Source images: Ruddiman, 2007 (Chapter 12)

deglaciation model https://www.youtube.com/watch?v=GaGIPGQ06ww
Deglaciation animation https://youtu.be/wbsURVgoRD0
LGM paleogeography https://www.youtube.com/watch?v=Pg0Z3LappEM

DEGLACIAL CLIMATE CHANGE

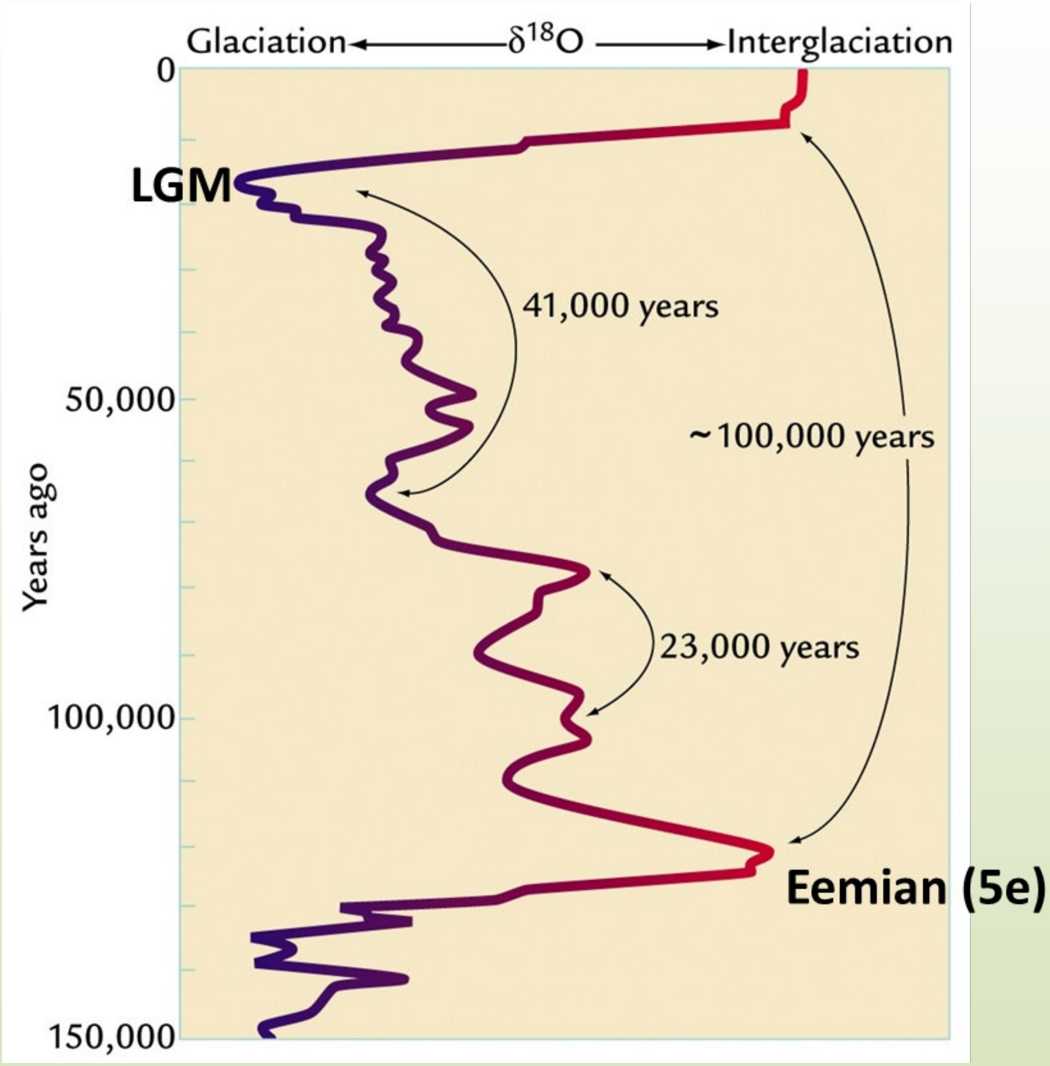
Over the last tens of thousands of years, significant climate changes have occurred, notably the **LGM transition** (~20kyr ago) and the **warming of the current interglacial period**.

This recent interval allows for climate reconstruction through ^{14}C dating.

Reconstructing regional climate changes provides a "**geographical" perspective** on past climates.

Geological records provide **boundary conditions, such as ice volume, seasonal insolation, and greenhouse gas levels**, which are used to model past climates. Model outputs can then be compared to independent geological data.

High-resolution archives reveal millennial-scale climate shifts that cannot be fully explained by orbital forcing, with the causes still unknown.



Glaciation ← $\delta^{18}O$ → Interglaciation
0
LGM
41,000 years
50,000
~100,000 years
Years ago
23,000 years
100,000
Eemian (5e)
150,000

LAST GLACIAL MAXIMUM - LGM

During the last ice age, which peaked around 20 kyr ago, Earth's surface was vastly different.

Ice caps over 2 km thick covered Canada, the USA, northern Europe, and parts of Eurasia.

Sea level was 110-125 meters lower than today, connecting areas like Great Britain to Europe.

Forests in North America, Europe, and Asia were replaced **by grasslands or tundra.**

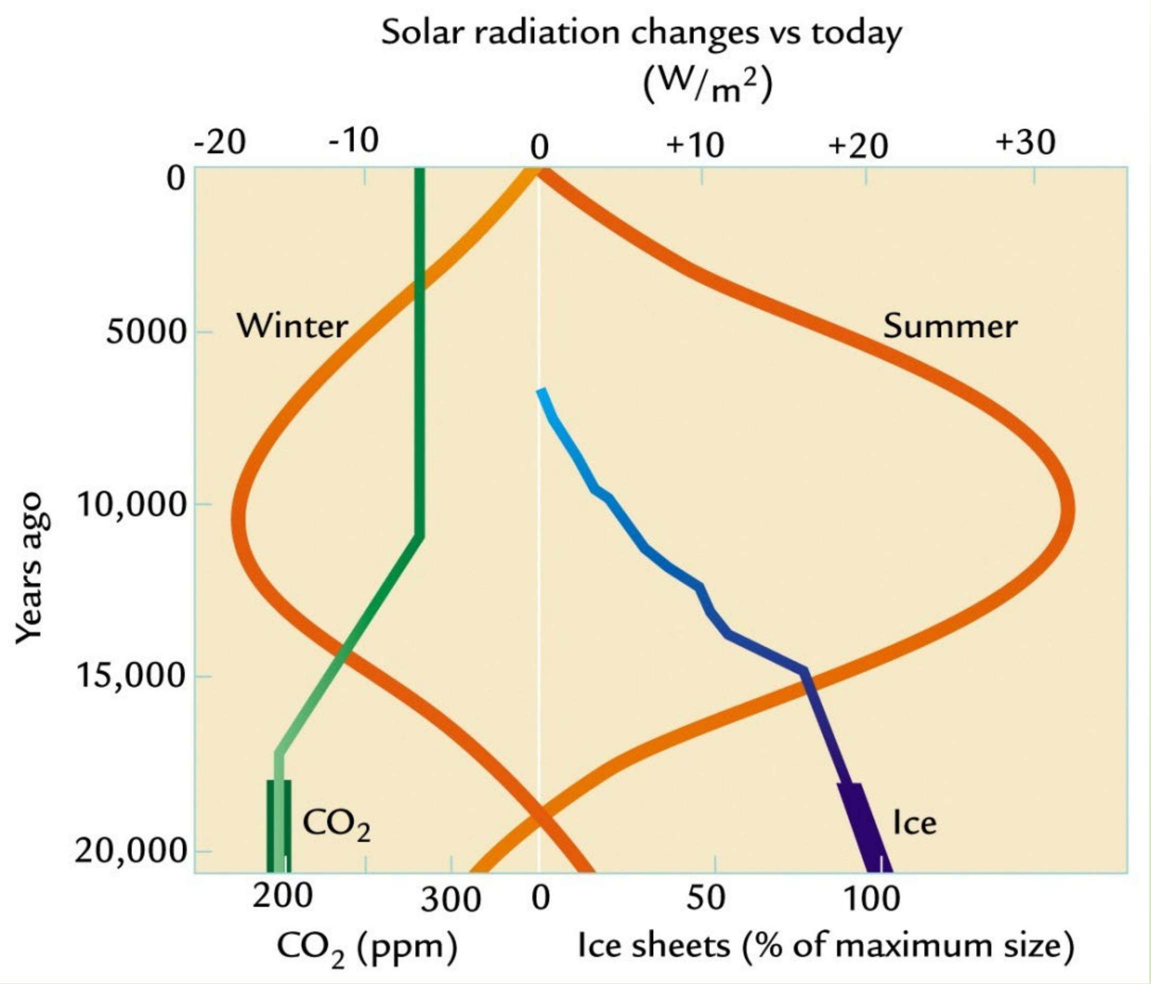
low CO_2 and CH_4 levels contributed to cooling in the tropics and Northern Hemisphere.

THE GLACIAL WORLD: MORE ICE, LESS GAS

The **LGM** world was **icy, cold, dry, windy**, and **sparsely vegetated**, but tectonically similar to today.
Climate control factors: insolation, ice caps, and CO_2.

Insolation: Levels during the LGM were similar to today, with intervals of low summer insolation.

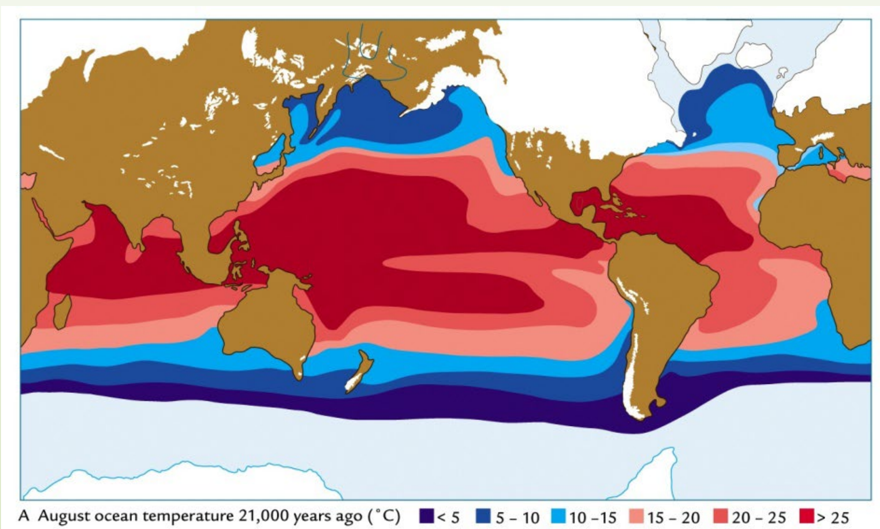
Ice Sheets and CO_2: The primary factors were likely the vast ice sheet expansion and lower CO_2 levels, leading to low temperatures.

