JP 2.15 HIGH RESOLUTION REGIONAL CLIMATE SIMULATIONS OVER ICELAND USING POLAR MM5

David H. Bromwich[1*], Lesheng Bai[1], and Gudmundur G. Bjarnason[2]
[1]Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus, OH, U.S.A.
[2]HALO, Laboratory for Oceanic and Atmospheric Sciences, Iceland

1. INTRODUCTION

Iceland is a high latitude island that contains a variety of microclimates because of its complex mesoscale terrain and land use. An important issue is how to use large-scale atmospheric analyses in conjunction with high-resolution topography and land use to reconstruct the historical states of local climate over Iceland. An alternative approach to climate modeling is limited area modeling where the horizontal resolution typical for the mesoscale is applied to a small region of interest.

Two approaches are generally used to simulate regional climate. One is long period simulations that have the advantage of keeping the long-term forcing uninterrupted but the model atmosphere in the domain interior will drift from the observations because of model limitations such as inaccurate numerics and errors in physical parameterizations. Another is a sequence of short integrations that can minimize possible drift caused by accumulated model errors but the spin up problems introduced by the reinitailization must be addressed. Pan et al. (1999) evaluated the two approaches and found that the locations of specific meteorological features drifted downstream because simulated winds were too strong during long-term integration and that the simulation results can be improved by a sequence of short segment integrations. Regional climate simulation studies of the Greenland area using short segment integrations obtained good results (Bromwich et al. 2001, Cassano et al. 2001) in part because the large scale flow is across the integration domain.

The Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) fifth generation mesoscale model (MM5, Grell et al. 1995) has been modified for use in polar regions by the Polar Meteorology Group of the Byrd Polar Research Center at The Ohio State University and is referred to as the Polar MM5. Model validations and case studies of Polar MM5 simulations over Greenland and Antarctica have been performed, and the model is currently being used for synoptic and climate studies in the data sparse high latitudes. Cassano et al (2001) simulated a complete annual cycle over the Greenland ice sheet using Polar MM5, and the results showed a high degree of forecast skill for all variables when verified with automatic weather station (AWS) data. Bromwich et al. (2001) simulated katabatic winds over Greenland with the Polar MM5. Global atmospheric analyses as well as AWS and instrumented aircraft observations from Greenland were used to verify the forecast atmospheric state. The results show that the Polar MM5 can reproduce the observed atmospheric state with a high degree of realism. In addition the model is able to simulate a realistic diurnal cycle for the surface variables, as well as capturing the large scale, synoptically forced changes in these variables. Comparisons of the modeled profiles of wind speed, direction, and potential temperature in the katabatic layer with aircraft observations are also favorable, with small mean errors. Polar MM5 is also being used in a special numerical weather prediction program, the Antarctic Mesoscale Prediction System (AMPS) that supports the forecasting needs of the United States Antarctic Program at McMurdo Station, Antarctica (Bromwich et al. 2003, Powers et al. 2003). Olafur and Olafsson (2002) did experiments with the standard MM5 model to determine the optimal configuration for climatological downscaling studies of precipitation over Iceland.

In this study the Polar MM5 version 3.5 is used to simulate the high-resolution regional climate from 1991 to 2000 over Iceland driven by the European Centre for Medium-Range Weather Forecasts Tropical Ocean - Global Atmosphere (ECMWF TOGA) operational analyses. Three nested model domains are used to get reasonable lateral boundary condition information from the global analyses for the mesoscale simulation. To limit the systematic bias of the regional model a short integration time is used to predict the regional climate from the large-scale circulation.

2. MODEL DESCRIPTION

The Polar MM5 model used here is based on version 3.5 of the PSU / NCAR MM5. A detailed discussion of the modifications made to the standard version of MM5 for use over polar regions is described in Bromwich et al. (2001) and Cassano et al. (2001). The key modifications are: revised cloud / radiation interaction; modified explicit ice phase microphysics; optimal turbulence (boundary layer) parameterization; implementation of a sea ice surface type; and improved treatment of heat transfer through snow/ice surfaces.

Heat transfer through the model substrate is predicted using a multi-layer "soil" model. The thermal properties used in the "soil" model for snow and ice surface types are modified following Yen (1981). In addition the number of substrate levels represented in the "soil" model is increased from six to eight, with an increase in the resolved substrate depth from 0.47 m to 1.91 m. Also, a sea ice surface type is added to the 13

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[*] *Corresponding author address*: David H. Bromwich, Byrd Polar Research Center, The Ohio State University, Columbus, OH 43210-1002;
e-mail: bromwich@polarmet1.mps.ohio-state.edu

surface types available in the standard version of MM5 (Hines et al., 1997a,b). The sea ice surface type allows for fractional sea ice cover in any oceanic grid point, with surface fluxes at the sea ice grid points calculated separately for the open water and sea ice portions of the grid point. These fluxes are then averaged before interacting with the overlying atmosphere.

