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Validation of the Polar MM5 for Use in the Simulation of the Arctic River Basins

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ABSTRACT

The simulations were performed using a modified mesoscale model, the Polar MM5, which was adapted for use within polar regions. The objective of the study was to illustrate the skill of the Polar MM5 in simulating atmospheric behavior over the Arctic river basins. Automatic weather station data, global atmospheric analyses, as well as near-surface and upper-air observations were used to verify the simulation. Parallel simulations of the Polar MM5 and the original MM5 within the period 19–29 April 1997 simulations revealed that Polar MM5 reproduced better near-surface variables forecasts than the original MM5 for the region located over the North American Arctic regions. The well predicted near-surface temperature and mixing ratio by the Polar MM5 confirmed the modified physical parameterization schemes that were used in this model are appropriate for the Arctic river regions. Then the extended evaluations of the Polar MM5 simulations over both the North American and Eurasian domains during 15 December 2002 to 15 May 2003 were then carried out. The time series plots and statistical analyses from the observations and the Polar MM5 simulations at 16 stations for the near-surface and vertical profiles at 850 hPa and 500 hPa variables were analyzed. The model was found to reproduce the observed atmospheric state both at magnitude and variability with a high degree of accuracy, especially for temperature and near-surface winds, although there was a slight cold bias that existed near the surface.

Key words: validation, polar MM5, arctic river basins

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1. Introduction

There are many northward flowing rivers that discharge into the Arctic Ocean. The geography and dynamics of the water mass located across this region, which are dependent upon the alterations in the sea-ice distribution and the Arctic Ocean circulation, are important elements to both the Arctic climate and global climate change. High resolution numerical weather predictions provide one possible method for deriving the atmospheric inputs to explain variations in the Arctic river discharge.

During 1997, observations of the Katabatic circulation and the boundary layer structure over Greenland were conducted (KABEG'97) using automatic weather stations and instrumented aircraft (Heinemann, 1999). The surface heat budget of the Arctic Ocean (SHEBA) project conducted one year (1997–1998) field experiment on a drifting sea ice camp in the Arctic Ocean to emphasize the interactions between the surface radiation and mass changes of the sea ice. Numerical weather models have previously been used to understand the atmospheric processes as well as some of the characteristics of the atmospheric circulation over Greenland ice sheet (Bromwich et al., 1996, 2001; Cassano et al., 2001; Box et al., 2004, 2006). Wei et al. (2002) validated the standard MM5 that incorporated the National Center for Atmospheric Research (NCAR) land surface model (LSM) and a simple thermodynamic sea-ice model for the Pan-Arctic hydrological simulation and the validation of the model was concentrated on factors that were relevant to the water cycle. But the limitations of the associated research areas, the complexity of the atmospheric flow over the Arctic areas and the sea ice environment presented obstacles to obtaining realistic simulations of the atmospheric circulation within the Arctic river basins and to obtaining accurate forecasts of the different

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meteorological elements. Moreover, the related hydrostatic studies and field operations in the Arctic river basins also demanded accurate short-range numerical weather forecasts. Therefore one regional atmospheric model was required to produce near real-time weather forecasting for the Arctic river basins. It is an essential prerequisite for the model application at the Arctic river basins that the model skill is determined through a detailed comparison with all available observations.

In this paper a detailed assessment of the performance of a model system that was adapted specially for the Arctic river basins environments is presented. We examined a modified version of the Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) fifth-generation Mesoscale Model (MM5) in simulating the atmospheric circulations across the Arctic river basins. MM5 was adapted by the Polar Meteorology Group at the Byrd Polar Research Center, at The Ohio State University, located in the USA, for use in polar regions, and is termed Polar MM5. Successful numerical simulations of the atmospheric circulations over the Antarctic and Greenland ice sheets using the Polar MM5 have been conducted and have shown improved performance in comparison to previous results obtained using the earlier versions of the MM5 (Bromwich et al., 2001; Cassano et al., 2001; Guo et al., 2003; Box et al., 2004, 2006).The purpose of the present paper is therefore to study atmospheric situations using the Polar MM5 and to illustrate the model skill in simulating atmospheric circulations over the Arctic river basins. The North America (Fig. 1) and Eurasia (not shown) were set into two model domains and the results of both a 10-day (from 19 to 29 April 1997) and five-month (from 15 December 2002 to 15 May 2003) simulations over the aforementioned two domains were validated.

The model and data for this study are discussed in section 2. Section 3 is reserved for a discussion of the results. In this section, the comparisons between the simulations using the model and the experimental observations in terms of global analyses, surface- and upper-air variables were analyzed. Finally conclusions are presented in section 4.

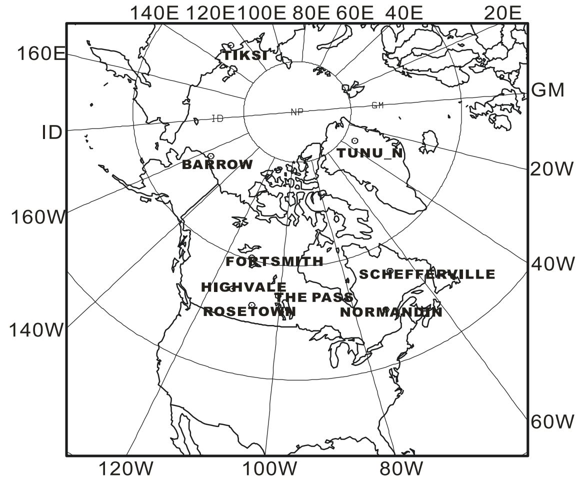

Fig. 1. Map of the North American model domain with a spatial resolution of 60 km.

2. Model and data

2.1 *Brief model description*

The Polar MM5 used for these simulations is based on version 3.4 of the PSU-NCAR Mesoscale Model (MM5), and the general description of MM5 is provided by Grell et al. (1994). The atmospheric mesoscale model configuration and the changes made to the standard version of MM5 for use over the polar region are described below.

