Last Glacial Maximum - Deglacial Climate History

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Chapter 12 - Last Glacial Maximum
The Glacial World: More Ice, Less Gas
    sections 12-1, 12-2, 12-3
    sections 12-3, 12-6, 12-7, 12-8, 12-9
How Cold were the Glacial Tropics?
    sections 12-10, 12-11, 12-12

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The Last Glacial Maximum

Large portions of the northern continents were covered by continental ice sheets, the largest being the Laurentide ice sheet of North America, extending outward from the present-day Hudson Bay region.
greatest extend of ice volume ($\delta^{18}O$) was 21,000 years ago
Summer insolation 21,000 years ago during the last glacial maximum was nearly what it is today and continued rising. So why was there so much more ice then than now?
Remember the lags:
    glacial growth lags the insolation curve (~6000 yrs)
    crustal subsidence lags the loading by ice (thousands of years); the top of the ice sheet was a couple km above sea level making the summer air cold even as sea level temperatures increased; eventually crustal loading subsidence did lower the ice sheets enough for melting to begin

CLIMAP Climate Mapping and Prediction (1976)
Notice that sea surface temperatures weren't much different 21,000 year ago compared to now. Some areas warmer, some areas colder. But look at all of that ice (in Fig 12-2). Not all details of the, at the time state of the art, CLIMAP project have stood the test of time though.
There is broad agreement on the total lateral extent of the ice sheets (e.g., Laurentide) at the last glacial max. CLIMAP originally assumed that the ice everywhere extended to the most distant terminal moraines, and this has been validated by radio-carbon dating of those terminal moraines.
But the maximum thickness of the ice sheets is still debated. CLIMAP concluded that there were large areas thicker than 3 km. Arguments based on sea level studies (and therefore total ice volume) conclude that almost all of the Laurentide was less than 3 km thick.

There were extensive ***loess deposits*** at the time of the last glacial max. Loess is silt produced as "rock flour" from the rock grinding action of glaciers. The silt-size rock flour is deposited in terminal moraines and then carried out across the outwash plain be braided streams. Winds in the cold dry climate carried the silt from the outwash plain, depositing them in thick downwind deposits.

Sand dune building was much more active during the last glacial max than today. cooler global temperatures = less global humidity = narrower equatorial rain belts = larger desert belts Northern hemisphere summer insolation 21,000 years ago during the last glacial
maximum was nearly what it is today. So why was there so much more ice then?

Remember the lags:
- glacial growth lags the insolation curve (~6000 yrs)
- crustal subsidence lags the loading by ice (thousands of years)

Glacial Max Climate was colder and drier than today.
there was higher albedo from all the ice
there were regional circulation and cooling effects from the ice
atmospheric concentrations of CO_2 and CH_4 were both lower

Glacial World Aridity: Dry, desert regions were more extensive during the cold and dry conditions of glacial max than they are today.

North Atlantic Cold: The North Atlantic, surrounded by ice sheets, was very cold. Ice-rafted debris extended quite far south. Greatest concentrations were deposited where icebergs reached warmer waters.

Global Climate Model of Modern Climate reproduces the typical pass of the jet stream over Oregon & Washington, which bring them wet winters due to the path of winter storms.

Global Climate Model of Glacial Max Climate indicates a branched jet stream around the Laurentide Ice Sheet, deflecting the southern branch and the winter storm track through the U.S. southwest - implying wetter winters there during the last glacial maximum.

Also, note the spiral of cold winds surrounding the Laurentide ice sheet. As very cold, dense air descended off the high elevation of the ice sheet it was deflected to the west by the coriolis effect.

Glacial Era Lakes in the Desert Southwest: Numerous large lakes filled the flat valleys of the Basin and Range during the last glacial max as a result of the more southerly winter jet stream and storm track indicated by glacial climate modes. Washington & Oregon were drier then as a result of the more southerly course of winter storm tracks.

Today the region is desert with basins only occasionally gathering temporary shallow lakes that dry up leaving behind salt deposits.

Displacement of Vegetation Belts

Cold-hardy spruce were displaced much farther south of their present geographic range by during glacial max.
Vegetation belts were displaced well south in Europe during the last glacial maximum.
Forests were displaced well south in Asia as well.

Antarctic winter sea ice extended much farther north during the last glacial maximum.

The Big Question: How much cooler were the tropics?
climate in high latitude regions was affected by
- the ice sheets
- lower CO_2 & CH_4

climate in the tropics was only affected by
- lower CO_2 & CH_4

So glacial max temperatures in the tropics tell us how sensitive climate (including modern climate) is to changes in greenhouse gas concentrations.

