Modeled climate variability of the Arctic atmosphere, the impact of Greenland, vertical resolution, and different land surface schemes

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Introduction

Recent climate modeling studies have highlighted the Arctic as a region of particular importance and vulnerability to global climate changes. For instance, the worldwide strongest warming due to increasing greenhouse gases may be expected over the northern polar region. However, the results from different models as well as from different scenarios disagree regarding both the magnitude of the projected climate changes and the regional aspects of these changes (see Cubasch et al., 2001). Comparison studies of the performance of global climate models in polar latitudes have shown that different models produce large variations in the simulation of the Arctic climate (e.g. Tao et al., 1996). These discrepancies appear in consequence of inadequacies in the parameterization of physical processes and the fairly coarse horizontal resolution of global models (Rinke et al., 1997).

Natural climate variability is likely to affect the future Arctic climate evolution as well, since recently observed climate changes over northern latitudes could partly be attributed to changes in the atmospheric circulation regime, especially to regime changes of the North Atlantic Oscillation (NAO; e.g. Hurrell and van Loon, 1997). Some attempts have been done to detect the causes of this oscillation, but not all underlying mechanisms that control the NAO are known until now. In addition, it is generally difficult to distinguish between forced and internal (unforced) climate variations, because the climate system is extremely complex due to the nonlinear interactions between and within its subsystems. Therefore, small changes within the climate system, whatever their reason is, may have large effects on the entire atmospheric circulation with the consequence of strong regional climate changes.

In the present study, the dominant patterns of climate variability have been analyzed in unforced and forced long-term simulations of a global coupled atmosphere–ocean model. A high-resolution regional atmospheric climate model of the Arctic has then been applied for simulations of the Arctic winter climate with particular attention to NAO regime changes. In addition, the regional model has been used for sensitivity experiments concerning the impact of removed orography of Greenland, additional vertical levels in the planetary boundary layer (PBL), and an alternative land surface scheme.

Model description

The long-term simulations have been carried out with the global coupled atmosphere–ocean model ECHO–G (Legutke and Voss, 1999), which consists of the atmosphere model ECHAM4 at T30/L19 resolution (3.75°, 19 layers) and the ocean model HOPE–G at T42/L20 resolution (2.8°, 20 layers). One simulation is a 1000-year unforced control run with fixed external boundary conditions, and the other is a forced 500-year run with time-dependent external boundary conditions, including reconstructed variations of solar irradiance, volcanic dust indices, and greenhouse gas concentrations for the last 500 years.

The Arctic climate simulations have been performed using the regional atmospheric climate model HIRHAM4 which was developed by Christensen et al. (1996) and adapted for simulations of the Arctic climate by Dethloff et al. (1996). HIRHAM4 includes prognostic equations for horizontal wind components, temperature, specific humidity, cloud water, and surface pressure, and uses the physical parameterization package of ECHAM4 (Roeckner et al., 1996). The integration domain comprises the whole Arctic north of 65°N with 110 by 100 grid points at a horizontal resolution of 0.5° ($\sim$ 50 km). In its standard version, the vertical resolution is given by 19 unequally spaced levels.

Dominant patterns of climate variability

The spatial and temporal variability of the atmospheric flow patterns in global climate simulations has been studied on the basis of an Empirical Orthogonal Function (EOF) analysis and a continuous wavelet transformation of the corresponding principal component time series. Figure 1 shows the first EOF of Northern Hemisphere 500 hPa geopotential anomalies in winter from the ECHO–G runs and from NCEP reanalyses. Both long-term runs reveal as most dominant variability patterns quasi-zonally symmetric annular structures similar to the observed Arctic Oscillation (AO; Thompson and Wallace, 1998), which appears to be fundamentally the same physical phenomenon as the NAO. However, the degree of zonal symmetry is higher than in the reanalyses, and differences between model and observation appear also in higher EOFs.

