# Global implications of Arctic climate processes and feedbacks

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## 1. Motivation

Arctic and the Antarctic are the cold poles of the atmospheric circulation and influence the global circulation through the meridional energy gradient between the tropics and the poles. Present climate models suggest that the largest human induced warming will take place in the Arctic and the Antarctic although there are considerable variations in the magnitude of the warming between the models. The temporal development of atmospheric circulation structures over years to several decades differs between different projections from the same model, suggesting large natural variations. Therefore the challenge is to identify and model the important components of the climate system and to explore this in order to assess and predict changes in the Arctic and Antarctic climate system caused by natural and anthropogenic effects. Because of the complexity of the climate system this research requires modelling and prediction studies that include interactions between the processes in the atmosphere, oceans, cryosphere, land surfaces and the biosphere encompassing time scales from hours to centuries.

This approach includes the improvements of global and regional models in the Arctic especially in the physical parameterization schemes for radiation, planetary boundary layer (PBL) turbulence, clouds and aerosols. A key scientific focus is to clarify the robustness of Arctic climate change and the dynamic and thermal feedbacks processes responsible for the large climate variations. In this respect, it is necessary to better understand and quantify to what extent Arctic and Antarctic climate change is due to regional or global processes. The Arctic is recognised as an area of the world where climate change is likely to be largest, and is also an area where natural variability has always been substantial. Current climate models predict a greater warming as a result of increased carbon dioxide for the Arctic than for the rest of the world. The impacts of this warming, including the melting of sea ice and changes to terrestrial and marine ecosystems are likely to be significant. The projections of future climate changes are complicated by complex interactions and nonlinear feedbacks of the Arctic climate system with other parts of the world as a result of global teleconnections. For this reason, current estimates of future climate changes for the Arctic based on coupled Atmosphere-Ocean General Circulation Models (AOGCM) vary significantly. The model results disagree as to both the magnitude of changes and especially the regional aspects of these changes.

The main goal of the EU funded GLIPMSE project (Global Implications of Arctic Climate Processes and Feedbacks) was to address the deficiencies in understanding the Arctic by developing, in concert with the ARCMIP (Arctic Regional Climate Model Intercomparison Project), improved physical descriptions of Arctic climate feedbacks in atmospheric and coupled regional climate models and to implement the improved parameterizations into global climate system models to determine their global influences and consequences for decadal-scale climate variations.

## 2. Evaluation of an ensemble of high resolution Arctic regional atmospheric climate models

The Arctic regional climate model intercomparison project ARCMIP has been organized under the auspices of the WCRP GEWEX Cloud System Studies Working Group on Polar Clouds and the ACSYS Numerical Experimentation Group. Funding for coordination of ARCMIP activities is provided by the International Arctic Research Consortium, and the Global Implications of Arctic Climate Process and Feedbacks (GLIMPSE http://www.awi-potsdam.de/www-pot/atmo/glimpse/index.html project (funded by the European Union). The primary ARCMIP activities have focused on coordinated simulations by different Arctic regional Climate Models (RCM) and their evaluation using observations from satellites and field measurements. The combination of model intercomparison and evaluation using observations allows assessing strengths and weaknesses of model structures, numerics and parameterizations. The simulation experiments are carefully designed so that each of the models is operating under the same external constraints (e.g. domain, boundary conditions). The ARCMIP experiment 1 has been conducted for the 1997/1998 period of Surface Heat Budget of the Arctic Ocean (SHEBA), which included extensive field observations and accompanying satellite analyses.

Simulations of eight different Arctic RCMs (ARCSyM, COAMPS, CRCM, HIRHAM, RegCM, PolarMM5, RCA and REMO) have been performed for the SHEBA period. Each of the models employed the same domain covering the Beaufort Sea (~70x55 gridpoints), the same horizontal resolution of 50 km, and the same atmospheric lateral boundary (ECMWF analyses) and the same ocean/sea ice lower boundary forcings (AVHRR, SSM/I). The surface temperatures over land and glaciers are not prescribed, but calculated individually by each model, using their own energy balance calculations. The models differ in the vertical resolution as well as in the treatments of dynamics and physical parameterizations. Tjernström et al. (2005) and Rinke et al. (2006) discussed the results of this first intercomparison experiment: First, compared with the SHEBA observations, the modelled near surface variables (e.g. surface pressure, temperature, wind, radiation, etc.) agree well with the observations. Two examples are given: The model ensemble mean bias in net radiation is -10 W/m$^2$ and less than 1 m/s in wind. Although the mean turbulent heat flux bias is also small, the models differ strongly from each other and reveal some common bias features compared to ECMWF analyses. They share a common large-scale flow bias in all seasons (an underestimation of the geopotential height by the models) and a common seasonal bias in temperature and humidity profile (models are colder in lower levels in the transition periods and warmer elsewhere, relatively dry in the near surface layers and wet in the free troposphere) compared to ECMWF analyses. Even using a very constrained experimental design (small integration domain, specified lower boundary condition for ocean and sea ice) and specified “perfect” horizontal boundary conditions from data analyses, there is considerable scatter among the different RCMs. The largest across-model scatter is found in the 2 m air temperature over land (up to 5°C), in the surface radiation fluxes (up to 55 W/m$^2$), and in the cloud cover (5-30%). This is not surprising given the very complex and individually different land-surface and radiation-cloud schemes within the models. The quantified scatter between the individual models highlights the magnitude and seasonal dependency of the disagreement and unreliability for current Arctic regional climate simulations.

The simulations showed a remarkable scatter between the model temperature and humidity profiles due to different dynamics and parameterizations (radiation, clouds, PBL, soil schemes). The scatter between the warmest and coldest model is in the order of 3°C. There is a need for improvements in the parameterizations of Arctic processes. The mentioned scatter is in the range of the model scatter of climate change scenarios. The stronger model deviations in winter are due to differences in the simulation of meso-scale cyclones, as discussed in Rinke et al. (2006). The direct climatic impact of Arctic Haze was investigated in Rinke at al.

(2004). It was shown that aerosols can trigger changes in the development of cyclones over the Arctic Ocean and exert climate influence on global teleconnection pattern like the Barents Sea Oscillation. The physical parameterizations for sub-grid-scale processes are generally adapted from global atmosphere models. The regional climate model HIRHAM uses he physical parameterization package of ECHAM4 that includes parameterizations for radiation, vertical diffusion, land surface processes, cumulus convection, stratiform clouds, and gravity wave drag. Since most of these parameterizations are adapted for global and mid- latitude climate simulations, they are not always sufficient for the specific Arctic climate conditions, for example, for the vertical diffusion in a shallow stable boundary layer, see Dethloff et al. (2001). Several efforts have been done to develop improved process descriptions for Arctic climate simulations.

