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Validation of surface fluxes in climate simulations of the Arctic with the regional model REMO

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ABSTRACT

To study the variability of the thermohaline circulation in the North Atlantic on decadal time scales, the atmospheric regional model REMO is currently investigated as a component of a fully-coupled atmosphere–ice–ocean model for the Arctic/North Atlantic. A comparison of a 5-year uncoupled simulation of the regional model with a 5-year NCEP/NCAR reanalysis period is carried out in order to assess the performance of the regional model in polar and subpolar regions. The model simulates basic structures realistically. It performs well in middle latitudes but shows some problems in the region of the marginal ice zone and in continental regions with extreme temperature amplitudes. The high elevations of Greenland in the central part of the model domain give rise to problems in the model dynamics, resulting in moderate deviations from NCEP/NCAR reanalysis.

1. Introduction

The rôle of the thermohaline circulation (THC) in climate variability has recently become a central point in climate research. Because the THC is a result of the complex interaction between atmosphere, ocean, and sea–ice, a realistic numerical simulation requires the application of a fully coupled atmosphere–ice–ocean model. This model system however requires accurate individual model components. In a sensitivity study, Fischer and Lemke (1994) investigated the response of the sea–ice cover to near surface meteorological variables. They found, e.g., that errors in near surface temperature should not exceed values of about 0.8 K to keep errors in sea–ice cover below 10%.

Furthermore, the small spatial scales of processes influencing the THC, and the time scales of climate variability require long integrations with high horizontal resolution. Presently, global climate model simulations cover the climatological time scales, but horizontal resolution is insufficient to resolve processes relevant for the THC. Bromwich et al. (1994) showed in simulations with the global model CCM1 that pressure fields and storm tracks in Arctic regions are steered by the Greenland topography in an unrealistic way, because the topography is strongly smoothed due to the poor model resolution of the general circulation model (GCM). A higher model resolution covering climatological time scales is presently only available for limited area models because of limitations in computer resources.

To prepare for a coupling of the high resolution atmospheric regional model REMO (Jacob and Podzun, 1997) with a viscous-plastic sea–ice model (Harder et al., 1998) and the GFDL Modular Ocean Model (MOM) (Pacanowski, 1995) REMO has been integrated in uncoupled mode over five years assessing the ability of the model to properly simulate the Arctic climatology. To reduce the model's dependence on large-scale forcing fields the model domain should be sufficiently

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large. In this paper, the atmosphere model covers a domain similar to Dethloff et al. (1996). Additionally, the North Atlantic Ocean north of 40°N is included to ensure a proper lateral boundary for sea–ice and to enable cyclogenesis in the regional model independent from the large scale model. Effects of the lateral boundaries are therefore minimized.

The goal of this study is a validation of the near surface climatology for a five year period in the atmospheric regional model REMO in uncoupled mode. Emphasis is focused on quantities which influence the ocean/sea ice system: surface layer temperature and fluxes of sensible heat, freshwater, and momentum. Possible consequences of errors in the individual variables for the coupled model system are discussed briefly. Because of continuous developments in the regional model system the results presented here are of preliminary character. The validation performed in this paper, however, is a first step in the process of fully coupling a regional atmospheric model to a sea-ice/ocean model.

2. The atmosphere model REMO

The 3-dimensional hydrostatic model REMO (Jacob and Podzun, 1997) originates from the "Europa-Modell (EM)" (Majewski, 1997) developed by the German Weather Service (DWD). At the Max-Planck-Institute for Meteorology (MPIFM) in Hamburg the model has been expanded to run with physical parameterizations of the ECHAM4 climate model (Roeckner et al., 1996) of the Deutsche Klimarechenzentrum (DKRZ). In this study these parameterizations were used since they are optimized for long term climate simulations, while physical parameterizations of the DWD are optimized in order to perform accurate weather forecasts. The short description of the implemented parameterizations, therefore, refers to the ECHAM4 physics.

The prognostic variables of the model are the horizontal wind components, surface pressure, temperature, specific humidity and cloud water content. Turbulent fluxes within the surface layer are described by the Dyer–Businger equations with drag coefficients according to Louis (1979). Above the surface layer the vertical turbulent fluxes of the individual variables are related to their respective gradients. The vertical eddy diffusion coefficient is parameterized with the turbulent kinetic energy (Garratt, 1992). Above the atmospheric boundary layer turbulent fluxes are assumed to vanish. Precipitation is subdivided into large scale and convective precipitation. Stratus clouds and large scale precipitation are parameterized using diagnostic equations adopted from Sundqvist (1978). Convective clouds and convective precipitation are parameterized by applying the mass flux scheme of Tiedke (1989). For radiation the two-stream ECMWF scheme is used separating the radiative spectrum into six longwave and two short-wave bands. Because of the large computational expense of this scheme, radiative fluxes are recomputed only every 1.5 h, whereas the dynamical time step is 5 min. Horizontal diffusion is calculated with a 4th order approximation.

