Lectures in Climate Change: Volume 1

Our Warming Planet
Topics in Climate Dynamics

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

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, l981) 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 (l985) 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*. (l995) 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 (l981) 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, l994). 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 CO_2 and CH_4, 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 CO_2 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 × 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. 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 CO_2.

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, l986) 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 CO_2 rise and then how important is the CH_4 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

Anderson, R.F., Ali, S., Bradtmiller, L., Nielsen, S., Fleisher, M., Anderson, B. and Burckle, L.H. (2009). Wind-drivenupwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. *Science*, **323**, 1443–1448.

Balco, G. and Schaefer, J.M. (2006). Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England. *Quaternary Geochronology*, **1**, 15–28. doi:10.1016/j.quageo.2006.06.014.

Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C. and Schaefer, J.M. (2009). Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology*, **4**, 93–107.doi:10.1016/j.quageo.2008.09.001.

Braconnot, P., Otto-Bliesner, B.S., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., and Zhao, Y. (2007). Results of PMIP2 coupled simulations of the mid-holocene and last glacial maximum–Part 1: Experiments and large-scale features. *Climates of the Past,* **3**, 261–277.

CLIMAP Project Members. (1981). Seasonal reconstructions of the earth's surface at the last glacial maximum. *Geological Societyof America Map and Chart Series*, MC-36, 18.

Crucifix, M. (2006). Does the last glacial maximum constrain climate sensitivity? *Geophysical Research Letters,* **33**, L18701. doi:10.1029/2006GL027137.

Farrera, I., Harrison, S.P., Prentice, I.C., Ramstein G., Guiot, J. and Yu, G. (1999). Tropical paleoclimates at the Last Glacial Maximum: a new synthesis of terrestrial data. I. Vegetation, lake levels, and geochemistry. Climate Dynamics **15**(1), 823–856. doi:10.1007/s003820050317.

Guilderson, T., Fairbanks, R.G. and Rubenstone, J. (1994). Tropical temperature variations since 20,000 years ago: Modulating interhemispheric climate change. *Science*, 263, 663–664.

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

Kohfeld, K., Graham, R.M., de Boer, A.M., Sime, L.C., Wolff, E.W., LeQuere, C. and Bopp, L. (2013). Southern hemisphere westerly wind changes during the last glacial maximum: Paleo-data synthesis. *Quaternary Science Reviews*, **68**, 76–95.

Mahowald, N., Kohfeld, K., Hansson, M., Balkanski, Y., Harrison, S., Prentice, C., Schulz, M. and Rodhe, H. (1999). Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments. *Journal of Geophysical Research,* 1041, D13, 15895–15916.

Parrenin, F., Masson-Delmotte, V., Kohler, P., Raynaud, D., Paillard, D., Schwander, J., Barbante, C., Landais, A., Wegner, A. and Jouzel, J. (2013). Synchronous change of atmospheric CO_2 and Antarctic temperature during the last deglacial warming. *Science*, **339**, 1060–1063.

Peteet, D., Beh, M., Orr, C., Kurdyla, D., Nichols, J. and Guilderson, T. (2012). Delayed deglaciation or extreme Arctic conditions 21–16 cal. kyr at southeastern Laurentide Ice Sheet margin? *Geophysical Research Letters*, **39**, L11706. doi:10.1029/2012GL051884.

Previdi, M., Liepert, B.G., Peteet, D., Hansen, J., Beerling, D., Broccoli, A.J., . . . Ramaswamy, V. (2013). Climate sensitivity in the Anthropocene. *Quarterly Journal of the Royal Meteorological Society*. doi:10.1002/qj.2165.

Ridge, J.C. (2004). The Quaternary glaciation of western New England with correlations to surrounding areas. In J. Ehlers and P.L. Gibbard (Eds.), *Quaternary Glaciations-Extent and Chronology Part II* (pp. 169–199), Amsterdam: Elsevier. doi:10.1016/S1571-0866(04)80196-9.

Rind, D. and Peteet, D.M. (1985). Terrestrial conditions at the last glacial maximum and CLIMAP sea surface temperature estimates: Are they consistent? *Quaternary Research*, **24**, 1–22.

Schneider von Deimling, T., Held, H., Ganopolski, A. and Rahmstorf, S. (2006). Climate sensitivity estimated from ensemble simulations of glacial climate. *Climate Dynamics*, **27**, 149–163. doi:10.1007/s00382-006-0126-8.

