Climate System II

(Winter 2023/2024)

4th lecture:

The last glacial maximum (LGM)

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

Gerrit Lohmann, Martin Werner

Tuesday, 10:15-11:45

https://paleodyn.uni-bremen.de/study/climate2023_24.html

Climate change on orbital time scales

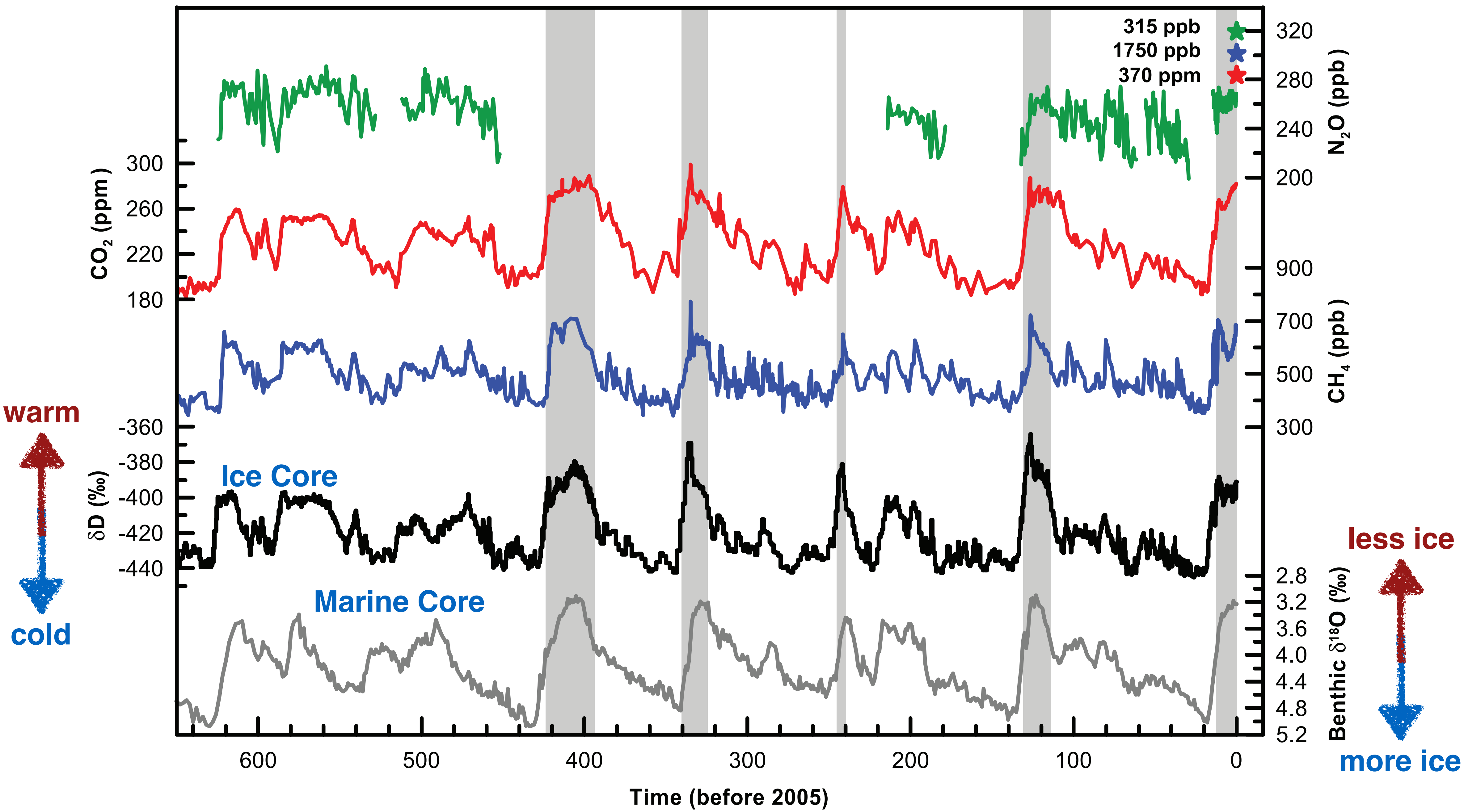


Figure 6.3. *Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH_4 (blue), and nitrous oxide (N_2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements (Petit 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.*

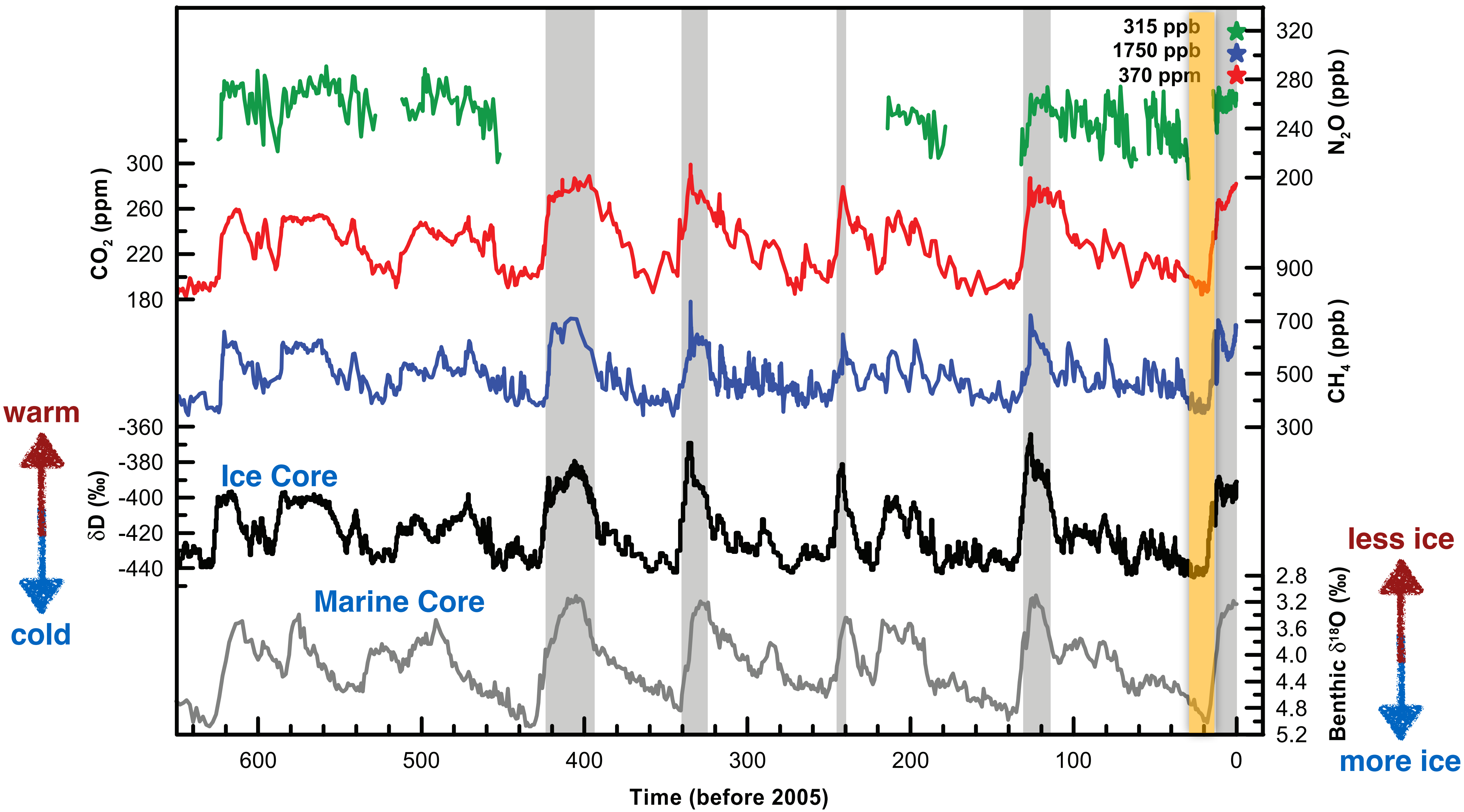
Ice sheet growth and decay on orbital time scales

Supplementary Video V1.

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

[from: Abe-Ouchi et al, Nature, 2013]

The last glacial maximum (LGM)



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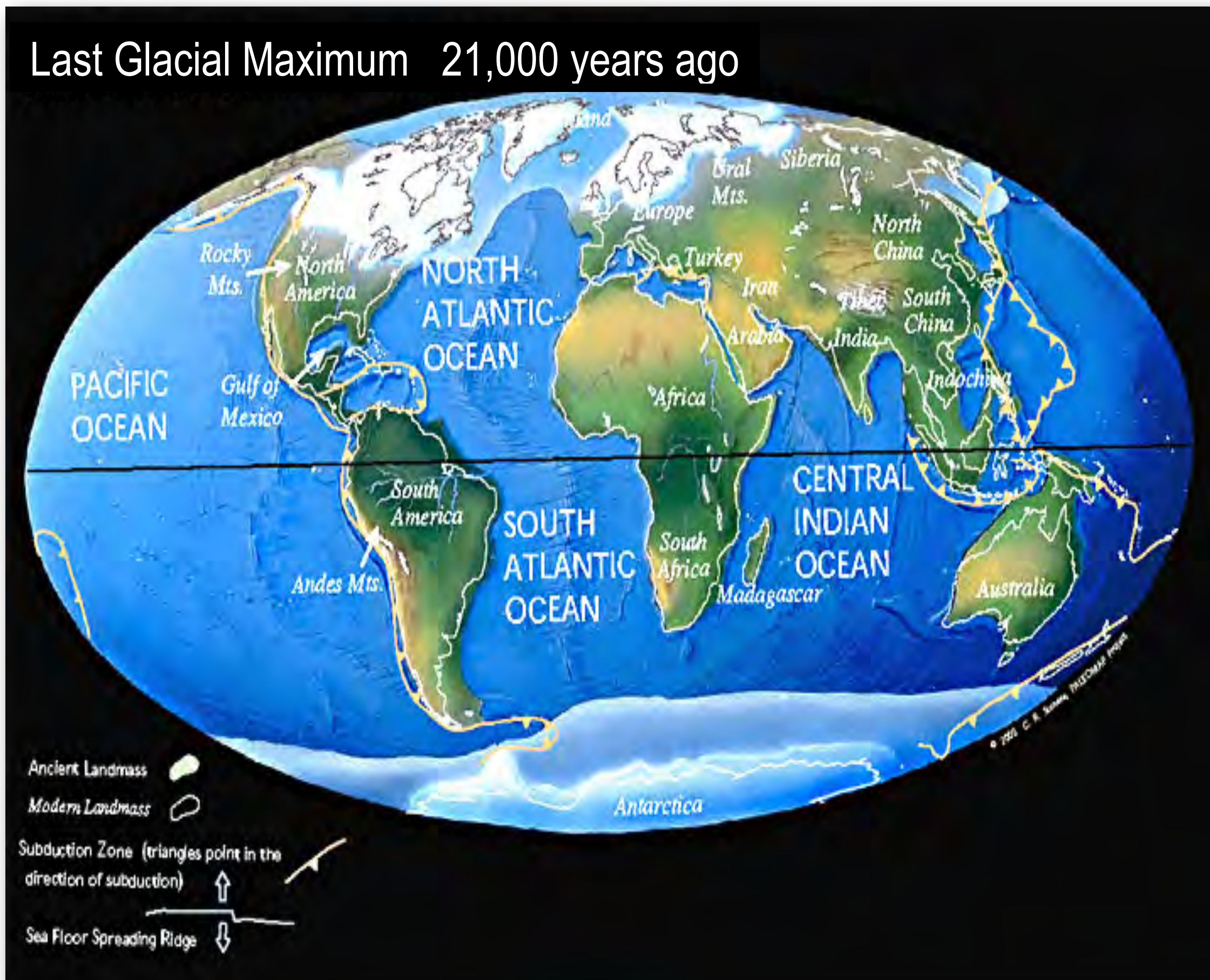
IPCC, 2007

Overview: the last glacial maximum

- approx. 21,000 years before present (end of the last glacial period)
- CO_2 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