Large scale meteorological information is provided from a global model. At initialization time, data from the global model are interpolated onto the grid of the regional model. During the model run, atmospheric data from the global model are provided every 6 h at the lateral boundaries of the regional model, using a relaxation zone of 8 gridpoints following the concept of Davies (1976). At the lower boundary, sea surface temperature (SST) is prescribed by the values of the forcing global model. If the SST falls below 271.4 K, a sea–ice cover is assumed with implications for albedo, surface temperature, and turbulent fluxes. For land surfaces the thermal diffusion equation is solved with five vertical layers reaching down to about 10 m depth. Soil moisture is approximated with a modified bucket-model separated into an upper layer and a lower layer in order to avoid evaporation from deep soil (Roeckner et al., 1996).

The finite difference equations are solved on an Arakawa-C grid in a rotated spherical coordinate system using central differences in space and time. In the vertical, a terrain-following hybrid coordinate system with 20 levels has been used. Time stepping is performed using the "leap-frog" scheme. To avoid artificial computational modes inferred by this numerical method, an Asselin-Filter has been applied. A detailed description of the ECHAM parameterizations can be found, e.g., in Roeckner et al. (1996).

3. Model domain and forcing data

The horizontal resolution of the regional model for the Arctic model domain is $0.5° \times 0.5°$ (about 56 km × 56 km) with a total number of 145 × 121 grid-points. The rotated pole of the model is located on the equator at 60°E. The model domain contains the northern areas of Canada and Eurasia near the lateral boundaries and Greenland in the centre part of the model domain. The north Atlantic is covered down to about 40°N. The model includes the complete Arctic Ocean which is relevant for the subsequent coupling with the ice–ocean model.

As large scale meteorological conditions, 4 times daily data from the NCEP/NCAR reanalysis project (Kalnay et al., 1996) with a horizontal resolution of $1.9° \times 1.9°$ have been used for the arbitrarily chosen time period 1992–1996.

4. Results

In this section, the results of the regional model are compared with those of the NCEP/NCAR reanalyses. Such a validation, however, is not perfect, since the reanalyses are model data itself. This procedure is chosen because there are only few observations in polar regions available. The reanalyses, however, are interpolated from most of the available observations, so this way of validation is suitable for polar regions. When considering differences between regional model and reanalyses, however, the reader should keep the character of the model intercomparison in mind.

4.1. Near surface temperature and sensible heat flux

The near surface temperature is a useful variable to assess the quality of a given climate model, because it is a basic constituent of observational data. Furthermore, near surface temperature is one of the most important factors influencing the sea–ice cover. Therefore, the proper simulation of the near surface temperature is substantial for a realistic simulation of sea–ice formation and melting in coupled models. On the other hand, sensible heat flux is a basic variable for the description of the communication between atmosphere and ocean. Measurements of the sensible heat flux are however difficult to obtain and are, therefore, rare.

4.1.1. Near surface temperature. A comparison of the near surface temperatures for the years 1992–1996 simulated by REMO with those obtained from the reanalysis project for the same time period is shown in Fig. 1. The spatial distribution of the 2 m temperature within REMO is in good agreement with the reanalysis data. Characteristic features like the high temperatures over the North Atlantic Current and the relatively low temperatures over the Labrador Current are found in the regional model as well as in the reanalysis data. The regional model however seems to underestimate the temperatures in large areas of the model domain. Especially in continental areas where annual mean values are significantly below the freezing point as, e.g., in Siberia, the near surface temperatures are about 4 K too low. The time series of monthly mean temperature values for Siberia (A2 in Fig. 2) show an exessively large annual amplitude. The underestimated annual mean temperature and the overestimated temperature amplitude indicate problems due to a missing parameterization of freezing and melting within the soil.

In limited areas over the ocean near the marginal ice zone, the annual mean temperature is up to about 6 K too low. This is a result of differing areas of sea–ice cover in the regional model and the reanalysis data as shown in Fig. 3. While in the regional model areas with SSTs below $-1.8°C$ are *defined* to be covered with sea–ice, the reanalysis model uses data from remote sensing to differentiate between sea–ice cover and open water. SST is obtained using measurements (Kalnay et al., 1996). Therefore, sea–ice cover and SST in the reanalysis are not that strongly linked as in the regional model. It is possible that the regional model simulates sea–ice cover while the reanalysis indicates open water. This error however is a consequence of the atmospheric model in uncoupled mode. In fully coupled mode, ice distribution is a result of physical processes and thus will be treated much more realistic. The time series of monthly mean temperatures for the region of the Fram Strait (A3 in Fig. 2) shows good correspondence between regional model and reanalysis in the summertime, when most of the area is ice free. In the wintertime, temporarily large deviations occur because of the mentioned differences in ice extent.