A new snow albedo scheme was developed with a surface temperature dependent scheme which is different for forested (linear dependency) and non-forested (polynomial approach) areas. A new sea ice albedo with three different surface types (snow covered ice, bare sea-ice, melt ponds and leads) and a surface temperature dependent scheme with a linear dependency was developed by Køltzow et al. (2003). By implementing this scheme into the HIRHAM model for the pan-Arctic GLIMPSE domain it was shown that the gross features of the annual surface albedo cycle are reproduced by such a surface temperature dependent scheme. A polynomial temperature dependency of snow albedo improves HIRHAM simulations in spring compared to the old linear temperature dependency and improves especially the surface air temperature in spring and autumn. This new scheme improves the mean sea level pressure in spring and autumn, but decreases mean sea-level pressure (MSLP) skill in mid-summer compared to ERA40. HIRHAM is highly sensitive to the sea ice albedo for the large Arctic simulation area.

## 3. Coupled regional models of the Arctic climate system

A coupled regional climate model of the Arctic climate system has been developed at AWI as described in Rinke et al. (2003) and Dorn et al. (2006). This coupled model is based on the atmospheric model HIRHAM, parallelized version, 110×100 grid points, horizontal resolution 0.5° and 19 vertical levels and the ocean–ice model NAOSIM, which uses MOM-2 with elastic-viscous-plastic sea-ice rheology, 242×169 grid points, horizontal resolution 0.25° and 30 vertical levels. The boundary forcing is based on ERA-40 data. A series of sensitivity experiments concerning the influence of sea-ice parameters have been carried out with this coupled Arctic climate system model.

The impact of the lead closing parameter $h_0$, which describes the ratio between lateral and basal ice growth, and initial sea-ice thicknesses on sea-ice volume and extent was analyzed by a series of sensitivity experiments for the period from May 1989 to December 1999. The coupled regional model was driven by ECMWF re-analyses (ERA-40) at HIRHAM's lateral boundaries and also at HIRHAM's lower and NAOSIM's upper boundary points that lie outside of the overlap area of the two model domains. The initial ocean and sea-ice fields were taken from a stand-alone run of NAOSIM.

In one of the experiments (h1.2-uni), described in Figure 1, the initial ice thickness was uniformly set to 1 m in all grid cells with ice cover greater than 50%, while all other grid cells were initialized with open water. Although the other experiments (h0.5-std and h1.2-std) were initialized with sea-ice fields from a stable run of the stand-alone ocean–ice model, the modelled ice volume is far from a steady-state at the beginning in all coupled model experiments (top panel of Figure 1). However, all simulations arrive at a quasi-stationary cyclic state of equilibrium after about 6–10 years, and this equilibrium is only little affected by the initial sea-ice state. The coupled model's state of equilibrium depends significantly on the rate of increase in ice concentration given by $h_0$. The simulation with $h_0 = 0{:}5$ m results in a mean ice volume that is just about half as large as using $h_0 = 1{:}2$ m.

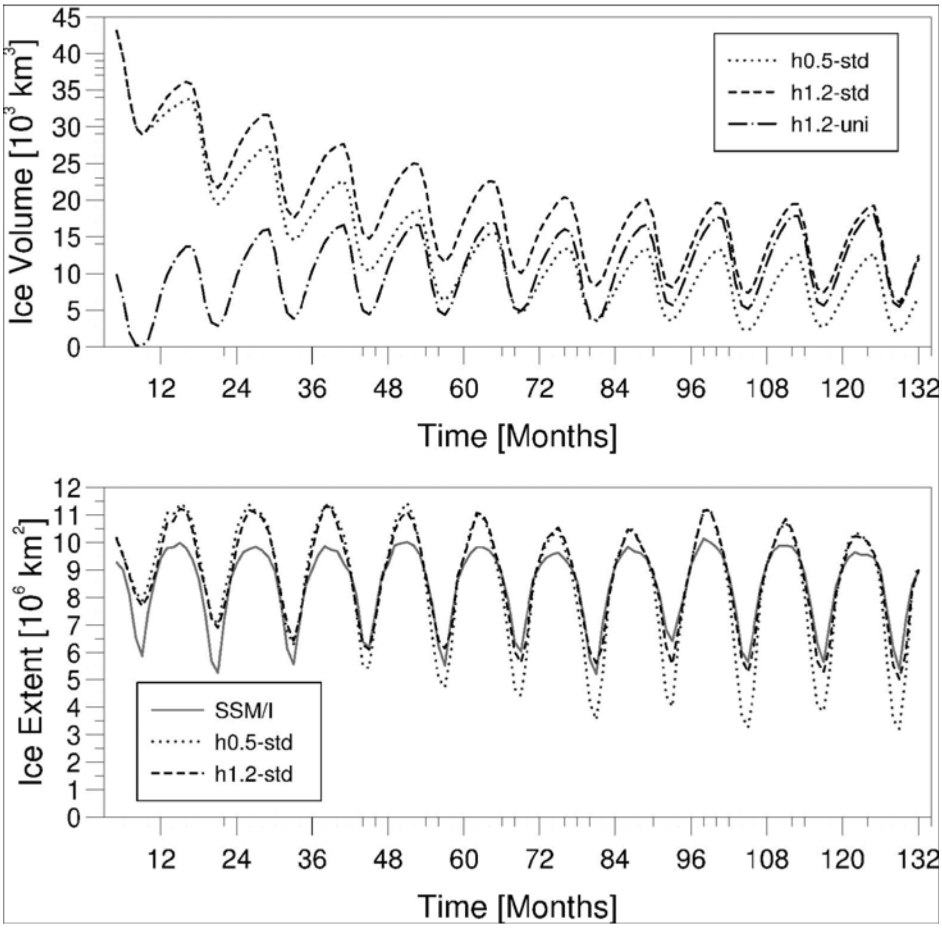


*Figure 1: Simulated monthly means of sea-ice volume (top) and sea-ice extent (bottom) within the model domain from May 1989 (Month 5) to December 1999 (Month 132). The sea-ice extent is here dened as the area of all grid cells with at least 15% sea-ice concentration. For comparison, the SSM/I satellite derived sea-ice extent (solid line) was calculated for the same domain. The model simulations with HIRHAM-NAOSIM were carried out with $h_0$=0.5m (h0.5-std, dotted lines), with $h_0$=1.2 m and standard ice initialization (h1.2-std, dashed lines), and with $h_0$=1.2 m and initialization with uniform 1 m ice thickness (h1.2-uni, dot and dash line).*

A rough comparison with available ice thickness observations, for instance with the climatologies of Laxon *et al.* (2003), shows that the simulation with $h_0$ = 0:5 m clearly underestimates the ice volume, while the simulation with $h_0$ = 1:2 m is much closer to these observations. The corresponding sea-ice extent of the $h_0$ experiments is shown in the bottom panel of Figure 1 in comparison with SSM/I satellite derived data using the NASA Team algorithm (Cavalieri *et al.*, 1990, updated 2004). The model generally overestimates the sea-ice extent during winter, and none of the experiments has been able to reduce this shortcoming substantially. In contrast, both simulations also overestimate summer ice extent during the first years, but the simulation with $h_0$ = 1:2 m agrees quite well with the observations after some years, while the simulation with $h_0$ = 0:5 m now tends to underestimate the summer ice extent considerably. A common result of the experiments is that summer ice extent is significantly correlated with the ice volume at the beginning of the melting period (ensemble correlation coefficient of 0.92 between ice volume in April and ice extent in September).

