TOWARD HIGH-RESOLUTION SIMULATIONS OF THE LAST GLACIAL MAXIMUM USING THE POLAR MM5

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1. INTRODUCTION

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) has been used in recent studies of the atmospheric state over Greenland and Antarctica. These ice sheets likely represent the range of conditions that occurred over the Laurentide ice sheet during the Last Glacial Maximum (LGM) roughly 20,000 BP (years before present); thus they serve as reasonable analogs for the purpose of model evaluation. The present study provides an overview of the model performance in simulations over Greenland (Bromwich et al. 2001; Cassano et al. 2001) and Antarctica (Guo et al. 2001) with an emphasis on model biases as an essential prerequisite to simulations over the Laurentide ice sheet.

Section 2 provides a brief description of the modifications made to the standard version of the MM5 for simulations over Greenland and Antarctica with a summary of the model performance presented in Section 3. Section 4 discusses the applicability of the regional model to simulations over the Laurentide ice sheet.

2. DESCRIPTION OF THE POLAR MM5

Several researchers in the Polar Meteorology Group at the Byrd Polar Research Center have used the standard version of MM5 to simulate atmospheric conditions over Antarctica and Greenland (Hines et al. 1995; Bromwich et al. 1996; Hines et al. 1997a,b). Biases in the model representation of cloud cover and radiation over the ice sheets led to modifications to the standard version of MM5 for polar applications (Polar MM5), which are summarized here.

Hines et al. (1997a,b) note extensive cloud cover in MM5 (MM4) simulations over Antarctica. Similarly, Manning and Davis (1997) find an over-prediction of cold high clouds over the continental United States. To minimize the cloudy bias, following the recommendation of Manning and Davis (1997) the Meyers et al. (1992) equation for ice nuclei concentration is used in the Polar MM5 explicit microphysics parameterizations.

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Regional climate simulations with the MM5 over Antarctica revealed an over-prediction of downwelling longwave radiation during cloudy conditions during austral winter (Hines et al. 1997a,b). The cloud-radiation interactions in the standard version of MM5 are from the NCAR Community Climate Model version 2 (CCM2) radiation parameterization, in which the cloud radiative properties are a simple function of the grid point relative humidity (Hack et al. 1993). MM5 sensitivity tests showed that the cloud cover predicted by the grid point relative humidity overestimated the cloud cover compared to that predicted by the explicit microphysics parameterization. In the Polar MM5, the cloud-radiation bias is resolved by using the predicted cloud ice and water content from the explicit microphysics scheme to determine the cloud radiative properties. This treatment is similar to the CCM3 radiation parameterization (Kiehl et al. 1996).

In the Polar MM5, turbulent fluxes in the planetary boundary layer (PBL) and surface layer are parameterized using the 1.5 order turbulence closure parameterization of Janjić (1994; ETA PBL parameterization). Heat transfer through the model substrate is treated using a modified multi-layer soil model with the number of substrate levels increased by two (resulting in an increased substrate depth from 0.47 to 1.91 m). Thermal properties for snow and ice surface types are modified following Yen (1981). A variable sea ice surface type has also been added to the Polar MM5. The surface fluxes are computed individually for sea ice and open ocean fractions of the model grid point and averaged before interacting with the atmosphere.

The simulations summarized here were conducted over Greenland and Antarctica using hydrostatic and nonhydrostatic dynamics options, respectively, in the Polar MM5. In each experiment, 28 vertical sigma levels were used with 40 km (60 km) horizontal grid spacing over Greenland (Antarctica). The fine-scale resolution is generally sufficient to resolve terrain slope over all but the steepest ice sheet margins (Cassano and Parish 2000).

3. POLAR MM5 PERFORMANCE OVER GREENLAND AND ANTARCTICA

Bromwich et al. (2001) present detailed results from a Polar MM5 two-month simulation over Greenland with initial and boundary conditions from ECMWF (European Centre for

Medium-range Weather Forecasts) analyses. Model output is compared with observations from the Greenland Climate Network (GC-NET) automatic weather station (AWS) array, instrumented aircraft observations, and ECMWF analyses. Bromwich et al. (2001) find that the Polar MM5 captures the large scale atmospheric state with a high degree of accuracy. The magnitude of the monthly mean bias (Polar MM5 - ECMWF) in the temperature field is less than 1 K throughout much of the depth of the model atmosphere. The largest biases in the mixing ratio occur over the ocean adjacent to Greenland, where the model tends to be slightly more moist (< 0.15 g kg^{-1}) at low levels (σ > 0.9) and slightly drier (< 0.1 g kg^{-1}) at mid levels than the ECMWF analyses. The wind field is also well represented by the Polar MM5, with the magnitude of the wind speed bias less than 0.5 m s^{-1}, except near the model top.

