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A mesoscale model used in the Polar regions: modification and verification

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Abstract A polar version of mesoscale model, PolarMM5 is introduced in the paper. The modifications for the polarMM5 dynamics and physics compared with standard MM5 are described. Additionally, parallel simulations of the PolarMM5 and original MM5 reveal that the PolarMM5 reproduces better near-surface variables forecasts than the original MM5 over the North American Arctic regions. The well predicted near surface temperature and mixing ratio by the PolarMM5 confirm the modified physical parameterization schemes in the PolarMM5 are appropriate for the research region.

Key words Polar regions, Mesoscale model.

1 Introduction

China has been carrying out 23 field experiments over the Antarctic since 1984 and many observations on the aspect of oceanography were conducted. The changes of temperature and precipitation in the polar regions have effect on global climate change through alterations in sea ice distribution and Antarctic Ocean circulation. Numerical modeling has been widely used to complement the above observational and diagnostic investigations. Another potentially model application is numerical weather prediction in support of field operations on the ice sheet.

In the last decade, many advances have been achieved in improving the numerical simulations of polar regions' atmospheric circulation. The boundary layer structure (Heinemann and Rose 1990), mesoscale disturbance formed in the coastal region (Carrasco *et al.* 1997a, b), and nonhydrostatic mesoscale model simulation (Guo *et al.* 2003) have improved our understanding of Antarctic atmospheric circulation. On the other hand, mesoscale modeling of Katabatic winds over Greenland (Bromwich *et al.* 2001), regional model simulations of Greenland's atmospheric circulation (Cassano *et al.* 2001) and coupling land-atmosphere model over Arctic river basins (Ma and Chen 2005) also have strengthened our learning on the Arctic atmospheric behavior. In this paper, a polar version of the Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) fifth-generation mesoscale model, termed PolarMM5 is introduced significantly.

Successful numerical simulations of the atmospheric circulation over the Antarctic and Greenland ice sheets with the Polar MM5, which is based on version 2 of the PSU-NCAR MM5, have been conducted (Bromwich *et al.* 2001; Cassano *et al.* 2001; Guo *et al.* 2003). Model validations over Greenland and North America are performed here. Therefore, one purpose of the paper is to illustrate the model skill in simulating atmospheric behavior over high-latitude regions. The description of the modified mesoscale model, the Polar MM5, is given in Section 2. Section 3 is the results, which discuss the comparisons between the simulations with the model and observations. Conclusions and discussions are shown in Section 4.

2 Description of the Polar MM5

The Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) fifth-generation Mesoscale Model (MM5) is a widely used and publicly available regional atmosphere model. MM5 was adapted by the Polar Meteorology Group at the Byrd Polar Research Center, The Ohio State University, USA for use in the polar regions, and is referred to as Polar MM5. The Polar MM5 used for the simulations in this study is based on version 3.4 of MM5, and the general description of version 3 of MM5 is given by Grell *et al.* (1994). The atmospheric mesoscale model configuration and the changes of the standard version of MM5 made for use over polar regions are described below.

2.1 *Polar MM5 Dynamics and Physics*

The Polar MM5 is a limited-area, three-dimensional, non-hydrostatic primitive equation model with multiple options available for various physical parameterization schemes. The model employs a terrain-following vertical coordinate σ, where $\sigma = (p-p^{top})/(p^{sfc}-p^{top})$, p is pressure, and p^{sfc} and p^{top} are the pressures at the surface and the model top, respectively. The model includes three-dimensional prognostic equations for the horizontal and vertical components of the wind and temperature and pressure perturbation. Additional three-dimensional prognostic equations for water vapor mixing ratio and the mixing ratio of various cloud species are also part of model equations. Physical options used in the Polar MM5 include the Reisner explicit microphysics parameterization for the large-scale cloud and precipitation processes (Reisner *et al.* 1998), Grell cumulus parameterization for the subgrid-scale cloud processes (Grell *et al.* 1994), Community Climate Model version 2 (CCM2) radiation scheme for radiative transfer, and 1.5-order turbulence closure parameterization for turbulence fluxes. The key modifications on the Polar MM5 are focused on modified explicit ice phase microphysics, revised cloud / radiation interaction, optimized turbulence (boundary layer) parameterization and implementation of a sea ice surface type and improved treatment of heat transfer through snow / ice surfaces. A detail description on the above modifications is shown below.