Higher temperatures are simulated in the Canadian Archipelago (A1 in Fig. 2) where the regional model shows positive differences of up to

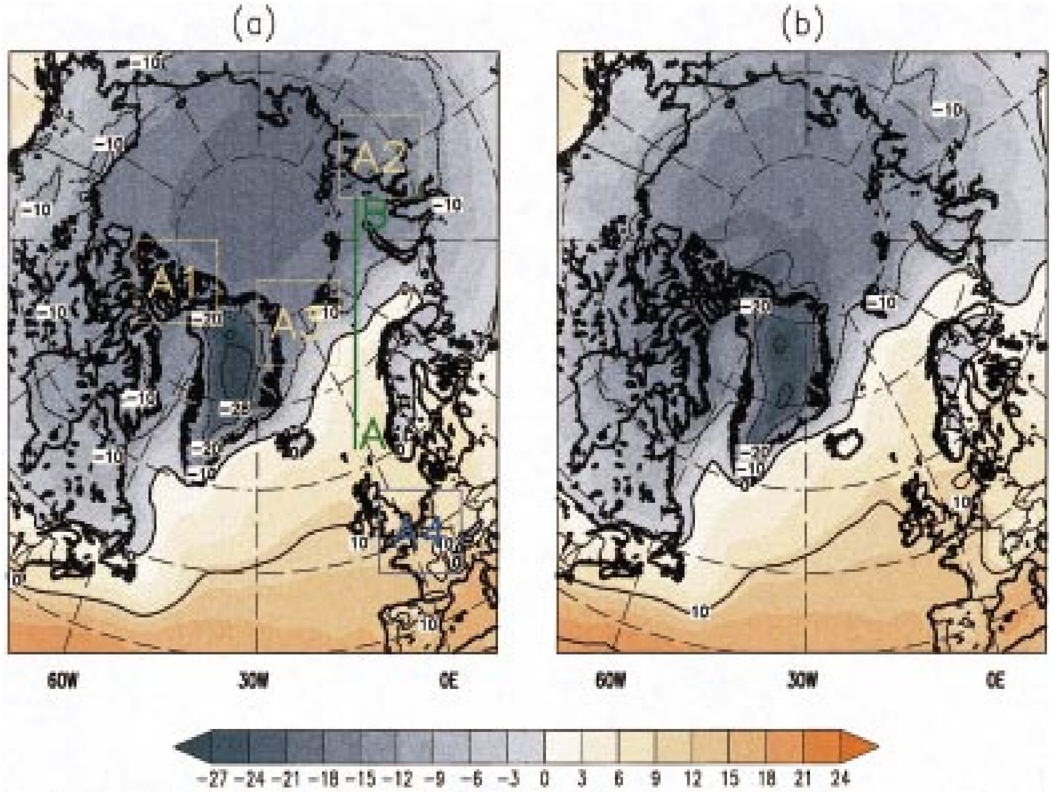

Fig. 1. Mean values of the 2 m temperature for the years 1992–1996. (a) Regional model REMO, (b) NCEP/NCAR reanalysis. Additionally indicated in the left figure are the areas for the evaluation of the time series A1–A4 and the line AB for Figs. 2, 3.

6 K in the annual mean compared to the reanalysis. These deviations occur mainly in the summer season as a result of a strongly differing wind field (see below) compared to the reanalyses. The locally strong deviations between REMO and NCEP/NCAR reanalysis in topographic regions, like, e.g., the Rocky Mountains, Baffin Island and Greenland are a result of the differences in topography due to the different resolution.

For the central and western European areas the regional model shows good correspondence with reanalysis. Deviations are within the range of natural variability.

4.1.2. Sensible heat flux. A comparison of the mean sensible heat flux of the years 1992–1996 simulated with the regional model and obtained from the NCEP/NCAR reanalysis project is shown in Fig. 4. The regional model as well as the reanalysis data show negative values of sensible heatflux, representing a heatflux *into* the atmosphere, over most parts of the model domain. Heat fluxes from the atmosphere to the surface (positive) are dominant especially over Greenland and parts of the Arctic Ocean. In contrast to REMO, reanalysis indicates positive values of sensible heat flux also over Siberia and Canada.

Maximum heat fluxes into the atmosphere occur around the marginal ice zone in the Greenland Sea and south of Spitsbergen. While the reanalysis shows maximum mean values of up to $-120\ \mathrm{W\,m^{-2}}$ for the 5 year period, the regional model gives maximum mean values of about $-95\ \mathrm{W\,m^{-2}}$ in these regions. Another area with large sensible heat fluxes into the atmosphere is the marginal ice zone in the Labrador Sea with values of $-90\ \mathrm{W\,m^{-2}}$ in the reanalysis and $-60\ \mathrm{W\,m^{-2}}$ in the regional model. These max-