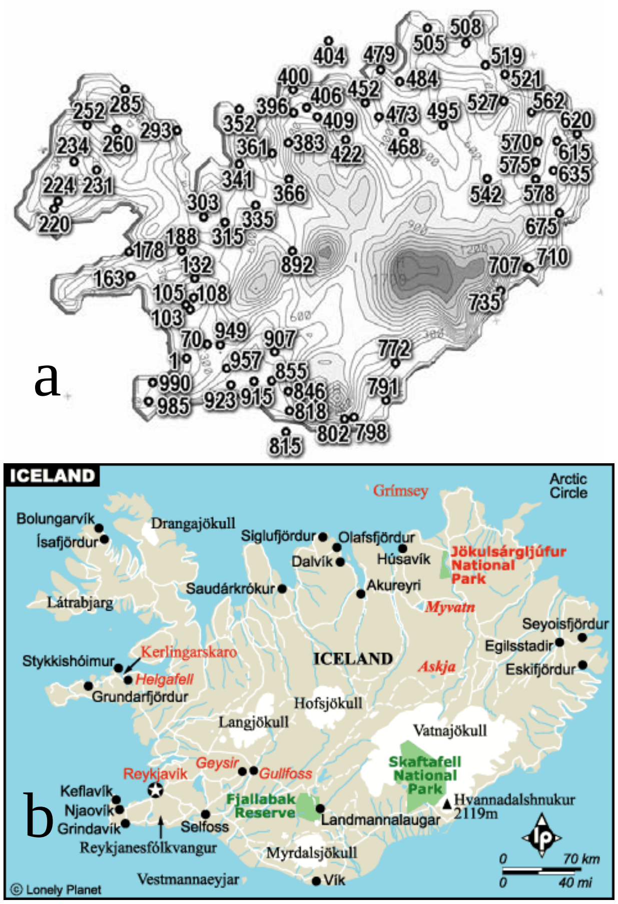


Figure 1. (a) Meteorological stations with monthly mean climate data for Iceland. Station numbers are given, (b) Location map of Iceland (http://www.lonelyplanet.com/mapshells/europe/iceland/iceland.htm).

Polar MM5 with 8 km resolution has been applied to simulate the regional climate over Iceland. Three nested model domains are used. The horizontal resolution and grid points are 73x85, 72km for domain 1; 121x103, 24km for domain 2; and 73x85, 8km for domain 3. The vertical discretization consists of 28 irregularly spaced levels in σ-coordinates from the surface up to 10 hPa. The model physics options are: mixed phase explicit moisture scheme for three domains; Grell cumulus scheme for domain 1 and domain 2; CCM2 atmospheric radiation scheme; and the MRF planetary boundary layer scheme. The 2.5^{o} horizontal resolution ECMWF TOGA surface and upper air operational analyses are used to provide the initial and boundary conditions for the model. The Polar MM5 is used to produce short duration (30 h) simulations from 1991 to 2000. The integration strategy is a sequence of 30 h simulations, with the first 6h being discarded for spin-up reasons.

3. EVALUATION OF POLAR MM5 SIMULATION OVER ICELAND

The monthly mean climate data for 70 surface observation stations for 1991 to 2000 are used to evaluate the simulation results (Figure 1). The evaluation results show that Polar MM5 has very good forecast skill for monthly mean near-surface temperature, 2m dew point and sea level pressure over Iceland. For monthly mean near-surface wind speed, Polar MM5 has good forecast skill and can reasonably simulate the near-surface mesoscale wind climate over Iceland.

Figures 2 show the biases, root mean square errors (RMSs) and correlation coefficients between the simulated and observed precipitation from 1991 to 2000. The monthly mean precipitation biases between simulated and observed are -69 to 61 mm, RMSs are 22 to 87 mm, and the correlation coefficients are 0.33 to 0.89, with the values larger than 0.60 for all except for seven stations. The mean bias, RMS and correlation coefficient are -0.5mm, 44mm and 0.72 for the seventy stations respectively. The simulated precipitation is larger than observed in northern Iceland and smaller in the southern part. The comparatively high correlation coefficient indicates the simulations can reasonably reproduce the precipitation variability. Polar MM5 has good forecast skill for monthly mean precipitation over Iceland.