The modelled ice volume is generally affected by ice growth during winter as well as ice decay during summer, and thus not only by the lead closing parameter but also by the parameterizations of the energy fluxes within the atmospheric model. Due to the importance of the ice–albedo feedback for summer ice retreat, a new snow and ice albedo scheme following suggestion 2 of Køltzow *et al.* (2003) has been tested in the coupled model. An important point is that the new scheme decreases the ice albedo in most instances, particularly for melting conditions when snow has already disappeared. As a result, the energy input into the ocean–ice system is increased by the new scheme, leading to quicker decay of sea-ice during summer and accordingly to reduced ice volume at the end of the summer. On the other hand, there is not only an indirect influence on summer sea-ice by the changed ice volume but also a direct modification of sea-ice and atmospheric conditions by the albedo.

Figure 2 shows the satellite derived and modelled sea-ice concentration in September 1998. The two $h_0$ experiments demonstrate the effects of an unrealistic ice thickness distribution on summer ice extent and concentration: If the sea-ice is too thin at the beginning of the melting period, the ice cover is quicker to open with the result of stronger ice retreat and underestimation of sea-ice concentration throughout the Arctic. In contrast, too thick sea-ice results in effects exactly the opposite to the above. The experiment whose ice thicknesses are closest to reality also shows the best agreement in ice extent and concentration.

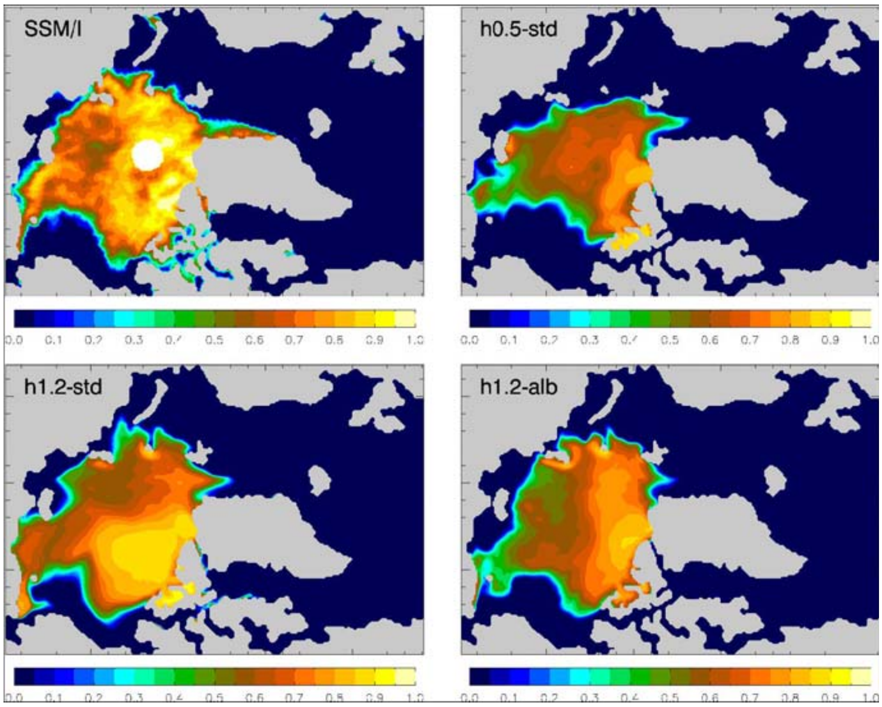


*Figure 2. Sea-ice concentration in September 1998 from SSM/I satellite derived observations (top left) and three simulations of the coupled regional model HIRHAM-NAOSIM with $h_0$=0.5 m (h0.5-std, top right), with $h_0$=1.2 m and standard ice albedo scheme (h1.2-std, bottom left), and with $h_0$=1.2 m and a new ice albedo scheme (h1.2-alb, bottom right).*

Although the experiment with the new albedo scheme shows quasi realistic sea-ice retreat in the Beaufort Sea and also in the Barents and Kara seas, there are considerably larger areas of open water in the Laptev and East Siberian seas. This underestimation of sea-ice is associated with differences in the atmospheric circulation during the previous summer months (see Figure 3). In contrast to observations and the other experiments, the albedo experiment shows a pronounced cyclone over the Laptev Sea which provides an atmospheric flow for drifting ice away from the East Siberian seas towards the central Arctic Ocean and Kara Sea. The redistribution of ice mass within the Arctic leads to a situation in which thermodynamic loss of ice is regionally either intensified by dynamic ice loss or partly compensated by increased influx of ice.

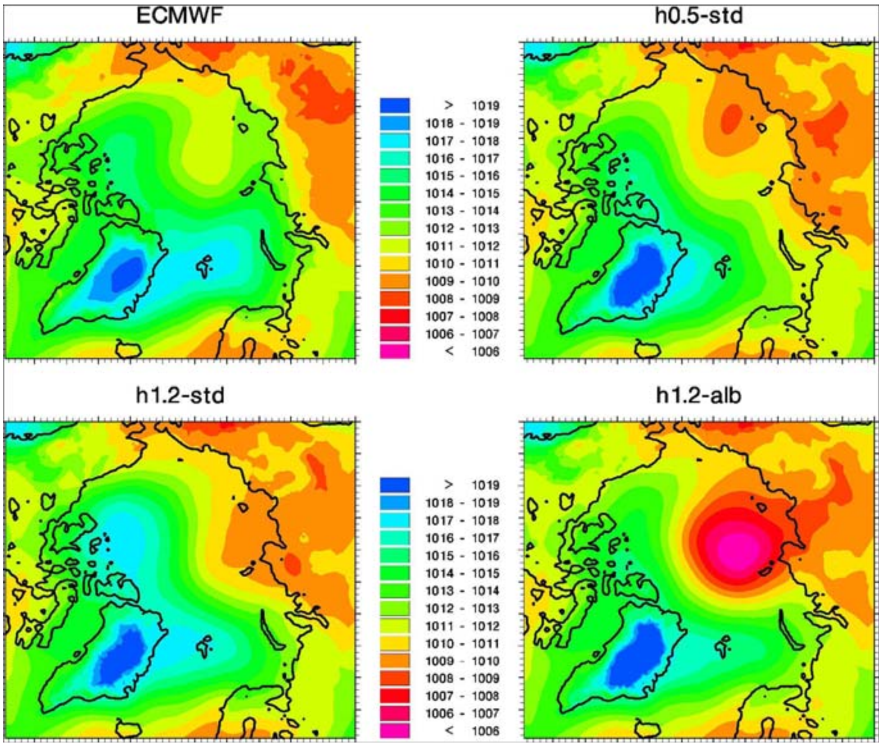


*Figure 3 Mean sea level pressure in summer 1998 (June to September) from ECMWF operational analyses (top left) and the same model simulations as in Figure 2.*

In order to achieve a realistic regional distribution of sea-ice in late summer, it also requires that the coupled model reproduces the observed atmospheric circulation during the preceding summer months. But in contrast to the clear response of the sea-ice cover to the atmospheric circulation, the atmospheric response to incorrect sea- ice cover is not that definite. Unrealistic sea-ice cover, as a result of incorrect thermodynamic ice loss, may favour model deviations in atmospheric circulation, but these deviations can clearly differ in their strength, probably in consequence of regional feedbacks. Owing to the variety of processes involved in such regional feedbacks, it is hard to distinguish between cause and effect of model deviations in a coupled model system without systematic sensitivity experiments. Some of such experiments have been presented in this paper, but a couple of further experiments, especially with respect to the cloud scheme and the treatment of snow and ice melt, are required to assess the importance of individual process for the simulation of Arctic sea-ice and to develop improved parameterizations for these processes.

