High resolution climate simulations over the Arctic

Annette Rinke, Klaus Dethloff, Arne Spekat,
Wolfgang Enke & Jens Hesselbjerg Christensen

The regional atmospheric climate model HIRHAM has been applied to the Arctic. Simulations for the whole year 1990 and for an ensemble of winter months (January of 1985–1995) have been performed. The comparison of the simulations with observational data analyses shows that the general spatial patterns are in good agreement with the data, in both the vertical structure and the annual cycle. For an additional validation of the model results, a multivariate classification of large-scale circulation patterns has been applied to the January ensemble model simulations.

A. Rinke & K. Dethloff, Alfred Wegener Institute for Polar and Marine Research, Telegrafenberg A43, D-14473 Potsdam, Germany; A. Spekat & W. Enke, Institute of Meteorology, Free University of Berlin, C.-H.-Becker-Weg 6-10, D-12165 Berlin, Germany; J. H. Christensen, Danish Meteorological Institute, Lyngbyvej 100, DK-2100 Copenhagen Ø, Denmark.

Introduction

An improved understanding of the Arctic climate system is necessary to provide a quantitative assessment of the magnitude of global change and to clarify the role of Arctic regions in the global climate system. Several intercomparison studies analysed the performance of general circulation models (GCMs) in the Arctic, for example Cattle (1991), Walsh & Crane (1992), Bromwich, Chen et al. (1995), Bromwich, Tzeng et al. (1994), Chen et al. (1995) and Tao et al. (1996). These results show wide discrepancies in the GCM simulations of the Arctic climate; large variations were found in simulated sea level pressure (SLP), cloud cover and other variables. The deficiencies of the GCMs in describing the Arctic climate are partly due to inadequate parameterizations of physical processes. Typical Arctic phenomena like summertime stratus, ice crystal clouds and, during winter, very shallow planetary boundary layer with strong inversions are not captured by current parameterizations. Moreover, current GCMs are characterized by a rather coarse horizontal resolution which fails to capture mesoscale features caused by coastlines, ice sheets, and mountains. Finally, errors in Arctic large-scale dynamics can arise as a consequence of insufficient description of low latitude processes.

An alternative approach in climate modelling is limited area modelling wherein the horizontal resolution typical for the mesoscale is applied to a limited area of interest. Forcing at the lateral boundaries using observation-based analyses avoids the import of large-scale errors from GCMs. An atmospheric regional modelling system for the Arctic was developed by Lynch et al. (1995) and Dethloff et al. (1996). Dethloff et al. applied a regional atmospheric climate model, called HIRHAM, to the whole Arctic region north of 65°N. Winter and summer simulations performed subsequently show that the simulated spatial patterns are consistent with observations, although deviations occurred which are due to deficiencies in the cloud-radiation scheme, surface processes, and boundary layer scheme. Rinke et al. (1997) showed that the results can be clearly improved using the new parameterization package ECHAM4.

The model is briefly described below, followed by a description of high horizontal resolution simulations of the present Arctic climate. The model results are compared with observational data analyses. Finally, the model results are further validated with the application of a multivariate classification of weather patterns.

