HIGH RESOLUTION LGM SIMULATIONS OVER THE LAURENTIDE ICE SHEET USING POLAR MM5

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1. INTRODUCTION

Understanding and properly simulating past climate regimes is key to predicting future climate change and perhaps no other period has been studied as intensively as the Last Glacial Maximum (LGM). During this interval, approximately 21,000 calendar years before present (21 kBP; Mix et al. 2001), the Laurentide and Fennoscandian ice sheets covered much of North America and Scandinavia, respectively, and the climate was much colder than present. The relative abundance of proxy data available from the LGM provide boundary conditions for atmospheric global climate model (GCM) simulations with the specification of the sea surface temperature (SST) boundary condition being of first order importance.

CLIMAP (Climate/Long-range Investigation, Mapping, and Prediction; CLIMAP 1976, 1981) produced the first systematic, global SST reconstruction for the LGM derived from the distribution of plankton in marine sediment cores. The CLIMAP annual mean SSTs are fairly similar to present values with modest (1-2^{o}C) cooling in much of the deep Tropics and slight warming in the Pacific subtropical gyres. However, GCM simulations of the LGM climate using the CLIMAP SST distribution have been unable to reproduce the magnitude of atmospheric cooling implied by proxy data (Rind and Peteet 1985). Evidence from ice-age corals (Guilderson et al. 1994), snowline depressions (Rind and Peteet 1985), noble gases (Stute et al. 1992; Stute et al. 1995a,b), pollen (Colinvaux et al. 1996), and tropical alpine glaciers (Thompson et al. 1995, 1998, 2000) indicates that LGM temperatures were 3-5^{o}C cooler than today. Although a recent reassessment of the CLIMAP faunal data may have resolved some of the discrepancy with the proxy data (Crowley 2000), there is general agreement that the CLIMAP SSTs, particularly in the Tropics, are too warm.

Previous LGM climate modeling studies use global atmospheric GCMs only, which, even at the smallest currently available resolution (2.8^{o} lat/lon grid), are unable to capture mesoscale processes associated with large ice sheets (e.g., katabatic winds). In the present study, the Polar MM5 (PMM5; Bromwich et al. 2001), a modified version of the Pennsylvania State University (PSU) / National Center for Atmospheric Research (NCAR) fifth-generation mesoscale model (MM5; Dudhia 1993; Grell et al. 1994), is coupled to the NCAR Community Climate Model version 3 (CCM3; Kiehl et al. 1998) for simulations of the LGM climate over the Laurentide Ice Sheet. Boundary conditions include 21 kBP orbital forcing, trace gases, vegetation, sea level, and a modified version of the CLIMAP SSTs based on proxy data. The objective is to assess the atmospheric state over the Laurentide Ice Sheet with model resolution sufficient to adequately quantify temperature, precipitation, and flow regimes that contribute to ice sheet growth and ablation.

Section 2 briefly describes the PMM5, the LGM boundary conditions, and the modeling approach used for the experiments. Section 3 compares preliminary results from one-month simulations of the LGM and present-day climate with conclusions in Section 4.

2. POLAR MM5 AND EXPERIMENTAL DESIGN

The PMM5 used in the current study is based on the standard release MM5 version 3.4 and features several modifications to optimize model performance over polar regions. These include: implementation of the Meyers et al. (1992) ice nuclei concentration equation to correct a bias in the high cloud amount; improved treatment of cloud/radiation interaction using predicted cloud water and ice; improved treatment of boundary layer fluxes via the 1.5 order turbulence closure parameterization (Janjić 1994); increased number of soil substrate levels and depth to more accurately resolve heat transfer; improved treatment of thermal properties of ice and snow surface types (following Yen 1981); implementation of a variable sea ice thickness and open water fraction. The PMM5 has been tested extensively over present-day Greenland (Bromwich et al. 2001; Cassano et al. 2001) and Antarctica (Bromwich et al. 2002; Guo et al. 2002) and shown to have generally minimal bias. Hence, the PMM5 is well-suited for simulations over the Laurentide Ice Sheet, which at the LGM had spatial dimensions similar to present-day Antarctica.

The PMM5 LGM and present-day simulations are run at a 60-km grid interval over a 8400 km x 7800 km domain centered over North America. Figure 1 shows the domain and terrain elevations for the LGM simulations. There are 29 vertical sigma levels and the model top is set to 10 hPa to minimize surface pressure anomalies resulting from vertically propagating gravity waves generated by steep terrain slopes (Guo et al. 2002). The Grell cumulus parameterization and Reisner microphysics option are used in all simulations.