## 4. Global impacts of Arctic feedbacks connected with teleconnection pattern

Recent observational studies of the Arctic region reveal significant changes in temperature, sea ice distribution, precipitation, permafrost distribution and other climate variables, e.g. Johannessen et al. (2004). In order to attribute these changes to internally generated and externally forced climate variations, a general understanding of Arctic climate variability in the context of global climate variability is necessary. A basic concept for the understanding of climate variability not only on the global scale, but also for the Arctic region is the concept of atmospheric circulation regimes. It is well-known that atmospheric variability is characterised by a few preferred large-scale flow patterns which occur at fixed geographical regions. The concept of atmospheric circulation regimes connects these observations with atmospheric dynamics. In the framework of this concept, low-frequency climate variability can arise due to transitions between the distinct atmospheric regimes and is manifested, primarily, in terms of changes in the frequency of occurrence of the preferred circulation regimes (Palmer 1999). Analogy studies with simple nonlinear atmospheric models, data analyses by e.g., Corti et al. (1999), analyses of model runs with increased greenhouse gases (e.g., Monahan et al., 2000) and paleoclimatic simulations (Casty et al., 2005) suggest, that response patterns of external forcing can in principle project onto natural variability modes, but the probability density of the preferred circulation regimes alters.

Sensitivity runs over 500 years with fixed solar constant (1365 W/m2) and CO2 (353 ppm) and a new ice- and snow albedo scheme for the Arctic has been carried out by use of the state-of-the-art coupled climate model ECHO-G. As shown by Benkel et al. (2006) the Arctic sea ice coverage within ECHO-G improved, especially the minimum extend and area in summer. There is an Arctic cooling in winter and summer owing to the improved albedo parameterisation similar to the results in regional coupled climate models. Strongest global impacts occur during winter. Diagnostic studies have been carried out by computing the localized Eliassen-Palm fluxes, which describe the interaction between the time mean state and the transient eddies.

The localised Eliassen-Palm flux differences for the old and the new snow and sea-ice albedo scheme for ECHO-G "New albedo minus Control" for 8 years has been computed. Changes in the planetary wave trains between tropics and Arctic over the Pacific and the Atlantic occur and have been described in Dethloff et al. (2006). Figure 4 presents the low-passed filtered Eliassen-Palm flux divergence differences at 850 and 500 hPa for the sensitivity experiment with the ECHO-G model "New albedo minus Control". Along the east Pacific coast a large scale planetary wave train is clearly visible on both pressure levels as a result of the feedbacks between the westerly wind jets and planetary waves. Changes occur also in the storm tracks over Northern America and Northern Europe owing to the improved Arctic albedo parameterisation.

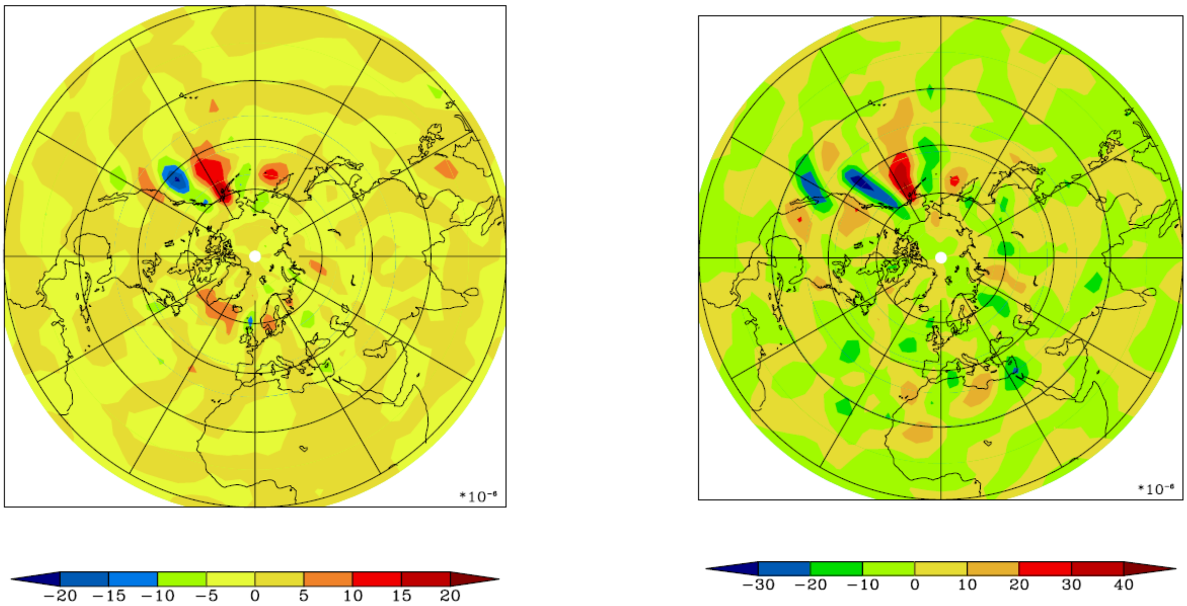


*Figure 4 Divergence [$10^{-6}$ $ms^{-2}$] differences of the localised Eliassen-Palm fluxes between the ''New sea-ice and snow albedo run and the control run'' at 500 hPa, averaged 8 winter (DJF). Low-pass filtered (10–90 days). 850 hPa (left) and 500 hPa (right)*

The global impact of improved Arctic sea-ice and snow albedo leads to annular mode structures similar to the Arctic Oscillation. This implies an influence on the meridional coupling between the energy sources in the tropics and the energy sink in the Arctic and would have strong implications for CO2 scenario runs. 500 year long simulations with the state-of-the-art AOGCMs ECHAM4/OPYC and the ECHO-G with the old and the new snow and sea-ice albedo scheme have been carried out and described by Benkel et al. (2006) and Stendel et al. (2005). Multi-decadal circulation anomalies are seen, e. g. the Maunder Minimum and both models are able to simulate cold and warm 25 year long lasting anomalies as deviations from the 200 year mean 1500-1700. The models are driven with most relevant forcings, both natural (solar variability, volcanic aerosol) and anthropogenic (greenhouse gases, sulphate aerosol, land-use changes).