4. SIMULATION RESULTS

4.1 LONG-TERM MEAN ANNUAL PRECIPITATION

Modeling the spatial and temporal distribution of precipitation is one of the most challenging problems for mesoscale regional climate simulations. The precipitation process involves climate, soil, vegetation and orographic characteristics. The cyclonic forcing changes control the annual cycle of precipitation while the spatial distribution is controlled by the terrain. As a result of these factors, precipitation is extremely variable in space and time. Furthermore, climate variability in Iceland is enhanced by the North Atlantic Oscillation (NAO) phenomenon, which is the dominant mode of interannual climate variability over and around the North Atlantic Ocean. In a general sense, there are two precipitation seasons, one wet that occurs from October through April, and the other dry from May through September. The annual distribution of precipitation over Iceland is directly dependent on the position of the Icelandic Low.

The observed mean annual precipitation distribution for 1931-1960 is shown in Fig. 3a. This analysis is derived from mostly low elevation station precipitation observations (not corrected for systematic errors, like wind effects) and supplemented by hydrologic observations and snow accumulation measurements for subjective evaluation in areas with no direct precipitation data (Einarsson 1984; T. Jonsson, personal communication, 2004). The minimum annual precipitation is about 400 mm yr^{-1} and occurs on the northeastern basin regions of Myvatn and Askja. The mountain zones have an average annual precipitation of 2800 mm yr^{-1}. Along the southeast coast of Iceland, there is an average annual precipitation of about 3000 mm yr^{-1}. The heaviest precipitation is located in this zone, with maxima exceeding 4000 mm yr^{-1} over Myrdalsjökull and south of Vatnajökull. Given that the relationship between large and regional/local scale atmospheric behavior is highly nonlinear (Moss et al. 1994), atmospheric physically-based models need to be extended to these regions and scales to complement approximate observational syntheses.

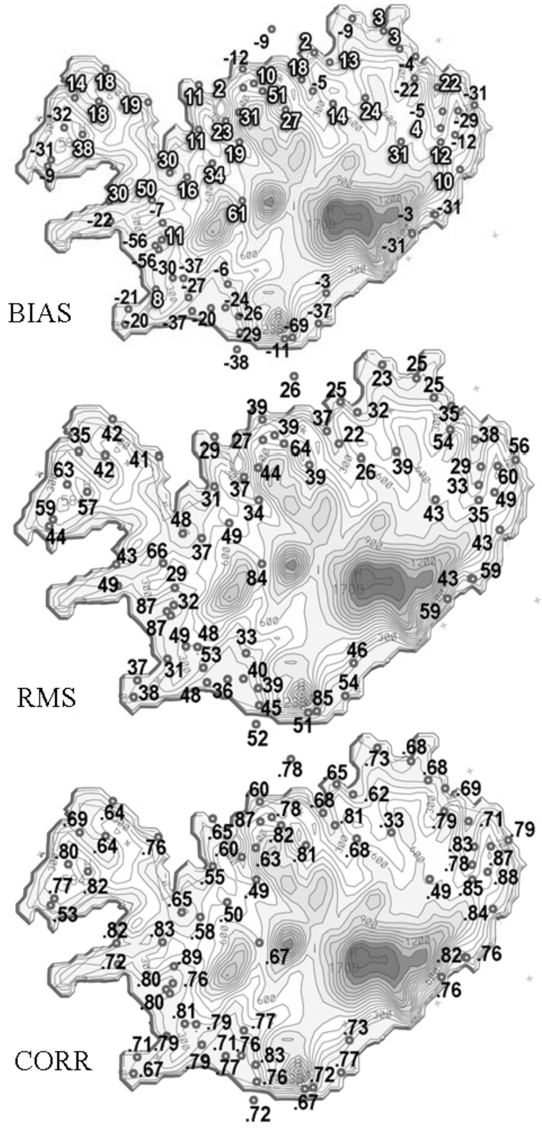


Figure 2. The monthly mean precipitation bias, RMS and correlation between observed and simulated by Polar MM5 from 1991 to 2000 for precipitation (mm). Terrain is shaded for reference; contour interval is 200m. Positive bias values are highlighted.

