THE LAST GLACIAL MAXIMUM CLIMATE OVER THE LAURENTIDE ICE SHEET: HIGH-RESOLUTION SIMULATIONS USING POLAR MM5

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1. INTRODUCTION

In the effort to better understand possible climate change mechanisms, particular attention has been focused on the Last Glacial Maximum (LGM) roughly 21,000 calendar years before present (21 kBP; Mix et al. 2001). During this period, the Laurentide and Fennoscandian ice sheets covered much of North America and Scandinavia, respectively. The presence of these continental-scale ice sheets contributed to a higher planetary albedo and substantially influenced the Northern Hemisphere atmospheric standing wave pattern. Numerous studies have been conducted using atmospheric global climate models (GCMs) to simulate the LGM climate. However, the full influence of the continental ice sheets has not been conclusively determined. For instance, some early GCM studies indicate that the Northern Hemisphere midlatitude westerlies were split around the Laurentide ice sheet (e.g., Manabe and Broccoli 1985). Many other modeling studies do not indicate a split jet stream flow (e.g., Hall et al. 1996). Obviously, the structure of the midlatitude circulation in which the ice sheets are embedded has a first order impact on the distributions of temperature and precipitation both proximate to and downstream of the ice sheets.

Several studies have used coarse resolution GCMs to quantify the height and albedo effects of the LGM continental ice sheets (Rind 1987; Felzer et al. 1996; Shinn and Barron 1989). However, even at the smallest currently available resolution (2.8^o lat/lon grid), GCMs are unable to capture important mesoscale processes associated with large ice sheets (e.g., katabatic winds). Regional atmospheric models, with high spatial resolution and multiple options for physical parameterizations, are being more commonly used for climate applications. Foremost among these models is the Polar MM5, a version of the Pennsylvania State University (PSU) / National Center for Atmospheric Research (NCAR) fifth-generation mesoscale model (MM5; Dudhia 1993; Grell et al. 1994) modified specifically for simulations over polar regions (Bromwich et al. 2001; Cassano et al. 2001). The Polar MM5 has been tested extensively over present-day Greenland (Bromwich et al. 2001; Cassano et al. 2001) and Antarctica (Bromwich et al. 2003; Guo et al. 2003). The results from these contemporary Polar MM5 simulations are very robust with generally minimal bias in the modeled fields. Hence, the Polar MM5 is well suited for simulations over the Laurentide Ice Sheet, which at the LGM had spatial dimensions similar to present-day Antarctica.

In the present study, Polar MM5 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. We extend the work of previous GCM studies of the impact of the continental ice sheets by examining the influence of the Laurentide ice sheet on the circulation using a high resolution regional climate model that is known to perform well over continental-scale ice sheets. The objective here is to examine the winter atmospheric circulation at the LGM and determine, through sensitivity tests, the effect of ice sheet height and albedo on the circulation.

Section 2 briefly describes the Polar MM5, the LGM boundary conditions, and the approach used for the model experiments. Section 3 compares results of the January full ice sheet simulation with two sensitivity tests. Concluding statements are given in Section 4.

2. MODEL AND EXPERIMENTAL DESIGN

The Polar MM5 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 large positive bias in the polar cloud amount; improved treatment of cloud/radiation interaction using predicted cloud water and ice; optimal treatment of boundary layer fluxes via the 1.5 order turbulence closure parameterization (Janjić 1994); increased number of glacier substrate levels and depth to more accurately resolve heat transfer; improved treatment of thermal properties of ice and snow surface types (following Yen 1981); and implementation of a variable sea ice thickness and open water fraction.

The Polar MM5 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 gravity waves generated by steep terrain slopes (Guo et al. 2003). The Grell cumulus parameterization and Reisner 1 microphysics option are used in all 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 sheet volume. Since glaciological models tend

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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).