The Polar MM5 is a limited-area, three-dimensional, non-hydrostatic model with multiple options available for various physical parameterization schemes. Physical options used in this study include the Reisner explicit microphysics parameterization for the large-scale cloud and precipitation processes (Reisner et al., 1998), the Grell cumulus parameterization for the sub-grid scale cloud processes (Grell et al., 1994), Community Climate Model version 2 (CCM2) radiation scheme for radiative transfer, and the 1.5-order turbulence closure parameterization used for turbulence fluxes.

Overestimated cloud cover was found to be a problem over the Antarctic in sensitivity simulations using an older version of MM5 (MM4) (Hines et al., 1997a,b) 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 resulted in an unrealistically small size as well as large values for the number concentration of the simulated ice crystals at very low air temperatures. In the Reisner explicit microphysics parameterization scheme, replacement of the Fletcher (1962) equation for the concentration of ice nuclei by the equation from Meyers et al. (1992) in the explicit microphysics eliminates the cloudy bias which was found in simulations using the standard MM5 in the polar region. And NCAR CCM2 radiation scheme for the prediction of the radiative transfer of long-wave and short-wave radiations through the atmosphere was also modified and used in the Polar MM5. Cloud cover was predicted by the cloud water and ice mixing ratios from the Reisner explicit microphysics parameterization scheme in the Polar MM5 instead of being a simple function of the grid-box relative humidity, or the cloud liquid-water path which was determined from the grid-box temperature in the standard version of MM5. Sensitivity experiments revealed this approach eliminated excessive cloud liquid-water path, which resulted in a large downwelling of the long-wave radiation fluxes during the austral winter over the Antarctic ice sheet (Hines et al., 1997a,b). These modifications allowed for a consistent treatment for the radiative and microphysical properties of the clouds and therefore for the separate treatment of the radiative properties of both the liquid- and ice-phase cloud particles.

The turbulent fluxes in the planetary boundary layer (PBL)was parameterized using the 1.5-order turbulence closure scheme of Janjic (1994) that was used in the National Centers for Environmental Predictions (NCEP) Expected Time of Arrival (ETA) model. A sea-ice surface type was added to the 13 types used in the original MM5. Heat transfer through the model substrate was predicted using a multilayer soil model. The thermal properties used in the multi-layer soil model for snow and ice surface type were 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 to 1.91 m also being conducted. The surface fluxes and ground temperature were considered separately over sea-ice, open water and land surface grid points based on the thermal properties of the surface, which were then combined before interacting with the overlying atmosphere.

Two model domains were used in this study, one centered at (65°N, 95°W) with 150 by 150 grids, termed "North America" (Fig. 1), and the other centered at (65°N, 75°E) with 180 by 180 grid points, referred to as "Eurasia" (not shown), both having a horizontal resolution of 60 km. Figure 1 is the first domain, North America, from a southern boundary including all the northward flowing river basins beyond the northern coast. A total of 28 vertical sigma levels were used with the lowest model level being located at a height of 50 m above ground level in the Polar MM5. The high vertical resolution near the surface provided the potential possibility of handling the evolution of the near-surface meteorological variables over the Arctic river basins.

2.2 *Data*

Parallel sensitivity simulations comparing the Polar MM5 with the original MM5 for the time period between 19–29 April 1997 (10-day simulation) were carried out to verify what effect of these physical processes modifications were on the original MM5 over the North American domain. Then extended evaluation of the Polar MM5 five-month simulation (from 15 December 2002 to 15 May 2003) over both the North American and Eurasian domains were presented jointly to indicate the forecasting skill of this model over the Arctic river basins. The forecast model simulations were run over the North American and Eurasian domains simultaneously, while keeping all other model conditions identical.

The initial and boundary conditions for the 10-day simulation were obtained from the NCEP global analyses, and the daily 0000 UTC run of the Aviation Model (AVN) that is issued by NCEP provided the initial and boundary condition data for the five-month simulation. The original MM5 and Polar MM5 runs were initialized at 0000 UTC for a series of 48-h short duration simulation.

The data used for the validation of models in this study included the NCEP global analyses, NCEP/NCAR reanalysis, surface and sounding observations from the University of Wyoming as well as Automatic Weather Station (AWS) observations from the Greenland Climate Network (GC-NET) (Steffen and Box, 2001). Based on the record completeness, reliability and location representation, 16 surface or sounding sites located over the Arctic river basins were used to verify the model simulations in the study. The more detailed information for these stations is presented in Table 1.

3. Results

Model outputs from both the original MM5 and

Table 1. List of stations used for the model verification.

Station	Latitude (°N)	Longitude (°E)	Elevation (m)
Aleksandrovskoe	60.4	77.9	48
Barrow	71.3	−156.8	4
Fort Smith	60.0	−111.9	203
Highvale	53.5	−114.5	747
Jakutsk	62.0	129.7	101
Jyväskyla	62.4	25.7	145
Moscow	55.4	37.9	168
Munster	52.1	7.7	52
Normandin	48.8	−72.6	137
Rosetown	51.6	−107.9	586
Salehard	66.5	66.7	16
Schefferville	54.8	−66.8	521
The Pass	54.0	−101.1	271
Tiksi	71.6	128.9	7
Tunu_N	78.0	−34.0	2113
Verhojansk	67.6	133.4	138

Note: negative value means longitude west.

