

Danish Climate Centre Report 07-02

Regional climate change for Greenland and surrounding seas

Part I: Atmosphere and land surface

Martin Stendel, Jens Hesselbjerg Christensen, Guðfinna Aðalgeirsdóttir, Nicolai Kliem and Martin Drews





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Abstract

We present results of a transient climate simulation for the period 1950 to 2080 using a regional climate model covering Greenland and surrounding seas at a horizontal resolution of 25 km. The report is divided into two parts, the present dealing with aspects related to the atmospheric model, HIRHAM4, including the discussion of surface and sea ice properties. The second part, published as Climate Centre Report 07-04, describes aspects of the ocean component of the coupled model system.

Compared to climate change simulations using global climate models with a horizontal resolution on the order of 150 to 200 km, the regional model projects locally much larger temperature increases of up to 18°C in winter. This is related to the retreat of sea ice, in particular along the east coast of Greenland. Precipitation is projected to increase everywhere with respect to present-day conditions, and a considerably larger percentage than at present is expected to fall as rain rather than snow. This leads to an increase of snow depth in the northern half and a decrease in the southern half of Greenland.

Resumé

Der præsenteres resultater af en transient simulation af Grønlands og omgivende havregioners klima for perioden 1950 til 2080. Modellen blev kørt med en horisontal opløsning af 25 km. Rapporten er delt op i to dele. Den foreliggende behandler den atmosfæriske del af modelsystemet og indeholder en diskussion af forskellige variabler ved jordoverfladen. Den anden del, publiceret som Klimacenterrapport 07-04, beskriver aspekter af ocean-komponenten af det koblede system.

Vi finder lokalt meget større temperaturændringer (op til 18°C om vinteren) end med globale modeller med en typisk opløsning af 150-200 km. Dette hænger sammen med tilbagetrækningen af havisen, specielt ved Grønlands østkyst. Der forventes øget nedbør i forhold til i dag i dag alle steder. En betydelig større andel af denne nedbør vil falde som regn i stedet af sne som i dag. Konsekvensen er en øget snedækte i de nordlige og en reduceret snedækte i de sydlige egne af Grønland.

1. Introduction

Paleoclimatic evidence suggests that the Arctic presently is warmer than during the last 125000 years (Jansen *et al.*, 2007), and it is very likely that the increase in concentration of greenhouse gases in the atmosphere has an effect, which is larger in the Arctic than elsewhere on the globe (Christensen *et al.*, 2007a). In recent years, concerns about the stability of the Greenland Ice Sheet, the fate of arctic sea ice and a possible weakening of the thermohaline circulation under future warming conditions have led to increased research activities, including an assessment of arctic climate and climate change (ACIA, 2005), the fourth assessment report (AR4) of the International Panel on Climate Change (IPCC, 2007) and a large number of research project related to the International Polar Year (IPY).

Assessments of climate variability and change with a focus on the Arctic in general and Greenland in particular have to consider uncertainties related to the paucity of reliable observations and, for projections of future climate, the large natural variability that makes it difficult to detect an anthropogenic climate signal. Further uncertainties are due to the underlying emission scenarios as well as model deficiencies including insufficient horizontal resolution. As the typical resolution of the AR4 models of 150–200 km is hardly adequate to realistically simulate many arctic processes, we present here results from a new transient simulation using a regional climate model (RCM) for Greenland and the surrounding seas with a horizontal resolution of 25 km.

There is considerable short-term (weather) and long-term (climate) variability in the Arctic and in models as well as observations, the interannual variability of monthly temperatures has maximum values at high latitudes (Räisänen, 2002). An assessment of climate variability in the Arctic in general and Greenland in particular is quite complex due to numerous nonlinear interactions across all time scales between atmosphere, cryosphere, ocean, land surface and ecosystems. The most important positive feedbacks are the snow-ice albedo feedback, changes in the duration of time that the atmosphere is insulated from the Arctic Ocean by sea ice and the feedback between permafrost and methane hydrate (CH₄) as well as carbon dioxide (CO₂). Furthermore, huge amounts of CH₄ are stored as methane hydrate on the ocean floor at present. The present approximate equilibrium might become unstable when the ocean water warms, releasing methane into the atmosphere. On the other hand, negative feedbacks can result from enhanced freshwater input increasing the stratification of the upper ocean layers, from a reduction in the intensity of the thermohaline circulation and from a connection between vegetation and CO₂, where increased vegetation results in a reduction of albedo.