Overestimated cloud cover was found to be a problem over the Antarctic in sensitivity simulations using old version of MM5 (MM4) (Hines *et al.* 1997) and for cold, high clouds over the continental United States (Manning and Davis 1997). The use of the Fletcher (1962) equation in the microphysics parameterization results in an unrealistically small size and large values of the number concentration of simulated ice crystals at very low air temperatures. In the Reisner scheme, replacement of the Fletcher (1962) equation for ice nuclei concentration with that of Meyers *et al.* (1992) in the explicit microphysics eliminates the cloudy bias which is found with standard MM5 in the polar regions.

The National Center for Atmospheric Research (NCAR) community climate model version 2 (CCM2) radiation scheme for prediction of radiative transfer of long-wave and short-wave radiation through the atmosphere is also modified and used in the Polar MM5. Cloud cover is predicted by cloud water and ice mixing ratios from the Reisner explicit microphysics parameterization in the Polar MM5 instead of being a simple function of the grid-box relative humidity, and the cloud liquid water path is determined from the grid-box temperature that is used in the standard version of MM5; this approach eliminates excessive cloud liquid water path, which resulted in large downwelling long-wave radiation fluxes during the austral winter over the Antarctic ice sheet (Hines *et al.* 1997; Cassano *et al.* 2000). The modification allows for a consistent treatment of the radiative and microphysical properties of the clouds and for the separate treatment of the radiative properties of liquid and ice phase cloud particles.

Turbulent fluxes in the planetary boundary layer (PBL) is parameterized using the 1.5-order turbulence closure scheme of Janjic (1994) used in the National Centers for Environmental Predictions (NCEP) ETA model. Heat transfer through the model substrate is predicted using a multilayer soil model. The ETA PBL scheme is also modified in the Polar MM5. The thermal properties used in the multi-layer soil model for snow and ice surface type are modified following Yen (1981). The number of substrate levels in the soil model was increased from six to eight, with an increase in the resolved substrate depth from 0.47 m to 1.91 m. A sea ice surface type is added to the 13 types used in the original MM5. The sea ice surface type allows for the specification of fractional sea ice cover in the model initial conditions for any oceanic grid point, and this sea ice distribution does not change during the model simulation. The surface fluxes and ground temperature are considered separately for sea ice, open water and land surface grid points based on the surface characteristics thermal properties, which are then combined before interacting with the overlying atmosphere.

2.2 *Model grid and data*

The North America domain centered at (65 °N, 95 °W) with 150 by 150 grids at a horizontal resolution of 60 km, is set as model domain and the results of 10-day (from 19 April to 29 April 1997) of 48-h simulations are analyzed in this study. Fig. 1 is the model domain including the North Pole, from a southern boundary including all the northward flowing river basins to beyond the northern coast. 28 vertical sigma levels are used and the lowest model level is located at a height of 20 m AGL in the Polar MM5. The high vertical resolution near the surface has potential possibility in handling the evolution of the near-surface meteorological variables over the North American Arctic river basins.

Parallel simulations of the Polar MM5 and original MM5 for 19-29 April 1997 over North America are carried out to verify physical processes modification on original MM5. The initial and boundary conditions for the 10-day simulations are obtained from National

Centers for Environmental Prediction (NCEP) global analyses The input of sea ice frac-

