Modeling of atmospheric circulation at mid- and high latitudes of the northern hemisphere – evaluation studies using ARPEGE

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Preface

This thesis consists of the work for the degree of philosophize doctor (PhD) in meteorology at the Geophysical Institute, University of Bergen, Norway. In this thesis evaluation studies on the climate information (climatological variables and heat transport) and synoptic phenomenon (storm tracks over North Atlantic) have been made by dynamical downscaling techniques with the atmospheric part of Bergen Climate coupled model. This thesis has also involved numerical simulations to study the impacts of realistic snow forcing on the variability of North Atlantic Oscillation (NAO) that might exert a strong influence on societies, ecosystems and infrastructures at mid- and high latitudes of the northern hemisphere.

I have an enormous gratitude for the support of many people during the work on this thesis for the last three and a half years.

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1 Introduction

From evaluation of climate research, done by United Nations' Intergovernmental Panel on Climate Change (IPCC 2001), it is known that anthropogenic emissions of greenhouse gasses (GHGs) lead to higher concentrations of such gasses in the atmosphere. Higher concentrations of GHGs in the atmosphere exert a considerable positive radiative forcing on the climate system, i.e. a positive imbalance between the radiation of energy to the climate system from the sun and the radiation of energy from the climate system to space. The climate system will respond on the increased greenhouse effect with a global warming in order to restore a new radiative balance between the radiation of energy from the sun and to space. Very likely, the observed global warming, which is estimated to 0.2 °C per decades during the last 30 years (e.g. Hansen et al. 2006), is attributed to increased anthropogenic greenhouse effect strengthened by certain feedback mechanisms within the atmosphere, such as increased humidity in the air. The warming is expected to become stronger during the present century, and it is believed that it might cause serious environmental impacts on societies, ecosystems and infrastructures. Accordingly, it is of vital importance to estimate the strength of future global warming, as a result of past and future emissions of greenhouse gasses, and how the climate might change locally all over the globe.

In order to assess climate change impacts, projections of the physical climate change must first be estimated. Climate models are primary tools for the studies of physical climate, its sensitivity to external and internal forcing factors, and the mechanisms of climate variability and change. Climate models that couple atmosphere and ocean (Atmospheric-Ocean-General-Circulation-Models; AOGCMs) are steadily developed through improved spatial resolution, improvements in numerical schemes and parameterisations of unresolved physical processes. The climate model at the Bjerknes Centre for Climate Research (BCCR), called Bergen Climate Model (BCM; Furevik et al. 2003), is one of several internationally recognised climate models. The model is basically a coupling of the atmospheric climate model ARPEGE, developed at Meteo-France (Déqué et al., 1994, 1998; Déqué and Piedelievre, 1995; Doblas-Reyes et al. 1998) and built on the numerical integration scheme used in the weather prediction model used at EWMWF (IFS; e.g. Hortal 1998), and the ocean model MICOM (Bleck et al. 1992). Like other models BCM is steadily being improved - ARPEGE through cooperation with Meteo-France - and is now one of several climate models that are run without ocean flux adjustment (methods to remove long-term drift in the simulated climate, see Section 2).

The skill of the climate models to simulate future climate change is evaluated from their ability to describe present day climate and variability. Recent decades, when extensive observations are available, become the most important test period. Extensive climate research is also devoted improvements and evaluation of simulations with the different component of AOGCMs. The atmospheric component of AOGCMs – denoted AGCMs - enables simulation of the evolution of the atmospheric flow, expressed by the dependent variables temperature, humidity, wind components and surface pressure fields, together with other parameters diagnosed from the dependent variables, such as clouds and precipitation. When integrated separately, boundary conditions at the ocean surface, mainly sea surface temperature and sea ice, are normally prescribed.

AGCMs have been extensively used to simulate present climate during the last 50 years. For these decades observational data are available that can be used to evaluate the skill of the models, in particular reanalyses of the geographical distribution of daily states of the atmosphere throughout the troposphere and the stratosphere. Reanalyses are provided by two major meteorological centers; NCEP, USA (Kalnay et al. 1996) and ECMWF, Europe (Uppala et al., 2005). The research objective connected to simulations for the same time period is mainly to evaluate and improve the atmospheric models, but also to get a better understanding of the general circulation of the atmosphere and its variability.

In several ways climate research communities try to increase the climate information provided by the global coupled climate models towards more details on regional and local scales. We call this activity downscaling, and certain downscaling techniques exist to increase the regional information (IPCC 2001). The main downscaling method is dynamical downscaling, where additional details are extracted using a climate model of the atmosphere with higher resolution than in AOGCMs. In this way both regional forcing from the surface and individual weather systems will be better described. Regional limited area climate models (RCMs) are commonly used, but also AGCMs with higher resolution than in coupled models.

In the present thesis we evaluate experiments with the atmospheric part of BCM, named ARPEGE, performed for present day climate during the last 50 years. The objectives have been to evaluate the ability of ARPEGE to simulate the general circulation at mid- and high northern latitudes in winter. Particular emphasis is put on the dependence of systematic errors on the horizontal resolution in the model, the climatology and variability of storm tracks, the poleward energy transport and the North Atlantic winter circulation expressed by the North Atlantic Oscillation (NAO; e.g. Hurrell 1995). In addition, use of ARPEGE for downscaling purposes has been evaluated. The work on storm tracks, poleward energy transport and the variability of the NAO include pure observational studies, mainly based on reanalyses, bringing forward new knowledge on extratropical storm tracks, heat transport variations and links between Eurasian snow cover and wintertime NAO.

Boer (2000a) distinguishes three major categories of model evaluation: the morphology of climate, including spatial distributions and structures of means, variances and other statistics of climate variables; budgets, balances, and cycles in the climate system; and process studies of climate. In this thesis we have made evaluation studies, using ARPEGE, belonging to the first two categories. The results are contained in five separate manuscripts found in the second part of this thesis:

Paper I: **Downscaling experiments with a global atmospheric model – systematic errors and added value**

Paper II**: Properties of latitudinally directed cyclone tracks in NCEP data and in the ARPEGE general circulation model**

Paper III: **Estimates of poleward energy transport in experiments with a global atmospheric model with different horizontal resolution**

Paper IV: **The potential contribution of autumn Eurasian snow cover to wintertime NAO**

Paper V: **The influence of snow conditions on wintertime extratropical atmospheric variability – a study based on numerical simulations**

Paper I clearly belongs to the first of Boer's categories. The circulation of mid- and high northern latitudes in integrations with ARPEGE for approximately 15 year have here been evaluated. In a control run a standard T63 resolution - horizontal grid distance 2.875 degrees – was used. The other experiments employed higher horizontal resolution: one with T159, which correspond to a grid length of 1.1 degrees, and one with T319, which corresponds to a grid length of 0.5 degrees. In addition, in one experiment high resolution – T319 – was focused to Arctic only, on the expense of lower resolution in the southern hemisphere. In paper I simple statistics, including pattern of climatological means and variances, such as in mean sea level pressure (SLP), are discussed. Since the resolution in some of the experiments has been higher than normal for coupled climate models, the downscaling ability of ARPEGE has also been evaluated.

