

# Climate II

(Winter 2020/2021)

**5th lecture:**

## **The last glacial maximum (LGM)**

(characteristics, ice core data, SST reconstructions, terrestrial climate)

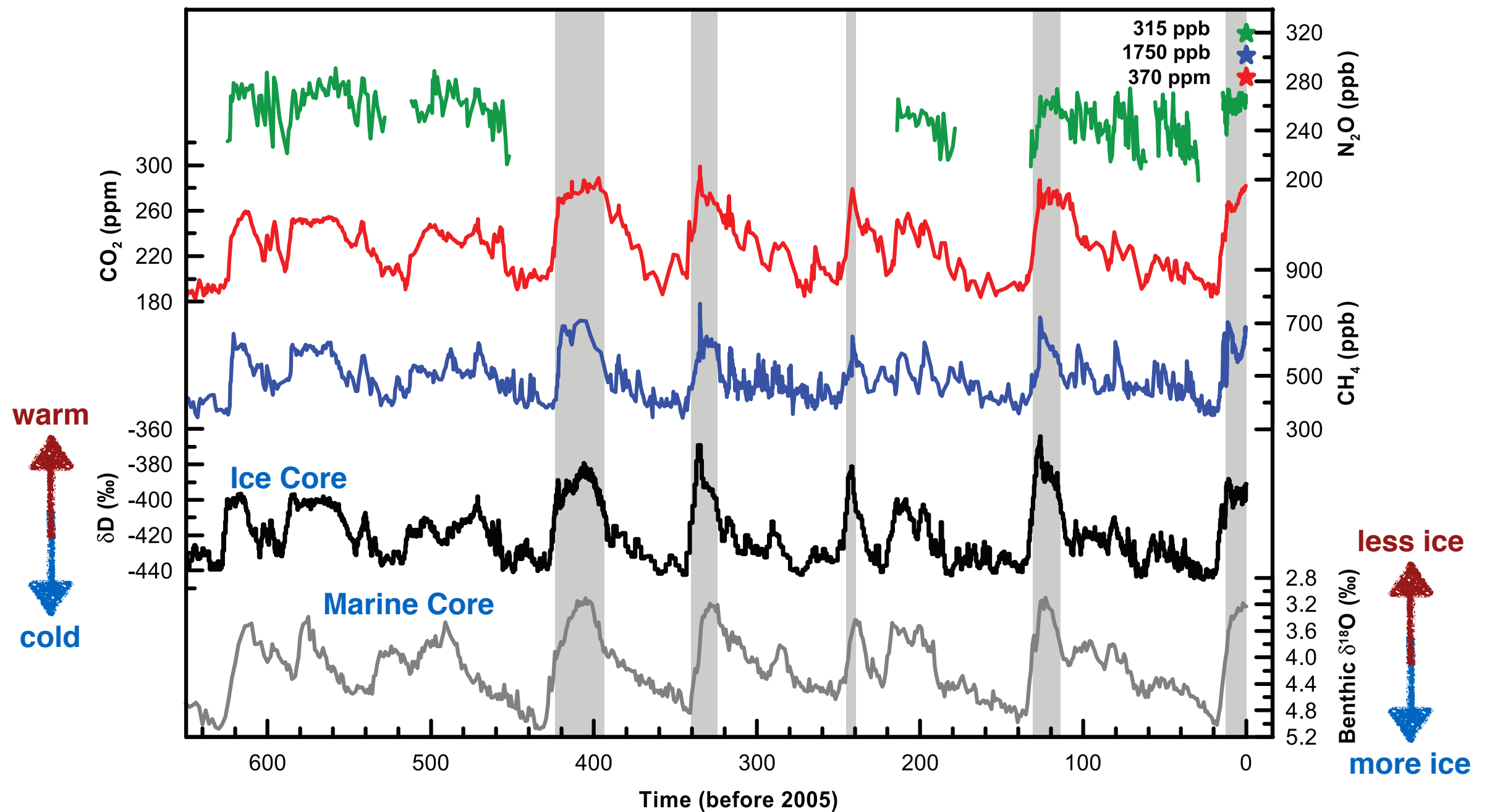
**Gerrit Lohmann, Martin Werner**

**Tuesday, 10:00-11:45**

(sometimes shorter, but with some exercises)

**[https://paleodyn.uni-bremen.de/study/climate2020\\_21.html](https://paleodyn.uni-bremen.de/study/climate2020_21.html)**

# Climate change on orbital time scales



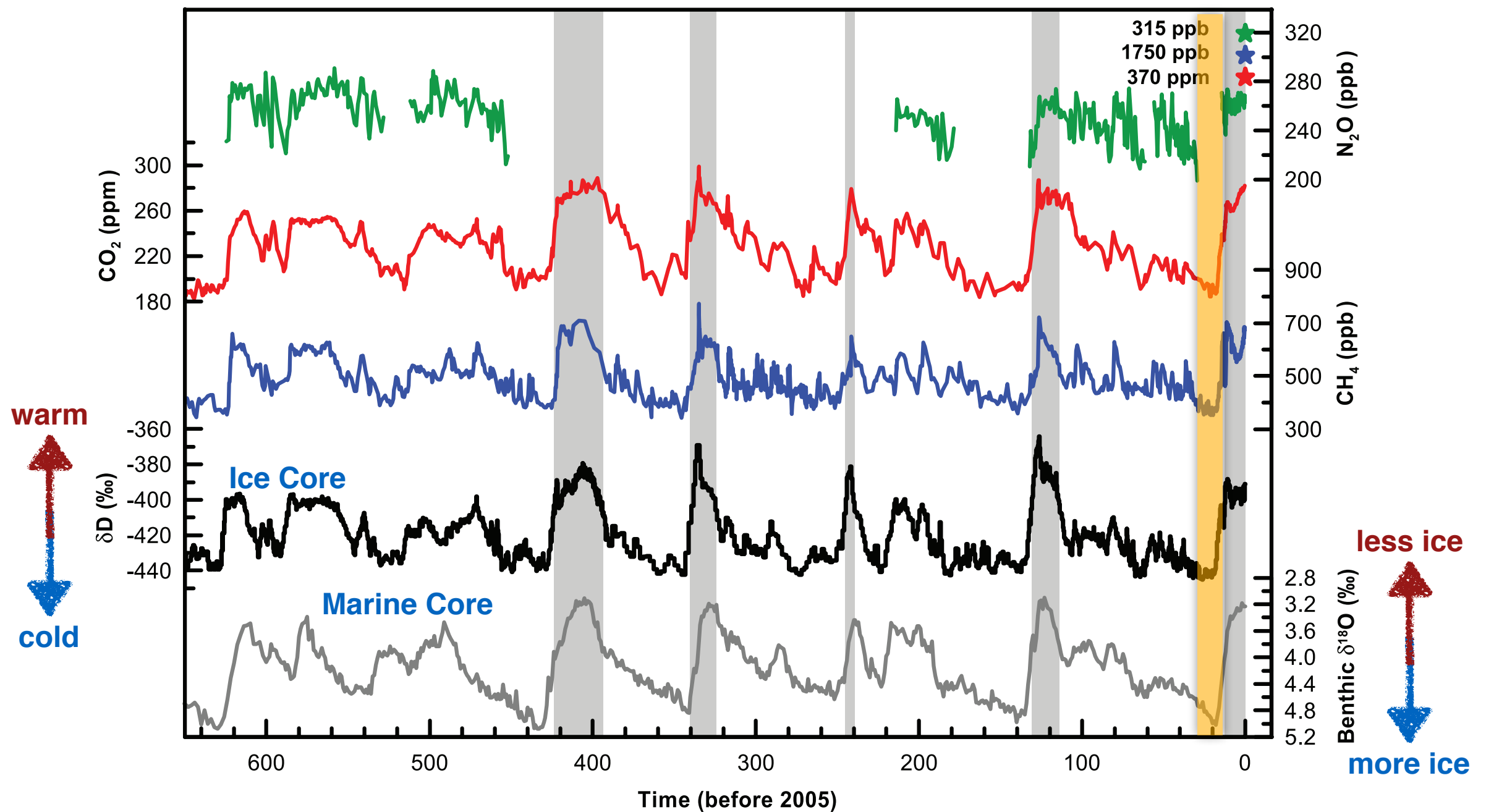
**Figure 6.3.** Variations of deuterium ( $\delta D$ ; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases  $CO_2$  (red),  $CH_4$  (blue), and nitrous oxide ( $N_2O$ ; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic  $\delta^{18}O$  marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic  $\delta^{18}O$  curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.

# Ice sheet growth and decay on orbital time scales

Supplementary Video V1.

Simulated ice sheet change for the last 400 kyr with IceES-MIROC model

# The last glacial maximum (LGM)

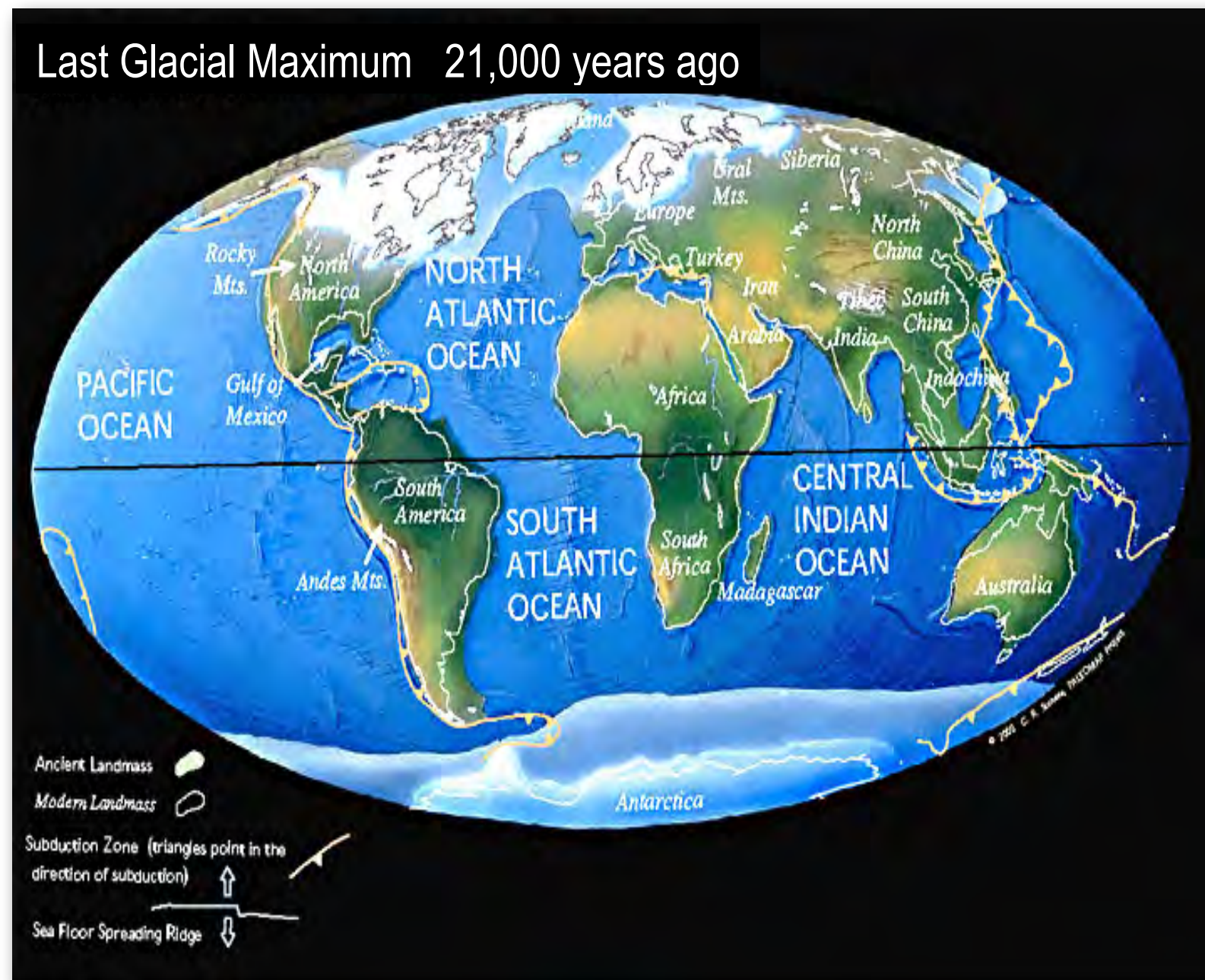


**Figure 6.3.** Variations of deuterium ( $\delta\text{D}$ ; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases  $\text{CO}_2$  (red),  $\text{CH}_4$  (blue), and nitrous oxide ( $\text{N}_2\text{O}$ ; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic  $\delta^{18}\text{O}$  marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic  $\delta^{18}\text{O}$  curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.



# Overview: the last glacial maximum

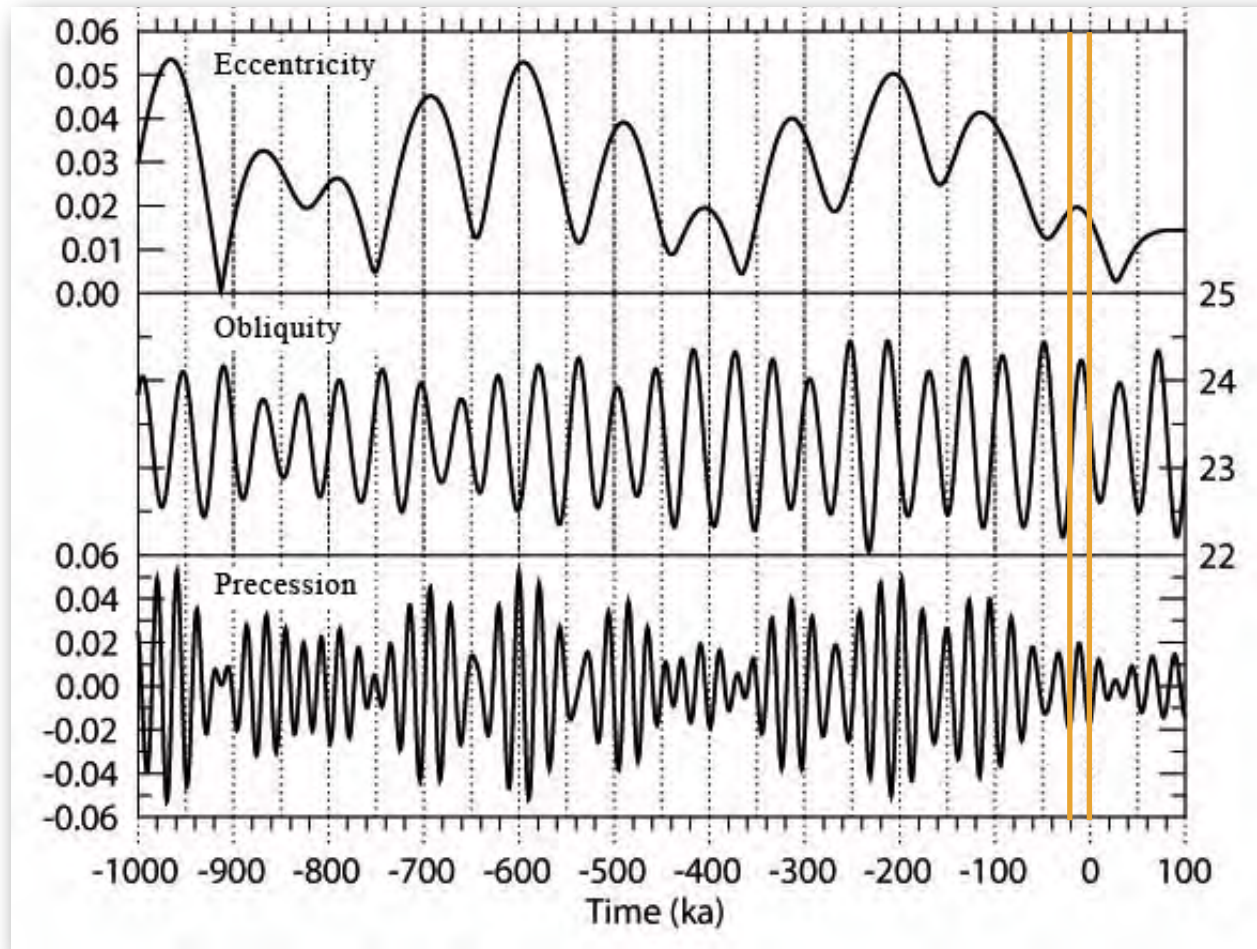
- approx. 21,000 years before present (end of the last glacial period)
- CO<sub>2</sub> and other greenhouse gases were much lower than during warm interglacials
- North America and Eurasia were covered by large ice sheets
- sea level was lower by approx. 108m