The Polar MM5 simulations are one-month (January) 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. 2003). The boundary conditions are identical in each Polar MM5 simulation except for the treatment of the Laurentide Ice Sheet. The control run (FullLIS) has the full height glaciated ice sheet. The FlatLIS experiment uses a zero thickness Laurentide Ice sheet (i.e., a snowfield) to examine the elevation effect of the ice sheet. Finally, the Laurentide Mountain (LMtn hereafter) experiment examines the effect lower albedo by retaining the Laurentide topography, but with modern vegetation in place of ice over the Laurentide Ice Sheet extent. In each Polar MM5 simulation, lateral boundary conditions are updated every 12 hours. Model output is every 6 hours from which monthly averages are computed.

3. RESULTS

Figure 2 shows the mean January 500-hPa geopotential height field for the FullLIS simulation. The height field clearly indicates a bifurcation of the mid-tropospheric flow along the western coast of North America as the westerlies encounter the Laurentide Ice Sheet. The northern branch of this split flow traverses north and eastward around a 500-hPa ridge positioned over the ice sheet, then turns southeastward over the Canadian Arctic Islands. The southern branch of the flow forms a broad trough to the south of the Laurentide Ice Sheet. The two branches merge in a confluence zone at the base of a pronounced trough leeward of the Laurentide Ice Sheet. The large 500-hPa height gradient over the North Atlantic is indicative of a strong (> 50 m s^{-1}) trans-Atlantic jet stream (not shown). It is worth noting that there is *no evidence* of a split mid-tropospheric flow in the CCM3 simulation that was used to initialize and continuously update the lateral boundaries of the Polar MM5.

By comparison, the 500-hPa flow regime is markedly different in the FlatLIS simulation where the Laurentide Ice Sheet is replaced by a zero thickness ice sheet (Fig. 3). Unlike the strongly bifurcated flow around the full height ice sheet, the prominent mid-tropospheric feature is a broad, intense trough and closed cyclonic circulation occupying much of the eastern portion of the model domain with a weak ridge upstream along the northwestern coast of North America. Further comparison of Figs. 2 and 3 indicates that the downstream trough in the FlatLIS simulation is more broad, more intense, and positioned further west relative to its FullLIS counterpart. Consequently, large negative 500-hPa height anomalies (FlatLIS minus FullLIS) occur over much of the northern portion of the domain (Fig. 4). The LMtn simulation indicated that changing the surface albedo (by implementing modern vegetation rather than ice) while retaining the Laurentide topography produces a flow regime similar to the FullLIS case. The 500-hPa flow also splits around the non-glaciated Laurentide Ice Sheet, but both branches of the flow are somewhat weaker than in the control (now shown).

The presence or absence of the Laurentide Ice Sheet also has substantial impacts in the lower troposphere. The FullLIS simulation produces a large glacial anticyclone in the January mean sea level pressure (MSLP) field, exceeding 1060 hPa and centered over the Laurentide Ice Sheet (not shown). A pronounced katabatic wind circulation dominates the near surface wind field over the extent of the ice sheet. Similar features are also evident in the LMtn simulation, though they are weaker in magnitude due to the decreased surface albedo and subsequently reduced cooling over the non-glaciated terrain. The decreased surface albedo in the LMtn simulation results in positive 10-meter temperature anomalies, ranging from 3-12^{o}C and decreasing with latitude over the elevated Laurentide topography.

In contrast to the pronounced anticyclone in the FullLIS and LMtn runs, the FlatLIS simulation shows a relatively weak (1032 hPa) area of high MSLP positioned over the central U.S. and a large, intense Icelandic Low in the North Atlantic with strong northwesterly flow over the Canadian Arctic Islands. The latter feature represents enhanced cold air advection where, for instance, mean January 10-meter temperatures over Baffin Island are approximately 18-25^{o}C colder than in the control run (not shown), despite the lower (~1-2 km) terrain elevations in this region of the FlatLIS domain. Correcting for the difference in elevation between the FullLIS and FlatLIS configurations using the dry adiabatic lapse rate, the mean January temperature anomalies are as much as 44^{o}C colder over Baffin Island in the FlatLIS simulation. Others have proposed that this cold advection pattern in the absence of an elevated ice sheet has important implications for glacial initiation (e.g., Felzer et al. 1996)

