CLIMATE LECTURE 16: The Importance of Understanding the Last Glacial Maximum for Climate Change


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The Importance of Understanding the Last Glacial Maximum for Climate Change

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Introduction

The last glacial maximum (LGM) at approximately 23–18k (k—thousand calendar years) provides an important contrast to our present and pre-industrial climate in a warming world. Global observational datasets of LGM land and sea surface conditions have been synthesized and present some interesting challenges both for providing another scenario for understanding climate change and for climate sensitivity. These challenges are ongoing, as data increase and modeling improves. By definition, the LGM is defined as the time during the last glacial interval in which maximum ice was sequestered in ice sheets as visible in the marine isotopic records. Maximum cooling is visible from pollen and macrofossil records $^{14}$C dated to this interval, and ice sheets and alpine glaciers are roughly at their maximum extent throughout the globe. The ice cores extracted from Greenland and Antarctica have given us high-resolution records of greenhouse gases, dust, and isotopes of hydrogen and oxygen which reveal the progression out of the LGM at 18k as climate warmed.

One of the first challenges addressed by D. Rind and D. Peteet (1985) was the disparity in temperature estimates they noted for the glacial using terrestrial vs. marine data. The disparity was very large, for while the marine sea surface temperature (SST) dataset produced by the Climate Long-range Investigation, Mapping, and Prediction group (CLIMAP, 1981) showed large areas of the subtropical ocean to be warmer than today at the LGM, both pollen data and glacial moraines indicated cold temperatures in the tropics and subtropics. The Rind and Peteet (1985) primary contribution was to show that modeling with the CLIMAP SST dataset did not produce enough surface air cooling to match the terrestrial
data. In particular, regions with both pollen and glacial evidence for strong cooling such as East Africa, Indonesia, and Hawaii were not cool enough to generate such change. A companion experiment with SST’s reduced everywhere by 2°C was in better agreement with the land data, but in some locations still not in agreement with the freezing line and pollen evidence of cooling. Similar modeling experiments by other groups produced similar results. One question posed was whether the lapse rate in tropical regions could have increased, but current understanding of atmospheric dynamics suggests that a strong divergence of the tropical LGM lapse rate from the moist adiabatic value is implausible. David Rind’s research on atmospheric dynamics was central to this conclusion. Moist convection still represents the dominant vertical heat-transporting process at low latitudes (Webster and Streeten, 1978), as Rind and Peteet argued in this paper.

Subsequent significant efforts in both the marine and the terrestrial realm have been targeted at the question of LGM conditions in various parts of the globe, but the subtropics in particular is where the conflict in temperature estimates is large. Several new techniques for determining temperature shifts were employed, including determining the content of noble gases in groundwater. A decade later, Stute et al. (1995) presented a terrestrial dataset from Texas to lowland Brasil (40°N–40°S) including new groundwater samples which showed significant cooling (5–6°C) in the same region that faunal abundances from CLIMAP (1981) showed very little change (2°C). However, Sr/Ca ratios and oxygen isotope ratios in corals also showed a much stronger cooling, implying that the subtropics and tropics were cooler than CLIMAP reconstructions implied (Guilderson, Fairbanks, and Rubenstone, 1994). However, alkenone data and some isotopic data were still in conflict, and the debate continues.

A decade later, a series of Paleoclimate Model Intercomparison Project (PMIP2) experiments focused on the LGM with newer climate models that were state-of-the-art and included an interactive ocean. These experiments included coupled simulations with the thermohaline circulation (THC) shifts as well as changes in vegetation albedo feedbacks (Braconnot et al., 2007). Some of these experiments included model results that had colder oceans than previously indicated by CLIMAP, and comparisons were made suggesting moisture shifts indicating more global aridity than previously modeled.

The 2007 Intergovernmental Panel on Climate Change (IPCC, 2007) showed a map of the difference in temperature between LGM and today, illustrating temperature shifts in the tropical oceans of not more than 2.5°C overall, but significantly colder than CLIMAP. Yet the radiative perturbation representing the forcings is presented with high scientific understanding of the forcings of orbital shift and greenhouse gases such as CO₂ and CH₄, but low understanding of the forcings of ice sheets, mineral dust, and vegetation. One of the benefits of numerous modeling efforts has been the understanding of how important the ocean circulation and SST forcing can be in influencing the global temperature. At the same time, it is clear that greenhouse gas forcings have been important but that shifts in vegetation, and feedbacks in albedo and the carbon cycle from those vegetational shifts can also be important. It is still unclear what the effects of the lowered carbon dioxide on vegetation really were, because experiments on vegetation with lowered CO₂ are difficult. It is also difficult to separate the effects of lowered temperature from moisture on vegetation, and
more multidisciplinary studies are needed using a variety of proxies at one site (i.e., deuterium isotopes in leaf waxes, pollen, macrofossils, bryophytes, glaciers, etc.)