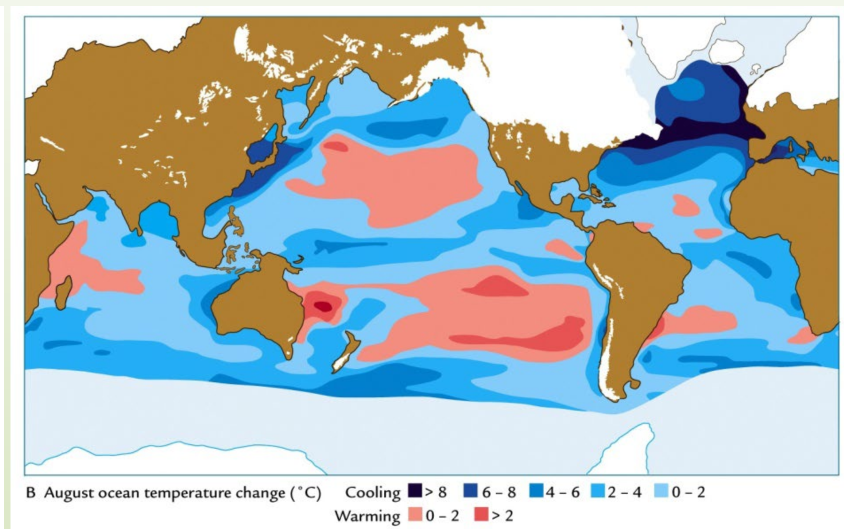


CLImate MApping and Prediction (CLIMAP)

In the 1970s, Imbrie, Hays, and Shackleton introduced a multidisciplinary approach to paleoclimatology. Though sometimes dated, **CLIMAP** reconstructions remain a key reference model for testing and validation.

CLIMAP (1981)



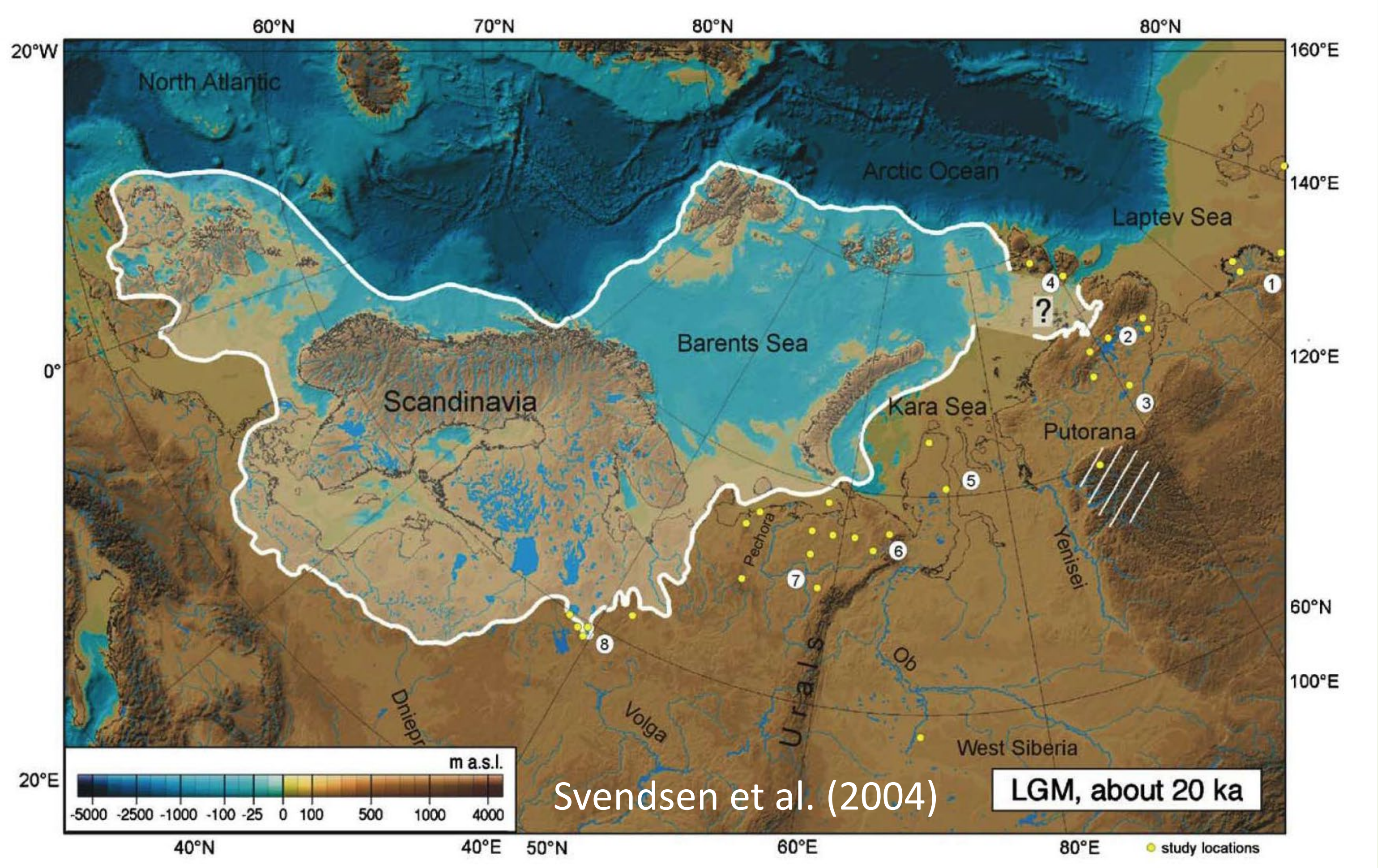


Summer SST **LGM**

Δ summer SST between today and the LGM ($T°C_{TODAY} - T°C_{LGM}$).

EXTENT OF THE ICE SHEET DURING THE LGM

The ice caps reached their maximum extent, extending to the ocean. In the Northern Hemisphere, CLIMAP identifies two marine-based ice sheets: one over the Barents Sea and another over the Kara Sea.



Svendsen et al. (2004)

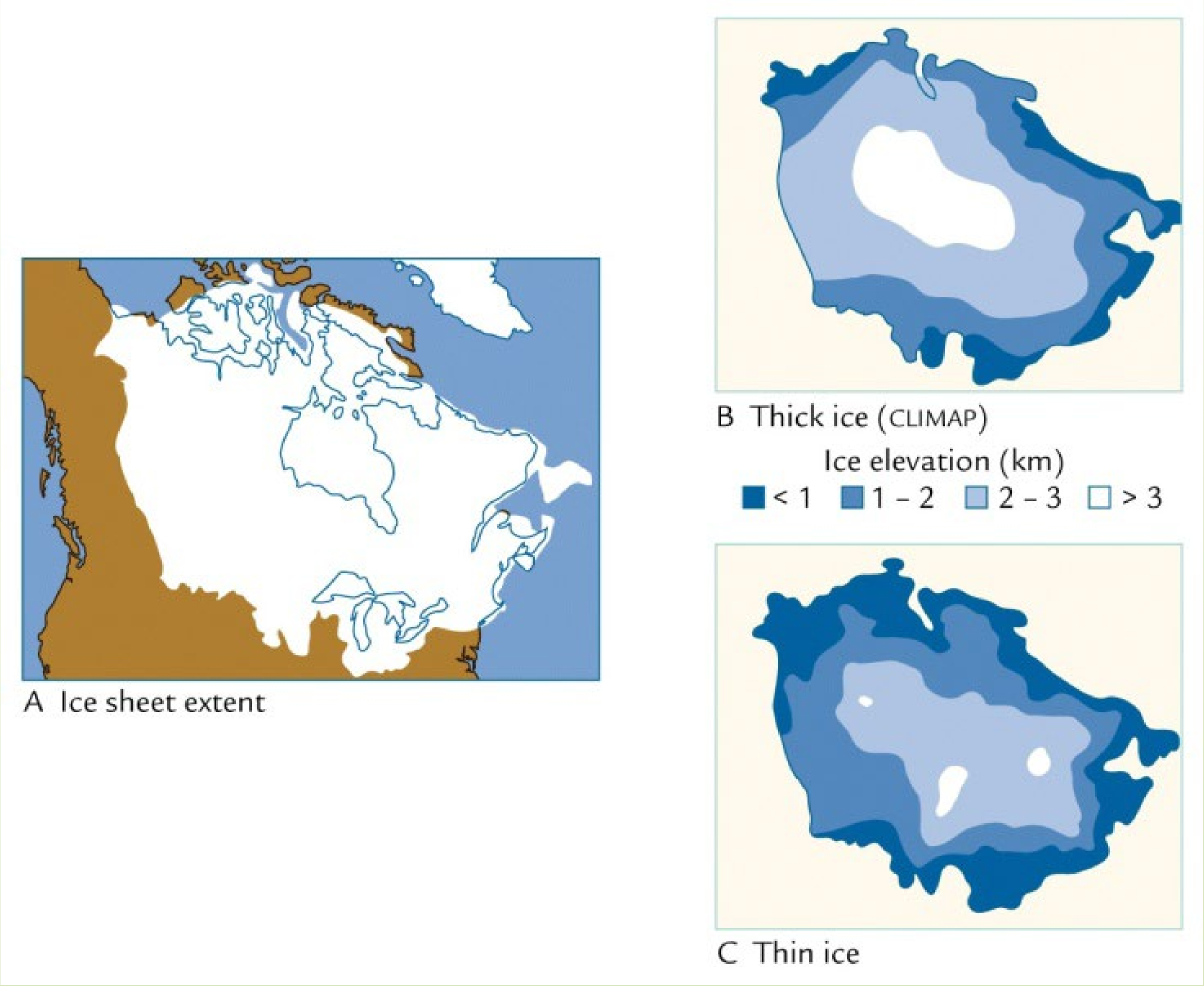
EXTENT OF THE ICE SHEET DURING THE LGM

Which was the thicknesses of the icesheet?