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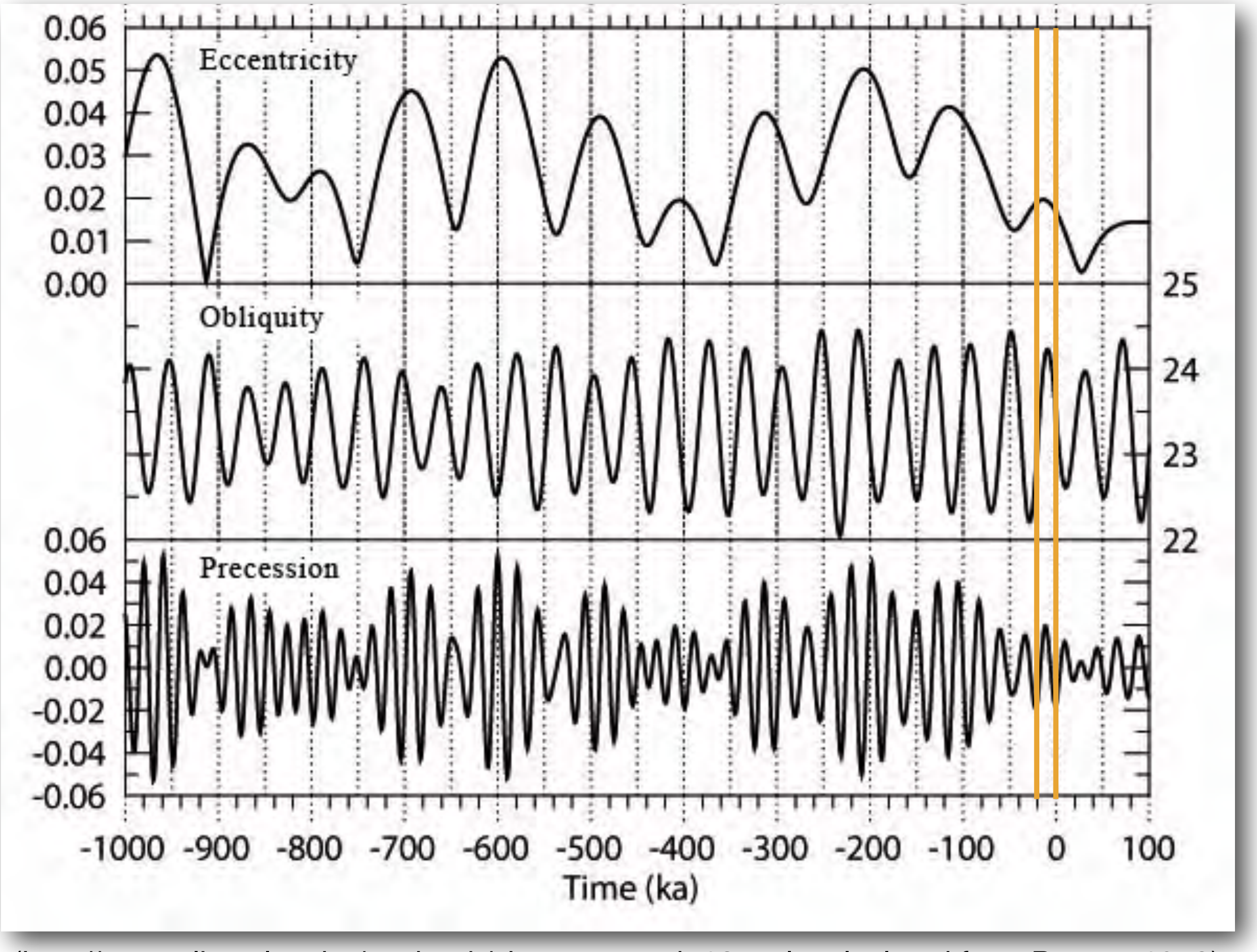
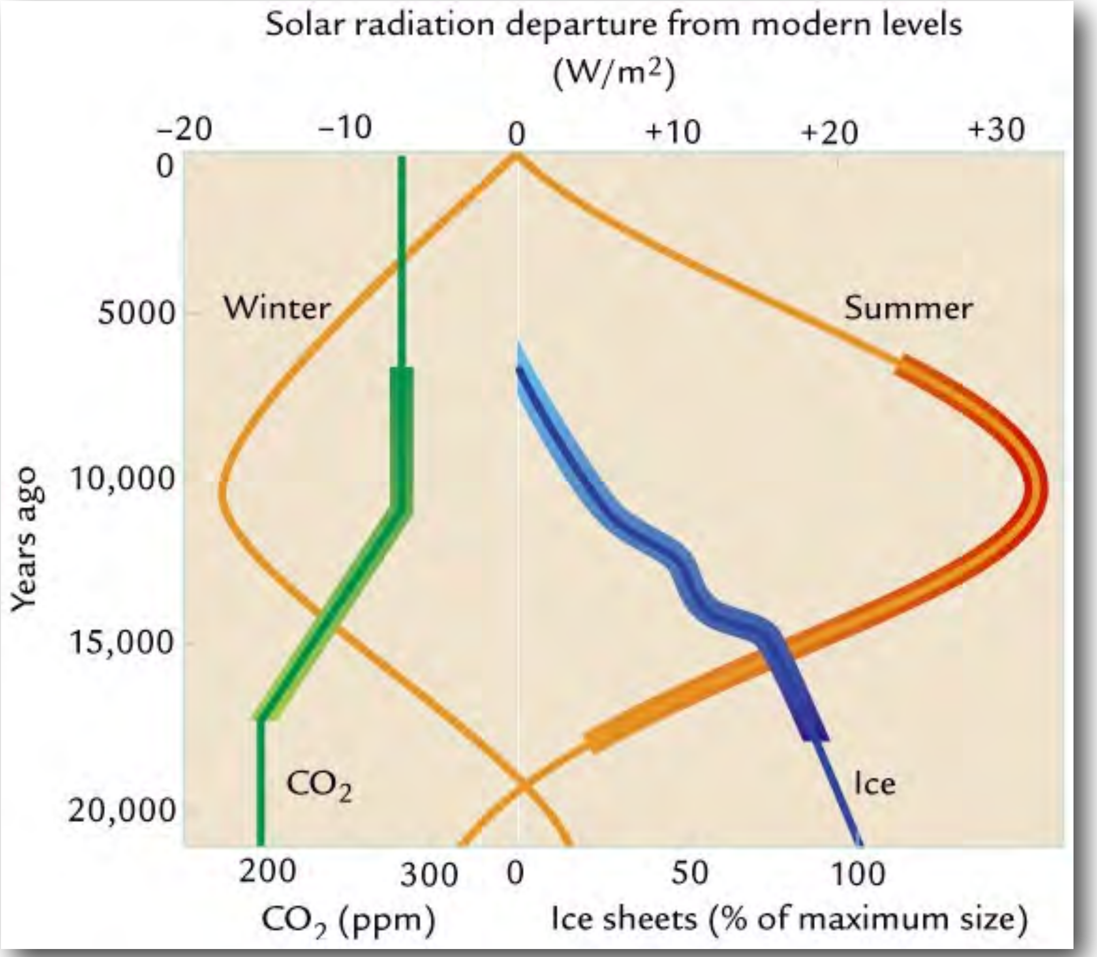


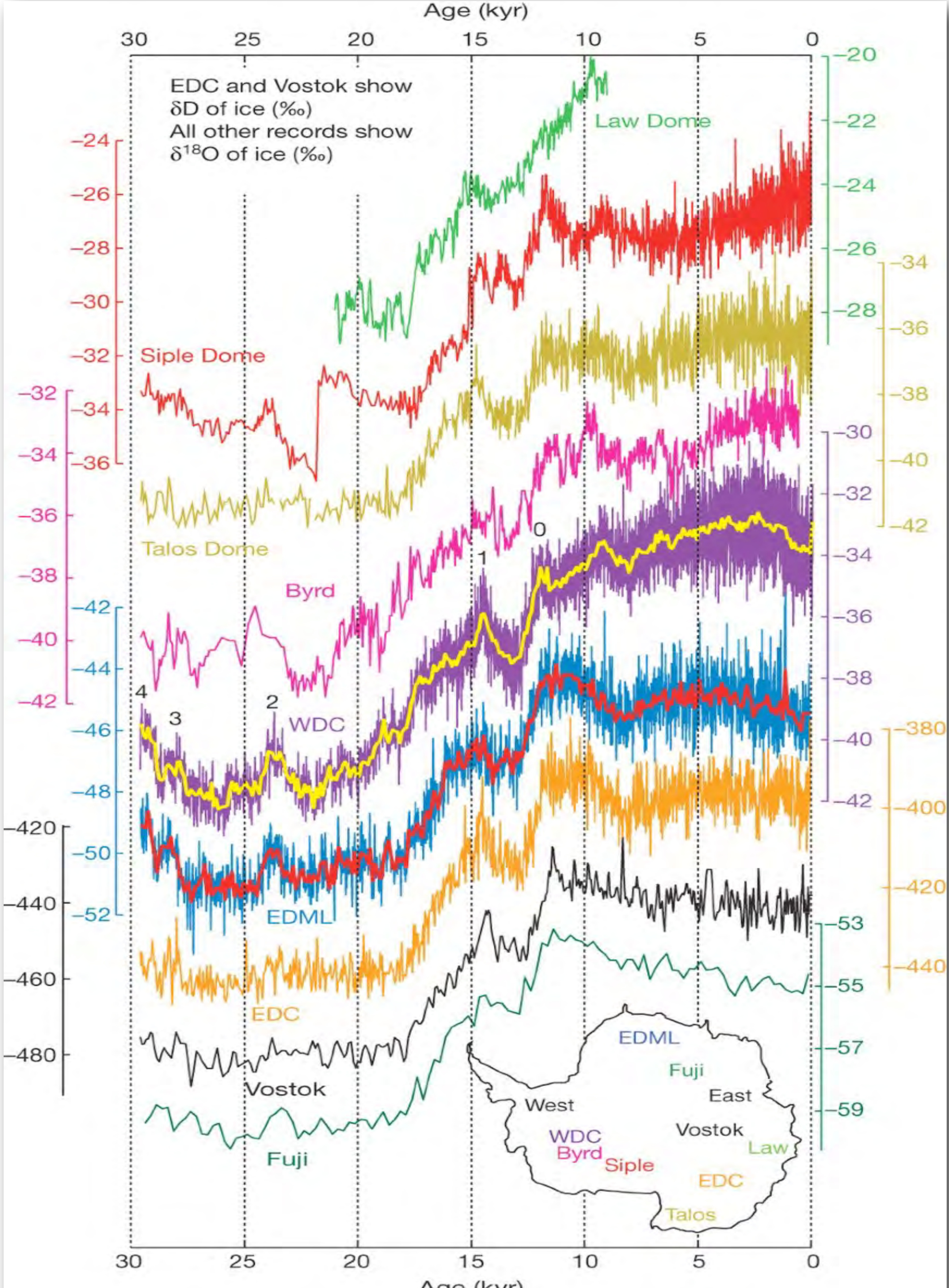
(http://www.elic.ucl.ac.be/textbook/chapter5_node12.xml, calculated from Berger, 1978)



(from Ruddiman, 2008)

Overview: the last glacial maximum

Climate of the LGM - key information from ice cores



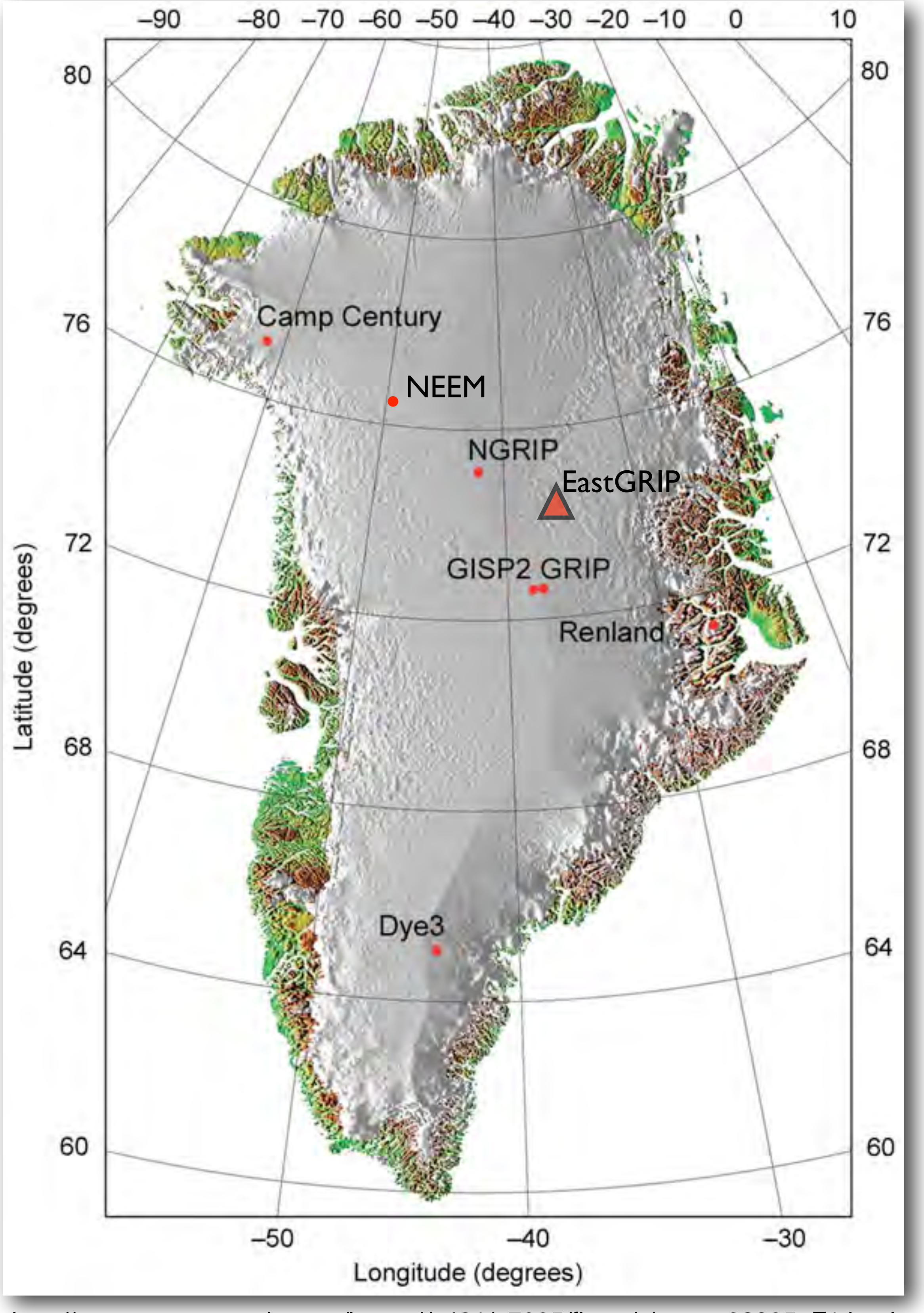
Antarctic ice cores

- at present, 9 deep ice cores from 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*
  - *Antarctica LGM ice sheet height is still unclear*
- warming at the end of the LGM may have started 2,000 years earlier in West Antarctica 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 (ACR: Antarctic Cold Reversal) and a second warming phase into the Holocene

source:
WAIS Divide Project Members, Nature, 2013

Greenland ice cores

- **8 deep Greenland ice cores have been drilled (Camp Century, Dye3, GRIP, GISP2, NGRIP, NEEM, Renland, EastGRIP)**
- **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 indicate 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*