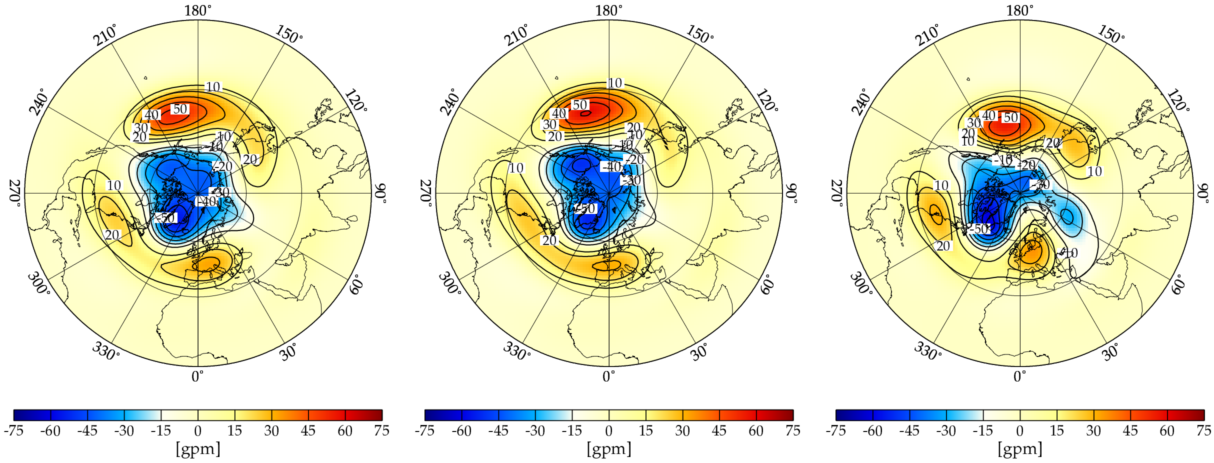

Figure 1: First EOF of Northern Hemisphere geopotential anomalies at 500 hPa in winter (Nov–Apr). Left: unforced control run; middle: forced run; right: NCEP reanalyses for the years 1948–2000.

Nevertheless, the model is able to simulate typical large-scale atmospheric flow patterns and to generate interannual, decadal and interdecadal climate variations merely on the basis of internal nonlinear dynamics. It seems that the external forcing has only little influence on the dominant variability patterns, but there are some indications for multimodal regime behavior in the model (Handorf et al., 2003) and that external forcing affects the frequency of occurrence of these regimes.

Impact of the NAO on the Arctic climate

In the recent debate on climate change and global warming, one of the central problems is the role of natural climate variability. The regional model HIRHAM4 has been used to determine the possible influence of NAO regime changes on the Arctic climate evolution in the near future. For this purpose, HIRHAM4 has been driven by selected time slices from a greenhouse gas and aerosol scenario simulation of the global coupled model ECHAM4/OPYC3 (Roeckner et al., 1999) and, for comparison, from the ECHO–G control run described above. Details on the model setup and main results have been described by Dorn et al. (2003).

The simulation results show a regionally significant influence of the NAO on winter temperatures and precipitation, especially over the northwestern Eurasian continent and parts of Greenland. For example, variations of mean winter temperatures of 3–6 K and mean winter precipitation of up to 100 mm occur over northern Europe and western Siberia as a result of regime changes of the NAO. However precisely there, precipitation responds even more to increasing greenhouse gases and aerosols than to the NAO, whereas in almost all other Arctic regions temperatures and precipitation are more strongly affected by the NAO. Thus, projected global changes of the atmospheric composition and internal circulation changes are competing with each other in their importance for the Arctic climate evolution in the near future.

Sensitivity studies

The sensitivity of Arctic climate simulations to removed orography of Greenland (GRL experiment), vertical resolution in the PBL (PBL experiment), and different land surface schemes (SRF experiment) has been investigated with the regional model HIRHAM4. For the GRL experiment, HIRHAM4 had to be driven with a global model simulation in which the orography of Greenland was removed as well. This global 20-year-long simulation was performed with ECHAM4 at T42 resolution. Figure 2 shows the differences in January between the run without Greenland's orography and the corresponding control run of the mean sea level pressure (SLP), the mean 2 m temperature as well as of the mean SLP variability within the 2–6-day window, which is an adequate proxy for strom track activity.