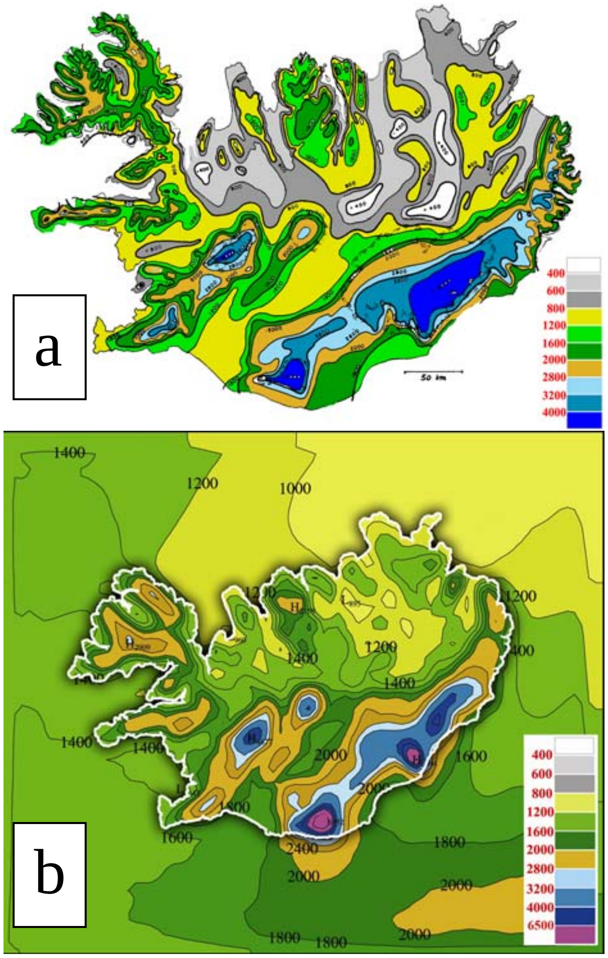


Figure 3. (a) The observed mean annual precipitation distribution which is derived from station precipitation observations and statistical extrapolation (units: mm), contour interval is 200 mm. (b) The annual mean precipitation in (1991-2000) simulated by Polar MM5 V3.5 (units: mm) contour interval is 200 mm.

The long-term mean annual precipitation simulated by Polar MM5 for 1991-2000 is shown in Fig. 3b. The overall precipitation distribution over Iceland is reasonably well simulated by Polar MM5, especially in the southwest, south and southeast regions. There are shortcomings to many of the simulated smaller scale precipitation features. The model cannot simulate the detailed structure and magnitude of the "observed" precipitation in northwestern and northern Iceland. Rögnvaldsson et al. (2004) applied a statistical model and MM5 to estimate the precipitation in the complex terrain over Iceland. The results suggest that on average MM5 simulates more precipitation than the statistical approach with the contrast being greater in the northern part of Iceland than in the south. To some extent this difference can be explained by gauge measurements not recording all of the solid precipitation during strong wind events, i.e., the observed values in north and northwestern Iceland are probably too small.

The computed annual precipitation amounts at Langjökull and Hofsjökull are larger than observed. It seems that the 8 km model resolution is still too coarse to resolve all the observed small-scale variations of precipitation. The winter (September 15-April 30) and summer (May -September 14) precipitation spatial distributions are consistent with the cyclonic forcing changes, the winter amounts are much larger than those during the summer. However, the spatial distribution is maintained in each season, reflecting the dominant control of topography, landuse, model physics and the persistent circulation pattern on the precipitation distribution (not shown).