Rapid climate change in the Arctic is possible since snow and ice regimes are sensitive to relatively small temperature changes and because of the cold oceans' sensitivity to small changes in salinity, but the large low-frequency variability in atmosphere and ice parameters (Polyakov *et al.*, 2003a,b) makes the detection and attribution climate change in the Arctic difficult. There is evidence that natural multidecadal variability has played a role for the large high latitude warming around the 1930s (Bengtsson *et al.*, 2004; Johannessen *et al.*, 2004) and the subsequent cooling until the 1960s. The sensitivity to changes in temperature and salinity can act to amplify initially small signals and contribute to the large climate variability in arctic regions.

The nonlinearity of arctic climate and the fact that many processes still are poorly understood is a challenge to climate models (ACIA, 2005). A further hindrance is the fact that only few direct observations of arctic climate are available, which makes model evaluation a difficult task. Precipitation measurements in particular are difficult in cold regions, especially under windy conditions (e.g. Bogdanova *et al.*, 2002). Despite promising attempts to derive the zonation of permafrost from

global climate models (GCMs; Stendel and Christensen, 2002), the spatial resolution of such models is generally not sufficient to reliably simulate arctic climate. On the other hand, the Arctic is a large region so that only few attempts have been made to use regional climate models (RCMs) over a pan-arctic domain. When these models are driven by observed sea surface temperatures (SSTs) and sea ice boundaries, they show smaller biases in temperature and precipitation than GCMs. This may be due to biases originating from lower latitudes, which are advected into the model domain (e.g. Dethloff *et al.*, 2001; Wei *et al.*, 2002; Lynch *et al.*, 2003; Semmler *et al.*, 2005) or to a more realistic representation of snow-cover in RCMs (see below). Across-model scatter in RCM simulations (Tjernström *et al.*, 2005; Rinke *et al.*, 2006) is related to differences in simulated sea ice cover (a reduction of ice extent leads to warming due to increased absorption of solar radiation at the surface).

This report comes in two parts. The present one focuses on the atmospheric part of the regional model system. Besides land surface properties and variables at or near the surface this also includes sea ice as far as it is relevant in this context. The second part of the report, published as Danish Climate Centre Report 07-04, deals with aspects of the ocean. The present report is organized as follows: in chapter 2, the model configuration and the setup of the regional climate change experiment are discussed. Chapter 3 deals with the validation of the model for present-day conditions, whereas future climate evolution is discussed in chapter 4. In chapter 5, local consequences of these changes are exemplified by discussing changes for the Zackenberg region in north-east Greenland. Finally, chapter 6 gives some conclusions.

2. Model configuration and experimental setup

There are several kinds of uncertainties related to climate projections using simulations with coupled atmosphere-ocean GCMs. Apart from uncertainties in future greenhouse gas and aerosol emissions and their conversion to radiative forcings (which will not be discussed here), there are uncertainties in global and regional climate responses to these forcings due e.g. to different parameterisations (discussed in detail by Stocker *et al.*, 2001). There is also large natural variability on the regional scale (consider, for example, the NAO), so that it is difficult to determine which part of the response of a model is due to anthropogenic forcing and which to natural variability (solar, volcanic, but also unforced). Additional uncertainties are caused by insufficient resolution of global models and different approaches to downscale their output to the regional scale.