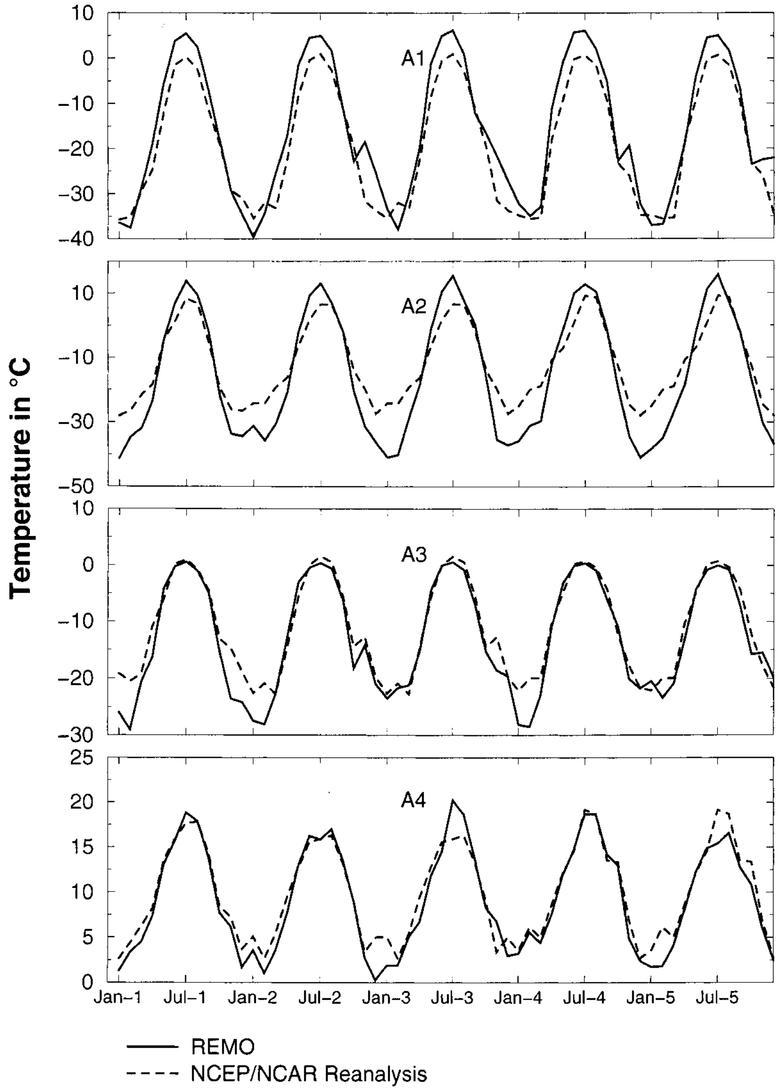

Fig. 2. Time series of monthly mean 2 m temperatures for different 10° × 10° areas for the 5-year simulation period. Areas are indicated in Fig. 1. A1 Canadian Archipelago; A2 Siberia; A3 Fram Strait; A4 west and central Europe.

imum values originate in cold air outbreaks from ice covered areas towards the open ocean. The generally lower absolute values of sensible heat flux in the regional model can be explained by the negative temperature deviations in the marginal ice zone shown above.

4.2. *Freshwater flux*

One basic forcing variable for the oceanic thermohaline circulation is the freswater flux out of the ocean surface due to evaporation. Precipitation on the other hand results in a stabilization of the surface water and thus in a weakening of the THC. An exact knowledge of the difference between precipitation and evaporation ($P–E$) is, therefore, another prerequisite for an accurate modelling of the variability of the THC.

Most of the simulated values of annual mean $P–E$ given in Fig. 5 are positive resulting in a

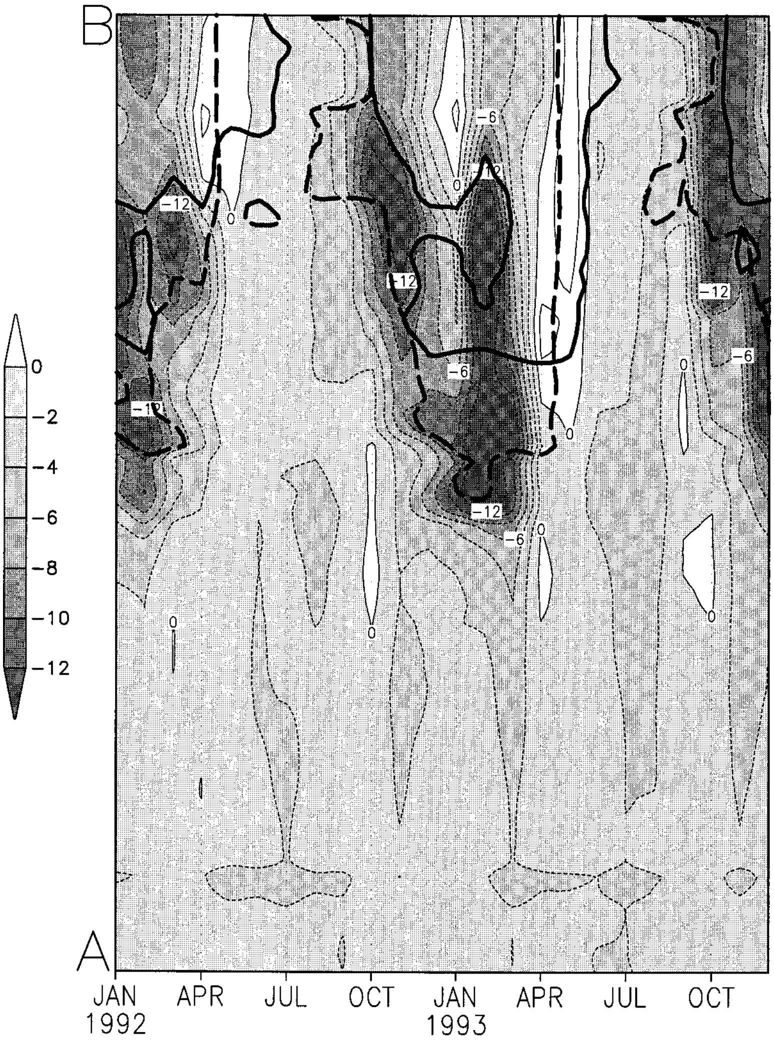

Fig. 3. Temporal development of the temperature differences between REMO and NCEP/NCAR reanalysis along the line AB in Fig. 1 for the first two years of the simulation. The marginal ice zone is indicated as solid line for NCEP/NCAR reanalysis and as dashed line for REMO.

