# LGM SUMMER CLIMATE OF THE LAURENTIDE ICE SHEET SIMULATED BY POLAR MM5

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## 1. INTRODUCTION

During the Last Glacial Maximum (LGM), a period roughly 21, 000 calendar years before present (21 kyr BP), the massive Northern Hemisphere continental ice sheets represented significant components of the climate system. The largest of these ice sheets-the Laurentide-covered much of North America with elevations above 3 km in what is now central Canada. Undoubtedly, the Laurentide Ice Sheet (LIS) had a first order impact on the large-scale atmospheric circulation in the Northern Hemisphere via topographic and thermal forcing as demonstrated in global climate model (GCM) simulations (e.g., Manabe and Broccoli 1985; Kutzbach and Wright 1985). The various GCM studies generally agree that the influence of the LIS on the large-scale atmospheric circulation is most pronounced in the boreal winter months when insolation is at a minimum and thermal forcing (albedo effect) from the ice sheet is relatively small. Hence, the influence of the Laurentide Ice Sheet on the wintertime atmospheric longwave pattern is attributed primarily to topographic forcing of strong midlatitude westerly flow impinging on the ice sheet (Cook and Held 1988; Bromwich et al. 2004).

While the simulated atmospheric response to the presence of the LIS is amplified during winter, the ice sheet response to the atmosphere occurs primarily in the warm season. That is, the distributions of summer temperature and precipitation, which are influenced by ice sheet topography, determine the location and rate of ice sheet growth or ablation and are therefore critical for ice sheet maintenance (Roe and Lindzen 2001). Furthermore, the juxtaposition of cold surface temperatures over the ice sheet and relatively warm temperatures over the adjacent ice-free surface enhances the atmospheric baroclinicity along the southern ice sheet margin, which results in locally increased summer precipitation (Manabe and Broccoli 1985; Kutzbach and Wright 1985). In previous GCM simulations, this enhancement is confined to a relatively narrow zone on the southern or southeastern margin of the ice sheet whereas much of the southern margin experiences reduced precipitation and net ablation during summer (Manabe and Broccoli 1985; Hall et al. 1996).

GCM simulations and climate reconstructions based on loess (fine grain sediment) distributions also form a general consensus that the region south of the LIS (the Great Plains) was dry during the LGM (e.g., Manabe and Broccoli 1985; Kutzbach and Wright 1985; Muhs and Bettis 2000). Much of the Great Plains loess is thought to have formed from erosion of a sparsely vegetated landscape south of the Laurentide Ice Sheet terminus and transported via prevailing westerly or northwesterly low level winds from source regions to deposition regions in the central Plains (Muhs et al. 1999). The prevailing wind direction over the Great Plains at the LGM inferred from the loess record has yet to be reconciled with GCM predictions of predominantly northerly or northeasterly low level winds generated by the broad anticyclonic circulation over the LIS (Muhs and Zárate 2001).

Bromwich et al. (2004) simulated the LGM winter climate over the LIS using a regional climate model (Polar MM5) coupled to the NCAR Community Climate Model version 3 (CCM3). In their study, Polar MM5 produced a pronounced wintertime split in the westerly jet stream around the LIS. The current study examines the LGM summer climate using output from the coupled Polar MM5/CCM3 LGM simulation of Bromwich et al. (2004). Here, results are presented for July as the representative summer month. Our objectives are to (1) describe the characteristics of the summer atmospheric circulation over the LIS as simulated by Polar MM5, (2) determine the sensitivity of the summer circulation to changes in ice sheet topography, and (3) relate the high-resolution model results to climate conditions inferred from proxy data, particularly those in the central Plains of the U.S.

Section 2 briefly describes the Polar MM5 (PMM5), the LGM boundary conditions, and the approach used for the model experiments. Section 3 compares results of the July LGM simulation with a flat ice sheet sensitivity experiment. A discussion follows in Section 4.

## 2. MODEL 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 as described elsewhere (Bromwich et al. 2001; Cassano et al. 2001). The PMM5 LGM simulations are run at a 60-km grid interval over a 10,200-km x 9600-km domain centered over North America (Fig. 1). There are 29 vertical sigma levels and the model top is set to 13 hPa to minimize surface pressure anomalies resulting from vertically propagating waves generated by steep terrain slopes (Guo et al. 2003). The Grell cumulus parameterization (Grell 1993) and Reisner 1 microphysics are used in the control simulations.