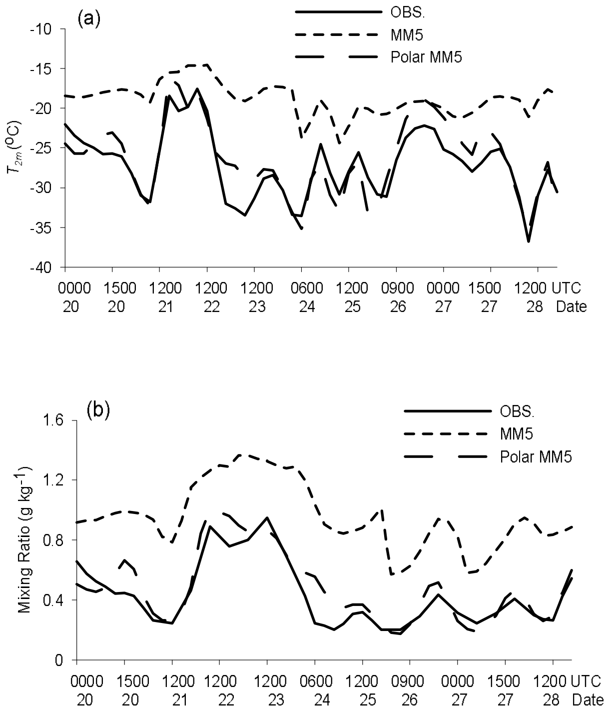

Fig. 2. The time series of the original MM5, Polar MM5 forecasts and Tunu_N observations from 0000 UTC 20 April to 0000 UTC 29 April 1997: (a) Temperature at 2 m and (b) Surface Mixing Ratio.

Polar MM5 simulations over the Arctic region were compared with NCEP global analysis, NCEP/NCAR reanalysis, the available station surface observations and the twice-daily upper-air data within the following sections. The time series of the surface pressure, sea-level pressure, near-surface temperature, dew-point temperature, wind speed and wind direction, as well as geopotential height, temperature, dew-point temperature, wind speed and wind direction at 850 hPa and 500 hPa pressure levels for the selected stations were compared to the observations that were analyzed. The bias, root-mean-square error (rmse), and correlation coefficients from the comparison of the models simulations to the available observations were also calculated from the observations and model outputs. The bias is defined as the difference between the modeled and observed mean values for a given variable.

3.1 *Verifications of the Polar and original MM5 simulations with AWS observations and NCEP global analysis*

There are many differences in the physical parameterization schemes used in the Polar and original MM5 models. Parallel simulations of the two methods during 19–29 April 1997 over the North American Arctic domain were carried out to show the validity of modified version of the Polar MM5 for regions over the Arctic river basins. The predictions for the Greenland station Tunu_N, which has a good time series of observations, was selected to display the improvement of the Polar MM5 over the North American Arctic region. The time series plots of the Polar MM5, original MM5 predictions and the AWS observations at Tunu_N for 3 hourly surface pressure, temperature, mixing ratio, wind speed and wind direction were analyzed. In general, the Polar MM5 performs provided improved model predictions than the original MM5, especially on the simulations of temperature and mixing ratio (Fig. 2). The trends in the time series of all of the variables were reproduced by the Polar MM5 well, which is similar to the study of Bromwich et al. (2001) at the Tunu_N site using the Polar MM5 version 2. With regard to the evolution of the near-surface temperature, Fig. 2a shows that the Polar MM5 reproduced the observed temperatures with a high degree of accuracy. The mean differences between the simulations and observations were -0.4°C for the Polar MM5 and 8.3°C using the original MM5. Another noticeable improvement was in the simulation of the near-surface mixing ratio (Fig. 2b). The Polar MM5 modeled mixing ratio displayed a slight moisture bias of 0.1 g kg^{-1} and the time series circle showed a very good agreement with the observations. In the contrast, the time series of modeled near-surface mixing ratio using the original MM5 showed a large moisture bias of 0.6 g kg^{-1}. The analyses of the modeled and observed near-surface winds indicated a slight bias for both models. The modeled wind speed and wind direction modeled with the Polar MM5 and original MM5, both at the magnitude and time series cycle, were in close agreement with the observed winds (not shown). The Polar MM5 did provide a slight improvement in the simulation of wind direction, however.

The above comparisons and analyses show that the Polar MM5 produced improved near-surface variable forecasts than the original MM5 for both magnitudes and trends. The high degree of forecasting skill at the Greenland site Tunu_N verified that the simulation capability of the Polar MM5 over the North American Arctic region. The well predicted near-surface temperatures and mixing ratios using the Polar MM5 further confirmed that the modified physical parameterization schemes in the aspect of explicit microphysics and radiation schemes and so on, were appropriate for the research domain.

To further determine the forecasting accuracy of the Polar MM5 over a large domain, the area-averaged characteristics of the near-surface meteorological variables for four areas located over North American domain were considered as well. They were area No.1

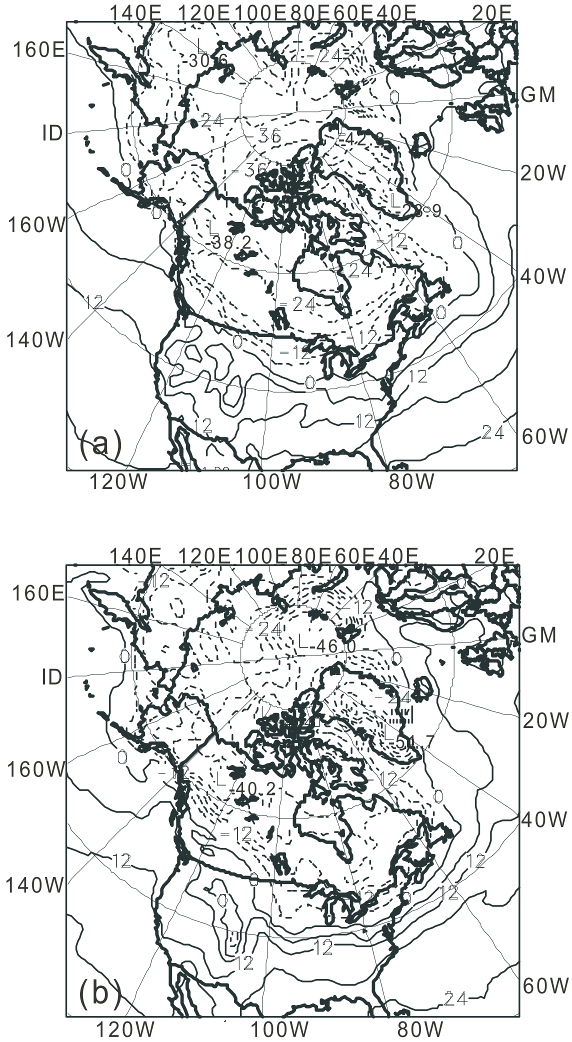

Fig. 3. Daily surface temperature from Polar MM5 (a) and NCEP/NCAR reanalysis data (b) on the 13th of March 2003 with a contour interval of 4°C.