freshening of the surface water. Only a few areas show negative values which would result in a saltening with subsequent destabilization of the surface water. One of these areas is located in the Norwegian Sea about 800 km south of Spitsbergen. In this region, relatively cold dry air flows over the warm North Atlantic Current resulting in strong evaporation rates and, because of the cold air, low precipitation amounts. As a result, negative or slightly positive values of *P–E* are simulated. Another region with negative or slightly positive values of *P–E* is located west of the British Isles as a result of strong evaporation rates over the relatively warm North Atlantic Current. The zone of negative *P–E* adjacent to the lateral boundaries is an effect of the relaxation zone and is, therefore, artificial.

Maximum values of freshwater fluxes are located in the southeastern parts of Greenland due to orographic precipitation with maximum values of up to 9.5 mm per day. In high latitudes, *P–E* represents only one part of the freshwater flux.

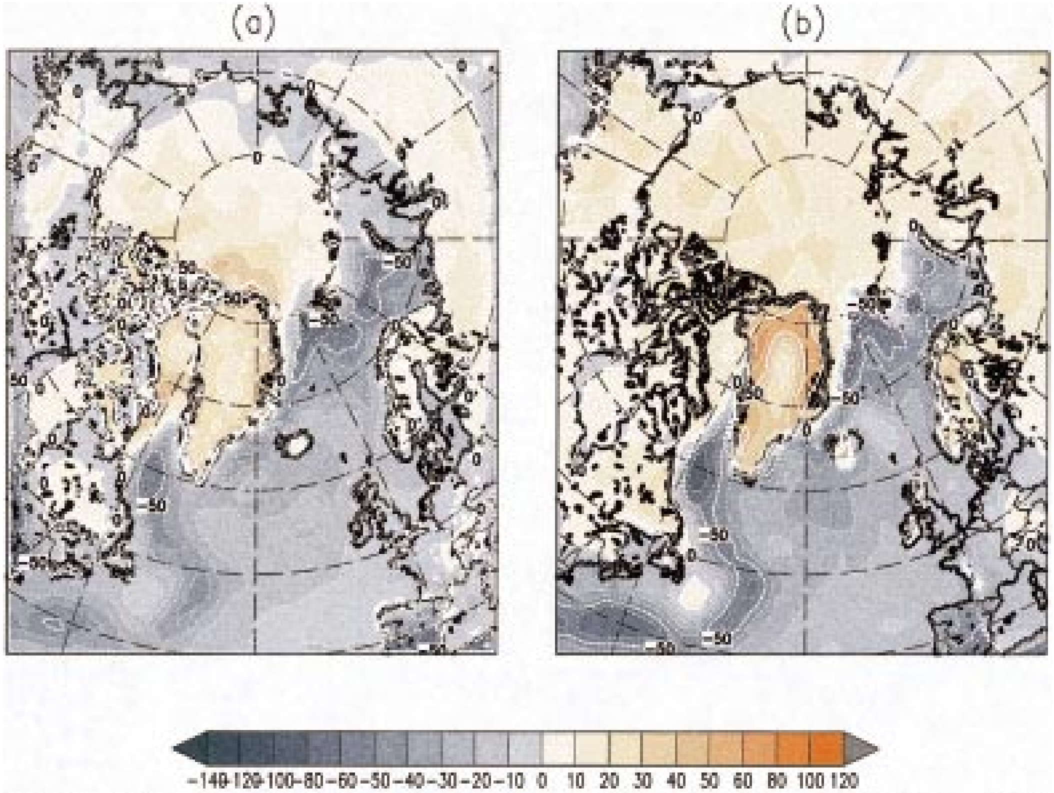

Fig. 4. Mean values of surface sensible heat flux in W m^{-2} for the years 1992–1996. Negative values represent fluxes *into* the atmosphere. (a) Regional model REMO, (b) NCEP/NCAR reanalysis.

Another important contribution is provided by the melting and freezing of sea–ice. In the East Greenland Current this amounts to more than 2 m per year. In the Labrador and Irminger Seas the melting of sea–ice is of the order of the precipitation rate (about 1 m yr^{-1}).

A quantitative validation of the freshwater fluxes is due to a lack of data in high latitudes impossible. Qualitatively however, the simulated pattern of freshwater fluxes seems reasonable.

4.3. *Sea level pressure and surface layer winds*

Surface layer winds and thus indirectly the patterns of sea level pressure are the main factors influencing the drift of sea–ice (Harder et al., 1998). The drift of sea–ice represents a transport of freshwater and thus is a relevant factor for the THC. A proper representation of sea level pressure and surface layer winds in the atmospheric model therefore is crucial for a proper simulation of climate in a coupled model system.

The pattern of the 1992–1996 winterly mean sea level pressure and surface layer winds (Fig. 6) shows a good correspondence of the regional model and the reanalysis data. The core pressure of the Icelandic low, however, is overestimated by about 6 hPa in the regional model while the Greenland Anticyclone is underestimated by about 6 hPa as compared with the reanalysis data. The horizontal gradient of sea level pressure therefore is underestimated in the regional model resulting in weaker surface layer winds. In the Norwegian and the Barents Seas, sea level pressure is overestimated by approximately 4 hPa in the core of the depression zone.