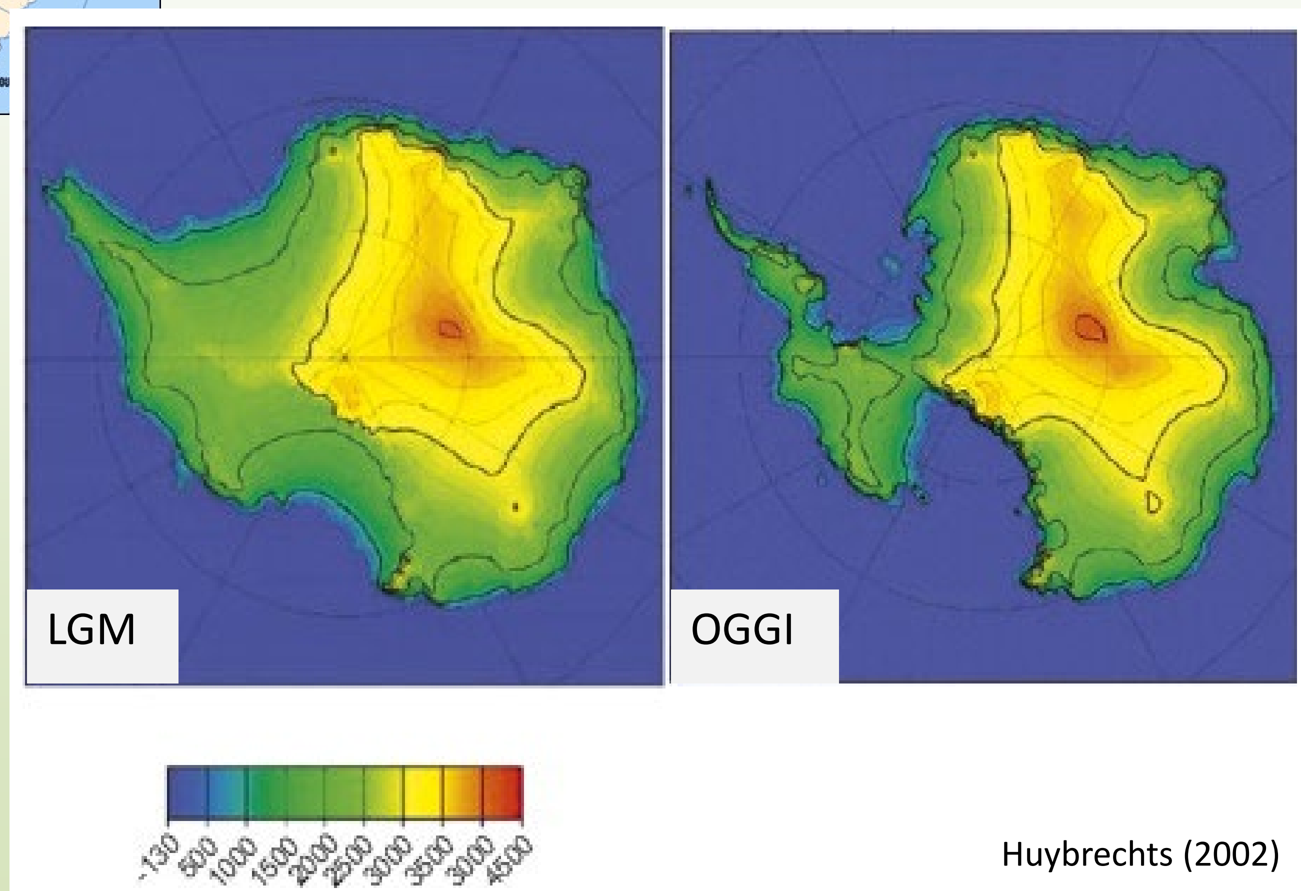
Reconstructing the precise thickness of ice caps remains challenging.

CLIMAP predicts very thick ice caps in North America, a point that remains controversial, particularly regarding sea level estimates (-110/-125m).

Conservative estimates also consider the “rebound effect”.



ANTARCTIC ICE SHEET DURING THE LGM



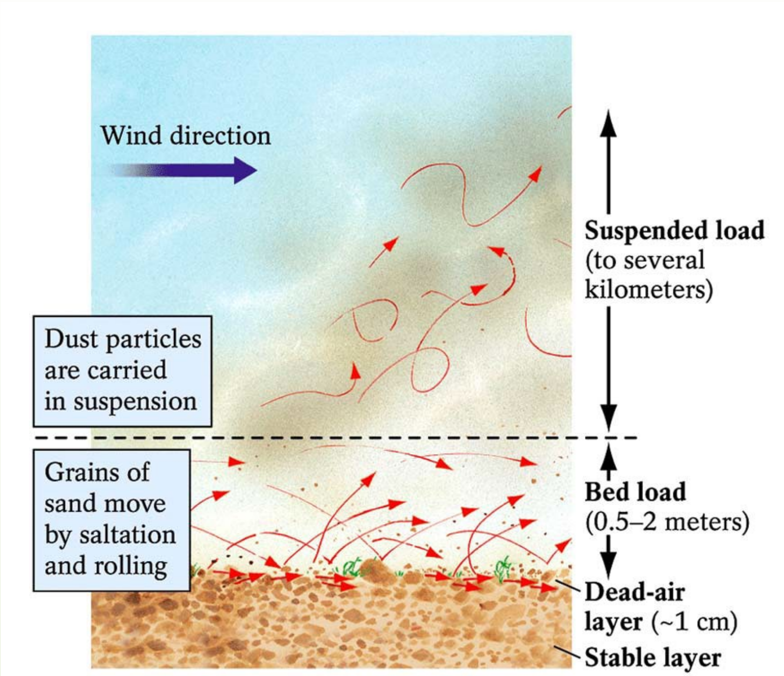
Huybrechts (2002)

GLACIAL DIRT AND STRONGER WINDS - 1

Deposits on the front of the Greenland ice sheet (Kangerlussuaq, Greenland)

Ice caps produce large amounts of debris, effectively **breaking up resistant bedrock through mechanical action, isostatic load, and freeze-thaw cycles**. They erode and transport material to their margins, where it is deposited during melting. Debris at the ice cap front undergoes washout, removing finer particles. In the margins there are also phenomena of continuous supply of material and denudation of the bedrock (melt water) which favors further degradation.

GLACIAL DIRT AND STRONGER WINDS - 2



(a)

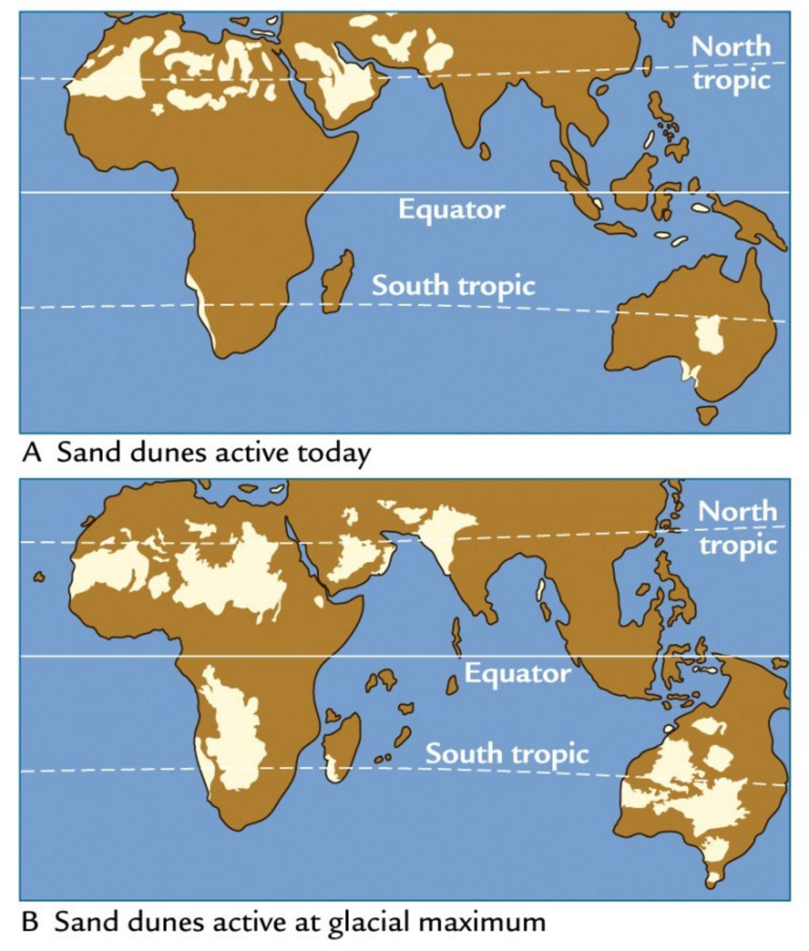
Winds redistribute sediments, leaving coarser particles in place, transporting sand a short distance, and carrying silt (**loess**) over considerable distances.

They can also carry **clay-sized dust** over long ranges. Ice accumulated during glacial periods contains ten times more dust than interglacial layers.

GLACIAL DIRT AND STRONGER WINDS - 3

During the LGM, fine dust transport was more widespread than today, even reaching low latitudes. North African and Arabian deserts currently produce large dust storms, but during the LGM, dust accumulation in sediments from the eastern Indian Ocean and Arabian Peninsula was five times higher.

Sand dune transport occurs today in North Africa, Arabia, and Australia, mainly in arid intervals without vegetation. **During the LGM, these movements were more extensive and intense due to stronger winds and drier conditions.** Dust found in Antarctica likely originated from Patagonia.

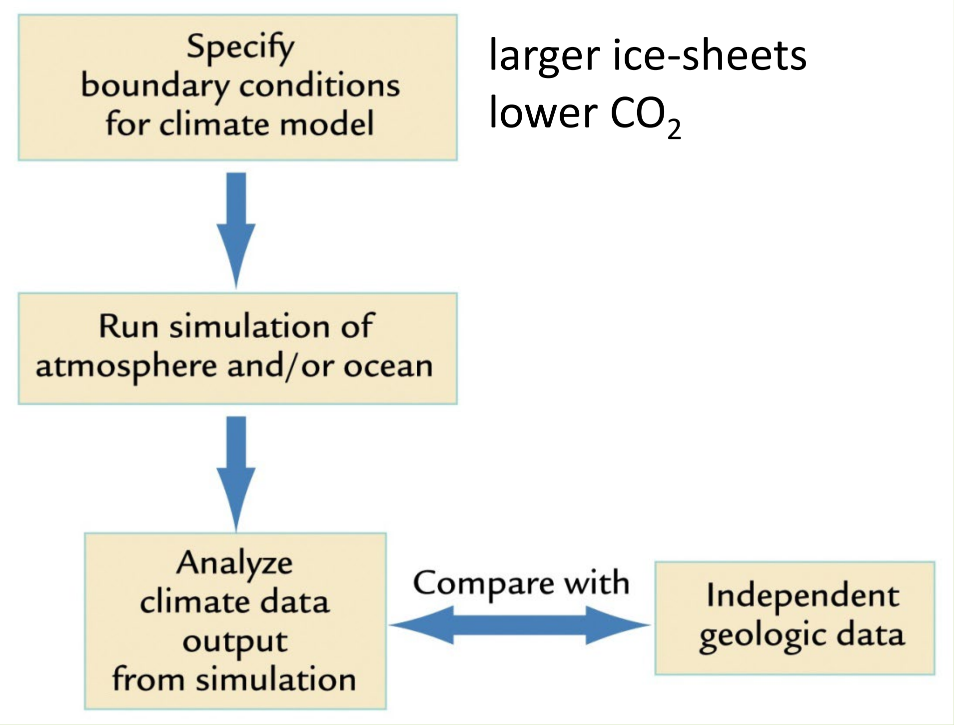


One way to test the LGM models could be to check the consistency between real and "simulated" dust distribution. Unfortunately, there are problems with the accuracy of large-scale air transport models.