For the LGM simulations, the Laurentide Ice Sheet elevation data were implemented from glaciological model output and sea level was lowered by 120 m commensurate with the LGM ice sheet volume (Jim Fastook, personal communication). The solar forcing was computed from 21 kBP orbital parameters (Berger 1977) and the CO_2 concentration was set to 180 ppm

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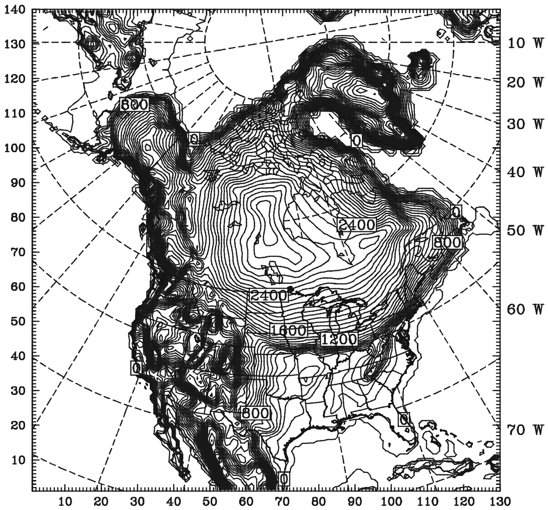

Figure 1. PMM5 domain and LGM terrain elevation. Contour interval is 100 m.

consistent with data from the Vostok ice core (Petit et al. 1999). Land use types were selected from among the 13 PSU/NCAR land use categories that best matched LGM vegetation reconstructions (Edwards et al. 2000; Thompson and Anderson 2000; Williams et al. 2000).

The LGM SSTs were derived by first cooling the annual mean CLIMAP SSTs by 4^{o}C in the tropical equatorial belt (30^{o}N-30^{o}S). From 30^o - 40^o latitude, the SSTs were linearly blended to the annual mean CLIMAP SST values, with CLIMAP values retained from 40^o - 90^o latitude. The present-day annual mean SST field was then subtracted from the modified annual mean CLIMAP SSTs and the difference field applied to the present-day monthly mean SSTs. The resulting annual mean SSTs are generally 2-4^{o}C cooler than the CLIMAP Tropics.

The PMM5 simulations are one-month continuous runs including a 6-day spin up that is discarded. National Centers for Environmental Prediction (NCEP)/NCAR reanalysis (NNR) data are used to provide initial and lateral boundary conditions for the present-day simulations, which focus on the extreme months January and July. To avoid strong El Niño/Southern Oscillation (ENSO) modulation, ten January and ten July months with near-neutral ENSO conditions are selected from the 50-year NNR record. The results for each month are a composite of ten simulations.

The initial and lateral boundary conditions for the LGM runs are from the final year of an 18-year CCM3 simulation. With the exception of modern vegetation and modified CH_4 levels in the CCM3 LGM run, the boundary conditions were identical to those used in the PMM5 LGM simulations.

In each month-long simulation, initial and lateral boundary conditions are updated every 12 hours. Model output is every 6 hours from which monthly averages are computed.

3. PMM5 RESULTS

The dominant feature in the January mean sea level pressure (MSLP) field for the LGM run is a large anticyclone centered west of Hudson Bay over the peak of the Laurentide Ice Sheet (Figure 2). Both the upstream Aleutian Low and the downstream Icelandic Low have deepened considerably (4 - 8 hPa) relative to their present-day counterparts (not shown). Mean January surface temperatures (Figure 3) at the LGM are sub-freezing over nearly all of North America with the coldest temperatures (< -45^{o}C) located south of Hudson Bay leeward of the Laurentide Ice Sheet elevation maximum. The coldest surface temperatures (< -60^{o}C) in the model domain occur over Greenland and are approximately 30 degrees colder than present (not shown).