Stone, B. and Borns, H.W.J. (1986). Pleistocene glacial and interglacial stratigraphy of New England, Long Island, and adjacent Georges Bank and Gulf of Maine.*Quaternary Science Reviews*, **5**, 39–52.

Webster, P. and Streten, N. (1978). Late Quaternary ice age climates of tropical Australasia, interpretation and reconstruction. *Quaternary Research,* **10**, 279–309.

Slide 1

The Importance of Understanding the Last Glacial Maximum for Climate Change

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Bering Glacier, AK, 1987

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

Slide 3

Evidence of LGM

Pine pollen

Dryas leaf

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

Dwarf birch cone scale

Foraminifera

Sediment core

Tundra Dryas fruits

Peteet, D.   The Importance of Understanding the Last Glacial Maximum for Climate Change   3

Slide 4

LGM Extended Coastlines

Coastlines
- Extended (-120m)
- Present

LGM extended coastlines: sea-level drop of 120 m computed from global bathymetry (Smith and Sandwell, 1997) in Ray and Adams (2001).

Peteet, D.   The Importance of Understanding the Last Glacial Maximum for Climate Change   4

Slide 5

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).

LGM stability, then rise of CO_2 & CH_4 in ice cores at 18k

— Parrenin *et al.* (2013).

Slide 6

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.

Slide 7
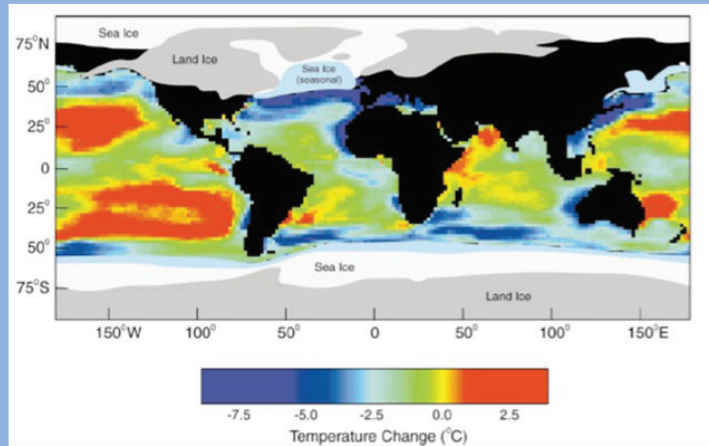
LGM to Modern temperature change using CLIMAP data. Note resulting warm air temperatures generated by warm SSTs in the model—this is in contrast to glacial advances and pollen evidence of temp declines in East Africa, Indonesia, S. America, and Hawaii.

Peteet, D.   The Importance of Understanding the Last Glacial Maximum for Climate Change   7

Slide 8
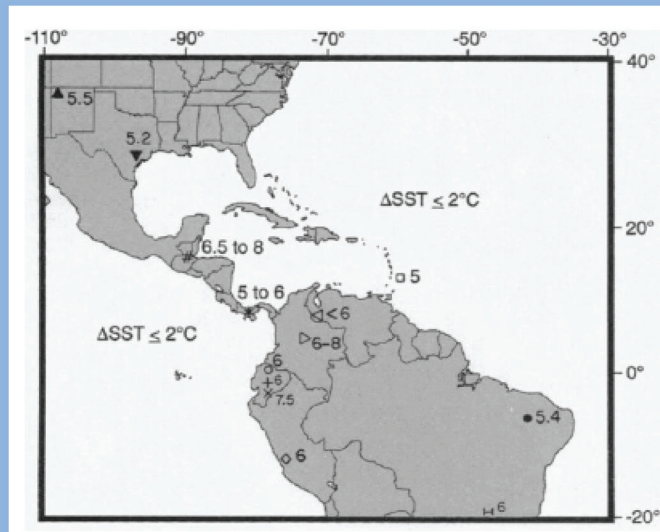
Data from Stute *et al.* (1995)

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).