One method for the detection of preferred circulation patterns is the search for teleconnected regions in atmospheric data, by the method of empirical orthogonal function (EOF) analysis. As most studies, here we focus on the NH winter months, when the atmosphere is dynamically most active and the global variability patterns have the largest influence on the Arctic climate. The application of the latter method onto the extratropical NH fields of sea-level pressure (SLP) from NCEP-reanalyses from 1948 to 2002 reveal the most dominant surface patterns. These patterns are shown in Figure 5, in their positive phase. The most dominant variability pattern in the northern hemisphere (EOF1, explained variance 20.7 %) is the Arctic oscillation (AO, Thompson and Wallace, 1998) representing an annular pattern with decreased SLP over the Arctic basin connected with increased SLP at mid-latitudes over the North Atlantic and North Pacific. This mode is strongly connected to the North Atlantic oscillation (NAO).

The NAO is the dominant mode of variability for the North Atlantic-European region and is mainly represented by a seesaw between Iceland and the Azores (Hurrell, 1996). The second variability pattern, explaining 13.7% of total variance, is dominated by a North Pacific centre of action. Due to the similarity with the correlation pattern of the North Pacific Index (NP, Trenberth and Hurrell, 1994) with SLP, it is referred as NP-related pattern. The dominant feature of the third pattern, which explains 9.8% of SLP-variance, is a wave-train structure from the North Atlantic into the Arctic Ocean. The strongest pressure gradients connected with rather strong meridional flow occur over the Barents Sea, thus this pattern is referred as Barents Sea (BS) pattern. Note, that this pattern is different from the Barents oscillation determined by Skeie (2000) as EOF2 of the SLP field, because in the EOF analyses presented here a cosine correction has been applied to take into account correct area weighting.

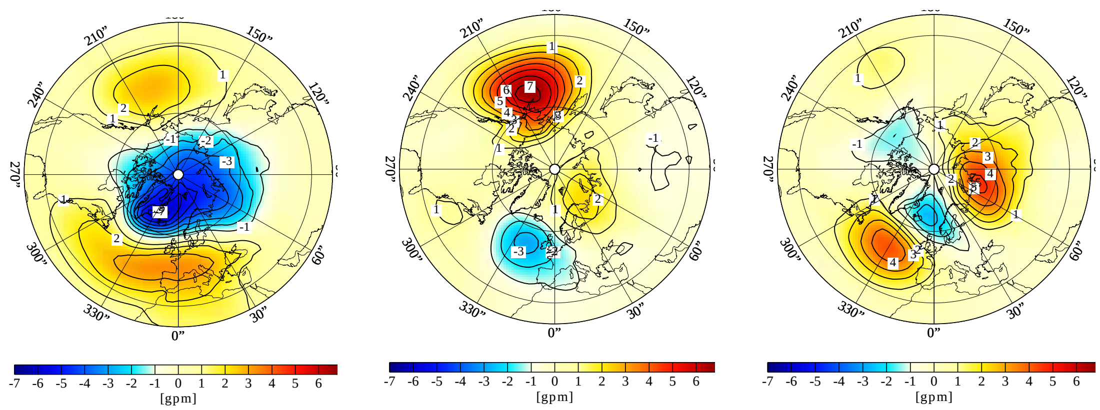


*Figure 5 The first three Northern hemisphere variability patterns, obtained by an EOF analyses of the NCEP reanalysis monthly mean winter (DJF) SLP-fields from 1948-2002. The spatial area is confined to the extratropics from 22.5°N to 90°N.*

During the positive phases of the NAO-AO (e.g., during the 1990s), lower SLP occurs in the whole Arctic, representing the typical atmospheric mass shift to mid-latitudes and subtropical regions. Northerly winds over Greenland and north-eastern Canada lead to negative temperature anomalies of surface air temperature (SAT) and sea surface temperature (SST). Related to the change of the mean circulation pattern, positive AO-NAO index is associated with a northeastward shift in the Atlantic storm track with enhanced activity from Newfoundland to Northern Europe and in the region of the Icelandic low. This is accompanied by fewer cyclones over the Barents and Kara Seas (e.g., Serreze et al., 1997).

The impact of the leading variability patterns is not confined to the surface. Thus, the AO is not just the leading pattern at the surface, but shows a quasi-barotropic structure and is strongly coupled to the troposphere and the stratosphere (Thompson and Wallace, 1998) leading to a stronger and colder polar vortex (PV) during positive AO phase. The state of the PV does not only influence the propagation of planetary waves from the tropo- into the stratosphere, but also the migration of extreme anomalies from the stratosphere down to the troposphere. Perlwitz and Harnik (2003) suggest that zonal mean coupling will dominate the downward interaction between strato- and troposphere during negative AO-phases, whereas reflection dominates this interaction during positive AO-phases. The relation of the more wave train-like variability patterns to the troposphere and stratosphere is much weaker and is dominated by baroclinic structures. How these patterns influence the vertical propagation of planetary waves and thus the flow in the tropo- and stratosphere as well as troposphere-stratosphere coupling is a topic of ongoing research.

Dorn et al. (2003) investigated the influence of changes in the NAO patterns under increased atmospheric carbon dioxide and aerosol content on the Arctic winter climate using a climate scenario run with the AOGCM ECHAM4/OPYC. The regional model has been driven with data of positive and negative NAO phases from a control simulation as well as from a time-dependent greenhouse gas and aerosol scenario simulation. The results indicate that the effects of NAO regime changes on Arctic winter temperatures and precipitation are regionally significant over most of north-western Eurasia and parts of Greenland. In this regard, mean winter temperature variations of up to 6 K may occur over northern Europe. Precipitation and synoptic variability are also regionally modified by NAO regime changes with a stronger synoptic variability during positive NAO phases. The climate changes associated with the NAO are in some regions stronger than those attributed to enhanced greenhouse gases and aerosols. This result indicates that the 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. The knowledge of the future AO-NAO trend on decadal time scales is vitally important for a regional assessment of climate scenarios for the Arctic.

## 5. Dynamical-chemical feedbacks between the tropo- and stratosphere

A new model ECHO-GiSP coupled Atmosphere-Ocean General Circulation Model (AOGCM) with simplified stratospheric chemistry, has been developed at the AWI Research Unit Potsdam (Brand et al. 2006). ECHO-GiSP ECHAM & HOPE-G including Stratosphere, created by AWI research unit Potsdam, is based on an ECHO-G basic version (39 level up to 1Pa ~ 80km) provided by the Free University Berlin, Department of Meteorology, and the MECCA chemistry module, developed at the MPI for Chemistry, Mainz. A central feature of the new model is the so called Integrated Stratospheric Chemistry (ISC), which allows a free choice of chemical tracers and equations, to translate it into model source code, and thereby to include it in the model. A main focus of ECHO-GiSP is the integration of the coupled atmosphere-ocean system with a tropo- and stratospheric chemistry. This aims to investigate interactions between the atmospheric model dynamics and tracer distributions/concentrations, e.g. leading to a better understanding of basic effects from the feedback of chemistry and dynamics. In order to be principally able to keep the chemistry scheme on a more simplified level, but also depending on computational restrictions, it is now possible to restrict the calculations of the tracer concentrations only on the upper tropospheric and stratospheric model levels.