(30°–50°N, 130°–70°W) that represented the United States, area No.2 (50°–60°N, 140°–70°W) and area No.3 (60°–70°N, 140°–70°W) that represented areas within Canada and the area No.4 (60°–80°N, 20°–60°W) that represented Greenland. Based on these comparisons, the number of observations, bias, rmse (root-mean-square error) and the correlation coefficients in terms of sea-level pressures and near-surface temperatures for the four areas are listed in Table 2 and provide indication of the skill of the models. With the exception of the area No. 3, the Polar MM5 simulated a slightly colder surface temperature over these three areas. This analysis is similar to the study of Bromwich et al. (2001) that indicated that there is a small cold bias in the Polar MM5 modeled near-surface temperatures over Greenland when compared with AWS observations. The maximum bias in the sea-level pressure for the four areas was 1.7 hPa and 2.0°C in the near-surface temperature. The time series of the modeled sea-level pressures and near-surface temperatures matched the observed time series very well (not shown).

3.2 *Verification of the Polar MM5 simulations with NCEP/NCAR reanalysis and surface and upper-air observations*

The simulations using the Polar MM5 over North America and Eurasia that were run for a series of 48-h simulation in an attempt to describe the atmospheric circulations that occurred in the Arctic river basins were compared to NCEP/NCAR reanalysis, surface and upper-air observations. The five month simulations were compiled from a series of 48-h short-duration simulations of the atmospheric state with the first 24-h being discarded for the purpose of spinup.

Daily mean temperatures at a height of 2 m were derived from Polar MM5 simulations and were compared with NCEP/NCAR reanalysis data (T62 Gaussian grid with 19×94 grids). The NCEP/NCAR reanalysis of the temperature at a height of 2 m was interpolated into the Polar MM5 model grids over the North American domain. Evaluation of the modeled daily mean near-surface air temperature fields on 13 March 2003 over the North American domain (Fig. 3a), was conducted using the air temperature at a height of 2 m as given by the NCEP/NCAR in Fig. 3b. The distribution and magnitude of the simulated surface temperature was similar to the values observed in the NCEP/NCAR reanalysis, although there were slight differences that existed. The simulated temperatures were slightly lower than the reanalysis data, as the area-averaged values of the temperature were about −3.67°C in comparison to the Polar MM5 and −2.83°C below the NCEP/NCAR reanalysis data. The three main minimum temperatures were shown on these two maps, though the location of the coldest temperature was located west and south of Greenland in the NCEP/NCAR reanalysis and a little farther north using the Polar MM5. Despite these differences, the Polar MM5 provided good performance in reproducing the distributions of the surface temperature over the North American model domain.

The time plots for the simulations of the sea-level pressure, near-surface and dew-point temperatures, wind speeds and wind directions at Schefferville were selected to represent North American domain, while Jyväskyla was selected to represent the Eurasian domain from 15 December 2002 to 15 May 2003 and are displayed in Figs. 4–5. These two sites were selected to represent the land-surface characteristics of the Arctic river basins, while confining the choice of the stations

Table 2. Statistics from the Polar MM5 predictions and the surface observations for the 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

Note: rmse means root-mean-square error, and corr means correlation coefficients.