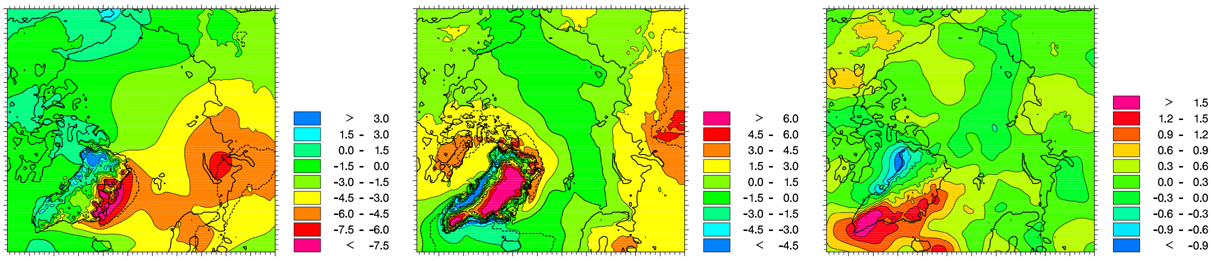

Figure 2: Differences between the run without Greenland's orography and the control run in January from HIRHAM4 simulations. Left: mean SLP (hPa); middle: mean 2 m temperature (K); right: mean SLP variability within the 2–6-day window (hPa).

The simulation without Greenland's orography shows an intensification and northeastward shift of the Icelandic low, a decrease in the strength of the Siberian high, and overall, a stronger zonal circulation. In addition, there is a shift and increase of the Atlantic and Pacific storm track activity associated with a stronger heat transport towards the continents. An overestimation of the zonal circulation may also occur in global models which cannot resolve the orography of Greenland as accurate as HIRHAM4 due to their coarser horizontal resolution (see Busch et al., 1999; Kristjánsson and McInnes, 1999). Therefore, high-resolution climate modeling is also essential in consideration of these results.

For the PBL experiment, six additional vertical layers have been introduced into the PBL below 922 hPa so that the vertical resolution of this HIRHAM4 version is given by 25 levels. A comparison of the HIRHAM4 simulations with 25 and 19 levels, in each case driven by ECMWF analyses for the year 1998, shows 2 m temperature differences of up to 5 K and mean SLP differences of up to 6 hPa both in summer and in winter. The increase in vertical resolution results predominantly in changes of the surface climate and the vertical stability. In case of a stable Arctic PBL there is a pronounced decoupling of the surface climate from that of the free troposphere, which remains rather unaffected by the changed vertical resolution. The differences above the PBL are generally small in temperature and humidity profiles, but sometimes not negligible in wind profiles due to changes in the vertical momentum flux above orographically strongly structured terrain.

In addition, an alternative land surface scheme has been implemented in the regional model in order to investigate the impact of soil freezing on the climate and possible feedbacks with the atmospheric circulation. At first, the current configuration (ECHAM4 parameterization) has been evaluated in a 15-year simulation (1979–1993) driven by ECMWF reanalyses (ERA15). This control simulation has been analyzed with respect to the key parameters surface temperature, surface albedo, snow cover, precipitation, soil temperatures, and soil moisture. Subsequently, the Land Surface Model (LSM) by Bonan (1996) has been applied to simulate land surface and soil processes with more sophisticated schemes. Output from HIRHAM4 is used to drive the LSM in a stand-alone mode for the ERA15-years. The strong winter cooling bias in soil temperatures over Siberia has been reduced by several Kelvin, but summer soil is a bit warmer than simulated by HIRHAM4, associated with changes in the thawing depth. Overall, the LSM results are closer to observations than the HIRHAM4 simulations with ECHAM4 parameterization.

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