Peteet, D.   The Importance of Understanding the Last Glacial Maximum for Climate Change   8

Slide 9

Moisture Differences Between the LGM and Present

http://www.pmip2.cnrs-gif.fr/pmip2/share/synth/glsdb/lakes.png

Peteet, D.   **The Importance of Understanding the Last Glacial Maximum for Climate Change**   9
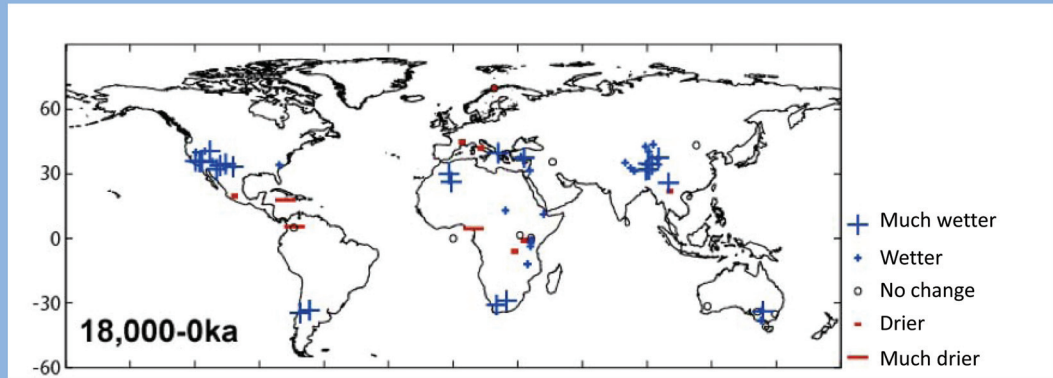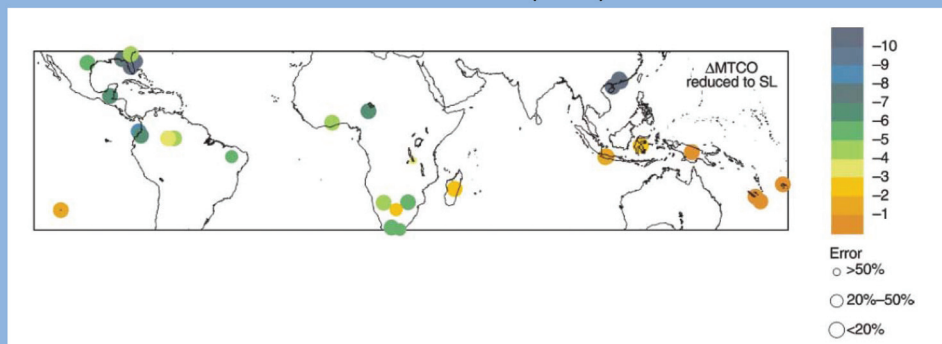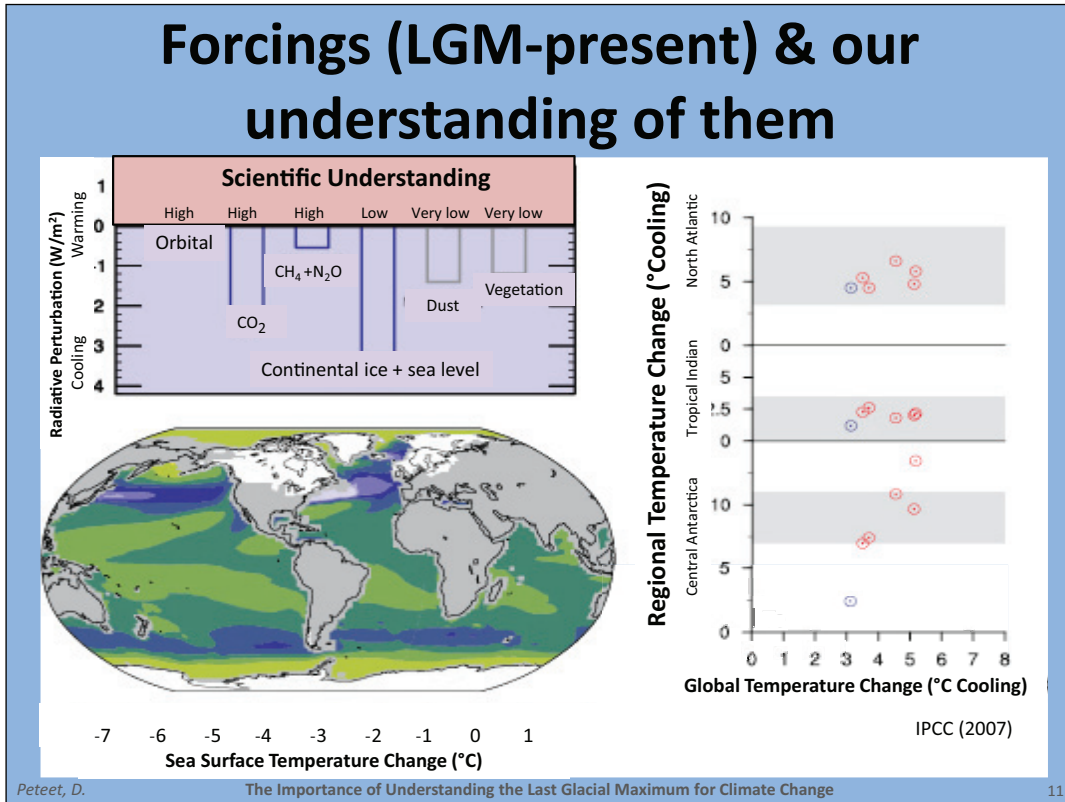
Slide 10