As discussed in e.g. Meehl *et al.* (2007), there are quite large differences between global models that simulate arctic climate and climate change. While part of this difference is due to natural variability, poorly understood physical processes and uncertainties in feedbacks, a substantial part is related to the coarse resolution and, therefore, inadequate parameterisation of physical processes in these models. It is therefore a common procedure to apply a dynamical downscaling procedure to drive a limited-area regional climate model. For practical reasons, such regional simulations have until now mostly been conducted as “time-slice” experiments, typically for present-day climate and for a period towards the end of the 21st century. In such a set-up, the forcing fields as well as sea surface temperatures, sea ice cover and the time-dependent concentrations of greenhouse gases are taken from a transient AOGCM simulation to drive the regional model. Due to the large interannual variability in the Arctic, these time-slices need to be long enough (on the order of 30 years at least). For the entire Arctic, only two such data sets exist (Dorn *et al.*, 2003; Kiilsholm *et al.*, 2003), both run with HIRHAM4 forced with data from a transient GCM simulation with ECHAM4/OPYC3 (Stendel *et al.*, 2002).

Here, we present for the first time results of a fully transient simulation at the very high horizontal resolution of 25 km, covering the period 1950 to 2080. The model domain is shown in Fig. 1. Of

course, it would be desirable to investigate an ensemble of RCM simulations (different RCMs forced by different GCMs, as exemplified in the PRUDENCE project, see Christensen *et al.*, 2007b). Running a large ensemble of transient simulations is far beyond present computer capacity, however, so that we had to restrict ourselves to the following configuration of one GCM and one RCM.

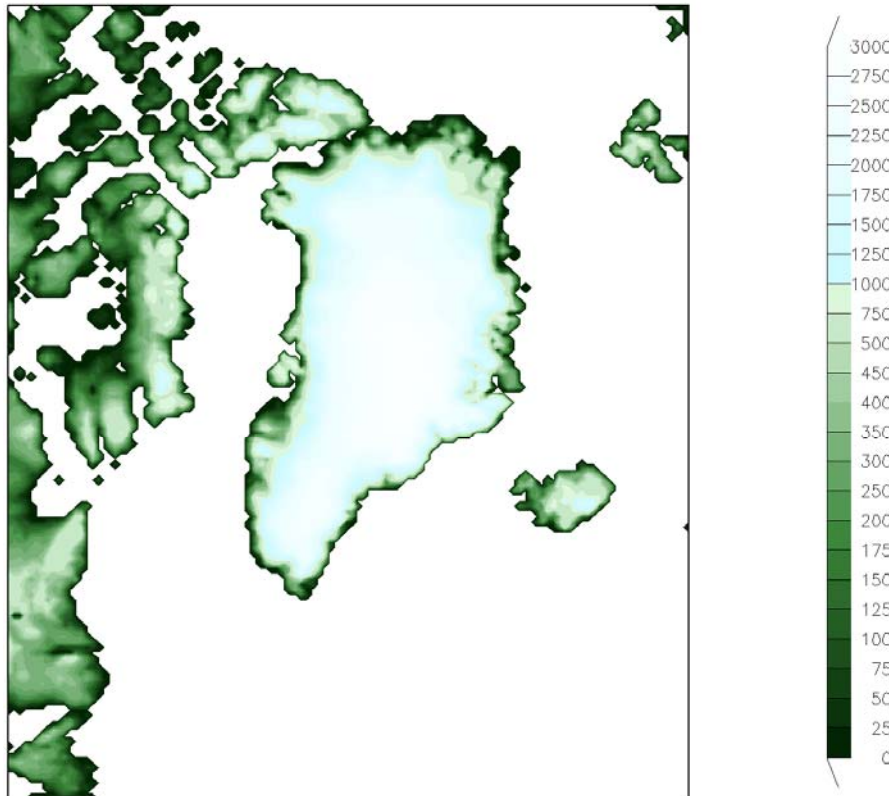


Figure 1: Model domain of the HIRHAM 25 km simulation

One of the state-of-the-art GCMs participating in the IPCC AR4 assessment is ECHAM5-MPI/OM1 (Roeckner *et al.*, 2003; Marsland *et al.*, 2003; Jungclaus *et al.*, 2006). All the forcing data for our Greenland simulation have been taken from a transient simulation with this model in the comparably high horizontal resolution of T63, i.e. approximately 1.8° by 1.8° (May, 2007a; May, 2007b). We note that ECHAM5-MPI/OM1 no longer requires a flux correction, as opposed to its predecessor versions.