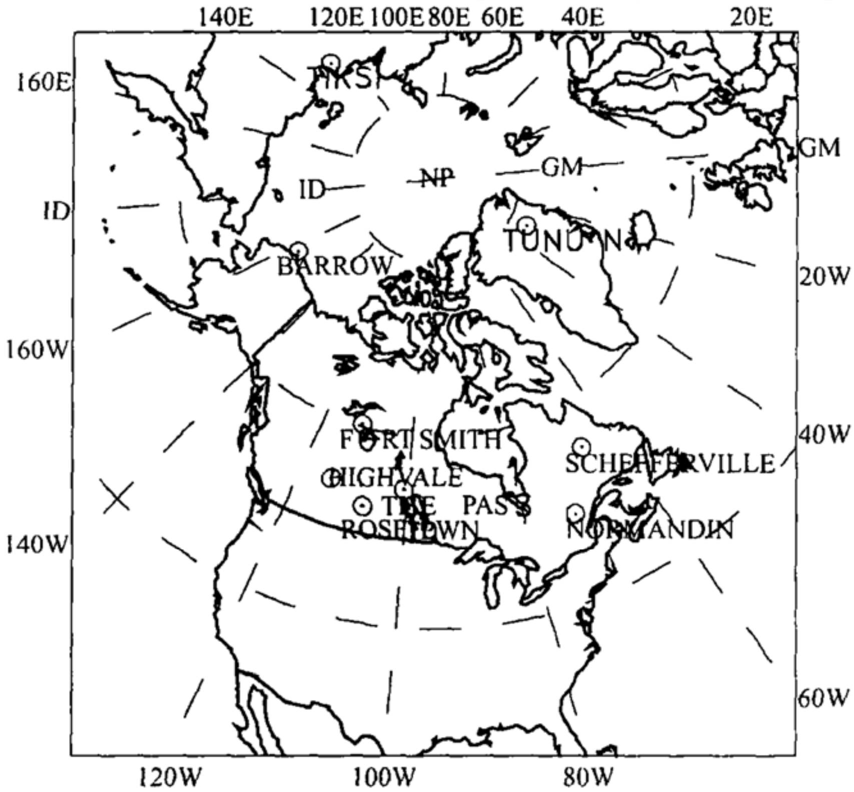

Fig 1 Map of model domain with a resolution of 60 km

tion, deep soil temperature and snow cover is also derived from the initial fields as well The Polar MM5 runs are initialized at 0000 UTC for a 48-h short duration simulation with the first 24-h simulation discarded for spin-up purposes The observations used for validation of the MM5 simulations are obtained from global surface observations from NCEP and automatic weather station (AWS) observations from the Greenland Climate Network (GC-NET) (Steffen and Box 2001).

3 Results

It is obvious from above descriptions there are many differences in physical parameterization schemes between the Polar MM5 and original MM5 Parallel simulations of the Polar MM5 and original MM5 for 19-29 April 1997 over North America are carried out to show the validity of modified version Polar MM5 over North American Arctic regions The prediction for Greenland station Tunu_N is selected to display the improvement of the Polar MM5 over the North American Arctic regions The basic information of Tunu_N can be gotten from Steffen and Box (2001). The predicted near-surface variables by the Polar MM5 and standard MM5 are obtained from the lowest sigma level To compare the modeled output with the AWS observed temperature at height of less than 3 m AGL, the temperature at the lowest model level is interpolated to the height of 2 m. The wind speed and wind direction from the lowest level are interpolated to the height of 10 m.