Paper II also belongs mainly to Boer's first category. Here individual storm tracks have been investigated both in reanalyses since 1950 and in simulations with ARPEGE over the same period. Since temporal variation is included, this study also covers items belonging to category two. Paper II includes observational studies of cyclone tracks in winter, concentrating on the difference between tracks with a track component from south towards north and tracks with a component from north to south. In addition, monthly track statistics in the two classes have been related to dominant teleconnection patterns in the main flow.

Paper III belongs mainly to Boer's second category. Here the total atmospheric energy, the sum of the internal energy, potential energy, latent energy and kinetic energy, from the effective top of the atmosphere to the surface has been considered both in reanalyses and in simulations with ARPEGE for approximately 12 year. The mean meridional energy transport in the atmosphere can be divided into the contribution of mean flow, stationary eddies and transient eddies. In addition, the poleward energy transport in the North Atlantic Oscillation events has also been evaluated for understanding the climate variability in NAO events.

Paper IV and V are studies of temporal variation of wintertime circulation over the North Atlantic as expressed by NAO. Paper IV is an observational study based on reanalyses and snow observations showing links between Eurasian snow cover in autumn and wintertime NAO. Paper V studies the importance of proper snow representation in two ensemble runs from 1972 to 1996 with ARPEGE, for the variability of the wintertime NAO. In this way paper V to a large extent belongs to the second of Boer's categories.

The first part of the thesis gives an introduction to climate models and BCM, with emphasis on the atmospheric part, and an overview of the results of papers I to V. The text is organized in the following sections: Section 2 gives an introduction of the climate BCM coupled model and its atmospheric part ARPEGE in particular. Section 3 introduces dynamical downscaling methods and the simulation experiments used in this thesis. Section 4 gives an overview of the results of the studies. In 4.1 an evaluation of ARPEGE for the tropospheric circulation at mid- and higher latitudes of the northern hemisphere is given for different horizontal resolutions. In addition, the potentials of ARPEGE for downscaling purposes are evaluated. Section 4.2 presents winter latitudinally distributions of storm tracks and the variance and succession of cyclone occurrence both in ERA40 and in experiments with ARPEGE, the relationship between latitudinally directed cyclone tracks and atmospheric teleconnection patterns is also investigated. Section 4.3 evaluates the poleward energy transport in NCEP reanalyses and in simulations with ARPEGE. Section 4.4 discusses the importance of Eurasian snow cover in autumn for wintertime NAO in both observations and simulations. Finally, concluding remarks are given in Section 5. The second part of the thesis contains the separate manuscripts I to V in Section 6.

2 The climate models

2.1 Climate models

Physical climate models are based on the laws of physics expressing that momentum, mass and energy are conserved in the climate system. Discrete numerical representations of these laws allows for computer simulations. Trenberth (1992) describes the underlying physical principles of climate models and how they can be constructed. Global coupled atmosphere-ocean general circulation models (AOGCMs) are the principal tools for simulating the response of the global climate system to increasing GHG concentrations. In its Third Assessment Report, IPCC (2001) concluded that state-of-the-art AOGCMs provided "credible simulations of climate, at least down to subcontinental scales and over temporal scales from seasonal to decadal", and as a class were "suitable tools to provide useful projections of the future climate" (McAvaney et al., 2001). The separate components - models of the atmosphere (AGCMs), ocean, cryosphere, and land surface - are interactively coupled via exchange of data across the interfaces between them.

Uncertainty

IPCC (2001) identified the following primary sources of uncertainty in future climate scenarios based on AOGCM projections: uncertainties in emissions scenarios of GHGs and aerosols; in conversion of the emissions to atmospheric concentrations and to radiative forcing of the climate; uncertainties in the global climate responses – calculated by different AOGCMs – to different radiative forcings; and uncertainties due to inaccurate representation of regional and local climate. The selection of climate scenarios for impact assessments is always controversial and vulnerable to criticism (Smith et al., 1998). Mearns et al. (2001) suggested that climate scenarios should be consistent with global projections at the regional level (i.e. projected changes in regional climate may lie outside the range of global mean changes, but should be consistent with theory and model-based results); be physically plausible and realistic; provide a sufficient number of variables and appropriate temporal and spatial scales for impact assessments; be representative, reflecting the potential range of future regional climate change; and be accessible.

Climate drift and flux correction

Owing to interaction between ocean and atmosphere, a climate simulated by an AOGCM-is less constrained than climates simulated by atmospheric or oceanic general circulation models (AGCMs or OGCMs). A climate simulated with a coupled model typically undergoes a large coupling shock in the beginning of simulations, which means a fast climate drift due to imbalances in the initial conditions between the atmospheric part and the oceanic part. A near balance between the two components might be obtained after short time. However, a gradual slow drift – typically for periods longer than 100 years - from the observed climate towards the model's equilibrium climatic state might take place. Large drifts can potentially distort the behavior of various feedback processes present in the climate system and in this way destroy the calculated climatic response to a given climate forcing.

Intercomparison projects

In Model intercomparison projects (MIPs) the ability of different models to simulate current and perturbed climates is compared in order to identify common deficiencies. This activity stimulates further investigation into possible causes of the deficiencies (Boer, 2000a, b). In MIPs, models of the same class (AOGCMs, stand-alone AGCMs or oceanic GCMs, RCMs) are run for the same period using the same climate forcings. Different subprojects have been established concentrating on analyses of specific variables, phenomena, or regions.

