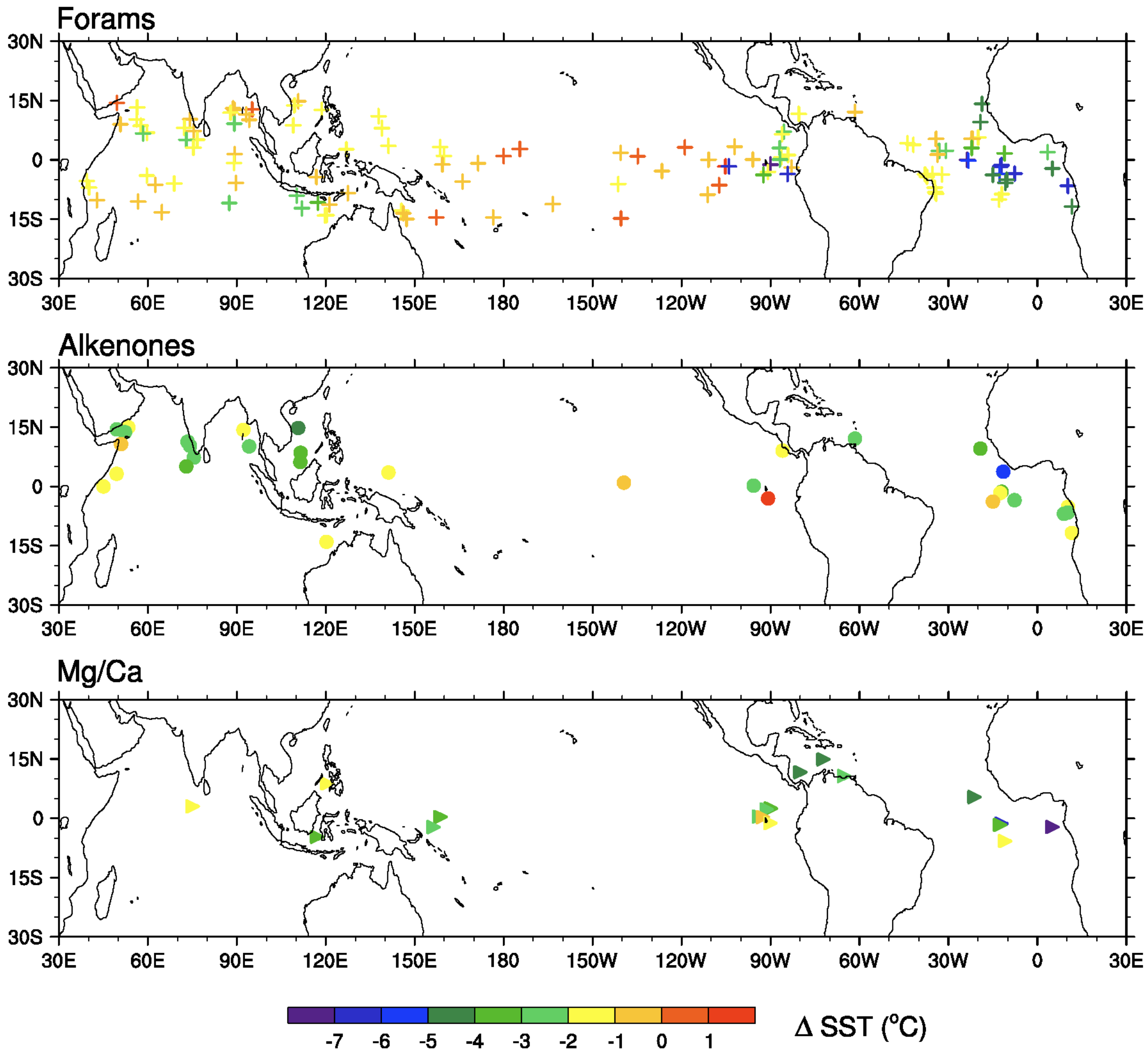
Number of records per 5x5 degree box

Number of data types

The Margo Team 2009

The Last Glacial Maximum:

the sites where SST is reconstructed using proxy data



LGM minus PI

Fig. 1 Proxy estimates of LGM sea surface temperature change (°C) based on foraminifera transfer functions (top), alkenones (middle), and foraminifera Mg/Ca (bottom) in MARGO synthesis (http://margo.pangaea.de)

Xx 200x

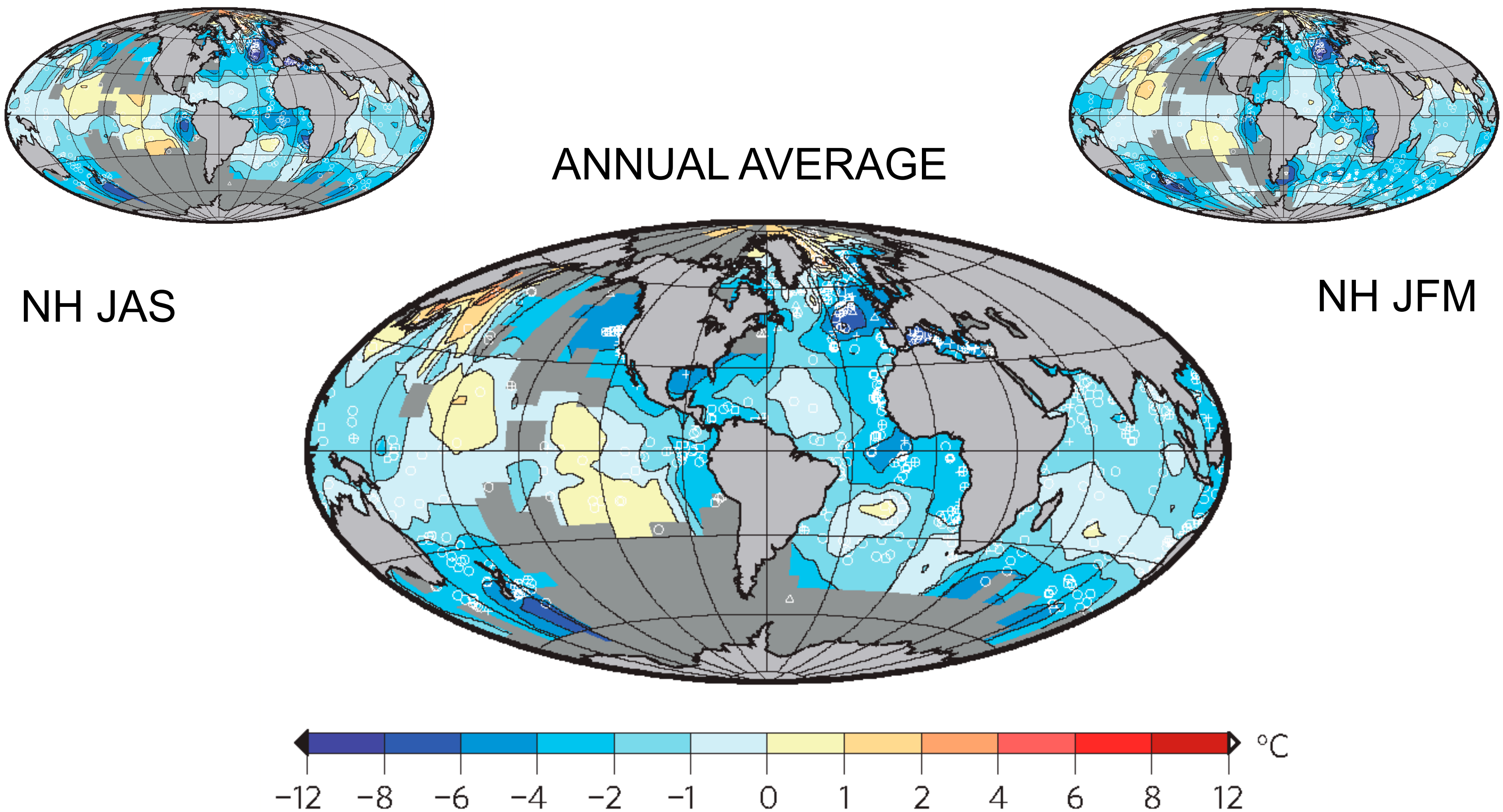
The Last Glacial Maximum:

the “observed” sea surface temperature (SST)

ANNUAL AVERAGE

NH JAS

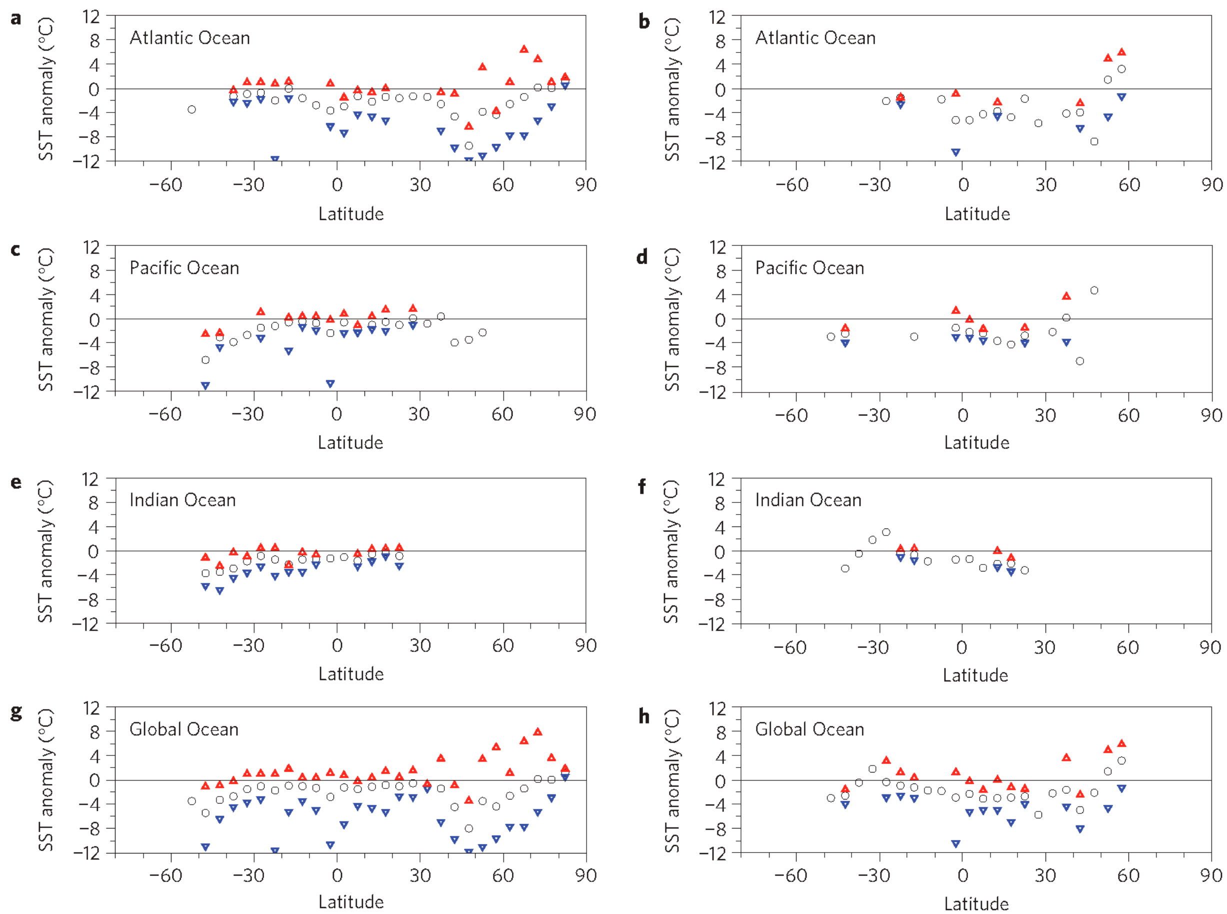
NH JFM



The Margo Team 2009

The Last Glacial Maximum:
the "observed" SST, LGM minus PI

Modern Analog Method | Mg/Ca ratios



Atlantic

Pacific

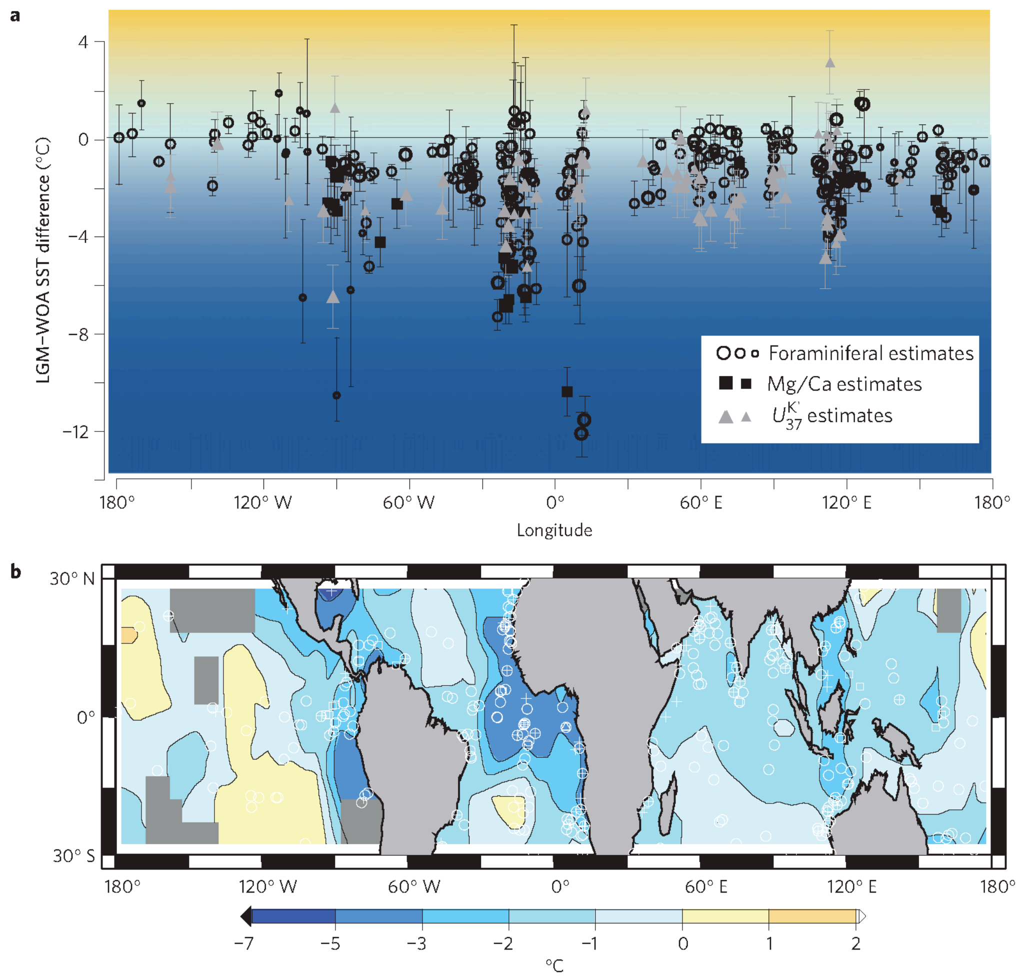
Indian

All

O = Mean   = Extreme

The Margo Team 2009

The Last Glacial Maximum:
the "observed" SST, LGM minus PI



E-W across the tropics

Figure 4 | Map and longitudinal averages of LGM SST annual mean anomalies for the 30° S–30° N tropical band. a, Longitudinal averages of the LGM SST annual mean anomalies derived from foraminifera assemblages, foraminifera Mg/Ca and alkenones $U^{K'}_{37}$. The symbol size is proportional to the average of the three quality indices (see Supplementary Information). Error bars indicate RMSEP (Mg/Ca and alkenones-$U^{K'}_{37}$) or range of the estimates by the different statistical techniques (foraminifera assemblages). **b**, Map of gridded (5° × 5°) SST annual mean anomalies showing the location of the data as in Fig. 1.