http://www.nature.com/nature/journal/v431/n7005/fig_tab/nature02805_F1.html

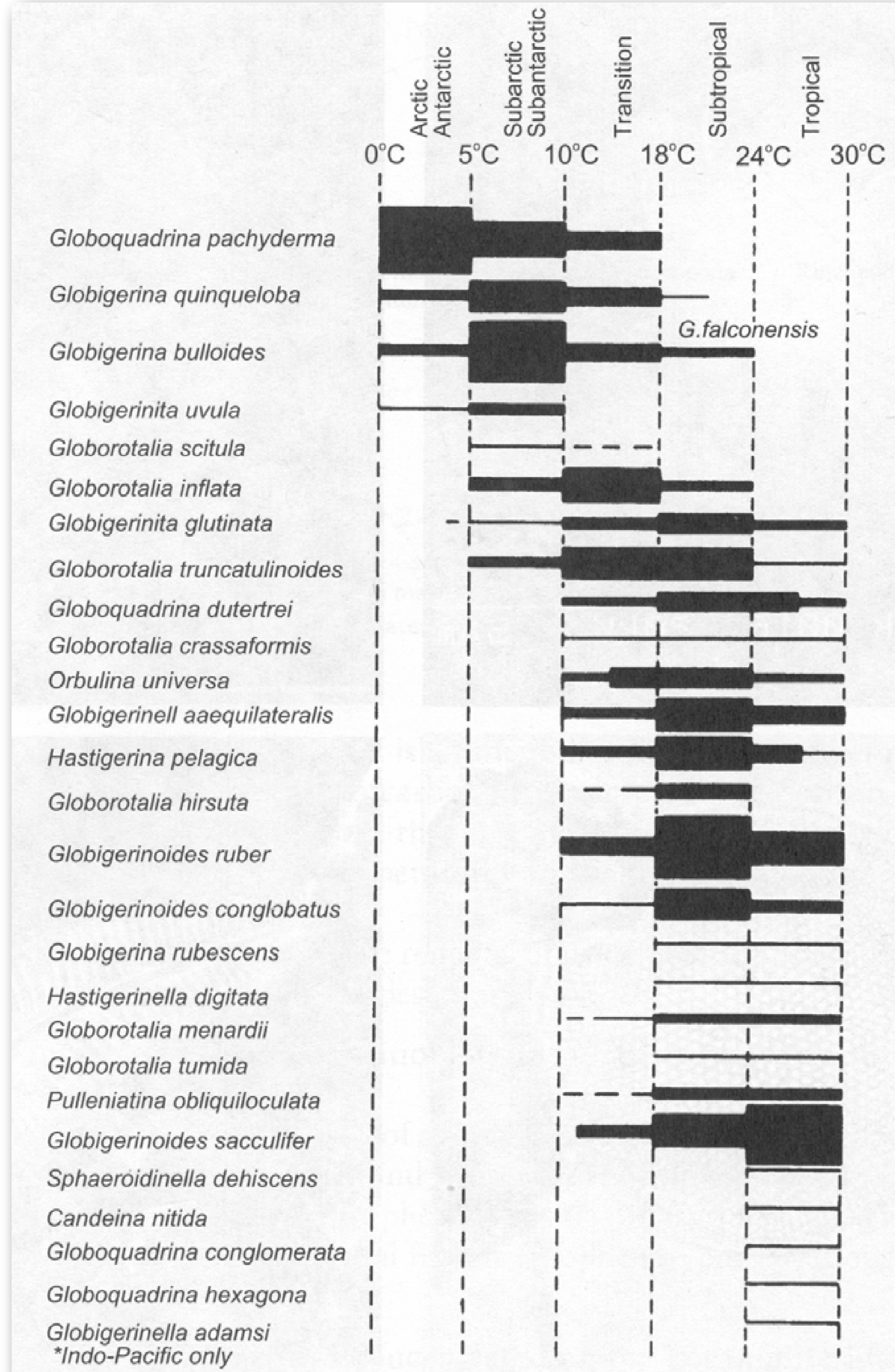
Overview: the last glacial maximum

How cold were the oceans and the tropics?

The CLIMAP projekt

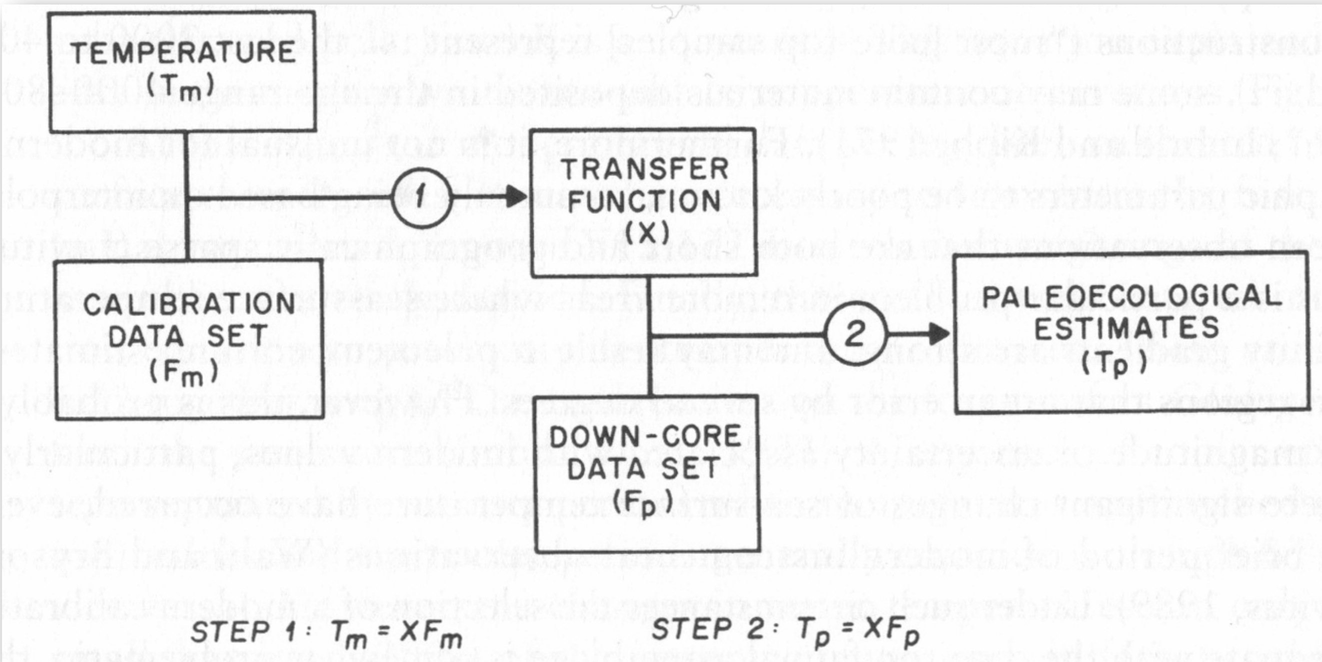
- aim: reconstruction of sea surface temperatures (SST) for August and Februar during the LGM (21,000 B.P.)
- based mainly on Foraminifera data, partly on silicate containing fossils and other temperature estimates

Marine records: temperature range of different foraminifera species



Bradley, Abb. 6.6

Marine records: the modern analogue method (MAT)



Bradley, Abb. 6.18

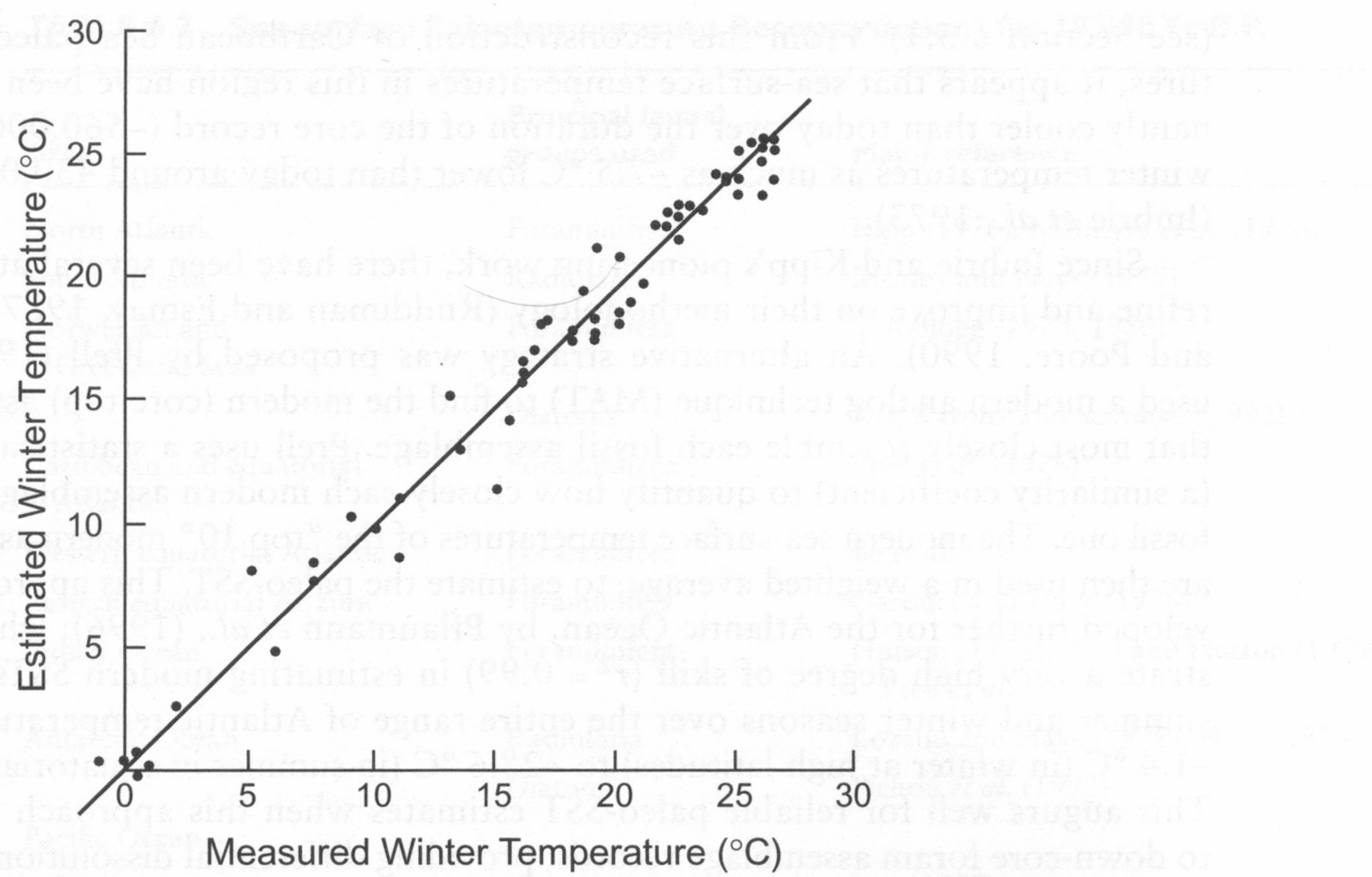
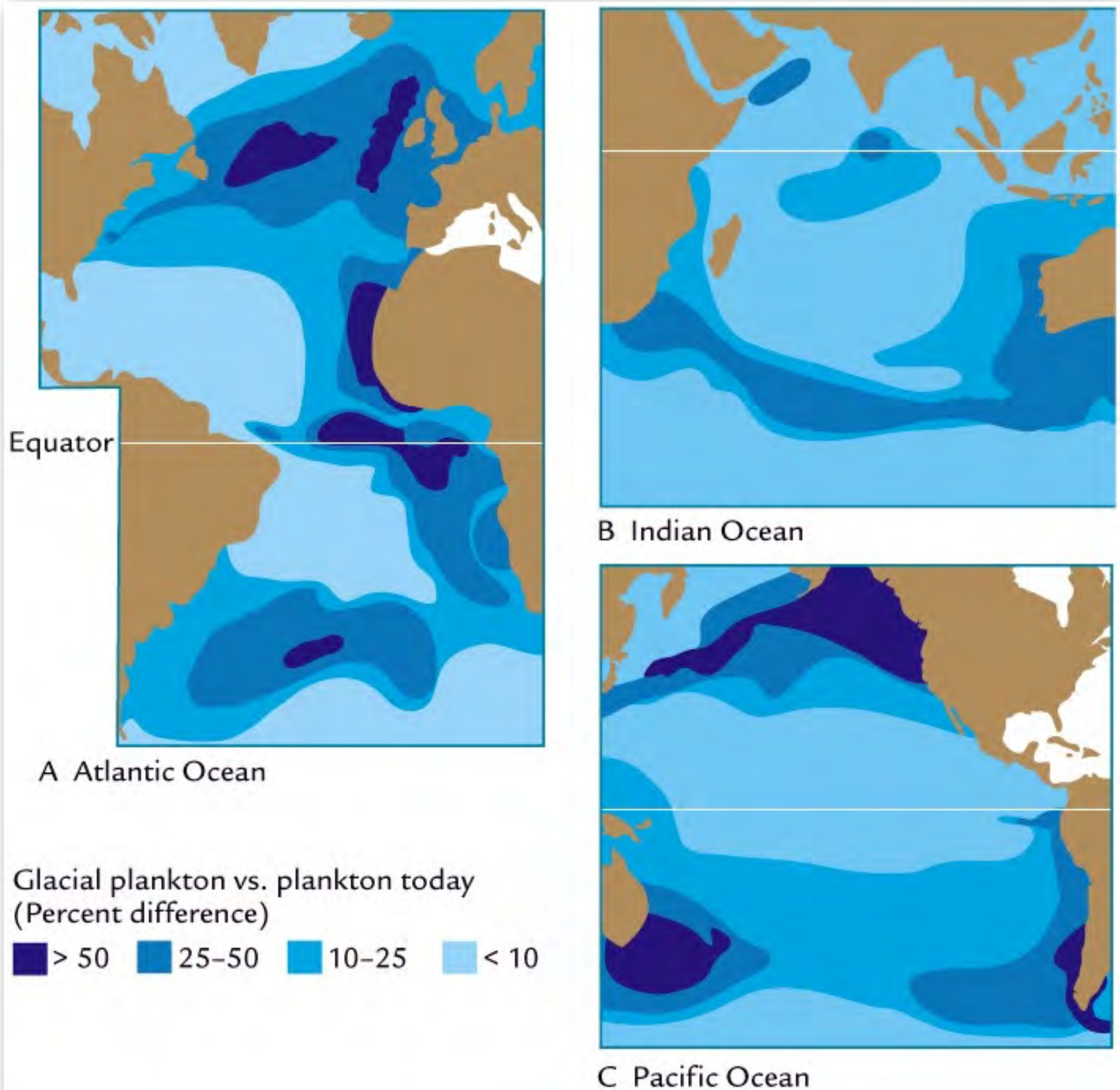


FIGURE 6.21 Winter sea-surface temperature based on modern instrumental observations (including interpolated values) vs those estimated from faunal assemblages in 61 core-top samples using factor analysis and transfer function methods (Imbrie and Kipp, 1971).