One of the modeling experiments (Crucifix, 2006) posed the question as to whether the LGM constrained climate sensitivity. A set of experiments with four different models showed large variation in short-wave cloud feedbacks at low latitudes both during the LGM and in the 2 × CO₂ experiment. For the latter, they get a climate sensitivity ranging from 2.1 to 3.9 °C, while the sensitivity of the LGM, they concluded, cannot be calculated because the amount of actual forcing of cooling from greenhouse gases and the feedbacks is not known. Another modeling experiment used ensembles of 100 paired runs for pre-industrial and LGM boundary conditions and found global sensitivity was 4.3–9.8 °C, due to changes in both vegetation and dust. Using a reconstructed tropical SST (30°N–30°S) cooling of 2.7 ± 1 °C, they constrained the range to 5.8 +1.4 °C, larger than most estimates (Schneider von Demling, Held, Ganopolski, and Rahmstorf, 2006). Recent attention to climate sensitivity has focused on the need to include fast feedbacks (such as climate-greenhouse gas) as well as slower feedbacks such as ice sheets and vegetation, although the name of this quest has shifted from ‘climate sensitivity’ to ‘earth sensitivity’ (Previdi et al., 2013). This change in our understanding of the importance of feedbacks for greenhouse gases and vegetation has large implications for understanding climate sensitivity of the LGM as well as for doubled CO₂.

Beyond looking at an equilibrium LGM climate, it is useful to understand the forcings that shifted the LGM towards warming. Questions concerning the triggers for warming focus on the very small orbital shifts and on ocean circulation as well as greenhouse gases. Comparison of Northern and Southern Hemispheres and the shift towards warming in each and the timing of this warming becomes critical to understanding how the climate system works. Rapid feedbacks such as shifts in the THC and sea ice must be important, as well as aerosols. Attention to detailed records of land, sea, and ice cores aid in piecing together this puzzle, which provides clues to how our climate system functions. Polar ice cores indicate dust deposition rates average 2–20 times greater during the LGM compared to the Late Holocene in some regions (Mahowald et al., 1999); and links to possible ocean fertilization and shifts in the strength and the change in the position of the Southern Hemisphere westerly winds has been used to explain climate fluctuations through the carbon cycle and greenhouse gas forcing (Anderson et al., 2009). Kohfeld et al. (2013) assembled datasets relevant to changes in the westerly winds and concluded that either the stronger or equatorward-shifted wind scenarios appear easier to tie to evidence for increased moisture on the west coast of continents, cooler temperatures and higher productivity in the southern ocean. However, they caution that many assumptions limit the certainty with which winds can be invoked as responsible for controlling glacial–interglacial conditions.

Defining the details of the termination of the LGM includes both the timing and the characteristics of the retreating ice sheet. The history of the retreat of the southeastern margin of the Laurentide Ice Sheet (LIS) is particularly relevant today as Greenland warms and meltwater enters the N. Atlantic. The conventionally accepted ages of the LGM retreat of the southeastern LIS are 26–21 calendar kyr (cal. kyr) (derived from bulk-sediment radiocarbon
ages) (Stone and Borns, 1986) and 28–23 cal. kyr (varve estimates) (Ridge, 2004), but these estimates are problematic because they are so early.

Cosmogenic-nuclide exposure dating of the LGM requires the derivation of a local nuclide production rate. Balco and Schaefer (2006) first derived a production rate for 10Be using primarily radiocarbon dates of bulk sediment and/or varves, and derived an age of deglaciation of 22 cal. kyr. However, more recently Balco et al. (2009) utilized varve chronologies from New England to re-calculate the deglacial age for the New Jersey terminal moraine near 25 cal. kyr, and the Connecticut moraines at 21 cal. kyr (see arrows in Slide 19). Using accelerator mass spectrometry (AMS) 14C dating of initial macrofossils in 13 lake/bog inorganic clays, Peteet et al. (2012) find that vegetation first appeared on the landscape at 16 cal. kyr, suggesting that ice had not retreated until that time. The gap between previous age estimates is significant and has large implications for understanding the meltwater timing and links to shifts in THC. This new AMS chronology of LIS retreat is consistent with marine evidence of deglaciation from the North Atlantic, showing significant freshwater input and sea level rise only after 19 cal. kyr with a cold meltwater lid, perhaps delaying ice melt. It is also more consistent with the rise of greenhouse gas forcing beginning at 18k.