TESTING MODEL SIMULATION AGAINST BIOTIC DATA

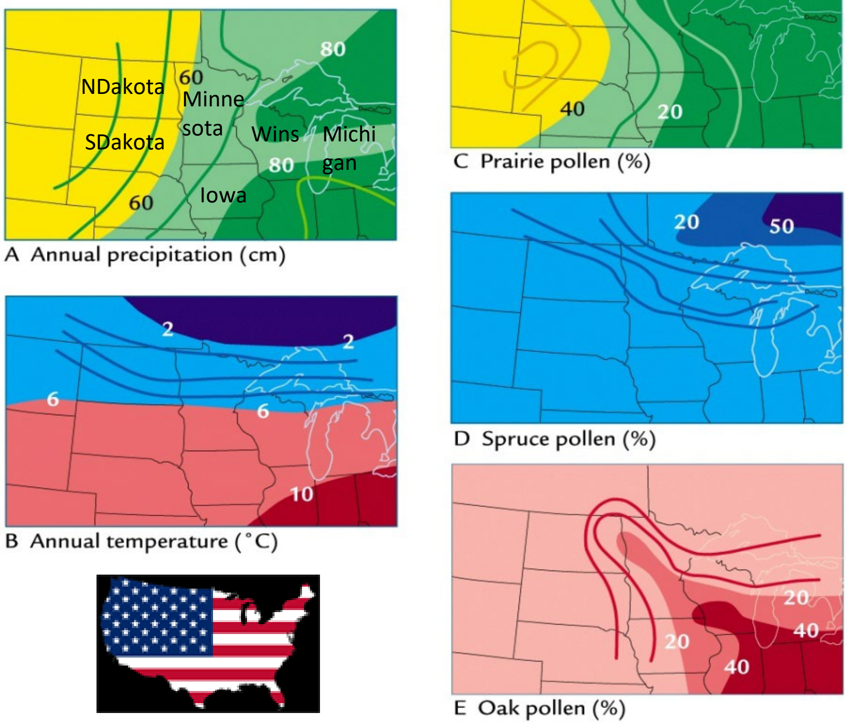
While we have focused on the physical environment, biota also provides crucial insights into LGM conditions.
In the 1980s, the interdisciplinary COHMAP project (led by Kutzbach, Webb, Wright & Street-Perrott) used a combined data-model approach to study the LGM and subsequent interglacial changes.

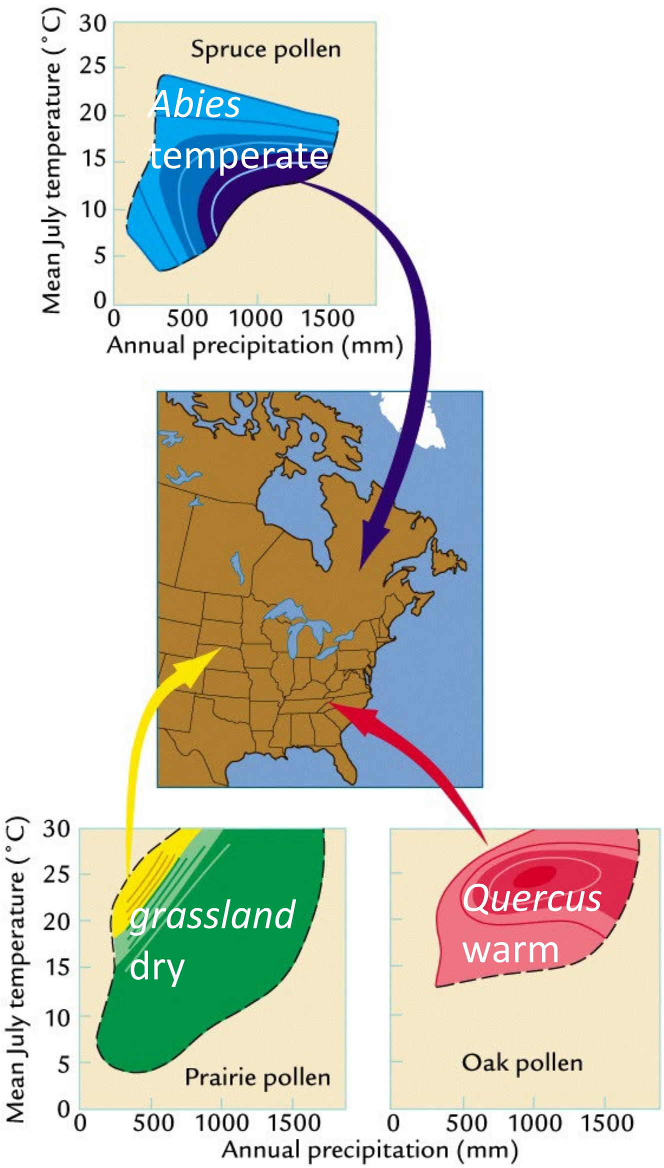
Main steps of COHMAP



POLLENS: A PROXY OF TERRESTRIAL CLIMATE

USA - Northern Midwestern





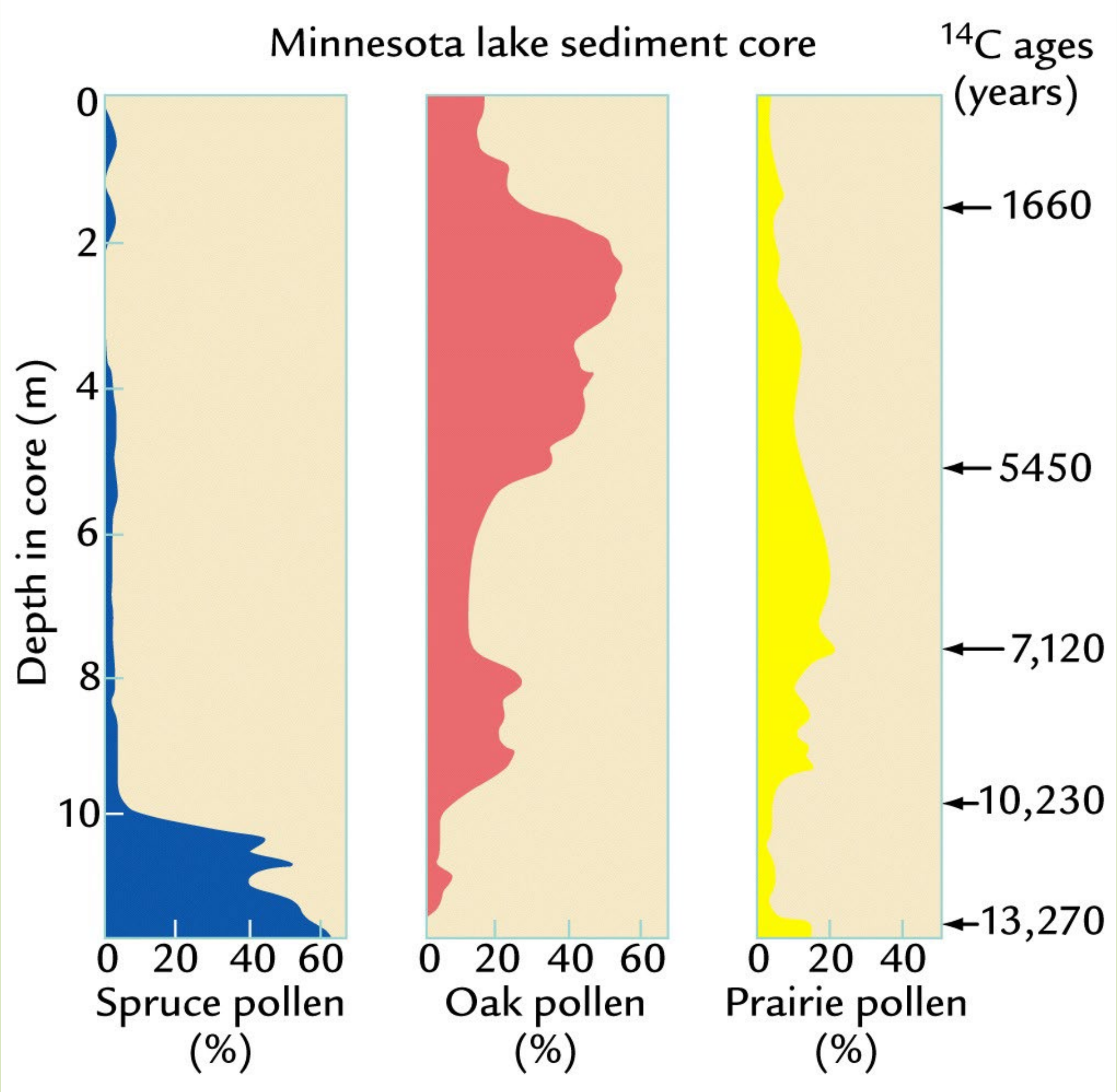
Precipitation and temperature determine vegetation distribution.

Pollens, carried by wind, water, and insects, reflect local vegetation once adjusted for taxa over- or underproduction.

How can you interpret the change in pollens observed in the plot in terms of rainfall and temperature?