2.2 The atmospheric part of climate models

The atmospheric component of AOGCMs – denoted AGCMs - enables simulation of the evolution with time of atmospheric states expressed by the mentioned dependent variables. This is done by some kind of numerical treatment of the basic equations. Discretised equations are solved on a fast computer from an initial state to find future states. This is done at small fixed time intervals – time steps - that typically vary from a few minutes to tens of minutes, depending on the method used and the resolution. The solution gives a simulation of the atmospheric state expressed by the dependent variables, together with other parameters diagnosed from these variables, such as clouds and precipitation. The models might be spectral, where parameters are represented as a sum of several waves, such as Fourier component along latitudes and Legendre polygons along longitudes. It could also be a grid point model, where the parameters are defined in grid points covering the globe for various levels of the atmosphere. AGCMs are normally operated on grids with a horizontal spacing of 200 to 300 km and 15 to 30 vertical levels.

Physical processes

An important task is the simulation of the basic physical processes that take place in the atmospheric and determine many of the feedbacks for climate change. Examples include the representation of clouds and radiation; convective processes; the formation of precipitation as rain or snow; the interactions between the atmosphere and the mountains; and atmospheric boundary-layer processes. Because these processes take place on scales much smaller than the model grid, they must be represented in terms of the dependent large scale variables in the model. This activity is called parmeterisation. Generally, AGCMs have difficulties with proper representation of turbulent mixing processes found in the atmospheric planetary boundary layer (ABL). This might have implications for the representation of boundary-layer clouds (IPCC, 2001).

Representation of the stratosphere

AGCMs usually concentrate on tropospheric processes and the effects of stratospheric processes on the troposphere. Descriptions of stratospheric processes are less satisfactory. Insufficient vertical resolution in the stratosphere often prevents AGCMs from proper representation of stratospheric phenomena, such as sudden stratospheric warmings (Takahashi, 1999). The atmospheric photochemical processes are today simulated with chemical transport models (CTMs) that use prescribed atmospheric variables from observational data or from GCM simulations. CTMs can be used to study the evolution of the atmospheric content of ozone, greenhouse gases and aerosols (Austin et al., 2003).

Atmospheric processes on higher latitudes

Key atmospheric processes for higher latitudes include the representations of the planetary boundary layer, clouds, and radiation. The ABL in the Arctic differs significantly from its mid-latitude counterpart, so parameterizations based on mid-latitude observations might perform less well in the Arctic. Parameterizations of the surface fluxes, usually based on the Monin-Obukhov similarity theory, work reasonably well when the vertical stratification of the atmosphere is weakly stable. When the stratification becomes very stable, common for large parts of Arctic, the simulated surface fluxes of momentum, heat, and water vapor are too small (Poulus and Burns, 2003). Turbulence may then not fulfill assumptions used in ABL parameterizations: that is should be stationary, local, and continuous (Mahrt, 1998).

Vertical resolution is a critical issue in Arctic, and the vertical discretization of current AGCMs have problems in resolving the large temperature gradients and inversions that exist in the arctic ABL. Simply increasing the resolution will not always solve the problem since a fundamental problem remains in current method to predict too small turbulent fluxes. Comparison of ABL fluxes with observations clearly indicates a need for improvements in the parameterization of surface energy exchange (Dethloff et al., 2001). Specific cloud types observed in the arctic ABL present a serious challenge for atmospheric models. Parameterizing low-level arctic clouds is particularly difficult because of a complex radiative and turbulent interaction with the surface (e.g., Randall et al., 1998).

2.3 BMC and ARPEGE

A number of AOGCMs have been developed more or less independently at major centres for climate research throughout the world. IPCCs forth assessment report, due to come in February 2007, will include simulations from many different AOGCMs. Each model has been run to cover climate variation since 1880 and future projections towards year 2200 according to different emission scenarios prepared by IPCCs. One of these models is the Bergen Climate Model developed at the Bjerknes Centre for Climate Research in Bergen, Norway (Furevik et al. 2003). As already mentioned, the atmospheric part of BMC is

ARPEGE/IFS is a spectral model which was originally developed for weather prediction by Météo-France and ECMWF, (European Centre for Medium-Range Weather Forecasts; Courtier et al. 1991), and later extended to a climate version by Déqué et al. (1994). Descriptions of later model improvements can be found in Déqué and Piedelievre (1995) and Déqué et al. (1994).

The spectral ARPEGE model applies semi-Lagrangian two-time level time integration. This scheme provides a doubling of efficiency as compared with a three-time level leapfrog scheme. The semi-Lagrangian formulation also gives the opportunity to use a linear grid for discrete computations. As the number of grid points are smaller in the linear grid than in the more common quadratic grid, this saves additional computational costs (Hortal 1998). In Furevik et al. (2003) a spectral truncation of wave number 63, linear grid and a time step of 1800s were used. The linear T_L63 grid has the same number of points as the quadratic T42 grid. The acceleration of gravity depends on latitude and height. The model atmosphere is a mixture of air, water vapour and an optional number of dynamically passive constituents. The energy sources and sinks in the equation system described arise from discretisation and horizontal diffusion. Sources and sinks due to small-scale physical processes are parameterised. The grid-boxes are defined by the computational grid, consisting of the points at which the non-linear terms in the equations are calculated (linear grid). This is a latitude/longitude grid, which in the T_L63 case has 64 nearly equidistant latitudes. The reduction of the grid near the poles (Hortal and Simmons 1991) gives approximately uniform horizontal resolution. The vertical hybrid coordinate (Simmons and Burridge 1981) follows the topography in the lower troposphere, but becomes gradually parallel to pressure surfaces with increasing height. For the experiments presented in Furevik et al. (2003), 31 model levels, ranging from the surface to 10 hPa were used.

The physical parameterisation is divided into several explicit schemes, which in turn calculate the flux of mass, energy and/or momentum due to a specific physical process. The physical parameterisation schemes in ARPEGE were originally taken from the climatic version of Météo-France's EMERAUDE model, described in Coiffer et al.

(1987). Unlike the model description in Déqué et al. (1998), the particular version used in BCM contains a convective gravity-wave drag parameterisation (Bossuet et al. 1998), a new snow scheme (Douville et al. 1995), an increase of the orographic wave drag (Lott 1999) and modifications in deep convection and soil vegetation schemes.