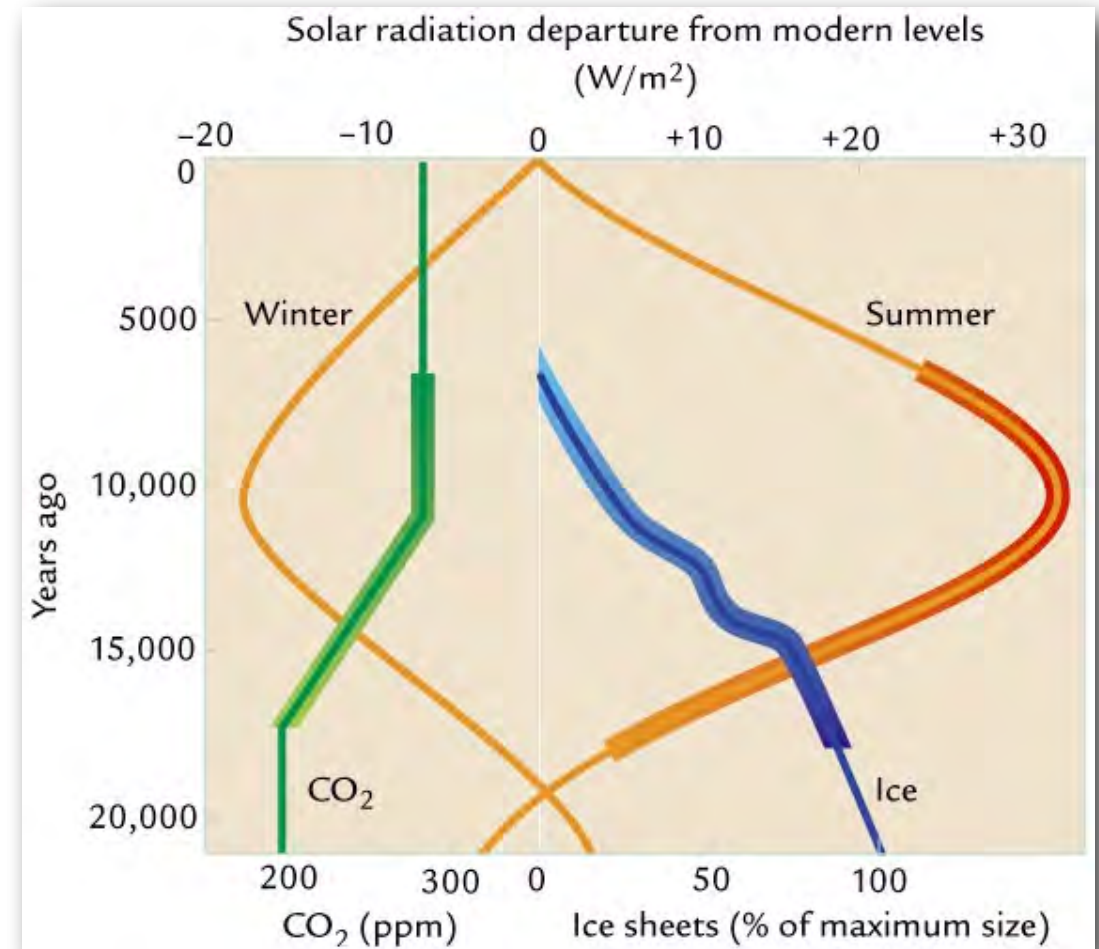


# Overview: the last glacial maximum

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([http://www.elic.ucl.ac.be/textbook/chapter5\\_node12.xml](http://www.elic.ucl.ac.be/textbook/chapter5_node12.xml), calculated from Berger, 1978)



(from Ruddiman, 2008)

# Overview: the last glacial maximum

Last Glacial Maximum 21,000 years ago



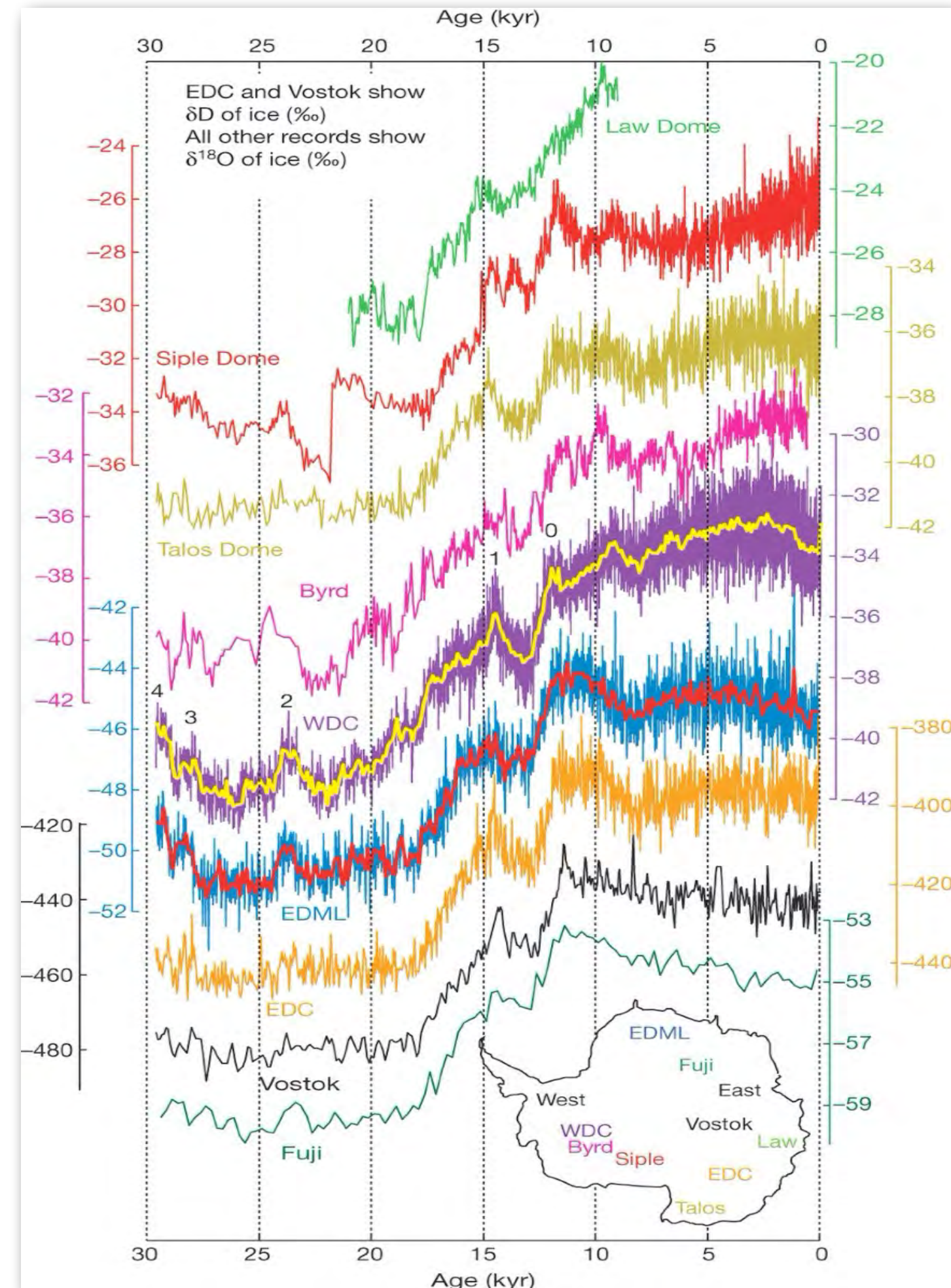
## Climate of the LGM - key information from ice cores





# Antarctic ice cores

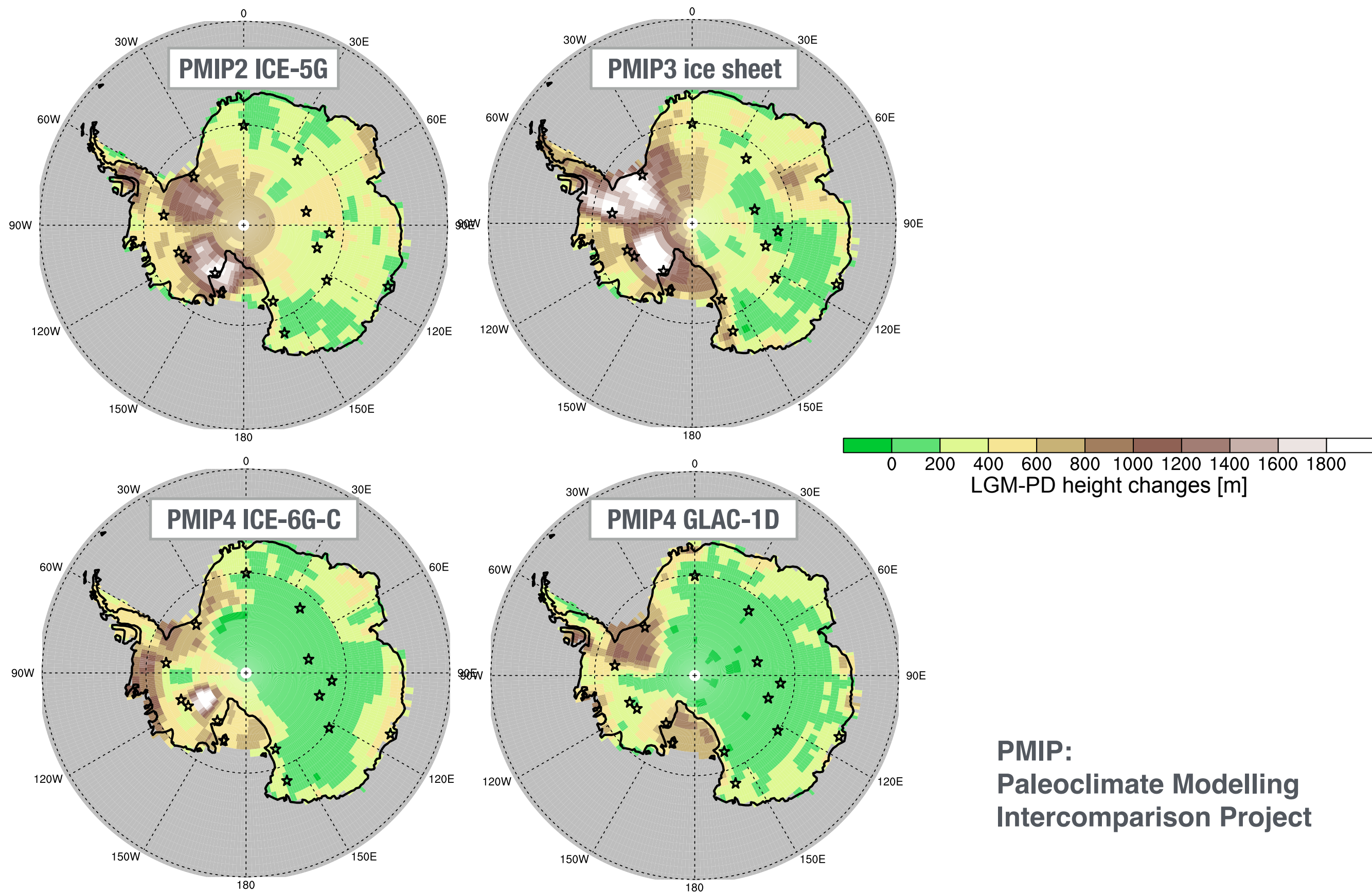
- at present, 9 deep ice cores from West and East Antarctica exist
  - *they all show very low water isotope values during the LGM (=cooling of -5°C...-12°C)*
  - *accumulation was strongly reduced in the cooler LGM climate*
  - *LGM ice sheet height is still unclear*



source:  
WAIS Divide Project Members, Nature, 2013



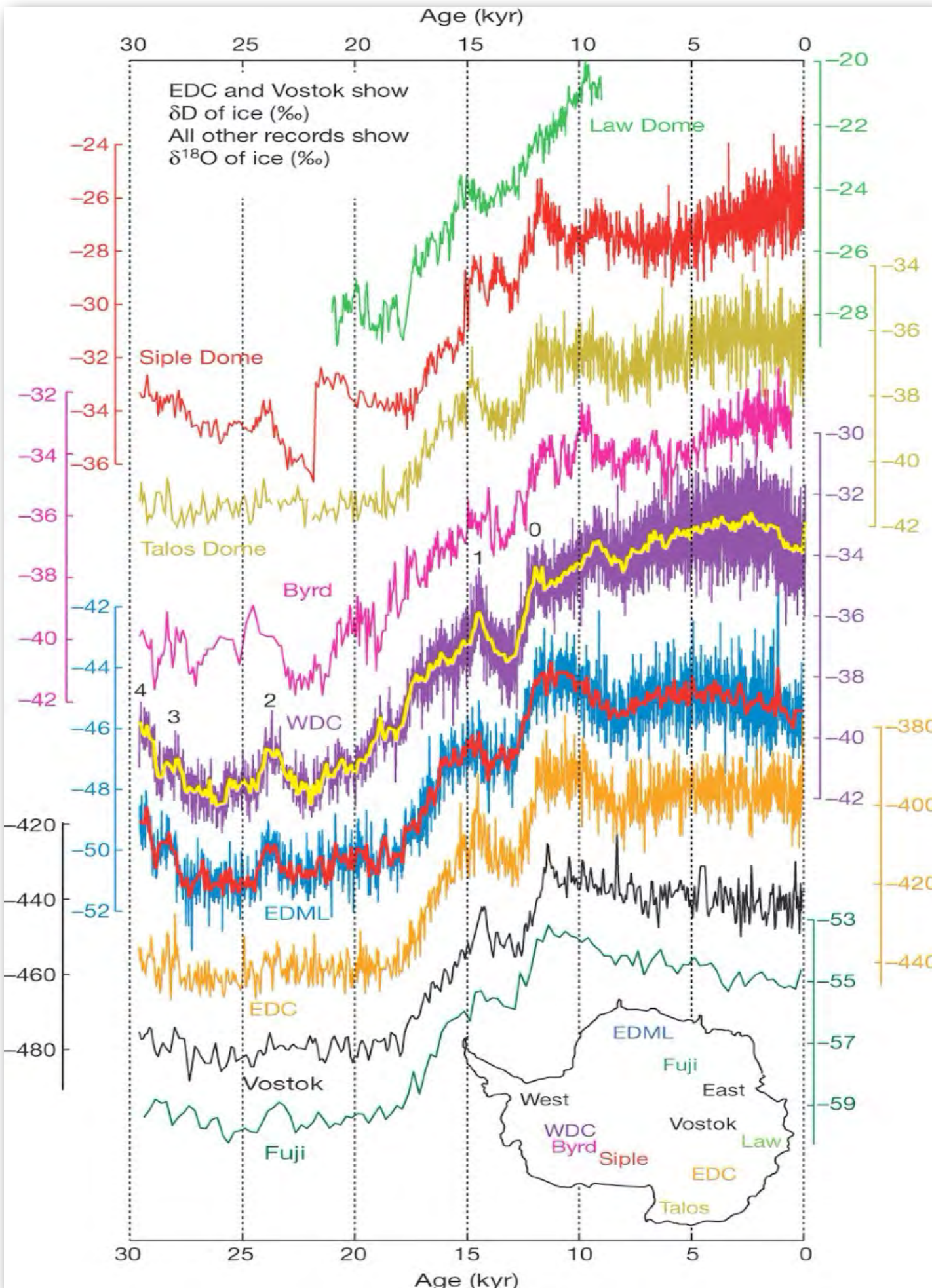
# LGM - Antarctic ice sheet reconstructions





# Antarctic ice cores

- at present, 9 deep ice cores from West and East Antarctica exist
  - *they all show very low water isotope values during the LGM (=cooling of -5°C...-12°C)*
  - *accumulation was strongly reduced in the cooler LGM climate*
  - *LGM ice sheet height is still unclear*
- ice core data indicates that warming in West Antarctica may have started 2,000yr earlier than in East Antarctica
  - *circum-Antarctic sea-ice decline, driven by increasing local insolation, might be the cause of this earlier warming*
- all ice cores show an initial warming, followed by a short cooling (Antarctic Cold Reversal (ACR)) and a second warming phase into the Holocene



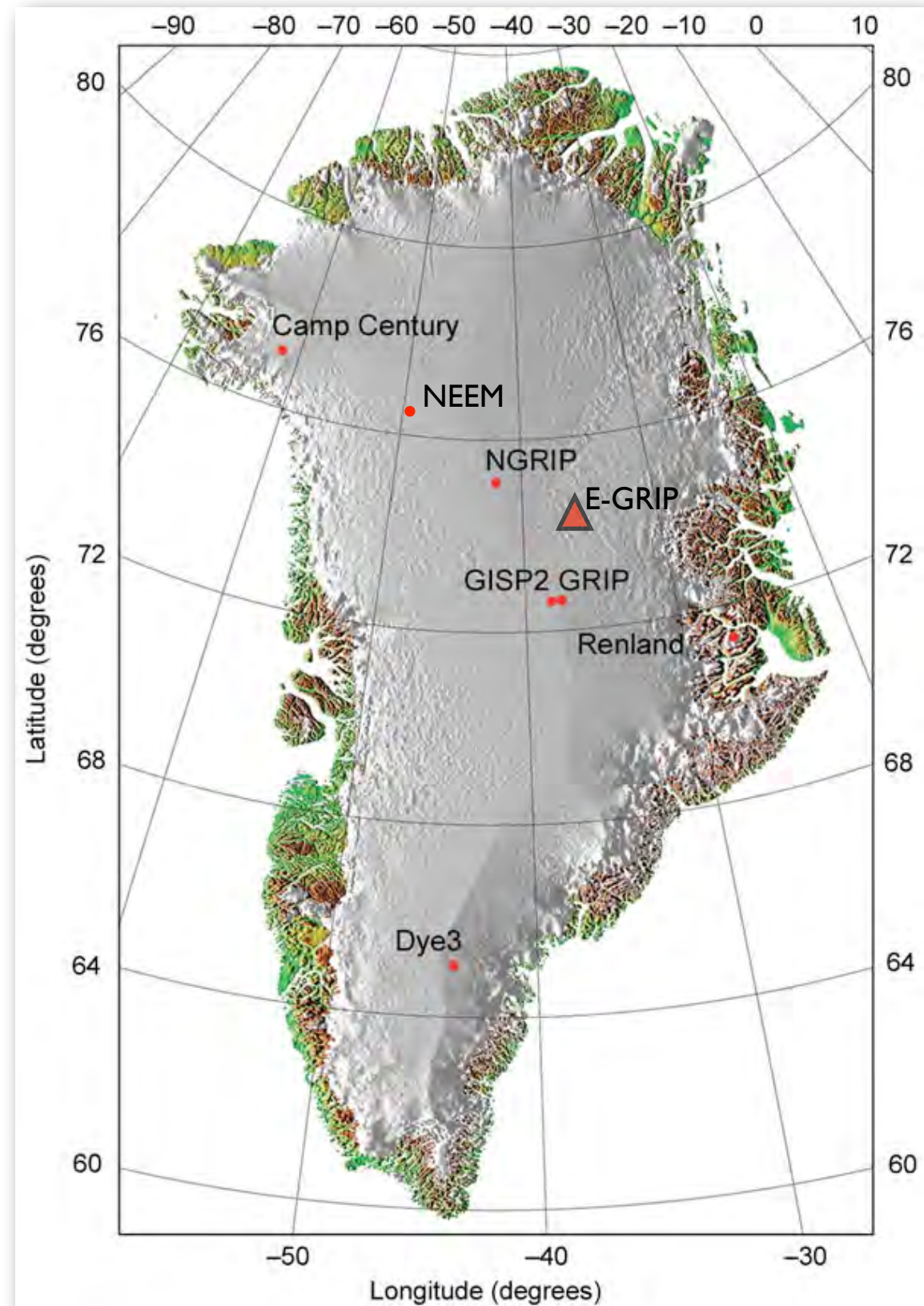
source:

WAIS Divide Project Members, Nature, 2013



# Greenland ice cores

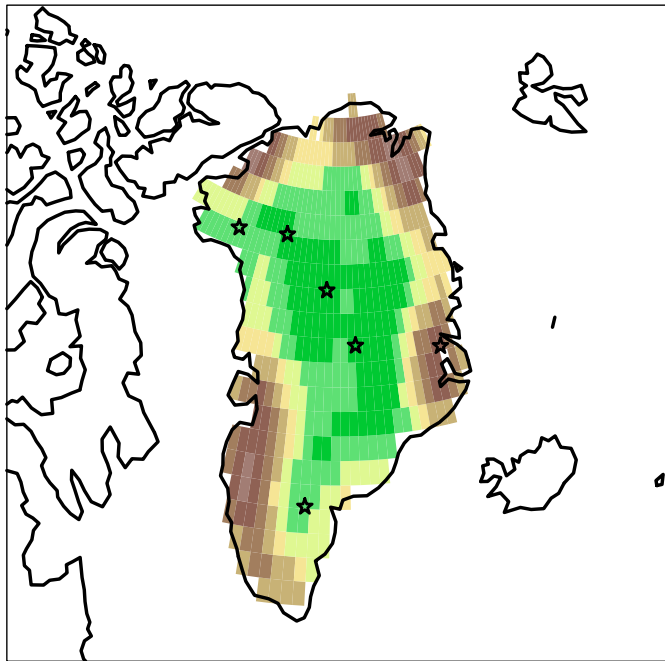
- several deep Greenland ice cores have been drilled (Camp Century, Dye3, GRIP, GISP2, NGRIP, NEEM, Renland)
- GRIP & GISP2 cores are located on Greenland's summit, only 30km apart from each other
- *most Greenland ice cores enabled temporal highly resolved climate analyses of the last 100,000 years, only*
  - **NEEM ice core** extended data to the **last interglacial period** (Eemian, 125 kyrs B.P.)
- all cores are well correlated with each other
  - *they all show strong cooling of -20°C...-23°C during the LGM*
  - *accumulation was strongly reduced in Greenland, too*
  - *LGM ice sheet in central Greenland similar to today, but much more ice at Greenland's coastal regions*



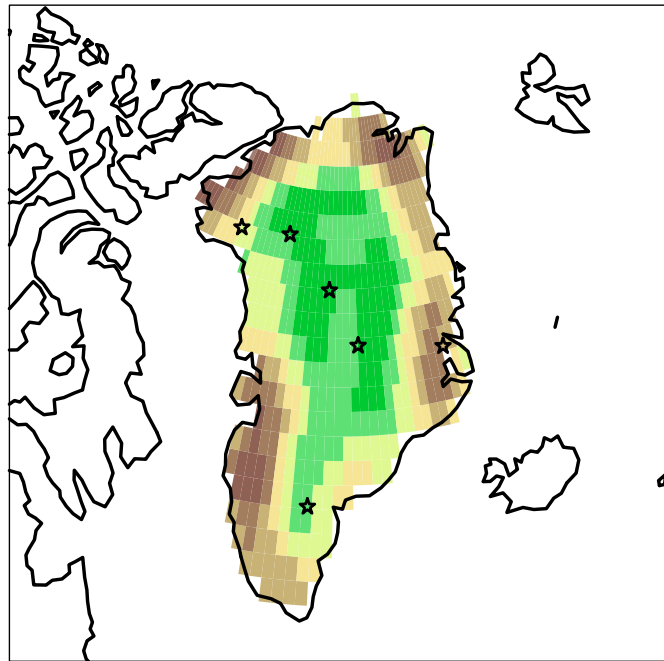


# LGM - Antarctic ice sheet reconstructions

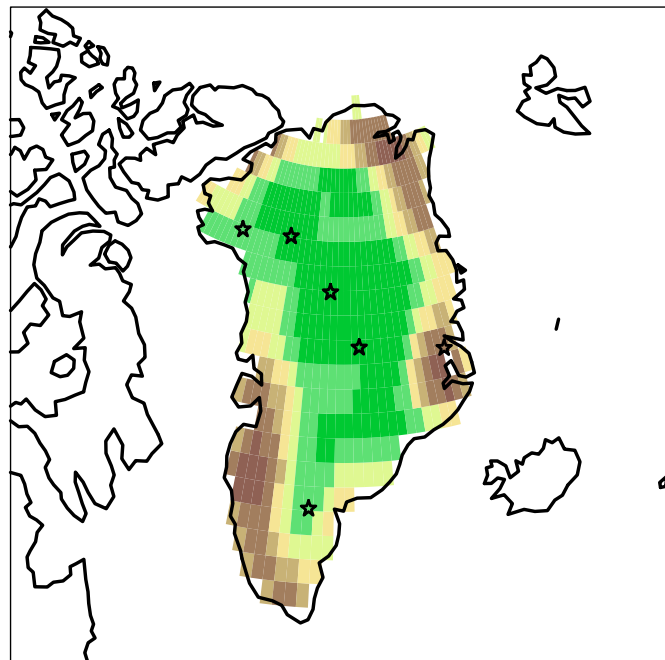
PMIP2 ICE-5G



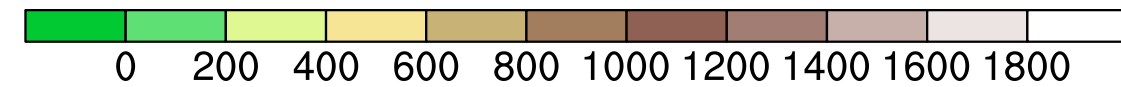
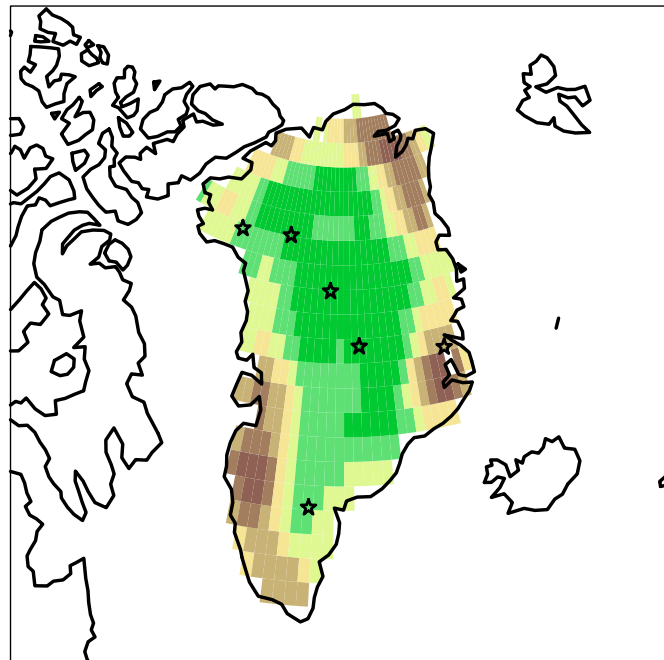
PMIP3 ice sheet



PMIP4 ICE-6G-C



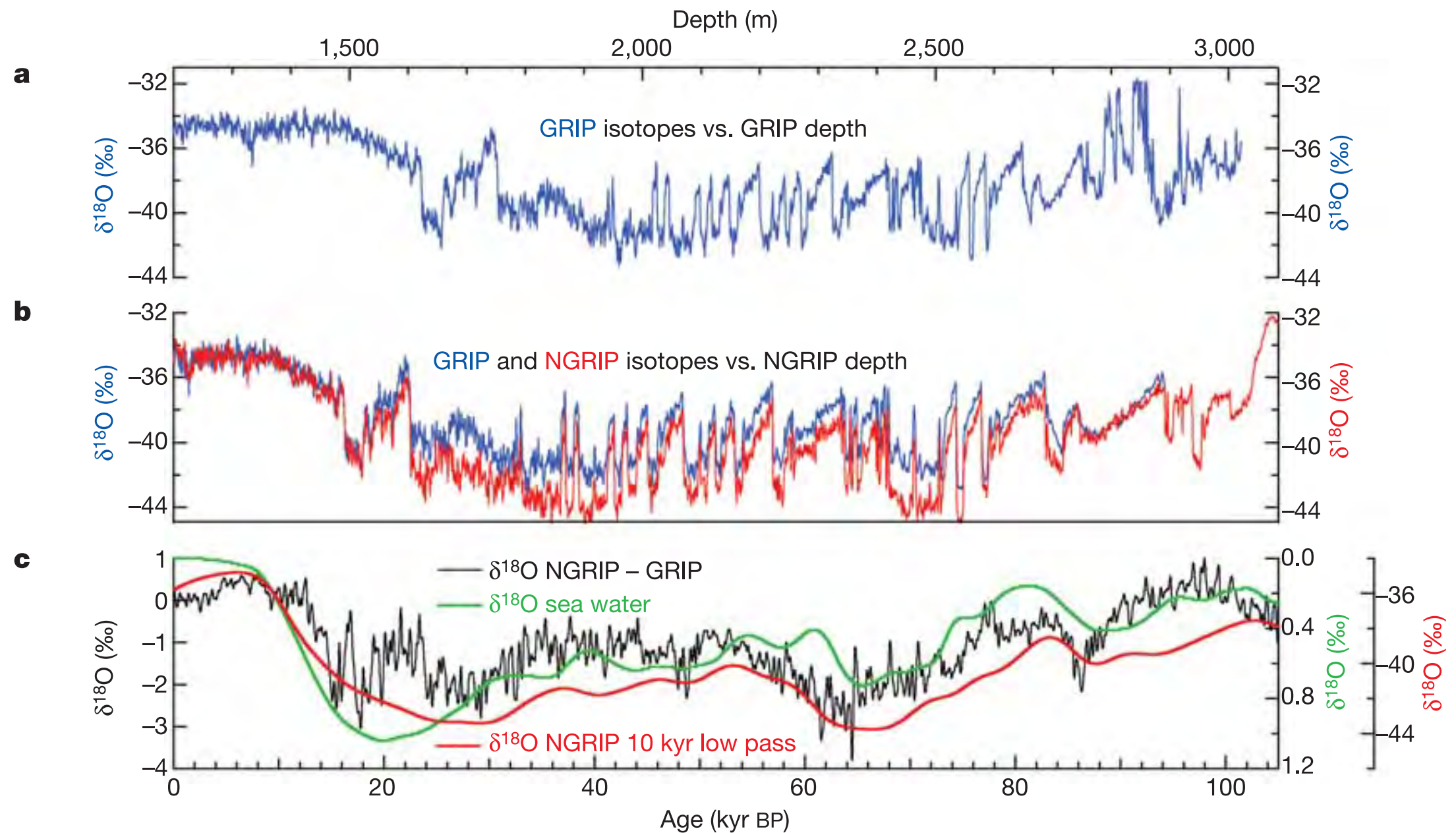
PMIP4 GLAC-1D



LGM-PD height changes [m]

**PMIP:**  
Paleoclimate Modelling  
Intercomparison Project

# Comparison: $\delta^{18}\text{O}$ -record of Greenland ice cores



**Figure 2** The NGRIP stable oxygen isotopic record compared to the GRIP record. **a**, The GRIP oxygen isotopic profile (blue) with respect to depth at GRIP. Isotopic values ( $\delta^{18}\text{O}$ ) are expressed in ‰ with respect to Vienna Standard Mean Ocean Water (V-SMOW). The measurements have been performed on 55 cm samples with an accuracy of  $\pm 0.1$ ‰. **b**, The NGRIP oxygen isotopic profile (red) with respect to depth at NGRIP. For comparison,

the GRIP record (blue) has been plotted on the NGRIP depth scale using the rapid transitions as tie points. **c**, The difference between the NGRIP and GRIP oxygen isotopic profiles plotted above on the GRIP2001/ss09sea timescale<sup>15</sup> in 50 yr resolution (black). The record is compared to a record representing sea level changes<sup>39</sup> (green) and a 10-kyr smoothed oxygen isotope profile from NGRIP (red).

# LGM climate in Greenland & Antarctica - summary

- temperature difference between LGM and present-day:
  - **strong cooling on Greenland:** -20...-23°C (from  $\delta^{18}\text{O}$  and other proxies)
  - medium cooling on Antarctica:** -5...-12°C (from  $\delta\text{D}$ )
- **precipitation rate** during LGM: reduced by ca. 40-70%
- **greenhouse gases ( $\text{CO}_2$ ,  $\text{CH}_4$ ) at minimum level during the LGM** (e.g.  $\text{CO}_2$ : pre-industrial: 280ppm, LGM: 180ppm)
- **extrem strong correlation between  $T_{\text{surf}}$  (local change) and  $\text{CO}_2$  &  $\text{CH}_4$  (global change), even for smaller scale variations**
- **temperature changes and global ice volume** correlate well, too



# Overview: the last glacial maximum

Last Glacial Maximum 21,000 years ago



How cold were the oceans and the tropics?