The Laurentide and Fennoscandian ice sheet elevation data were implemented from glaciological model output from the University of Maine and sea level was lowered by 120 m commensurate with the LGM ice

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sheet volume. Since glaciological models tend to build too much ice in Alaska at the LGM, the Alaska glacier extent was implemented according to reconstructed boundaries (Manley and Kaufmann 2002) and the elevations set to present day values (i.e., zero thickness glaciers). The solar forcing was computed from 21 kBP orbital parameters (Berger 1977) and the $CO_2$ concentration was set to 180 ppm, 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 (e.g., Williams et al. 2000).

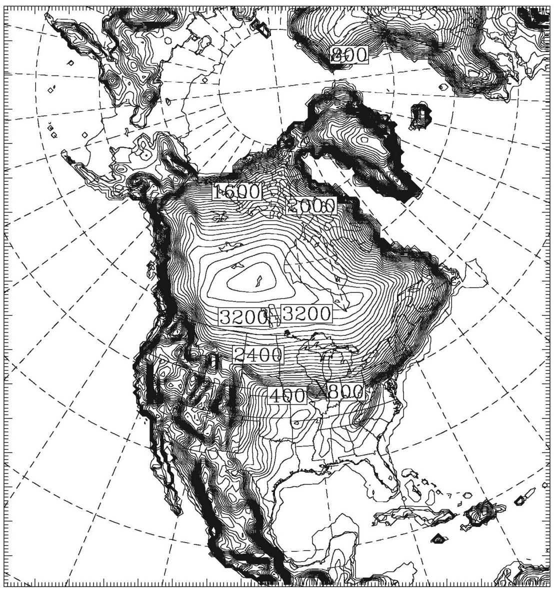


Figure 1. PMM5 domain and LGM terrain elevation. Contour interval is 100 m. Tick marks denote horizontal grid spacing. The location of the time series in Fig. 4 is denoted by an 'X' (40.6°N, 88.6°W).

The PMM5 simulations are one-month continuous runs preceded by a 2-week spin-up. The initial and lateral boundary conditions are from the final year of an 18-year CCM3 LGM simulation (Toracinta et al. 2004). In addition to the LGM control run, a sensitivity experiment is conducted which uses a zero thickness LIS (i.e., a snowfield) to examine the elevation effect of the ice sheet. In each PMM5 simulation, lateral boundary conditions are updated every 12 hours and 3-hourly PMM5 output is used to compute monthly averages.

## 3. RESULTS

Mean July 2-m air temperatures are coldest over Greenland and east of the LIS summit (Fig. 2). With the ice sheet buffered at freezing, a large thermal gradient is established along the LIS southern margin. The mean July mid-tropospheric (500 hPa) jet stream is nearly zonal along the LIS southern margin (not shown) and is clearly tied to the low level thermal gradient.

Consistent with the jet stream configuration, a band of July accumulated precipitation extends from the eastern North Pacific and across the LIS southern margin where a local maximum (> 400 mm) is located. Local maxima also occur on the southern margin in June and August (not shown). To explore the nature of this precipitation maximum, Fig. 4 shows the 13-21 July case study time series of sea level pressure, 2-m temperature, meridional near surface wind speed[1], and 3-hourly accumulated precipitation at a location on the Laurentide Ice Sheet (40.6°N, 88.6°W; 1099 meters elevation) near the southern terminus where the largest summer accumulations occur.

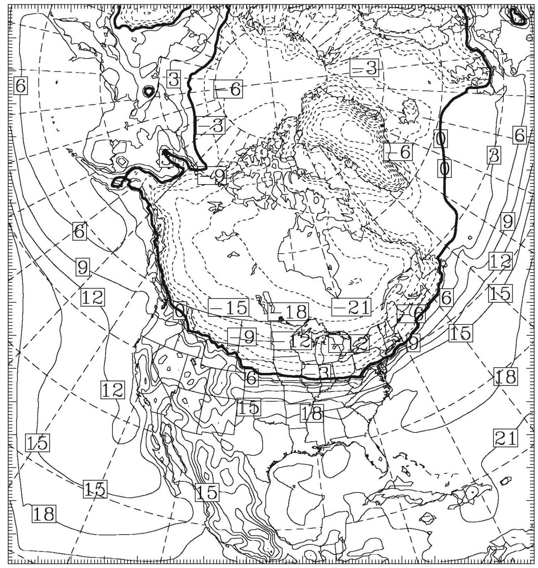

Figure 2. LGM mean July 2-m air temperature. Contour interval is 3°C and the 0°C isotherm is bold.