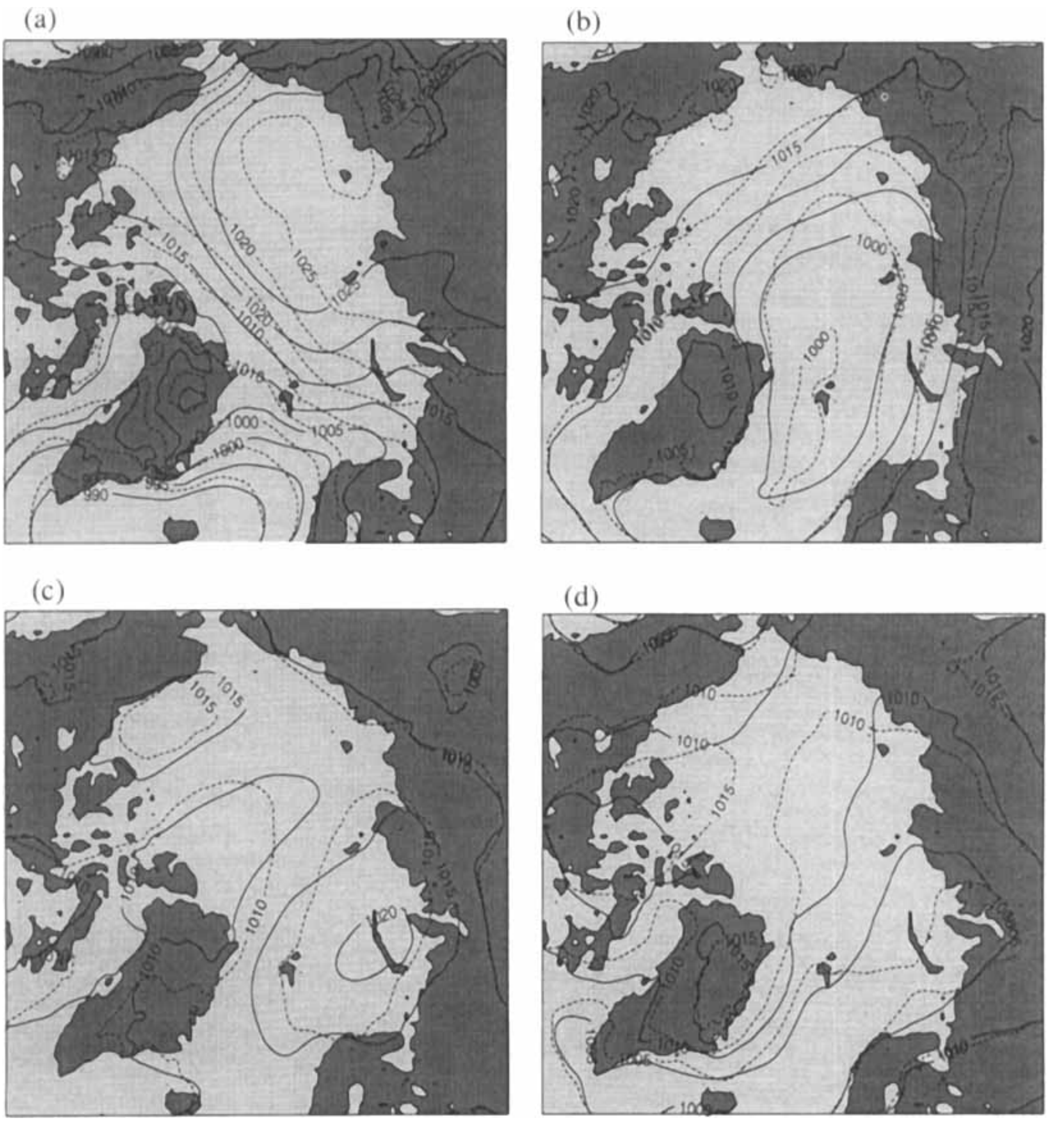

Fig. 1. Geographical patterns of the monthly averaged sea level pressure in hPa for (a) January, (b) April, (c) July and (d) October of the year 1990. Simulation results are shown as solid lines; ECMWF analyses are shown as dashed lines.

Model description

The regional atmospheric climate model we employed is called HIRHAM (Christensen et al. 1996). At the lateral boundaries the model is forced by ECMWF analyses, updated every six hours. The information from the lateral boundaries is transferred into the model by a relaxation procedure using a 10 gridpoint wide boundary zone. At the lower boundary the model is forced by ECMWF analysed sea surface temperature and sea ice fraction, updated daily. The simulations are performed at a horizontal resolution of 0.5 degrees in rotated latitude and longitude and 19 vertical layers with the model top at 10 hPa. The regional climate model HIRHAM uses the physical parameterization package of the general circulation model ECHAM (Roeckner et al. 1992, 1996). A detailed description of the dynamical and physical properties of the model was given in Dethloff et al. (1996). Physical parameterizations include: radiation, cumulus convection, stratiform clouds, land