Time series plots of the Polar MM5, standard MM5 predictions and AWS observation at Tunu_N for surface pressure, temperature, mixing ratio and wind direction are shown in Fig 2 In general, the Polar MM5 performed better model predictions than original MM5 over the North American Arctic, especially on the simulations of temperature and mixing ratio. The PolarMM5 time series of the near-surface meteorological variables are in good agreement with the observations, apart from a slight cold bias. There are large biases (mean modeled-mean observed) for surface pressure both at the predictions of the PolarMM5 and the originalMM5. The mean surface pressure biases range from − 8.4 hPa to − 7.8 hPa with the PolarMM5 and originalMM5. Bromwich *et al.* (2001) also showed the noticeable bias in surface pressure at the Tunu_N modeled by the PolarMM5 version 2.12. One possible reason is there is a large difference between the modeled terrain and the reported elevation of the site; the other is a measurement error at Tunu_N. Although a large bias is existed between the modeled and the observed surface pressure, the distribution pattern of the surface pressure indicates the PolarMM5 produces the similar observed trend (Fig. 2a). The time series of near-surface temperature, Fig. 2b, show the PolarMM5 reproduces the observed temperature with a high degree of accuracy. On the other hand, the originalMM5 does not have good forecasts for the near-surface temperature at Tunu_N. The mean biases in temperature are − 0.4 ℃ with the PolarMM5 and 8.3 ℃ with the originalMM5. The originalMM5 predicted much too warm near-surface temperatures. Compared with the prediction of the originalMM5, the PolarMM5 simulated more clear diurnal temperature cycle. Another noticeable comparison is the near-surface mixing ratio (Fig. 2c). The PolarMM5 modeled mixing ratio displays a slight moist bias of 0.1 g kg^{-1}; the time series circle shows a very good agreement with the observed. The time series of near-surface mixing ratio by the original MM5 shows a large moist bias of 0.6 g kg^{-1}. Evaluations of the modeled and observed near-surface winds indicate a slight bias both in the PolarMM5 and the originalMM5. The modeled wind speed and wind direction with the PolarMM5 and originalMM5, both at the magnitude and time series cycle, are in close agreement with the observed winds (Figs. 2d). However, the PolarMM5 has a slight improvement in the simulation of wind direction.

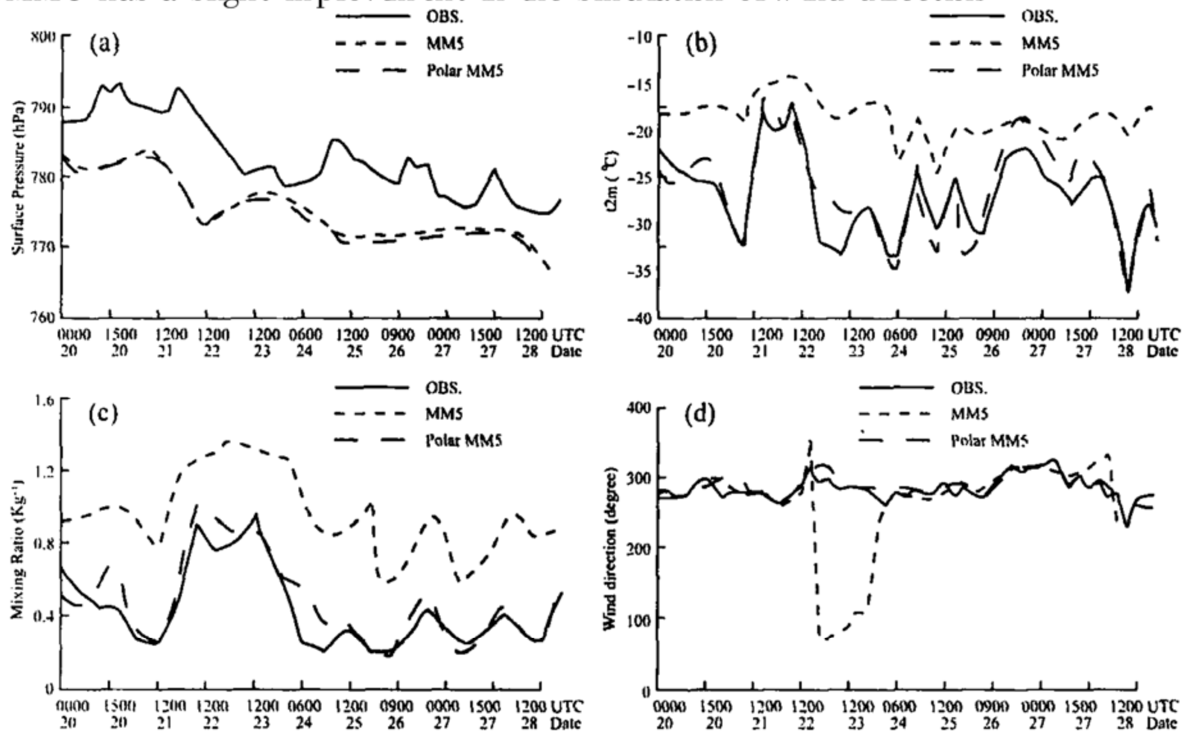

Fig. 2 Time series of the originalMM5, PolarMM5 forecasts and the Tunu_N observations from 0000 UTC 20 April to 0000UTC 29 April 1997: (a) Surface pressure, (b) Temperature at 2m, (c) Surface Mixing Ratio and (d) Surface wind direction