The regional model we use here is HIRHAM4 (Christensen *et al.*, 1996), which is based on the adiabatic part of the HIRLAM (High-Resolution Limited Area Model) short-range weather forecast model (Källén, 1996) that was jointly developed by a number of European weather services.¹ For climate modelling purposes, the standard physical parameterisation of HIRLAM was replaced by that of the global climate model ECHAM4 (the predecessor of ECHAM5), so that HIRHAM4 can be thought of as a high resolution limited area version of ECHAM4. HIRHAM4 uses a rotated latitude-longitude coordinate system, where the rotated South Pole is positioned at the intersection of equator and Greenwich Meridian. The boundary forcing from the global model (see previous paragraph) is updated every six hours in a region 10 grid points wide with a simple relaxation of all

¹ Denmark, Finland, the Netherlands, Iceland, Ireland, Norway, Sweden and (in part) France and Spain.

prognostic variables. HIRHAM4 has been shown to be able to simulate present-day climate realistically (Christensen *et al.*, 1998). In general, predicted temperatures in RCMs follow the patterns of the driving GCMs. However, Dethloff *et al.* (2002) and Kiilsholm *et al.* (2003) show that HIRHAM4 shows closer agreement to observations than the forcing model (in both cases ECHAM4-OPYC3), which is mainly due to a more realistic treatment of precipitation and snow-cover (see also Christensen and Kuhry, 2000) in the regional model. Both the Dethloff *et al.* and Kiilsholm *et al.* papers also present results of coarse resolution (50 km) time-slice climate change projections for Greenland.

Varying concentrations of well-mixed greenhouse gases (CO₂, CH₄, N₂O, CFC-11 and CFC-12) as well as ozone (O₃), and sulphate aerosols (SO₄) have been prescribed following observations over the period 1861-2000 and according to the SRES A1B scenario (Nakićenović *et al.*, 2000) thereafter. In the A1B scenario, the CO₂ concentration in 2100 is near 700 ppm, and the globally averaged warming with respect to present-day climate is 3.5°C.

3. Model validation

In this chapter, we compare the simulated present-day (1961-1990) climate over Greenland with observation-based data. For a region as remote as Greenland, this is not a straightforward task. A number of stations, run by the Danish Meteorological Institute, exist along Greenland's coasts. For seven of them (Upernavik, Ilulissat/Jakobshavn, Nuuk/Godthåb, Narsarsuaq, Tasiilaq/Ammassalik, Ittoqqortoormiit/Scoresbysund, Danmarkshavn), observations covering the reference period 1961-1990 exist. Due to the rugged orography, such station-based comparisons are not necessarily representative for large regions, let alone the ice cap. One therefore has to refer to reanalysis data, which consists of a combination of model data and observations. Here we compare the model results to both reanalyses and station-based data. For convenience, an overview of observed temperature and precipitation over Greenland is also given.

We have chosen the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis, henceforth termed ERA40 (Uppala *et al.*, 2005), which covers the period January 1958 to August 2002. The general principle behind a reanalysis of atmospheric data is to combine observations with background information obtained from a short-range forecast initiated from the most recent preceding analysis to produce an estimate of the state of the atmosphere at a particular time. Observations all have their own accuracies and (spatial and temporal) distributions. They are combined with the model-based background information using estimates of their error statistics by means of a variational data assimilation procedure. This means that the background forecast carries forward in time the information from observations used in earlier assimilation cycles. The degree of dependence on the particular forecast model varies with density and relative accuracy of the observations and therefore generally differs from place to place and from one variable to another. In regions with poor data coverage, such as the Arctic, the background information obviously has a relatively large weight. This is why we have chosen ERA40 (there are a few other reanalyses available), which is generally regarded to be of high quality in the Arctic.