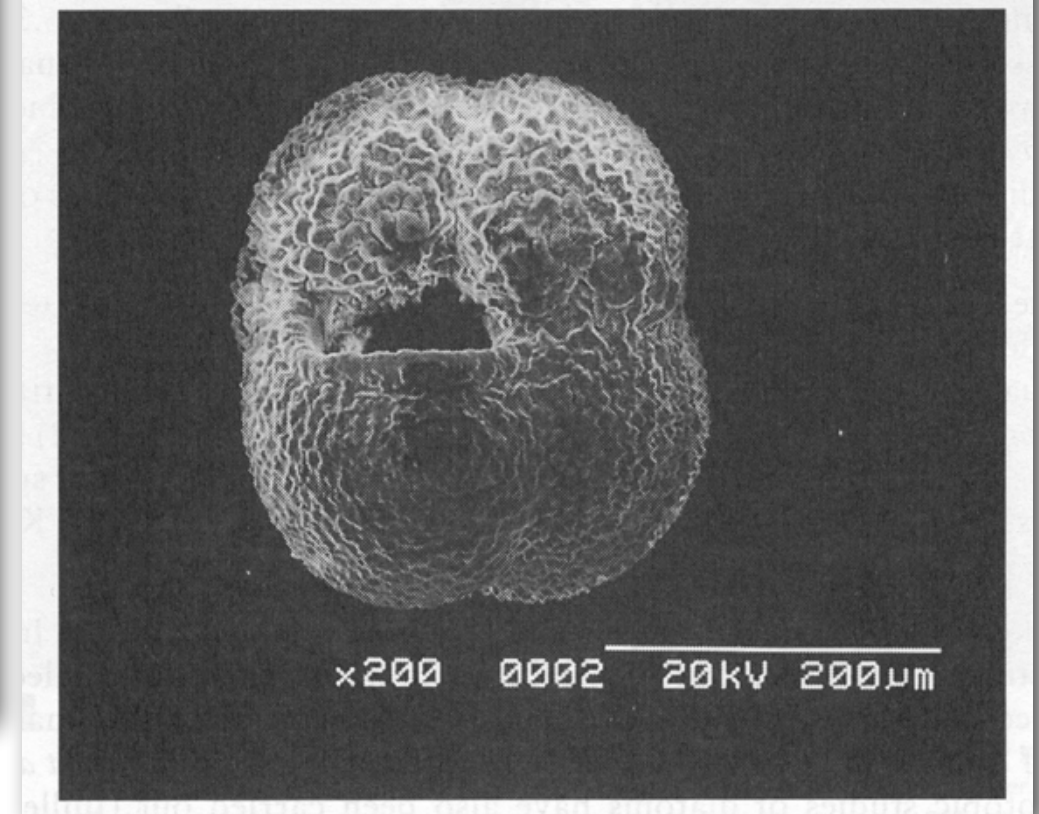
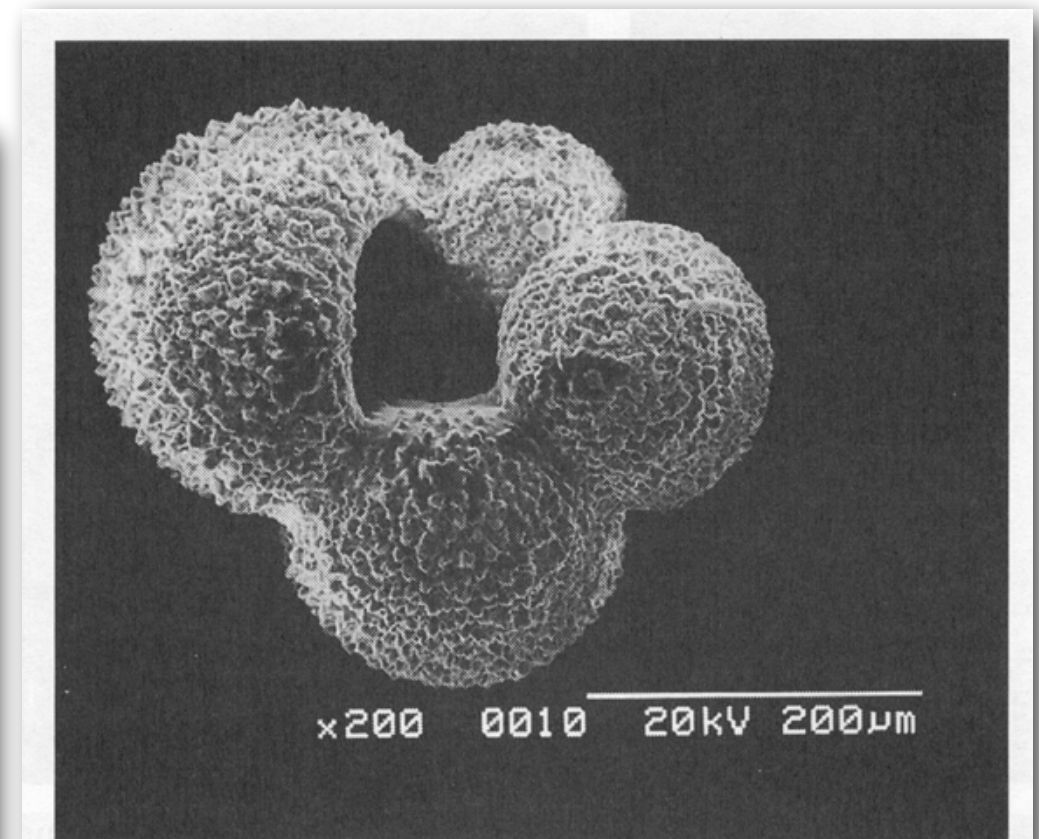
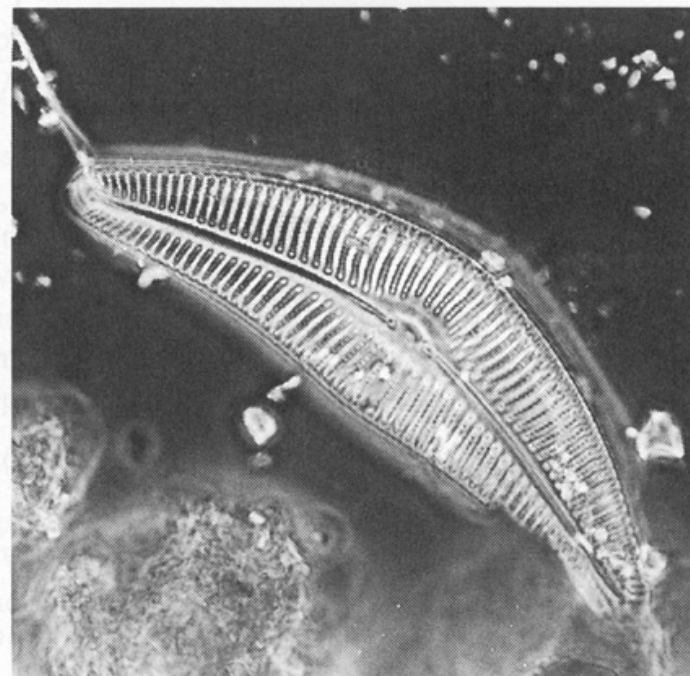
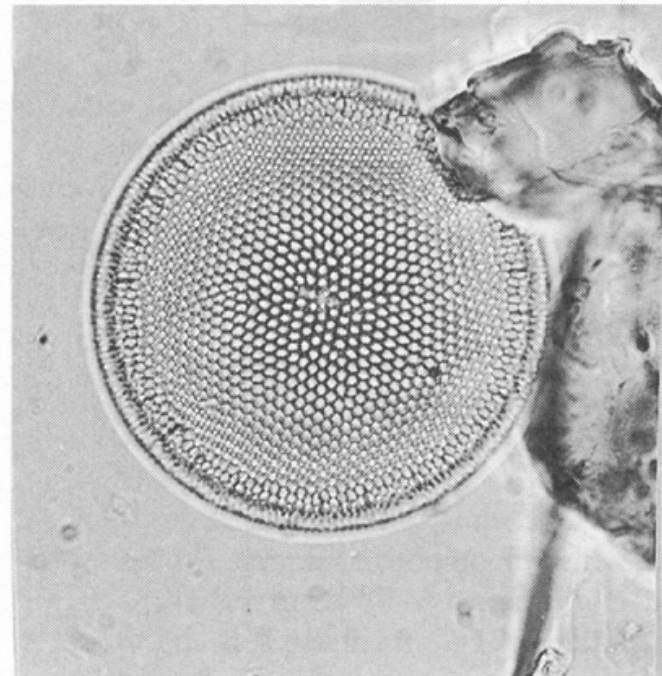
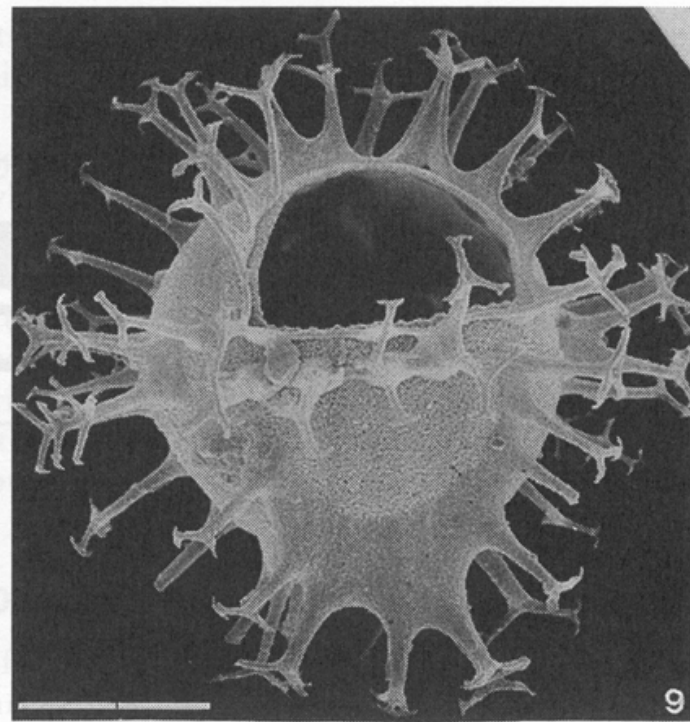
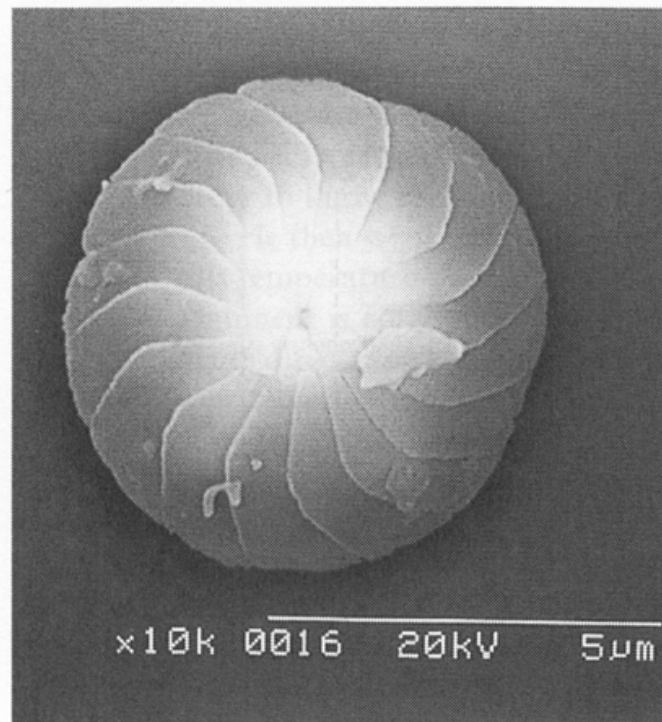
# The CLIMAP projekt

- **aim: reconstruction of sea surface temperatures (SST) for August and Februar during the LGM (21,000 B.P.)**
- **based mainly on Foraminifera data, partly on silicate containing fossils and other temperature estimates**



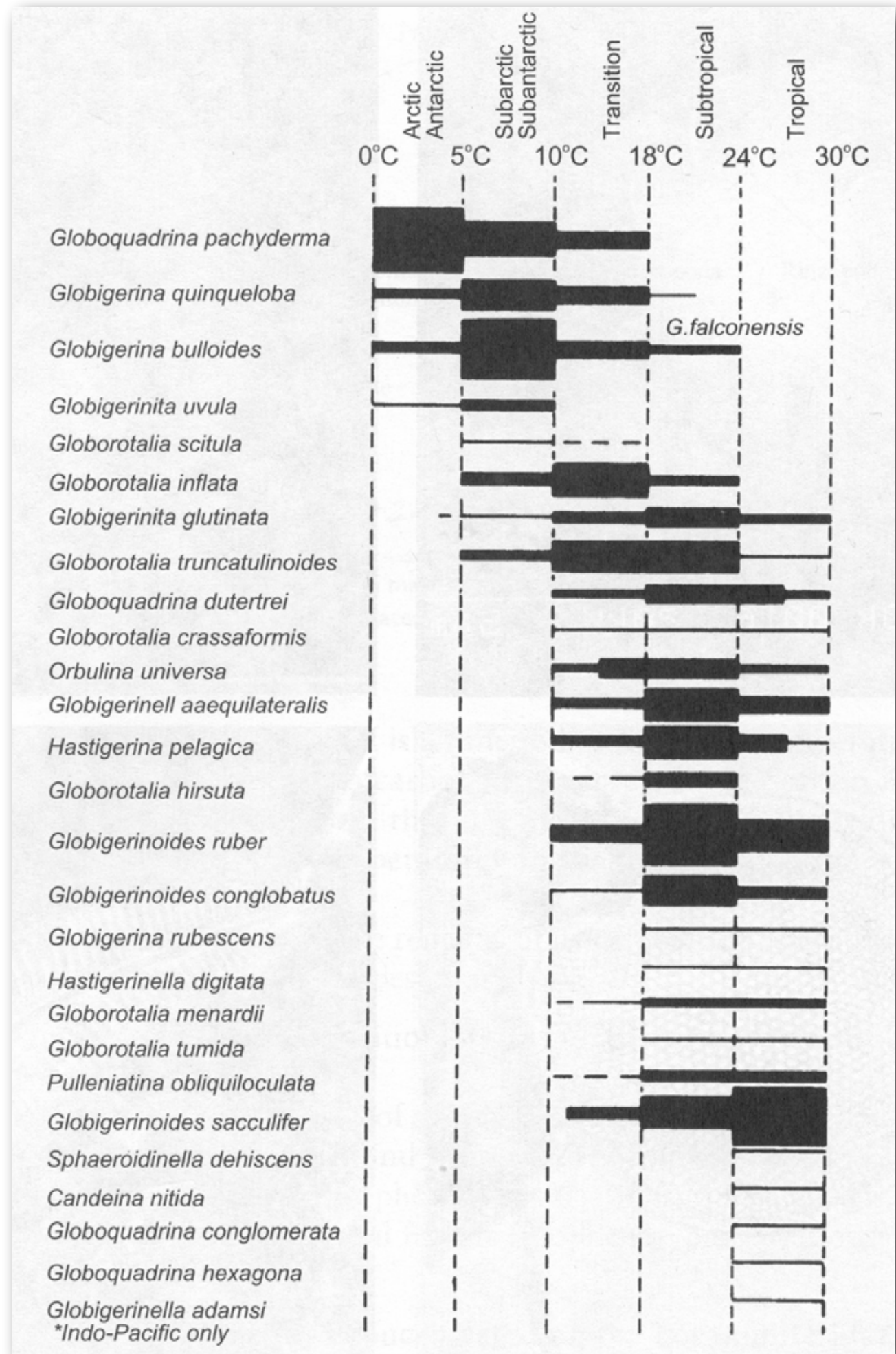
# Foraminifera (zooplankton)