CLIMAP and biochemical studies of glacial max sea surface temperature indicate ~1-2 °C cooler
original studies based on altitude of tropical mountain glaciers concluded ~5-6 °C cooler
climate modelling ~3 °C cooler
the true answer may lie in the middle ground

Climate During and Since the Last Deglaciation

Evidence of Melting Glaciers
Dating (^{14}C) of terminal moraines gives us the ***maximum extent of the ice sheets*** at the last glacial maximum. The edges of the Laurentide ice sheet extended out to the furthest terminal moraine in most locations 21,000 years ago.
Dating (^{14}C) indicates the retreat of the Laurentide ice sheet between ~15,000 years ago to ~6000 years ago, at which time is was essentially gone. The Scandinavian ice sheet in Europe was gone a few thousand years earlier because of its smaller size.

The evidence above indicates the ***lateral extent*** of the continental ice sheets, but what about the ***total ice volume****,* since glaciers got thinner with time also? Estimates of sea level rise would indicate volumes of ice melted.
Sea Level Curves based on submerged coral from Barbados show the rise of sea level (melting of ice sheets) beginning around 15,000 years ago.
Changes in slope of sea level curves indicate changing rates of sea level rise/ice loss. peak melting/sea level rise occurred ~15,000 yrs ago and ~12,000 yrs ago with a pause in between
Meltwater pulses, recorded as negative shifts in $\delta^{18}O$ in the Gulf of Mexico and Norwegian Sea, were caused by influx of glacial meltwater (light oxygen isotopes).

Temporary Pause in Rapid Melting

The Younger Dryas was a temporary return to cold glacial conditions in the North Atlantic and Europe.

The Younger Dryas event is recorded in % polar foraminifera in North Atlantic sediment cores, % tree pollen in Scotland, changes in populations of temperature sensitive beetles in England, changes in Greenland ice accumulation rate and windblown dust concentration in the ice

The warmth before and after the Younger Dryas is when the major melting of the ice sheets occurred. Glaciers continued melting during the Younger Dryas, just at a much slower rate.

Rapid Climate Change

The changing climate at the end of the last glaciation and the short term reversal of the Younger Dryas occurred in very short transitions of about 100 years, with much of the climate change from nearly full glacial to nearly full interglacial temperatures occurring within a decade or two.

Did a sudden discharge of freshwater cause the Younger Dryas? Could freshening of the North Atlantic inhibit the sinking of surface water (stop the formation of North Atlantic Deep Water) and slow down the ocean conveyor belt, slow down the northward flow of warm Gulf Stream waters to the North Atlantic?
(Wally Broeker, Columbia/Lamont-Doherty Earth Observatory)

Glacial meltwater flowed into the North Atlantic rather than down the Mississippi during the Younger Dryas, but would this be enough? Research continues.

Glacial Max Exposed Continental Shelves

The shallow continental shelves, <100 m depth, surrounding the continents were exposed during the last glacial maximum allowing free passage between Siberia and North America, between Asia and Japan, Borneo, and Indonesia, between Australia and New Guinea, and between England and continental Europe.

Proglacial Lakes

Glacier meltwater ponded in front of glacial terminus in depression produced by isostatic subsidence from the weight of the ice sheet.

As the glacial terminus retreated, the bedrock gradually rebounded, and the lake followed the glacier.

Lake Agassiz, northwest of present day Lake Superior, was the largest, but small portions existed sequentially on the edge of the retreating Laurentide ice sheet.

Lake Missoula, another proglacial lake, burst down the Columbia/Snake River valley when a receding tongue of the ice sheet opened a passage. An enormous flood produced gigantic current ripples and erosion features in a region called the ***channeled scablands***.

Postglacial Climate

"Insolation Max" was about 10,000 years ago (northern hemisphere summer insolation, that is). But northern hemisphere climate was not completely warmed.
- Why wasn't it also "Warm Max"?
- Because the ice sheets were still large
  - regional cooling effects
  - ice albedo

"Insolation Max" Climate
- Summer monsoon rains were strong in northern Africa and southern Asia due to very strong summer heating.
- North African lake levels were high

Northern hemisphere summer insolation has continued to decline for the past 10,000 years.
- northern African lake levels declined from highs around 8,000 - 9,000 years ago to low levels by ~4,0000 years ago (most dried up) as a result of weakening summer monsoonal circulation

"Warm Max" was about 6,000 years ago
- after insolation max (why?)
- after the glaciers were gone! (no more regional cooling effect from glaciers)
- and summer insolation was still ~5% greater than today

Climate Changes Since "Warm Max"
- decreased glacial melting on arctic islands ice caps
- increased sea ice cover off Greenland
- glaciers on Svalbard Island have advanced
- decreased sea surface temperature in North Atlantic off Norway
- 300 km southward shift of Canadian boreal forest

Northern hemisphere summer insolation is near a minimum today.
It will stay near this level for the next 15,000 years.
- Will northern hemisphere glaciers begin to grow again or have we changed the atmosphere to the point where that won't happen?