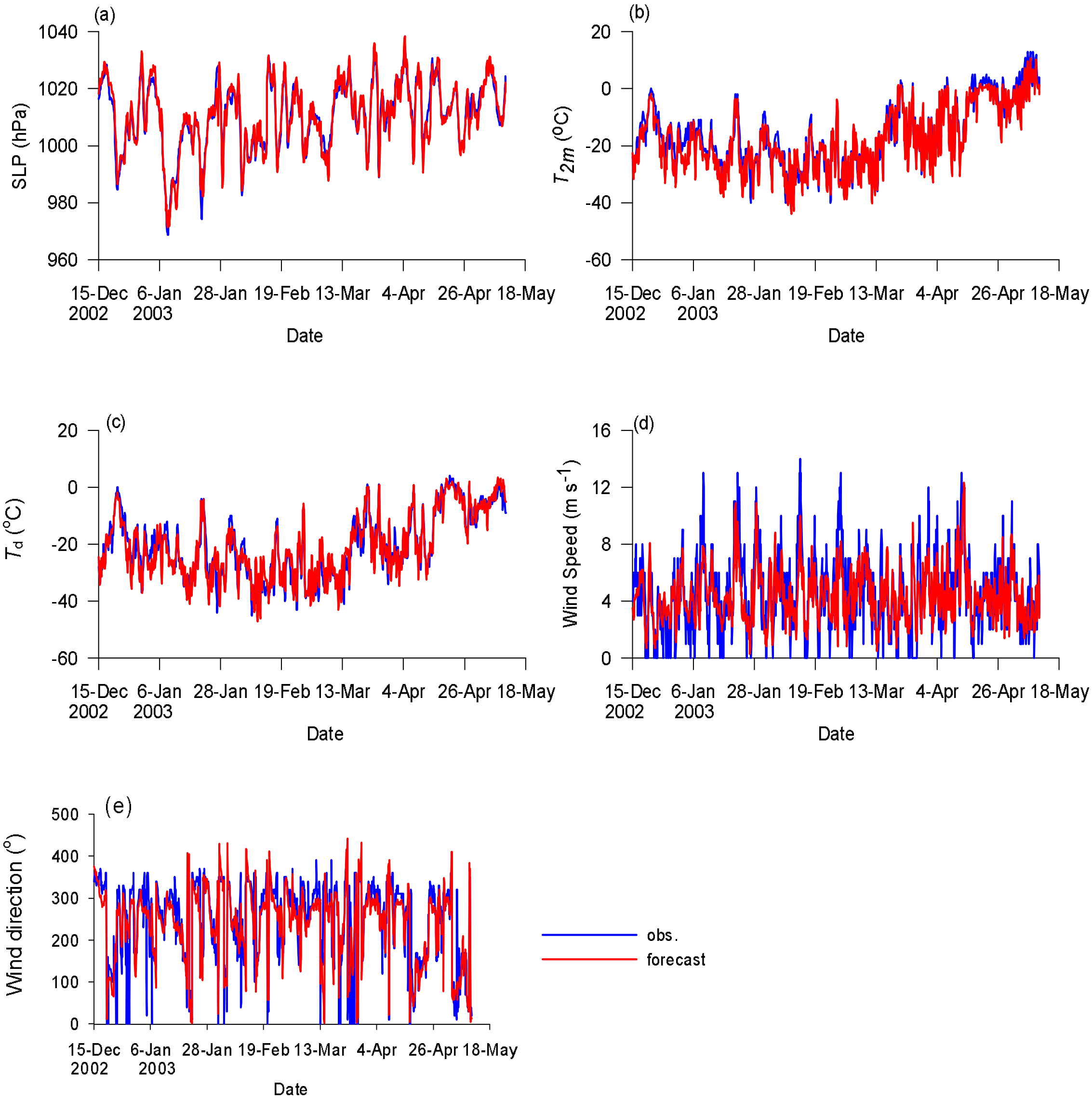

Fig. 4. The time series of the Polar MM5 forecasts and Schefferville observations from 15 December 2002 to 15 May 2003: (a) sea-level pressure, (b) temperature at 2 m, (c) surface dew-point temperature, (d) surface wind speed and (e) surface wind direction (°).

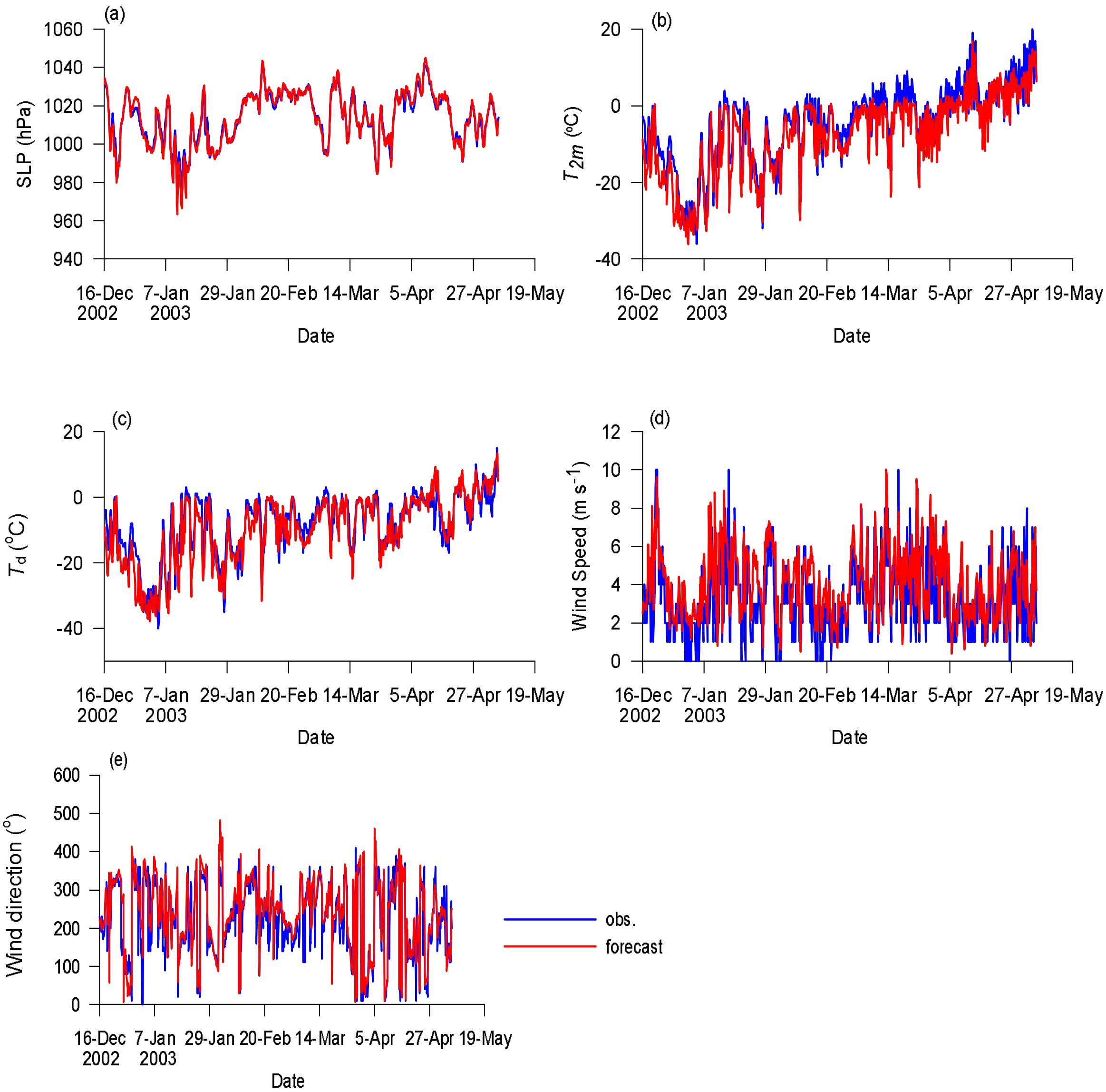

Fig. 5. The time series of the Polar MM5 forecasts and Jyväskyla observations from 16 December 2002 to 15 May 2003: (a) sea-level pressure, (b) temperature at 2 m, (c) surface dew-point temperature, (d) surface wind speed and (e) surface wind direction (°).

to those exhibiting nearly complete records from 15 December 2002 to May 2003. The figures show that the time series of the modeled near-surface variables matched the observed trends very well and with a high degree of accuracy. The statistics of the simulations from the Polar MM5 at the 6 surface observations that represented the North American Arctic river basins domain and the 4 surface observations that represented the Eurasian domain during this period confirmed the forecasting skill of the Polar MM5 further (Table 3). In general, the modeled sea-level pressure, near-surface and dew-point temperatures, wind directions and wind speeds all had small mean biases relative to the observations. From the winter into spring months (December to May), the Polar MM5 modeled temperature bias was negative, the modeled sea-level pressure bias was slightly negative, consistent with a hydrostatic increase in the model surface pressure due to the colder atmosphere. The cold bias implied a reduced capacity of the model atmosphere to hold water vapor and led to the negative bias in the modeled dew-point temperature. The period of positive wind speed bias corresponded to the time period with the largest negative temperature bias and was thought to be caused by enhanced drainage flow that was forced by the colder near-surface air in the model.