## Coccolithophors (phytoplankton)



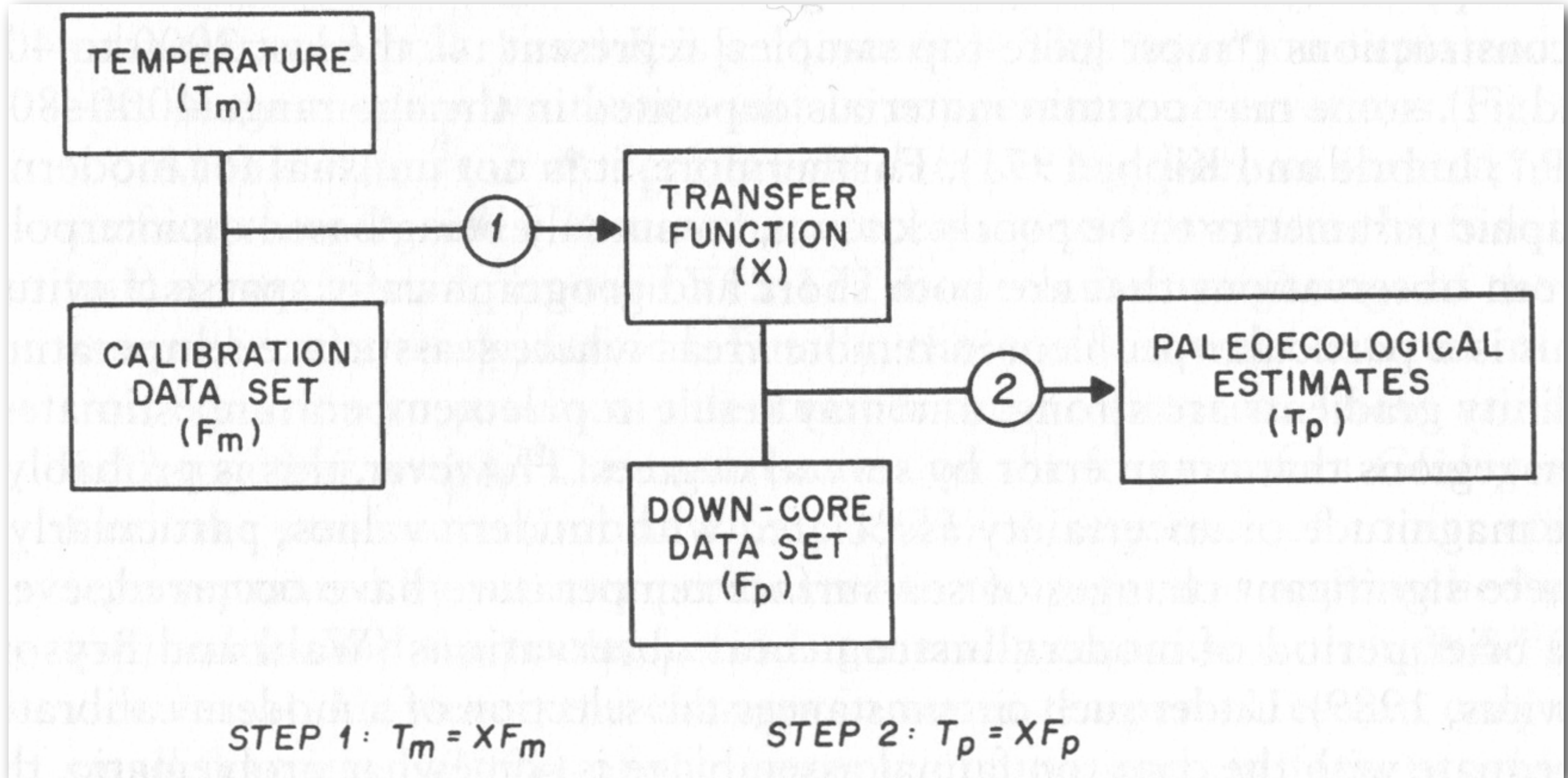


# Marine records: temperature range of different foraminifera species

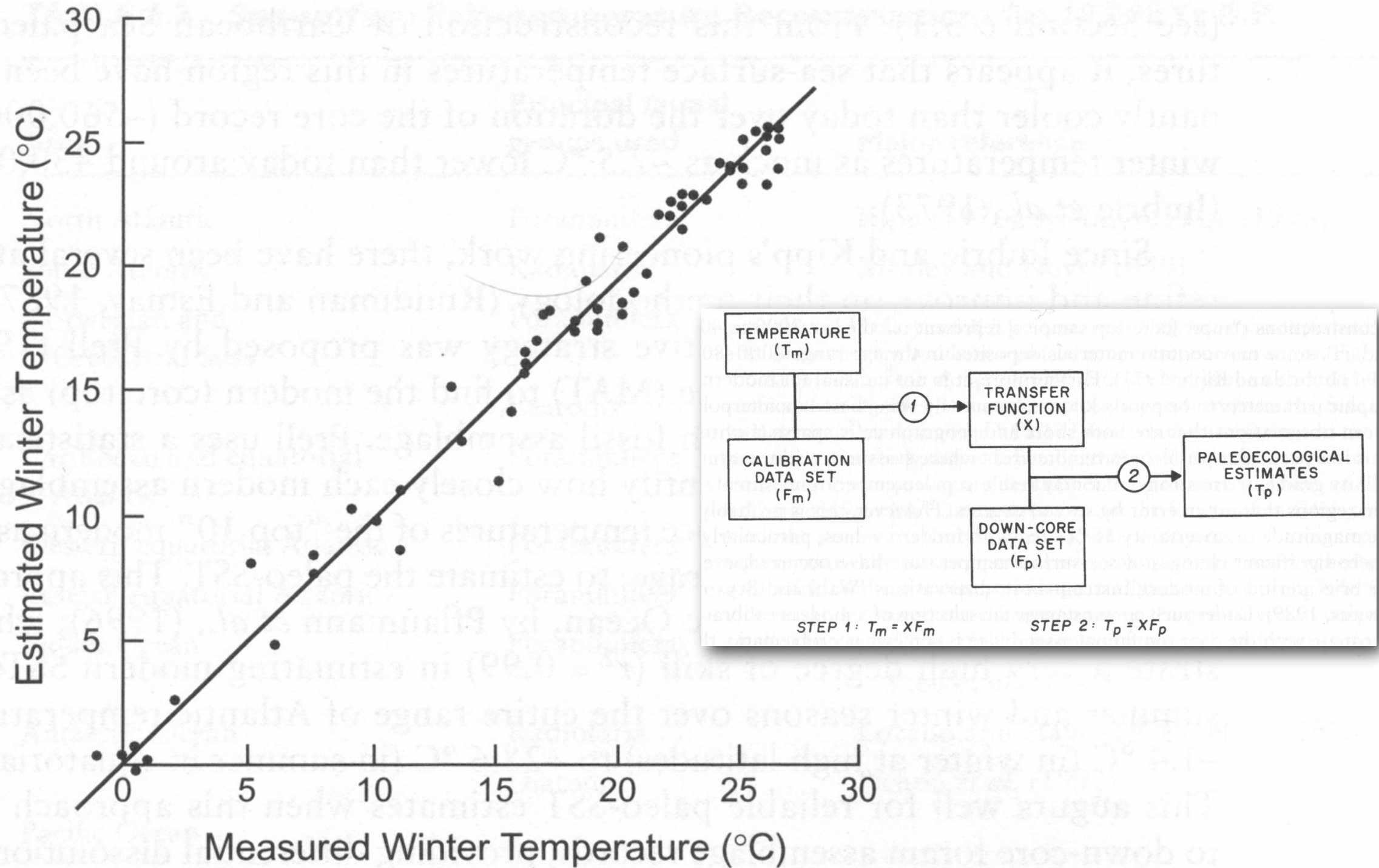




# Marine records: the modern analogue method (MAT)



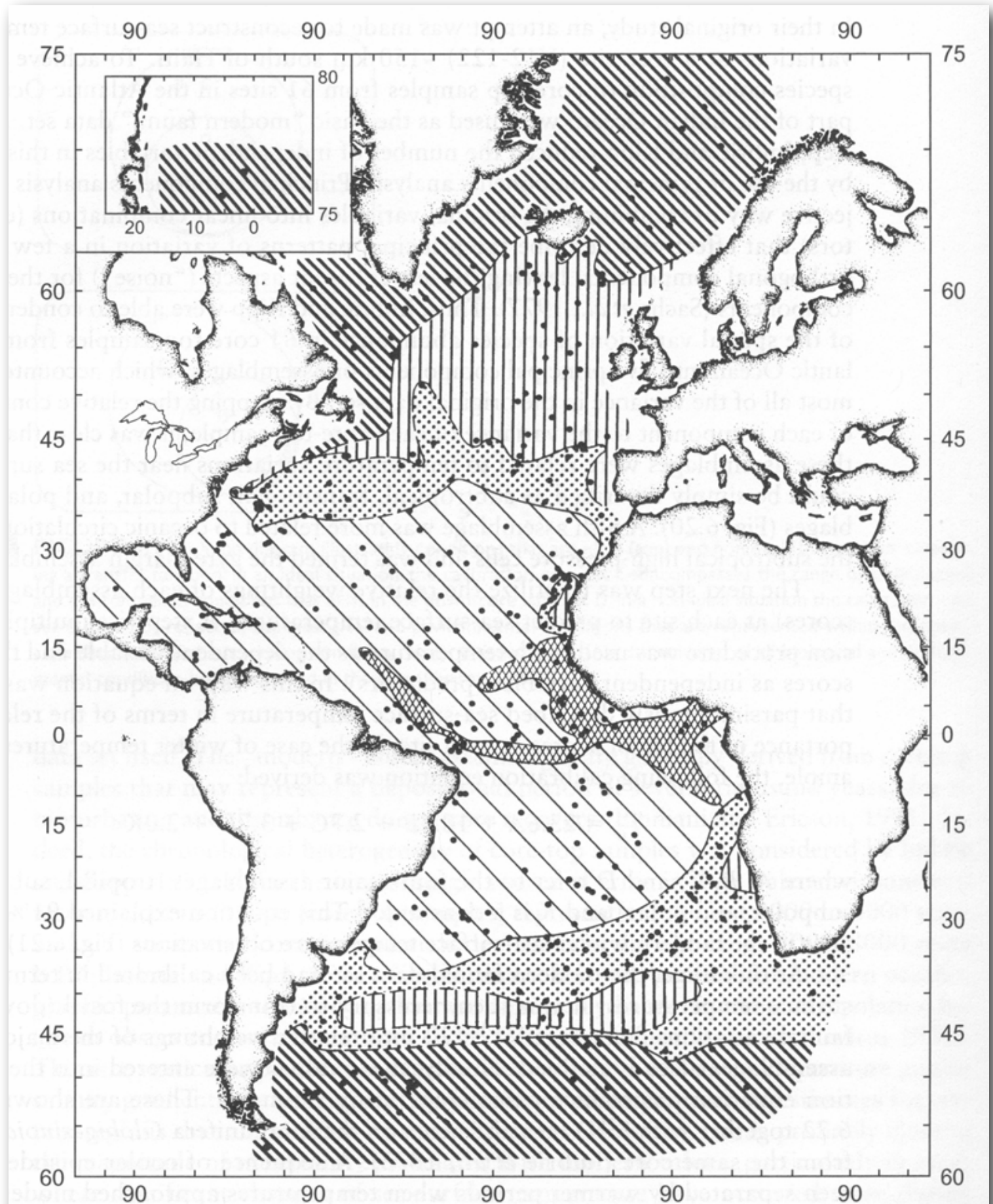
# Marine records: MAT temperature reconstructions



**FIGURE 6.21** Winter sea-surface temperature based on modern instrumental observations (including interpolated values) vs those estimated from faunal assemblages in 61 core-top samples using factor analysis and transfer function methods (Imbrie and Kipp, 1971).



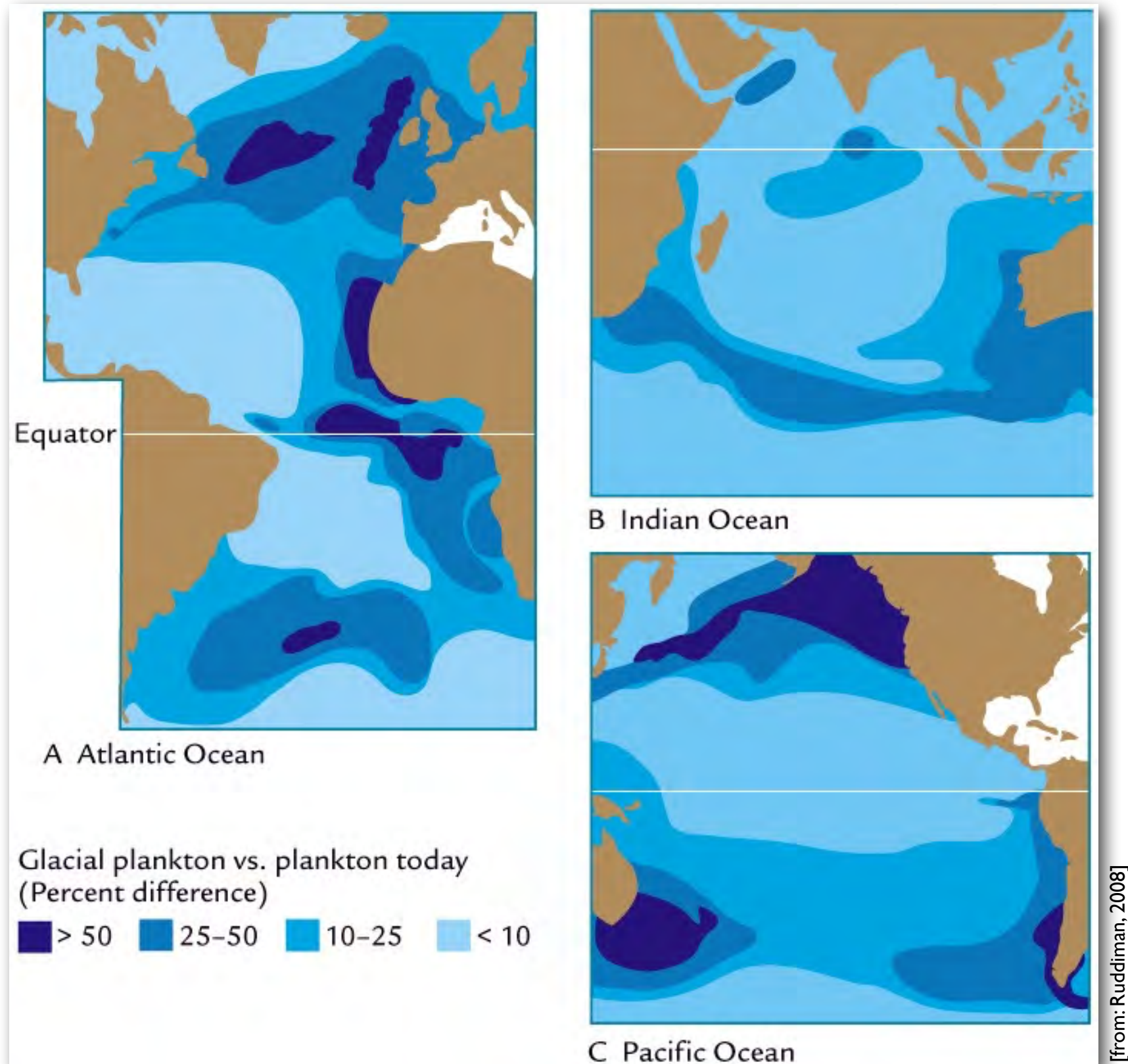
# Marine records: foraminifera grouping in the Atlantic



**FIGURE 6.20** Core-top foraminifera assemblages, defined by factor analysis. Each zone represents an area dominated by a particular assemblage (polar, subpolar, transitional, subtropical, or gyre margin) (Molfini *et al.*, 1982).

## Marine records

### CLIMAP: changes of planktic fauna during the LGM

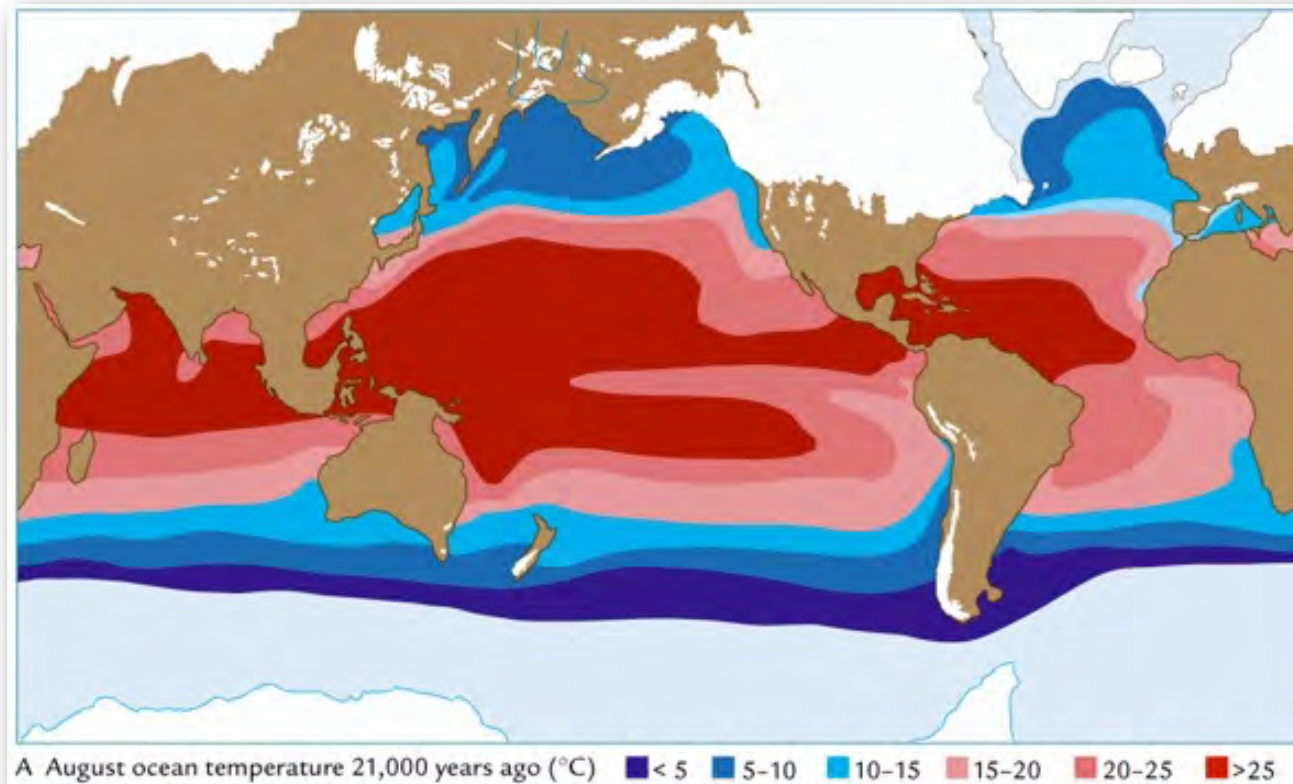




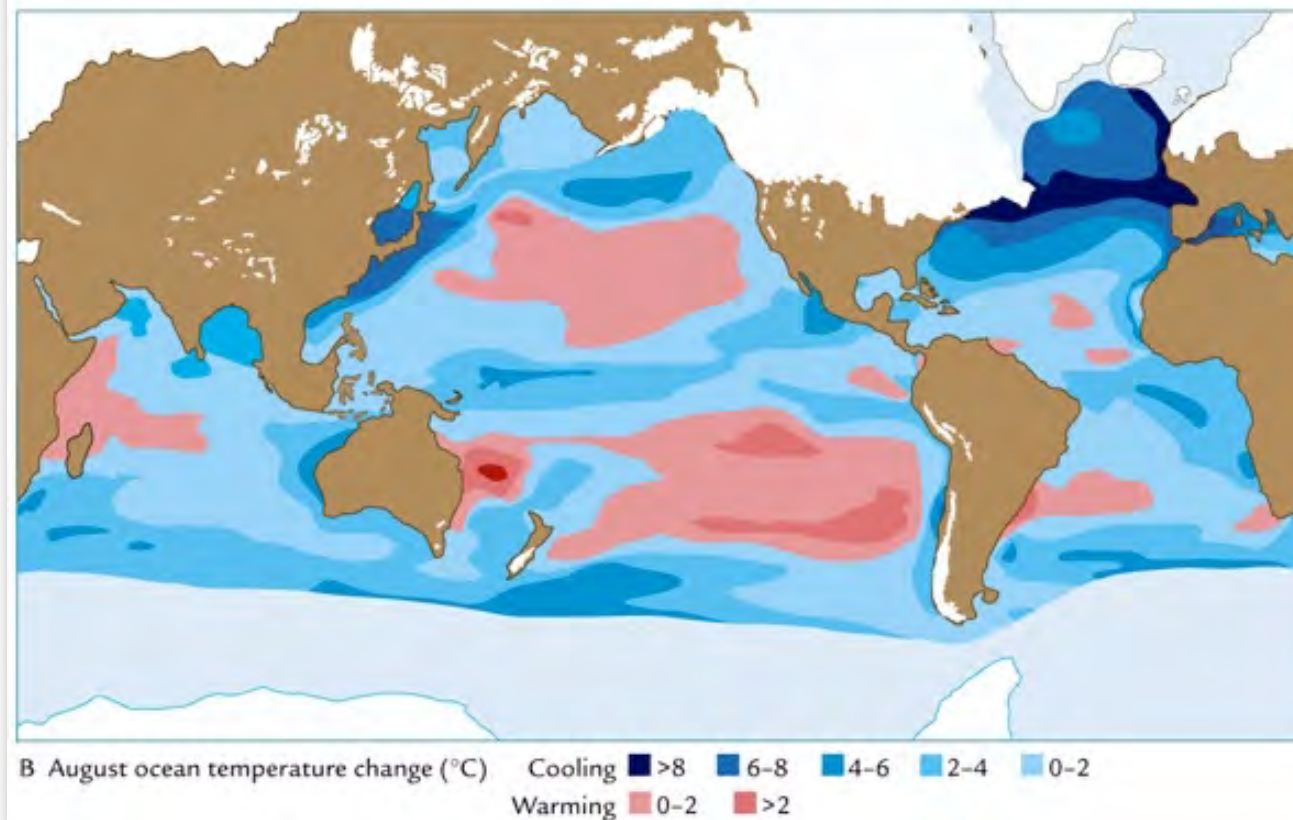
## Marine Records:

### **CLIMAP: Changes of SST during the LGM**

LGM SST  
(NH summer)



LGM-present  
SST change  
(NH summer)



[from: Ruddiman, 2008]