Bradley, Abb. 6.21

Marine records

CLIMAP: changes of planktic fauna during the LGM



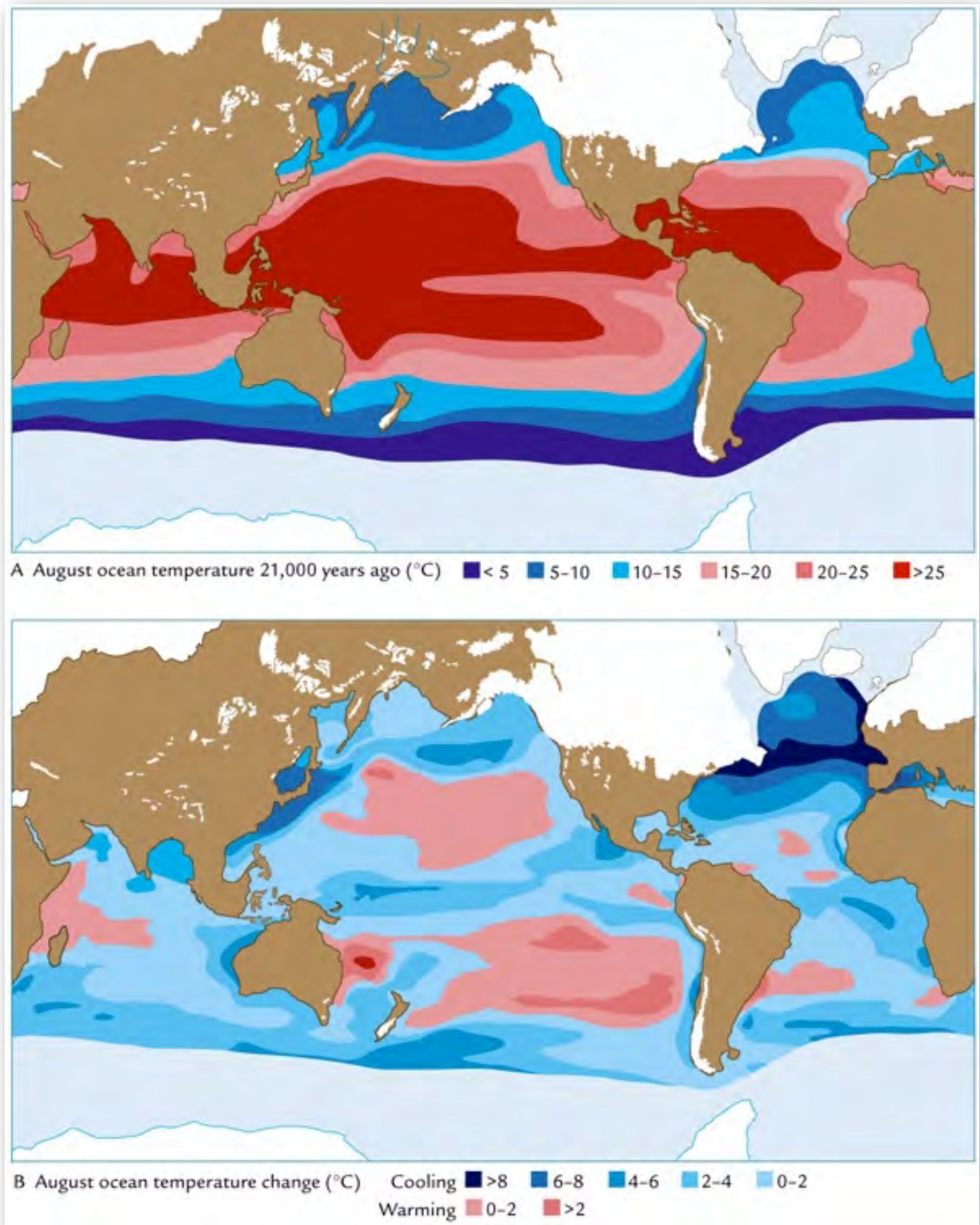
[from: Ruddiman, 2008]

Marine Records:

CLIMAP: Changes of SST during the LGM

LGM SST
(NH summer)

LGM-present
SST change
(NH summer)



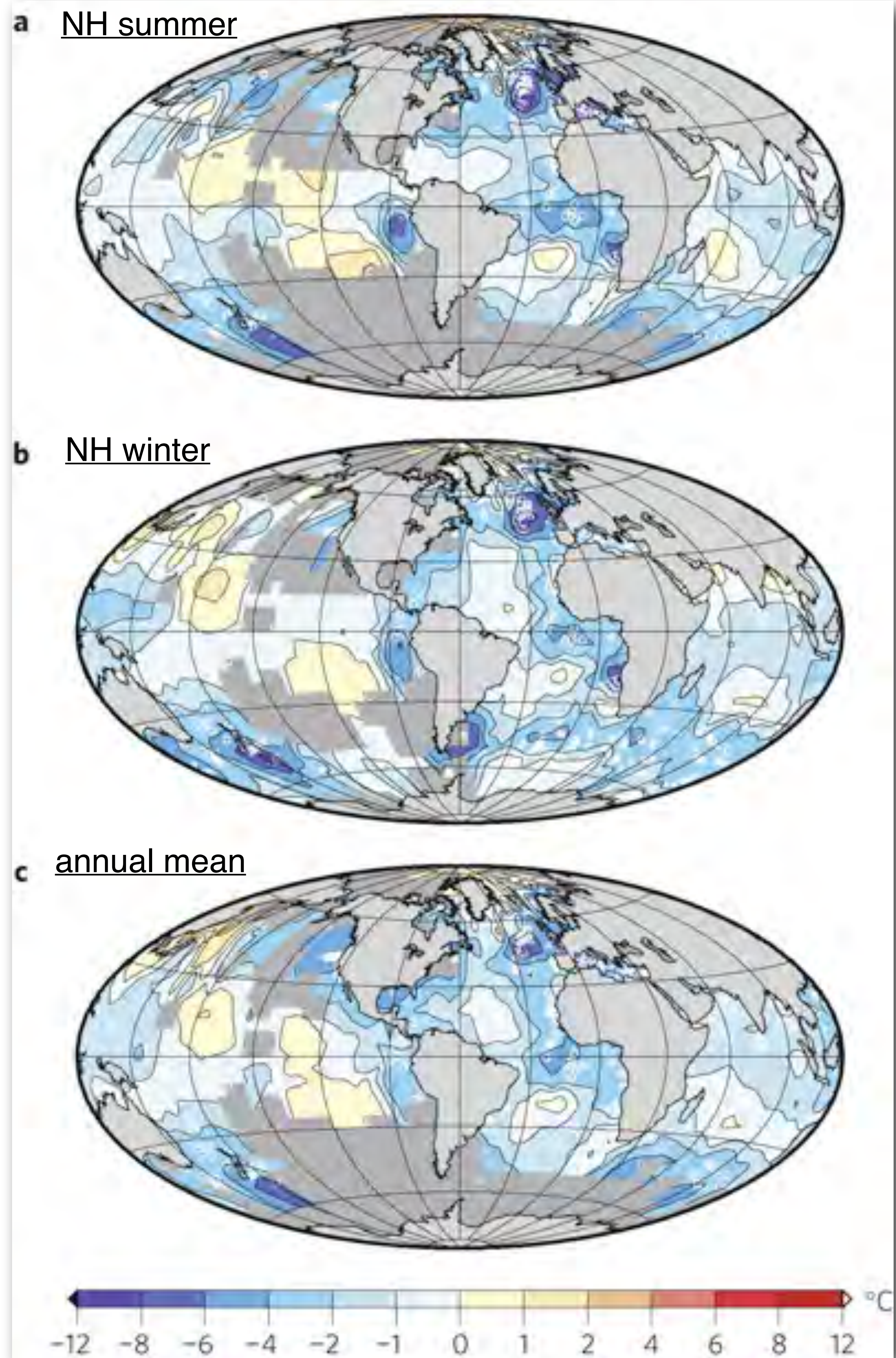
[from: Ruddiman, 2008]

<u>Marine records:</u> The CLIMAP projekt

- **aim: reconstruction of sea surface temperatures (SST) for August and Februar during the LGM (21,000 B.P.)**
- ***<u>controversial</u>*** **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_2 (LGM: 180ppm)***
- **another critical issue:**
  CLIMAP maps are based on interpolation between different data records, ocean dynamics has not been considered properly

Marine records:

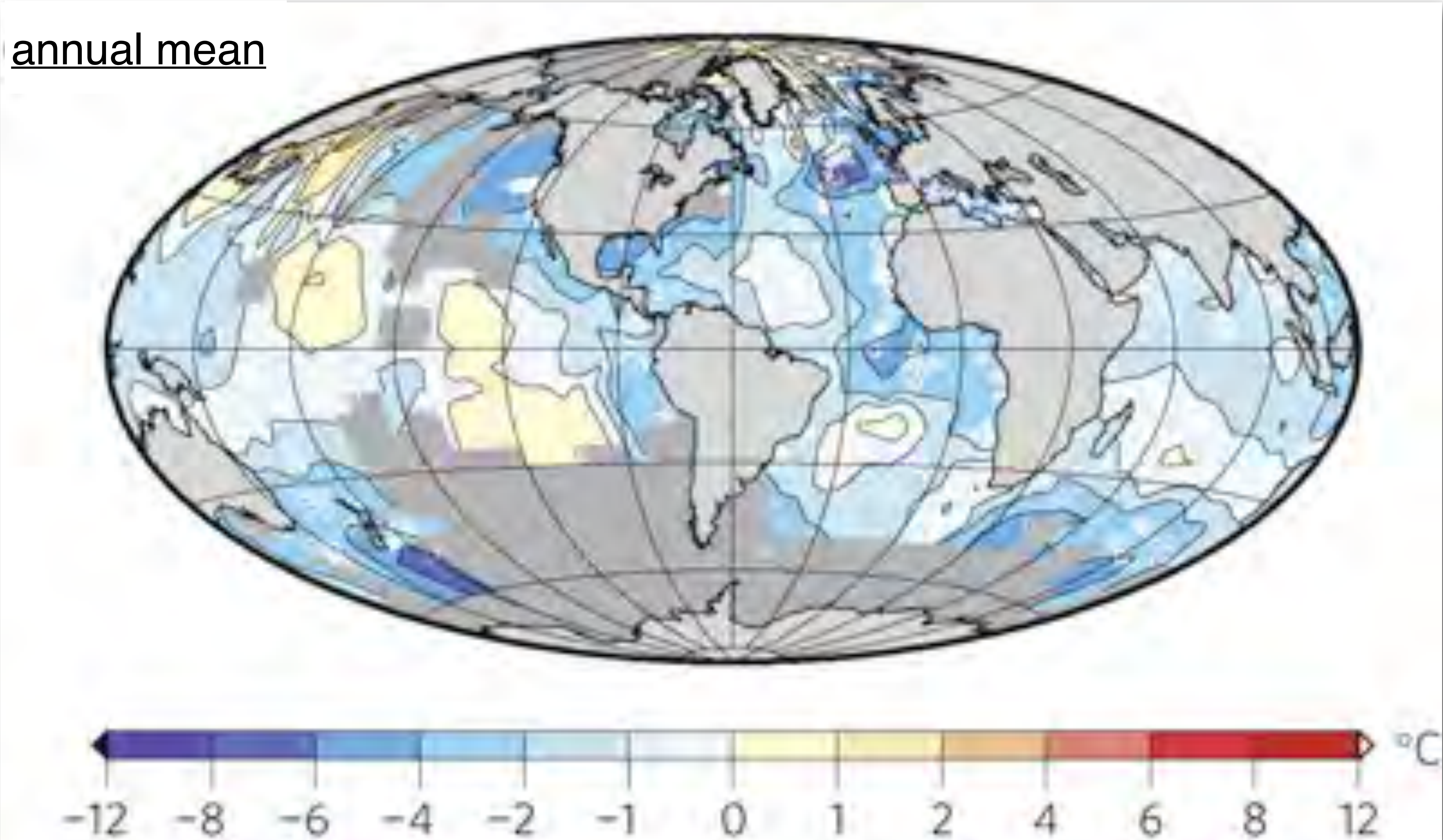
The MARGO project - Multiproxy approach for the reconstruction of the glacial ocean surface



[MARGO Project Members, Nature Geoscience, 2009]

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



[MARGO Project Members, Nature Geoscience, 2009]

Glacial cooling and climate sensitivity revisited

Jessica E. Tierney[1]✉, Jiang Zhu[2,3], Jonathan King[1], Steven B. Malevich[1], Gregory J. Hakim[4] & Christopher J. Poulsen[3]