The Margo Team 2009

The Last Glacial Maximum:

the "observations"

Table 1 | Regional mean SST anomalies (modern — LGM) based on block-averaged data with reliability weighting.

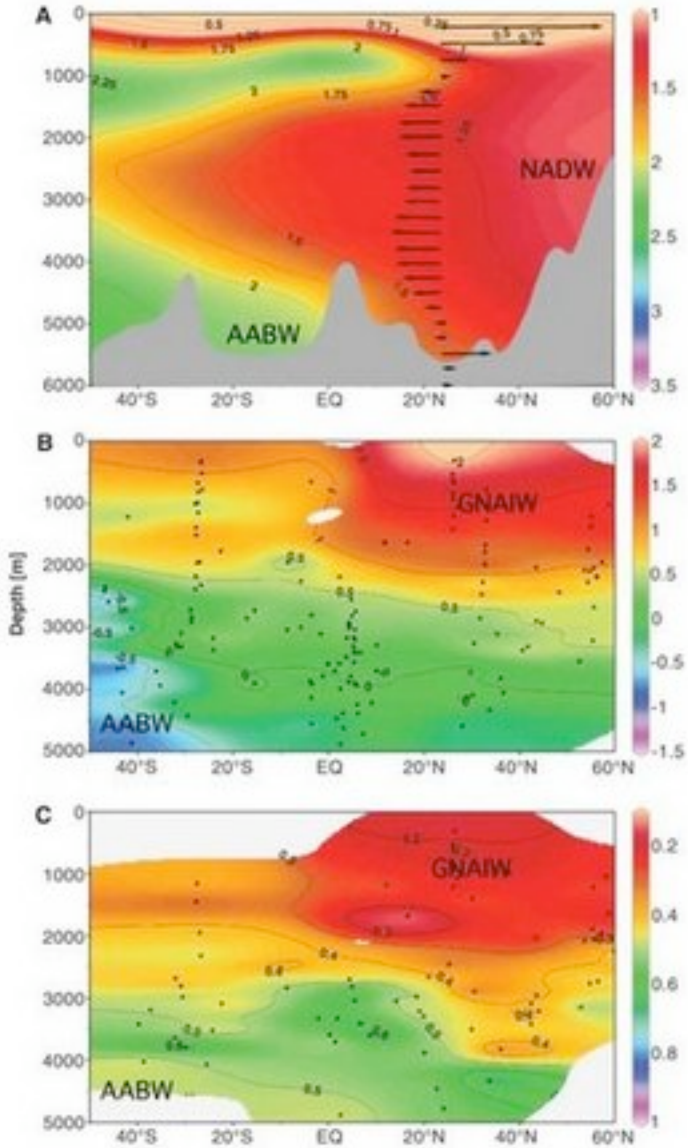
		Global Ocean		Atlantic Ocean		Indian Ocean		Pacific Ocean	
	Latitude zone	Regional mean (°C)	Total error (°C)	Regional mean (°C)	Total error (°C)	Regional mean (°C)	Total error (°C)	Regional mean (°C)	Total error (°C)
Annual mean	15° S-15° N	−1.7	1	−2.9	1.3	−1.4	0.7	−1.2	1.1
	30° S-30° N	−1.5	1.2	−2.3	1.5	−1.3	0.7	−1.1	1.2
	60° S-60° N	−1.9	1.7	−2.6	2	−1.6	1	−1.5	1.8
	90° S-90° N	−1.9	1.8	−2.4	2.2	−1.6	1.1	−1.5	1.8
JAS*	15° S-15° N	−1.5	1.6	−3	1.9	−1.2	1	−0.9	1.8
	30° S-30° N	−1.3	1.7	−2.3	2.3	−1	1	−0.9	1.7
	60° S-60° N	−1.9	2.1	−2.7	2.7	−1.5	1.3	−1.4	2
	90° S-90° N	−1.8	2.2	−2.5	2.9	−1.5	1.3	−1.4	2
JFM†	15° S-15° N	−1.6	1.4	−2.5	1.7	−1.3	0.8	−1.2	1.7
	30° S-30° N	−1.4	1.6	−2.2	2.1	−1	1	−1.1	1.7
	60° S-60° N	−2	2	−2.8	2.3	−1.8	1.3	−1.6	2.1
	90° S-90° N	−2	2	−2.7	2.4	−1.7	1.3	−1.5	2.1

*JAS: July-August-September.
† JFM: January-February-March.

Proxy climate info over land comes from pollen and vegetation data, boreholes, moraines, trim lines, etc.

The Margo Team 2009

The Reconstructed Atlantic Ocean



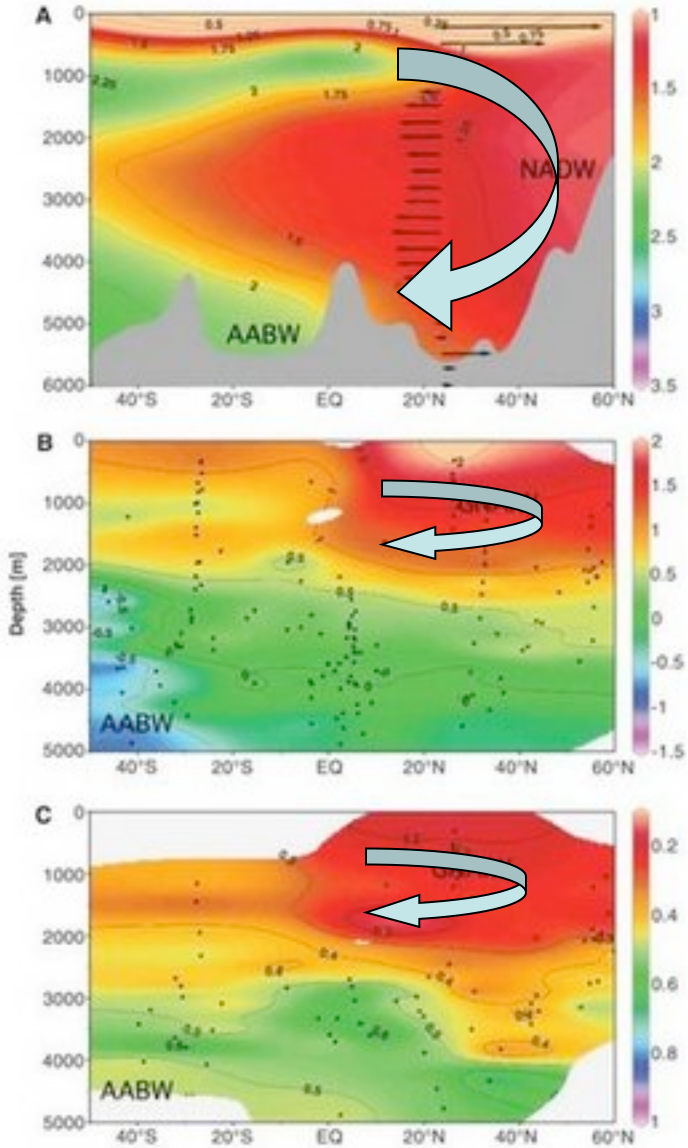
Modern Ocean

LGM Ocean
(from C_{13})

LGM Ocean
(from Cd/Ca)

Steiglitz et al 2007

The Reconstructed Atlantic Ocean



Modern Ocean

LGM Ocean (from C_{13})

LGM Ocean (from Cd/Ca)

Steiglitz et al 2007

Climate Models Simulations of the LGM

Paleo Modelling Intercomparison Project II (PMIP2)

Table 2 PMIP2 forcings and boundary conditions for LGM and preindustrial simulations

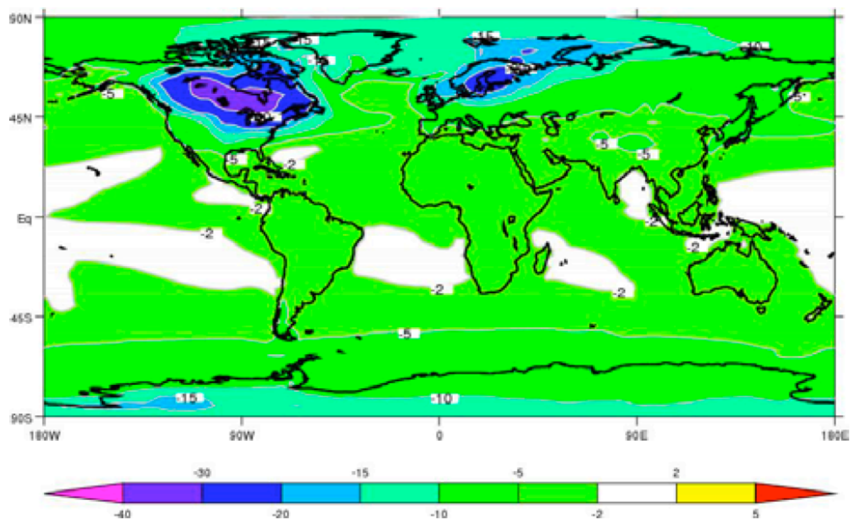
	LGM	Preindustrial
Greenhouse gases		
Carbon dioxide (ppmv)	185	280
Methane (ppbv)	350	760
Nitrous oxide (ppbv)	200	270
Orbital	21,000 year BP	1950 AD[a]
Eccentricity	0.018994	0.16724
Obliquity (°)	22.949	23.446
Angular precession (°)	114.42	102.04
Ice sheets	ICE-5G	Present-day
Land-sea mask	ICE-5G	Present-day
Vegetation	Present-day	Present-day

[a] The orbital parameters for the preindustrial control simulation are prescribed to the reference values of 1950 AD, as done in PMIP1. The differences in 1750 and 1950 insolation induced by changes in the orbital parameters are negligible