# Marine records: The CLIMAP projekt

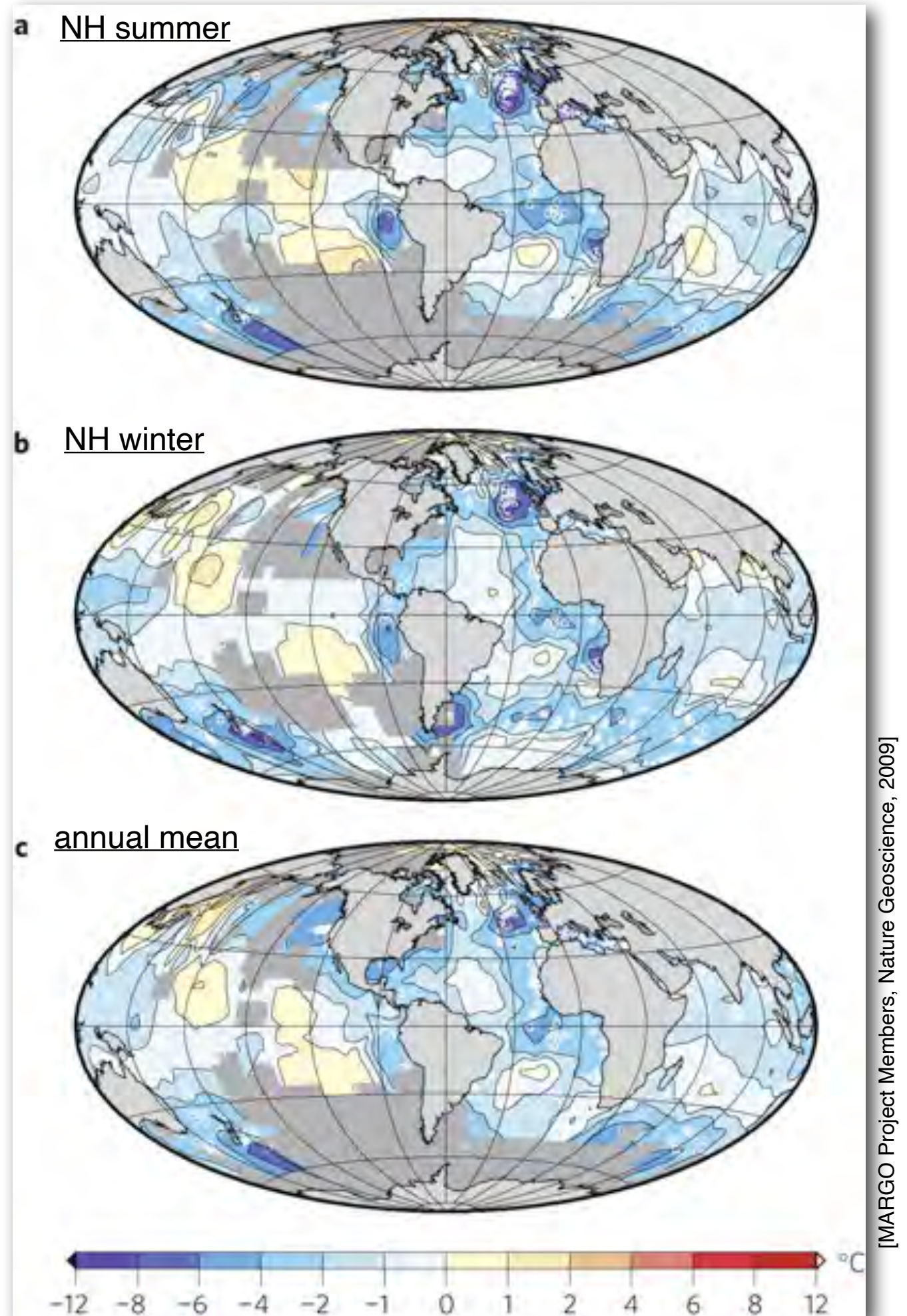
- aim: reconstruction of sea surface temperatures (SST) for August and Februar during the LGM (21,000 B.P.)
- controversial CLIMAP result:  
*the (sub)tropical SST have barely changed during the LGM!*
- tropical SST changes are very interesting, since
  - *the most part of water vapour transported into the atmosphere stems from the tropical regions*
  - *tropical SST changes can reveal information on the general climate sensitivity on changes in CO<sub>2</sub> (LGM: 180ppm)*
- another critical issue:  
CLIMAP maps are based on interpolation between different data records, **ocean dynamics has not been considered properly**
- CLIMAP result disagree with other LGM temperature reconstructions (mainly from terrestrial records), but are also (partly) supported by other temperature proxy analyses



# Marine records:

## **The MARGO project - Multiproxy approach for the reconstruction of the glacial ocean surface**

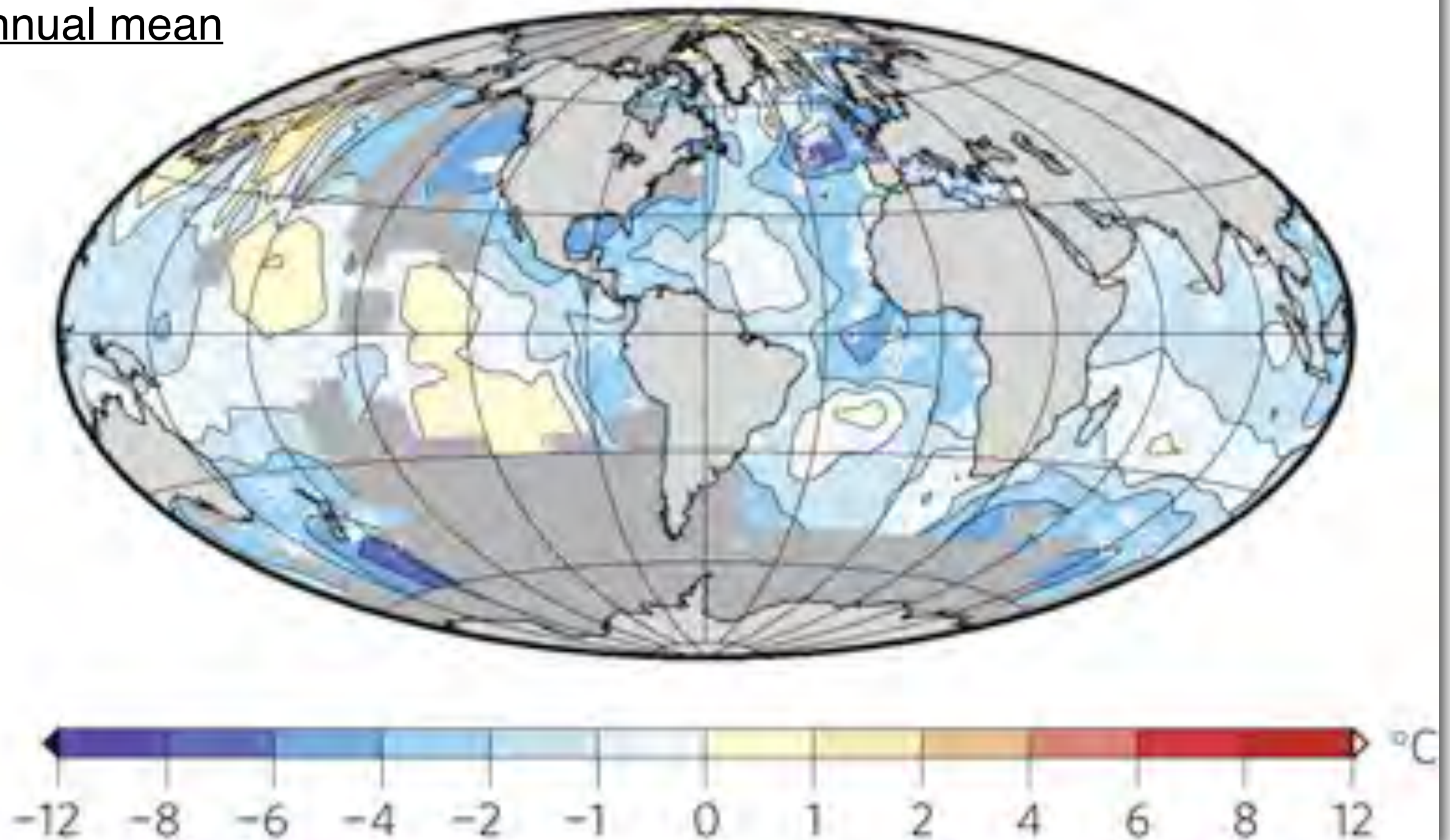
Anomalies are computed as LGM–WOA98 (ref. 12) values. a, Northern Hemisphere summer (July–August–September). b, Northern Hemisphere winter (January–February–March). c, Annual mean. The symbols show the location and proxy type of the original available data (see Fig. 1). Note the uneven spacing of the diverging colour scheme and isotherms.





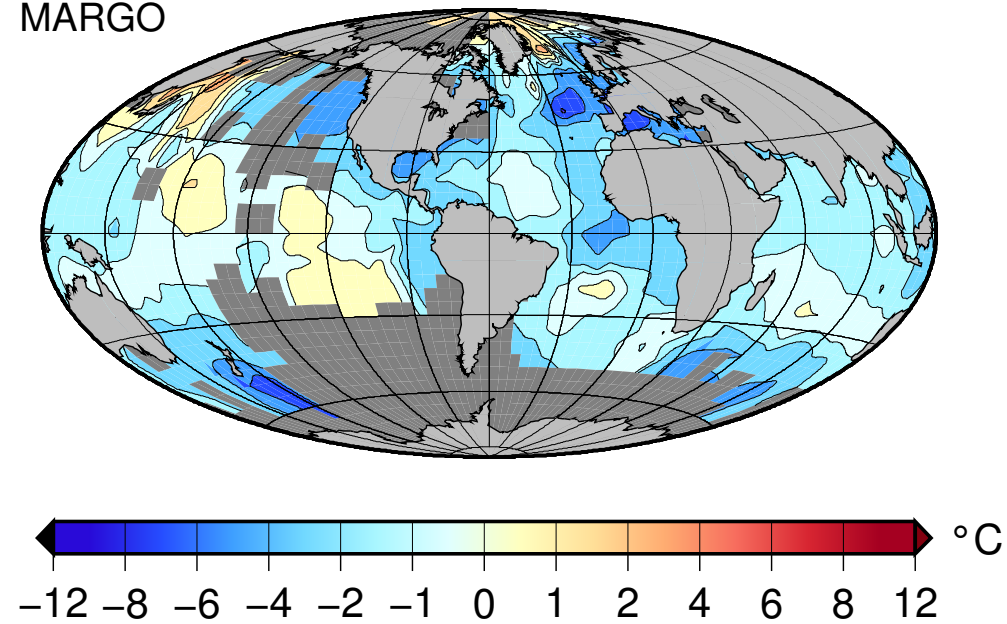
# Glacial global SST reconstructions: MARGO data set

annual mean

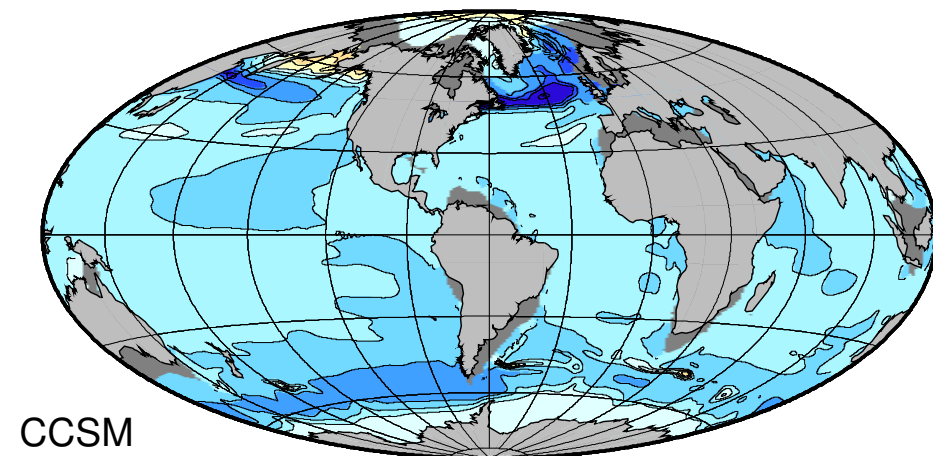
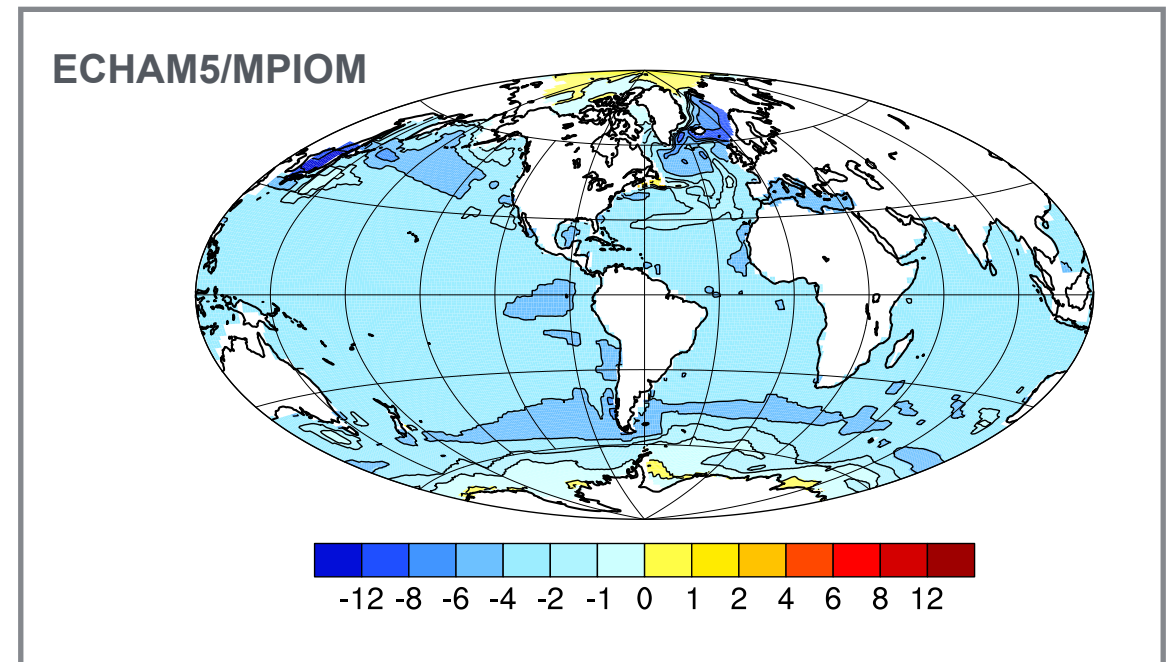