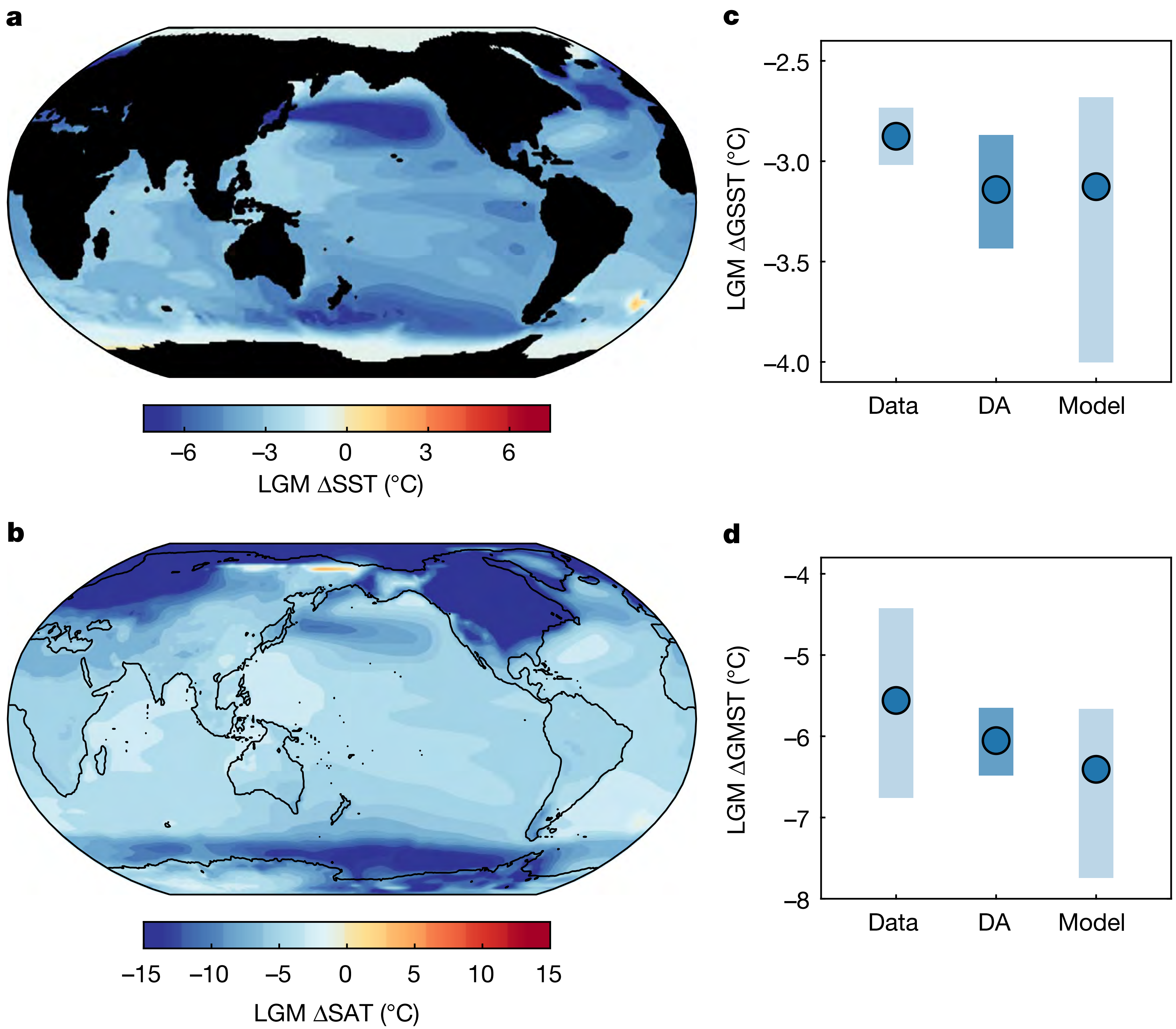
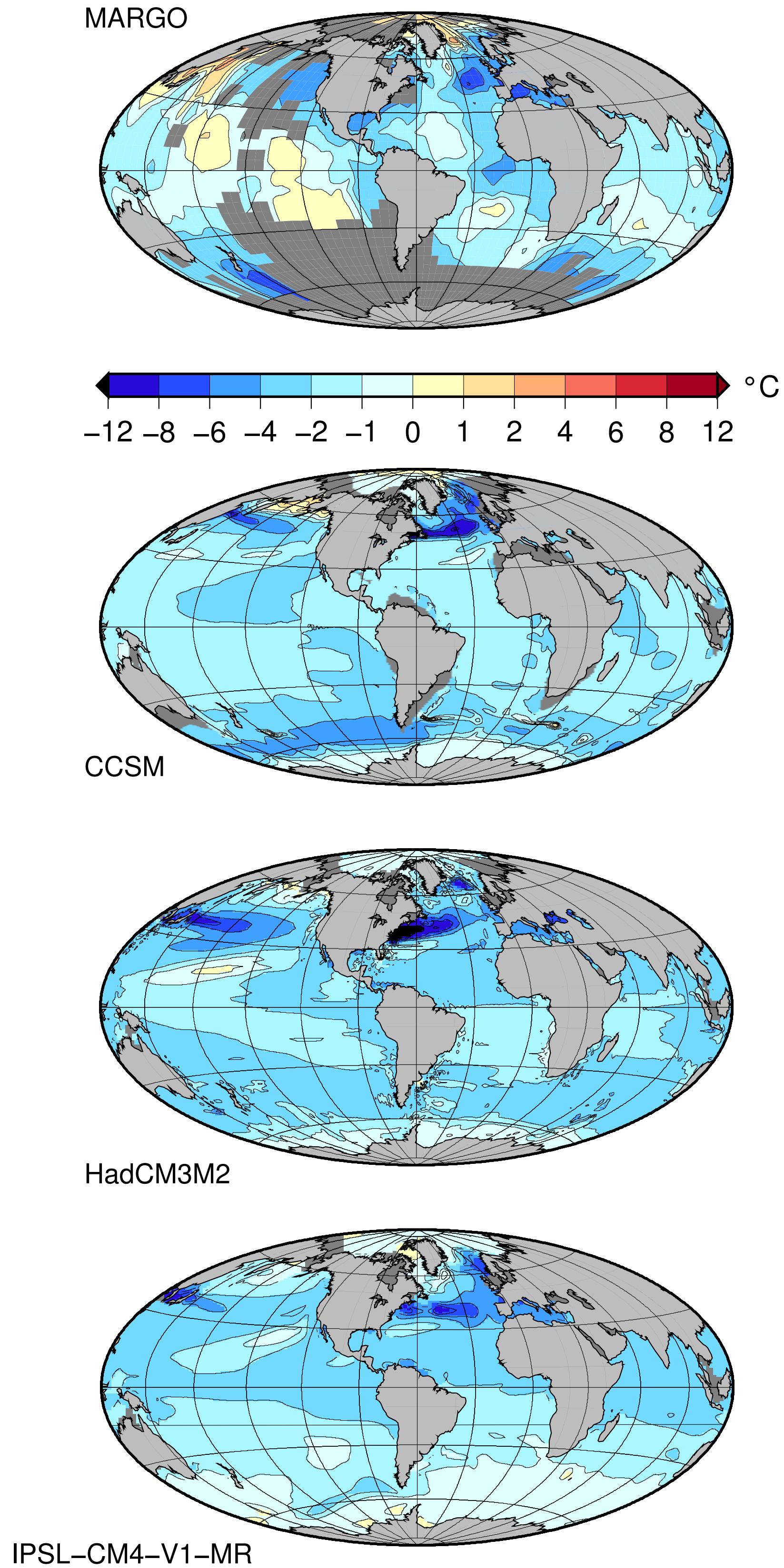


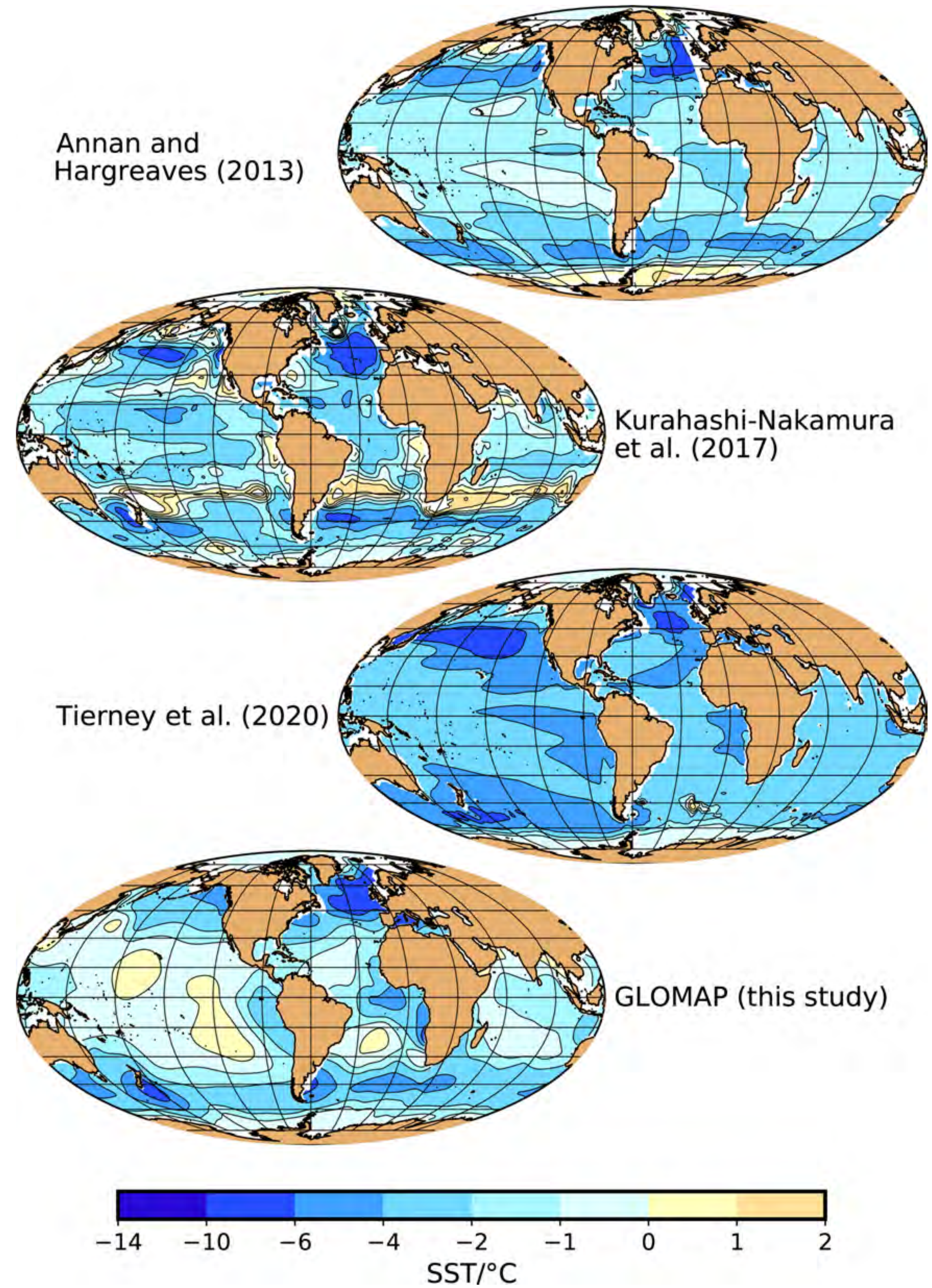
Fig. 2 | Global changes in temperature during the LGM derived from palaeoclimate data assimilation. **a**, LGM–late Holocene ΔSST. **b**, LGM–late Holocene ΔSAT. **c**, LGM ΔGSST. **d**, LGM ΔGMST. In **c** and **d**, dots represent the median values and bars the 95% CI for values derived from the data, the data assimilation (DA) and the model prior (Model).

Glacial SST: Various reconstruction and model results

climate models



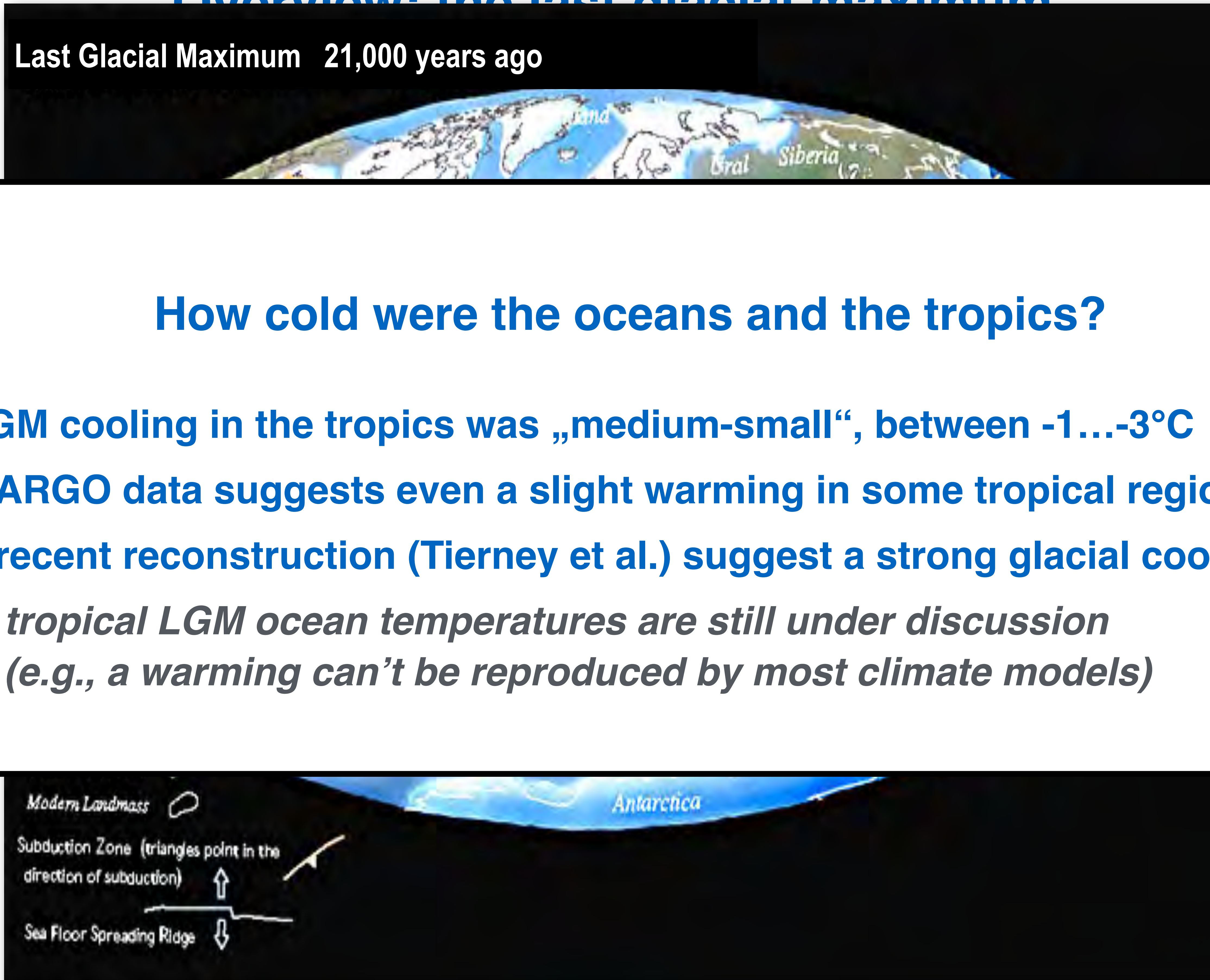
(MARGO Project Members, NatGeo, 2009)



paleodata-based reconstructions

(Paul et al., ClimPast, 2021)

Overview: the last glacial maximum



How cold were the oceans and the tropics?