Radiation

In their control run for 300 years with no additional radiative forcing – constant forcing from the sun - Furevik et al. (2003) made thorough comparison of the model climatology with available data sets bases on observations. It was found that the model simulated the annual globally averaged total cloud cover fairly well. In addition, both annual and monthly zonal averages agreed well, with monthly biases being less than 15% at all latitudes except for the polar areas during summer, where the model overestimated the cloud cover. This feature is seen in several GCMs (Beesley and Moritz 1999). Global averages of net top-of-atmosphere (TOA) longwave and shortwave radiation was found to be well simulated and within the error estimates of the satellite observed values (Rieland and Raschke 1999). The simulated net cloud radiative forcing was estimated to –23.7 Wm^{-2}, which is within the range of the ERBE and NIMBUS-7 estimates (Kiehl et al. 1994; Ardanuy et al. 1991). The global longwave cloud forcing was estimated to 32 Wm^{-2}, which also is close to the ERBE estimate of 30 Wm^{-2} reported by Kiehl et al. (1994). The meridional distribution of the TOA net outgoing longwave radiation (OLR) was also realistically simulated compared to the ERBE data (Harrison et al. 1990; Barkstrom 1984). The largest difference compared to the ERBE data was found in the Southern Hemisphere mid-latitudes during JJA. In the tropics, OLR was found to be too high in DJF and MAM. In the Arctic winter the OLR was too high due to too large cloud amounts absorbing the LW radiation from the colder surface and re-emitting at higher temperatures. Simulated global TOA average shortwave cloud forcing was 6 Wm^{-2} higher than the estimates of Kiehl and Trenberth (1997).

Precipitation

Global annual average precipitation was found to be close to climatological estimates with 3.10 mm day^{-1} compared to 3.05 mm day^{-1} from the CMAP data (Xie and Arkin

1997). Precipitation is a difficult field to observe and the zonal mean climatologies may differ by as much as 40% in the tropics, but in general the model zonal mean distribution showed a similar pattern as the observations. However, the amplitude of the second maximum in the South Pacific (the South Pacific Convergence Zone) seemed to be too high and situated too far south, a feature shared with many other AOGCMs (Covey et al. 2000). Monthly differences between the BCM simulation and the climatological datasets showed that the largest differences in the tropics are related to the MAM season where the model underestimated the precipitation both compared to the CMAP (Xie and Arkin 1997) and the GPCP (Huffman et al. 1995) climatologies. There was also found an incorrect location and possibly an overestimation of the precipitation maximum in JJA related to the simulated width and the strength of the rising branch of the Hadley cell. Net freshwater fluxes over the ocean were compared to estimated values of da Silva et al. (1994) and Oberhuber (1988). Both datasets are based on the Comprehensive Ocean–Atmosphere Data Set (COADS) (Woodruff et al.1987). Evaporation is estimated using bulk formulas in both cases. In the da Silva dataset the precipitation was derived from Present Weather (PW) information of standard ship reports (Tucker 1961; Dorman and Bourke 1978), while the Oberhuber dataset was based on land and island station records complemented by satellite observations (Shea 1986). The climatological estimates diverged polewards of 60°N/S. This was found to be mainly due to the rather unrealistic precipitation estimates in the da Silva dataset, which differs significantly from other precipitation climatologies in these regions. The simulated average zonal patterns in the net freshwater flux agreed well with the climatologies. The monthly mean differences in freshwater fluxes between the Oberhuber climatology and the simulations showed to a large extent the same pattern as the precipitation comparison. In MAM, the underestimation of precipitation in the equatorial belt leads to an underestimation in the freshwater flux in the same area. The overestimation of tropical precipitation in JJA was associated with the model's representation of the rising branch of the Hadley cell.

Circulation

The simulation reproduced the annually averaged meridional circulation with fairly realistic positions and values of the Hadley, the Ferrel and the polar cells. The Hadley cells were, however, slightly broader than in the reanalysis and the annual mean strength was overestimated by 10–30% compared to the NCEP estimates. The overestimation was largest in winter. The DJF Ferrel cells were well positioned in both hemispheres, but the strength of the cell in the Northern Hemisphere was overestimated. A significant overestimation is seen in the Hadley cell in JJA, The positioning of the JJA cell was fairly good, but slightly broader than in the reanalysis. The positioning and strength of the subtropical jet-streams were well simulated both in DJF and JJA with errors in the order of 2 ms^{-1}. However, there were some errors in the simulation of the lower stratospheric jets. This was related to substantial errors in the horizontal temperature gradients in the same area, a feature that may be due to too low vertical resolution in the lower stratosphere. The general impression of the simulated zonal mean temperature structure was that it was in good agreement with the reanalyses. Both seasonal and spatial variations were well captured. There were, however, some disagreements. The stratosphere was too cold and the horizontal temperature gradients between the poles and equator too weak. This was consistent with the weak stratospheric model jets.

Interannual variability

Interannual variability was investigated in terms of the two strongest natural modes of variability of the global climate: the El Niño-Southern Oscillation (ENSO) and the North Atlantic/Arctic Oscillation (NAO/AO). Both of these modes of variability can be detected in a wide range of variables. The focus the analysis by Furevik et al. (2003) was on SLP and 2 m air temperature (T2m) fields. They found that the ENSO mode was well simulated in BCM, we will here concentrate on the NAO/AO mode.

The winter (DJFM) mean SLP anomalies, regressed upon the principal component of the leading mode of winter mean SLP variability calculated for the region northwards of 20°N was computed for the BCM and NCEP data. The leading mode is the well known NAO/AO dipole pattern, where anomalous high pressure in the subtropics is associated with anomalous low pressure over the Nordic Seas and Arctic Ocean. The main discrepancy between the BCM and NCEP results was that the negative centre of action in the BCM was too far west, and did not have the pronounced trough into the Nordic Seas seen in the NCEP data. This is consistent with the storm tracks being too zonal in this area. The mode explained 32% of the winter mean variability for both the BCM and NCEP data. For the leading mode calculated from the monthly means, the corresponding figure was 18%, again for both model and observations.

The correlations between the first principal components calculated from the SLP and T2m data were 0.68 and 0.85 for the BCM and NCEP winter data, and 0.60 and 0.66 for the monthly data, respectively. Thus there was slightly weaker correlation between the SLP and T2m pattern in the BCM than what is found in the NCEP data.

3 Dynamical downscaling methods and simulation experiments

3.1 Dynamical downscaling methods

As mentioned, AOGCMs constitute the primary tool for simulating the global climate system. They are also the main tool to study the processes responsible for maintaining the general circulation and natural variability, and its response to external forcing. Since there is a need to integrate the complex, computer-demanding AOGCMs for many centuries, horizontal resolutions of the atmospheric components of the AOGCMs range from 400 km to 125 km, with 300 km a typical value.

Dynamical downscaling is achieved through high-resolution numerical climate models for the atmosphere that use needed boundary conditions from AOGCM simulations or from observations. The models are atmosphere-only climate models, of uniform or variable horizontal resolution, and nested regional RCMs. Dynamical downscaling models have the potential to describe mesoscale nonlinear effects and extreme values of parameters such as surface wind and precipitation. Confidence in these methods to realistically downscale future climates comes from their ability to reproduce widely varying climates around the world with the same model.