Table 3. Statistics from the comparisons between the Polar MM5 predictions and the surface observations from 15 December 2002 to 15 May 2003.

Station	Sea-level pressure (hPa)			Temperature (°C)			Dew-point temperature (°C)			Wind speed (m s^{-1})			Wind direction (°)		
	bias	rmse	corr	bias	rmse	corr	bias	rmse	corr	bias	rmse	corr	bias	rmse	corr
Barrow	0.9	4.2	0.96	−1.2	4.0	0.91	−1.5	4.5	0.90	0.8	2.5	0.68	−14.1	48.8	0.88
Highvale	–	–	–	−3.4	5.5	0.89	−2.3	5.2	0.91	0.0	1.9	0.50	23.3	85.2	0.65
Normandin	0.9	3.2	0.96	−1.9	4.1	0.95	0.6	3.8	0.95	−0.4	2.1	0.62	1.2	77.9	0.64
Rosetown	0.2	5.3	0.92	−0.5	2.0	0.95	−0.2	2.1	0.93	0.3	1.5	0.56	17.6	75.0	0.74
Schefferville	0.1	3.5	0.96	−1.9	4.3	0.94	0.1	4.1	0.94	−0.1	1.9	0.71	−7.9	60.0	0.80
The Pass	0.7	4.4	0.91	−2.0	3.9	0.97	1.4	4.3	0.95	−0.4	1.8	0.70	1.9	55.4	0.86
Moscow	−1.3	3.2	0.98	−3.5	4.5	0.93	−2.5	4.0	0.92	0.2	1.4	0.67	17.2	54.9	0.78
Munster	0.5	3.4	0.97	−2.2	3.3	0.93	−0.6	3.2	0.87	0.0	1.5	0.68	15.2	64.0	0.77
Jakutsk	−0.3	3.9	0.97	−0.8	4.5	0.98	0.8	4.2	0.97	0.9	1.8	0.50	–	–	–
Jyväskyla	−0.2	3.1	0.98	−2.7	4.4	0.94	−2.7	4.4	0.94	0.8	1.5	0.73	16.4	46.5	0.89

Note: – means no value, rmse means root-mean-square error, and corr means correlation coefficients.

Table 4. Statistics from the Polar MM5 predictions and the sounding observations at 850 hPa and 500 hPa from 15 December 2002 to 15 May 2003.

Station	Level (hPa)	Geopotential height (m)			Temperature (°C)			Dew-point temperature (°C)			Wind speed (m s^{-1})			Wind Direction (°)		
		bias	rmse	corr	bias	rmse	corr	bias	rmse	corr	bias	rmse	corr	bias	rmse	corr
Aleksandrovskoe	850	−35.1	41.9	0.98	−0.7	2.2	0.96	0.7	4.2	0.84	−0.3	3.5	0.78	−0.1	29.9	0.90
	500	−40.5	53.1	0.98	−0.2	1.9	0.95	0.3	4.4	0.79	0.0	4.3	0.87	−0.6	20.4	0.96
Barrow	850	1.8	33.0	0.96	0.5	2.0	0.96	0.8	5.6	0.74	1.3	3.9	0.67	4.5	68.6	0.77
	500	10.8	34.3	0.98	1.0	2.2	0.94	1.4	5.2	0.72	−0.1	4.9	0.82	−3.8	51.7	0.86
Fort Smith	850	−3.1	38.2	0.90	−0.5	2.9	0.96	2.4	6.0	0.87	0.4	4.2	0.56	−4.6	64.3	0.82
	500	−2.2	39.4	0.96	0.7	2.4	0.94	2.0	7.2	0.72	−1.0	6.7	0.74	−2.3	48.6	0.82
Salehard	850	−31.2	44.4	0.97	−0.8	2.7	0.94	−0.9	4.2	0.86	0.0	4.5	0.72	−3.8	51.8	0.84
	500	−31.0	57.5	0.97	−0.3	2.2	0.94	−0.8	4.5	0.79	0.1	5.9	0.77	−6.6	48.3	0.83
The Pass	850	−10.0	34.8	0.91	−0.5	2.7	0.97	2.0	6.7	0.86	0.0	4.1	0.70	−2.5	67.1	0.78
	500	−8.9	34.6	0.98	0.8	2.0	0.97	3.2	8.5	0.70	−1.5	6.8	0.77	−3.6	45.9	0.86
Tiksi	850	−11.5	21.6	0.98	−0.1	2.2	0.96	0.5	3.0	0.90	−0.9	3.0	0.71	−4.6	47.6	0.81
	500	−6.5	26.3	0.99	0.2	1.3	0.98	0.5	3.5	0.84	−0.6	3.9	0.82	−0.5	32.8	0.92
Verhojansk	850	−9.3	30.2	0.95	0.2	2.1	0.96	1.3	3.1	0.92	0.7	3.3	0.58	−0.2	67.8	0.73
	500	1.0	34.2	0.97	0.3	1.6	0.96	0.4	3.7	0.80	0.6	4.7	0.73	5.9	39.7	0.91

Note: rmse means root-mean-square error, and corr means correlation coefficients.