In the summer season (Fig. 7), the regional model shows a totally different pattern in comparison to the reanalysis data. While in the reanalysis a polar depression and a weak Icelandic Low are

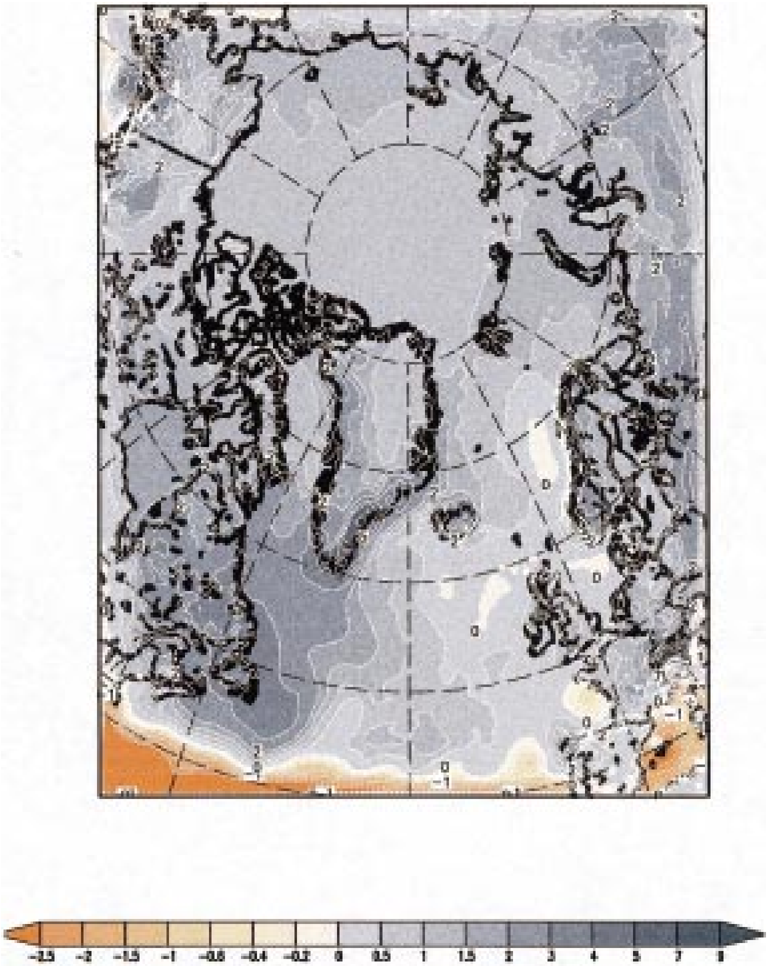

Fig. 5. Mean daily freshwater flux in mm day^{-1} simulated with REMO for the years 1992–1996.

the most significant features, the regional model shows a strong anticyclone over the Greenland/Arctic region and a relatively strong depression over Siberia. This pattern of sea level pressure leads to anomalous northerly winds in the Greenland Sea and southerly winds in the Labrador Sea as compared to NCEP/NCAR reanalysis. The anomalous southerly winds in the region of the Labrador Sea result in positive temperature deviations in REMO as compared to the reanalysis. In a coupled model system, this simulated sea level pressure pattern would most possibly enhance sea–ice export. Additionally, the differences in sea level pressure between regional model and reanalysis result in an opposite direction in surface layer winds over the Arctic Ocean.

The reason for the difference in performance of the regional model in the summer and the winter season is clearly demonstrated with the 500 hPa geopotential height (Fig. 8). In the winter season, depressions are often imported from the relaxation zone near the Newfoundland/Labrador region and are subsequently transported with the mean flow at the 500 hPa level to the region south of Iceland and the Norwegian Sea. For this reason the pattern of sea level pressure corresponds relatively well with the reanalysis as discussed above. The geopotential height field of the regional model itself