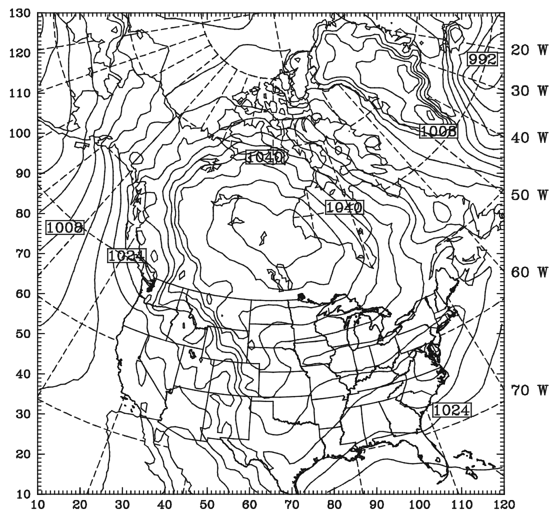

Figure 2. PMM5 LGM January mean sea level pressure. Contour interval is 4 hPa.

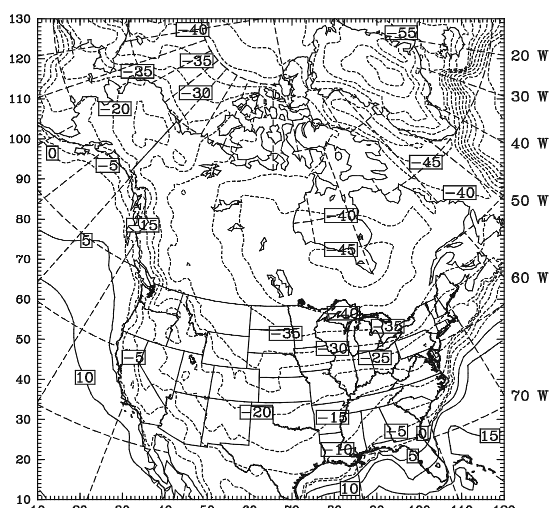

Figure 3. PMM5 LGM January mean near surface temperature. Contour interval is 5^{o}C.

The January mean near surface (10 m) winds and surface topography for the LGM run are shown in Figure 4. In response to the cold atmospheric temperatures, strong anticyclonic katabatic winds drain off the Laurentide Ice Sheet, exceeding 15-20 m s^{-1} along much of the sloped ice sheet terrain. The katabatic winds along the southern margin of the ice sheet encounter much weaker flow over the central U.S. implying enhanced low level mass convergence there. Strong southerly near surface winds also occur off the northwestern coast of North America in response to the MSLP gradient between the Aleutian Low and the anticyclone over the ice sheet. Katabatic winds also occur over Greenland at the LGM, but are weaker than in the present-day simulation.

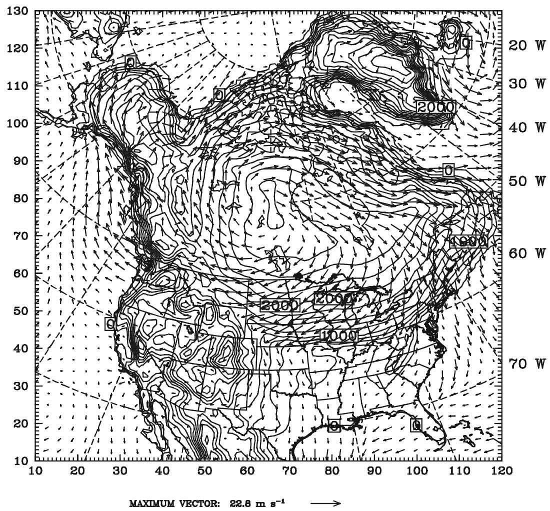

Figure 4. PMM5 LGM January mean near surface wind vectors (m s^{-1}) and contoured terrain elevation. Contour interval is 250 m.

The January mean 500 hPa geopotential height field for the LGM run is shown in Figure 5. The large anticyclone over the Laurentide Ice Sheet is evident at 500 hPa over western Canada. The downstream trough east of Greenland is considerably stronger, more amplified, and positioned further east than its present-day counterpart (not shown). The 500 hPa height field for the LGM suggests a split flow due to the presence of the ice sheet with a northern branch over Beringia and the Canadian Arctic islands and a southern stream affecting southern and southeastern North America.

The distribution of accumulated January precipitation is consistent with the upper level flow regime (Figure 6). Precipitation totals are maximized along the western margins of the Cordilleran ice sheet on the Alaska coast. Along the southern stream, relatively large accumulations (> 200 mm) occur along the west coast of North America, Mexico, and from the Gulf of Mexico northeastward to the western Atlantic Ocean. It is evident that the Gulf of Mexico is a primary winter moisture source for the eastern margins of the Laurentide Ice Sheet. Precipitation accumulation is also maximized in the North Atlantic. In contrast to the present-day, little or no accumulation occurs during January along the southeastern margins of Greenland, consistent with the southeastward displacement of the Icelandic Low at the LGM (see Figure 2).