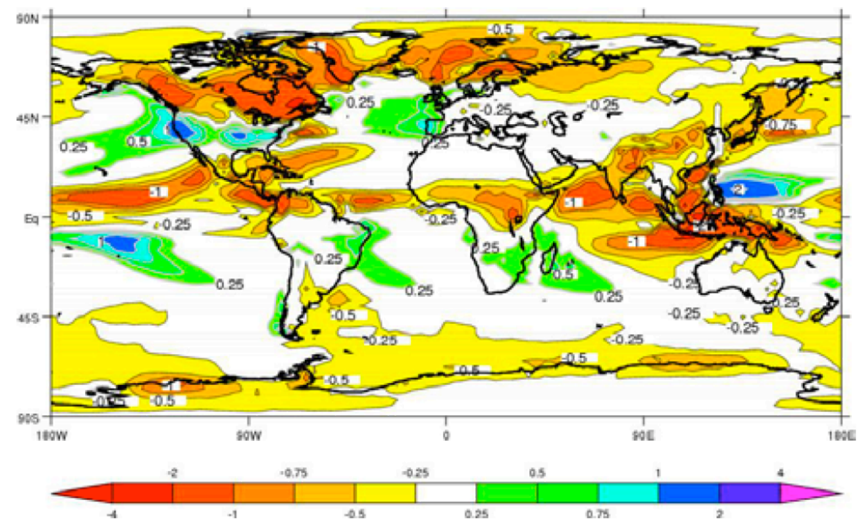
Brancannot et al 2007

Surface Temperature & Precip Change
LGM minus Pre-Industrial

Surface Temperature



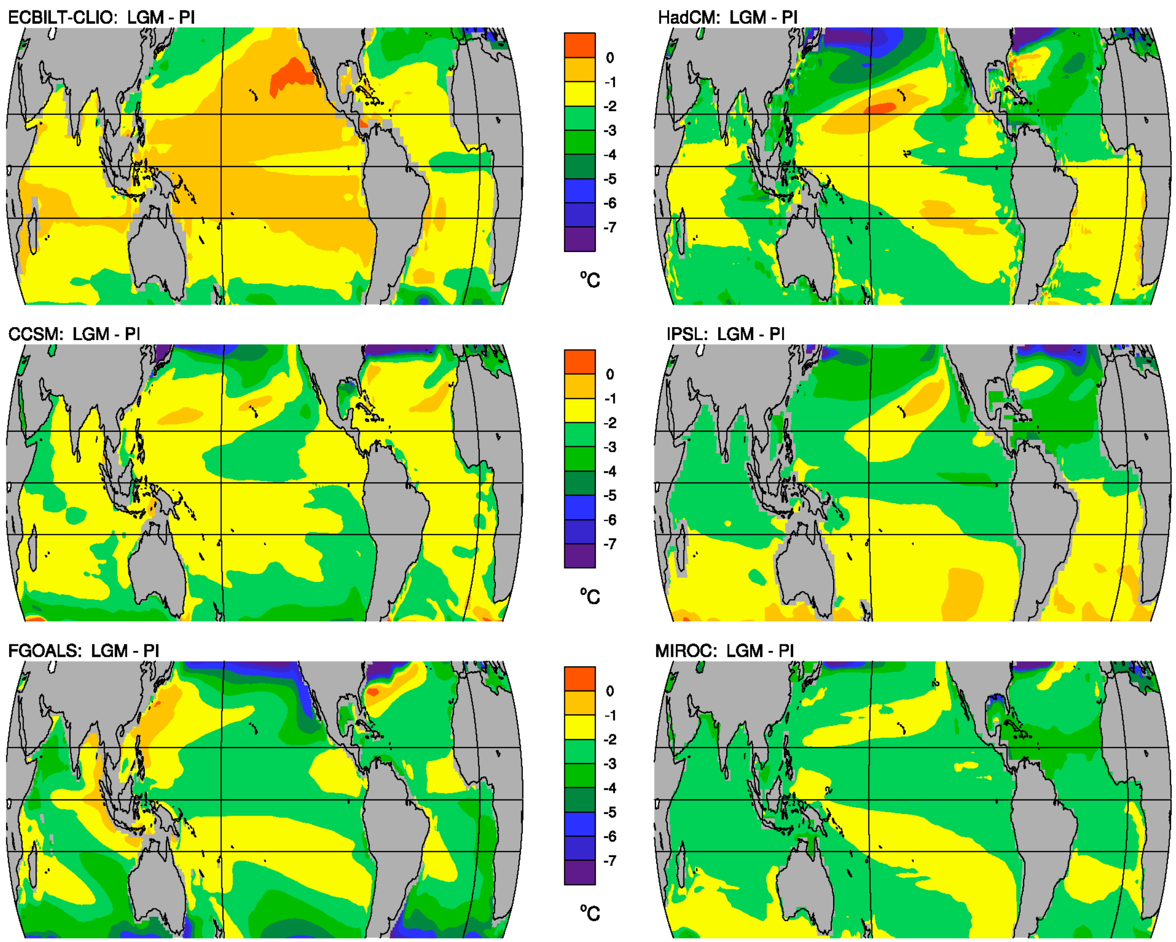
Precipitation



Average of Six Climate Models

Braconnot et al 2007

Sea Surface Temperature Change
LGM minus Pre-Industrial



Average of Models

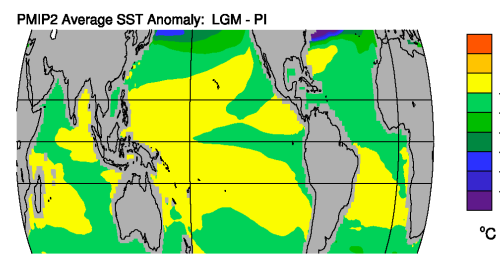
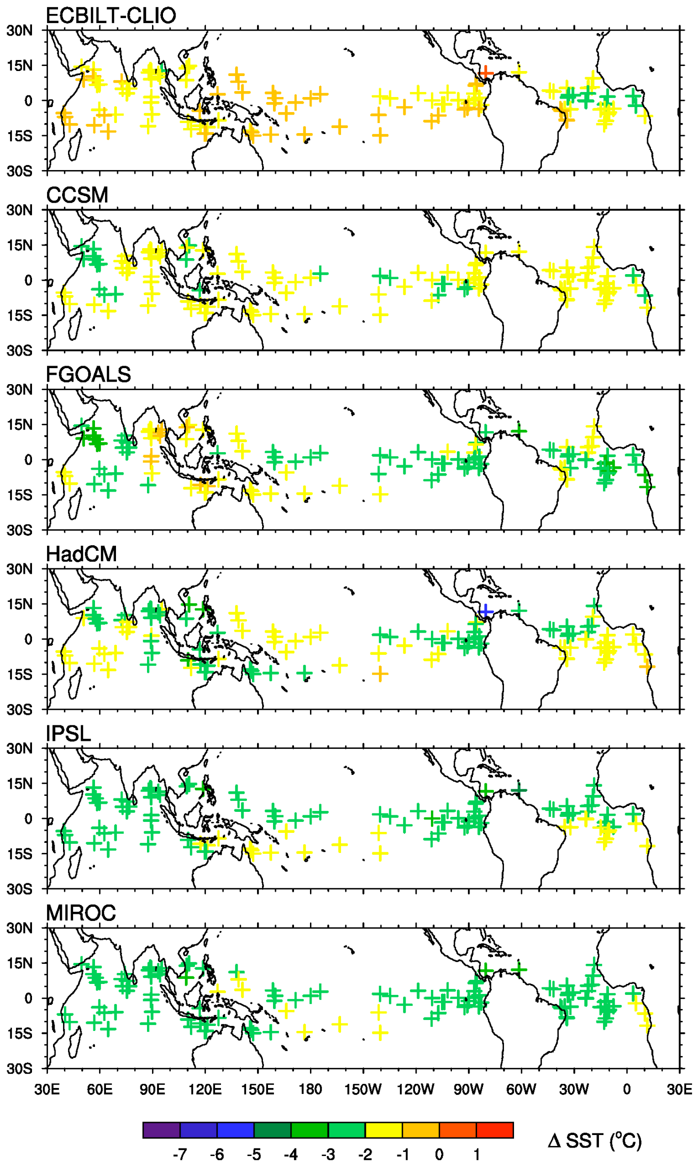


Fig. 3 Sea surface temperature (°C). Top two panels show the multi-model mean LGM SST and SST change, LGM minus PI. Also shown are the SST change, LGM minus PI, simulated by each of the six PMIP2 models. *Black horizontal lines* delineate latitudes15°S, equator and 15°N

Otto-Bleisner et al 2009

The Last Glacial Maximum:

Comparison of models w/ reconstructed SST



LGM minus PI

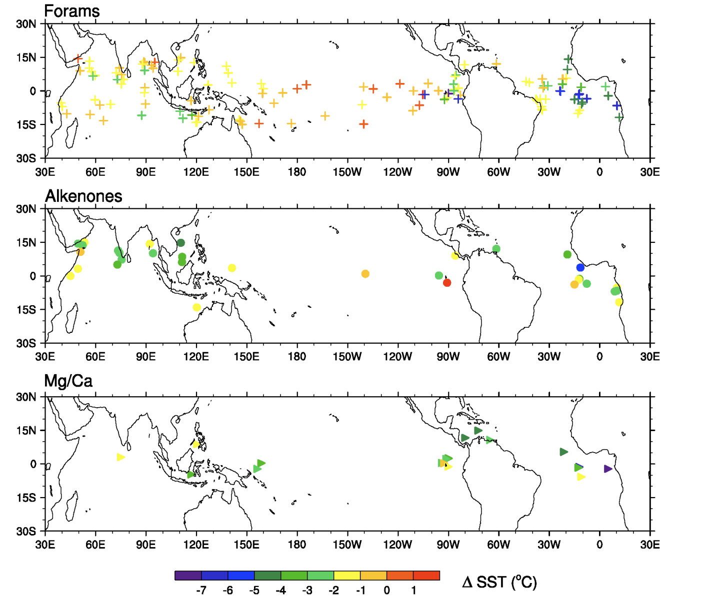


Fig. 1 Proxy estimates of LGM sea surface temperature change (°C) based on foraminifera transfer functions (top), alkenones (middle), and foraminifera Mg/Ca (bottom) in MARGO synthesis (http://margo.pangaea.de)

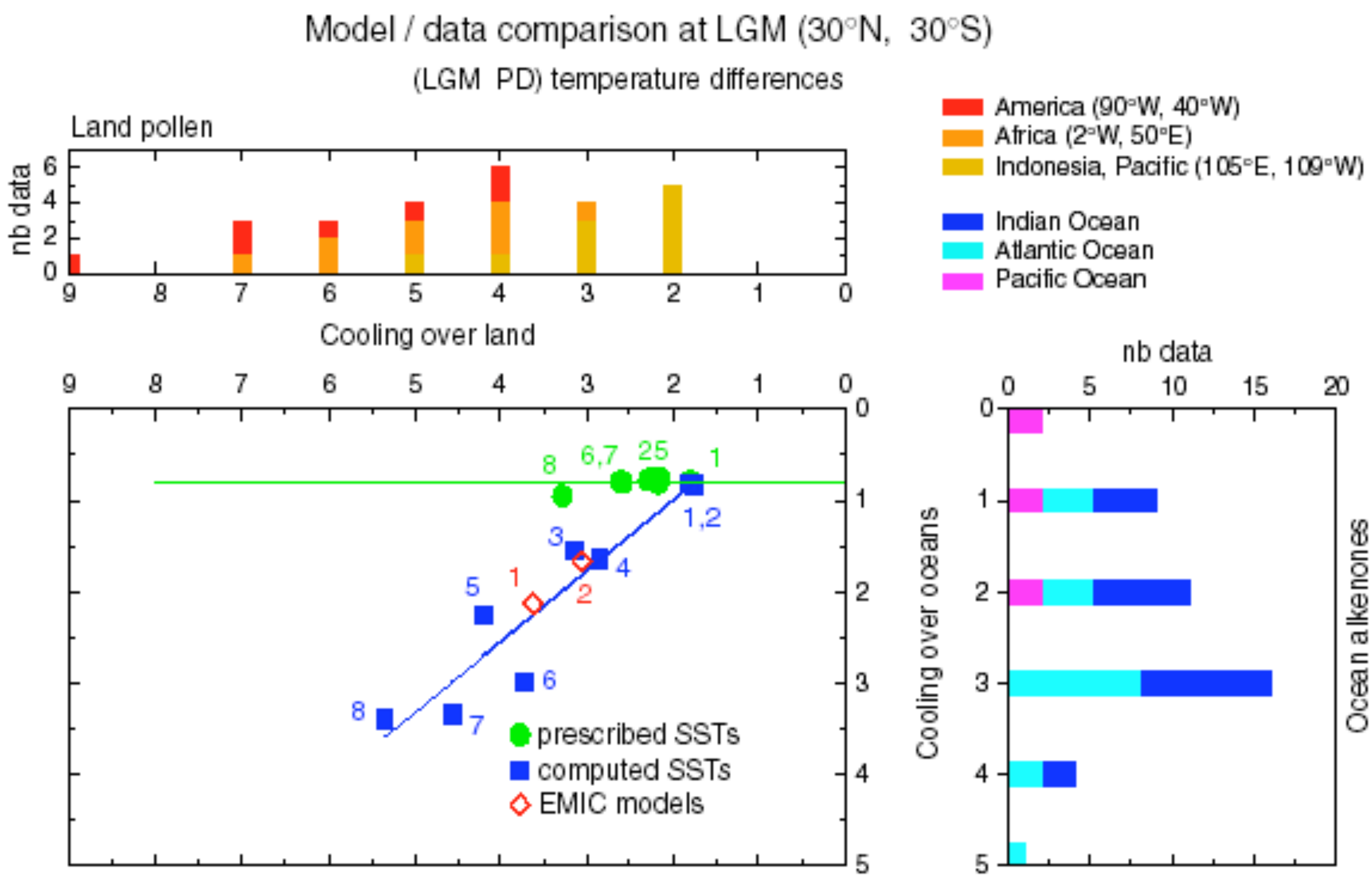
Table 3 Annual mean changes of sea surface temperature (SST), LGM minus PI, as simulated by the PMIP2 models and estimated from the MARGO data

	ΔSST LGM 15°S–15°N All basins	ΔSST LGM 15°S–15°N Indian[a]	ΔSST LGM 15°S–15°N Pacific[b]	ΔSST LGM 15°S–15°N Atlantic[c]
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

Otto-Bleisner et al 2009

LGM vs PI Temperature Changes

Summary of PMIP experiments using AGCMs (w/ slab oceans)



From IPCC 2001; adapted from Pinot et al. 1999

LGM vs PI Precipitation Changes

Summary of PMIP experiments using AGCMs (w/ slab oceans)

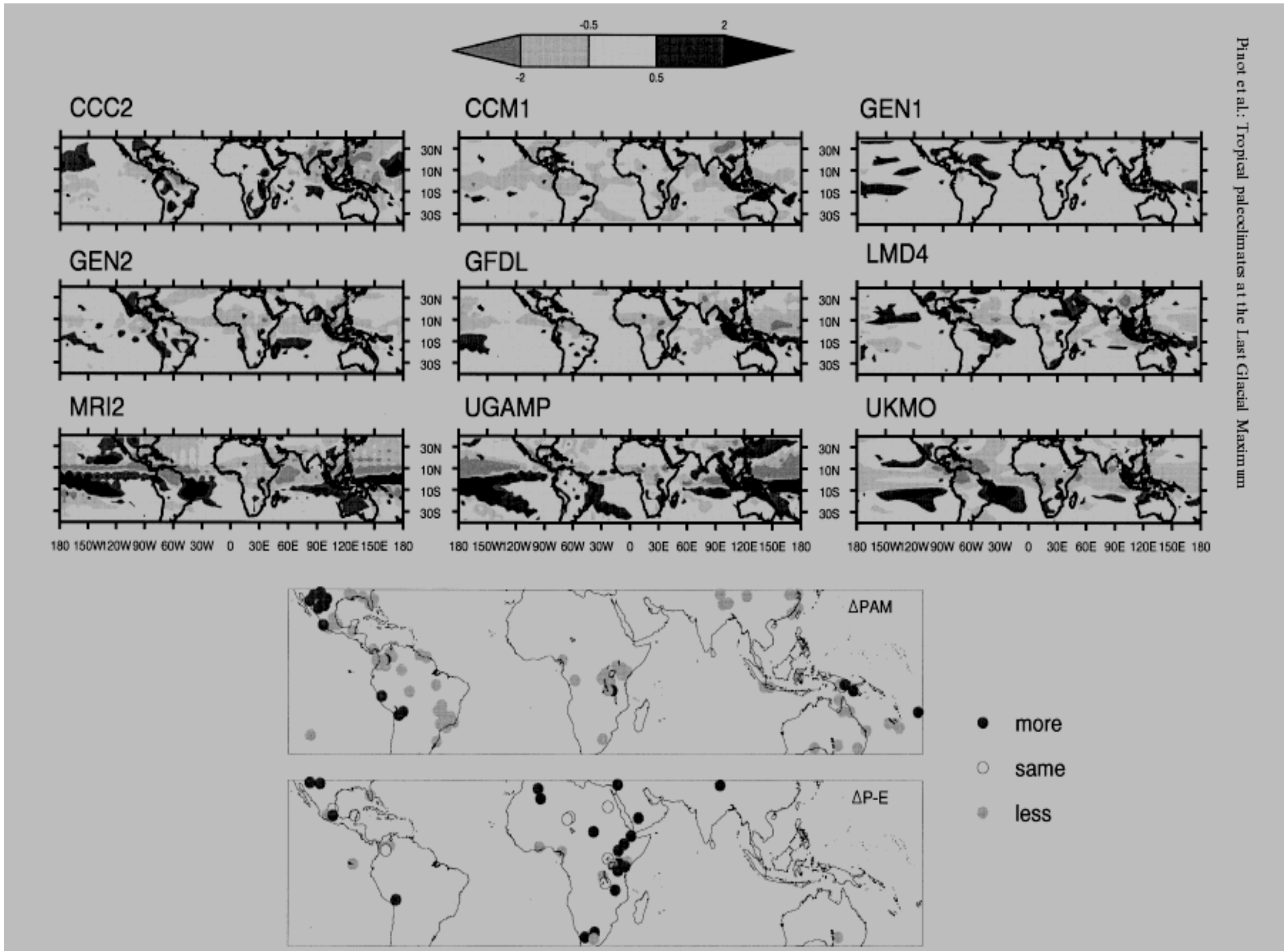
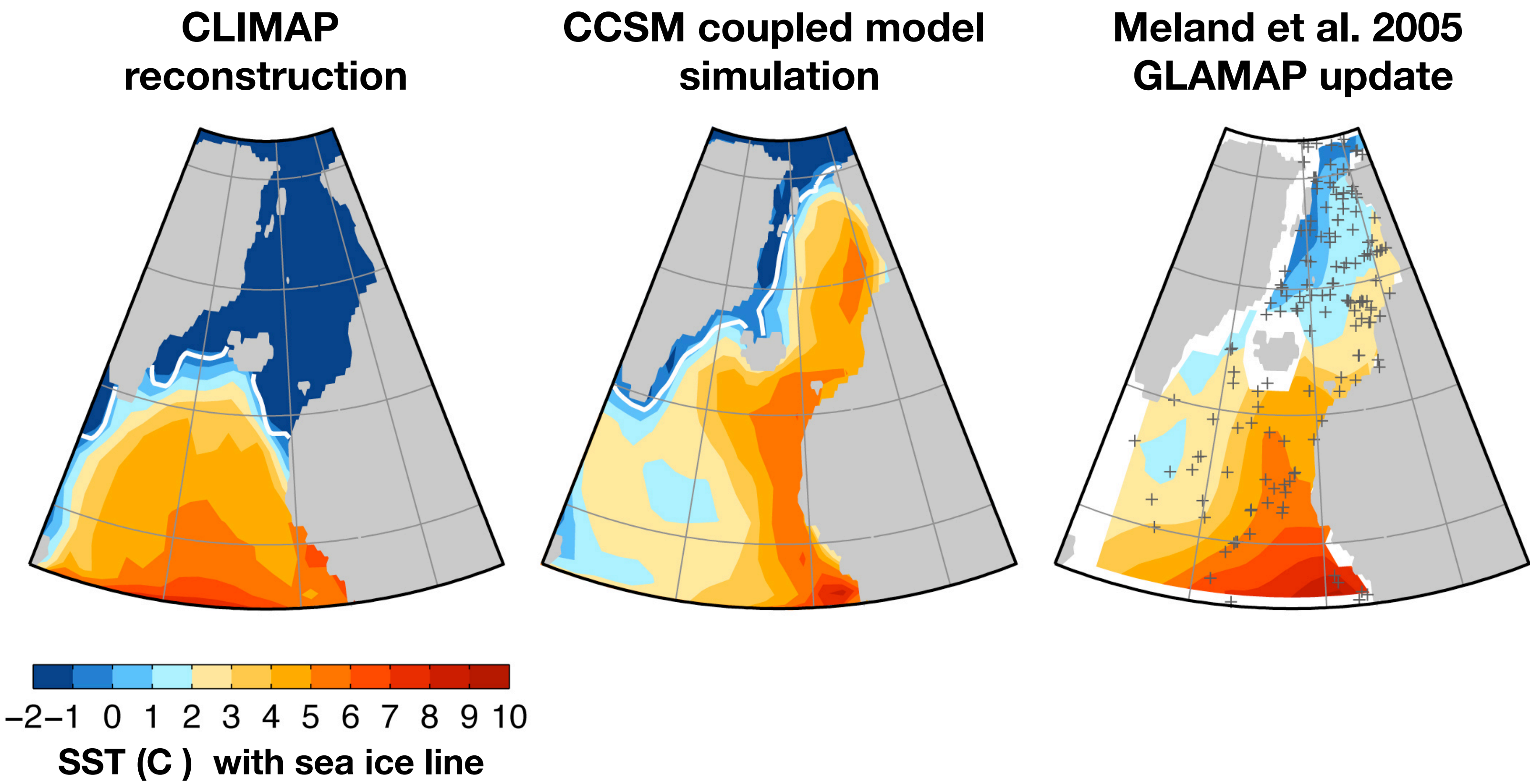