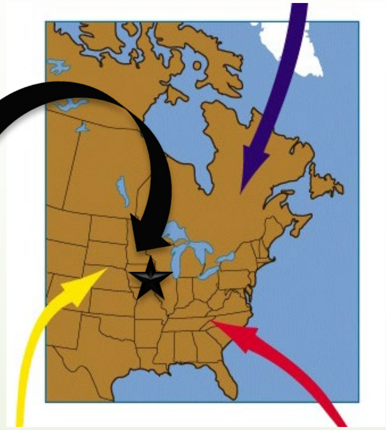
https://app.wooclap.com/events/PCCM24/0

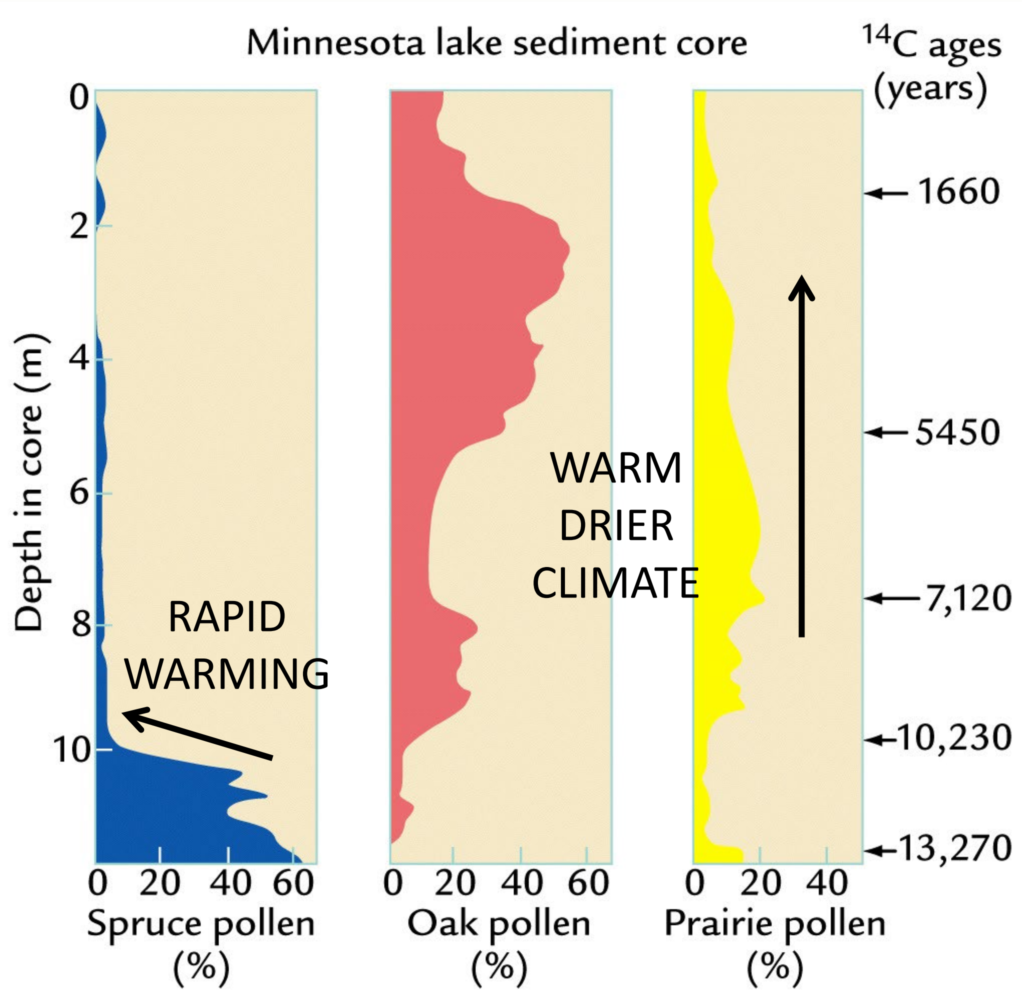
How can you interpret the change in pollens observed in the plot in terms of rainfall and temperature?



APPLICATION TO MINNESOTA LAKE DATA

Minnesota Lake

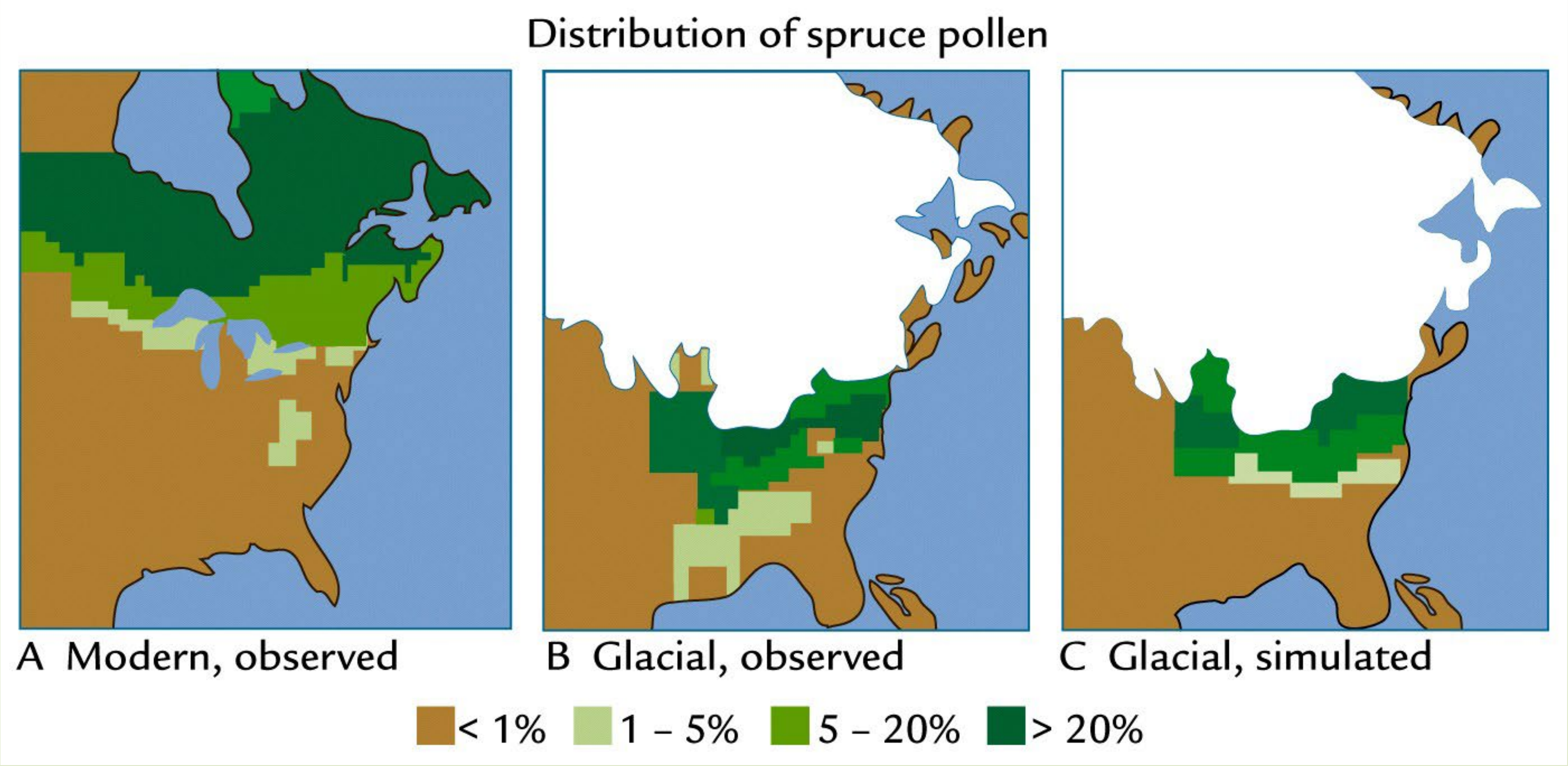




This model interprets data from Minnesota Lake (~10,000 years ago), highlighting the postglacial phase of the current interglacial period.

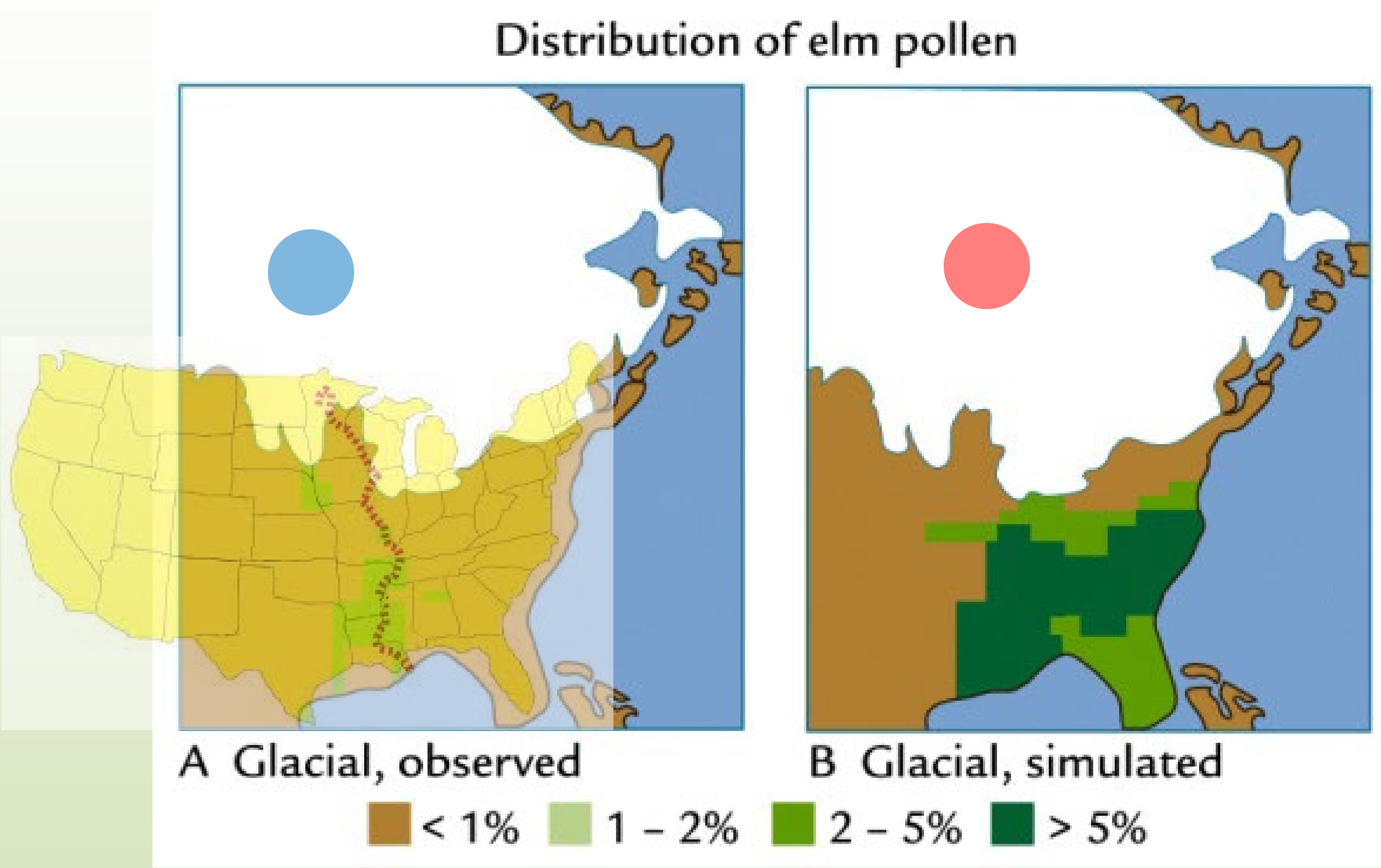
Spruce dominance (**COLD**) is disrupted by a sharp rise in oaks (**WARM**) and grasslands (**DRY**).

DATA (POLLENS) – MODEL COMPARISON



The data-model comparison relies on pollen distribution across specific time intervals in different areas.
Pollen abundance maps are generated and compared to model-simulated distributions, which are based on boundary conditions incorporating P and T data to reconstruct pollen abundances.