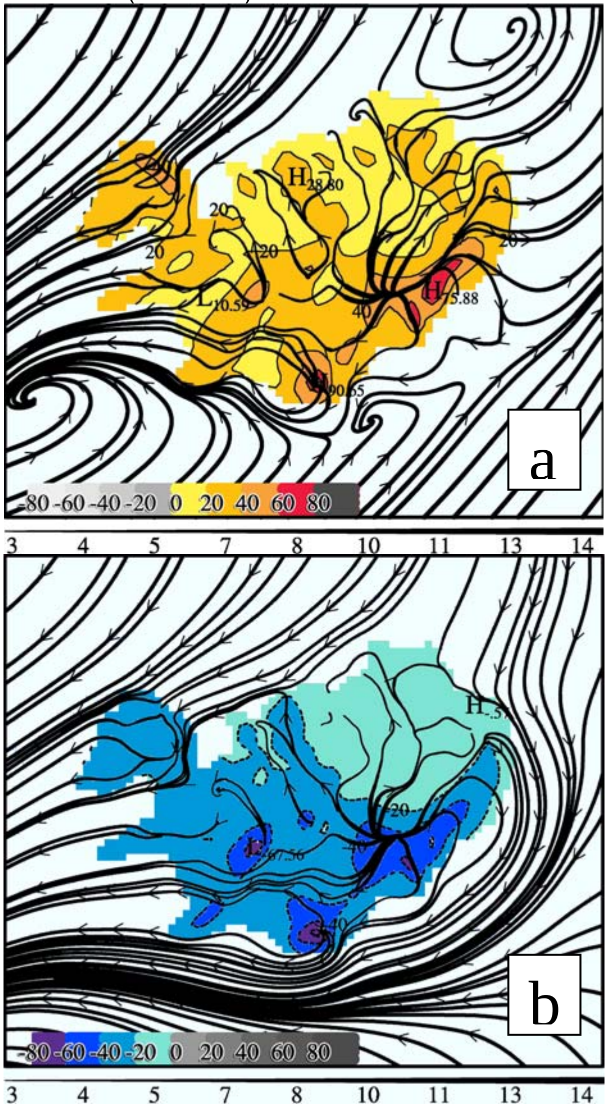


Figure 4. The simulated monthly precipitation anomaly and 10m wind for (a) NAO-positive phase, (b) NAO-negative phase 1991-2000. Contour interval is 20 mm and negative values are dashed. Width of streamlines is proportional to wind speed with scale shown at bottom of each figure.

Figure 4 shows simulated monthly precipitation anomaly and the streamlines of monthly mean near-surface winds for NAO-positive phase and NAO-negative phase simulated by Polar MM5. Rogers (1984) normalized seasonal NAO index (http://polarmet.mps.ohio-state.edu/) is used. The NAO index is taken to be larger than 1 for “NAO-positive phase” and less than -1 for “NAO-negative phase”. During NAO-positive phase, the surface wind is stronger than during the negative NAO phase over Iceland. The Icelandic low is stronger in NAO positive phase than during the negative phase and the center of Icelandic low is located just to the southwest of Iceland. The Greenland high is weaker in the NAO-positive phase and the resulting northerly winds are weaker, and most of Iceland is controlled by southwest winds. The southwesterly near-surface winds flow upslope over most of Iceland and result in the precipitation increase. For NAO-negative phase, Iceland is controlled by northeasterly winds, and precipitation decreases. For both NAO-positive phase and NAO-negative phase in winter, the near-surface wind pattern over Iceland is katabatic.

In general the precipitation over Iceland is positively correlated to the NAO index. In a positive NAO year precipitation over Iceland is larger than average, whereas in negative NAO years the precipitation is reduced.

4.2 TREND OF ANNUAL PRECIPITATION OVER ICELAND FROM 1991 TO 2000

Figure 5 shows the interannual variations of precipitation simulated by Polar MM5 at T12e and B16d sites over Vatnajökull ice cap, for winter, summer, and annual totals along with observed winter snow accumulation from ice cores for 1991-2000. Snow accumulation is the net result of precipitation, evaporation/sublimation, and drifting. Evaporation/sublimation is likely small in winter, and the net drifting effects are unknown, but should be small, so precipitation is equated with accumulation. The precipitation amounts at the grid points retrieved from simulations are interpolated to the snow stake locations.

It is seen that the observed linear decrease of winter accumulation is well captured by the simulated winter precipitation. The precipitation simulated by Polar MM5 is less than observed from 1992 to 1996 in winter, but larger than observed from 1997 to 1999 at site T12e. At site B16d, the simulated precipitation is larger than observed after 1994. T12e is located on the western part of the Vatnajökull ice cap at the northwestern margin of a zone of very large precipitation gradient, and B16d is at south central part of the ice cap where there is also a large precipitation gradient. A slight shift in the model simulation will easily give a different precipitation amount. If the model cannot simulate the mesoscale features, it is difficult to get a good precipitation result at both sites only 40 km apart (or 5 grid lengths), so Polar MM5 has good skill in capturing the terrain-forced precipitation over Iceland. The year-to-year variations in observed winter accumulation are reasonably well represented by the simulated precipitation at B16d and T12e. The winter precipitation decrease determines the annual signal, and there is no significant change in summer. During summer the simulated precipitation is about 500 mm at both sites, and the year-to-year variations are very small.