It is important to note that ERA40, even though run with a comparatively high spatial resolution (N80 Gaussian grid equivalent to 1.125° in latitude and longitude), has a considerably coarser resolution than our HIRHAM simulation. This becomes clear from Fig. 2 where we compare the orographies of ERA40 and HIRHAM over Greenland.² With respect to the high resolution HIRHAM data, ERA40 generally overestimates elevations along the coasts, in particular the west coast,

² As can be seen in Fig. 2, the maps for ERA40 and HIRHAM do not cover exactly the same geographic area. This is due to the different projections of the two data sets, but has no effect whatsoever on the results.

whereas the opposite is the case over the southern part of the ice sheet. These differences need to be taken into account when comparing model results and observations, since they introduce a systematic bias in e.g. temperatures.

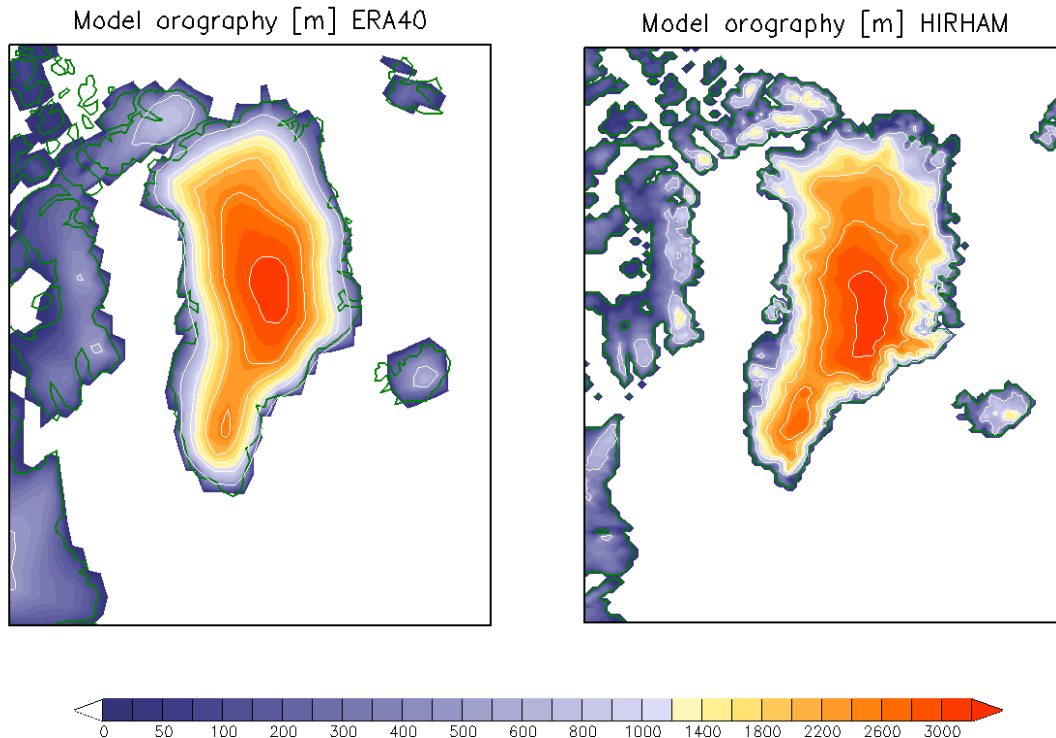


Figure 2: Elevations [m] in ERA40 and in the 25 km HIRHAM simulation. Contours every 500 m.