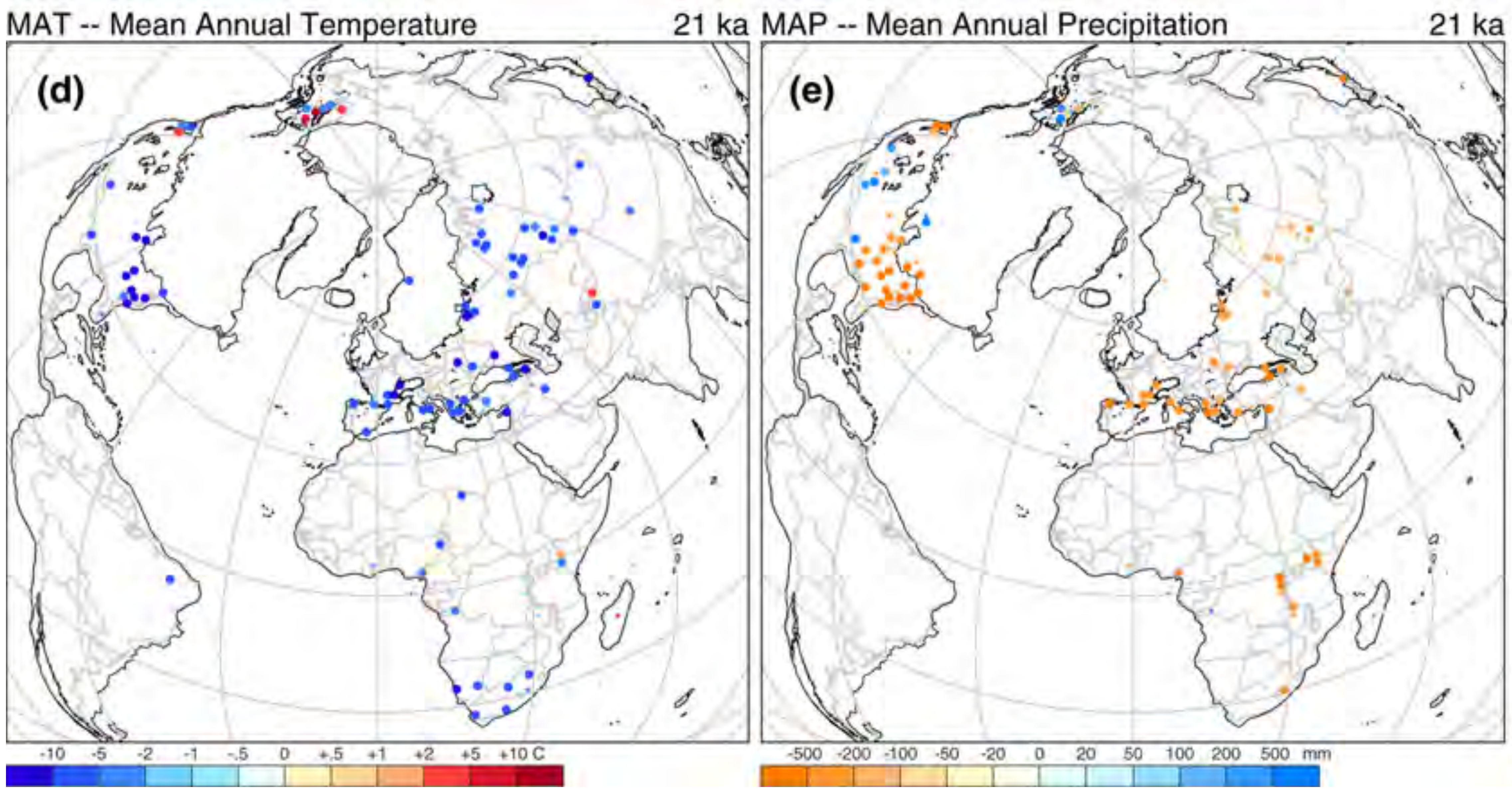
- LGM cooling in the tropics was „medium-small“, between -1…-3°C
- MARGO data suggests even a slight warming in some tropical regions
- a recent reconstruction (Tierney et al.) suggest a strong glacial cooling

tropical LGM ocean temperatures are still under discussion
(e.g., a warming can’t be reproduced by most climate models)

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



Bartlein et al., Climate Dynamics, 2011

LGM temperature changes over land

Article

Widespread six degrees Celsius cooling on land during the Last Glacial Maximum

https://doi.org/10.1038/s41586-021-03467-6
Received: 6 November 2020
Accepted: 17 March 2021
Published online: 12 May 2021

Alan M. Seltzer[1✉], Jessica Ng[2], Werner Aeschbach[3], Rolf Kipfer[4,5,6], Justin T. Kulongoski[2], Jeffrey P. Severinghaus[2] & Martin Stute[7,8]

Nature | Vol 593 | 13 May 2021

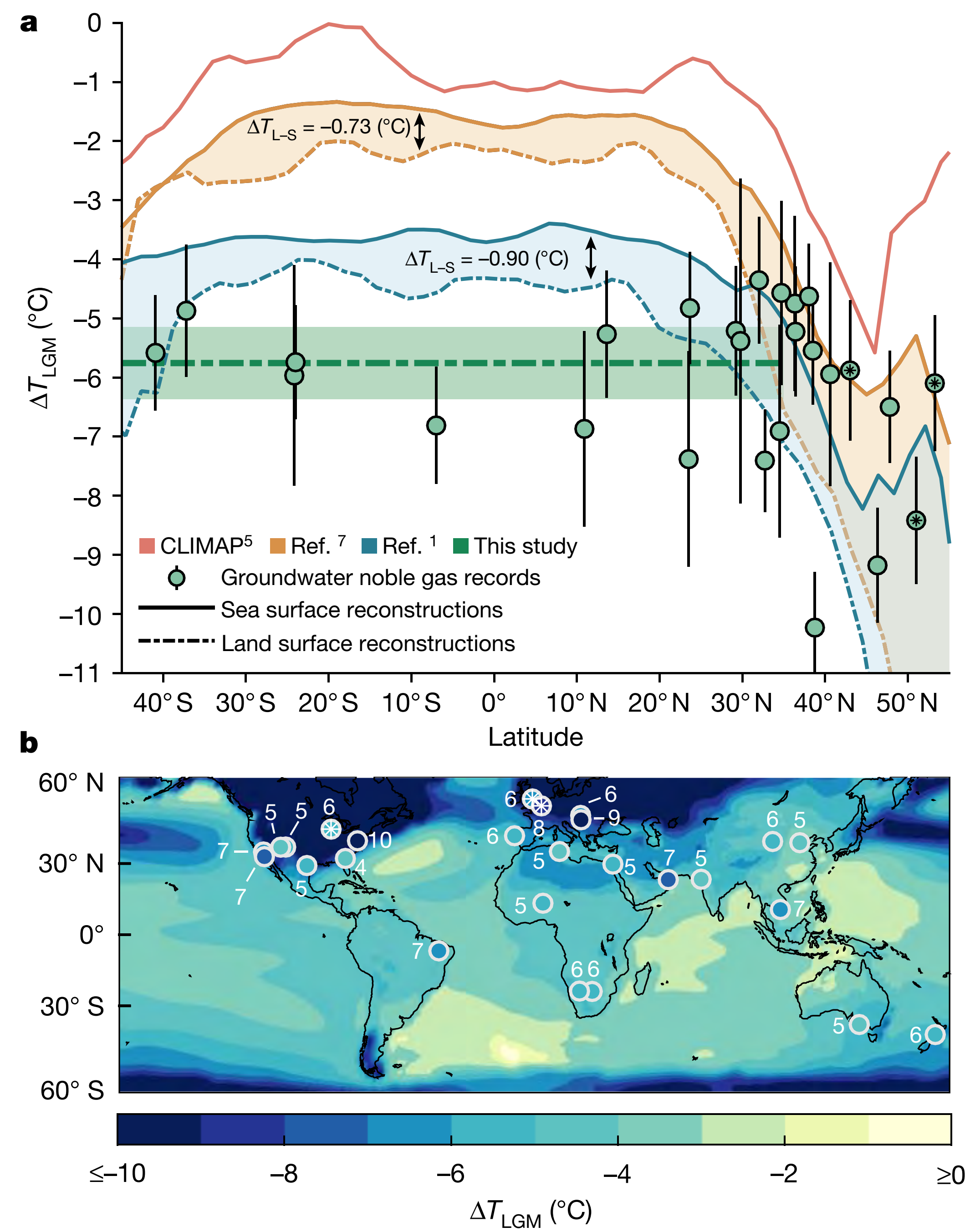
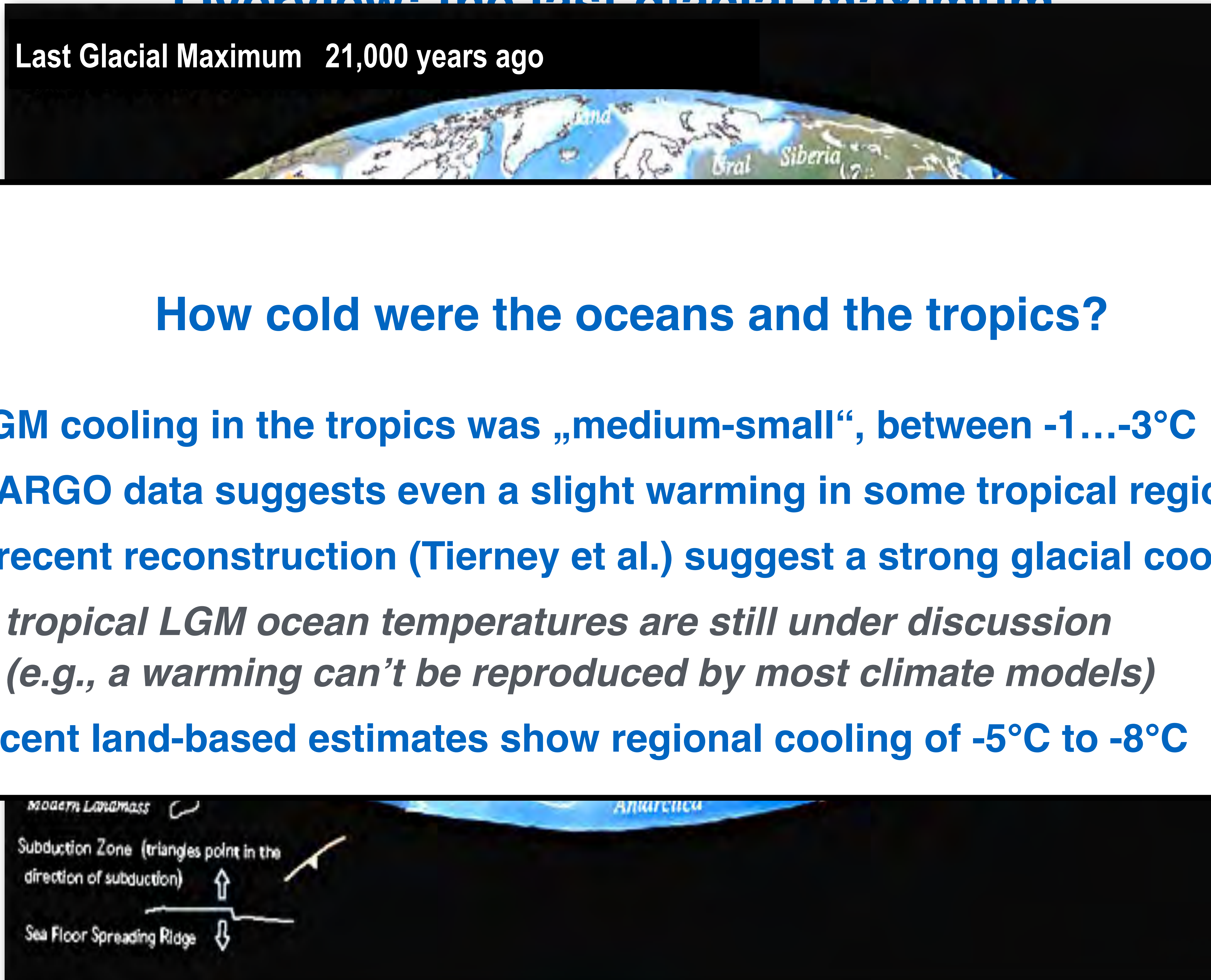


Fig. 3 | Noble gases suggest around 6 °C of low-elevation, low-latitude LGM cooling on land. a, Comparison by latitude of noble-gas-derived ΔT_{LGM} (this study, approach AP1) to zonal-mean land-surface (solid lines) and sea-surface (dashed lines) estimates of ΔT_{LGM} from key previous studies[1,5,7]. Data are mean ± 1 s.e.m. Our land-based mean of −5.8 ± 0.6 °C between 45° S and 35° N (thick green dashed line, with 95% confidence error envelope) partially overlaps the previously suggested range of cooling[1] (error of around ±0.3 °C), but it is incompatible with previous influential LGM temperature reconstructions[6,7,13] that have suggested less low-latitude cooling during the LGM and lower climate sensitivity. **b**, Map showing individual noble-gas-derived ΔT_{LGM} values (annotated points) superimposed on the data assimilation results of ref. [1] (plotted using the MATLAB Mapping Toolbox). Asterisks indicate sites with LGM recharge gaps.