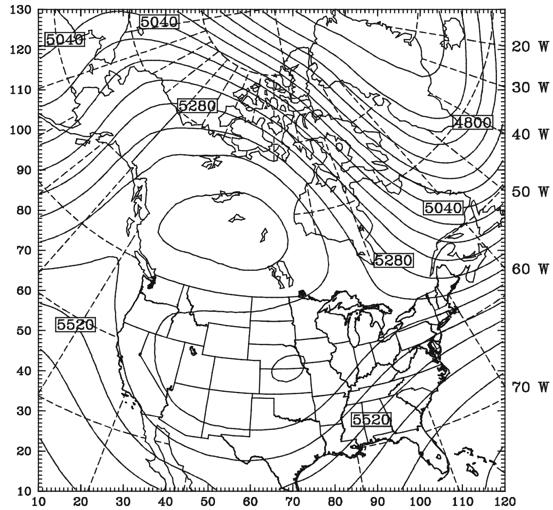

Figure 5. PMM5.LGM January mean 500 hPa geopotential height. Contour interval is 60 geopotential meters.

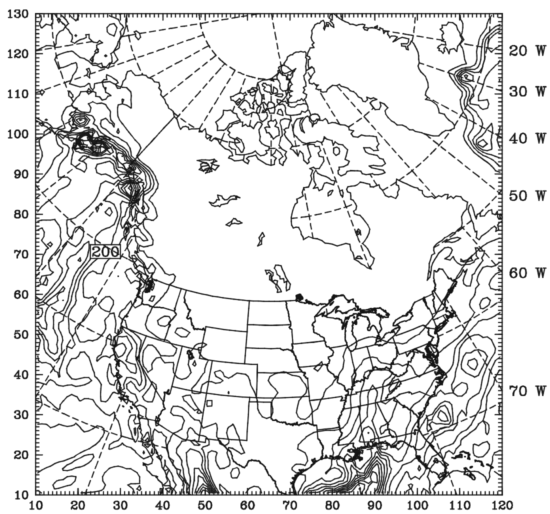

Figure 6. PMM5 LGM January accumulated precipitation. Contour interval is 50 mm.

4. CONCLUSIONS

The atmospheric circulation features apparent in the mean January results from PMM5 LGM simulations over the Laurentide Ice Sheet are generally consistent with previous GCM simulations of the LGM (e.g., Kutzbach et al. 1993), but at much higher spatial resolution. Obtaining a high-resolution depiction of the LGM climate over the Laurentide Ice Sheet, using optimal boundary conditions, is important for adequately quantifying, for instance, the distributions of temperature and precipitation that determine ice sheet mass balance. This, in turn, has direct implications for ice sheet growth and ablation and the subsequent feedback of the Laurentide Ice Sheet to the climate system. PMM5 LGM simulations are currently underway to complete a full annual cycle.

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REFERENCES

Berger, A., 1977: Long-term variations of the earth's orbital elements. *Celes. Mech.*, **15**, 53-74.

Bromwich, D. H., J. J. Cassano, T. Klein, G. Heinemann, K. M. Hines, K. Steffen, and J. E. Box, 2001: Mesoscale modeling of katabatic winds over Greenland with the Polar MM5. *Mon. Wea. Rev.*, **129**, 2290-2309.

Bromwich, D. H., A. J. Monaghan, J. J. Powers, J. J. Cassano, H. Wei, Y. Kuo, and A. Pellegrini, 2002: Antarctic Mesoscale Prediction System (AMPS): A case study from the 2000/2001 field season. *Mon. Wea. Rev.*, in press.

Cassano, J. J., J. E. Box, D. H. Bromwich, L. Li, and K. Steffen, 2001: Evaluation of Polar MM5 simulations of Greenland's atmospheric circulation. *J. Geophys. Res.*, **106**, 33867-33890.

CLIMAP Project Members, 1976: The surface of the ice-age Earth. *Science*, **191**, 1131-1137.

CLIMAP Project Members, 1981: *Seasonal Reconstruction of the Earth's Surface at the Last Glacial Maximum.*, Map and Chart Series, Vol. 36, Geological. Society of America, 18 pp.

Colinvaux, P. A., P. E. Deoliveira, J. E. Moreno, M. C. Miller, and M. B. Bush, 1996: A long pollen record from lowland amazonia: Forest and cooling in glacial times. *Science*, **274**, 85-88.