Key questions remain in our understanding of the LGM, its forcings, and climate sensitivity. These questions are relevant as we prepare for further warming with greenhouse gas increases and the feedbacks that accompany those increases. Hundreds of investigations have generated LGM data on land, ocean, and ice throughout the globe, and these are extremely valuable. Some questions that remain include the question of where the warming began (Northern or Southern Hemisphere) and whether the insolation increase was great enough to initiate Northern Hemisphere ice melt. If so, does this help explain the 100k cycle in paleorecords? Exactly, how strong are the forcings from the increases in carbon dioxide and methane throughout the deglaciation, and how strongly does ocean circulation control the CO₂ rise and then how important is the CH₄ forcing? As permafrost melts today, how important is the release of these greenhouse gases in changing our future temperature, and how much carbon will the ocean and northern peatlands sequester? How will Greenland meltwater affect the THC? Many other questions remain for us to investigate.

References


Intergovernmental Panel on Climate Change (IPCC). (2007).


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Slide 2

Definition of LGM

- Equilibrium climate 22-18k very different from today but with same continent configuration
- Climate processes same as today
- Vegetation same species as today
- Variation in orbital configuration, greenhouse gases, dust content
- C-14 and U-Th useful for dating
Evidence of LGM

- Pollen and macrofossils in sediment cores
- Isotopes in marine, ice, speleothem cores
- Glacial moraines
- Loess
- Marine fossils

LGM Extended Coastlines

LGM extended coastlines: sea-level drop of 120 m computed from global bathymetry (Smith and Sandwell, 1997) in Ray and Adams (2001).
LGM stability, then rise of CO$_2$ & CH$_4$ in ice cores at 18k

— Parrenin et al. (2013).

Time series during the last termination (Parrenin et al., 2013). Shown are δD from Dome C, Ant. (purple), Ant. Temp. stack (dark blue), atmospheric CO$_2$ (light green), radiative forcing of atmospheric CO$_2$ (dark green), atmospheric CH$_4$ (red), and δ$^{18}$O from NorthGRIP, Greenland (grey).

Modeling the LGM

Rind and Peteet (1985)

- Use of boundary conditions—CLIMAP (1981) land ice, sea ice, sea surface temperature, land albedo

- Results: Parts of subtropics air temperature is warmer than today...thus conflicts with terrestrial data...question of lapse rate increase posed.
LGM to Modern temperature change using CLIMAP data. Note resulting warm air temperatures generated by warm SSTs in the model—this is in contrast to glacial advances and pollen evidence of temp declines in East Africa, Indonesia, S. America, and Hawaii.

Data—LGM-Present Temp Difference

Temperature difference in degrees Celsius between the present and LGM derived from both ocean and continental records. Sites include those derived from noble gases, pollen data, Sr/Ca ratios, isotopes, and snow lines. Note large temperature difference in tropics from noble gases in groundwater (dark triangles) (Stute et al., 1995).
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**Moisture Differences Between the LGM and Present**

![Image](http://www.pnnl.gov/pns/docs/018943.pdf)

Slide 10

**LGM Temperature vs. Pre-Industrial Temperature—A Compilation from Data**

*Farerra et al. (1999)*

Mean Temperature of coldest month...back to conundrum with glaciers...drier overall
But had moisture for glaciers in tropics...cold
Forcings (LGM-present) & our understanding of them

Scientific Understanding
- Orbital
- \( CO_2 \)
- \( CH_4 + N_2O \)
- Dust
- Vegetation
- Continental ice + sea level

Sea Surface Temperature Change (°C)

Regional Temperature Change ('Cooling')
- Central Antarctic
- Tropical Indian
- North Atlantic

Global Temperature Change ('Cooling')

IPCC (2007)

LGM Boundary Conditions for more Recent Modeling

- Large ice sheets at high latitudes and expanded mountain glaciers
- Sea level drop of 120 m
- Colder ocean temperatures throughout the globe ...but how cold, and what are transports?
- Vegetation shifts due to cooling, moisture change, albedo feedbacks, and the carbon cycle?
- Vegetation shifts due to lower \( CO_2 \)?
- \( CO_2 \) and \( CH_4 \) at low values
**Model-model Variability in Climate Sensitivity**

Partial radiative feedback parameters to the LGM forcing (white) and CO₂ doubling (black)

PMIP2, four models used (HadCM3, NCAR-CCSM3.0 (T42), IPSL-CM4 and MIROC3.2.)