# Glacial SST: MARGO reconstruction vs. model results

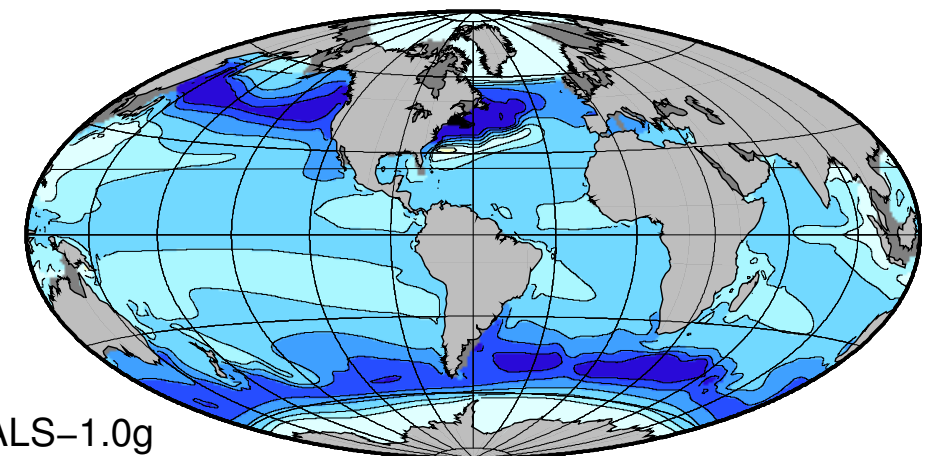
MARGO



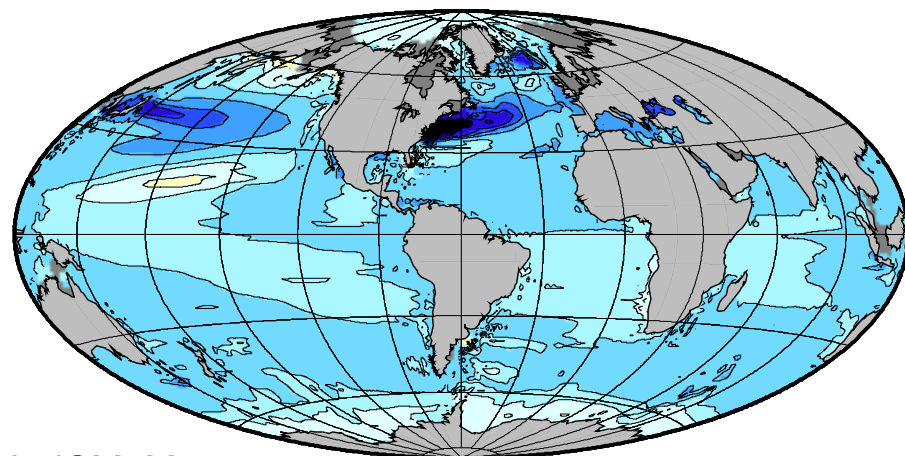
ECHAM5/MPIOM



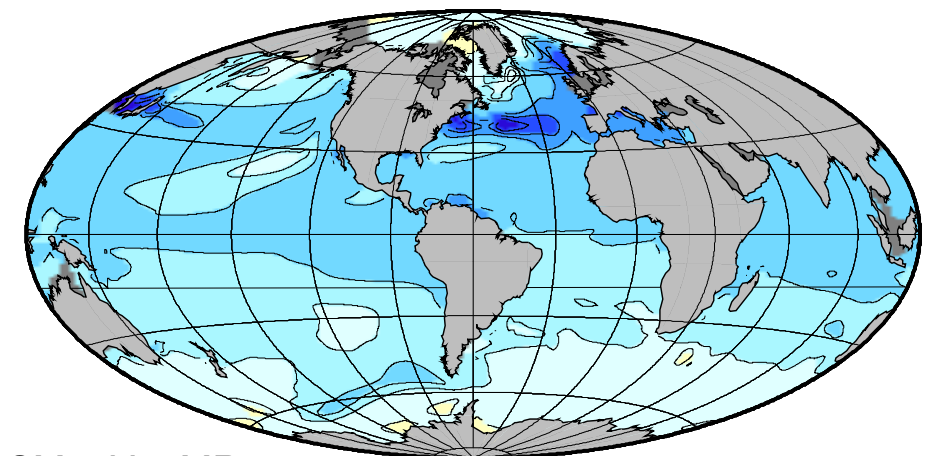
CCSM



FGOALS-1.0g



HadCM3M2



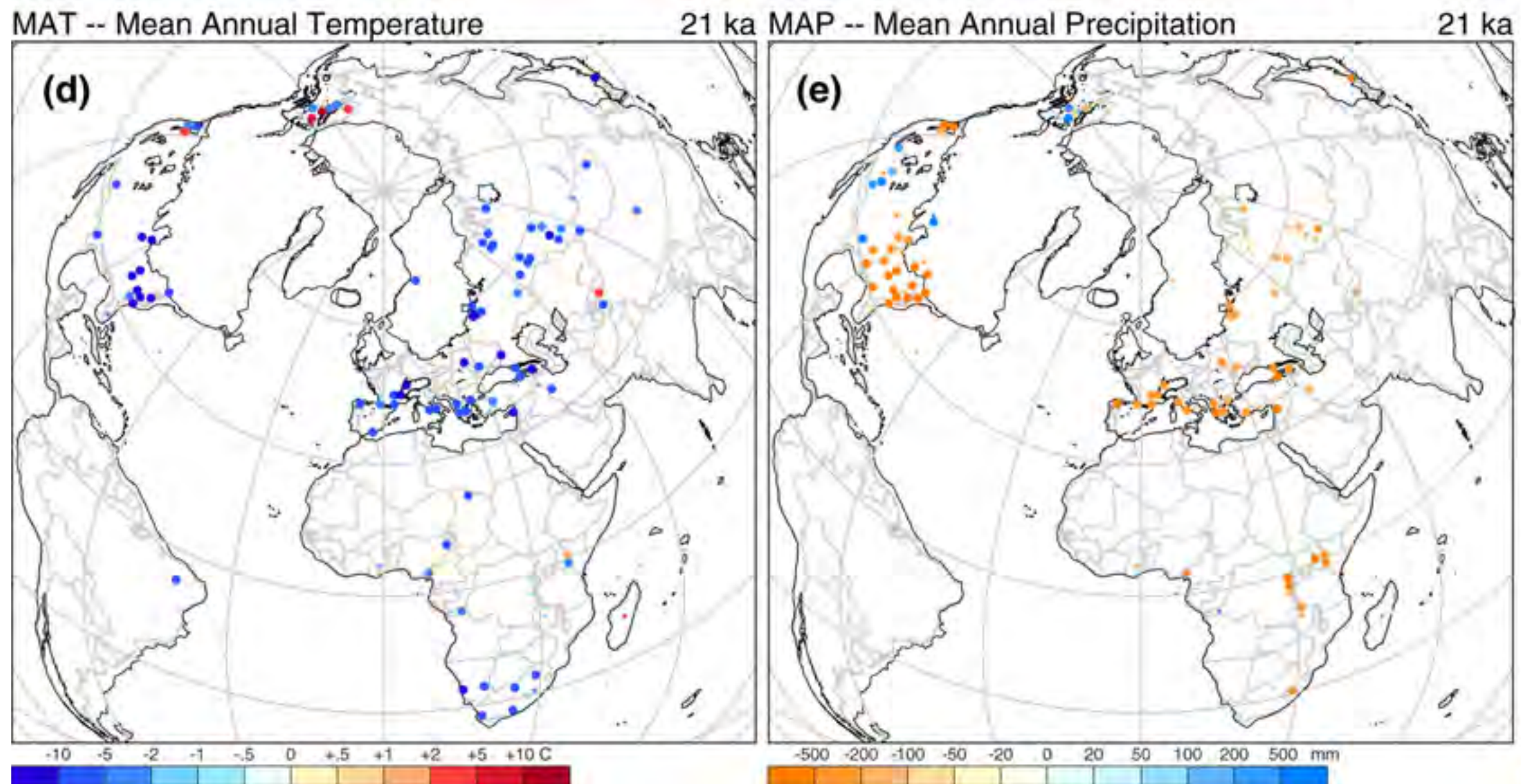
IPSL-CM4-V1-MR



# LGM temperature and precipitation changes over land

## Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis

P. J. Bartlein · S. P. Harrison · S. Brewer · S. Connor · B. A. S. Davis ·  
K. Gajewski · J. Guiot · T. I. Harrison-Prentice · A. Henderson ·  
O. Peyron · I. C. Prentice · M. Scholze · H. Seppä · B. Shuman · S. Sugita ·  
R. S. Thompson · A. E. Viau · J. Williams · H. Wu



# Overview: the last glacial maximum

Last Glacial Maximum 21,000 years ago



## How cold were the oceans and the tropics?

- the LGM cooling in the tropics was „medium-small“, between  $-1...-3^{\circ}\text{C}$
- MARGO data suggests even a slight warming in some tropical regions  
*this warming is still under discussion*  
*(e.g., such warming can't be reproduced by climate models)*
- land-based estimates show in some regions a cooling of up to  $-5^{\circ}\text{C}$



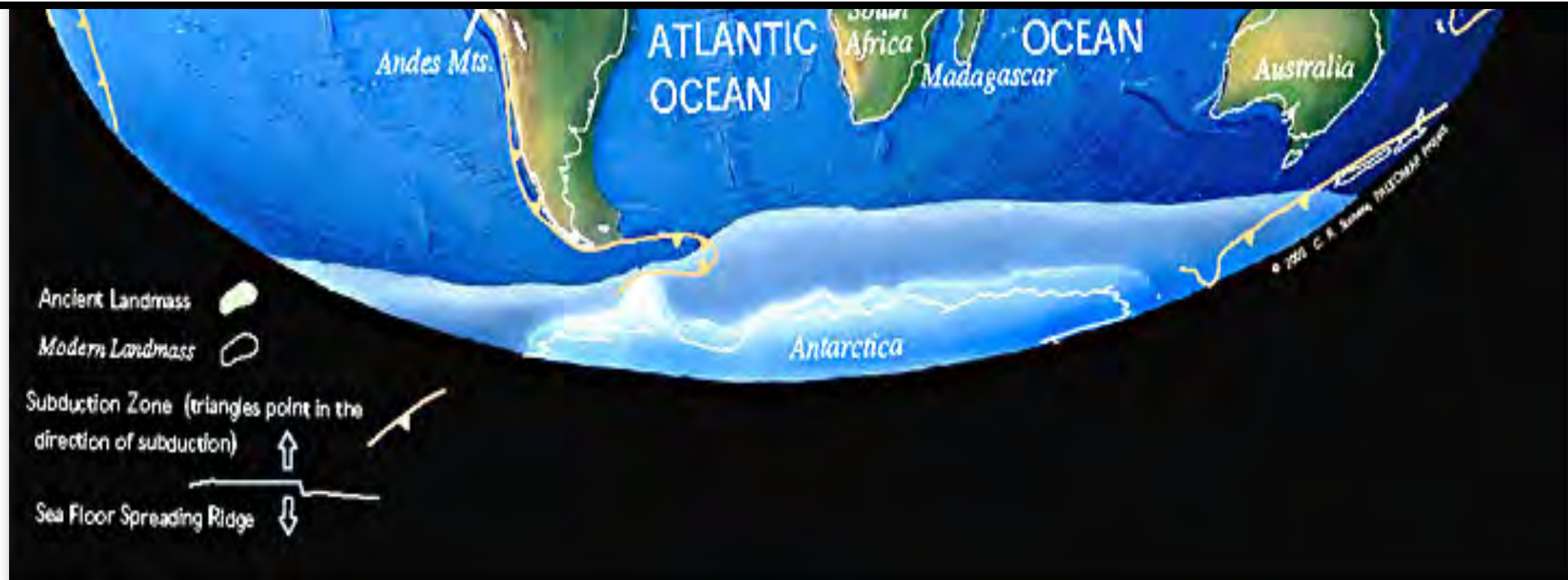


# Overview: the last glacial maximum

Last Glacial Maximum 21,000 years ago



## Further climate variations during the LGM





# Sea level variations

**TABLE 12.1 Approximate Volumes of Ice and Amounts of Water Stored in Glacial Ice Sheets by Lowering Sea Level beneath Today's Position**

Ice sheet	Location	Excess ice volume (million km <sup>3</sup> )	TSH:Sea level	
			Amount (m)	Change (m) <sup>a</sup>
Laurentide	East-central Canada	25–34 <sup>b</sup>	72–100	50–70
Cordilleran	Western North America	1.8	5	3.5
Greenland	Greenland	2.6 <sup>c</sup>	7	5
Britain	England, Scotland, Ireland	0.8	2	1.5
Scandinavian	Northern Europe	7.3	21	15
Barents/Kara	Shelf north of Eurasia	6.9	20	14
East Antarctic	Eastern Antarctica	13.3 <sup>d</sup>	9	6
West Antarctic	Western Antarctica	16.5 <sup>d</sup>	18	13
Others	Various	1.2	3	2
All ice sheets		55–64	155–183	109–129

<sup>a</sup>Net sea level changes are 30% smaller than the volumes of seawater removed from the ocean because ocean bedrock rises when the weight of water is removed.

<sup>b</sup>The higher estimate shown is for a thick ice sheet like that in the CLIMAP maximum reconstruction; the lower estimate is for a thin ice sheet.

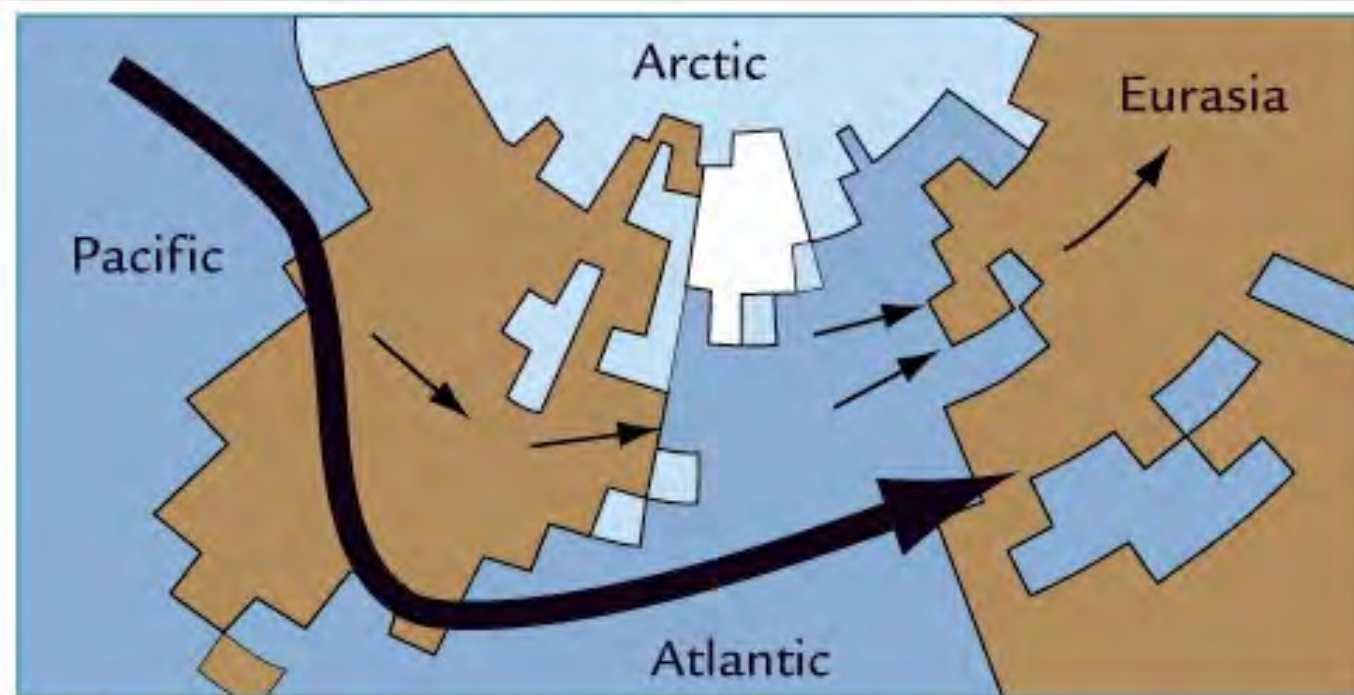
<sup>c</sup>Present volume of ice on Greenland is 3 million km<sup>3</sup>.

<sup>d</sup>Present volume of ice on Antarctica is 29 million km<sup>3</sup>.

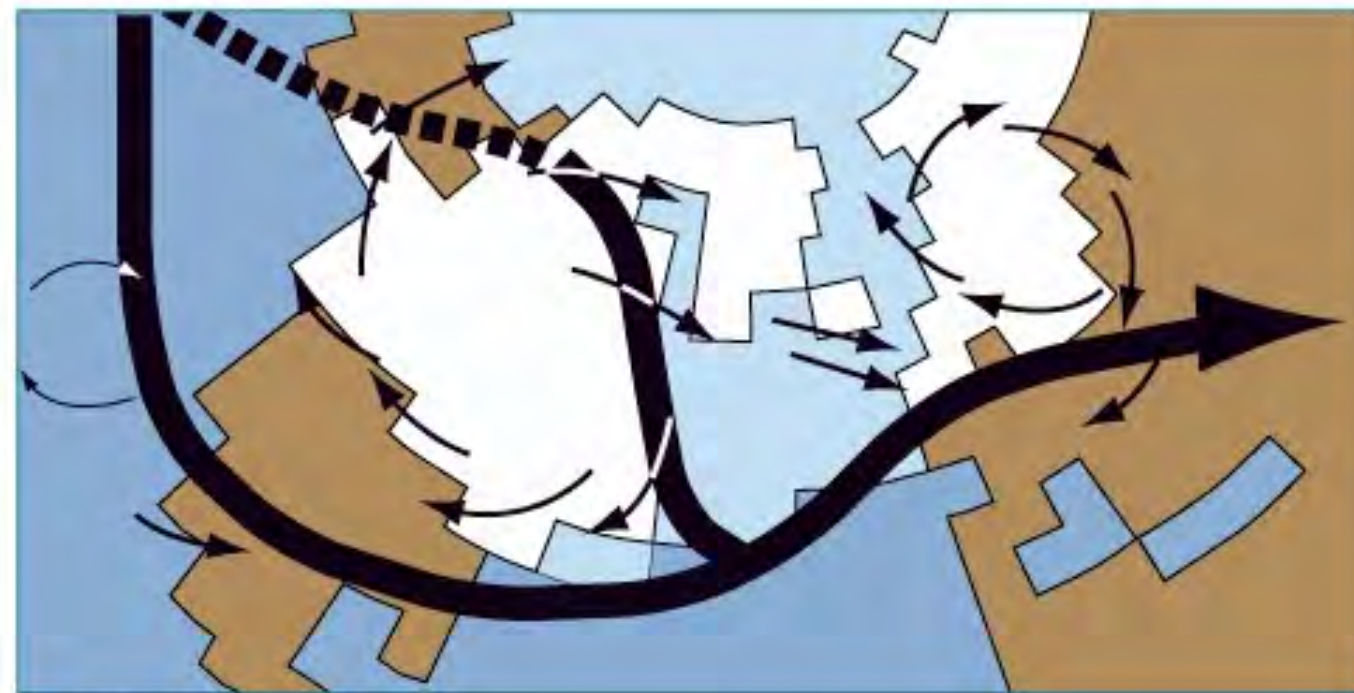
Source: Adapted from G. H. Denton and T. J. Hughes, *The Last Great Ice Sheets* (New York: Wiley, 1981).