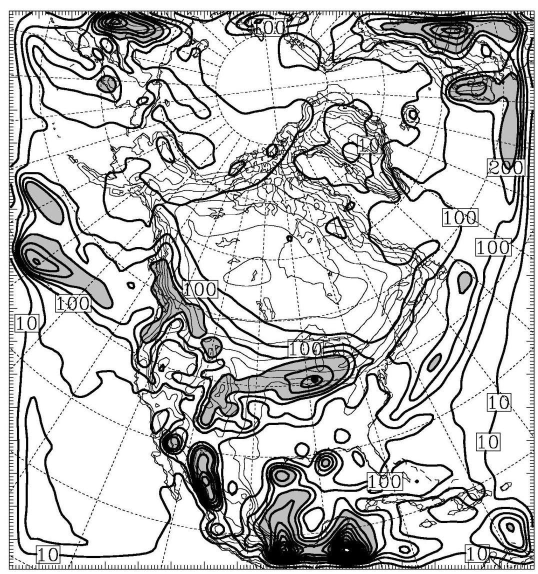

Figure 3. LGM July accumulated precipitation. Contours are 10, 50, 100, 150, and 200 mm, and every 100 mm thereafter. Accumulations greater than 200 mm are shaded.

Early in the period, the diurnal cycle is evident in the 2-m temperature time series, where temperatures are below freezing under the influence of northerly (down slope) near surface winds and relatively high SLP. From 15-19 July, the flow regime changes as a series of upper level disturbances and surface low pressure centers track along the LIS southern margin. Near-surface winds are predominantly southerly (upslope) at 7-15 m $s^{-1}$ resulting in an extended period of 2-m temperatures above freezing and a marked

[1] At this location, the meridional wind component is approximately parallel to the ice sheet slope.

increase in low level moisture. Precipitation is continuous during the period with maximum accumulations (roughly 3 mm $hr^{-1}$) occurring in association with a surface cyclone and frontal boundary along the LIS southern margin on 19 July. As the upper level shortwave and mature surface cyclone pass late in the period (not shown), there is an abrupt return to northerly near surface winds and a colder, drier air mass at the station location (Fig. 4).

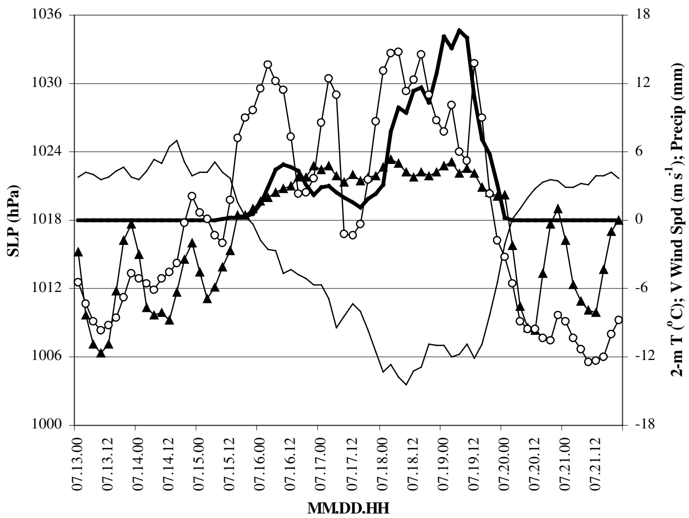


Figure 4. PMM5 LGM 13-21 July time series of 2-m temperature (triangles), meridional wind speed (circles), mean sea level pressure (thin), and 3-hr precipitation (bold) for the grid point at 40.6°N, 88.6°W.

During the five-day event nearly 215 mm of precipitation, most likely rain according to the Bocchieri (1980) algorithm, occurs at this location on the LIS. Although the mid-July case is the most highly amplified of those that occur along the southern margin of the ice sheet during summer, each of the other cases has similar characteristics, most notably the period of warm advection and the high probability of liquid precipitation. Such rain events have important implications for glacier dynamics since they are a potentially important source of water to lubricate the ice sheet bed along the LIS southern margin (e.g., Zwally et al. 2002).