Four models show large variations in short-wave cloud feedbacks at low latitudes with climate sensitivity of 2×CO₂ ranging between 2.1°C and 3.9°C, and LGM sensitivity not possible to calculate because forcings not known (Crucifix, 2006).

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**Tropical Forcing**

**Climate Sens. of 5.8°C—Large**

Schneider von Deimling et al. (2006) constrained the range of climate sensitivity to 5.8°C ±1.4°C, larger than most estimates...
Previdi et al. (2013) show that if climate sensitivity from fixed forcings (on left) is dependent only on fast feedbacks due to water vapor, clouds and sea ice, sensitivity to doubled CO₂ is only 3°C. In contrast, if changes in GHG feedbacks from climate-related terrestrial and marine C are included, the sensitivity to 2×CO₂ becomes greater than 4°C–6°C.

Data Compilation of LGM – Holocene Shifts

a) greater moisture on western side of continents,
b) abundant evidence of increases in dust,
c) SSTs warm in lower lats and cooler at high lats, and,
d) increase in export production at lower lats generally, with declines at higher latitudes.

Kohfeld et al. (2013)
Slide 17

LGM and Deglaciation

- Forcing of first warming?—abrupt shifts
- Land–ocean contrasts
- Trace gases
- N–S hemisphere contrast
- THC has power...affecting sea ice and winter temperature
- Aerosols?

Slide 18

New Timing of Laurentide Deglaciation

Suite of calendar ages (cal. kyr) calibrated from accelerator mass spectrometry (AMS) $^{14}$C dates on plant macrofossils at 13 NE US sites, including 7 new lakes. Dates cluster at 14.5–15.6 cal. kyr, with 2 sites 16.1 and 16.7 cal. kyr. Bulk radiocarbon ages (blue), are generally significantly older. 2s error bars are given. Peteet et al. (2012)
Greenland ice core oxygen isotopes (top), N. Atlantic SSTs (green, blue), ocean circulation changes (red), sea level rise (blue), insolation changes (brown), and pollen evidence (black) for warming during the LGM-Holocene transition. Orange stripe shows timing of Laurentide macrofossil AMS $^{14}$C de-glaciation in contrast to aqua and purple earlier $^{10}$Be chronologies.

Peteet et al. (2012)

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**Conclusions**

- Change in our understanding of the importance of feedbacks for greenhouse gases and vegetation has large implications for understanding climate sensitivity of the LGM, deglaciation, and doubled CO$_2$.

- Many questions remain which we can investigate using multidisciplinary methods.
Questions Remaining

- How are Northern and Southern hemispheres synchronized during shifts from LGM to present?
- Why is the 100k cycle dominant in paleo records?
- How strong a forcing are CO₂ and CH₄?
- Permafrost melt and methane release vs. net C increase?
- Runoff of water to arctic in shifting climate?
Slide Notes

Slide 1  Photo of a large piedmont glacier, the Bering Glacier, AK, 1984, the size of Rhode Island and a possible diminutive modern analog for the Laurentide Ice Sheet.

Slide 2  Definition of the LGM between approximately 22–18k ago. It represents an equilibrium climate comparable to pre-industrial climate when our continents were in the same position as today. We assume that climatic processes and vegetation types were the same, but that variations in boundary conditions such as orbital configuration, greenhouse gas composition, and dust content of the atmosphere were different.

Slide 3  Evidence of the LGM is visible in both terrestrial and marine archives, including pollen and macrofossils from vegetation, glacial moraines left by ice sheets and alpine glaciers, loess deposits of windblown outwash near glaciated regions, and marine microfossils as well as oxygen and carbon isotopes recorded in marine and ice cores and speleothems.

Slide 4  Estimates of sea level lowering of 120 m are derived from several lines of evidence including corals, isotope records from benthic foraminifera, glacial isostasy, and ice margin reconstructions.