Crowley, T. J., 2000: CLIMAP SSTs re-revisited. *Climate Dyn.*, **16**, 241-255.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State-NCAR Mesoscale Model: Validation tests and simluation of an Atlantic cyclone and cold front. *Mon. Wea. Rev.*, **121**, 1493-1513.

Edwards, R. L. and coauthors, 2000: Pollen-based biomes for Beringia 18,000, 6000 and 0 ^{14}C yr BP. *J. Biogeography*, **27**, 521-554.

Grell, G. A., J. Dudhia, and D. R. Stauffer, 1994: A description of the fifth-generation Penn State-NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+STR, 122 pp.

Guilderson, T. P., R. G. Fairbanks, and J. L. Rubenstone, 1994: Tropical temperature variations since 20,000 years ago: Modulating interhemispheric climate change. *Science*, **263**, 663-665.

Guo, Z., D. H. Bromwich, and J. J. Cassano, 2002: Evaluation of Polar MM5 simulations of Antarctic atmospheric circulation. *Mon. Wea. Rev.*, provisionally accepted.

Janjić, Z. I., 1994: The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927-945.

Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Boville, D. L. Williamson, and P. J. Rasch, 1998: The National Center for Atmospheric Research Community Climate Model: CCM3. *J. Climate*, **11**, 1131-1149.

Kutzbach, J. E., P. J. Guetter, P. J. Behling, and R. Selin, 1993: Simulated climatic changes: Results of the COHMAP climate-model experiments. In *Global Climates Since the Last Glacial Maximum.* Minneapolis, MN: University of Minnesota Press, pp. 24-93.

Meyers, M. P., P. J. DeMott, and W. R. Cotton, 1992: New primary ice-nucleation parameterizations in an explicit clould model. *J. Appl. Meteor.*, **31**, 708-721.

Mix, A. C., E. Bard, and R. Schneider, 2001: Environmental processes of the ice age: land, oceans, glaciers (EPILOG). *Quat. Sci. Rev.*, **20**, 627-657.

Petit, J. R. and coauthors, 1999: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, **399**, 429-436.

Rind, D., and D. Peteet, 1985: Terrestrial conditions at the Last Glacial Maximum and CLIMAP sea-surface temperature estimates: Are they consistent? *Quat. Res.*, **24**, 1-22.

Stute, M., P. Schlosser, J. F. Clark, and W. S. Broecker, 1992: Paleotemperatures in the southwestern United States derived from noble gases in ground water. *Science*, **256**, 1000-1003.

Stute, M., J. F. Clark, P. Schlosser, W. S. Broecker, and G. Bonani, 1995a: A 30,000 yr continental paleotemperature record derived from noble gases dissolved in groundwater from the San Juan Basin, New Mexico. *Quat. Res.*, **43**, 209-220.

Stute, M., M. Forster, H. Frischkorn, A. Serejo, J. F. Clark, P. Schlosser, W. S. Broecker, and G. Bonani, 1995b: Cooling of tropical Brazil (5^{o}C) during the last glacial maximum. *Science*, **269**, 379-383.

Thompson, L. G., E. Mosley-Thompson, M. E. Davis, P.-N. Lin, K. A. Henderson, J. Cole-Dai, J. F. Bolzan, and K.-b. Liu, 1995: Late Glacial Stage and Holocene tropical ice core records from Huascarán, Peru. *Science*, **269**, 46-50.

Thompson, L. G. and coauthors, 1998: A 25,000 year tropical climate history from Bolivian ice cores. *Science*, **282**, 1858-1864.

Thompson, L. G., E. Mosley-Thompson, and K. A. Henderson, 2000: Ice-core palaeoclimate records in tropical South America since the Last Glacial Maximum. *J. Quat. Sci.*, **15**, 377-394.

Thompson, R. S., and K. H. Anderson, 2000: Biomes of western North America at 18,000, 6000, and 0 ^{14}C yr BP reconstructed from pollen and packrat midden data. *J. Biogeography*, **27**, 555-584.

Williams, J. W., W. I. Thompson, P. H. Richard, and P. Newby, 2000: Late Quaternary biomes of Canada and the eastern United States. *J. Biogeography*, **27**, 585-607.

Yen, Y. C., 1981: Review of thermal properties of snow, ice, and sea ice. CRREL Rep. 81-10, 27 pp.