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

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Slide 11

Forcings (LGM-present) & our understanding of them

Slide 12

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

Slide 13

Model-model Variability in Climate Sensitivity

L18701   CRUCIFIX: LGM AND CLIMATE SENSITIVITY   L18701
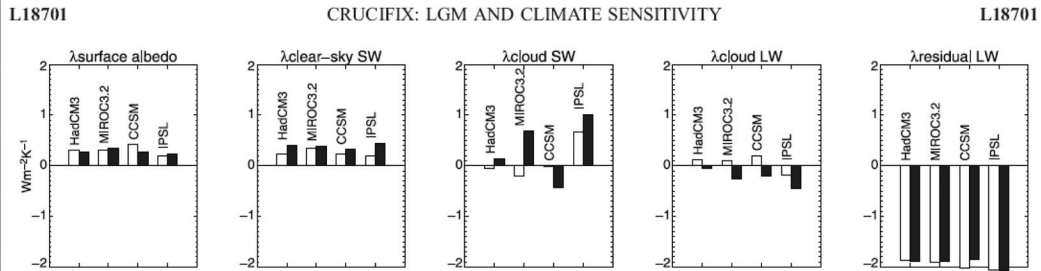
Partial radiative feedback parameters to the LGM forcing (white) and CO_2 doubling (black)

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 $2 \times CO_2$ ranging between 2.1°C and 3.9°C, and LGM sensitivity not possible to calculate because forcings not known (Crucifix, 2006).

Slide 14

Tropical Forcing
Climate Sens. of 5.8°C—Large
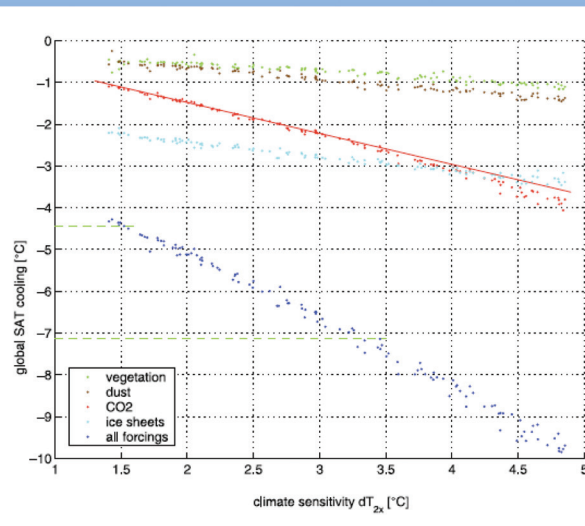
Schneider von Deimling *et al.* (2006) constrained the range of climate sensitivity to 5.8°C ±1.4°C, larger than most estimates…