AGCMs

AGCMs are run with finer meshes than the AOGCMs. They might include similar interactive land-surface processes as in AOGCMs, but SST and sea-ice are prescribed by interpolation of results from AOGCMs or from observations (analyses) when present day or historic climate is simulated. A resolution of 100 km is the present standard, less than 50 km will be likely in the near future (Déqué and Gibelin, 2002; Govindaswamy, 2003). Some computers, in particular the Japanese Earth Simulator, now allows for even higher resolutions (Yoshijaki et al., 2005)

Downscaling results using AGCMs with typical resolution agrees better with observations than current AOGCMs, i.e. the systematic errors in the atmosphere are reduced. A notable improvement is better description of extratropical and some extent even tropical cyclones. Since the topography and coastlines are better resolved, the mountain flows, e.g. orographic precipitation, become more realistic. The effect of increased resolution might, however, vary significantly with region (Duffy et al., 2003).

RCMs

In the regional climate models (RCMs) time-varying atmospheric fields (winds, temperature and moisture) are supplied as lateral boundary conditions, and SST and sea-ice are supplied as lower boundary conditions. If the integration area is relatively small, the lateral boundary conditions exert sufficient control to keep the large-scale flow consistent with the driving large-scale atmospheric circulation. Details of the regional climate are obtained as a result of better resolution, combined with suitable parameterisation of subgrid-scale physical processes and improved surface forcings from orography, land-sea contrast and land use. The first to demonstrate successful results were Dickinson et al. (1989) and Giorgi and Bates (1989). Recently a two-way nested RCM has been developed (Lorenz and Jacob, 2005) that allows feedback from the RCM onto the larger scales. RCMs are now being coupled interactively with other components of the climate system, such as regional ocean and sea ice (e.g., Maslanik et al., 2000; Döscher et al., 2002; Rinke et al., 2003; Debernard et al., 2003; Schrum et al., 2003; Meier et al., 2004; Rummukainen et al., 2004). Using reanalyses of the atmosphere Vidale et al. (2003) have shown that RCMs have skill in reproducing interannual variability in precipitation and surface air temperature. Typical RCM grid distance for climate-change projections is around 50 km, although some climate simulations have been performed at higher resolutions, with meshes such as 20 km. Since the ability of RCMs to simulate the regional climate depends strongly on the realism of the large-scale circulation that is provided at the lateral boundary conditions (e.g., Pan et al., 2001; de Elía et al., 2006), reduction of errors in AOGCMs remains a priority for the climate modelling community.

Approaches towards downscaling with coupled models

The Arctic climate is complex due to numerous nonlinear interactions between and within the atmosphere, cryosphere, ocean, and land. Sea ice plays a crucial role in the

Arctic climate, through the albedo-temperature feedback and feedbacks associated with the heat flux through the ice and with clouds. In both models and observations, the interannual and decadal climate variability has a maximum in high latitudes (Räisänen, 2002; Johannessen et al., 2004; Bengtsson et al., 2004; Sorteberg and Kvamstø, 2003). The complexity of Arctic climate includes many processes that are still poorly understood and thus continue to pose a challenge for climate models (ACIA, 2005). In addition, the evaluation of simulations in the Arctic is made more difficult by few available observations, and different data sets might differ considerably (Serreze and Hurst, 2000; Liu et al., 2005; Wyser and Jones, 2005; ACIA, 2005). One example is precipitation measurements which are notoriously problematic in cold environments (Goodison et al., 1998; Bogdanova et al., 2002).

Because of large errors in AOGCMs, the value of traditional dynamical downscaling, using atmospheric models only, has been questioned (e.g. Rinke and Dethloff, 2000). Some research communities have developed limited area coupled models with particular emphasis on interaction through sea-ice. The main goal with these developments is to get at a better representation of sea ice than in global climate models. The models are still in their infancy, and successful decadal integrations for present day climate, showing increased climate information for Arctic compared to downscaling with a atmospheric model only, have not yet been demonstrated. The models are of course computationally very expensive. Coupled global climate models like BCM, offer an alternative to limited area coupled models since both resolution might be focussed for both atmosphere and ocean. There is also a possibility to relax the regional results to reanalyses, ocean climatology or other global patterns that are available.

3.2 Simulation experiments

Four experiments have been made with the same model configuration, same number of vertical layer, but with different resolution in Paper I to III:

1. Experiment T63, which is run with linear grid T63 corresponding to a grid distance of 2.8°. This resolution is the standard resolution used for BCM, e.g. in control runs without external forcing (Furevik et al. 2003). T63 is run for 47 years starting 24 January 1950, i.e. longer than for the other experiments. However, the results of the experiments are shown for a period of 15 years starting 24 January 1978.

2. Experiment T159, which again means a run with linear grid T159 corresponding to a grid distance of 1.1°. T159 is run for 13 years stating 24 January 1978.

3. Experiment T319, a run with linear grid T319 corresponding to a grid distance of 0.5°. T319 is run for 11 years starting 24 January 1978.

4. Experiment T159S where the coordinates are stretched to that of T319 in Arctic on the expense of lower resolution, T42, over Antarctic. T159S is run for 15 years starting 24 January 1978. The number of grid points is the same as in T159. The stretching is given by a stretching factor of 2.0, which in our case means that grid distance increased from 0.5° in Arctic to 1.5°.

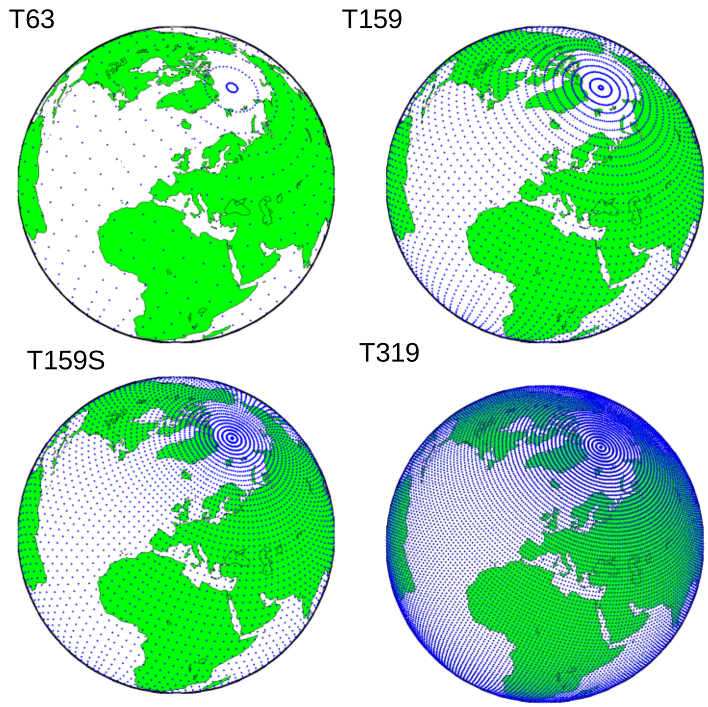

Figure 1. Distribution of grid points horizontally in the different experiments.