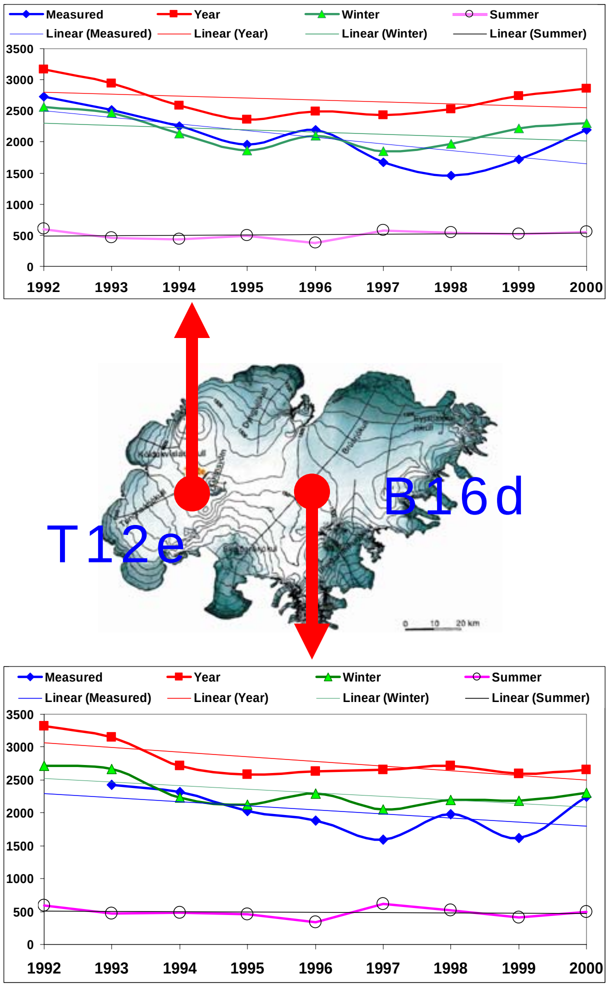


Figure 5. The interannual variations of the observed winter (Sep-Apr) accumulation and simulated annual, winter and summer total precipitation (mm) at the sites T12e and B16d over 1992-2000.

The spatial distribution of the slope of the linear regression line of annual precipitation from Polar MM5 for 1991-2000 has been computed, and the results are shown in Fig. 6. The annual modeled precipitation decreases for all Iceland except the northeastern part, specifically the Askja basin, the northeast coast and the coast close Olafsfjödur where the precipitation increases by about 0-26 mm yr^{-1}. The maximum decreases of modeled precipitation exceed 150 mm yr^{-1}at Hofsjökull, Langjökull, Myrdalsjökull and Vatnajökull ice cap. These simulated results are in good agreement with those obtained from station precipitation records (Fig. 6b). The model results during winter are similar to the annual results and agree with those obtained from ice cores measurements.

From central to southern Iceland, and over the sea to the east and west of Iceland, there is a major negative precipitation trend from 1991 to 2000. The large negative trend area is also found in model domain 2, and from the ERA-40 and ECMWF TOGA precipitation (not shown); this demonstrates that the precipitation decrease is a large scale climate feature that should be investigated.