To examine the role of ice sheet orography on the atmospheric circulation and precipitation distribution, the July simulation was repeated using a flat (zero thickness) LIS. All other initial and boundary conditions were unchanged. The mean July 500 hPa geopotential height field in the flat ice sheet case is dominated by a large cyclonic gyre located over the Canadian High Arctic (not shown). The mid-tropospheric flow is weaker and the jet stream positioned farther north than in the control run. The July accumulated precipitation distribution is shown in Fig. 5. Analysis of the near surface wind field (not shown) indicates that the absence of orographic forcing in the flat ice sheet case also allows moisture to advect farther northward with reduced precipitation on the southern margin, but increased precipitation farther north on the ice sheet.


Figure 5. As in Fig. 3, but for the flat LIS experiment.

## 4. DISCUSSION

The LIS strongly influences the large scale atmosphere during the LGM summer, primarily through baroclinic forcing. In the summer months, near surface air temperatures along the southern margin of the LIS are close to freezing while strong solar insolation (similar to present day) heats the adjacent land surface. The resulting sharp meridional low level temperature gradient along the southern margin anchors the jet stream over the ice sheet and facilitates the development of synoptic cyclones that track over the ice sheet and along the southern margin. This configuration is analogous to the contemporary Arctic frontal zone, a belt of frequent cyclogenesis and frontal activity in the Northern Hemisphere high latitudes. Serreze et al. (2001) find that the Arctic frontal zone is most clearly defined in summer and forms in response to differential heating of the snow-free land surface and the adjacent cold Arctic Ocean with some enhancement related to significant orography. Some high latitude regions receive more than 50% of their annual precipitation during summer in association with the contemporary Arctic frontal zone. Similarly, our modeling results indicate that over central North America more than half of the annual precipitation at the LGM occurs during summer (not shown) due to cyclones and frontal activity across the region.

The summer cyclones simulated by PMM5 are capable of producing copious *rain* on the southern margin of the Laurentide Ice Sheet and across the central Great Plains. The sensitivity experiment with a flat ice sheet clearly demonstrates that orographic lift on the ice sheet southern margin is an important mechanism for generating locally enhanced precipitation. The rain events on the southern margin are characterized by decreased 500 hPa geopotential heights (troughing) over central North America, decreased sea level pressure over the central U.S., increased low-level southerly flow from the Gulf of Mexico, and attendant increases in low level moisture. The low-level southerly flow regime, which resembles a contemporary Great Plains low level jet configuration (e.g., Walters and Winkler 2001), is clearly the primary mechanism of moisture transport to the central Plains at the LGM.

The consensus from GCM simulations supports inferences from geological proxy data (e.g., distribution of loess) that the central Plains south of the LIS was generally arid during the LGM. While the PMM5 depiction of wet summer conditions along the ice sheet terminus appears at odds with this interpretation, it corroborates previously proposed alternate climate scenarios that are reconcilable with the observed distribution of loess. Namely, sediment entrainment and deposition occurred via strong, but infrequent northwesterly wind events associated with the passage of low-pressure systems through the Plains. The PMM5 results show that rain events along the southern margin are episodic. While the cyclones traversing the ice sheet are capable of producing strong winds, not all cyclones are able to tap sufficient low level moisture from the Gulf of Mexico to produce rain along the southern margin. Furthermore, since the modeled easterly katabatic layer is relatively shallow (<100 hPa) with prevailing westerly winds above, strong low-level wind convergence capable of transporting fine-grain sediments through the boundary layer would be a plausible mechanism for downstream loess deposition. Unlike previous GCM simulations, the easterly katabatic zone in PMM5 is closely constrained to the ice sheet terminus suggesting that the low level wind distribution and loess transport mechanism is sensitive to the precise location (and perhaps the precise configuration) of the ice sheet margin.

Lastly, PMM5 simulations of alternate LGM summers (not shown) indicate that relatively minor changes in the large-scale circulation have a substantial impact on the distribution of precipitation across the central Plains. This suggests that variability on interannual (and possibly longer) time scales played a major role in modulating the climate along the southern margin of the ice sheet. Thus long periods of relatively dry conditions in the central Plains may have been interspersed with years having wet summers.

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