Fig. 11 Changes in mean annual precipitation (mm/d) between LGM and PD simulated by the 9 PMIP models with computed SSTs compared to changes in moisture as registered by lake levels and plant available moisture in the tropical area

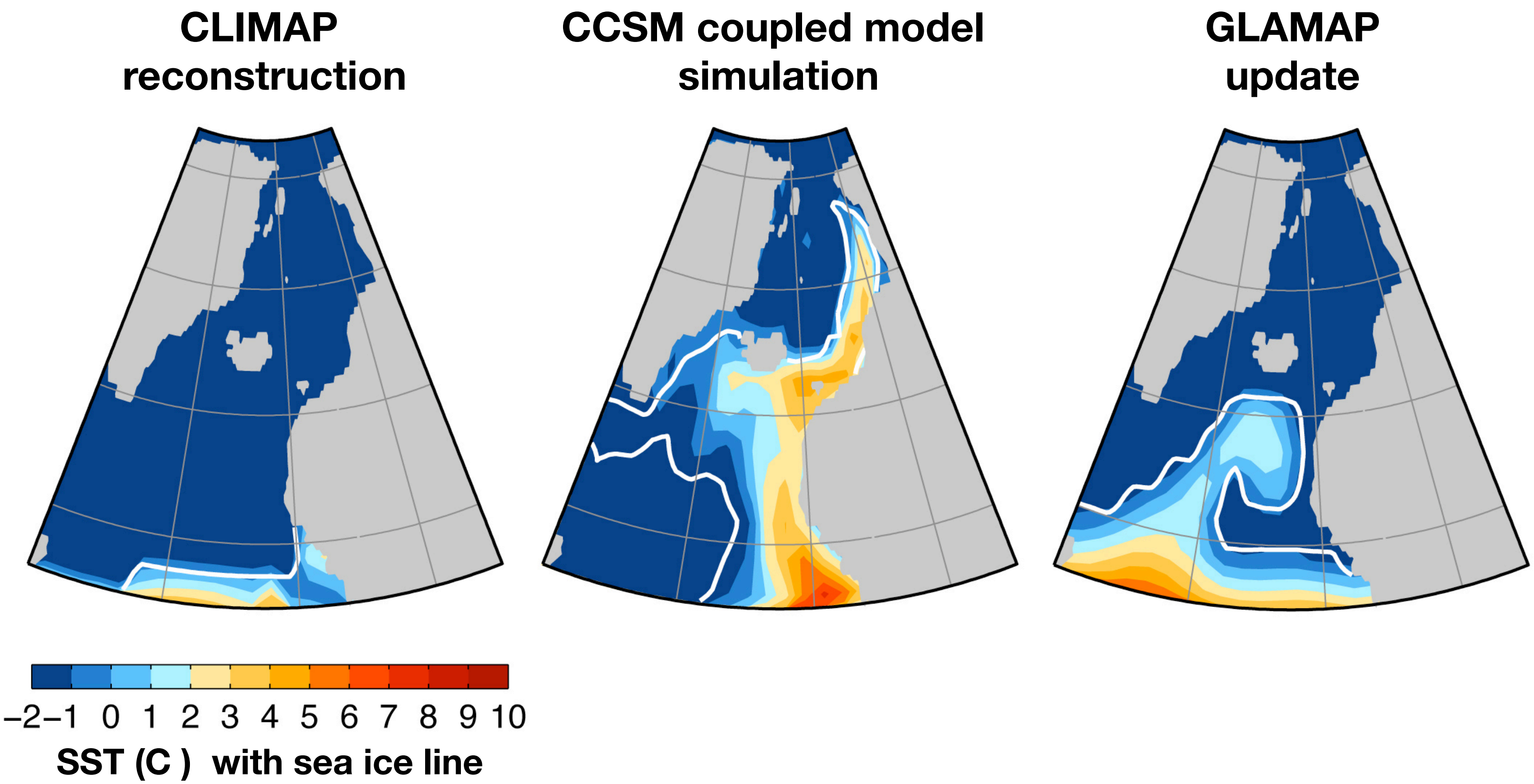
from Pinot et al. 1999

SST and sea ice: Summer



Using Ice5G gives a more realistic sea ice distribution

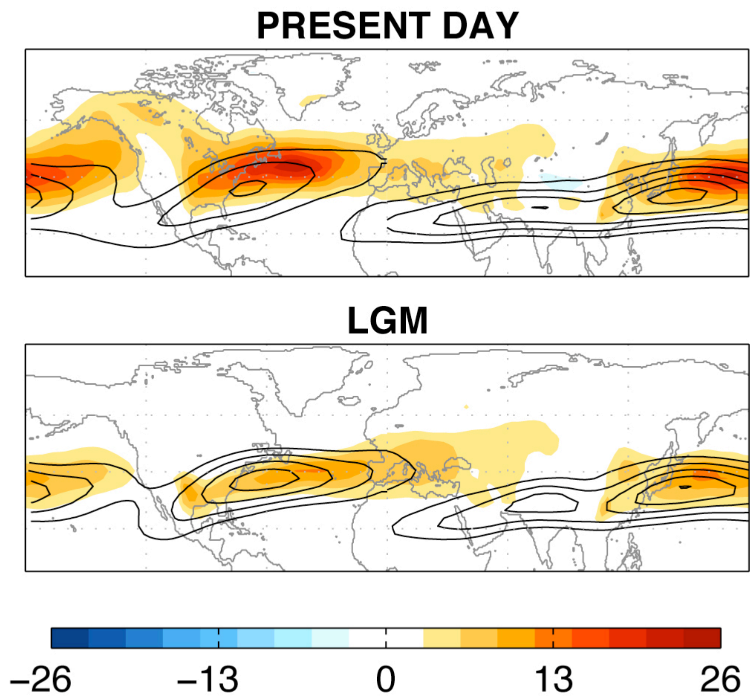
SST and sea ice: Winter



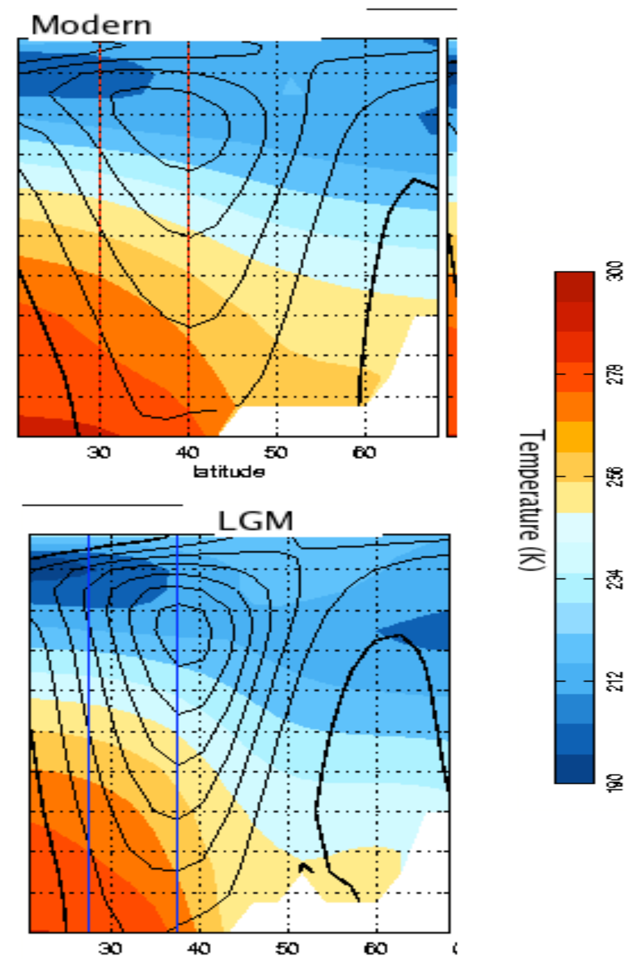
Using Ice5G gives a more realistic sea ice distribution

LGM vs. PI Storm Track
LGM uses Ice5G

Zonal Wind (c.i. = 20m/s)



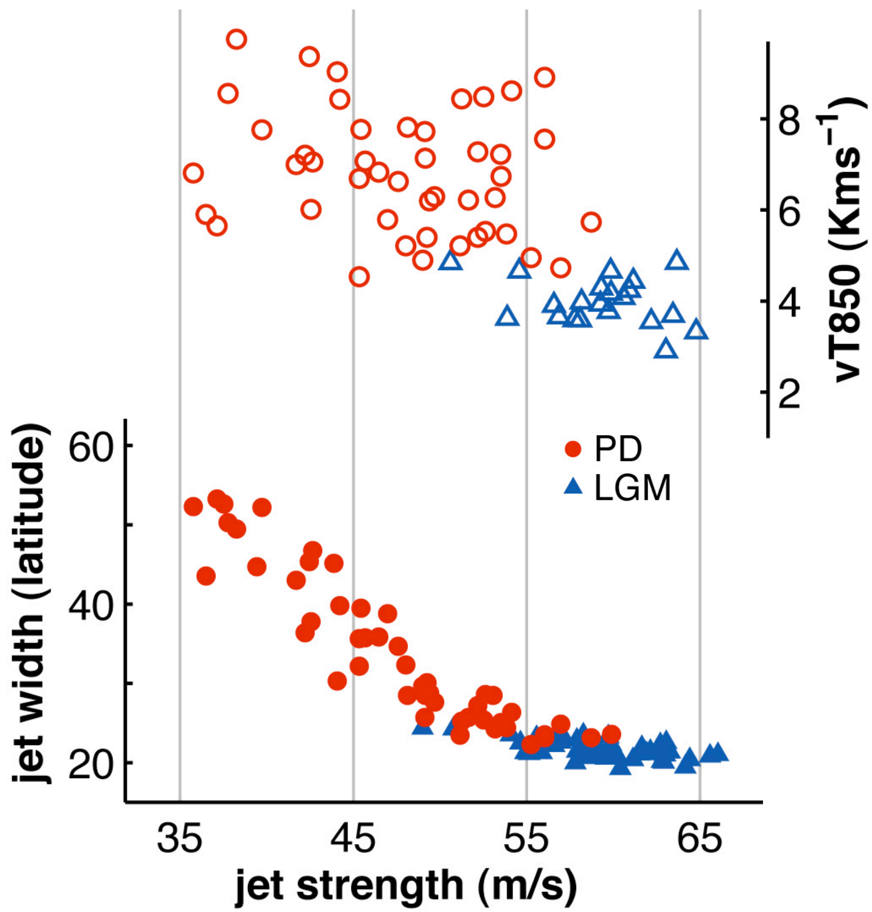
poleward atmospheric
heat flux (Km/s)



The LGM Jet was stronger, more zonal, and with a stronger north-south temperature gradient. But it was less stormy.

Li et al 2007

January Jet in the Atlantic



Compared to today's climate, the ice age climate simulated by the coupled model exhibits

- **a stronger, steadier Atlantic jet**
- **reduced storminess**

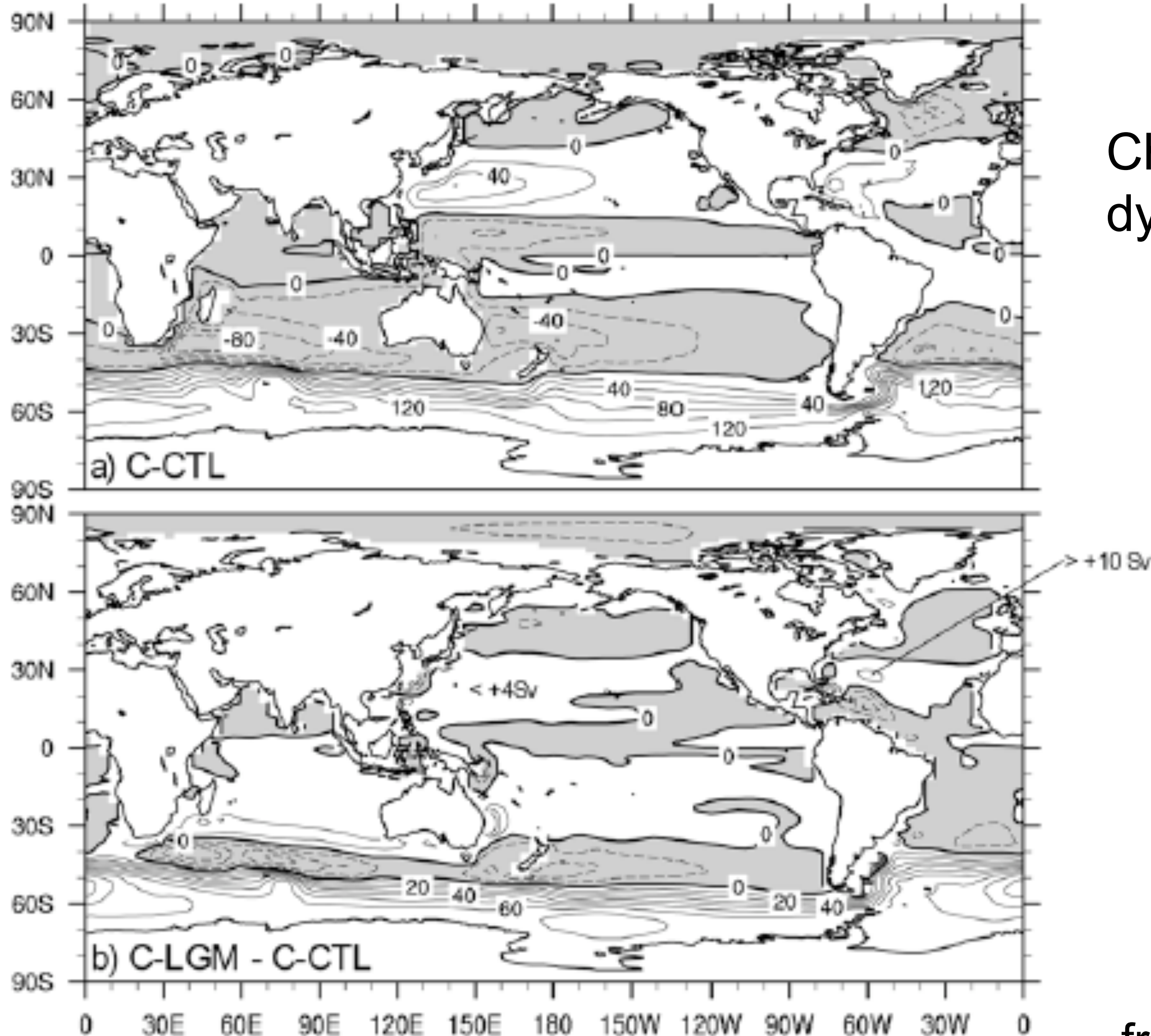
In contrast, the ice age climate simulated by the uncoupled models exhibit