# LGM climate of North America and Europe



A Modern winters



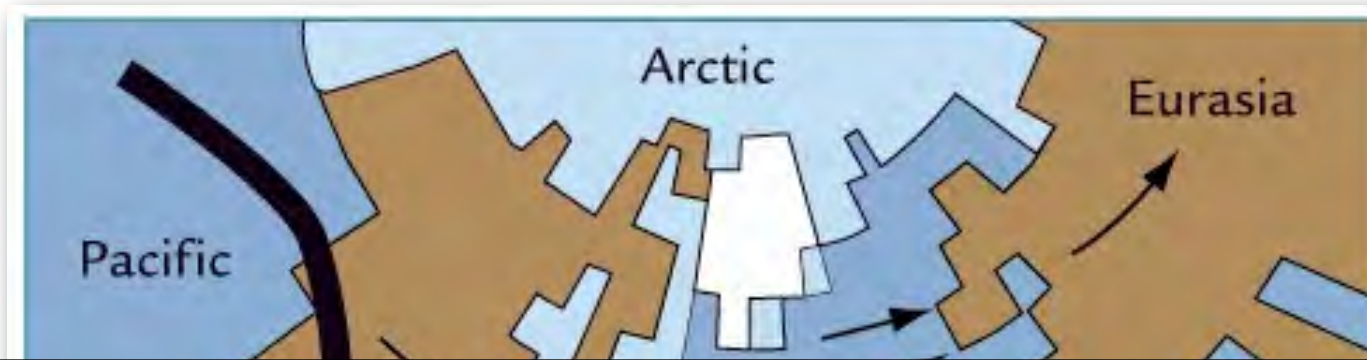
B Glacial winters

Sea ice  
Ice sheets

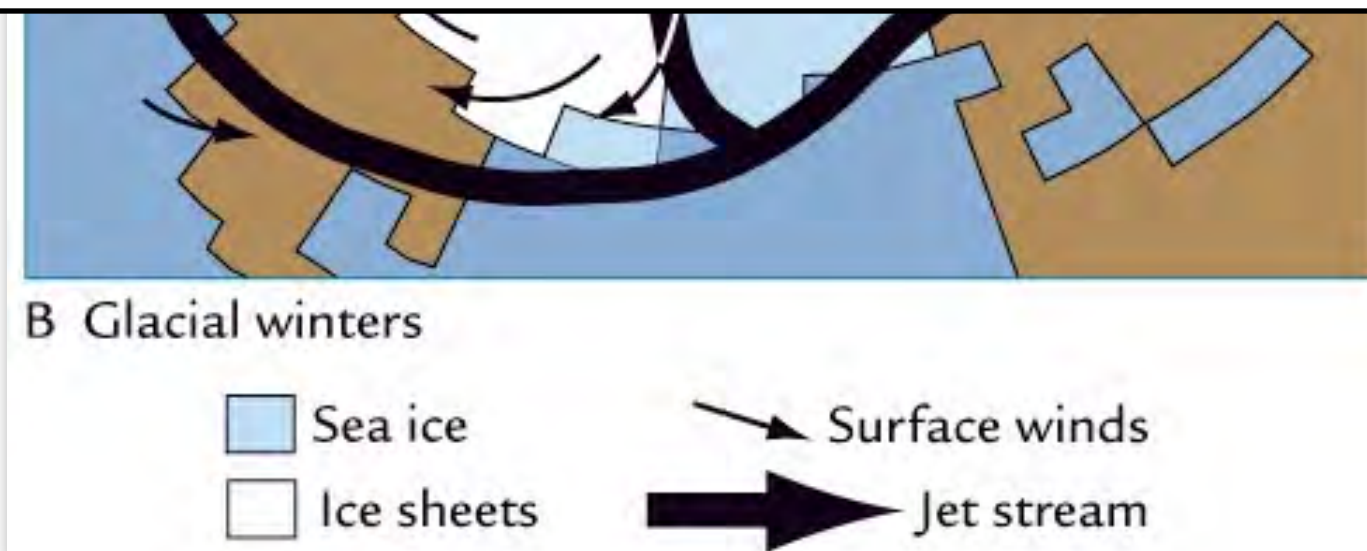
Surface winds  
Jet stream



# LGM climate of North America and Europe



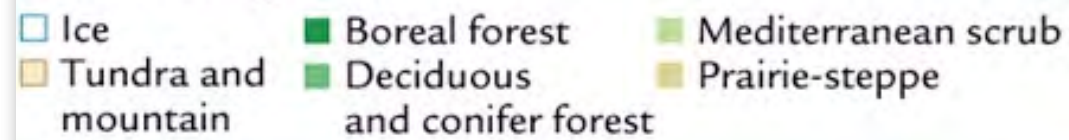
**Climate simulation results indicate that the Laurentide and Fennoscandian ice sheet caused drastic changes in atmospheric flow pattern (both at the surface and higher altitudes)**



# LGM climate of North America and Europe



A Modern vegetation



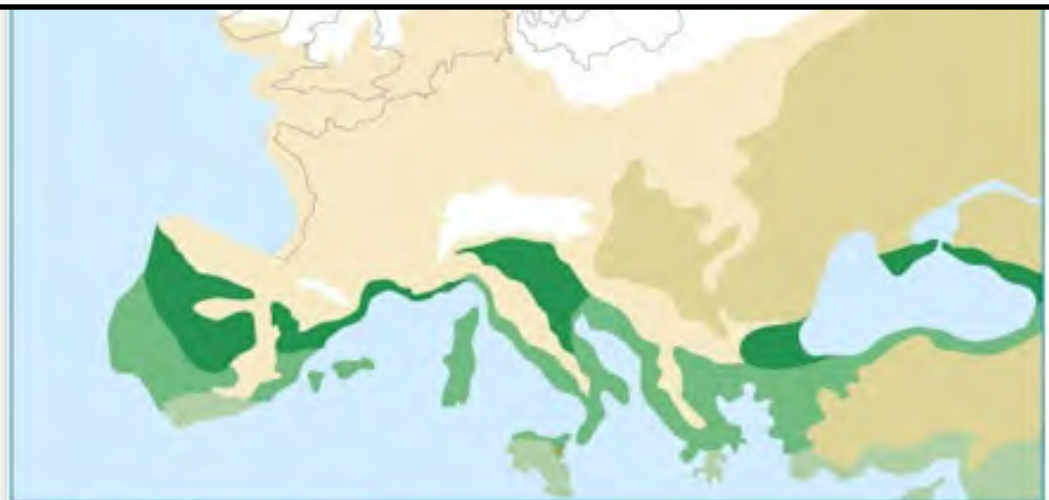
B Glacial vegetation

[from: Ruddiman, 2008]

# LGM climate of North America and Europe



- **vegetation in present-day Europe is dominated by forest**
- **during the LGM large parts of Europe were covered by tundra and steppe**

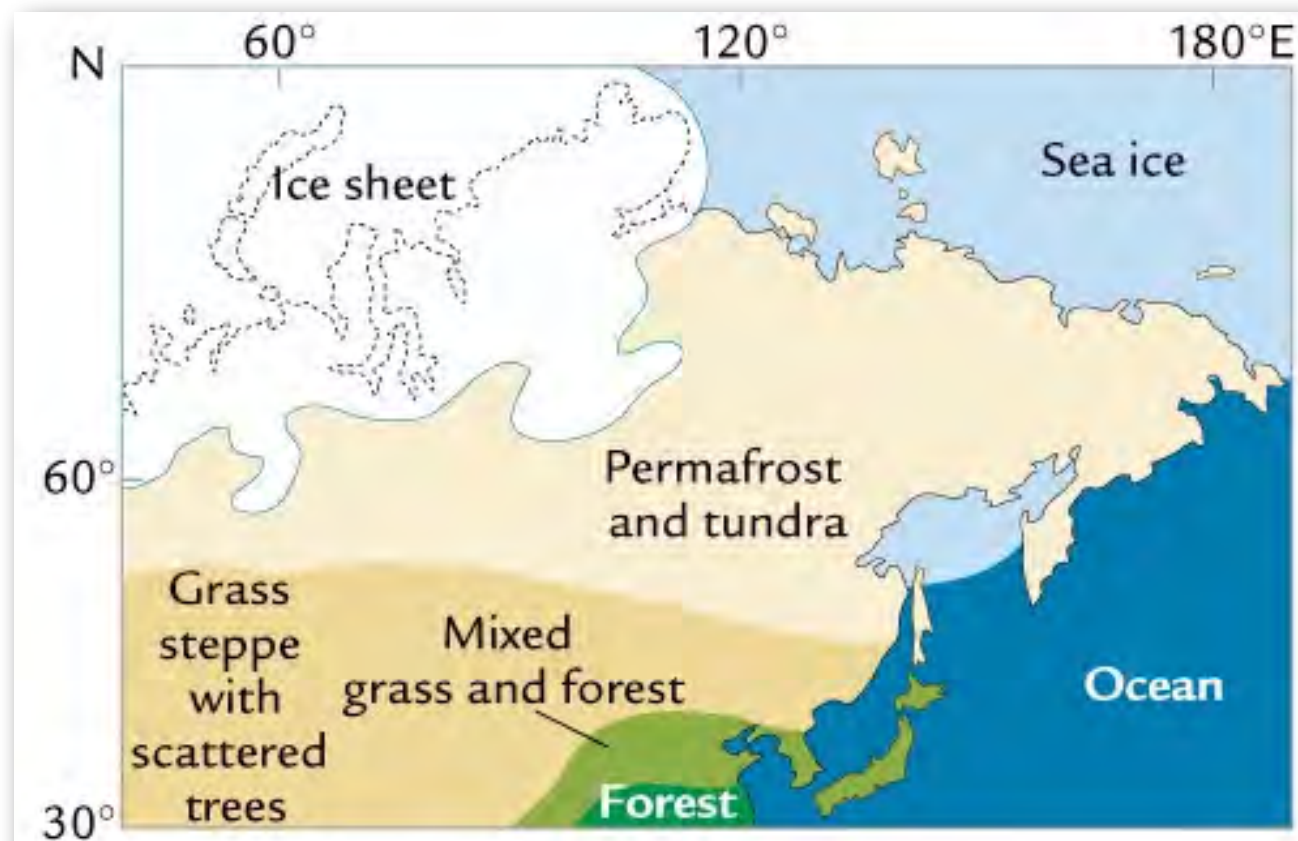


B Glacial vegetation

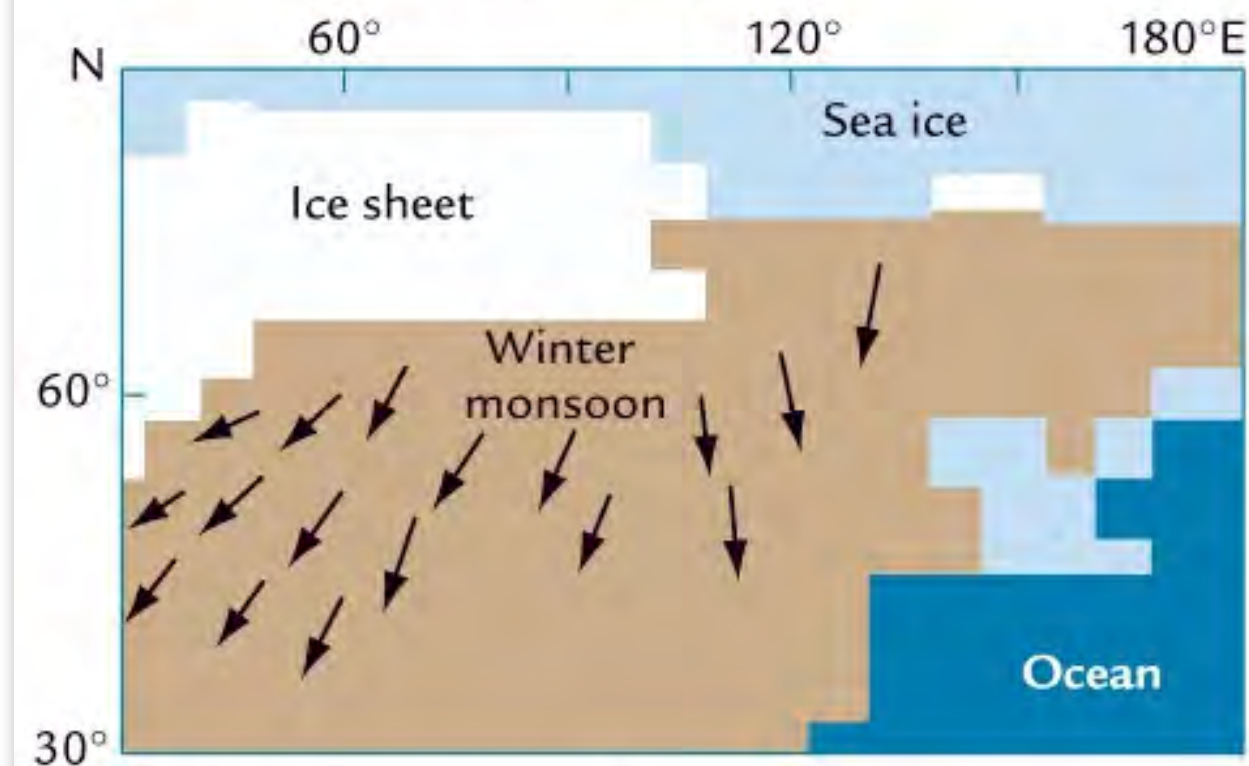
[from: Ruddiman, 2008]



# LGM climate of Asia



A Glacial maximum (observed)



B Glacial maximum (model)

# LGM climate of Asia



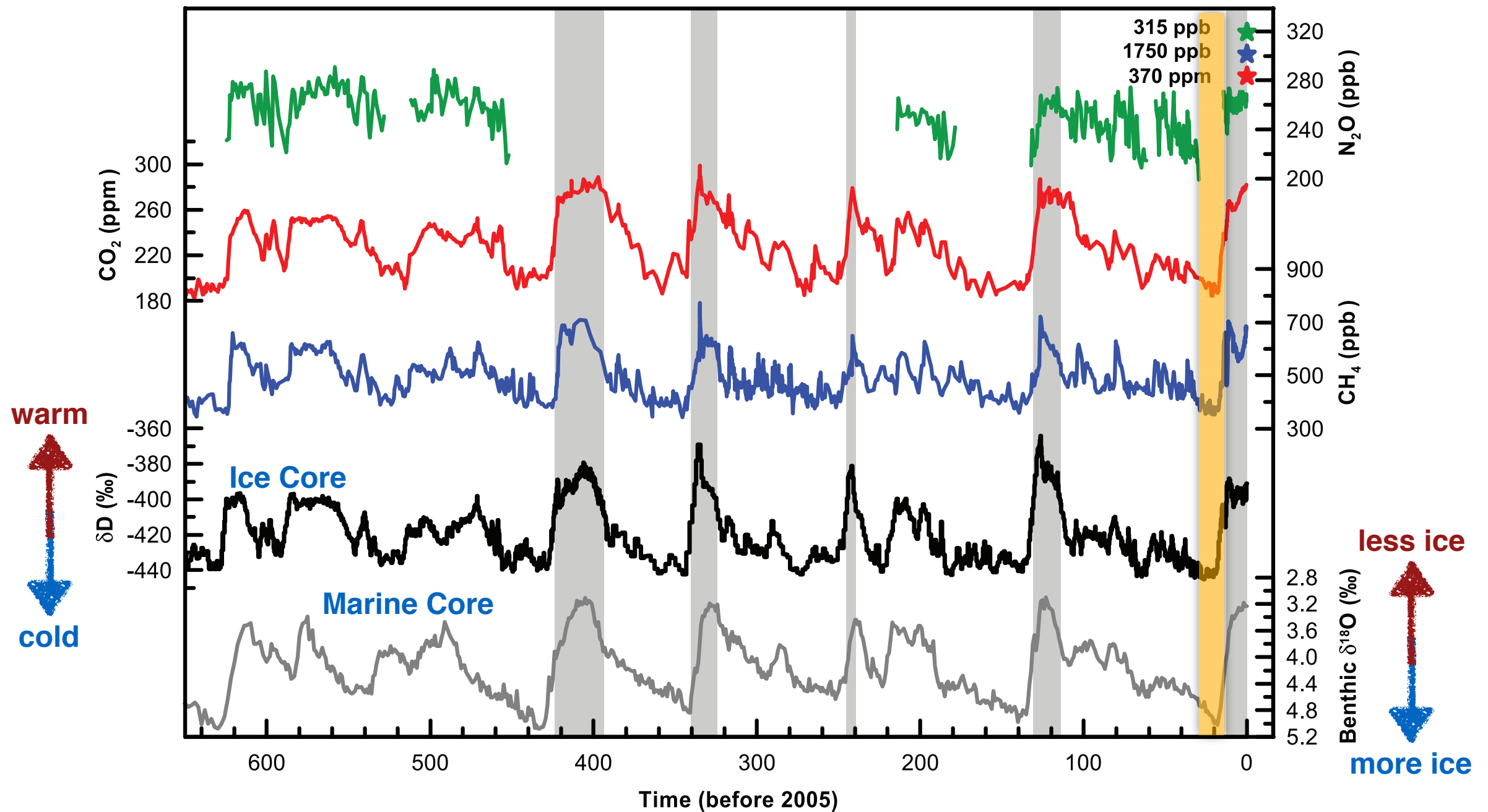
**Glacial Asia was covered by permafrost, tundra and steppe (i.e. reduced area of forest)**

**⇒ climate models indicate that these changes in vegetation were caused by a stronger winter monsoon (enhanced high-pressure cell located over northern Asia)**



[from: Ruddiman, 2008]

# The last glacial maximum (LGM)



**Figure 6.3.** Variations of deuterium ( $\delta\text{D}$ ; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases  $\text{CO}_2$  (red),  $\text{CH}_4$  (blue), and nitrous oxide ( $\text{N}_2\text{O}$ ; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit et al., 1999; Indermühle et al., 2000; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005a,b). The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. The stack of 57 globally distributed benthic  $\delta^{18}\text{O}$  marine records (dark grey), a proxy for global ice volume fluctuations (Lisiecki and Raymo, 2005), is displayed for comparison with the ice core data. Downward trends in the benthic  $\delta^{18}\text{O}$  curve reflect increasing ice volumes on land. Note that the shaded vertical bars are based on the ice core age model (EPICA community members, 2004), and that the marine record is plotted on its original time scale based on tuning to the orbital parameters (Lisiecki and Raymo, 2005). The stars and labels indicate atmospheric concentrations at year 2000.



# Climate II

(Winter 2020/2021)

**5th lecture:**

## **The last glacial maximum (LGM)**

(characteristics, ice core data, SST reconstructions, terrestrial climate)

**End of lecture.**

**Slides available at:**

**[https://paleodyn.uni-bremen.de/study/climate2020\\_21.html](https://paleodyn.uni-bremen.de/study/climate2020_21.html)**