Bromwich et al. (2001) also find that the Polar MM5 is able to simulate the katabatic flow over the Greenland ice sheet with an acceptable degree of accuracy. Model profiles of potential temperature and wind speed and direction in the katabatic layer are largely within 2.0 K for potential temperature and less than 5 m s^{-1} for wind speed compared with instrumented aircraft data (Heinemann 1999). Bromwich et al. note that the modeled katabatic layer is highly sensitive to the accuracy of the large scale atmospheric state, especially the predicted cloud cover and the parameterized radiative properties of the clouds.

Cassano et al. (2001) present results from the Polar MM5 over Greenland for a complete annual cycle (April 1997 - March 1998). Model output is compared with data from the GC-NET AWS array. The Polar MM5 demonstrates a surprising degree of skill in capturing the variability in AWS-observed fields over time scales ranging from diurnal to annual. Correlation coefficients are high (> 0.8) over most of the year for the pressure, temperature, mixing ratio, and downwelling shortwave radiation fields, although Cassano et al*.* (2001) note large errors in the modeled net radiation over the ice sheet ablation zone during the summer months. These are attributed to the use of a constant albedo (0.8) in the Polar MM5 simulations, whereas the observed albedo varied and was substantially lower (0.5) during summer due to melting of the ice surface. The winter net radiation budget, which is dominated by longwave radiation and its interaction with clouds, was well simulated by the model. Although the correlation coefficients are lower (0.62 to 0.75) for the wind speed, the model bias is near zero for the spring and summer months. The positive bias in the wind speeds during fall and winter months is likely related to the cold bias in the near surface temperatures, which implies an enhanced katabatic flow.

Guo et al. (2001) have recently conducted Polar MM5 simulations of the atmospheric state over Antarctica for January - December 1993. Model verification using observations from the University of Wisconsin automatic weather station (UW-AWS) array indicate that the Polar MM5 simulates the near surface atmospheric state with a high degree of accuracy, but with some exceptions. Figure 1 compares monthly mean values of near surface temperature, pressure, wind speed, and wind direction from the Polar MM5 and observations from the Dome C UW-AWS site in the high interior of Antarctica (74.5°S, 123°E; 3280 m elevation). The seasonal cycle in the near surface pressure (Fig. 1a) and temperature (Fig. 1b) fields is well represented by the model. The largest temperature biases occur in late winter (+5°C) and during autumn (-6°C), and are generally within ±3°C through the remainder of the year. Wind speeds at Dome C are typically light (< 5 m s^{-1}) during the simulation period and the monthly mean wind speeds are generally well represented (Fig. 1c). However, the model tends to underestimate the wind speed variance (not shown) such that periods of higher wind speeds are not well forecast. Coupling a "gust model" to Polar MM5 would help alleviate this problem. The model captures trends in the monthly mean wind direction with a reasonable degree of skill, despite significant errors in the ECMWF initialization (not shown). The model bias is generally within ±20° and correlation coefficient greater than 0.7 through the simulation period.

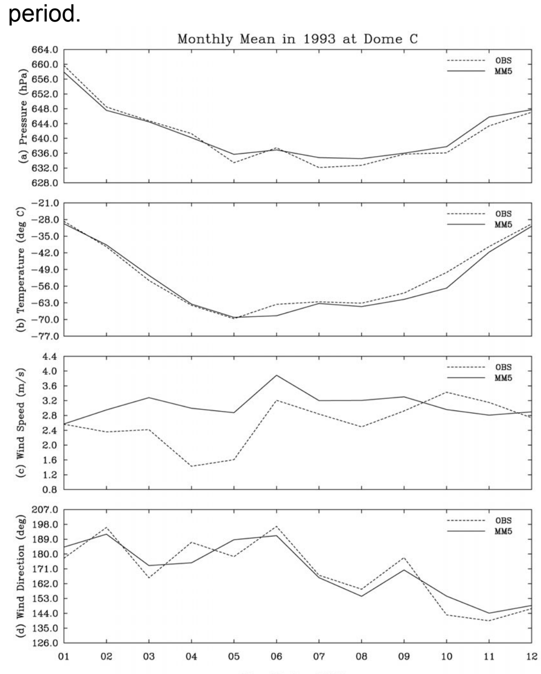

Figure 1. January-December 1993 monthly mean values of near surface pressure (a),

temperature (b), wind speed (c), and direction (d) at the Antarctica Dome C site from station observations (dashed line) and Polar MM5 forecasts (solid line).