NORTH EASTERN USA DURING THE LGM



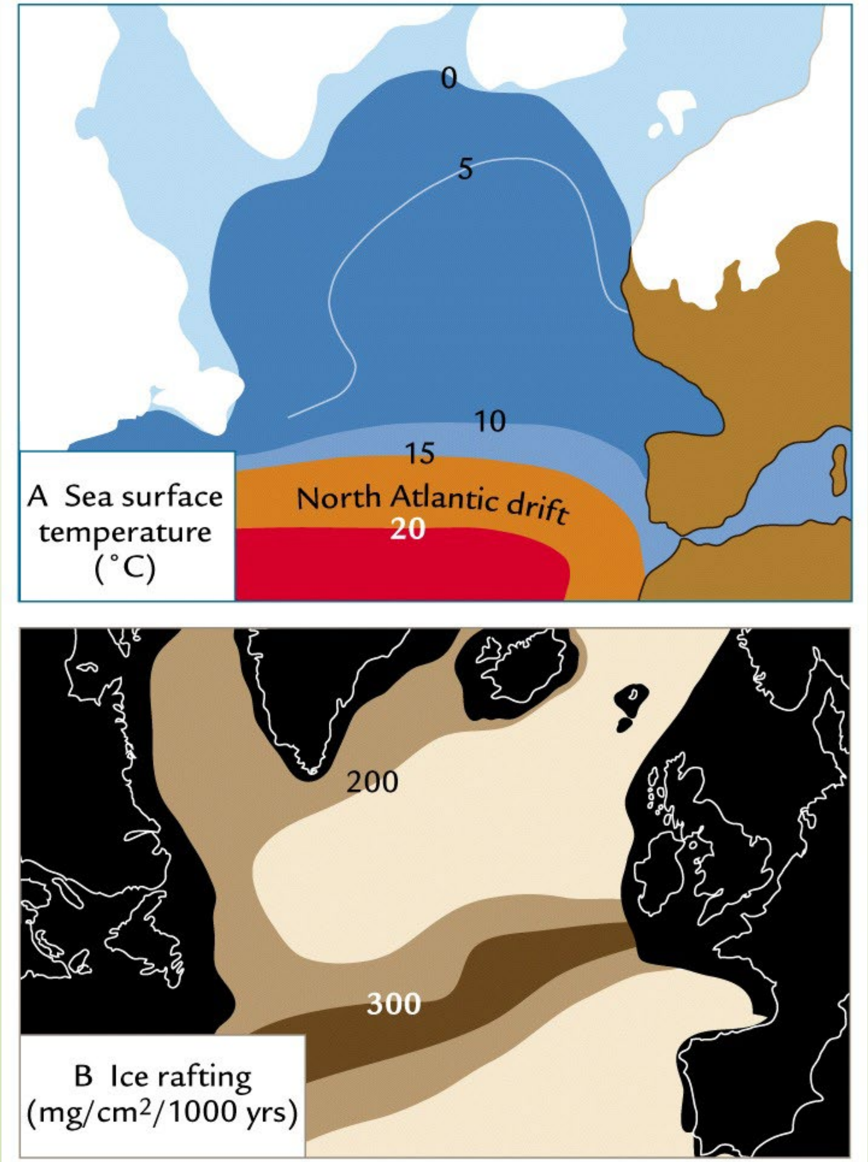
Data-model mismatch suggests that the simulated cooling for this area (Mississippi inflow) is underestimated.

NORTH ATLANTIC DURING THE LGM

Most climate changes simulated by models align with independent geological data.

However, CLIMAP's North Atlantic temperature estimates (from foraminifera) show notable differences, with cold waters and sea ice extending to lower latitudes.

INDEPENDENT GEOLOGICAL DATA
Ice-rafted debris distribution also indicates a reach to lower latitudes.

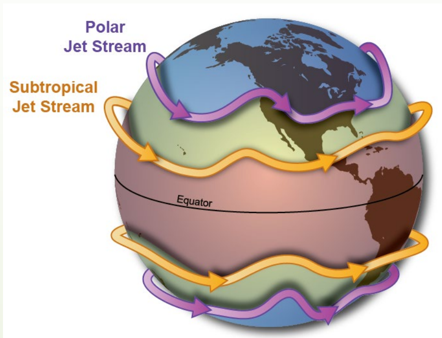


A Sea surface temperature (°C)

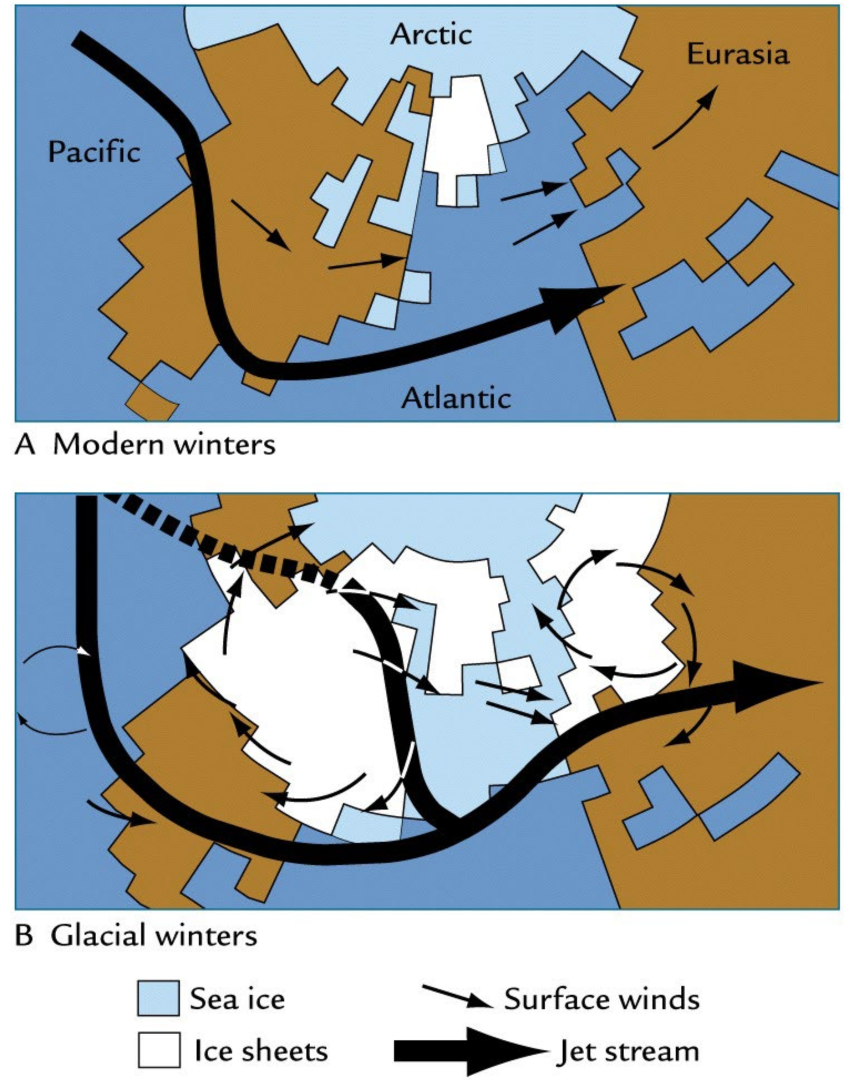
B Ice rafting (mg/cm²/1000 yrs)

WESTERN AMERICA DURING THE LGM - 1

LGM CLIMATE SIMULATIONS

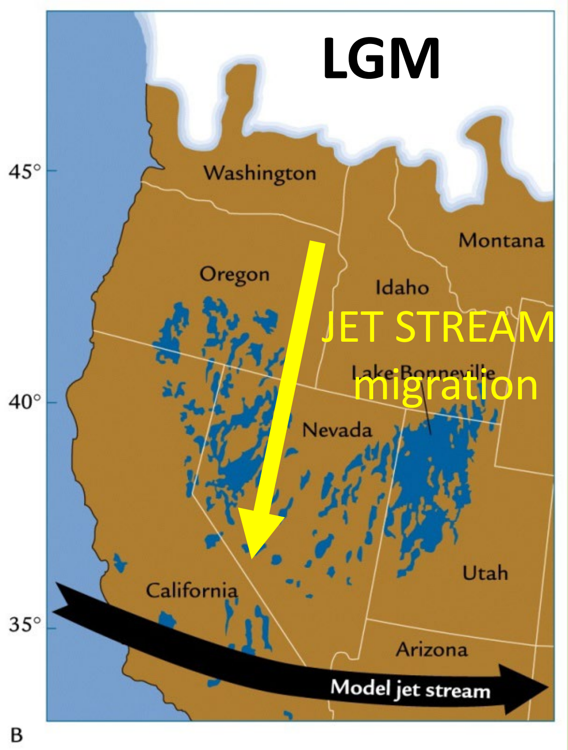


Ice cap expansion is a key boundary condition. Thick ice cap domes can significantly alter atmospheric circulation.

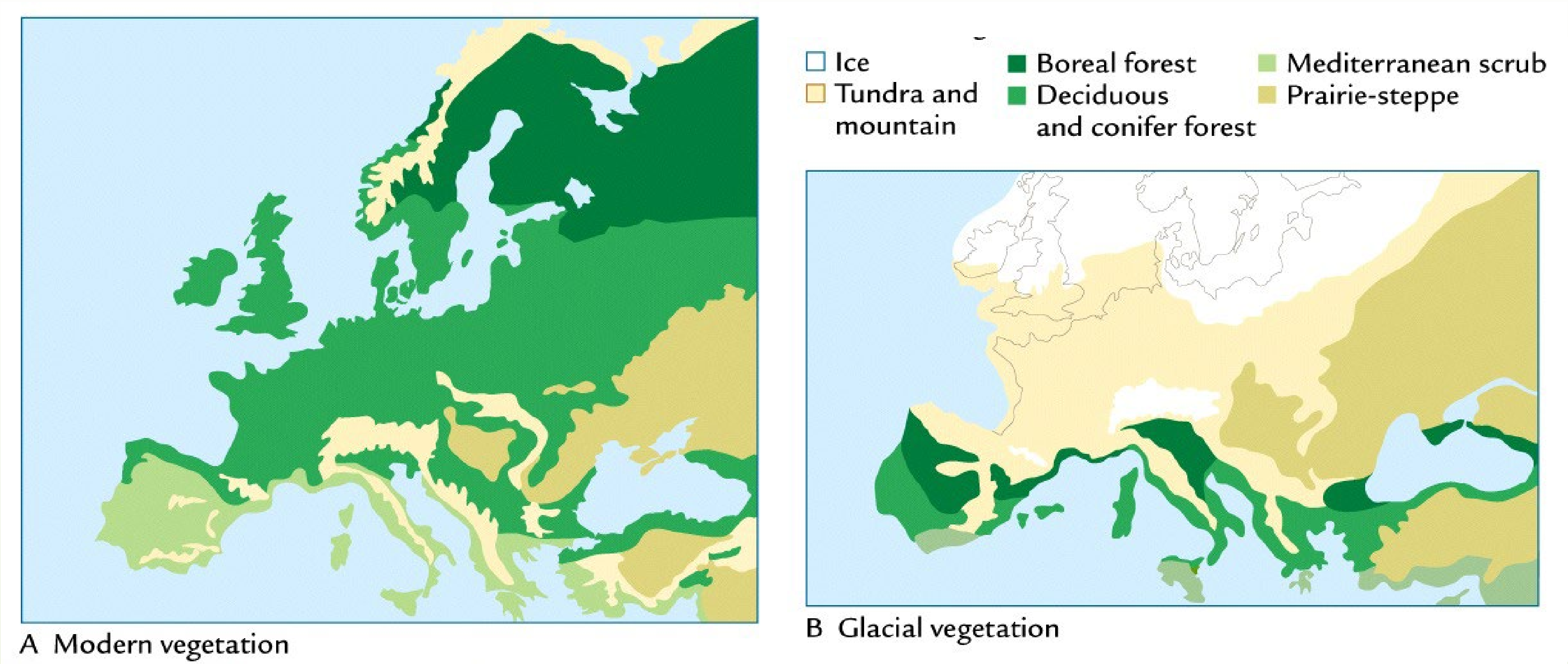


WESTERN AMERICA DURING THE LGM - 2

NORTHWESTERN USA
Today: Wetter, forested climate.
LGM: Drier climate; southward shift of winter Jet Stream reduces precipitation.
SOUTHWESTERN USA
Today: Arid and semi-desert, with winter snow and small glacial lakes.
LGM: Extensive lakes, including Lake Bonneville at 10 times the size of today's Great Salt Lake. Humid climate due to the southern branch of the bifurcated Jet Stream, enhancing rainfall.