From above analyses and comparisons, the PolarMM5 produces better near-surface variable forecasts than original MM5 for both magnitude and trend. The high degree of forecast skill at Greenland site Tunu_N verifies the ability of the PolarMM5 over the North American Arctic region. The well predicted near-surface temperature and mixing ratio with the PolarMM5 further confirm that the modified physical parameterization schemes are appropriate for high-latitude areas.

To further learn the forecast accuracy of the PolarMM5 over large domain, the averaged characteristics of the near-surface meteorological variables for four areas over North American domain are considered as well. They are area# 1 (30°– 50°N, 130°– 70°W) representing United States continent, area# 2 (50°– 60°N, 140°– 70°W) and area# 3 (60° – 70°N, 140°– 70°W) representing Canada and the fourth area (60°– 80°N, 20°– 60°W) representing Greenland. Based on the comparisons, the number of observations, bias, root mean square error and the correlation coefficient for the four areas are listed in Table 1 to show the model skill. Except the area# 3, the PolarMM5 simulates a little colder surface temperature over other three areas. This analysis is similar to the study of Bromwich *et al.* (2001) that indicated there is a little cold bias in the PolarMM5 modeled near-surface temperatures over Greenland compared with AWS observations. The maximum bias in the sea-level pressure for four areas is 1.7 hPa and 2.0 °C in the near-surface temperature. The time series of modeled sea-level pressure and near-surface temperature match the observed time series very well (not shown).

Table 1 Statistics of the PolarMM5 predictions and the surface observations for four areas during 19-29 April 1997

Area	Sea-level Pressure (hPa)				Temperature (°C)			
	number	bias	rmse	corr	number	bias	rmse	corr
30°– 50°N 130°– 70°W	292	0.1	1.2	0.98	311	– 1.8	1.9	0.98
50°– 60°N 140°– 70°W	122	– 0.5	2.1	0.96	133	– 1.1	2.0	0.94
60°– 70°N 140°– 70°W	39	0.6	1.9	0.93	41	2.0	2.6	0.96
60°– 80°N 20°– 60°W	23	1.7	3.1	0.97	28	– 0.7	1.1	0.87

4 Conclusions

The PolarMM5 is currently being used for synoptic and climate scale studies in the data sparse high latitudes and continues to provide numerical weather prediction to support U.S. Antarctic Program flight operations. Chinese scientists may understand the model through this paper and apply it to the Chinese polar scientific research. The PolarMM5 simulations during 19– 29 April 1997 are compared with AWS observations from GC-NET and NCEP global surface analysis for the purpose of the models verification over the North America Arctic regions. The verification reveals that the PolarMM5 simulations have a high degree of accuracy and indicates that the PolarMM5 simulates near-surface variables better than the original version of MM5, especially on variables of temperature and mixing ratio. It confirms reasonable modifications of the physical parameterizations on the original MM5 in simulating the atmospheric circulation over Arctic river basins. Then the verifications of 10-day simulations from the PolarMM5 with four area-averaged observations have been presented. The simulations of the PolarMM5 show the model has good representation not only at single station but also over large areas. However, the horizontal resolution of 60 km is a little coarser to learn the land surface characteristics over high-latitude areas in detail. Additionally, the possible reason for the clod bias of the near-surface temperature, appeared in the simulations with the PolarMM5, is there is too less downward long-wave. Therefore enhanced horizontal resolution and some physical parameterization improvements are desirable.

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