- **a SW-NE tilted Atlantic jet, strength similar to today's climate**
- **low level eddy activity similar to today's climate**

Li et al 2007

LGM vs Modern Ocean Changes

In a coupled Atmosphere-Ocean General Circulation Model (CCSM)

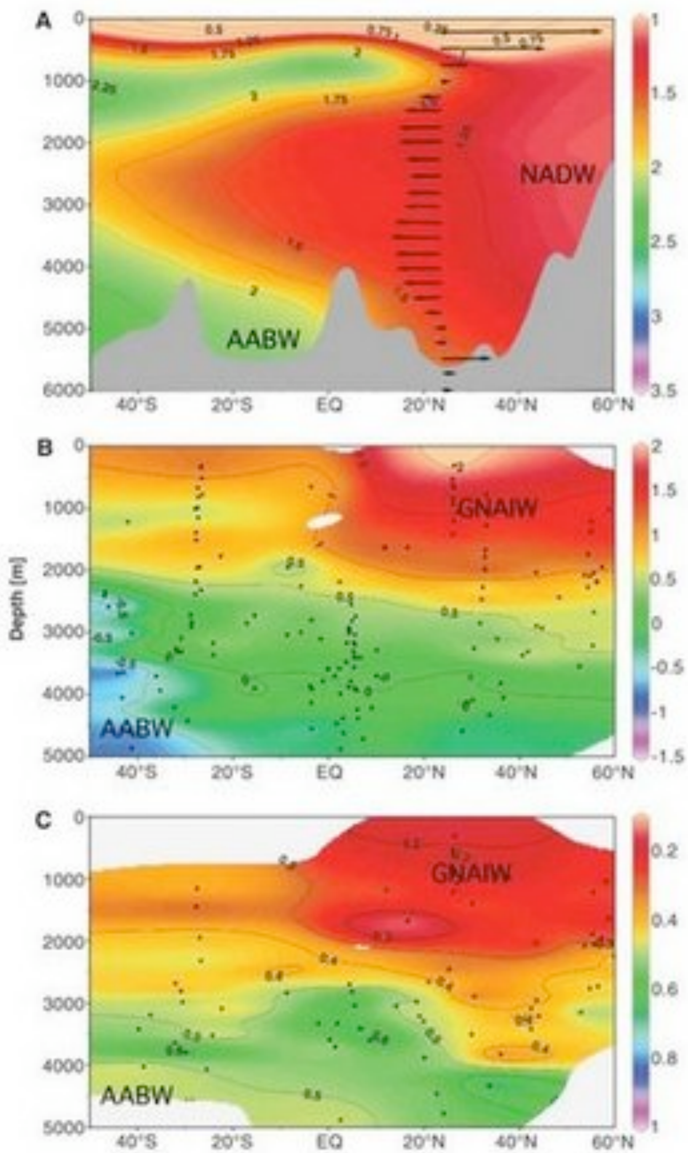


Change in ocean dynamics is subtle

Fig. 9 The annual oceanic barotropic stream function (Sv = 10^6 m^3-s) of the a control (C-CTL) and the difference, **b** LGM minus control (C-LGM-C-CTL). Contour intervals are 20 Sv and 10 Sv for **a** and **b** respectively. Negative values are *dashed* and *gray-shaded*

from Shin et al. 2003

The Reconstructed Atlantic Ocean



Modern Ocean

LGM Ocean
(from C_{13})

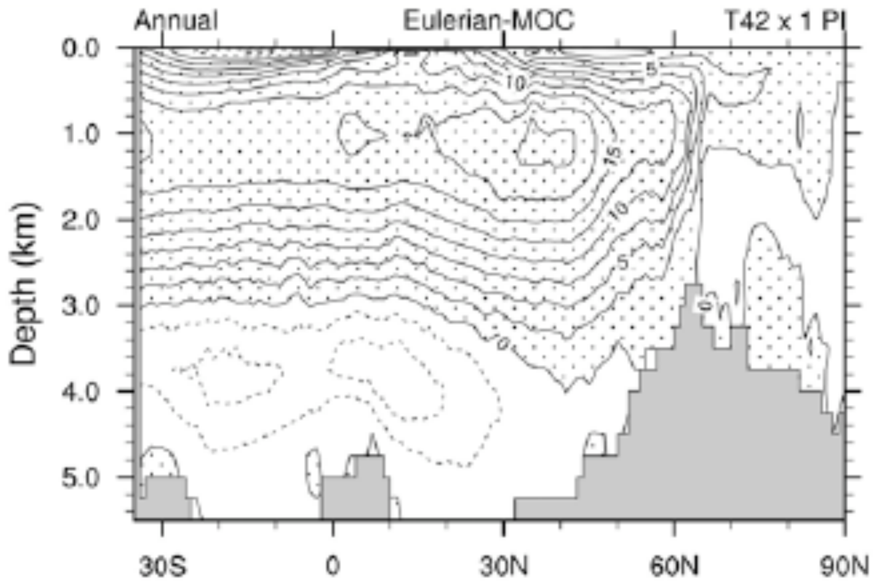
LGM Ocean
(from Cd/Ca)

Steiglitz et al 2007

LGM vs Modern Ocean Changes

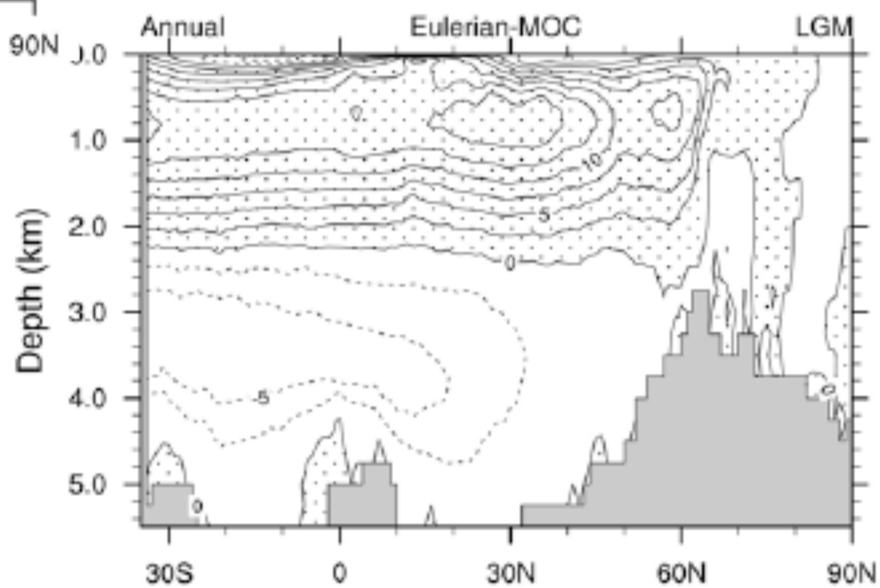
In a coupled Model (CCSM3) using Ice5G

Differences in ocean circulation are mainly due to dramatic changes in the jet across the N. Atlantic, which are mainly due to the ice sheet orography



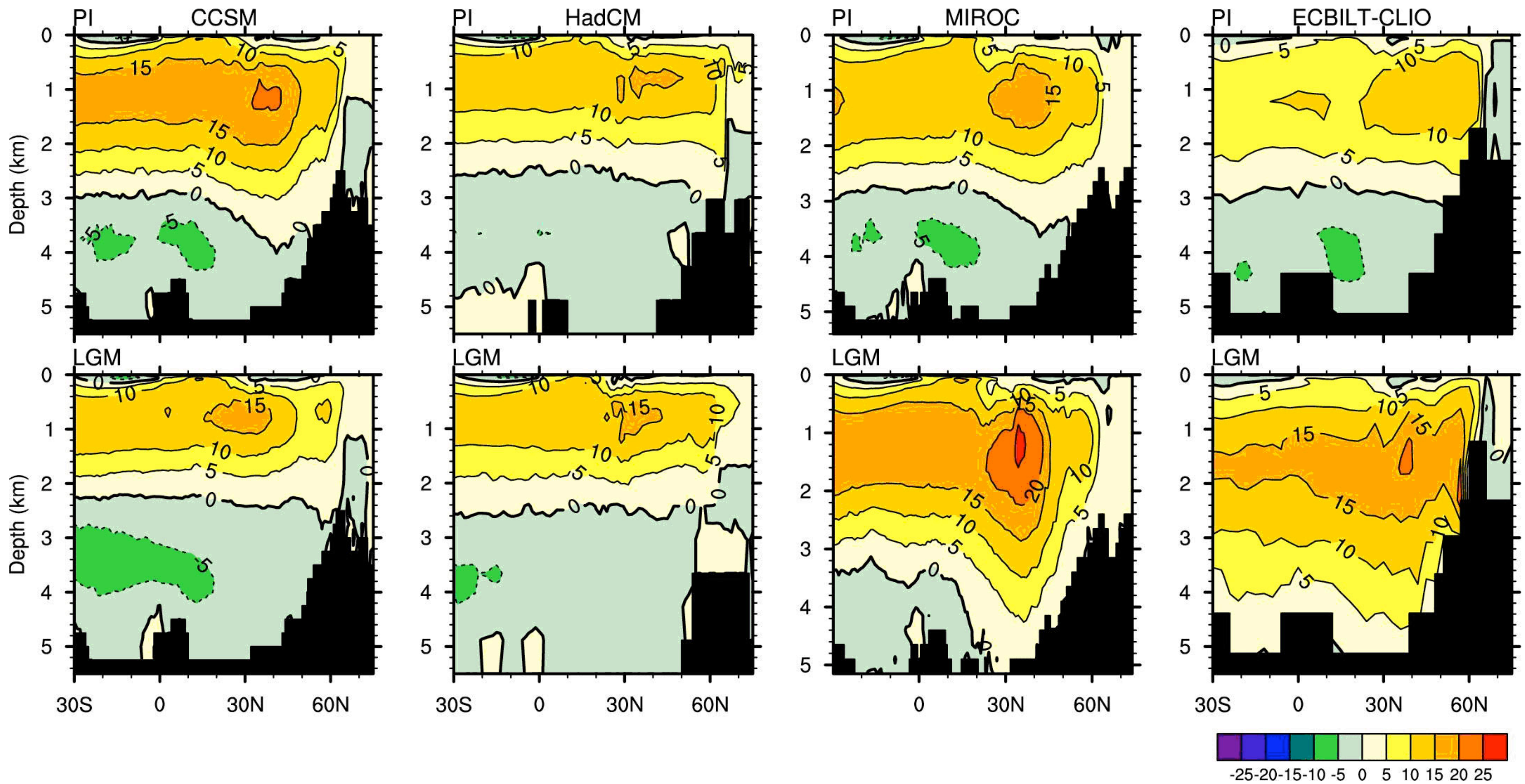
Modern

LGM



Otto-Blisner et al. 2006

The Simulated Atlantic Ocean Circulation



Observations indicate a weakening. Models show weakening, no change or even a strengthening of the Atlantic overturning circulation

Otto-Bleisner et al 2007

Why was the LGM climate different from PI?

- Insolation?
  - Wasn't much different from today
- Land Ice
  - Albedo effects (see HW #1)
  - Orographic effects
- Greenhouse gas changes?
  - CO_2 was 200ppm
  - CH_4 was 350ppb (vs 760 PI)

Broccoli and Manabe 1987

- Used a atmosphere general circulation model coupled to a slab ocean
  - Coarse resolution (R15), fixed clouds, no diurnal cycle, ..
  - Crude observational target (CLIMAP sea surface temperatures)

Experiments

Table 1. Boundary conditions and length of analysis period for atmosphere-mixed layer ocean model experiments (*P*: present, *L*: last glacial maximum)

Experiment	E1	E2	E3	E4
Land-Sea Distribution	P	L	L	L
Continental Ice Distribution	P	L	L	L
Atmospheric CO_2 Concentration (ppm)	300	300	300	200
Snow-Free Land Albedo Distribution	P	P	L	L
Length of Analysis Period (years)	15	8	6	8

L = LGM conditions

P = Pre-Industrial

Change in Forcing

Table 2. Radiative forcing calculations performed for each change in boundary conditions. $\Delta R = \Delta S - \Delta F$, where ΔS is the change in annual mean net incoming solar radiation and ΔF is the change in annual mean net outgoing longwave radiation. Values are in W m^{-2}

Control Experiment	Perturbation	ΔR Global	N. Hem.	S. Hem.
E1	LGM distribution of continental ice	−0.88	−1.71	−0.06
E3	atmospheric CO_2 reduced to 200 ppm	−1.28	−1.24	−1.31
E2	LGM distribution of land albedo	−0.67	−0.77	−0.58

Manabe and Stouffer 1987; Broccoli and Manabe 1987

Surface Temperatures: LGM – PI

modeled SST

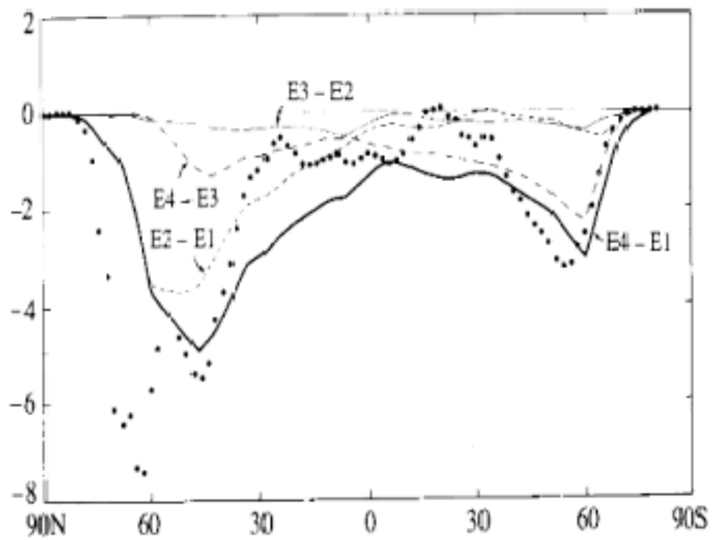


Fig. 11.14 SST changes (°C) induced by various ice age forcing mechanisms in the model of Broccoli and Manabe (1987) (various curves) compared with the SST inferred from ocean cores (dots). E2–E1, effect of ice sheets; E3–E2, effect of land albedo; E4–E3, effect of CO_2 concentration; E4–E1, difference between complete ice age simulation and simulation of current climate. [© Springer-Verlag.]