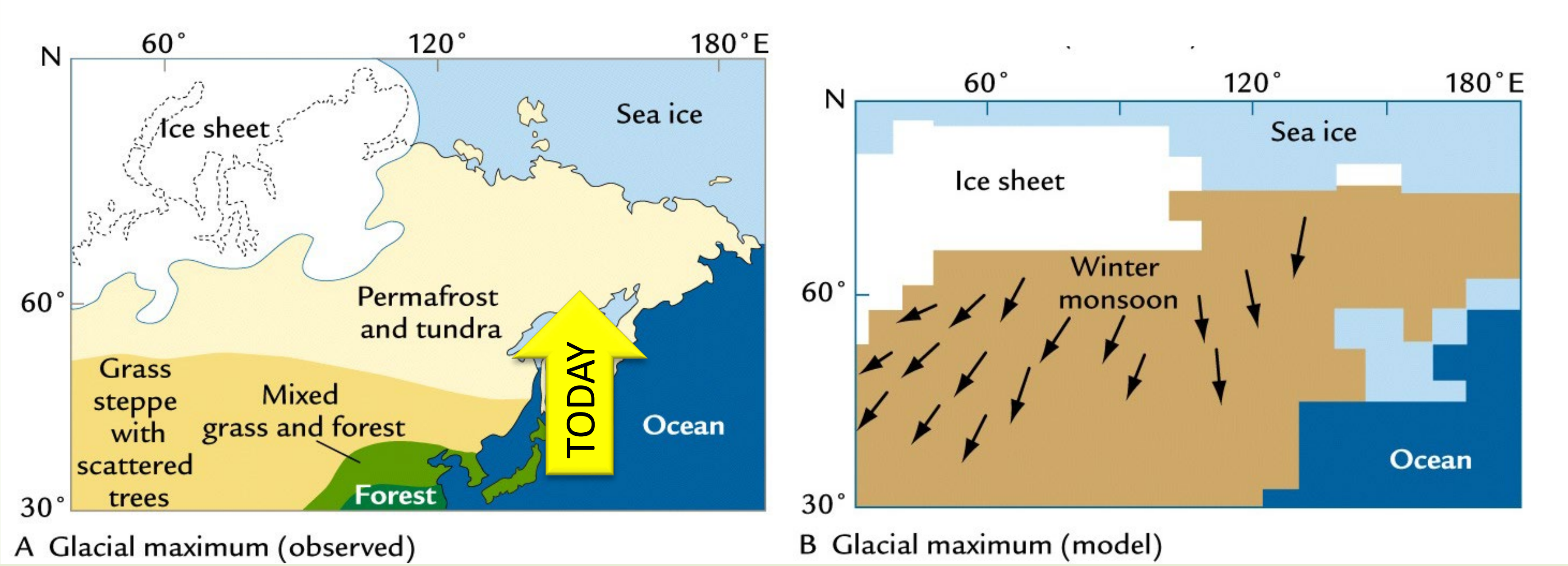
EURASIA DURING LGM -1



EUROPE

During the LGM, coniferous and deciduous forests were absent, replaced by tundra or steppe, consistent with dry, windy conditions and loess-carrying winds.

EURASIA DURING LGM -2



EURASIA

•**Observed LGM**: Permafrost and tundra in summer; steppe to the south, with high winter albedo.

•**Simulated LGM**: Model shows colder temperatures, likely from winter high-pressure in Siberia, driving a dry, cold southward flow.

•**Today**: Slightly stronger summer monsoons support forest expansion further north than in the LGM.

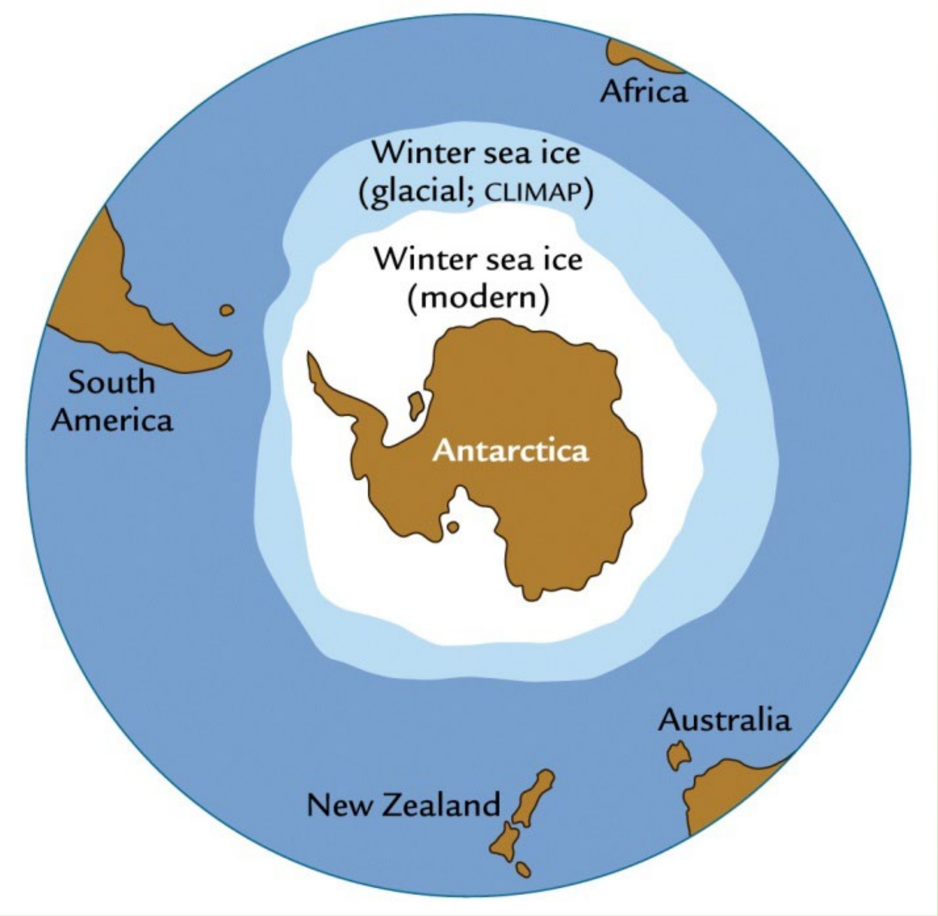
LGM Climate Change Beyond the Arctic Ice Cap

Outside the Arctic ice cap, changes were milder, often linked to low CO_2 levels.

ANTARCTICA
Slight northward sea ice expansion; changes in productivity.

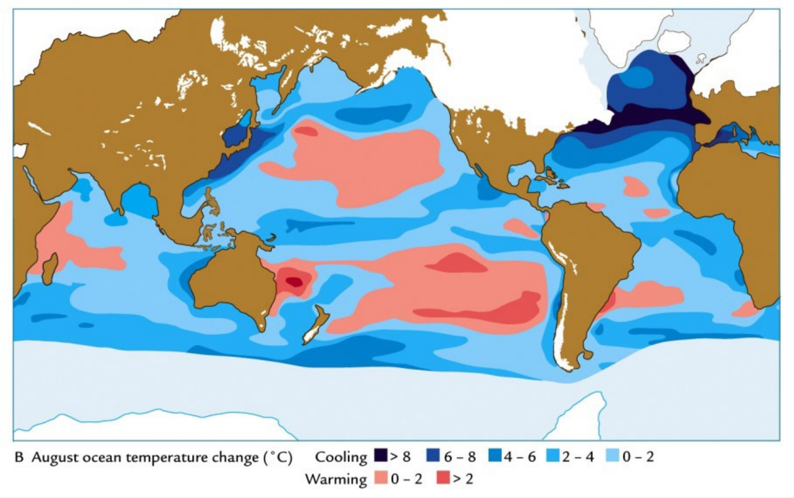
AUSTRALIA
Increased desertification and aridity, possibly due to ice sheet expansion or reduced ocean influence.

SOUTH AMERICA
Rainforest was less extensive; Andes pollen indicates drier LGM conditions.



HOW MUCH COLDER WAS THE LGM AT TROPICS? -1

CLIMAP (based on planktonic foraminifera) predicts LGM tropical temperatures **1-2°C lower** in some areas but higher in others, while other estimates suggest **4-6°C lower**.



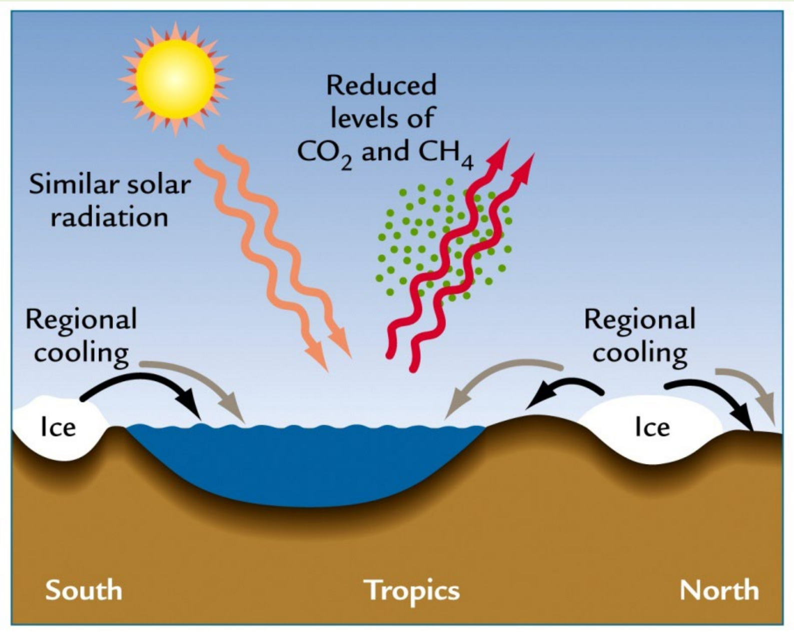
WHAT CAUSED TROPICAL COOLING?

- **REGIONAL ICE EFFECT**

The tropics, distant from the ice cap, were unlikely cooled by regional ice effects.