The distribution of the grid points in the different resolutions is shown in Figure 1 for the northern hemisphere north of 30°N. The results are compared to ERA40, which is available in T159 corresponding to a grid length of 1.1°. Although the length of the experiments varies a little, we make mean values over the integrated period and compare with means from ERA40 over 15 years (starting 24 January 1978).

Another experiment has been done to find the links between Eurasian snow cover in autumn and wintertime NAO in Paper IV and V:

In order to reproduce climate variability during last several decades and to explore the large-scale atmospheric response to improved snow conditions, we have generated two ensemble simulations (Table 1). The first ensemble of simulations is a control ensemble named CTL, in which boundary conditions (e.g. vegetation and its roughness length, deep soil temperatures, land ice extent and surface emissivity) are set to climatological values everywhere over land. Over sea observed interannual variation for SST and sea ice is used, and prescribed monthly global SST fields from 1972 to 1997 are employed as the major source of boundary forcing. The SST data is provided by a blend of two reconstructed datasets from GISST (Global sea Ice and Sea Surface Temperature) from 1950 to 1982 and from 1983 to 1997 respectively (Reynolds and Smith, 1994). Moreover, the latest dataset is constructed from both in situ and satellite observations using an optimum interpolation technique. Snow amount evolves freely in the model integrations of the ensemble CTL.

In the second ensemble, named SNS, the integrations are run with the same global distribution of observed SST and sea ice, but the representation of snow amount is different. In order to keep consistency and to decrease the chance of changing the model energy, the climatological snow amount, used in the mentioned proportional relationship, is derived from the control ensemble. The monthly snow mass in northern Hemisphere is then constructed from the observed snow cover by using the proportional relation. One advantage for doing this is no consideration about the variation of model snow density due to precipitation, snowmelt and sublimation when snow mass is constructed. Another advantage from using the proportional relation is that it is possible for the model to keep the information on the temporal variability of observed snow cover during the integrations. The daily snow forcing, by temporal interpolation in SNS, is put into the model every five days after 1972, and the snow is allowed to evolve freely in the ISBA scheme for the subsequent time periods until new forcing is inserted. The characteristics of the new snow conditions are explored in the next section.

Each ensemble consists of 5 independent realization members with slightly different initial conditions. The integration period is 1972-1997. Outputs of ensemble means spanning the whole period are considered.

GCM simulation	SST specification	Snow specification	numbers	period
CTL	observed	free	5	1972-1997
SNS	observed	fixed	5	1972-1997

Table 1: Design of the two simulation ensembles CTL and SNS

4 Scientific results

4.1 The tropospheric circulation at mid- and higher northern latitudes

It has been shown that an increase in the horizontal resolution from T63 to T159 improves the general circulation in the area investigated. The structure of the Icelandic and Aleutian Lows is improved, in particular the extension of the Icelandic Low over the Norwegian Sea towards the Barents Sea. The storm tracks, evaluated from band-passed standard deviations related to extratropical cyclones, are also improved and in accordance with the improvements in the mean structures. In particular, the storm tracks in Arctic and towards Arctic become more realistic. The main reason for the improvements seems to be that individual cyclones are better resolved with T159 than with T63. Further increase in the resolution to T319 gives some further improvements, primarily in flows over mountains like Greenland. Nevertheless, the main progress was achieved going from T63 to T159.

The experiments clearly demonstrated that some weaknesses in ARPEGE become more apparent when the resolution is increased. Compared to the reanalyses ERA40, the model showed excessive mid-latitude baroclinicity in all the experiments, e.g. upstream of the Icelandic Low. Better resolution of the individual cyclones resulted in too deep mean low systems, in particular the Icelandic Low. The strengthened baroclinicity naturally also contributed to stronger mid-latitude jets than in ERA40 and excessive storm tracks towards northern Europe on the expense of too little activity up the Norwegian Sea. However, better resolution gave some improvements in the excessive westerlies and in the storm tracks in the area.

Increased resolution improved the structure and the shape of the Arctic Ridge extending from the Siberian High over Arctic towards the ridge over Rocky Mountains. In addition the variability, as expressed by band-passed filtered standard deviations focussed on synoptic activity, was increased and improved. Nevertheless, a warm bias in Arctic was found causing too low amplitudes of the ridge. Some of the errors were found to be due to problems with the inversions and surface temperatures, some was due to a warm bias in tropospheric layers above the inversions. We have suggested that the latter bias might also be a consequence of the problems with Arctic inversions.

4.2 The distribution, variance and seriality of storm tracks

Cyclone tracks that occurred in the northern hemisphere during 47 extended winters (1950/1 - 1997/11) has been identified by means of an objective tracking method (Hodges 1995, 1996). The tracks (Fig. 2) have been divided in two classes, one with northward moving cyclones and a second with southward moving cyclones. The criteria for this selection are that a cyclone track crosses any longitude section from either side (south or north). In both cases mean number of occurrence, variance and seriality (succession of cyclone occurrence) at a grid point level have been investigated. Corresponding cyclone track datasets have been derived from a simulation with the ARPEGE model, forced with observed monthly SSTs from 1950 – 1997. The diagnostics listed above have been computed from the model dataset and compared diagnostics based on reanalyses.