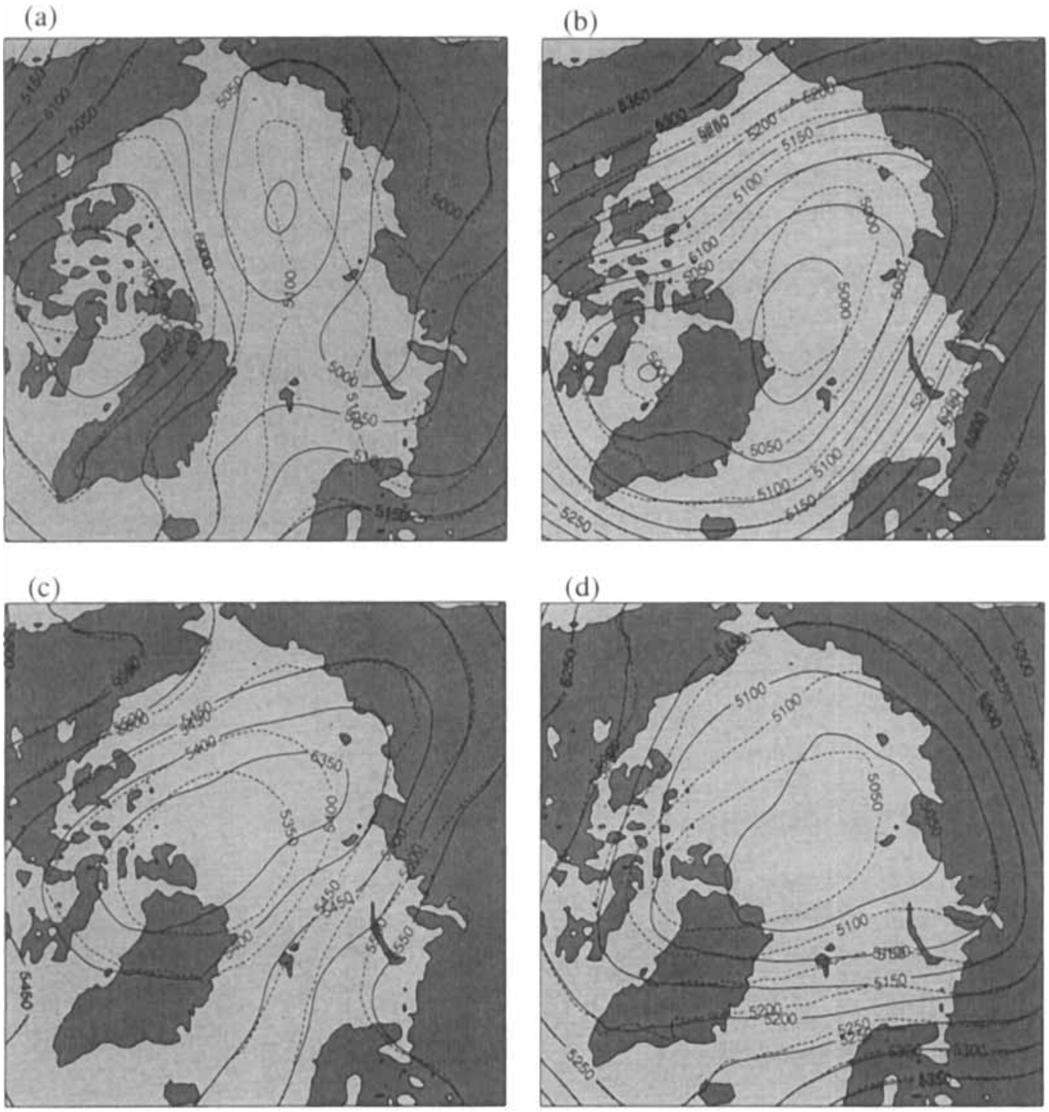

Fig. 2. Geographical patterns of the monthly averaged 500 hPa height in metres for (a) January, (b) April, (c) July and (d) October of the year 1990. Simulation results are shown as solid lines; ECMWF analyses are shown as dashed lines.