Since, in terms of decadal variability, the main focus is to examine the feedback of stratospheric chemistry and atmospheric dynamics, model runs of some hundred years simulation time will be performed using the restricted chemistry domain. Therefore the tropospheric sources and sinks have to be prescribed. The corresponding chemical boundary conditions on the excluded tropospheric levels, as well as the initial conditions on all 39 levels, were prepared in collaboration with the Research Centre Karlsruhe. This set of fields contains, on every grid point, the parameter values for an idealised, cyclic function, describing mean annual and semi-annual variations for that species on that grid point. Thus, especially the chemical boundary conditions can be provided time dependent, leading to a more realistic transport of tracer mass into the higher levels of the stratosphere, where the chemistry is explicitly calculated.

As a first step towards the envisioned long term runs over some hundred years, two 25-year simulations of ECHO-GiSP were performed. These runs were carried out with fixed chemical boundary conditions. One run was only including the dependence of chemistry on the model dynamics (offline mode), the other (online mode) included also the feedback, i.e. from the tracer concentrations back to the model dynamics. This feedback takes place via radiation processes. Although these test runs are just preliminary, there seem to be some interesting differences between the two runs, e.g. regarding the lower maximum value of the ozone concentrations and the stronger tropospheric jetstreams in the online mode simulation presented in Figure 6. This leads to changed zonal wind distributions and planetary wave patterns with influences on the Arctic Oscillation structure. These results indicate changes in the dynamical-chemical feedbacks between the tropo- and stratosphere.

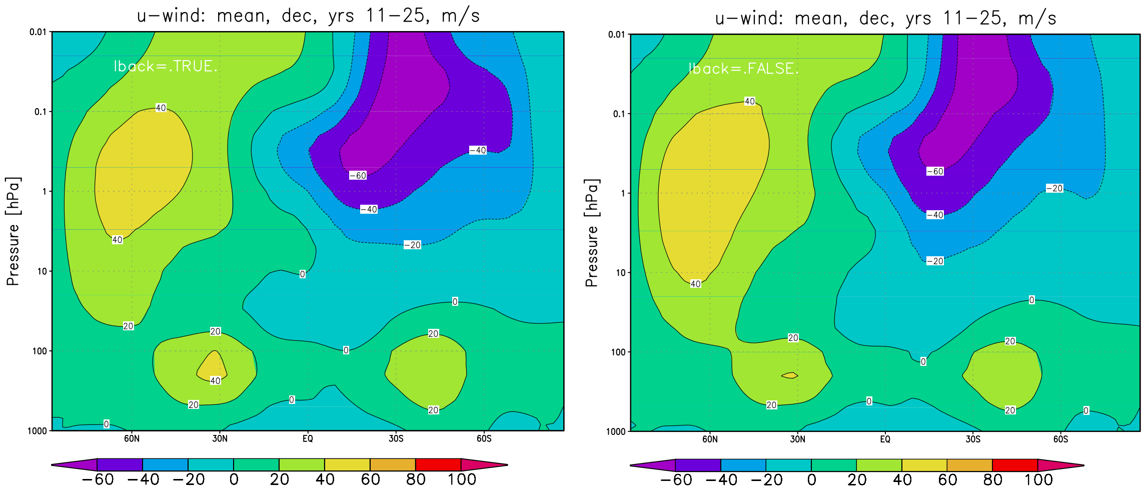


*Figure 6 Zonal mean wind (m/s) in December, averaged over years 11 to 25 from simulations with the coupled climate model ECHO-GiSP. Model results with interactive chemistry on the left hand side, presribed chemistry on the right hand side.*

## 6. Influence of improved permafrost description on future climate changes

A new land-surface model (LSM) from NCAR has been coupled with HIRHAM (HIR-LSM) in the Arctic permafrost region taking into account six moisture layers in the soil as described by Saha et al. (2006, 2006a). The new coupled atmosphere-soil model has reduced the cold winter bias in the soil and improved also the summer 2m air temperature. The new land surface scheme has a significant influence on the future projection of the Arctic temperature, precipitation and mean sea level pressure. The temperature differences between the HIRHAM coupled LSM and the old HIRHAM4 projections for the time period (2024-2029) minus (1990-1995) have been computed using the IPCC B2 scenario of ECHO-G.

Global B2 scenario simulations show for the last three decades of the 21st century (2071-2100), a change of 2.2 K (with a range of 0.9 to 3.4 K between the nine models used by IPCC) in globally averaged surface air temperature relative to the period 1961-1990. However, the models differ significantly in the simulated temperature response in the Arctic, not only in the magnitude but also in regional aspects of the projected temperature change. A model with high horizontal resolution will be very useful to find out the regional aspects of Arctic climate changes in the context of global warming. A dynamical downscaling of a B2 scenario simulation of the coupled Atmosphere–Ocean model ECHO–G (ECHAM4/HOPE–G) was done with the regional atmospheric model HIRHAM over a pan-Arctic domain at a horizontal resolution of 50×50 km. Two 6-year-long time slices (1990–1995 and 2024–2029) were chosen for the dynamical downscaling of this scenario with the uncoupled HIRHAM as well as with the coupled HIR-LSM and are shown in Figure 7.

The regions of warming and cooling during 2024-2029 winter (DJF) compared to 1990-1995 winter are similar for both model HIRHAM and its coupled version HIR-LSM. With advanced vegetation and soil schemes, the coupled model shows a deviation from HIRHAM in 2m air temperature by about ± 2°C. In both scenario runs there is an enhanced warming over the eastern hemisphere and parts of Northern America and a cooling over Alaska and Greenland. The difference plot shows that the impact of different soil schemes varies with a strong regional signature. The LSM reduces the anthropogenic warming over Siberia and enhances the warming over European Russia and Northern Canada.