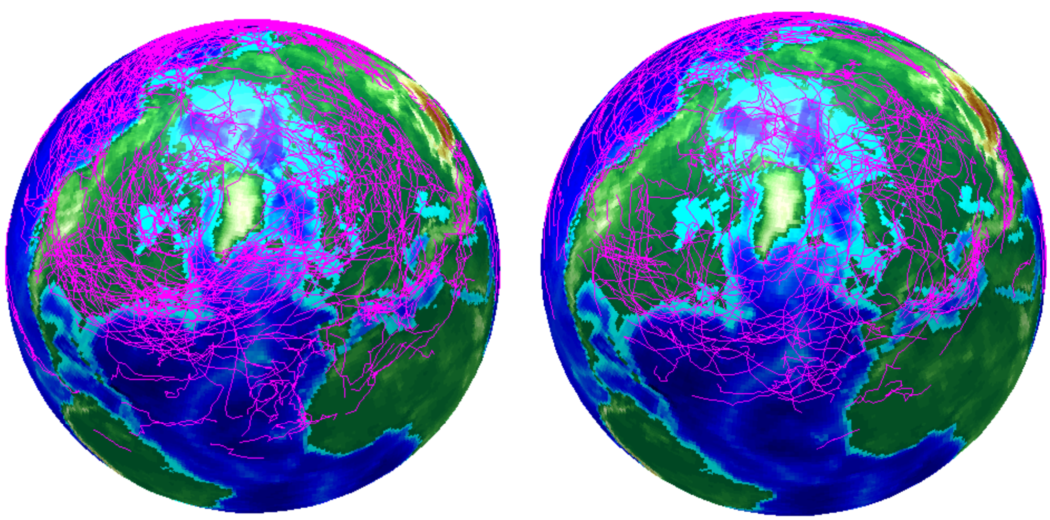

Figure 2. Storm tracks during DJF in 1999 (left), positive NAO year, and 1968 (right), negative NAO year.

The link between the monthly cyclone counts and the large-scale circulation, represented by the ten leading rotated principal components of monthly geopotential at 500hPa was investigated. It was found that the NAO does not have as dominating influence in determining the cyclone count variability as could be expected on basis of earlier literature. Namely, four additional patterns are actively affecting cyclone occurrences in various regions in the North Atlantic and European sector. These are the Eurasian pattern, the Scandinavian pattern, the East Atlantic/West Russian pattern and Polar Eurasian pattern. The details presented in the result section show that the south-northward cyclone behaviour's link to the larger scales to some extent in agreement with findings in Mailier et al. (2006) where east-westward cyclones were investigated.

4.3 The poleward energy transport

Atmospheric modeling provides an opportunity to reveal the mechanisms of heat transport (Fig. 3). Knowledge of observed meridional energy transport in the atmosphere can also be used in the evaluation of AGCMs. It is vital to represent the energy variation and keep energy conservation well in the AGCMs.

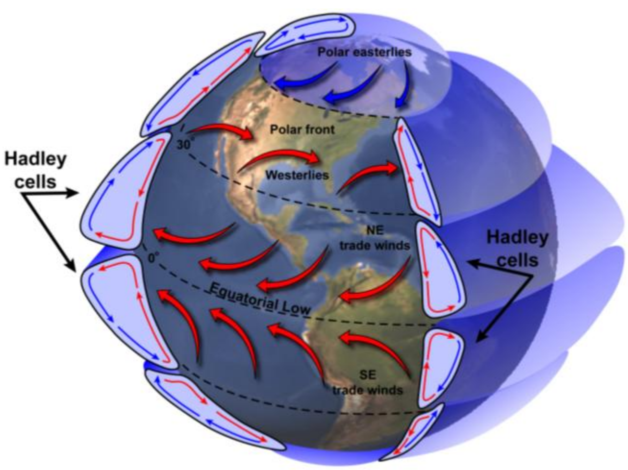

Figure 3. Illustration of global atmospheric circulation

The poleward total energy transport in high resolution experiments has a better agreement with NCEP reanalysis data at mid and high northern latitudes than in low resolution experiment. This is also found for poleward dry static energy transport and latent heat transport components. The poleward total energy transport in low resolution experiments is however closer to NCEP data in tropics. The energy transport by stationary eddies in higher resolution experiments agrees well with NCEP data. The higher amplitude of energy transport by transient eddies in higher resolution experiments is associated with simulating stronger baroclinic activity at mid-latitudes.

The time series variability of total northward energy transport in the northern hemisphere is better represented in higher resolution experiments than in the T63 experiment. Although there is a declining trend of total energy transport over north hemisphere in NCEP, it is hard to say there is less and less energy transported poleward. Hence we need longer time series to make it meaningful to study global warming. The energy transported into Arctic in higher resolution experiments is more closer to NCEP data, the T63 model transmit northwardly much less energy into Arctic, this is opposite to the situation of T63 above. There is a rising trend of northward energy transport at 70 °N latitude from 1991 in observation.

The poleward energy transport is less at low latitudes and higher at mid-high latitudes over north hemisphere during positive NAO events than that during negative NAO events. This is mostly contributed by dry static energy transport and stationary energy transport. As the impacts of NAO on precipitation over Europe, the distribution of evaporation and precipitation is consistent exactly with the transport and convergence of atmospheric moisture.

4.4 Links between Eurasian snow cover in autumn and wintertime NAO

There is a relationship on the basis of SVD analysis that the extensive (deficient) snow cover over large areas of Northern Europe and Siberia in October heralds the negative (positive) DJF NAO. When the Eurasian snow cover extent is anomalously high in October, it is driven simultaneously by the upstream meridional circulation at mid- and high latitudes, and the subsequently atmospheric dynamical evolution is important for the wintertime negative NAO. Under conditions with less than normal Eurasian snow cover, the possible response of the positive NAO to Eurasian snow is mainly through the persistent thermal heating over Siberia in lower troposphere and the enhanced effect of Polar/Eurasia teleconnection pattern on the circumpolar vortex.

Simulation experiments with realistic snow forcing indicate that a significant negative correlation exists between wintertime thermal variation over the Azores High and Eurasian snow cover in autumn, but no similar correlation is found for the Icelandic Low. This indicates that snow variation over Eurasia can influence the wintertime NAO through modulation of the Azores High on a seasonal time scale. Extensive Eurasian snow cover in autumn heralds the negative wintertime NAO, and vice versa. In addition, while anomalies in SST influence quasi-decadal NAO variability, it is found that the variability of the NAO on shorter time scales (2-4.5 years) is clearly modulated by realistic interannual snow forcing, mainly through variation in the Azores High.

5. Summary and concluding remarks

In this thesis we have evaluated different simulation experiments with the atmospheric general circulation model ARPEGE, which is the atmospheric part of the coupled climate model BCM developed at BCCR. Observed SST and sea ice, included in reanalyses, have been used for forcing from the sea surface. The evaluation of the model has been made from comparisons of model results against similar results from reanalyses of daily atmospheric states of the atmosphere, partly reanalyses from NCEP available for more than 50 years and partly reanalyses from ECMWF available from 1958. The evaluation has been concentrated to mid- and higher northern latitudes in winter.