Seltzer et al., Nature, 2021

Overview: the last glacial maximum



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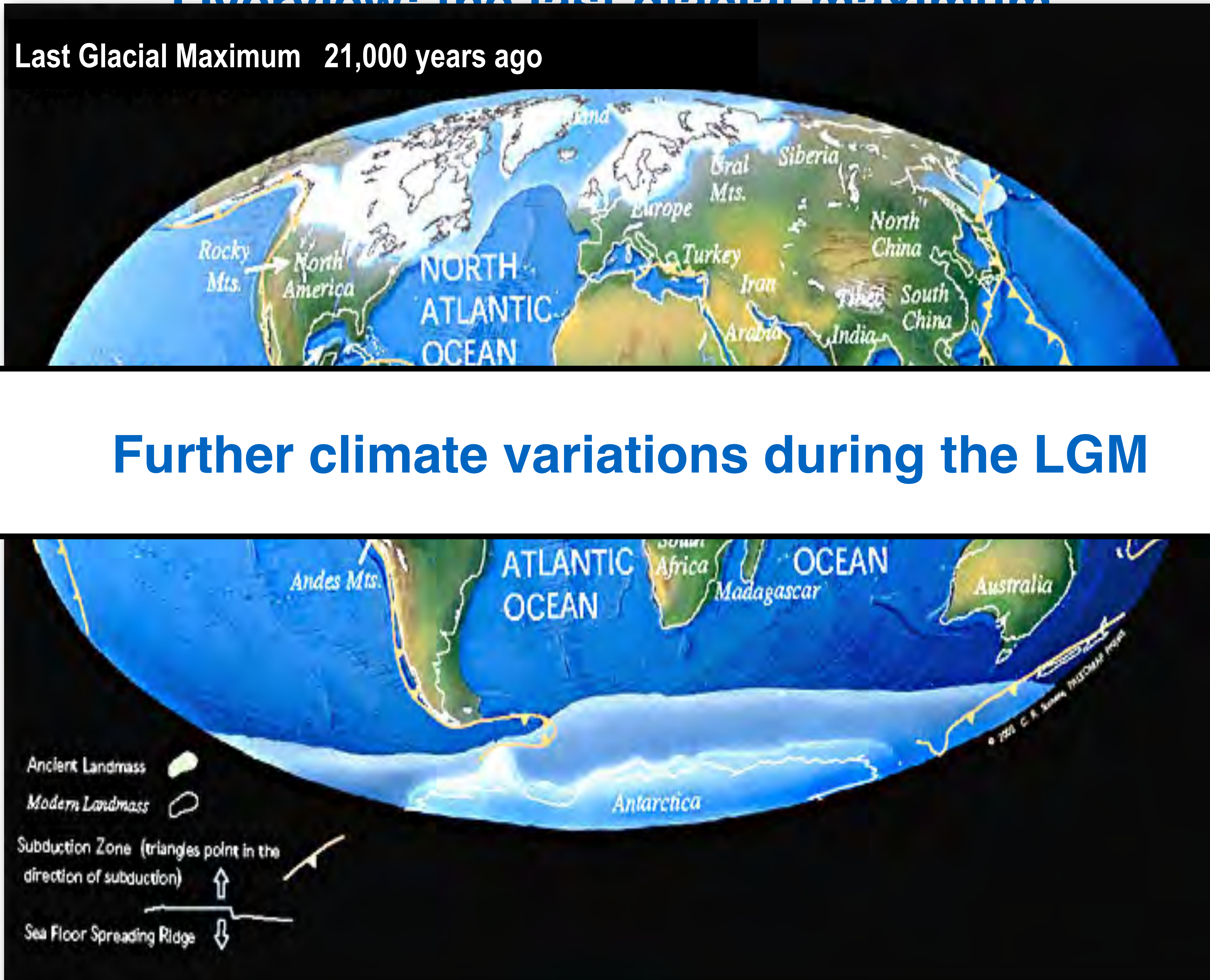
- a recent reconstruction (Tierney et al.) suggest a strong glacial cooling

  tropical LGM ocean temperatures are still under discussion
  (e.g., a warming can’t be reproduced by most climate models)

- recent land-based estimates show regional cooling of -5°C to -8°C

Overview: the last glacial maximum



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

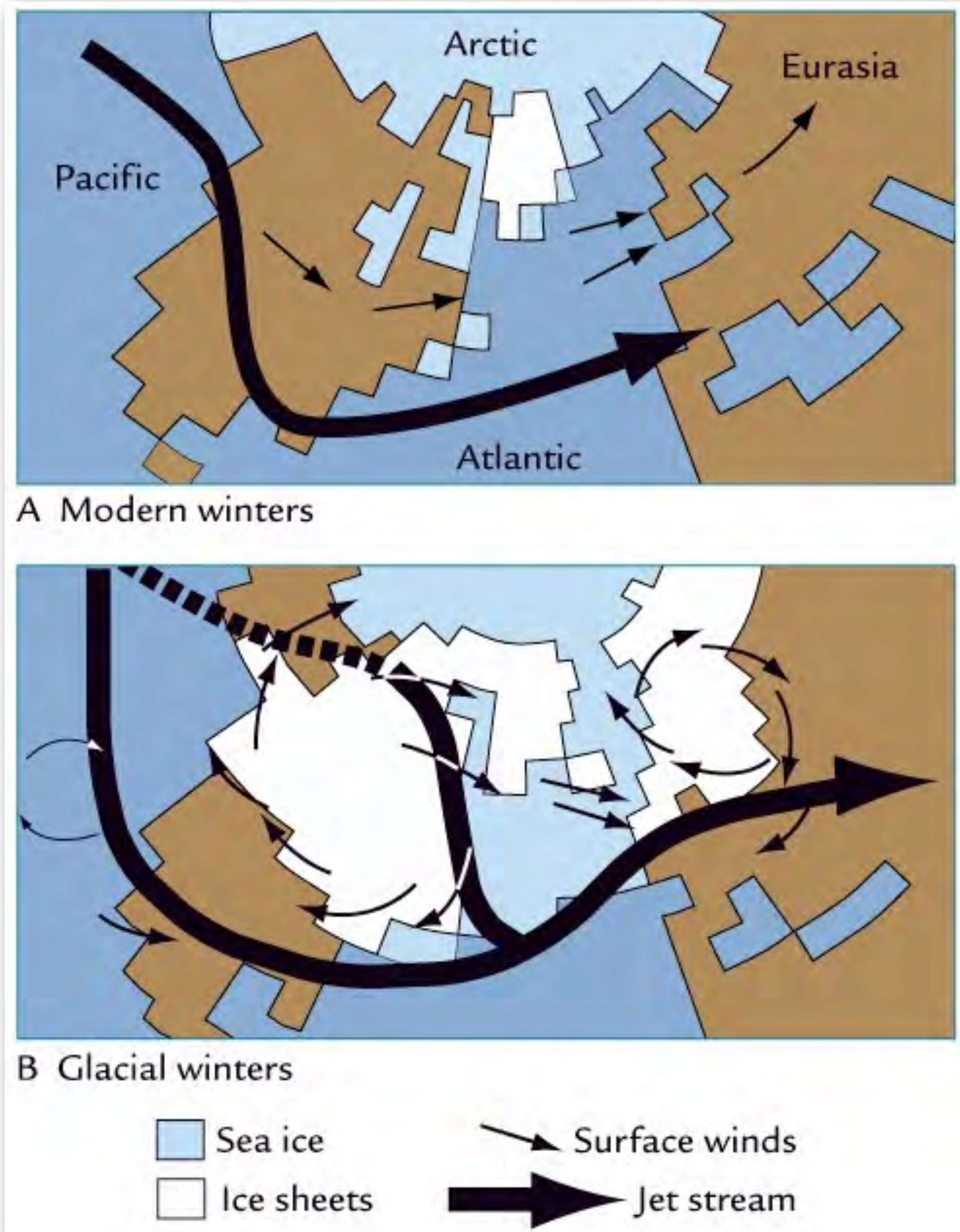
Ice sheet	Location	Excess ice volume (million km³)	TSH:Sea level Amount (m)	TSH:Sea level Change (m)[a]
Laurentide	East-central Canada	25–34[b]	72–100	50–70
Cordilleran	Western North America	1.8	5	3.5
Greenland	Greenland	2.6[c]	7	5
Britain	England, Scotland, Ireland	0.8	2	1.5
Scandinavian	Northern Europe	7.3	21	15
Barents/Kara	Shelf north of Eurasia	6.9	20	14
East Antarctic	Eastern Antarctica	13.3[d]	9	6
West Antarctic	Western Antarctica	16.5[d]	18	13
Others	Various	1.2	3	2
All ice sheets		55–64	155–183	109–129

[a] *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.*
[b] *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.*
[c] *Present volume of ice on Greenland is 3 million km³.*
[d] *Present volume of ice on Antarctica is 29 million km³.*

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

[from: Ruddiman, 2008]

LGM climate of North America and Europe



[from: Ruddiman, 2008]

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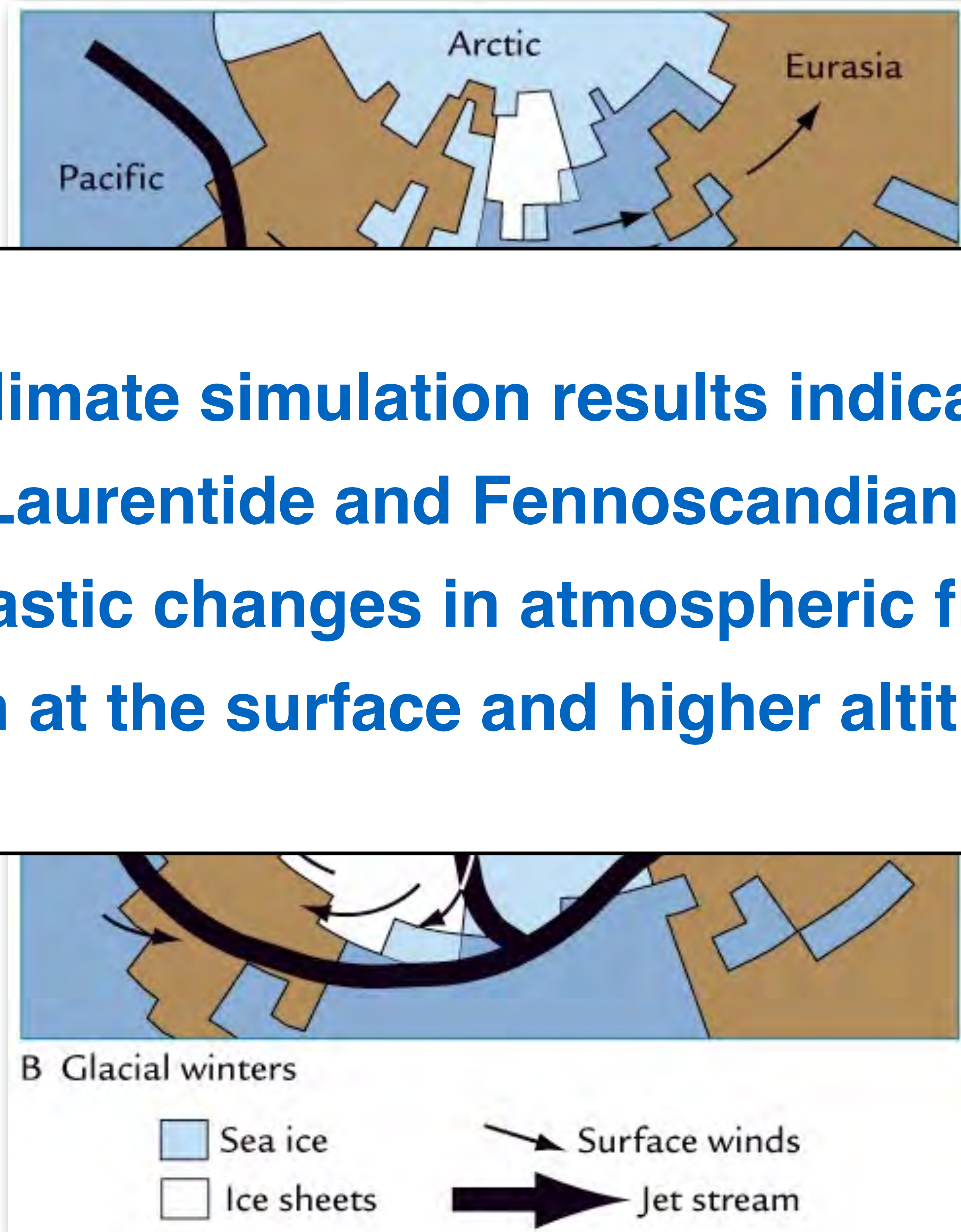
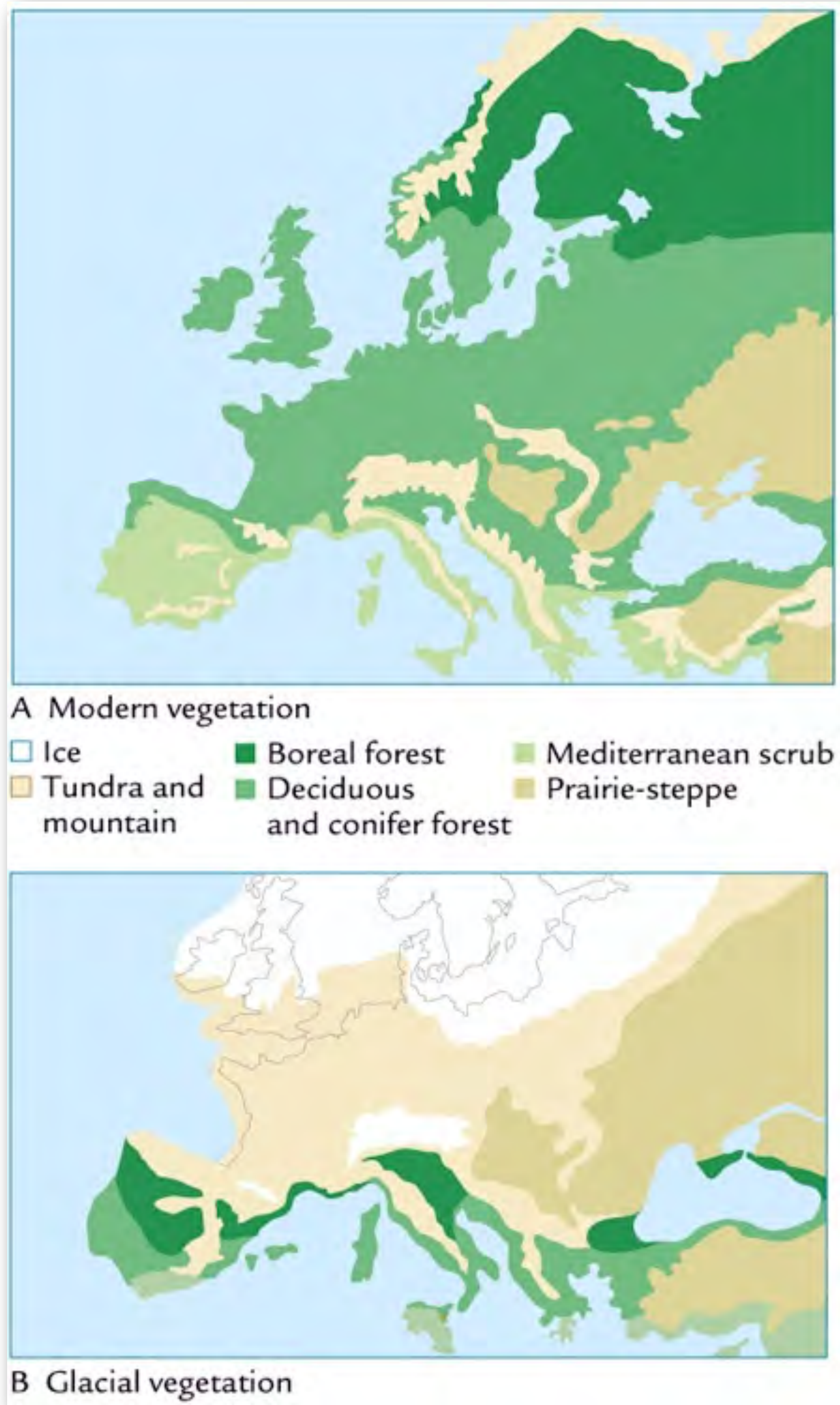