surface processes, hydrology, sea surface and sea ice processes, planetary boundary layer and gravity wave drag. The simulations are performed with two different versions of the physical parameterizations, called ECHAM3 and ECHAM4. Cloud and radiation, moisture transport, convection, cloud-turbulence interaction in the planetary boundary layer, and land surface data are the major processes revised in the ECHAM4 version compared to the previous version ECHAM3.

Simulation of the present Arctic climate

To simulate the Arctic circulation HIRHAM has been run for an entire year – the year 1990 – and for an 11 member winter ensemble (January of the years 1985–1995). The focus here is the description of the monthly mean atmospheric structures.

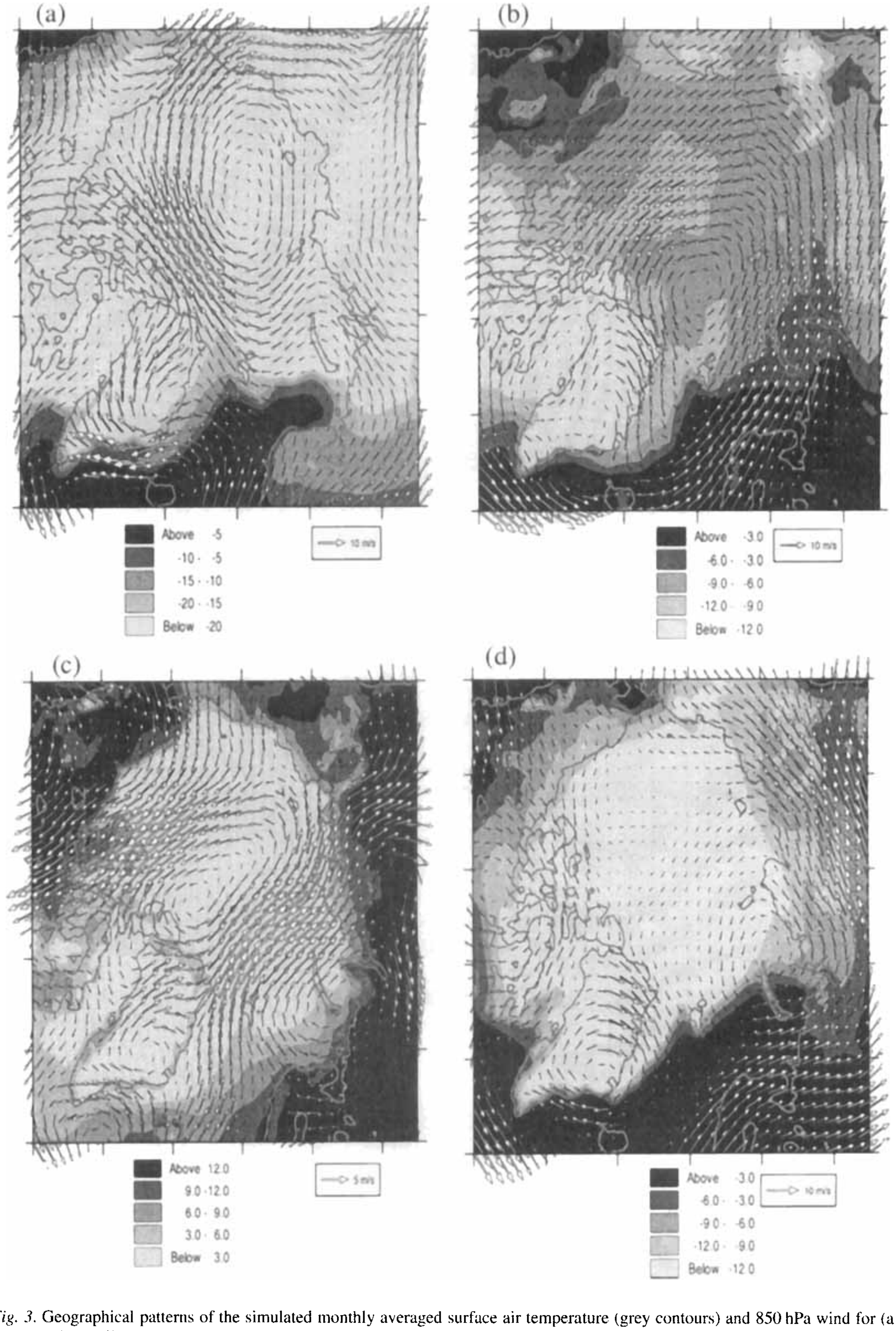

Fig. 3. Geographical patterns of the simulated monthly averaged surface air temperature (grey contours) and 850 hPa wind for (a) January, (b) April, (c) July and (d) October of the year 1990.

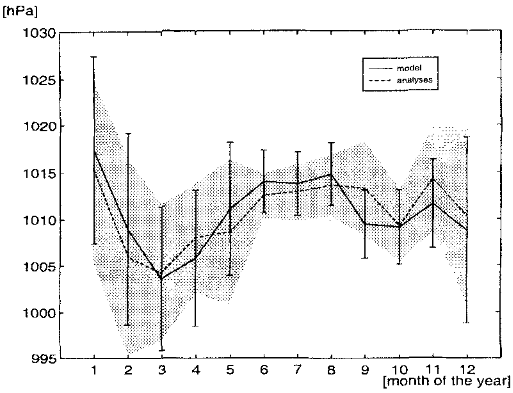

Fig. 4. Annual cycle of the simulated (solid line) and analysed (dashed line) monthly mean sea level pressure averaged over the Arctic Ocean north of 70°N. The spatial deviations from the area mean are indicated as bars for the simulation and as shading for the ECMWF analyses.

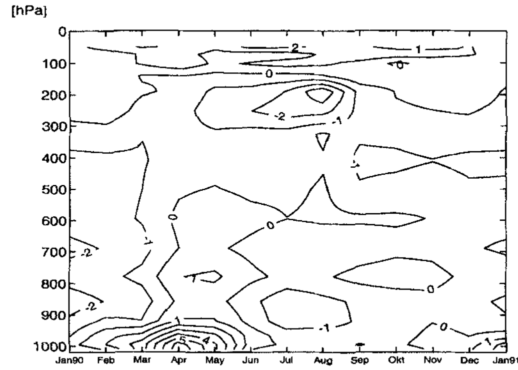

Fig. 5. Monthly and area mean height dependent temperature bias "model minus ECMWF analyses" in Kelvin in relation to time of the year 1990.