SST

Table 3. Differences in area-averaged annual mean SST between pairs of experiments (°C). CLIMAP estimates of SST differences between the LGM and the present are also included for comparison. Only those grid-points that represent oceans in all experiments are used in computing these values

		Global	N. Hem.	S. Hem.
E2-E1	(Ice Sheet)	−0.8	−1.6	−0.2
E4-E3	(CO_2)	−1.0	−0.7	−1.1
E3-E2	(Albedo)	−0.2	−0.3	−0.2
E4-E1	(Combined)	−1.9	−2.6	−1.5
CLIMAP		−1.6	−1.9	−1.3

All Surface

Table 4. Differences in area-averaged annual mean surface air temperature (°C) between pairs of experiments. Only gridpoints free of continental ice in all four experiments are used in computing the differences

		Global	N. Hem.	S. Hem.
E2-E1	(Ice sheet)	−1.3	−2.4	−0.3
E4-E3	(CO_2)	−1.2	−1.1	−1.3
E3-E2	(Albedo)	−0.3	−0.4	−0.3
E4-E1	(Combined)	−2.8	−3.9	−1.9

Manabe and Stouffer 1987; Broccoli and Manabe 1987

Surface Temperatures: LGM – PI

Atmospheric models coupled to a slab ocean model

Change in Surface Temperature

Broccoli 2000

	Global	Northern Hemisphere	Southern Hemisphere	Tropics (30°N–30°S)	Northern Hemisphere Tropics (0°–30°N)	Southern Hemisphere Tropics (0°–30°S)
Land and ocean	−4.0	−5.9	−2.1	−2.0	−2.4	−1.7
Land only	−6.4	−7.9	−3.4	−2.7	−3.2	−2.2
Ocean only	−2.7	−4.1	−1.8	−1.7	−2.0	−1.5

Table 5. Annual mean 1.5 m temperature change, in Kelvin, induced by the changed boundary conditions simulated and estimated. Note that the land-sea mask is different at 21 kBP

Hewitt & Mitchell 1997

		Globe	N.Hemis	S.Hemis	Land	Ocean
Total	(simulated)	− 4.4	− 6.5	− 2.3	− 8.1	− 1.7
Topography and surface albedo	(simulated)	− 3.0	− 5.0	− 1.1	− 6.3	− 0.6
CO_2	(estimated)	− 1.4	− 1.6	− 1.2	− 1.8	− 1.2
Insolation	(simulated)	− 0.1	0.1	− 0.2	0.0	− 0.1
Topography	(estimated)	− 0.7	− 1.0	− 0.3	− 1.9	0.0
Total of rows 2, 3, 4		− 4.5	− 6.5	− 2.5	− 8.1	− 1.9

Why is LGM colder than PI? NH = land albedo; SH = CO_2 (plus GH feedbacks)

LGM vs PI SST Changes

In a coupled Atmosphere-Ocean General Circulation Model (CCSM)

Light Grey = GH gas changes only

Dark Line = All forcings

CLIMAP = old estimate of observed

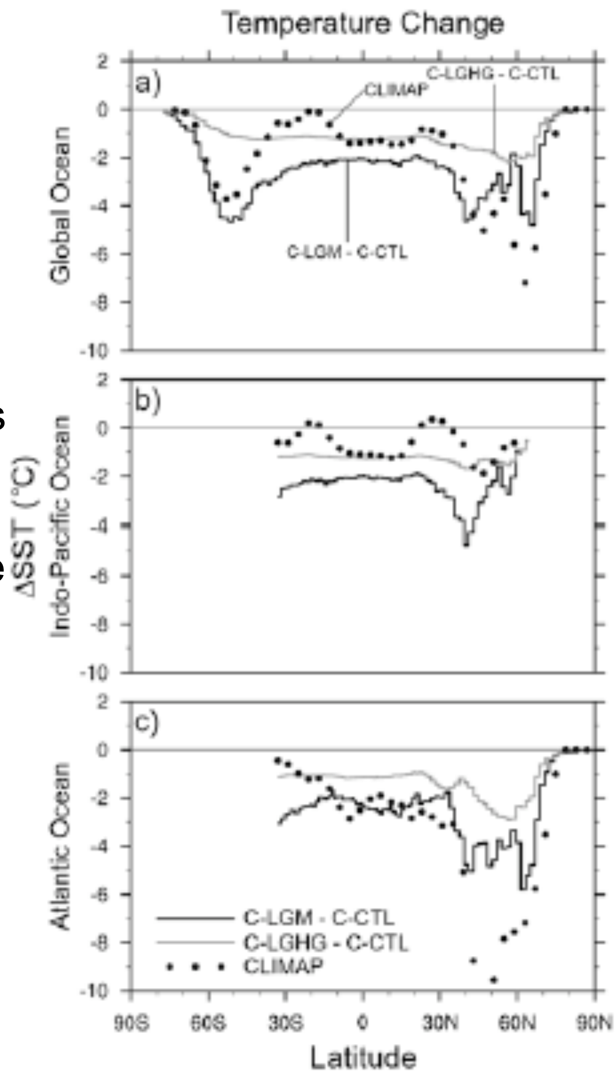


Fig. 3 The differences of zonally averaged annual SST (°C) in the **a** global Ocean, **b** Indo-Pacific Ocean and **c** Atlantic Ocean including the Arctic, for the LGM minus control (C-LGM-C-CTL, *black lines*) and for the LGM greenhouse gas forcing minus control (C-LGHG-C-CTL, *gray lines*).

The difference between the GHG and "all forcing" is due to:

* Ice sheet orography enhances winds and cold air advection onto ocean

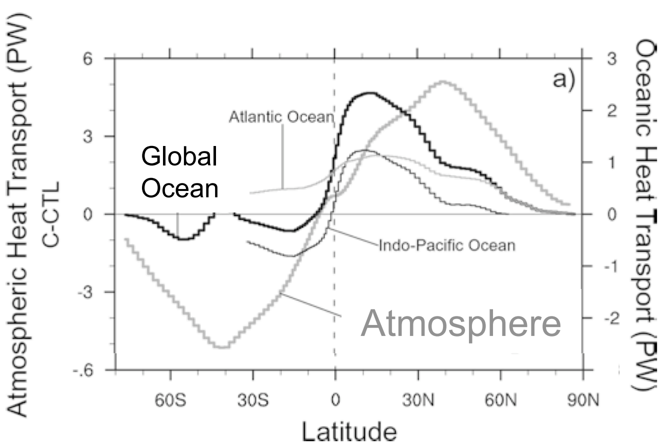
* Exposed land cools more than ocean

* Antarctic Ice sheet expands

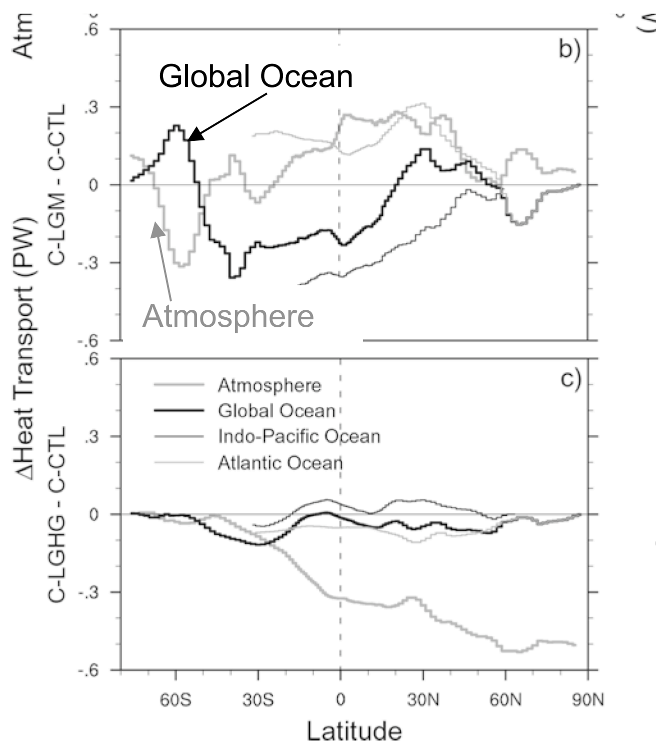
from Shin et al. 2003

Meridional Heat Transport
(in one climate model, CCSM)

PI (control)



LGM minus PI



Impact of Land Ice only

Impact of CO_2 change
(300 - 200ppm)

Observations indicate a weakening. Models show weakening, no change or even a strengthening of the Atlantic overturning circulation

Shin et al 2003

Lessons from Climate Models:
Last Glacial Maximum (LGM)

- Orbitally induced insolation changes do pace the Glacial cycles, but …

- Local insolation changes are not sufficient to explain the paleo records:

  - Albedo feedbacks associated with sea ice and especially land ice are the dominant forcings in the Northern Hemisphere

  - Carbon Dioxide changes are important for explaining the interhemispheric synchrochroneity of the Glacial cycles, and amplitude of cooling in the NH

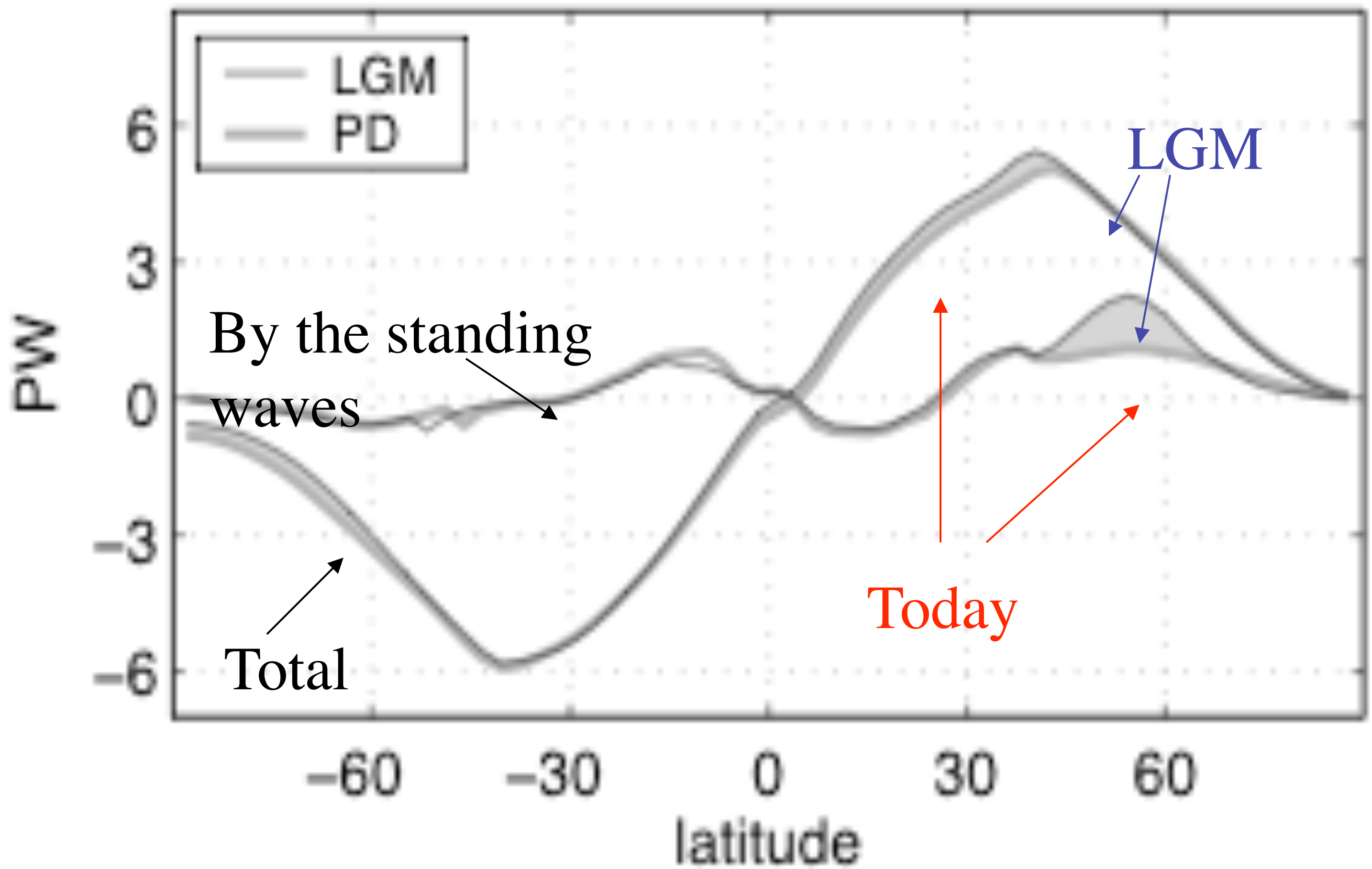
- Models are in gross agreement on larger scales and for temperature. For precipation (on any scale) and regional scale temperature, answers differ greatly.

- Climate System is not in equilibrium with solar forcing on the time scales of Glacial Cycles.

The End

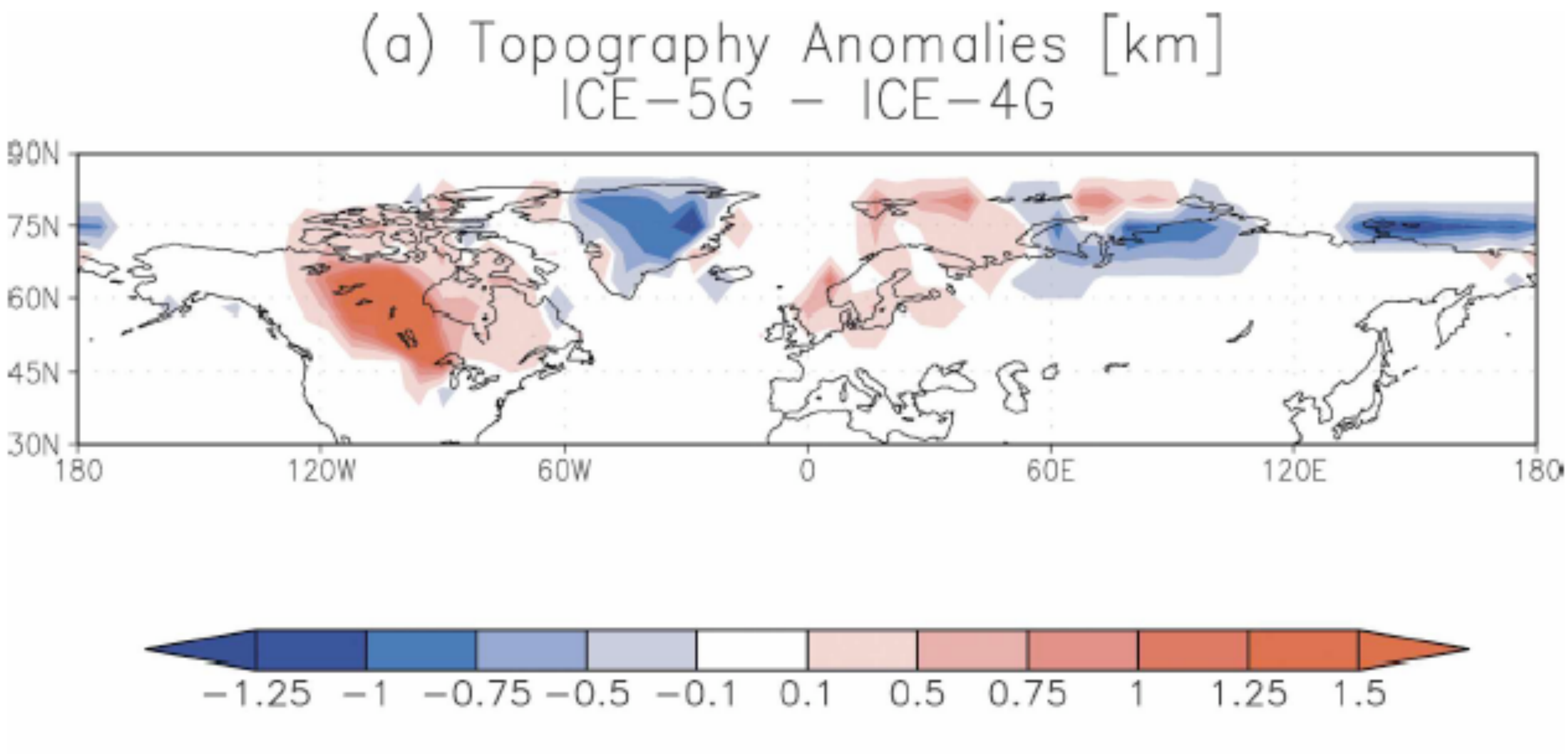
Meridional Heat Transport in the Atmosphere

Annual and Zonal average



The Atmospheric Heat Transport by storms is *down* in the LGM compared with today. Stationary waves come to the rescue.