[from: Ruddiman, 2008]

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)

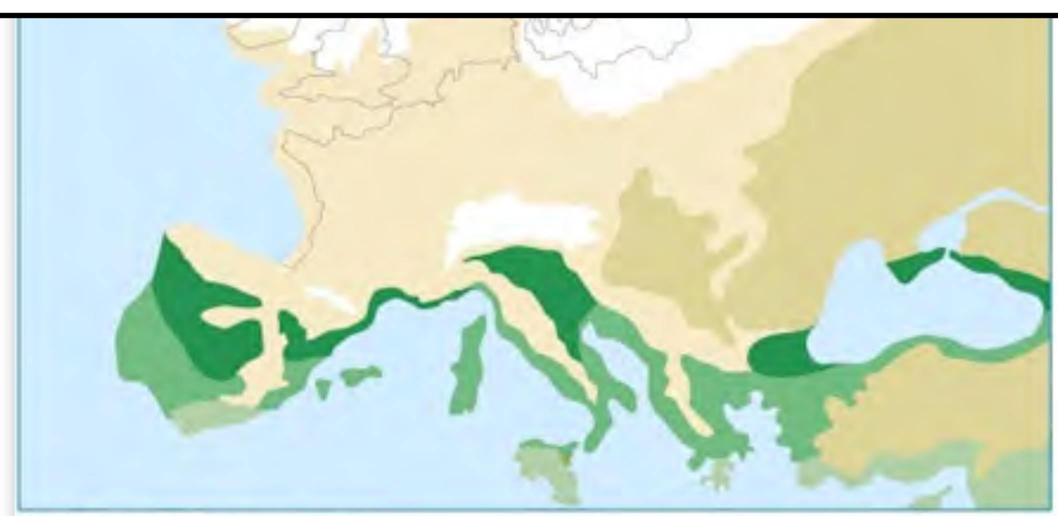
LGM climate of North America and Europe



[from: Ruddiman, 2008]

LGM climate of North America and Europe

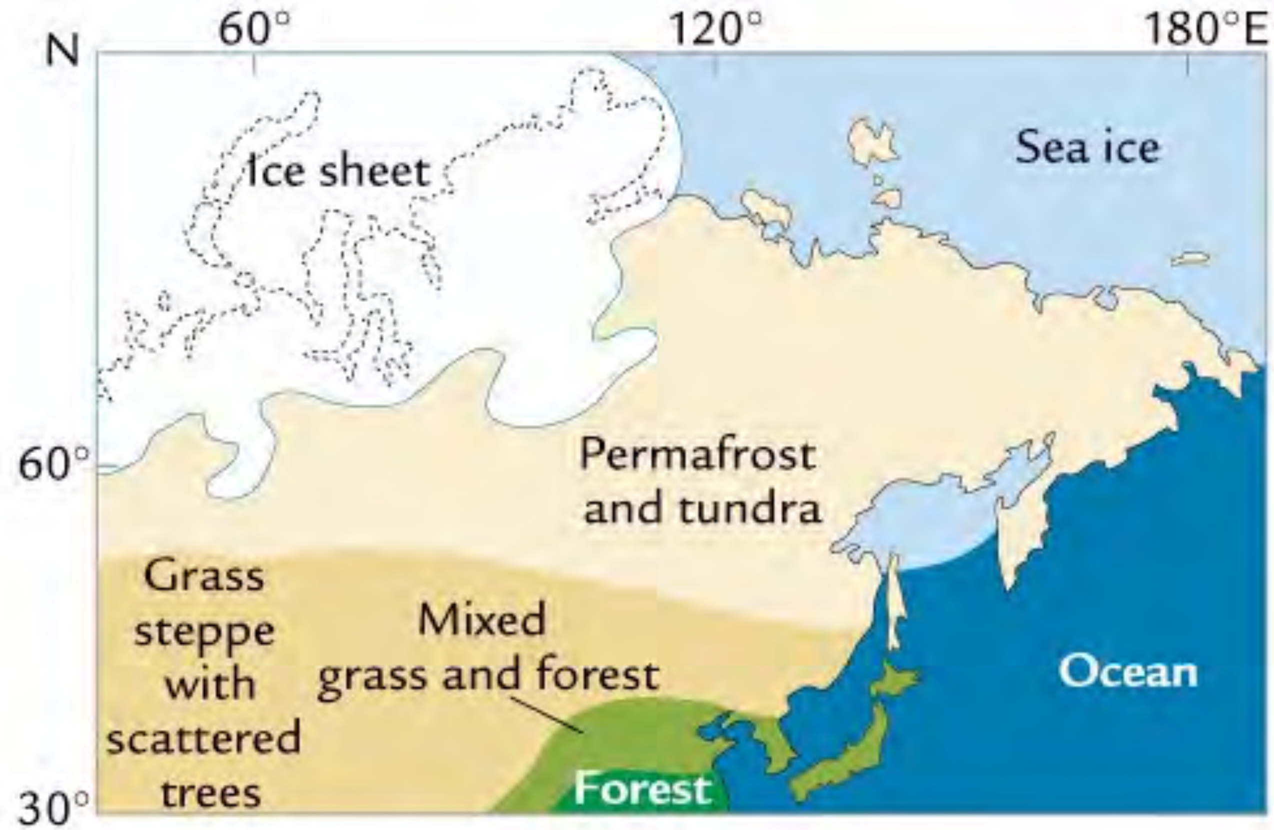
- vegetation in present-day Europe is dominated by forest
- during the LGM large parts of Europe were covered by tundra and steppe



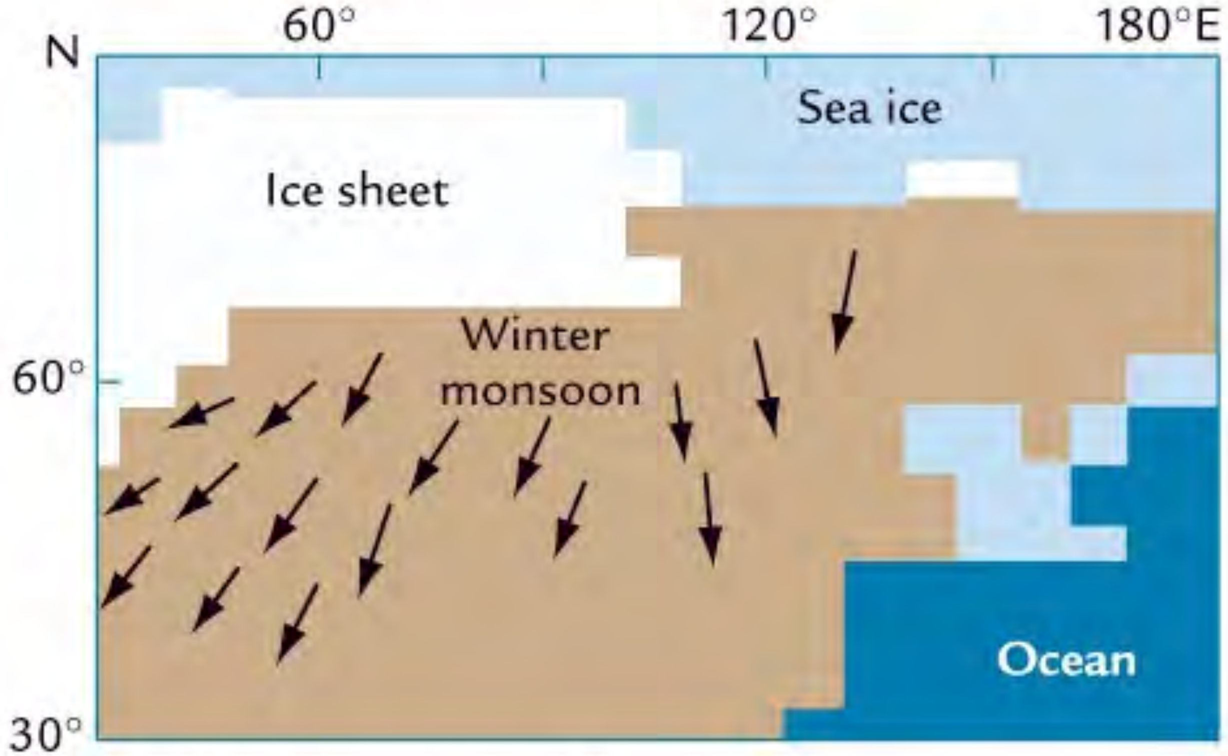
B Glacial vegetation

[from: Ruddiman, 2008]

LGM climate of Asia



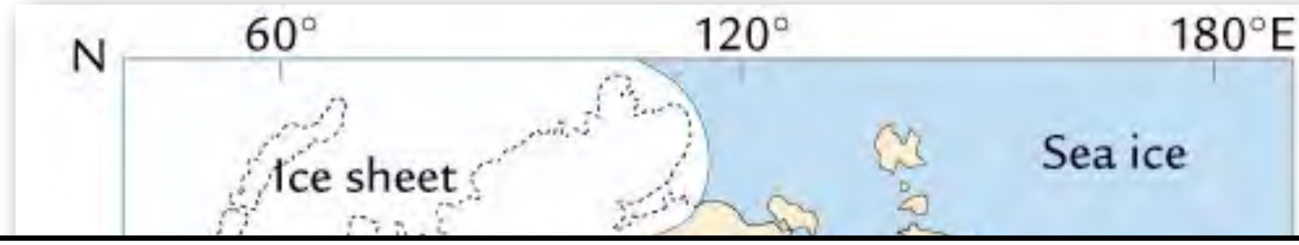
A Glacial maximum (observed)



B Glacial maximum (model)

[from: Ruddiman, 2008]

LGM climate of Asia



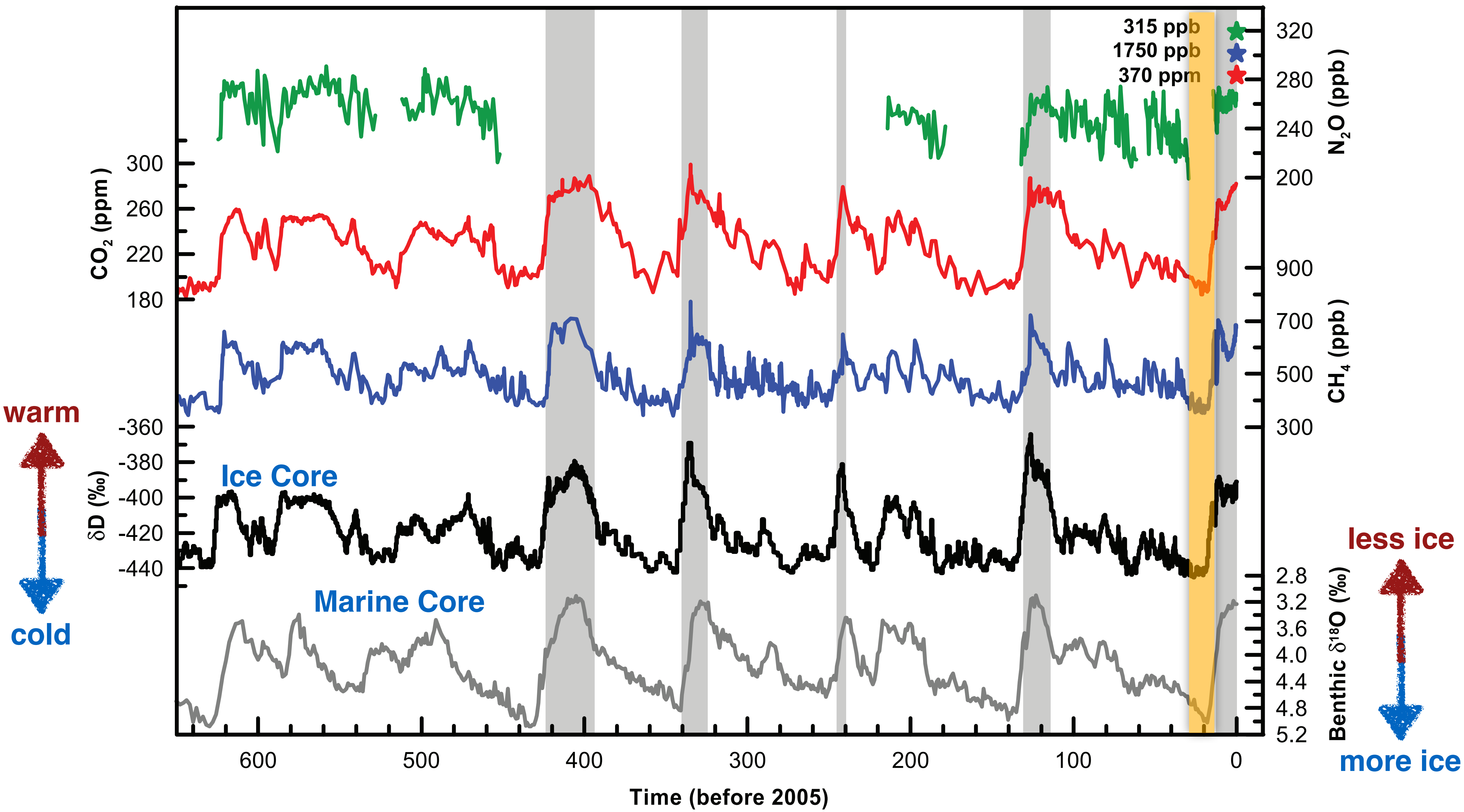
Glacial Asia was covered by permafrost, tundra and steppe (i.e. reduced area of forest)

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

B Glacial maximum (model)

[from: Ruddiman, 2008]

The last glacial maximum (LGM)



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Climate System II

(Winter 2023/2024)

4th 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/climate2023_24.html