4. APPLICABILITY TO SIMULATIONS OVER THE LAURENTIDE ICE SHEET

The Polar MM5, coupled to the NCAR CCM3 global climate model, will be used to assess the atmospheric state over the Laurentide ice sheet at the Last Glacial Maximum. The primary objective is to determine whether abrupt changes (~200 years) Laurentide ice sheet could have actively triggered rapid climate changes beyond the vicinity of the ice sheet.

We are interested in both the local and far-field response of the atmosphere to the presence of Laurentide ice sheet. The modeling results of Kageyama et al. (1998) indicate that the meteorological impact of an ice sheet is greatest downstream. The presence of the Laurentide ice sheet might, for instance, effect substantial changes in the position and/or intensity of climatological long-wave features. Model simulations by Felzer et al. (1996) show that a full height LGM ice sheet contributes to increased warm advection across the Atlantic and the potential for enhanced snow accumulation over the Scandinavian ice sheet.

Regarding the local mesoscale atmospheric response, we are particularly interested in determining the role of the Great Plains low level jet (LLJ) in the distribution of precipitation on the Laurentide ice sheet. The LLJ, which has been successfully simulated with the MM4 (Igau and Neilsen-Gammon 1998), is an important conveyor in the present climate of atmospheric moisture from tropical low latitudes to the mid-latitudes of the central and eastern United States.

We are also interested in the behavior of the katabatic winds over the Laurentide ice sheet since these appear to play a complicated role in the growth and decay of ice sheets. The katabatic circulation may inhibit precipitation through sinking motions over the ice sheet, generation of low-level anticyclonic circulation, and opposition to intrusion of moist low-level air, thus limiting the growth of large ice sheets. The katabatic circulation may contribute to the growth of the Laurentide ice sheet in two ways. First, enhanced precipitation may result over the ice sheet as the dry, adiabatically-warmed katabatic outflow evaporates moisture from the proglacial lakes on the ice sheet periphery and is then re-circulated back onto the ice sheet. Secondly, the katabatic winds may have contributed to the development of mesoscale cyclones near the Laurentide ice sheet margins, which could represent a significant source of precipitation over the ice sheet slopes.

Modeling studies over the present day ice sheets have demonstrated that proper treatment of longwave radiation and boundary processes can produce a good representation of circulation features such as the katabatic flow (Parish and Bromwich 1991; Bromwich et al. 1994; Hines et al. 1995; Bromwich et al. 1996). Undoubtedly, the scale and terrain characteristics of the present day ice sheets are significant factors influencing the large and regional scale atmospheric state. Figure 2 shows the Polar MM5 model domain (8400 km x 7800 km) for the Laurentide ice sheet simulations. The Laurentide ice sheet is characteristically similar in terms of height and areal extent to the present day Antarctic ice sheet. Thus, based on its proven performance in present day simulations and aware of the model biases, we are confident that the Polar MM5 will provide a reasonable representation of the atmospheric state over the Laurentide ice sheet.

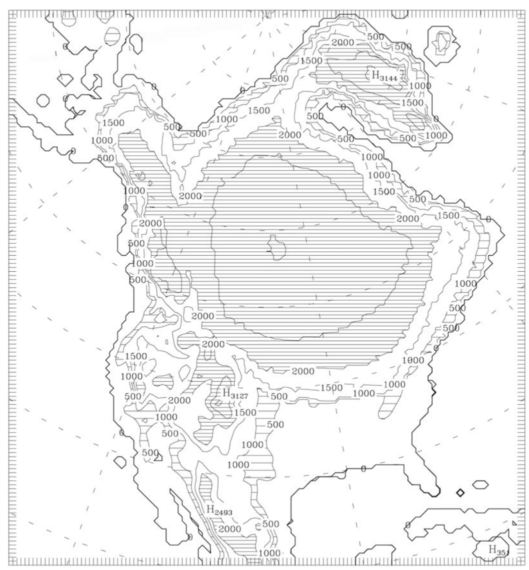

Figure 2. Polar MM5 model domain and terrain elevations for the Laurentide ice sheet at the Last Glacial Maximum. Elevations are contoured every 500 meters above sea level (elevations between 500 and 1000 meters and > 2000 meters are hatched). Tick marks indicate the 60 km model grid interval.

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