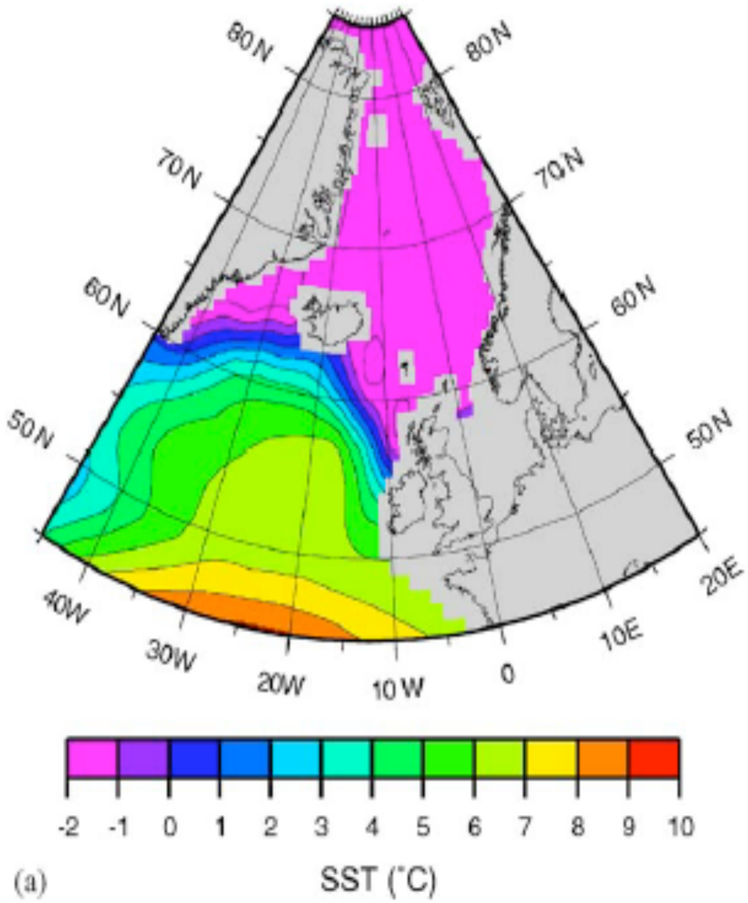
An update on the Land Ice



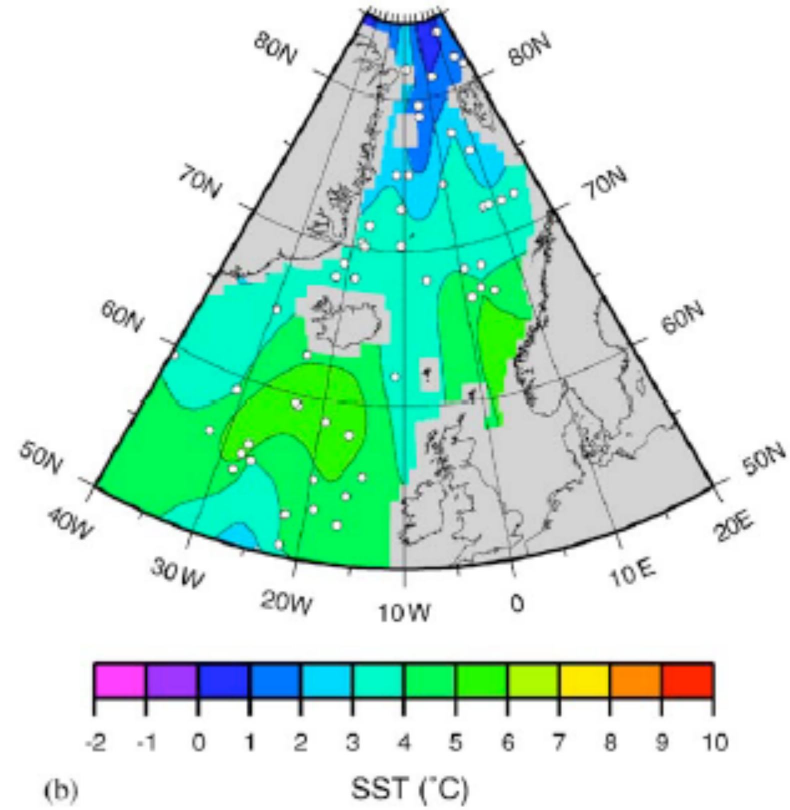
More ice over N. America, Less Ice over Greenland and northern Eurasian

Update to CLIMAP

Summer Sea Ice Reconstruction



CLIMAP (1976)



GLAMAP (2003)

"Forcing" at 21K BP

Insolation

Table 2. Orbital parameters for the control (present day) and LGM (21 kBP) experiments derived from Berger (1978)

	0 kBP	21 kBP
Longitude of perihelion (relative to the vernal equinox)	102.5°	114.4°
Obliquity	23.44°	22.95°
Eccentricity	0.0167	0.0190

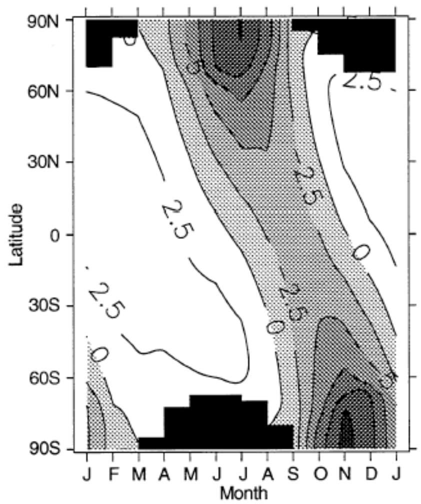


Fig. 1. Time-latitude diagram (zonal average of monthly mean values) of change in incoming shortwave radiation at the top of the atmosphere between 21 kBP and 0 kBP with *areas of decrease shaded*. The polar night has been masked out. Contours every 2.5 Wm^{-2}

Hewitt et al 1987

Land Ice

CLIMAP Ice4G Reconstruction

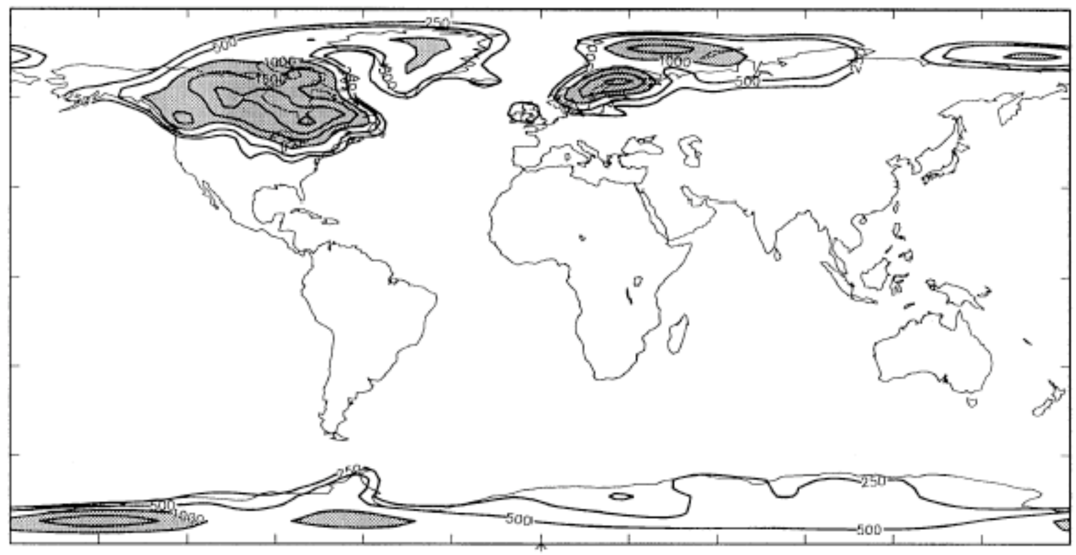


Fig. 1 Changes in ice sheet height and extent of the updated ice sheets (Peltier 1994) at the Last Glacial Maximum (LGM). Contours are at 250, 500 m, and then increasing by 500 m

Temperature Change: LGM minus Today

prescribed vs. modeled SST

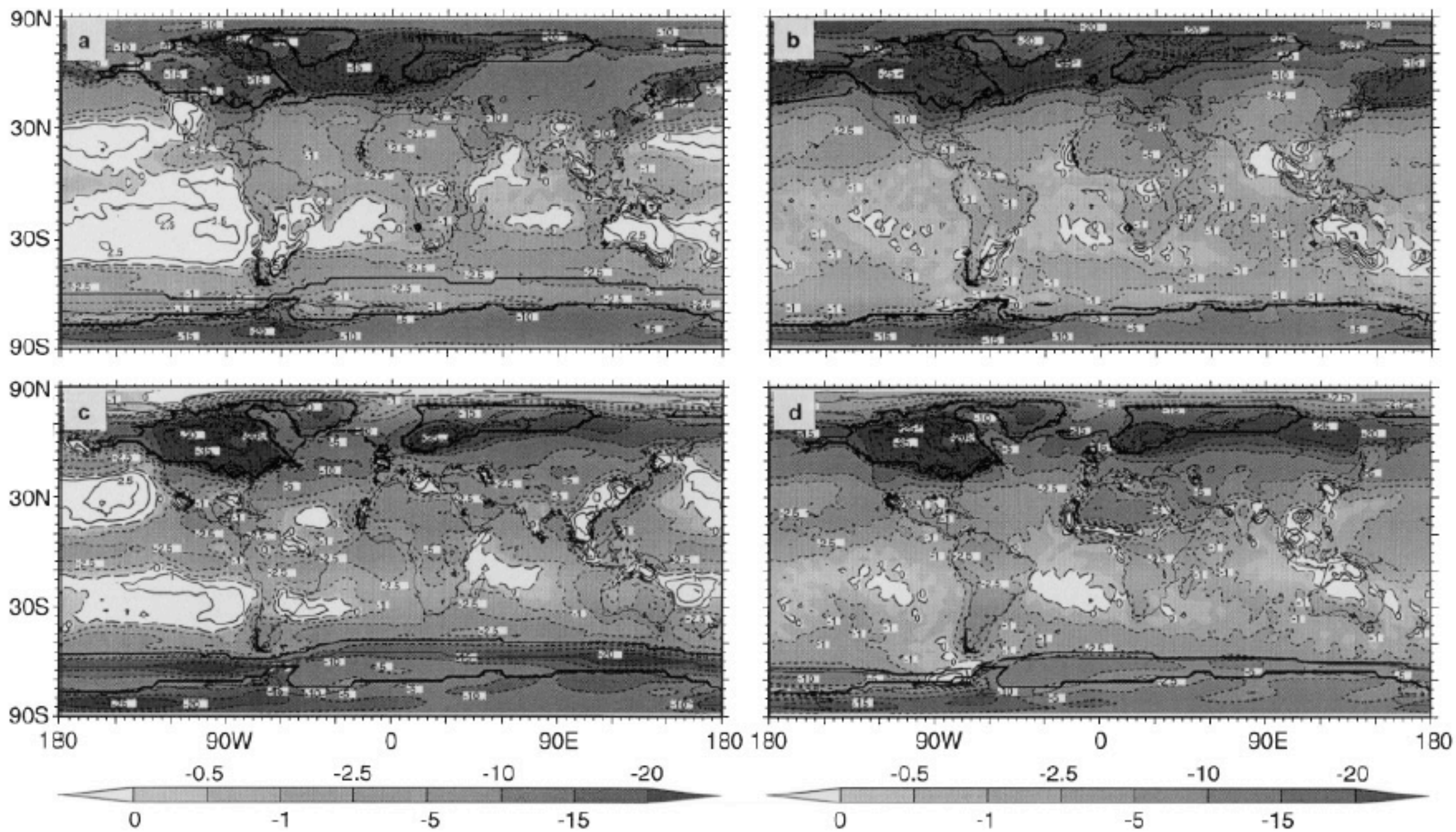
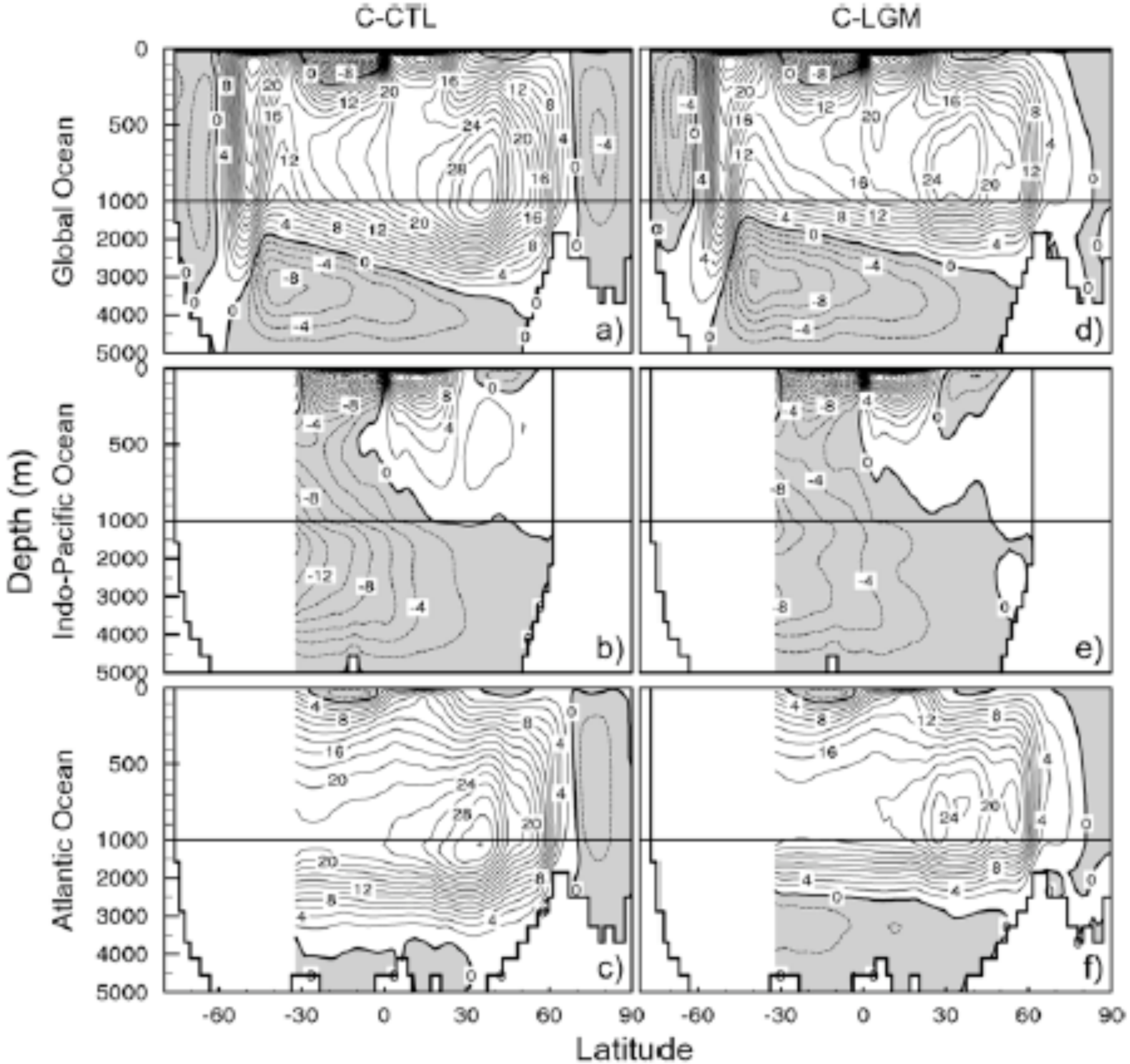