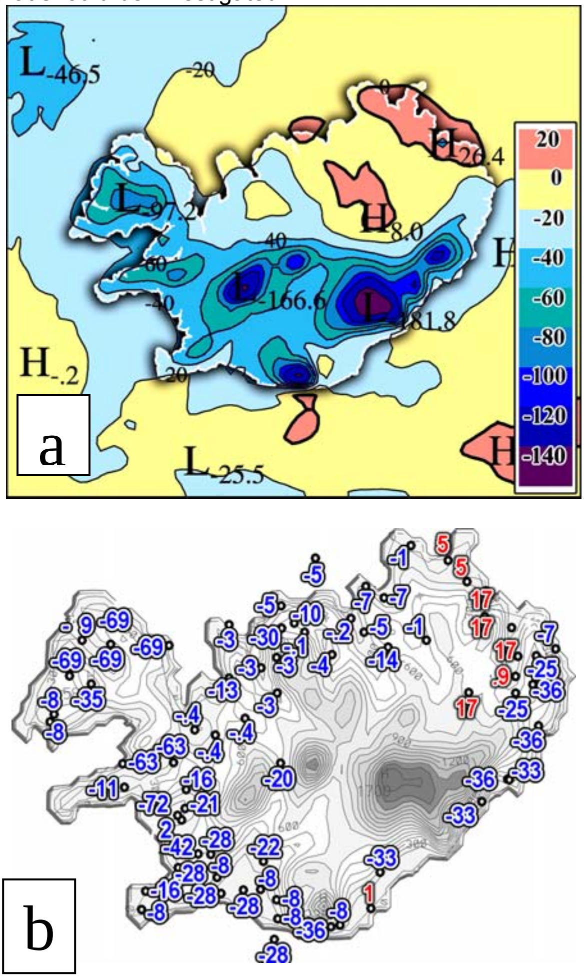
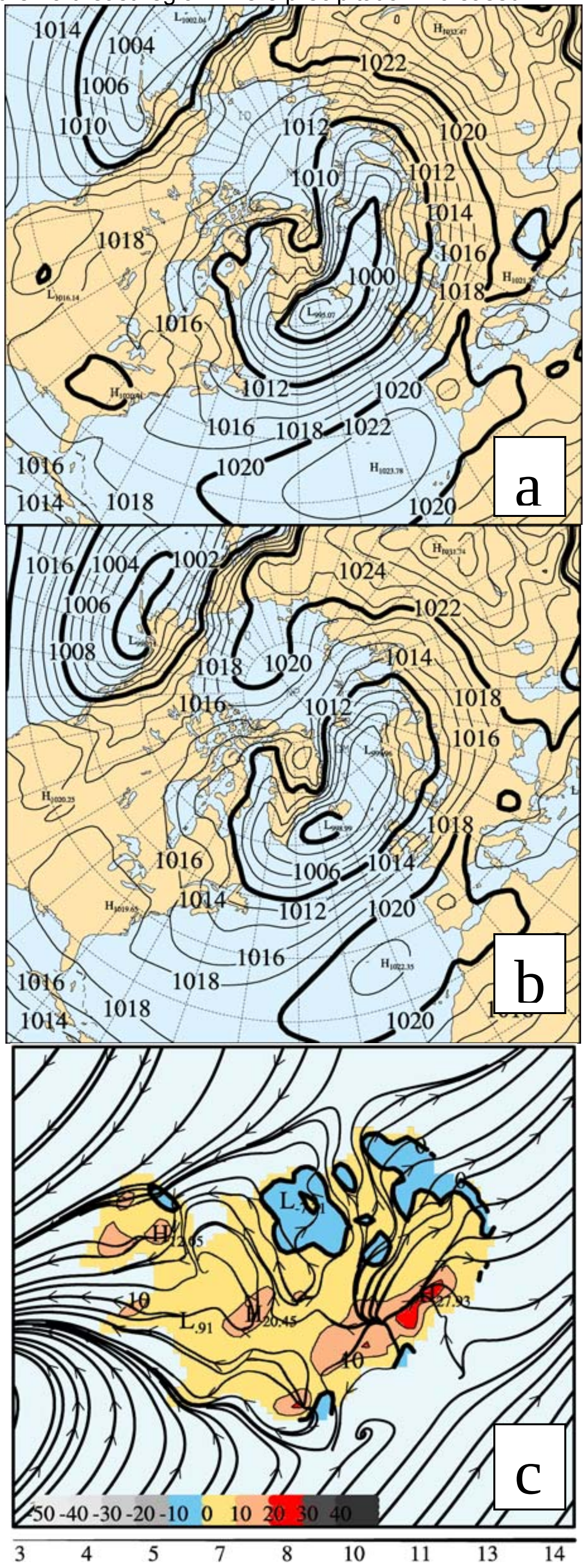


Figure 6. (a) Annual precipitation trend in Iceland simulated by Polar MM5 from 1991 to 2000 in mm/year, (b) Annual observed precipitation trend (mm/year) in Iceland for 1991-2000.

4.3 THE RELATIONSHIP BETWEEN CIRCULATION AND PRECIPITATION

ERA-40 sea level pressure was used to investigate the relationship between large scale circulation and precipitation from 1991 to 2000. Figure 7 shows the monthly mean sea level pressure in winter half year (ONDJFM) during 1992-1994 and 1996-1998, and the simulated monthly mean 10m-wind field and precipitation anomaly. It is can be seen that the Icelandic low during 1992-1994 is stronger than during 1996-1998 and the center of the Icelandic low is located to the southwest of Iceland. The Greenland high and associated northerly winds are weaker during 1992-1994 and most of Iceland is controlled by southwesterly winds. The southwest near-surface wind flows upslope over the southwest part of Iceland and results in the precipitation increase in this region. During 1996-

1998, the Icelandic low was weaker and shifted 4-5° toward the east; the Greenland high became stronger. Iceland was controlled by northeast winds, and precipitation decreased over most of Iceland except for the northeast region where precipitation increased.