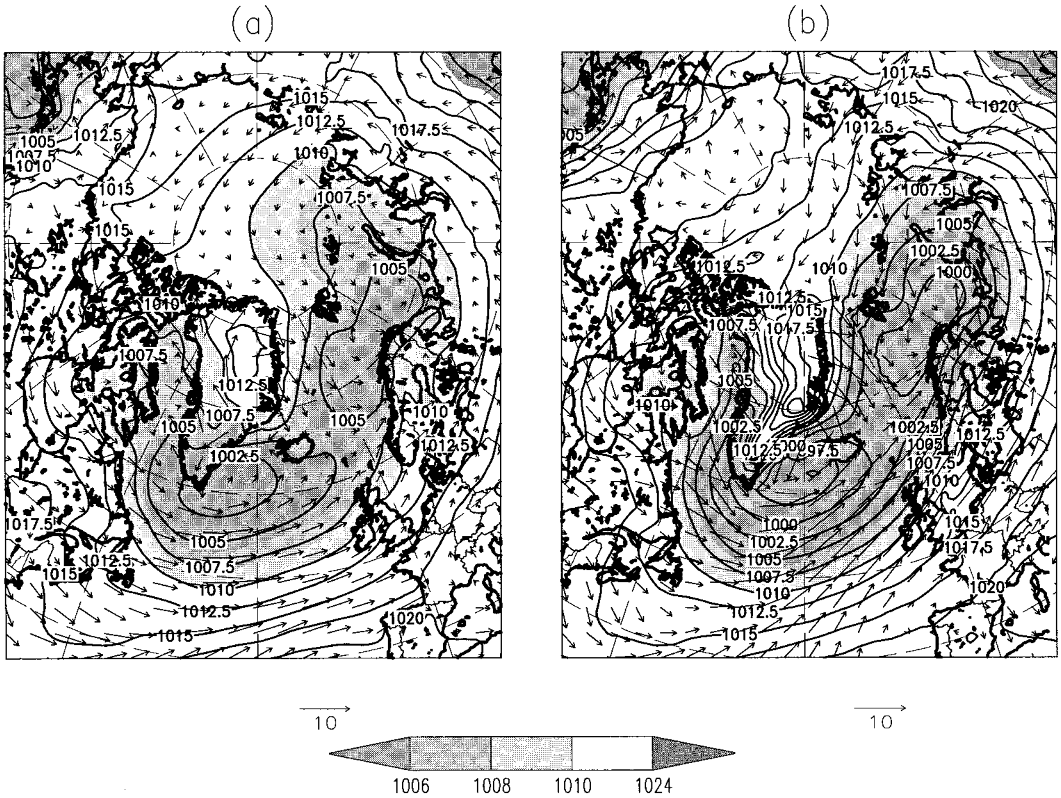

Fig. 6. Winterly (DJF) mean distribution of sea level pressure in hPa and 10 m winds in ms^{-1} for the years 1992–1996. Values below 1012 hPa are shaded. (a) Regional model REMO, (b) NCEP/NCAR reanalysis.

also corresponds fairly well with the reanalysis data (not shown). In the summer season, depressions from the Newfoundland/Labrador region cannot move into the inner parts of the model domain because of the more zonal orientation of the isoheights. The regional model therefore has to perform cyclogenesis on its own to reproduce the mean pattern of sea level pressure and wind field. In other words: In winter, the model is more influenced by the boundaries as compared to the summer season. Therefore, the regional model shows a better agreement with the reanalysis data during winter time.

It has been mentioned in the beginning of this section that the character of this validation study is more or less a model intercomparsion. The question arising especially in the case of the wind field is therefore, which of the both models is closer to the "truth". Most possibly, the reanalyses are more reliable, because reanalyses are designed to show closest correspondence with daily observations using the forecast mode. The regional model on the other hand, only has to show reliable fields in the climatological mean, not in daily fields. Because of the integration in climate mode used in the regional model, the model can drift away from the observations. The strong deviation of the pressure and wind fields in the climatological mean compared to the reanalyses is a result of the large model domain and the zonal orientation of all four lateral boundaries.

5. Summary and conclusion

Preliminary experiments with the regional model REMO for the Arctic for a five year period show reasonable results. Basic structures of temperature, precipitation and heat fluxes are represented fairly well compared with reanalysis data.

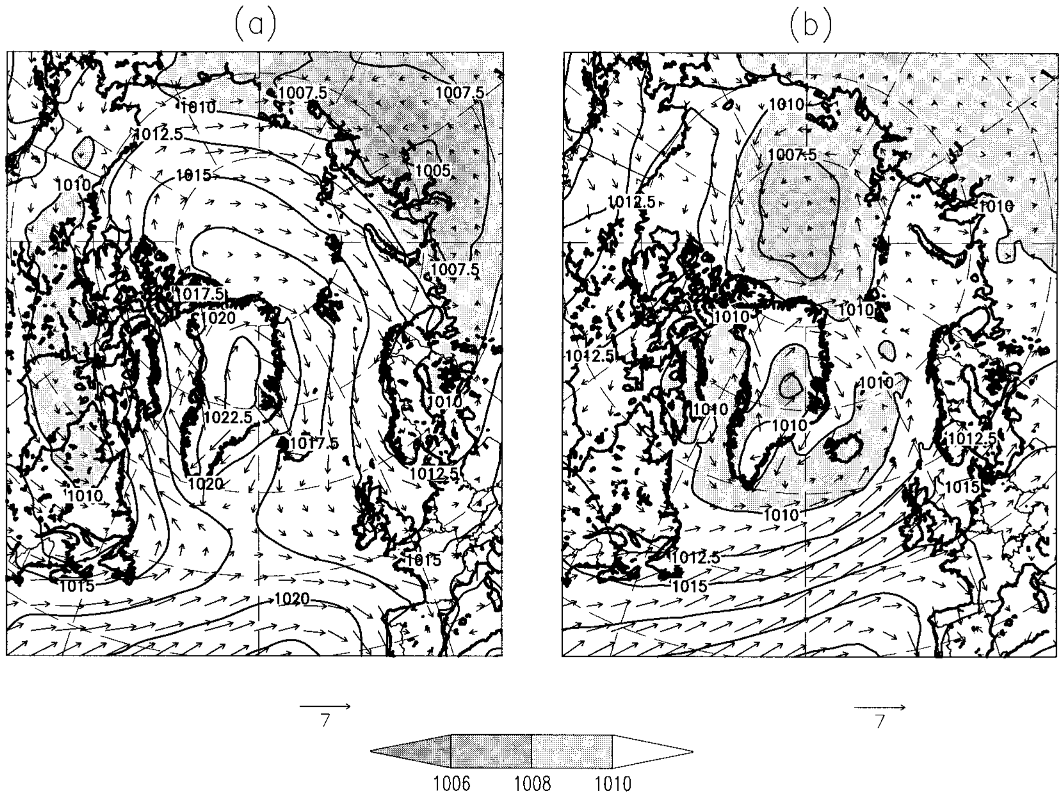

Fig. 7. As Fig. 6, only with summerly (JJA) mean values.