Fig. 4a–d Surface air temperature anomalies (°C) between the LGM and PD simulations. The *thick lines* give the sea-ice edge in PD and LGM simulation, and *dark thick line* the extent of ice sheet at LGM. **a** DJF and **c** JJA with prescribed SSTs. **b** DJF and **d** JJA with computed SSTs

Dong and Valdes 1998

LGM vs Modern Ocean Changes

In a coupled Atmosphere-Ocean General Circulation Model (CCSM)



Change in ocean dynamics is subtle

Fig. 10 The annual meridional overturning stream function (Sv) in the **a** global Ocean, **b** Indo-Pacific Ocean and **c** Atlantic Ocean including the Arctic of the modern control (C-CTL); **d**–**f** are the same as **a**–**c** but for the simulation of the LGM (C-LGM). Contour interval is 2 Sv. Negative values are *dashed* and *gray-shaded*

Shin et al. 2003

Surface Temperature Change
LGM - Today

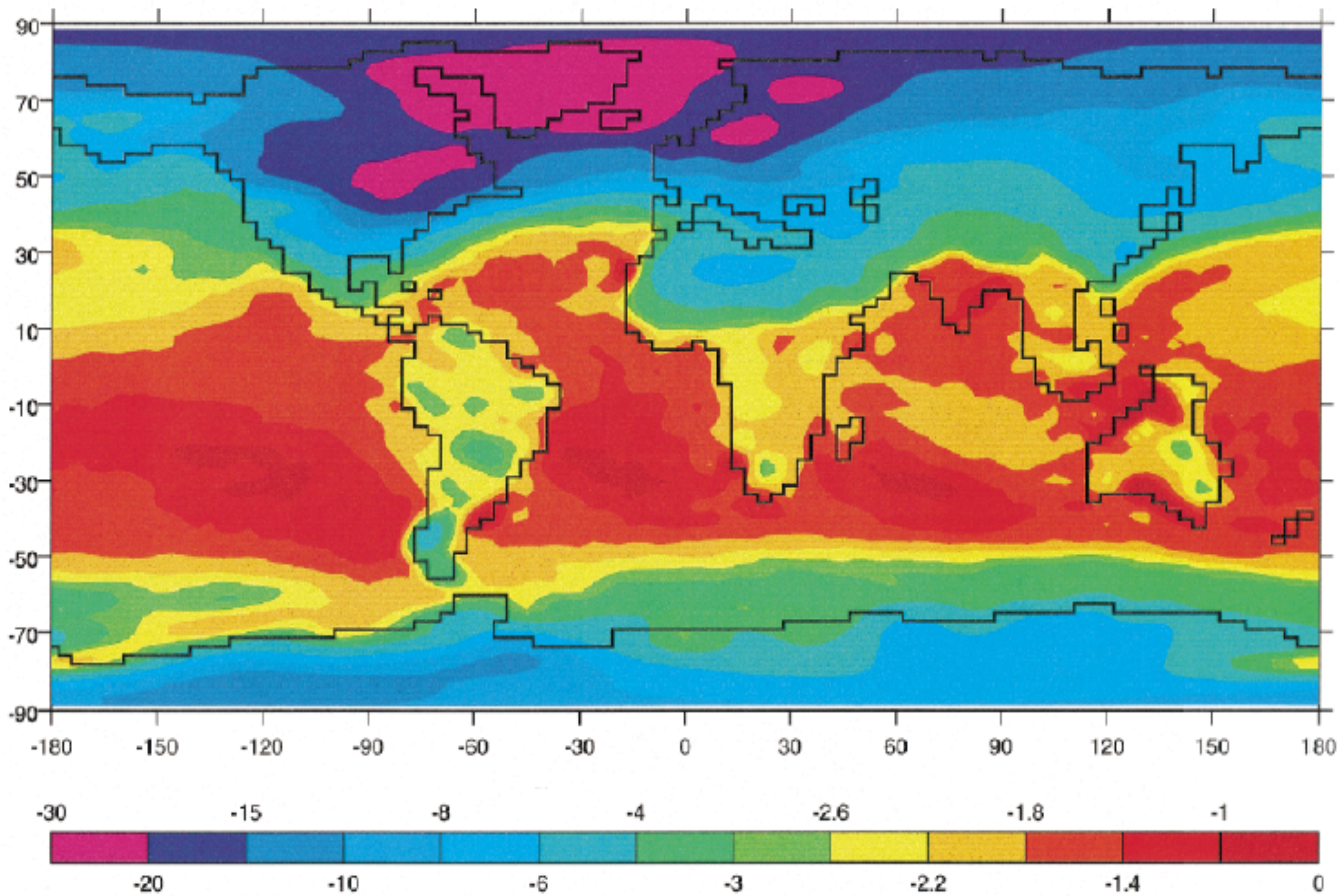


FIG. 3. Map of annual mean surface air temperature difference (ΔSAT) between LGM and modern integrations. Units are K with color scale below.

Broccoli 2000

Change in Zonal Mean SST

UKMO GCM coupled to a slab ocean

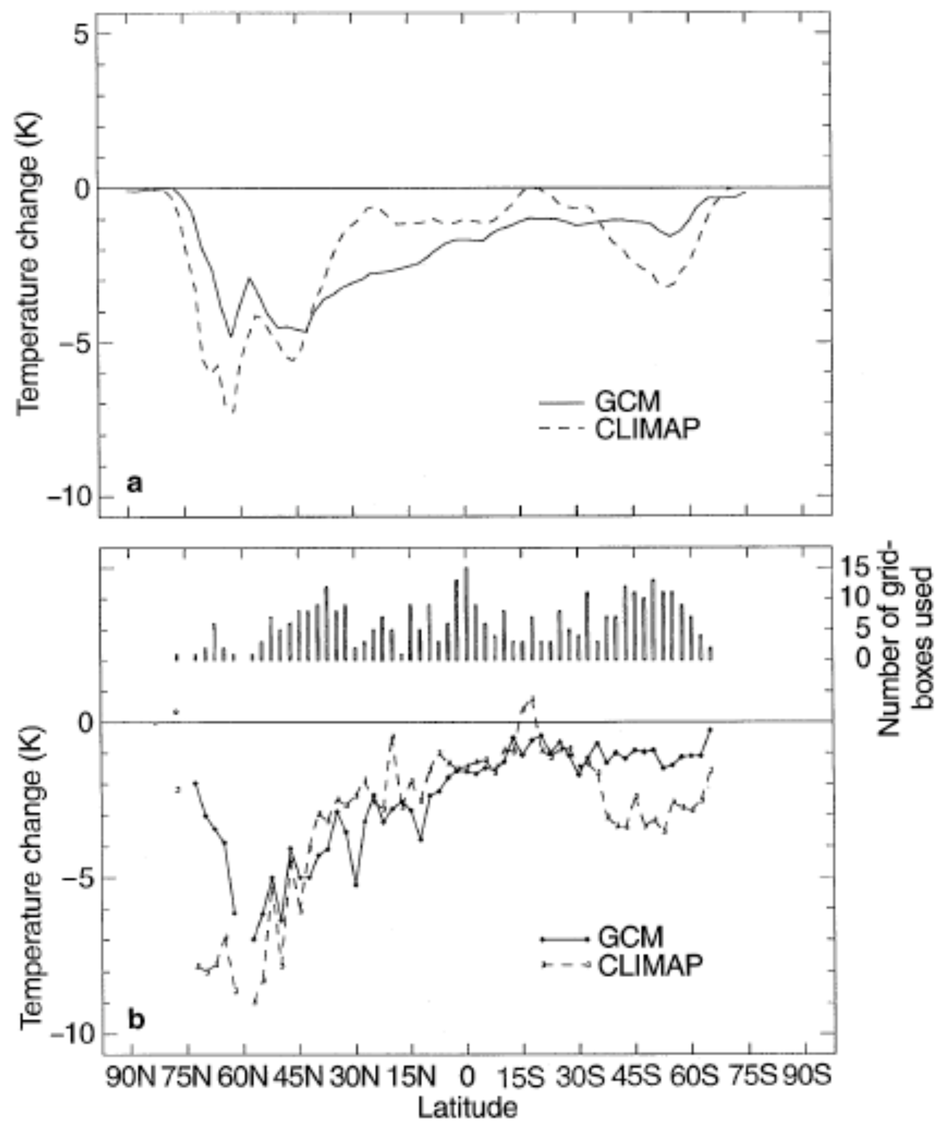


Fig. 4a, b. Zonal mean change in SST between 21 kBP and 0 kBP using the average of February and August SSTs. *Solid line* is GCM, *dashed line* is CLIMAP. **a** Using gridded subjective CLIMAP analysis. **b** Only using GCM grid-boxes where CLIMAP data is located, and a histogram showing the number of such grid-boxes at each latitude

Hewitt & Mitchell 1997

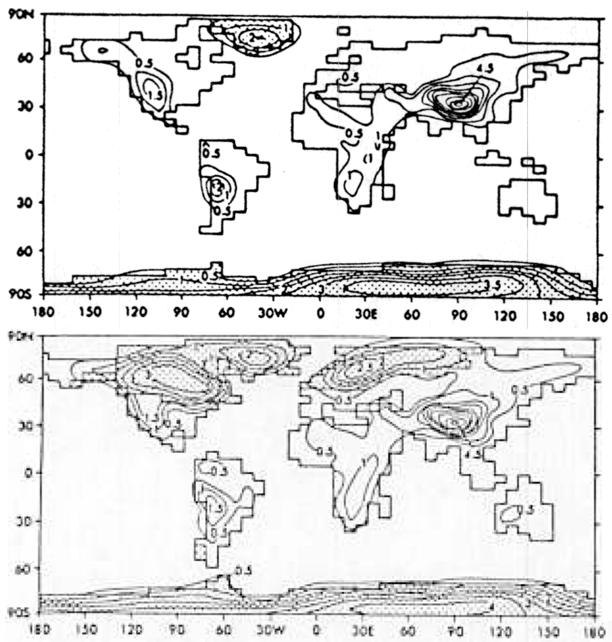


Fig. 1. Continental outlines, topography, and distribution of continental ice used in model experiments. Topographic contours indicate height above sea level (km). Regions covered by continental ice are stippled. *Top*: present. *Bottom*: last glacial maximum

Table 1. Boundary conditions and length of analysis period for atmosphere-mixed layer ocean model experiments (*P*: present, *L*: last glacial maximum)

Experiment	E1	E2	E3	E4
Land-Sea Distribution	P	L	L	L
Continental Ice Distribution	P	L	L	L
Atmospheric CO_2 Concentration (ppm)	300	300	300	200
Snow-Free Land Albedo Distribution	P	P	L	L
Length of Analysis Period (years)	15	8	6	8

in Fig. 1, and the differences in bare land albedo between the LGM and the present are shown in Fig. 2.

In each experiment, a substantial period of integration (~30–40 years) was required in order for a quasi-equilibrium model climate to be established. The models were then integrated for an additional period, ranging from 6 to 15 years, to provide an adequate sample for analysis. The exact length of the analysis period for each experiment is included in Table 1. Each of the experiments with the exception of E3 was started from an initial state consisting of a dry, isothermal atmosphere at rest coupled to an isothermal mixed layer ocean. A sample from the quasi-equilibrium period of E2 was used as the initial state for E3 in an effort to save computer time. [E1 and E4 are the stan-

Temperature Change:

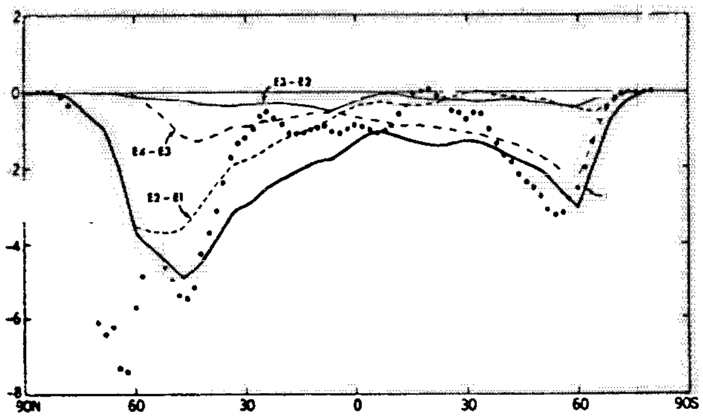


Fig. 3. Latitudinal distribution of annually averaged difference in zonal mean sea surface temperature (°C). Only gridpoints that represent oceans in all four experiments are used in computing the differences. The *solid circles* indicate the differences in sea surface temperature between the last glacial maximum and present as reconstructed by CLIMAP

Although some measure of the thermal impact of incorporating each of the changes in boundary conditions can be derived by examining the resulting changes in SST, it is more useful to study the climatic effects in continental as well as oceanic locations. Surface air temperature, defined as the temperature at the model's lowest finite-difference level (~80 m above the surface), is indicative of near-

Table 4. Differences in area-averaged annual mean surface air temperature (°C) between pairs of experiments. Only gridpoints free of continental ice in all four experiments are used in computing the differences

		Global	N. Hem.	S. Hem.
E2-E1	(Ice sheet)	−1.3	−2.4	−0.3
E4-E3	(CO_2)	−1.2	−1.1	−1.3
E3-E2	(Albedo)	−0.3	−0.4	−0.3
E4-E1	(Combined)	−2.8	−3.9	−1.9