Annual cycle: The HIRHAM simulations for the complete year 1990 are based on the ECHAM3 physics. A description of the simulated circulation is provided by the fields of mean SLP and 500 hPa height. Since the atmospheric circulation of the Arctic is characterized by strong seasonality, the simulated monthly averaged SLP and 500 hPa heights for January, April, July and October 1990 are shown in Figs. 1 and 2 as examples for winter, spring, summer and autumn circulations. A comparison of these patterns with ECMWF data analyses shows that the simulations are in good agreement with observed pressure patterns. The intensity and the location of the pressure centres do match the observations in detail. During January the model captures the overall pattern of the Siberian anticyclone and the Icelandic Low. The 500 hPa height field indicates a deep trough on the western Arctic over northern Canada which is paralleled by anomalous low surface temperatures for this month and region. The 500 hPa heights in the other months develop a pole-centred trough. Low pressure is located over the Barents Sea in all seasons except for summer. Summer pressure gradients are weak over the entire Arctic, whereas maximum gradients occur in April. In the July SLP pattern a closed anticyclone develops over the Beaufort Sea and a low pressure trough extends from the Icelandic Low far toward the pole, reflecting frequent cyclone activity. Comparing the simulations with ECMWF analyses yields an agreement in the area averaged SLP difference "model minus analyses" of 1.4 hPa, −1.5 hPa, 0.7 hPa, and −0.2 hPa for January, April, July and October, respectively. Figure 3 presents the simulated 850 hPa wind and near surface temperature fields for the four months. The annual cycle of the simulated and analysed SLP averaged over the Arctic Ocean north of 70°N is shown in Fig. 4. For a better assessment of the curves additional bars/shading have been plotted which were calculated by a spatial standard deviation indicating the spatial variation from the corresponding area mean. The figure shows no very clear annual cycle of the pressure; during winter and springtime the spatial variations are large and of about the same order as the seasonal variations. To evaluate the model simulations, a monthly and area averaged height dependent model bias "model minus analyses" has been computed for each month of the year. The area average has been performed over the whole integration area excluding the boundary zone. Figure 5 shows this temperature bias in relation to time of the year. Obviously, the bias is very small and in a range of ±1 K with the exception of surface regime in spring. Here, deviations up to 5 K occur, caused by the bias over sea ice points (not shown here). Deficiencies in the thermal forcing at the lower model boundary due to incorrect sea ice description are responsible for this effect. Furthermore, the planetary boundary layer parameterization does not describe the very stable and shallow boundary layer well (Abegg 1999). Deviations in the surface temperature cause deviations in the SLP, which change the wind circulation accordingly.

January climatology: The 11 January simulations (1985–1995) were performed using ECHAM4

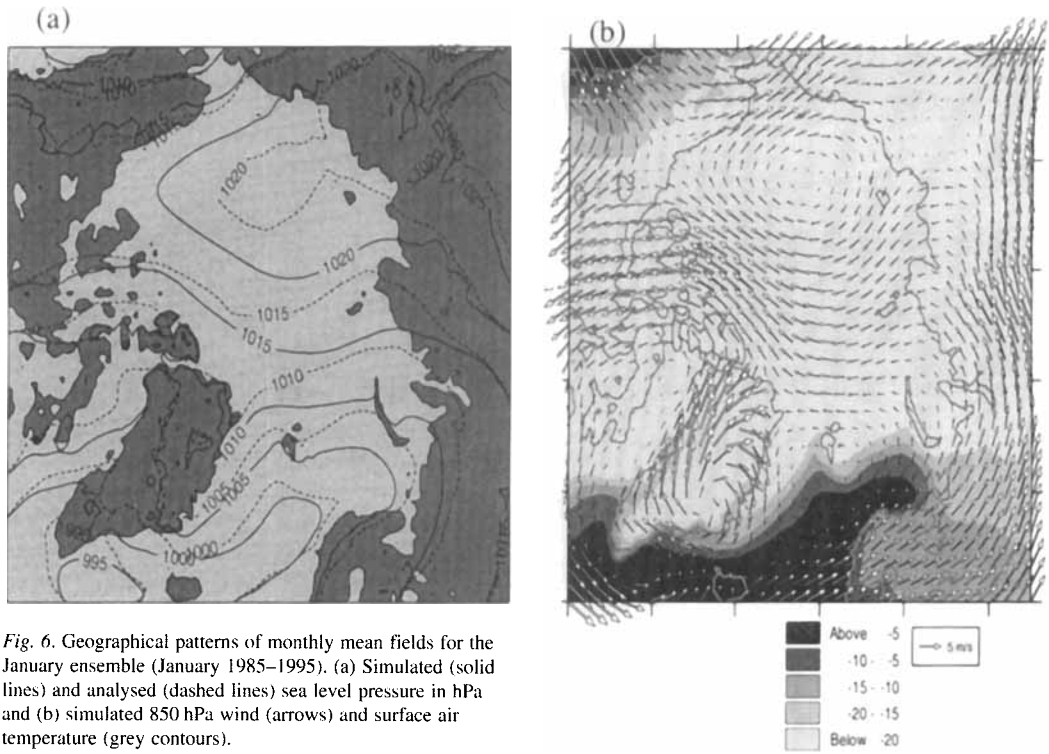

Fig. 6. Geographical patterns of monthly mean fields for the January ensemble (January 1985–1995). (a) Simulated (solid lines) and analysed (dashed lines) sea level pressure in hPa and (b) simulated 850 hPa wind (arrows) and surface air temperature (grey contours).