- **INSOLATION**

Insolation was similar to today, so it does not explain the cooling.



HOW MUCH COLDER WAS THE LGM AT TROPICS? -2

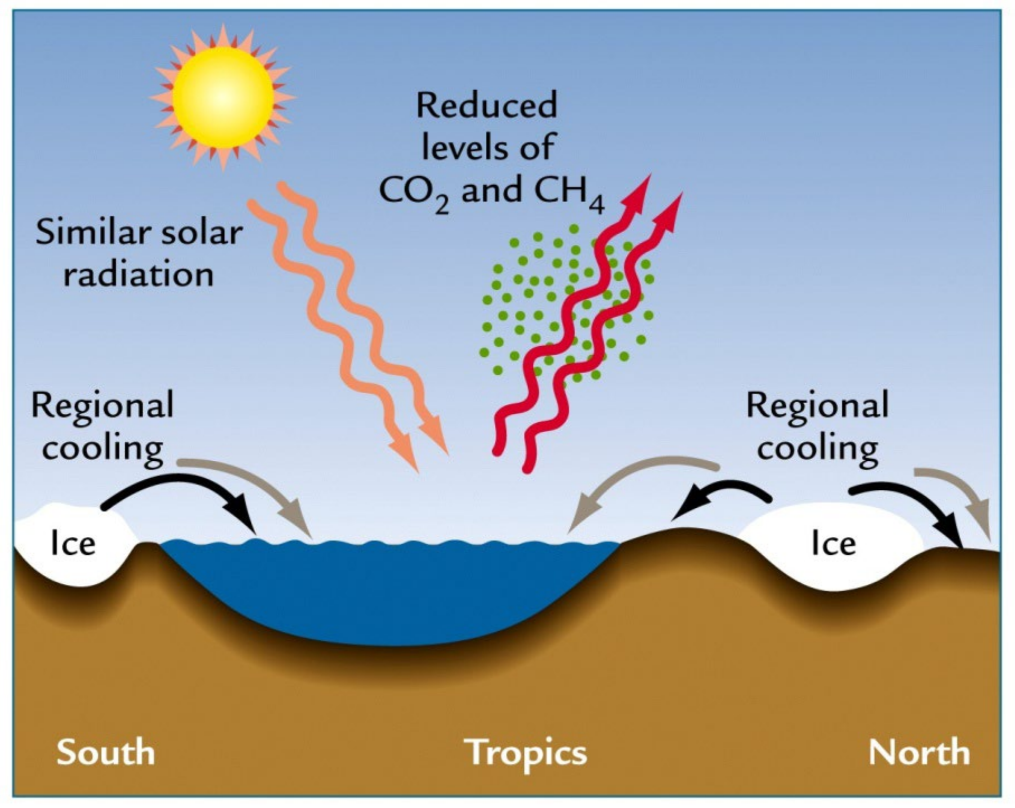
WHAT CAUSED TROPICAL COOLING?

- **LOW GREENHOUSE GASES**

CO_2 (190ppm, -30%) and CH_4 (-50%)

With lower greenhouse gases, Earth's reflected rays escape more easily, cooling the atmosphere. This tropical cooling highlights the region's sensitivity to greenhouse gas changes.

With 50% of landmass between 30°N and 30°S, this cooling reflects the climate system's sensitivity.

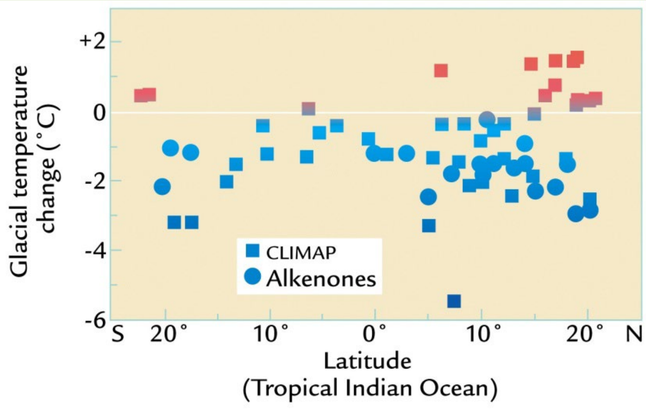


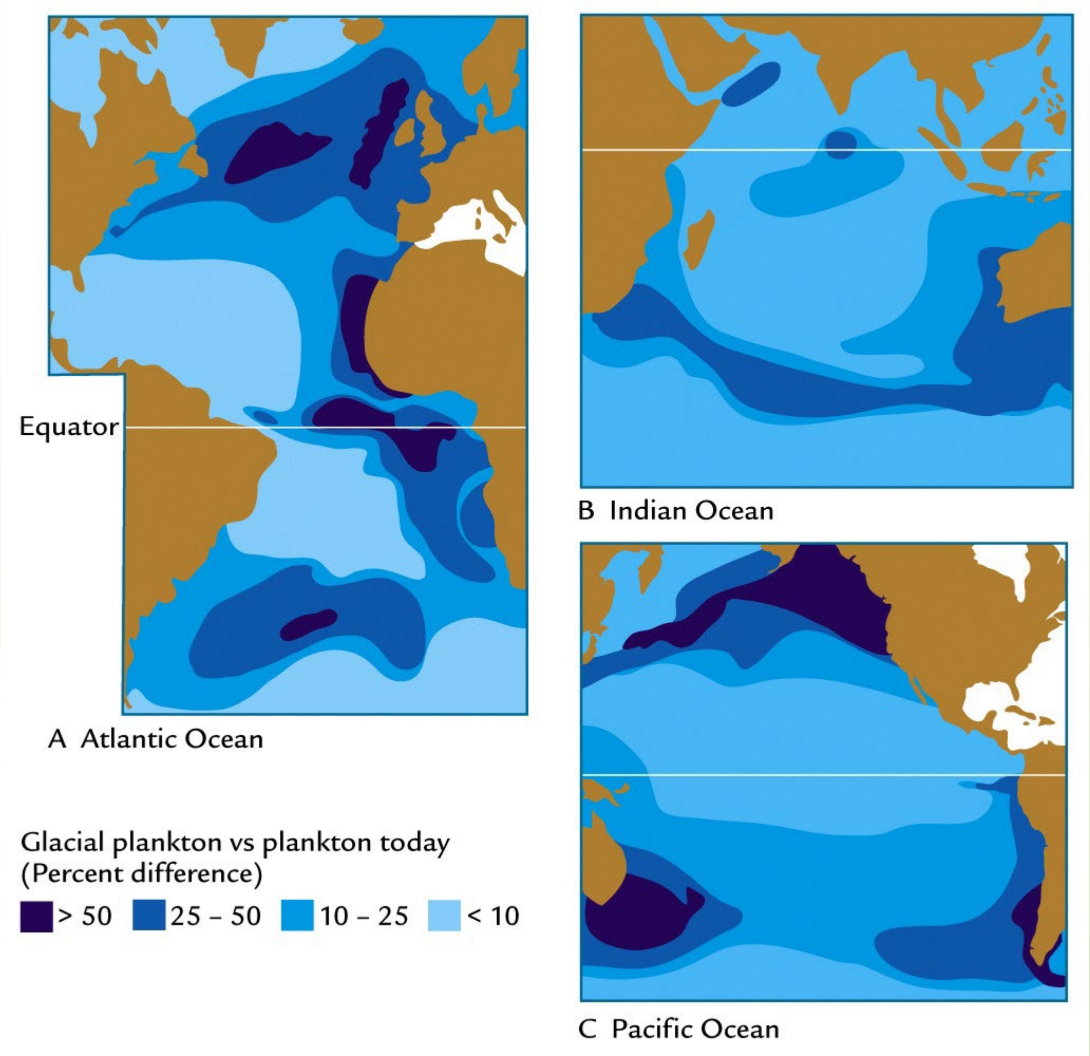
HOW MUCH COLDER WAS THE LGM AT TROPICS? -3

EVIDENCE OF MINIMAL TROPICAL COOLING

CLIMAP shows slight tropical cooling based on modest shifts in low-latitude marine fauna and flora.

Alkenones and Mg/Ca data support a cooling of around 1.5°C.





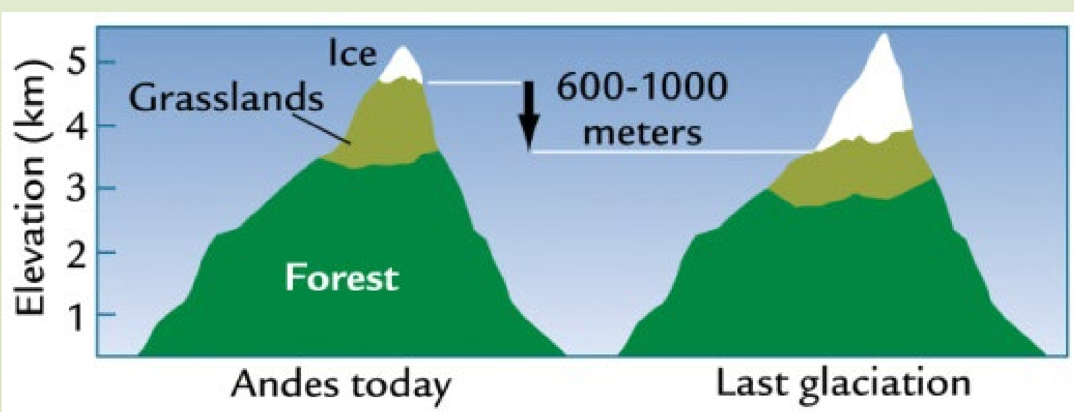
HOW MUCH COLDER WAS THE LGM AT TROPICS? -4

EVIDENCE OF SIGNIFICANT TROPICAL COOLING

A larger tropical cooling is suggested by continental indicators, like the permanent snowline and tree line.

Tropical mountain glaciers lowered by 600-1000m, indicating a 4-6°C cooling.

This limit, set mainly by temperature (and to a lesser extent by precipitation, topography, and exposure), implies that if glaciers exist above 5000m today with an atmospheric lapse rate of ~6.5°C/km, a 600-1000m drop corresponds to a temperature decrease of 4-6°C.



thermal gradient
"wet"

6.5°C /km

thermal gradient
"dry"

9.8°C /km

HOW MUCH COLDER WAS THE LGM AT TROPICS? -5

REALISTIC (MODERATE) TROPICAL COOLING

After years of debate, the cooling was concluded to be moderate—neither minimal, as per CLIMAP, nor as intense as other estimates.

Issues with Minimal Cooling (CLIMAP):

•Plankton in low latitudes are more sensitive to trophic conditions than to temperature.

•Pacific data are affected by altered dissolved material assemblage.

Issues with Large Cooling:

•Dry glacial climates may have steepened the thermal gradient (6.5 to 9.8°C/km).

•Glacier data are poorly dated, and sea-level drop (~110-125m) increased mountain heights, reducing temperature by ~0.75°C.

Additional Factors:

•Continental response is more pronounced than oceanic.

•Low CO_2 levels may have lowered the tree line.