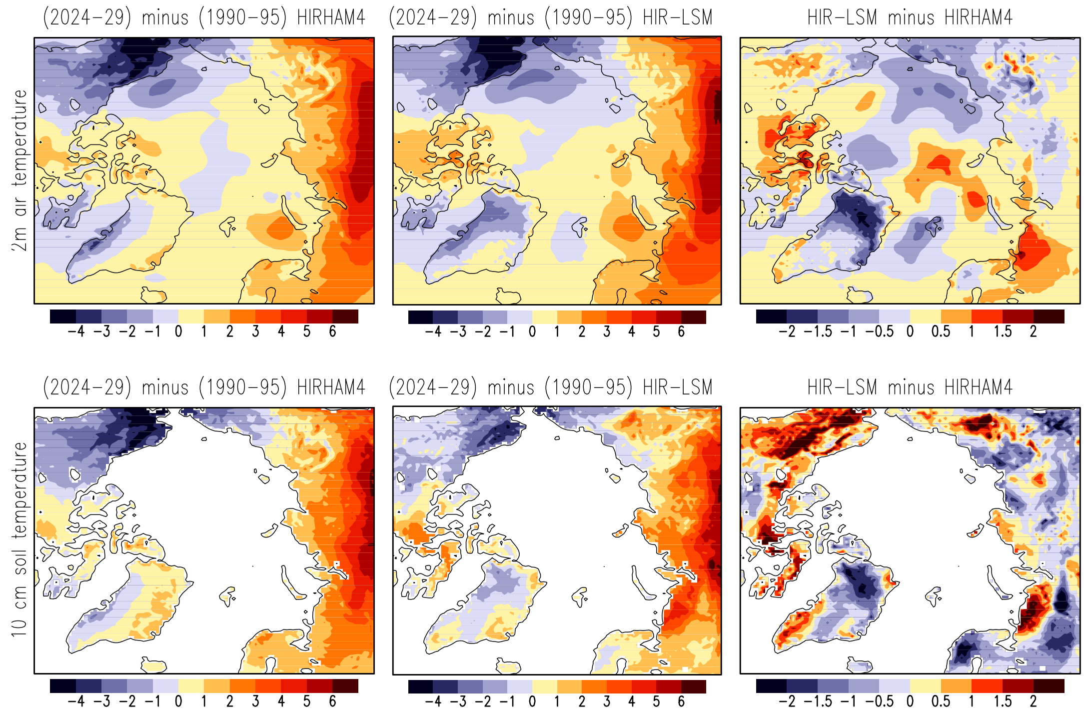


*Figure 7 Differences of mean winter (DJF) 2-m air temperatures (°C) (upper panel) and 10-cm soil temperatures (lower panel) between time slice 2024-2029 and time slice 1990-1995. Left: HIRHAM simulation; middle: coupled HIR-LSM simulation; right: difference between HIRHAM and HIR-LSM simulations.*

Both the stand-alone HIRHAM and the HIR-LSM show a similar warming and cooling trend in 2-m air and 10-cm soil temperatures at high latitudes but the HIR-LSM shows a stronger soil warming than HIRHAM. The anthropogenic impact is amplified by the use of a more advanced land-soil scheme in the Arctic. This would have strong implications for the additional release of methane from permafrost areas.

## 7. Outlook

Arctic climate changes are related to large scale circulation regime changes under the influence of regional feedbacks. These interrelation has to be taken into account for an evaluation of observed and an assessment of future Arctic changes and their subsequent implications for future changes, e. g. Dethloff et al. (2004). For example, the magnitudes of AO-NAO related Arctic temperature changes, estimated by regional climate simulations by Dorn et al. (2003) are in part higher than the recently observed warming in the corresponding regions. Thus, this warming could not be attributed directly to anthropogenic forcing.

Still, there are open questions for future research. This includes the feedback of regional Arctic changes on the large scale regimes including the aspect of tropo-stratosphere coupling via the stratospheric ozone layer. Furthermore, to characterize the current and future Arctic climate reliably, there is a need for climate models which are able to simulate circulation regimes and their associated variability. This requires an enhanced physical understanding of climate regimes and their changes under external forcing.

Sempf et al. (2006) investigated the dynamical mechanisms of atmospheric regime behaviour in the context of a quasi-geostrophic three-level T21 model of the wintertime atmospheric circulation over the Northern Hemisphere. The model, driven by realistic orography and using a thermal forcing determined by a newly developed tuning procedure, is shown to possess a reasonable climatology and to simulate the Arctic Oscillation quite realistically. It exhibits pronounced internally generated interannual and decadal variability and, in particular, circulation regimes which agree fairly well with observed ones. Two known hypotheses about the origin of regime behaviour, as it occurs in the model, are addressed. The multiple equilibria and chaotic itinerancy hypothesis between attractor ruins are investigated. The first hypothesis is falsified at very high probability, while the second is likely to be true.

The assessment of potential impacts of climate change has generally relied on model data from coarse resolution AOGCM, incapable of resolving spatial scales less than ~300 km. These models include only a limited physical representation of the coupled atmosphere-ice-ocean-land-biosphere system and are insufficient in simulating the spatial structure of temperature and precipitation in areas of complex topography (e.g. Greenland, Alaska, Siberia). The description of regional and local atmospheric circulation systems (narrow jet cores, mesoscale convective systems, see-breeze circulations, shallow stable planetary boundary layers) and the representation of processes at high frequency temporal scales (e.g. precipitation frequency, intensity distribution, surface wind variability, snow redistribution) are likewise insufficient to provide accurate information. There is further need to better identify and model the important key processes of the Arctic climate system, including natural variability, than has been done so far in the framework of the International Polar Year. This approach is carried out by introducing a better description of physical processes in the oceans, cryosphere, atmosphere, land and biosphere including their interactions in high-resolution regional climate models. This is based on identifying and modelling of the key processes and through an assessment of the improved understanding in the light of analysis of improved data and in-situ observations.

For an improved simulation of multiscale interaction like those between the planetary and barotropic waves with meso-scale circulation structures the new atmospheric model PLASMA has been developed and described in Läuter et al. (2006) as a parallel adaptive model of the atmosphere. For the discretization of the underlying spherical shallow water equations the adaptive Lagrange-Galerkin method, a combination of the finite element method and the semi-Lagrangian method, has been employed. The unstructured triangular grid is generated with the grid generator amatos and the large linear systems have been solved with a parallel solver interface. Both, uniform grid experiments as well as adaptive grid experiments can be performed with PLASMA. In the adaptive case the computational grid is adapted at every time step according to a physical error estimator. The comparison of uniform and adaptive grid experiments documents, that the adaptive model leads to a significant reduction of the number of grid points while the numerical error increases only slightly. This has been shown within convergence studies for steady-state and unsteady analytical solutions as well as for zonal flow over an isolated mountain. If the number of grid points is fixed for a uniform and an adaptive grid experiment, then these results demonstrate that in the adaptive case a more accurate simulation of local features of interest is possible compared to the uniform case. By means of a sample of quasi standard experiments the successful numerical approximation of the spherical shallow water equations has been shown. Convergence studies show the first order approximation for steady-state and unsteady analytical solutions. Furthermore, PLASMA shows satisfactory results for the simulation of a Rossby-Haurwitz wave and zonal flow over an isolated mountain. For the realization of adaptive atmospheric simulations from seasonal up to annual time scales the model has to be further improved. Longer model integrations require a discrete conservation of the physical variables mass, energy and potential enstrophy. Although, the presented simulations already show very satisfactory results for adaptive simulations, the physical error estimator could be further improved, especially inside turbulent flow structures. Finally, the application of the adaptive grid in PLASMA can be assigned to a baroclinic multi-layer model.