physics. Figure 6 shows simulated mean fields for the January ensemble which have been computed as the arithmetic average of the 11 corresponding monthly means. Figure 6a shows the comparison of the simulated and analysed mean SLP, whereas Fig. 6b shows the simulated 850 hPa wind and surface air temperature fields. The January pressure pattern is dominated by an anticyclone over Siberia and the Icelandic Low. Over the Arctic Ocean the SLP is relatively high, appearing as a saddle of relatively high pressure between the Siberian and the Alaskan highs. The model captures the monthly mean distribution of the SLP very well, with differences of less than 3 hPa and an area averaged difference to the ECMWF analyses of 1.5 hPa. The model has a slight tendency to overestimate the SLP over the whole area. The largest deviations in the simulated SLP are found over the central Arctic Ocean with an overestimation up to 3 hPa. This problem seems to be related to the crude sea ice representation mentioned above. The overestimated SLP is associated with slightly overestimated 500 hPa heights. The comparison of the simulated field of the surface air temperature with January climatologies over the Arctic Ocean from four independent sources quoted in Overland et al. (1997) and from Tao et al. (1996) confirms the well-known spatial patterns with coldest temperatures in the western Arctic north of Canada and warmer regions in the Chukchi, Greenland and Barents seas. Mesoscale features are developed over regions of highly variable topography (e.g. Alaska, Greenland, Siberian mountains). Figure 7 shows the standard deviation of the SLP derived by calculating the value for each separate month and then averaging over the ensemble. The spatial features of the analysed variability is well-reproduced; the difference is below 2 hPa. It is evident that maximum variability occurs in the North Atlantic. This is consistent with the interpretation that the wintertime year-to-year changes result primarily from the variation in the Atlantic storm tracks. On the basis of a climatological analysis of Arctic cyclone characteristics, Serreze et al. (1993) showed that under winter conditions the Atlantic side of the Arctic is the most synoptically active region and that the Arctic Ocean is characterized by frequent anticyclones.

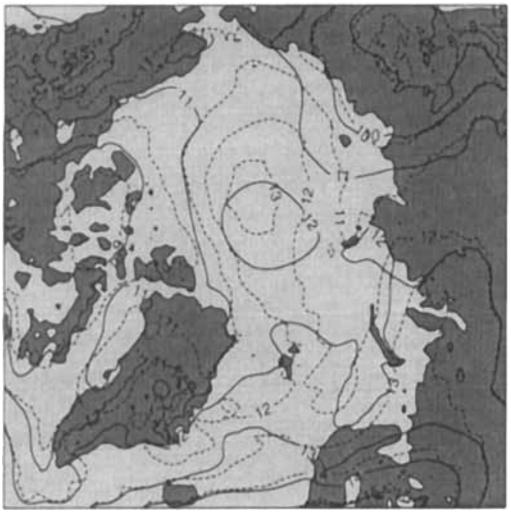

Fig. 7. Pattern of the standard deviation of simulated (solid lines) and analysed (dashed lines) sea level pressure for the January ensemble (January 1985–1995).