Compared to other modeling groups, deviations between observation and regional model are in the same order of magnitude. For polar regions, Dethloff et al. (1996) reports deviations from reanalyses of up to 12 K in near surface temperature for a 1 month integration during winter. For sea level pressure, they report deviations in the range of 6 hPa. Other regional modeling studies are not comparable because of the differing climatological areas.

Sea level pressure and surface layer wind fields show strong deviations from the reanalyses, especially in the summer. Because of the influence of the surface layer wind field on the drift of sea–ice, the accurate simulation of the distribution of sea level pressure and surface layer wind fields is strongly required (Serreze et al., 1992), especially when running a coupled atmosphere–ice–ocean model. Another problem is that almost all meteorological variables are influenced by the pattern of sea level pressure. The positive temperature deviation found in the region of the Canadian Archipelago, e.g., is most probably a result of the anomalous southerly wind components induced by the modelled Greenlandic anticyclone. Meteorological variables on the other hand influence sea level pressure. Because of these complex interactions, reasons for the deviations between regional model and reanalysis data are more or less speculative. It is however obvious that the correct representation of sea level pressure is a basic prerequisite for a significant improvement of the model results.

For this reason, the main focus in the future will concentrate on the improvement of the sea level pressure fields. Only if the meteorological fields presented in this paper are properly simulated, a coupling with the ocean and the sea ice model will be reasonable. For validation, additionally new data sources will be aquired in order to compare regional model results with more independent data.

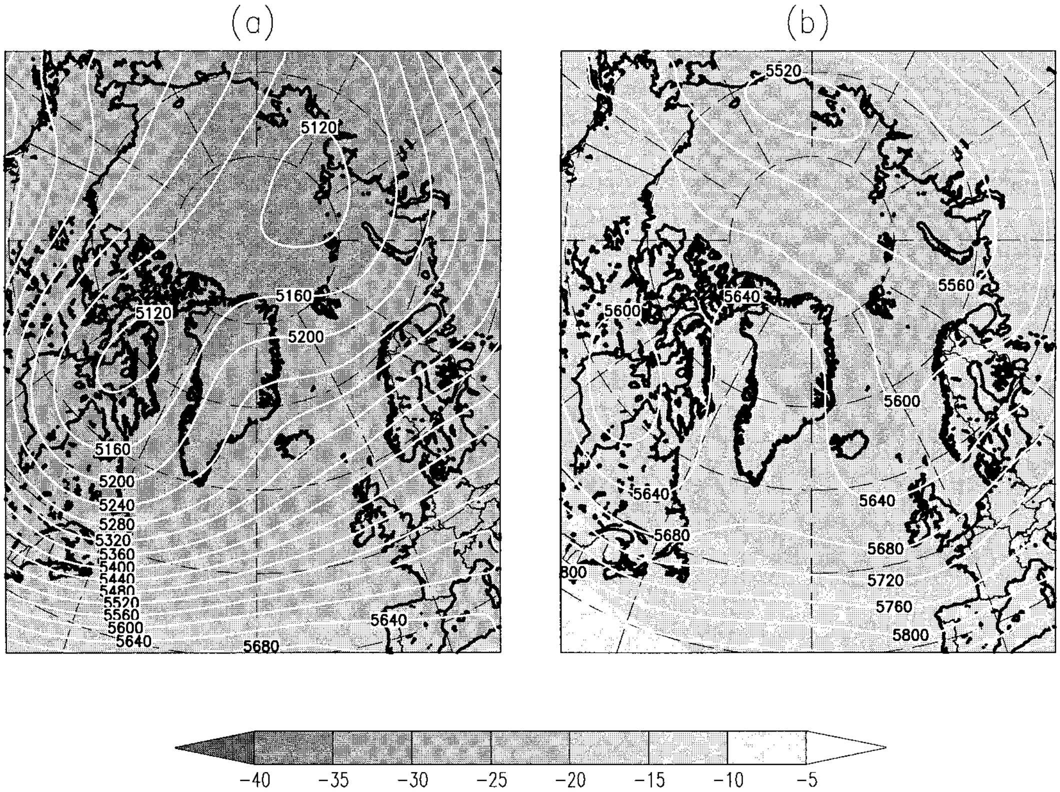

Fig. 8. Mean values of 500 hPa geopotential in gpm (solid lines) and temperature in °C (shaded) for the years 1992–1996 simulated with the regional model REMO. (a) winter (DJF), (b) summer (JJA).

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