The distribution of January accumulated precipitation for the FullLIS simulation (Fig. 5) is consistent with the large scale flow pattern. Precipitation maxima occur along the western coast of North America and along the southern branch of the split jet south of the Laurentide Ice Sheet. Accumulations are maximized near the east coast of North America where the juxtaposition of the cold ice sheet and warmer Atlantic SSTs creates an enhanced baroclinic zone. The northern branch of the split jet transports moisture across Alaska, resulting in large precipitation accumulations in coastal Alaska and into the Arctic where a local precipitation maximum occurs in the Canadian Arctic Islands. By comparison, the January FlatLIS minus FullLIS precipitation anomalies (Fig. 6) show much less precipitation in the southwestern and southeastern U.S. since the primary storm track is positioned much further north than in the FullLIS case. The intensified Icelandic Low in the FlatLIS simulation accounts for the enhanced precipitation over the North Atlantic (away from the lateral boundaries). Also, despite cold temperatures over the snowfield, the absence of the elevated ice sheet terrain allows more moisture advection and greater precipitation accumulation in the interior of the snowfield relative to the FullLIS case. This also has important implications for ice sheet initiation.

4. CONCLUSIONS

The Polar MM5 has been used to simulate the winter (January) LGM climate over the Laurentide Ice Sheet. Model results show a pronounced split in the mid-tropospheric flow as westerlies encounter the Laurentide Ice Sheet. In addition, a large glacial anticyclone and strong katabatic winds are prevalent over the ice sheet. A sensitivity test using non-glaciated Laurentide Ice Sheet produces similar flow characteristics, although the lower surface albedo reduces the radiative cooling resulting in slightly weaker flow features. Removing the elevation effect of the Laurentide Ice Sheet by replacing it with a snowfield causes a dramatic difference in the atmospheric circulation. The mid-tropospheric jet stream is not split in this case, but a larger and more vigorous Icelandic Low dominates the winter circulation. As a result, strong cold advection occurs over much of northern North America. As others have noted, this flow configuration may be an important component for the initiation of continental ice sheets.

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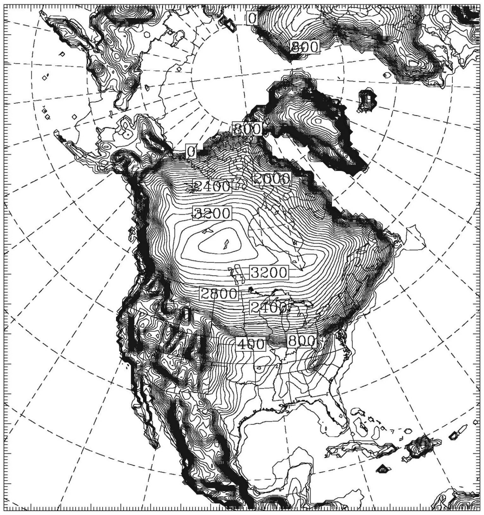

Figure 1. Polar MM5 domain and LGM terrain elevation. Contour interval is 100 m. Tick marks denote horizontal grid spacing.

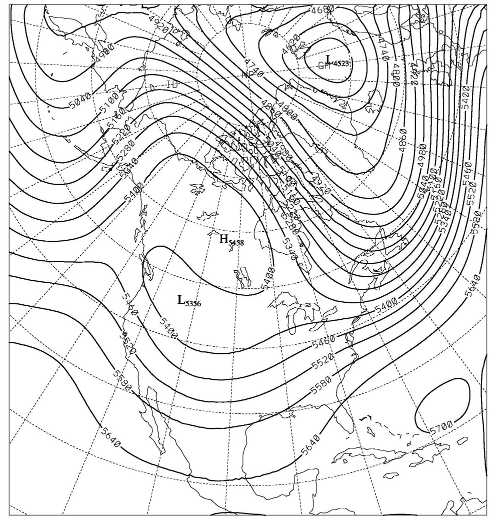

Figure 2. LGM mean January 500-hPa geopotential height for the FullLIS case. Contour interval is 60 m.