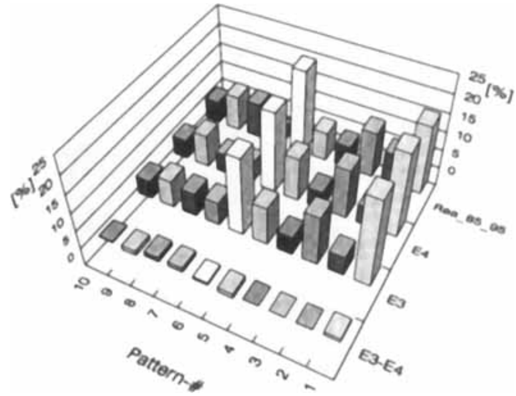

Fig. 8. Comparison of HIRHAM simulations with ECMWF re-analyses regarding the reproduction of Arctic circulation patterns during January. The relative frequencies of occurrence of each circulation pattern are shown.

Validation of the model results with a statistical method

The Arctic circulation has been described with the high resolution regional climate model HIRHAM. In contrast to the numerically extensive simulations of the dynamical regionalization method, a statistical regionalization method does not require this numerical effort. However; long data sets are a prerequisite for stable results. Statistically deduced weather patterns are useful in two ways. First, they are important inputs for synoptical climate diagnosis. Second, they are tools for the additional validation of the HIRHAM simulations when the simulations' accuracy in reproducing the shape and frequency of statistically found patterns is investigated.

Due to a statistical regionalization method which consists of a combination of cluster and regression analyses, a quasi-objective detection of circulation patterns is possible (Enke & Spekat 1997). Using 16 years (1981–1996) daily 500 hPa and 850 hPa geopotential of ECMWF re-analysis data, the ten most frequent winter and summer circulation patterns of the Arctic have been calculated by this statistical method. The patterns found (Spekat 1997) resemble in part distributions of vortices, e.g. described by the leading EOFs (Cheng & Wallace 1991) of the hemispheric circulation; they enable a finer distinction between polar circulation types and are thus a better representation of the polar flow regime. This number of patterns is necessary to obtain a model of optimum complexity which explains as much variance as possible and yet avoids overfitting. The method has been applied on daily geopotential HIRHAM data of January of the 11 years spanning 1985 to 1995. By analysing the HIRHAM fields (using the classification step) and comparing them with the corresponding ECMWF results we validate the frequency distribution of significant circulation patterns. The HIRHAM simulations have been carried out with both parameterization packages ECHAM3 and ECHAM4 to study the impact of different physical parameterizations on the simulation of the circulation regimes. As an indicator for the goodness of fit, Fig. 8 shows the comparison of the frequencies of each circulation pattern from ECMWF data and from the simulations. The figure shows that the model is able to reproduce the frequency distribution of the Arctic circulation pattern. The differences between the two model versions, represented in Table 1, are within 1%.

Summary

High resolution climate simulations have been performed over the Arctic region. The simulated circulation patterns are in a good agreement with the data, both in the annual cycle and in the height. A realistic representation of the Arctic circulation

Table 1. Calculated frequencies of the 10 most frequent January circulation patterns in the Arctic. The numbers are based on the time period 1985–1995.

	1	2	3	4	5	6	7	8	9	10
Re-analyses	17.9	7.9	11.7	5.9	7.3	21.7	3.5	9.1	9.1	5.9
HIRHAM4	22.1	5	12.9	4.7	11.2	20.9	5	5	8.2	5
HIRHAM3	22.9	5	12.9	4.7	10	20.3	6.2	6.2	7.1	4.7
HIRHAM(3–4)	0.8	0	0	0	−1.2	−0.6	1.2	1.2	−1.1	−0.3

in the atmospheric model is important for the next step of coupling with an ocean–sea ice model. The geostrophic wind field at the surface influenced by SLP is the major contributor to the field of sea ice motion, whereas the surface energy balance determines the ice thickness. Therefore the SLP and surface air temperature derived from a high resolution regional model could improve the quality of the sea ice distribution derived from coupled atmosphere–ice models. A further detailed examination of atmosphere–ice interaction on time scales of months and a spatial scale of ca. 25 km is needed. A first promising approach in this direction has been initiated by Walsh et al. (1993) for the area of the Bering Sea.

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