For the sea-level pressure, most of the variability at sites Schefferville and Jyväskyla was represented quite well by the Polar MM5 (Figs. 4 and 5). The excellent agreement between the modeled and observed sea-level pressure time series was consistent with the high correlation coefficients of the modeled and observed sea-level pressures. Table 3 shows the magnitude of the sea-level pressure bias, which ranges from 0.1 hPa to 1.3 hPa, with the magnitude of the bias generally being less than 0.9 hPa at the 9 sites. The rmse of sea-level pressure ranged from 3.1 hPa to 5.3 hPa and was an indication of the typical instantaneous magnitude of the difference between the modeled and observed sea-level pressures. The correlation coefficients between the modeled and observed sea-level pressures were high, ranging from 0.91 to 0.98.

There was still a slight cold bias for the predicted near-surface temperature at all 10 stations considered. The negative biases were mainly caused by the low downward long-wave radiation under clear skies over the Arctic river basins for the CCM2 radiation scheme. The bias in temperature has a magnitude of less than $-2.0°$C at most stations, but was significantly larger than $-3.5°$C that was observed at site Moscow. The rmse ranged from 2.0° to 5.5°C, with correlation coefficients being greater than 0.89 for all sites for both domains, which indicated that the Polar MM5 forecasts reproduced the observed trends in the near-surface temperature accurately. For example, the correlation coefficients for the temperature were 0.94 at stations Schefferville and Jyväskyla, respectively. At sites Schefferville and Jyväskyla, there was a noticeable synoptic variability in the observed temperature time series, which was well represented by the Polar MM5 simulations, with many of the significant variations in the temperature being depicted by the model simulations (Figs. 4–5). The similarity was attained for the near-surface dew-point temperature based on the synoptic variability evaluation and statistical comparisons. Aside from the slight bias in the model forecasts, the time series of the model-predicted dew-point temperature was similar to the observed time series and the Polar MM5 captured the timing of most of the maxima in the observed dew-point temperature time series. The high correlations between the modeled and the observed time series for the dew-point temperatures changed from 0.87 to 0.95, which was indicative of the accurate timing of the changes in the modeled near-surface atmospheric state.

The Polar MM5 simulations captured a great deal of the synoptic variabilities in the observed winds during the five-month period over the two sites selected (Figs. 4–5). As with the other variables, the Polar MM5 predicted wind speed and wind direction that were usually difficult to predict over the complex land surfaces, matched the observed changes quite well. The maximum and minimum wind speeds and the changes in direction were accurately represented by the model, although there were differences in the details of the modeled and observed time series. The correlation coefficient between the observed and modeled wind speed time series ranged from 0.50 to 0.70, and 0.64 to 0.88 for the wind direction at all stations considered (Table 3). The model reproduced the observed atmospheric state near the surface with a high degree of realism, which is consistent with the high correlation of the modeled and observed surface variables.

The synoptic variability in the model simulations was also evaluated by comparing the time series of the twice-daily, upper-air observations at 850 hPa and 500 hPa pressure levels with that of the corresponding Polar MM5 output over the North American and Eurasian domains in this section. Seven upper-air stations (Table 1)—Aleksandrovskoe, Barrow, Fort Smith, Salehard，The Pass, Tiksi and Verhojansk—were selected to show the forecasting skill of the Polar MM5 for the profile features over the Arctic river basins. It is noted that station Aleksandrovskoe is located in the Yenisei River basin and stations Tiksi and Verhojansk are located in the Lena River basin, station Salehard is located in the Ob River basin, The Pass is located in the Nelson River basin and Fort Smith lies in the Mackenzie River basin.

Comparisons of the observed and modeled geopotential height, temperature, dew-point temperature, wind speed and wind direction both at 850 hPa and 500 hPa are presented in this section. Table 4 provides a summary of the statistics from the comparisons between the model simulations and the sounding observations at both pressure levels for the 7 stations from 15 December 2002 to 15 May 2003. This shows that the forecasts from the Polar MM5 both at 850 hPa and 500 hPa, reproduced the observed variables with a high degree of realism. For example, the average biases for the modeled temperature at 850 hPa and 500 hPa differed from the observations by less than 1.0°C at the seven sites, while the rmse ranged from 1.3°C to 2.9°C. For the dew-point temperature, the maximum bias was 3.2°C, while the mean biases for the wind direction were less than 10° at the two levels for the seven sounding stations considered. The correlation coefficients for the variables were very high at both pressure levels. The correlation coefficients for the temperature, dew-point temperature, wind speed and wind direction at 850 hPa for Aleksandrovskoe reached 0.96, 0.84, 0.78 and 0.90, while they were 0.97, 0.86, 0.70 and 0.78 at The Pass (Table 4). The high