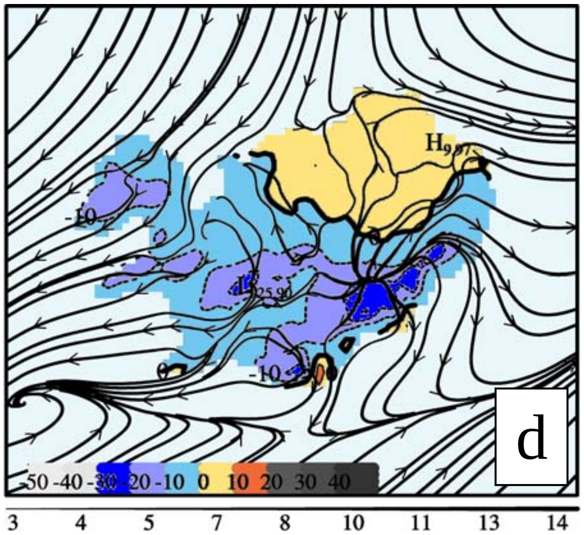


Figure 7. The monthly mean sea level pressure in winter half year (ONDJFM) (a) 1992-1994; (b) 1996-1998; contour interval is 2hPa and 1000, 1010 and 1020 isobars are bolded. The simulated monthly mean 10m-wind field and precipitation anomaly in winter half year (ONDJFM) (c) for 1992-1994 and (d) 1996-1998. Width of streamline is proportional to wind speed with the scale shown beneath each streamline plot. Contour interval is 10 mm for precipitation.

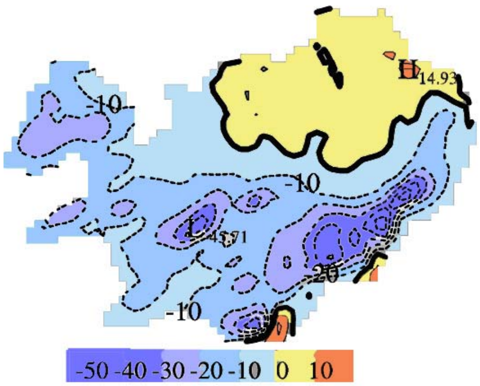


Figure 8. The mean precipitation difference between 1996-1998 and 1992-1994 in winter half year. Contour interval is 10 mm.

Figure 8 shows the simulated annual mean precipitation difference between 1996-1998 and 1992-1994 in the winter half-year. The precipitation decreased over most of Iceland except for the northeast region. The centers of precipitation decrease are located at Langökull, Hofsjökull, Myrdalsjökull and Vatnajökull mountain regions and the pattern is similar to that shown in Fig. 6. It can be summarized that the Icelandic low, Greenland high and their patterns determine the precipitation distribution and change over Iceland. During winter half year from 1991 to 2000, the Icelandic low intensity weakened and its center shifted toward the east (as also found by Rogers at al. 2004) and the Greenland high intensity became stronger. This pattern resulted in stronger north and east winds, and weaker southerly winds; as a consequence precipitation decreased in south and southwest Iceland, and increased in the east.

5. CONCLUSIONS

High resolution regional climate simulations over Iceland from 1991-2000 have been performed using Polar MM5 with three nested domains and short duration integrations. The verification indicates that Polar MM5 accurately simulated the mesoscale and large scale near-surface atmospheric circulations over Iceland on monthly time scales, thus the high-resolution regional climate in a limited area can be reasonably reconstructed using a limited area model with reasonable physical parameterizations, and high-resolution topography and land use.

The time-averaged mesoscale precipitation distribution over Iceland is reasonably simulated by Polar MM5. Consistent with the cyclonic forcing changes, the winter amounts are much larger than those during the summer. The spatial distribution is maintained in each season, reflecting the dominant control of topography. The precipitation over Iceland is larger than average for the positive NAO phase expecially over southeast Iceland, whereas for the negative NAO phase the precipitation is less than average and the large decrease regions are located to the west and south of Iceland.

The simulated interannual precipitation variations during winter for 1991-2000 well match those observed from accumulation measurements on Vatnajökull ice cap. This means that Polar MM5 has a good skill in simulating terrain forced precipitation over Iceland. The year-to-year variations in observed winter accumulation are well represented by the simulated precipitation at sites B16d and T12e. The winter precipitation decrease dominates the annual signal, but there is no significant change in summer over Vatnajökull ice cap.

The precipitation decreases for all Iceland except the eastern and northeastern part of Iceland where the precipitation increases about 20-100 mm from 1991 to 2000. During winter half year from 1991 to 2000, the Icelandic low intensity became weaker and its center shifted toward east, and the Greenland high intensity became stronger. This pattern resulted in stronger north and east winds, and weaker south winds; as a result precipitation decreased in south and southwest Iceland, and increased in the east.

The ten year simulation results indicate that Polar MM5 is a powerful tool for mesoscale regional climate studies in the data sparse high latitudes. The high resolution regional climate simulation can be improved by using 3DVAR in Polar MM5 which can assimilate observational data over steep topography and by using a land surface model over Iceland. The simulation results can also be improved by increasing the model resolution and model spin-up time.

ACKNOWLEDGMENTS

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