The application of a hierarchy of simplified models, regional coupled and uncoupled models of the Arctic atmosphere and the coupled climate system including the interaction between atmosphere, ocean, sea-ice, land surface and soil schemes together with global coupled climate models improved our understanding of the Arctic climate system and its feedbacks within the global system. With respect to the Arctic further investigations in the following directions are needed:

- Development of regional models of the coupled Arctic climate system, including the climate subsystems atmosphere, ocean, sea-ice, land and permafrost, glaciers and interactions with terrestrial and marine ecosystems.

- Improvement of the model performance in close collaboration of experimental and modelling activities during the IPY via atmospheric and oceanic measurements in different key regions of the Arctic.

- Process and feedback understanding of Arctic climate variations and observed variability patterns for improved description of atmospheric processes on seasonal to decadal time scales in global climate models.

- Determination of the impact of polar regions and regional polar feedbacks as key drivers for global climate changes and reduction of the uncertainties of future climate change scenarios and possible unexpected climate surprises.

## 8. Literature

Brand, S., et al., 2006, Decadal variability in a climate model with simplified stratospheric ozone chemistry, in preparation.

Benkel, A., et al., 2006, A new sea-ice albedo parameterization in ECHO-G and its global consequences, ep. *Polar and Marine Res*., **520**, 9-14.

Casty, C. et al., 2005, Recurrent climate winter regimes in reconstructed and modelled 500 hPa geopotential height fields over the North Atlantic/European sector 1659-1990., *Climate Dyn*., **24**, 809-822, DOI: 10.1007/s00382-004-0496-8;

Cavalieri D, Gloerson P, Zwally J. 1990, updated 2004. *DMSP SSM/I monthly polar gridded sea ice concentrations, 1988 to 2003*. edited by J. Maslanik and J. Stroeve, National Snow and Ice Data Center, Boulder, CO. Digital media.

Corti, S., F. Molteni, T.N. Palmer, 1999, Signature of recent climate change in frequencies of natural atmospheric circulation regimes. *Nature,* **398**, 799-802.

Dethloff, K., Abegg, C., Rinke, A., Hebestadt, I., Romanov, V.,2001, Sensitivity of Arctic climate simulations to different boundary layer parmeterizations in a regional climate model, *Tellus*, **53A**, 1-26.

Dethloff, K. et al., 2004, The impact of Greenland's deglaciation on the Arctic circulation, *Geophys. Res. Lett.* **31**, L19201, doi: 10.1029/2004GL020714.

Dethloff, K. et al., 2005, Global impacts of Arctic climate processes, *EOS transactions*, **86**, 49, 6 December 2005, 511-512.

Dethloff, K. et al., 2006, A dynamical link between the Arctic and the global climate system, *Geophys. Res. Lett*., **33**, L03703,DOI: 10.1029/2005GL02524.

Dorn, W., K. Dethloff, A. Rinke, 2003, Competition of NAO regime changes and increasing greenhouse gases and aerosols with respect to Arctic climate estimate, *Clim. Dyn*., **21**, 447-458. (DOI: 10.1007/s00382-003-0344-2)

Dorn, W. et al., 2006, Sensitivities and uncertainties in a coupled regional atmosphere-ocean-ice model with respect to the simulation of Arctic sea-ice. *J. Geophys. Res*., submitted.

Hurrell, J.W., 1996, Influence of Variations in Extratropical Wintertime Teleconnections on Northern Hemisphere Temperatures. *Geophys. Res. Lett*., **23**, 665-668.

Johannessen, O.M., et. al, 2004,  Arctic climate change: observed and modelled temperature and sea-ice variability. *Tellus A*, **56**, 328,341.

Køltzow M., Eastwood S., Haugen J. E., 2003. Parameterization of snow and sea ice albedo in climate models. *Research Report* 149, Norwegian Meteorol. Inst., Oslo, Norway.

Laxon S, Peacock N, Smith D., 2003, High interannual variability of sea ice thickness in te Arctic region. *Nature*, **425**, 947–950.

Läuter, M., Handorf, D., Rakowsky, N., Behrens, J., Frickenhaus, S., Best, M., Dethloff, K., Hiller, W., 2006, A parallel adaptive barotropic model of the atmosphere, *J. Comp. Phys.*, accepted.

Monahan A.H., J.C. Fyfe, G.M. Flato, 2000, Northern Hemisphere atmospheric variability and change under global warming. *Geophys Res Lett*., **27**, 1139-1142.

Palmer T.N., 1999, A nonlinear dynamical perspective on climate prediction. J Climate 12: 575-591.
Perlwitz, Ju., and N. Harnik, 2003, Observational evidence of a stratospheric influence on the troposphere by planetary wave reflection. *J. Climate*, **16**, 3011-3026.

Rinke, A., Gerdes, R., Dethloff, K., Kandlbinder, T., Karcher, M., Kauker, F., Frickenhaus, S., Koeberle, C., Hiller, W., 2003, A case study of the anomalous Arctic sea ice conditions during 1990: Insights from coupled and uncoupled regional climate model simulations, *J. Geophys. Res*., **108**, No.D9, 4275.
DOI: 10.1029/2002JD003146

Rinke, A. et al., 2004, Regional climate effects of Arctic Haze, *Geophys. Res. Lett*., **31**, L16202.

Rinke, A. et al., 2006, Evaluation of an ensemble of Arctic regional climate models. Spatiotemporal fields during the SHEBA year, *Climate dynamics*, **26**, 459-472, DOI: 10.1007/s00382-005-0095-3.

Stendel, M. et al., 2005, Influence of various forcings on global climate in historical times using a coupled atmosphere-ocean general circulation model, *Climate Dyn.*, **25**, 10.1007/s00382-005-0041-4.

Tjernström, M. et al., 2005, Modelling the Arctic Boundary layer: An evaluation of six ARCMIP regional-scale models using data from the SHEBA project, *Boundary-layer Meteor.*, **117**, 337 – 381, DOI: 10.1007/s10546-004-7954-z.

Saha, S. K., Rinke, A., Dethloff, K, Kuhry, P., 2006. The influence of a complex land-surface scheme on Arctic climate simulations, *J. Geophys. Res*., accepted.

Saha, S. K. et al., 2006a, Future winter extreme temperature and precipitation events in the Arctic, *Geophys. Res. Lett.*, **33**, L15818, DOI: 10.1029/2006GL026451.

Sempf, M. et al. , 2006, Circulation Regimes due to Attractor Merging in Atmospheric Models, *J. Atmos. Sci*., accepted.

Serreze MC, F. Carse, R.G. Barry, J.C. Rogers, 1997, Icelandic low cyclone activity: Climatological features, linkages with the NAO, and relationships with recent changes in the Northern Hemisphere circulation. *J Clim* **10**, 453-464.

Skeie, P., 2000, Meridional flow variability over the Nordic seas in the Arctic Oscillation framework, *Geophys. Res. Lett.*, **27**, 2569 2572.

Thompson D.W.J., and J.M. Wallace, 1998, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys Res Lett*., **25**, 1297-1300.

Trenberth. K.E. and J.W. Hurrell, 1994, Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics*, **9**, 303-319.