Slide 15

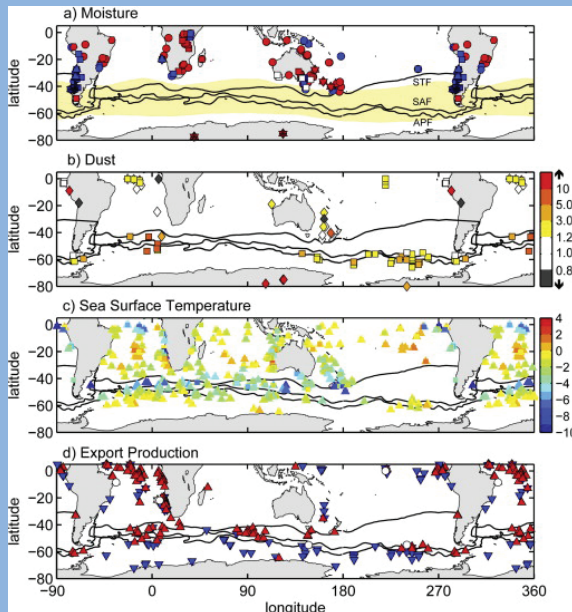
Climate Sensitivity to 2×CO$_2$
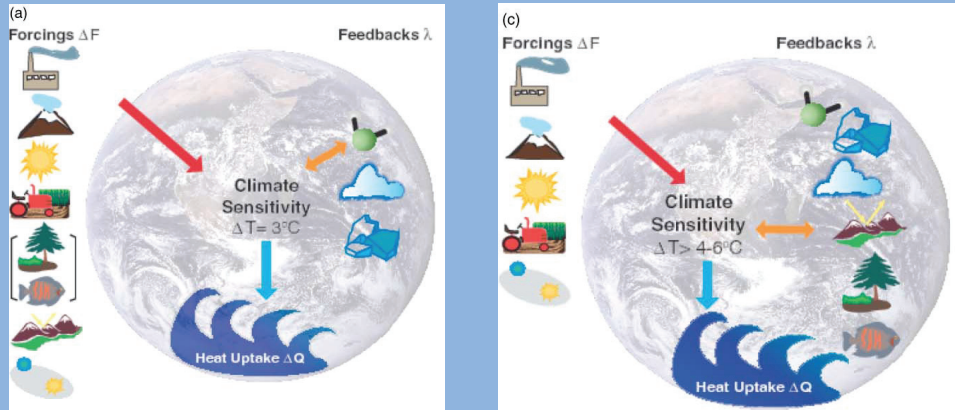
Previdi *et al.* (2013) show that if climate sensitivity from fixed forcings (on left) is dependent only on fast feedbacks due to water vapor, clouds and sea ice, sensitivity to doubled CO$_2$ is only 3°C.

In contrast, if changes in GHG feedbacks from climate-related terrestrial and marine C are included, the sensitivity to 2×CO$_2$ becomes greater than 4°C–6°C .

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Slide 16

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.
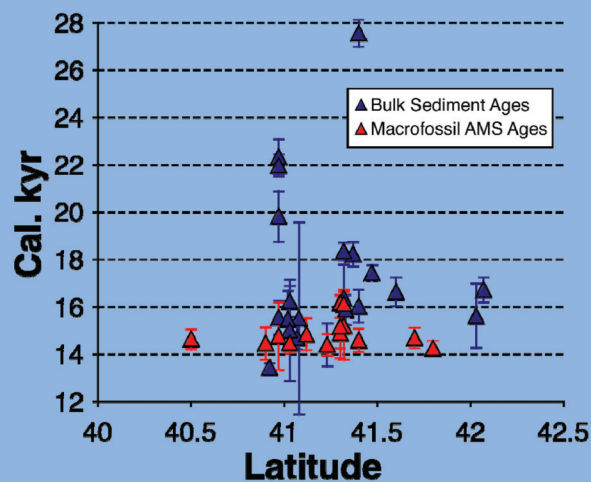
Kohfeld *et al.* (2013)

Peteet, D.   **The Importance of Understanding the Last Glacial Maximum for Climate Change**   16

Slide 17

Slide 18

Slide 19

Timing of Deglaciation from Ice, Ocean, Land

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)

Peteet, D.   The Importance of Understanding the Last Glacial Maximum for Climate Change   19

Slide 20

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.

Peteet, D.   The Importance of Understanding the Last Glacial Maximum for Climate Change   20

Slide 21

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 CH_4, CO_2, 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 (l981) 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, l985), 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 (l981) 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 CO_2 and CH_4, but low understanding of the forcings of ice sheets, mineral dust, and vegetation.

Slide 12   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.

Slide 13   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.

Slide 14   Using a reconstructed tropical SST (30°N–30°S) cooling of 2.7 +1°C, these model-ers constrained the range to 5.8 +1.4°C, larger than most estimates (Schneider von Demling *et al.*, 2006).

Slide 15   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.

Slide 16   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 west-erly 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.

Slide 17   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.

Slide 18   Understanding linkages among ocean, atmosphere, and land is key to discern-ing 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).

Slide 19   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.

Slide 20   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.