Results from observational studies

The studies have included some pure observational studies, which partly have served as a standard for which model experiment results have been evaluated against.

An observational study was included in paper II and dealt with two classes of storm tracks: one with northward moving extratropical cyclones and one with southward moving cyclones. In both classes mean number of occurrence, variance and seriality – which means succession of cyclone occurrence - were investigated. The winter mean distribution of northward moving cyclone transits in NCEP reanalyses was found to resemble the corresponding distribution of eastward cyclone transits shown in recent literature. This was also the case for variability of monthly counts during winter. Northward moving cyclones in the Pacific and Atlantic storm tracks were found to have a regular seriality in the westernmost parts, while time clustering of the cyclones was found in central (Pacific) and eastern (North Atlantic) parts. Monthly cyclone counts were compared with large-scale circulation represented by the ten leading rotated principal components of monthly geopotential at 500hPa. It was found that the NAO does not have as dominating influence in determining the cyclone count variability as could be expected from earlier literature. Four additional teleconnection patterns were also found to actively affect the cyclone occurrences in various regions in the North Atlantic and European sector. Also in this respect, similar behaviour was found for northward cyclone transits and eastward moving cyclones.

In paper III the energy transported poleward is less at low latitudes, but higher at mid-high latitudes over north hemisphere during positive NAO events than that during negative NAO events, this is mostly contributed by dry static energy transport and stationary energy transport. As the impact of NAO on precipitation over Europe, the distribution of evaporation and precipitation is consistent exactly with the transport and convergence of atmospheric moisture.

The influence of autumn Eurasia snow cover on the subsequent winter NAO was investigated in paper IV. It was found that the extensive (deficient) snow cover over large areas in Eurasia in October heralds the negative (positive) DJF NAO, a result also found by others. It was evident that the thermal cooling effect associated with early seasonal extensive Eurasian snow did not start in October, but was found to take place first in December. On the other hand, the surface warming over Siberia in years with less snow through snow-albedo feedback was found to act as a diabatic heating source to the lower troposphere from October to November. The main dynamical atmospheric response from an extensive autumn Siberia snow cover to a wintertime low NAO index was in this way found to be quite different in character from the response in years with less snow leading to a relative high NAO index.

In paper V it was found that periods of the NAO index between two and four years are associated with early season Eurasian snow cover. For those periods the NAO index was correlated with atmospheric anomalies over the Azorean High. On the contrary, no evidence was found for such a consistency for the Icelandic Low. This implies that the variability of the NAO on shorter time scales seems to be modulated by interannual snow forcing mainly through the variation of the Azorean High.

Model evaluation results

While better horizontal resolution in ARPEGE to a considerable extent improved the general northern mid- and high latitude tropospheric circulation, higher resolution also revealed some weaknesses in the model. The problem with excessive mid-latitude westerlies, common for several AGCMs, was found to be related to a too strong mid-latitude tropospheric baroclinicity, e.g. upstream of the Icelandic Low. The increased baroclinicity was believed to be connected to errors in the Hadley Cell which, in agreement with Furevik et al. (2003), was found to be too broad with an extension too far to the north. Excessive sinking of the air at the northern part then gave too high temperatures in the lower troposphere, contributing to stronger baroclinicity further north.

With resolution T63 the Iclandic Low was nearly correct despite too strong baroclinicity. With higher resolution on the other hand, too strong baroclinicity seemed to result in a too strong Iclandic Low. It was indicated that with the lowest resolution (T63), the individual extratropical cyclones will often be too shallow due to lack of resolution, and that this gives a reasonable explanation of the nearly correct Icelandic Low in this case. Resolution T159 and higher, on the other hand, gives a more realistic development of the individual cyclones. With too strong upstream baroclinicity, the Icelandic Low then became too deep because of too frequent and too strong cyclogenesis.

The studies of the tracks of the extratropical cyclones in winter revealed that the number of cyclones was systematically lower in simulations with ARPEGE - resolution T63 – than found in the NCEP reanalyses. In addition, the influence of modes in the large-scale flow on these cyclone count variability found in the reanalyses, was absent in the simulations with ARPEGE. In paper II it was speculated why a realistic climate could be maintained despite the clear shortcoming of the cyclone track climatology. It was suggested that that individual low pressure systems in the model are more efficient than the real ones in transporting energy polewards. If not, a larger part of the energy transport towards north must be provided by the quasi-stationary waves in the model than observed, this is illustrated in paper III. Cyclone track statistics of the same kind as in paper II have not yet been investigated for higher resolution experiments. However, standard track statistic based on the Blackmon method, which does not follow individual cyclones, improved the storm tracks considerably when higher resolution was used. We believe that at least some of the problems found for the cyclone track statistics using ARPEGE are connected to large systematic errors in simulating the individual lows using a low resolution like T63. This indicates that standard resolution of coupled climate models should clearly be higher than used today; a resolution at least similar to T159 seems to be needed to get realistic storm track statistics.

In addition to problems in simulating the right level of baroclinicity and right climatology of extratropical cyclones, problems were revealed in simulation of the inversions in Arctic and the variability of snow cover over Eurasia. It has earlier been shown by Byrkjedal (2006) that increased vertical resolution in simulation with ARPEGE and horizontal resolution T63, improves the simulation of inversions in Arctic. In this thesis it was demonstrated that the same was obtained with increased horizontal resolution. However, as earlier indicated, fundamental problems remain in parameterisation of ABL (atmospheric boundary layer) turbulence in strongly stratified air and low-level clouds frequently found in Arctic. The problem with unsatisfactorily representation of the variability of the snow cover also remains.

Model improvements needed

Better resolution in the experiments in paper I gave some improvements in the systematic errors in the westerlies and the baroclinicity and simulation of the Arctic circulation. However, the excessive Icelandic Low clearly demonstrated that severe systematic errors remain in the simulations of the extratropical lows. The reasons behind are probably very complex, since they involve structures like the Hadley Cell, where parmetrisation of deep convection is very important, and effects of mountains, where parameterisation of unresolved gravity drag is the main problem. Evaluation of experiments like those performed in this thesis are in several ways important, but probably more important is extensive work to improve parameterisations of vital sub-scale processes in the model, a task normally too extensive for a doctor student alone. A research group within BCCR on improvements of the atmospheric part of BCM is highly recommended. Extensive cooperation with institutions like Météo-France and ECMWF will then become even more important. In such a co-operation, it might be a good idea for BCCR to concentrate on the parameterisation of physical processes in Arctic.

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