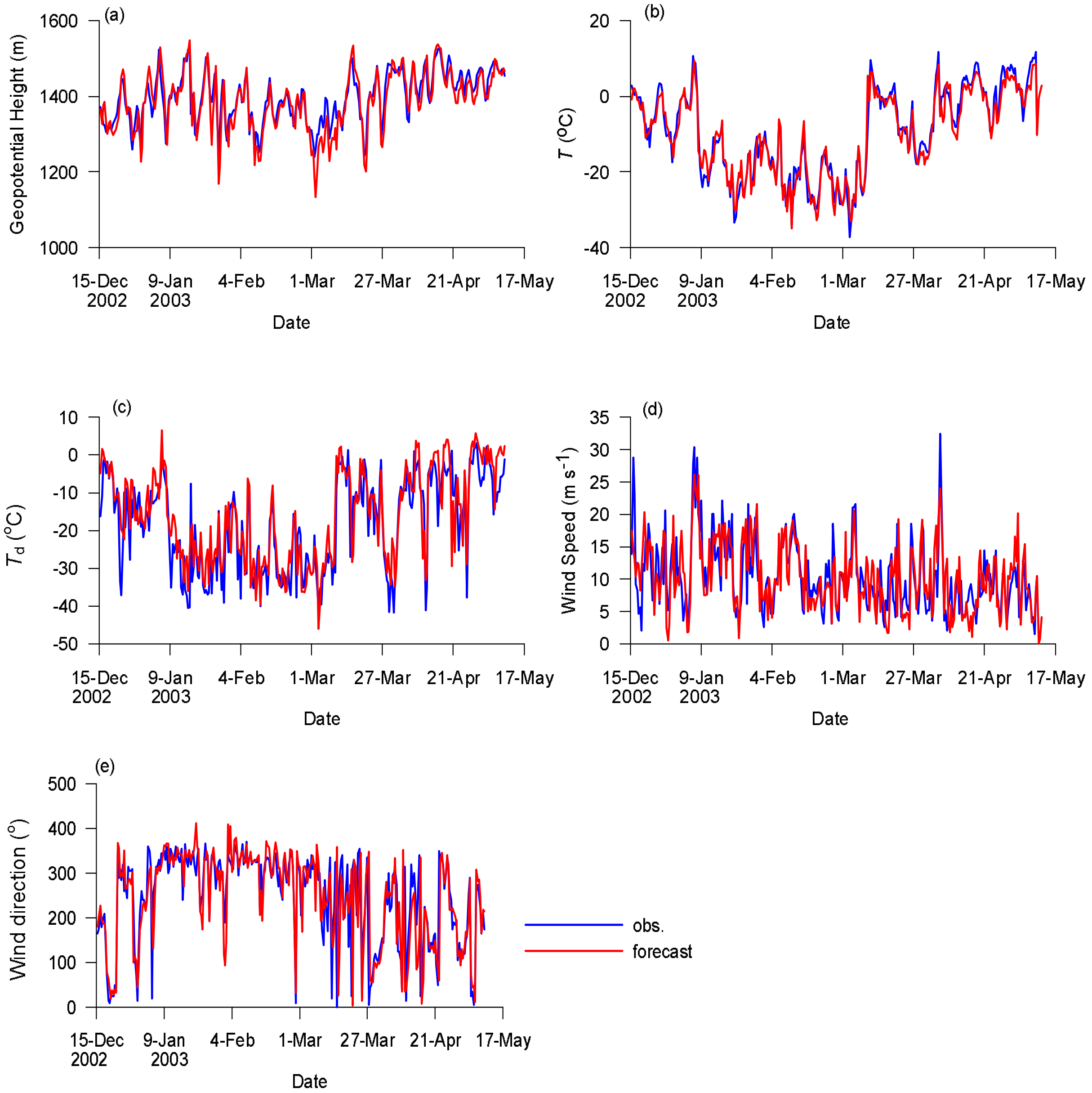

Fig. 6. The time series of the Polar MM5 forecasts at 850 hPa for The Pass from 15 December 2002 to 15 May 2003: (a) geopotential height, (b) temperature, (c) dew-point temperature, (d) wind speed and (e) wind direction (°).

correlation coefficient indicated that the model simulations can accurately reproduce the observed time series of the variables. It is obvious that the Polar MM5 provides improved forecasting skill over the North American Arctic river basins. Moreover, the time series of geopotential height, temperature, dew-point temperature, wind speed and wind direction at 12-h intervals for the model output at 850 hPa compared against the observations collected at station The Pass are shown in Fig. 6. The figure shows the Polar MM5 simulations accurately captured the synoptic variability at the 850 hPa pressure level in the observed variables during the five months, which is consistent with the above statistical analysis (Table 4).

4. Conclusions

The Polar MM5 simulations during 19–29 April 1997 and predictions during 15 December 2002–15 May 2003 were compared with AWS observations from GC-NET, NCEP global surface analysis, NCEP/NCAR reanalysis, surface and sounding observations obtained from the University of Wyoming for the purpose of verifying the model for the regions over the Arctic river basins. The verification revealed that the Polar MM5 simulations, both at near-surface variables and vertical profiles over the Arctic river basins, provided a high degree of accuracy based on five months of simulations and upon comparisons with 16 observation stations.

Sensitivity experiments between the Polar MM5 and the original MM5 indicated that the Polar MM5 simulated near-surface variables better, especially for the variables of temperature and mixing ratio. It confirmed that the reasonable modifications of the physical parameterizations in the original MM5 used in simulating the atmospheric circulations over the North American Arctic were justified.

Based on the five months of simulations and analysis, the Polar MM5 captured most of the variations in the near-surface variables at the 10 surface sites considered, although there was a slight difference near the surface. The statistical analyses and time plots from the comparisons of the Polar MM5 simulations to the surface observations showed that the observed sea-level pressure, near-surface temperature, dew-point temperature, wind speed and wind direction were reproduced by the Polar MM5 with a reasonable degree of accuracy over both the North American and Eurasian domains. The verifications revealed an agreement between the simulations and the observations (high correlations) and small biases between the forecasts of the geopotential height, temperature, dew-point temperature, wind direction and wind speed with the model output at both 850 hPa and 500 hPa and the observations. This illustrates that the Polar MM5 has a high level of forecasting skill over the Arctic river basins.

The horizontal resolution of 60 km was a little coarse for learning about the land surface characteristics over the Arctic river basins in detail. Additionally, the reasons for the cold bias of the near-surface winter temperature, appeared in the simulations with the Polar MM5 was because there was too little downward long-wave radiation as a result of there being too little cloud cover. During the winter the net radiation budget, which is dominated by long-wave radiation and cloud-radiation interactions, showed a surprising degree of skill, but evaluations of the model physics with detailed cloud and radiation observations was required. Therefore additional analysis and improvement on the physical processes should focus on the cloud properties and radiative effects, the surface energy balance and the turbulent fluxes, with these experiments including the use of more and more field observations. This current work has focused on the evaluation of the atmospheric circulation and has shown that the Polar MM5 reproduced the observed atmospheric state. Further analysis of the atmospheric processes is required in order to confirm that these accurate model simulations are achieved through physically correct mechanisms. Given the high level of skill present in the Polar MM5 simulations over Arctic river basins, the model output can be used to study spatial and temporal variability of the pan-Arctic land mass.

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