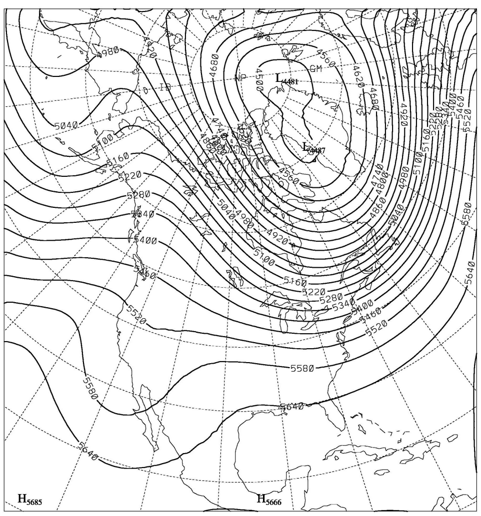

Figure 3. As in Fig. 2, but for the FlatLIS case.

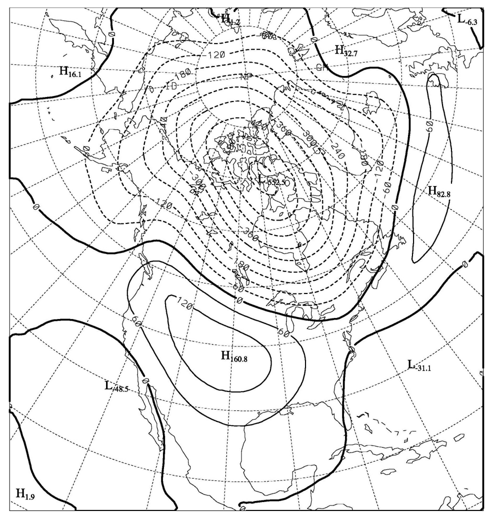

Figure 4. FlatLIS minus FullLIS mean January 500-hPa geopotential height anomalies. Contour interval is 60 m with negative values dashed.

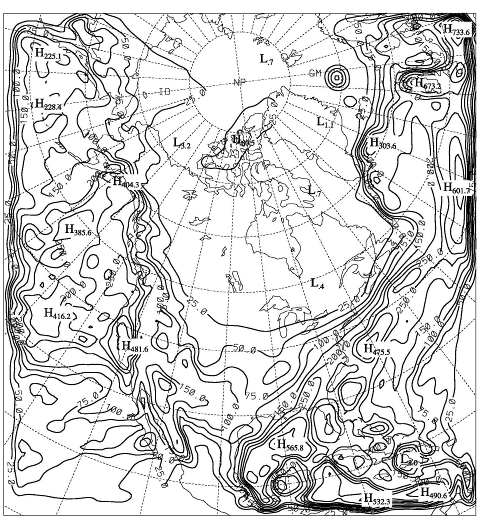

Figure 5. LGM January accumulated precipitation. Contour intervals are every 25 mm to 100, every 50 mm to 300, and every 100 mm thereafter.

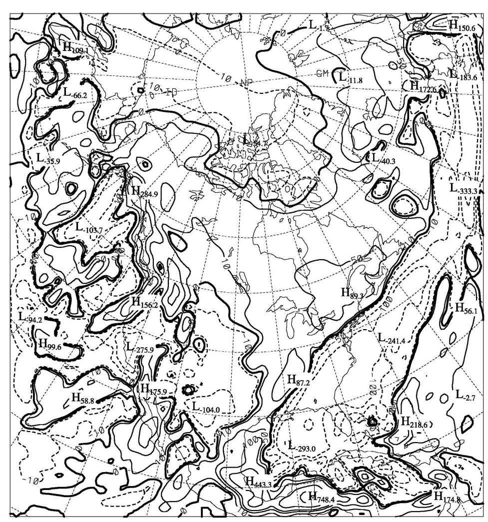

Figure 6. FlatLIS minus FullLIS January accumulated precipitation anomalies. Contours are ±10, 50, 100, 250, and 500 mm with negative values dashed.