Slide 5  Ice core records from both poles show stability of low values of CH₄, CO₂, and oxygen and hydrogen isotopes at the LGM between 22 and 18k (figure from Parrenin et al., 2013).

Slide 6  Use of the dataset compiled by CLIMAP (1981) for GCM modeling included LGM estimates of land ice, sea ice, SST, and terrestrial surface albedo.

Slide 7  Results of GISS GCM modeling of the LGM indicated an inconsistency in air temperatures with the terrestrial (pollen and glacial) data in the subtropics (Rind and Peteet, 1985), and a very low climate sensitivity of only 3°C.

Slide 8  Stute et al. (1995) showed the consistent terrestrial dataset from Texas to lowland Brasil (40°N–40°S) including new groundwater samples which showed significant cooling (5–6°C) in the same region that faunal abundances from CLIMAP (1981) showed very little change (2°C).

Slide 9  Moisture differences between the LGM and today based upon paleodata (PMIP2).

Slide 10  Farrera et al. (1999) compiled the temperature shifts from both land and ocean throughout the tropics, and concluded that the tropics were colder than the CLIMAP reconstructions, and that lapse rates must have been steeper.

Slide 11  The 2007 IPCC (IPCC, 2007) showed a map of the difference in temperature between LGM and today, illustrating temperature shifts in the tropical oceans of not more than 2.5°C overall, but significantly colder than CLIMAP. Yet the radiative perturbation representing the forcings is presented with high scientific understanding of the forcings of orbital shift and greenhouse gases such as CO₂ and CH₄, but low understanding of the forcings of ice sheets, mineral dust, and vegetation.
More recent coupled GCM modeling experiments include questions about ice sheets, THC circulation, and feedbacks in the carbon cycle with varying boundary conditions. Questions that may help us understand the LGM include those that focus on the uncertainties in ocean circulation and SST, temperature gradients throughout the oceans, the role of the greenhouse gases in forcing temperature change in the de-glaciation just following the LGM, the climate sensitivity of the earth, and the timing and forcing of the last de-glaciation.

One of the modeling experiments (Crucifix, 2006) posed the question as to whether the LGM constrained climate sensitivity. A set of experiments with four-different models showed large variation in short-wave cloud feedbacks at low latitudes both during the LGM and in the $2 \times CO_2$ experiment. For the latter, they get a climate sensitivity ranging from 2.1 to 3.9°C, while the sensitivity of the LGM, they concluded, cannot be calculated because the amount of actual forcing of cooling from greenhouse gases and the feedbacks is not known.

Using a reconstructed tropical SST (30°N–30°S) cooling of 2.7 +1°C, these modelers constrained the range to 5.8 +1.4°C, larger than most estimates (Schneider von Demling et al., 2006).

In a study of climate sensitivity, Previdi et al. (2013) showed that climate or ‘earth’ sensitivity is increased greatly if feedbacks such as ice sheets and greenhouse gases are included with terrestrial change.

Kohfeld et al. (2013) assembled southern hemisphere datasets of (a) moisture, (b) dust, (c) SST, and export production which are relevant to changes in the westerly winds. They conclude that either the stronger or equatorward-shifted wind scenarios appear easier to tie to evidence for increased moisture on the west coast of continents, cooler temperatures and higher productivity in the southern ocean, but caution that other interpretations are possible.

Understanding the termination of the LGM is important for learning how the climate system works. Key questions include examining the forcing for warming, the hemispheric responses in timing and magnitude, the greenhouse gas records and their relationship to surface air temperature on land and the vegetation, oceanic, and glacial responses. Aerosols such as dust may be very important.

Understanding linkages among ocean, atmosphere, and land is key to discerning causes of climate change. Careful attention to timing of de-glaciation has resulted in recent attention to the southeastern Laurentide margin, where AMS dating of macrofossils provides a suite of dates that define de-glaciation close to 16 cal. kyr = 16k (Peteet et al., 2012).

This new AMS-dated timing is 5–9k later than the previously accepted age of 21–25k for de-glaciation as evidenced by varves and $^{10}$Be dating of glacial moraines. However, it agrees with sea level rise and marine and ice core evidence of warming. The topic is controversial and needs further attention.

Key questions remain in the understanding of forcings and climate sensitivity. These questions are also very important in preparing for future climate shifts with global warming.