Fig. 3 shows a comparison between simulated and reanalysed 2m temperatures for winter and summer. ERA40 is close to observations (where they are available) with a cold bias in the north-west. Following a compilation by Box (2002), observed winter temperatures for the period 1961–1990 are between -23°C in the north (Pituffik / Thule Air Base) and -5°C in the south (Qaqortoq / Julianehåb). Generally, summer temperatures are above freezing, with maximum mean monthly values near 10°C in the south (Narsarsuaq, Kangerlussuaq / Søndre Strømfjord). All stations are situated in coastal areas away from the ice sheet. Much colder temperatures, however, are measured on the ice sheet itself. At the Summit station (elevation 3208 m), the average temperature is -41°C in winter (based on observations from 1987 to 2001) and -15°C in summer, yielding an annual average temperature of -30°C . ERA40 is generally colder over the north-western part of the ice sheet, as also can be inferred from the difference in elevation visible in Fig. 2. While temperatures above the sea ice are quite similar between ERA and HIRHAM, there is a warm bias in the latter over open water in winter and spring (not shown). Along the coasts, temperatures are very similar in model and reanalysis. We note, however, that there is no a priori reason why SSTs in HIRHAM should be identical to those in ERA40, since the latter are observation-based, whereas the former come from the coupled ECHAM5/MPI-OM, i.e., they are a model product not constrained by any observations. Given the fact that there is no flux correction in the GCM, the biases are actually rather small compared with earlier versions of the model which required such a correction.

As long as ice remains on sea water, the air temperature in HIRHAM is not allowed to rise above the freezing point, while there is no such constraint in ERA40. This explains the comparably large differences in summer over the northern half of the domain. Over open water as well as on the ice



sheet, differences are smaller.

The general distribution of precipitation over Greenland (Fig. 4) is captured very well by the HIRHAM model. Greenland is generally rather dry (Cappelen et al., 2001). In the north and on the ice sheet, precipitation is smaller than 100 mm per year. It is also comparably dry along the west coast (Aasiat / Egedesminde: 304 mm per year). Going further south, annual precipitation increases to 858 mm in Qaqortoq / Julianehåb (southwest coast) and even nearly 1000 mm on the southeast coast (Tasiilaq / Ammassalik). In the rugged terrain of the southeast coast, where strong winds prevail quite often, it is very difficult to estimate the amount of precipitation. Judged from the precipitation observations at Prins Christian Sund (2474 mm per year), there may be as much as 3 m of annual precipitation locally (J. Cappelen, pers. comm.). Apart from a general overestimation of precipitation along the eastern boundary of the integration domain discussed elsewhere (see Stendel et al., 2007 for a discussion of boundary effects), effects due to differences in resolution and elevation between ERA40 and HIRHAM are clearly visible. While nothing is visible of orographically forced precipitation in ERA40, HIRHAM covers these local precipitation maxima well and also has the correct magnitude.

As can be seen from Fig. 4, the central and northern part of the ice sheet generally is very dry in present-day climate. Further south, low pressure system occasionally can cross the ice sheet. There is also an indication of convective activity in summer in the southernmost part of Greenland. All these features are simulated by the HIRHAM model.

There is generally more precipitation in HIRHAM over the ice-free ocean than in ERA40. While this difference is well inside the range of uncertainty if one compares to other reanalyses (not shown), it may be related to the higher SSTs in the regional model discussed above.

The distribution of sea level pressure (Fig. 5) shows the well-known quasi-permanent features, namely the Icelandic Low and high pressure over the interior of the ice sheet. While there is large similarity between HIRHAM and ERA40 throughout the year, there is always a larger pressure gradient in HIRHAM, presumably due to the higher resolution.

We conclude that HIRHAM is able to realistically simulate present-day large- and regional-scale climate even over terrain as rugged as Greenland. We next validate the model by comparing time series of average temperature as well as mean and extreme maximum and minimum temperatures at DMI stations and corresponding model grid points (Fig. 6). With such an approach, we can assess interannual variability, which, as pointed out already by Putnins (1970) and, more recently, Cappelen *et al.* (2001), generally increases from south to north, particularly in winter.

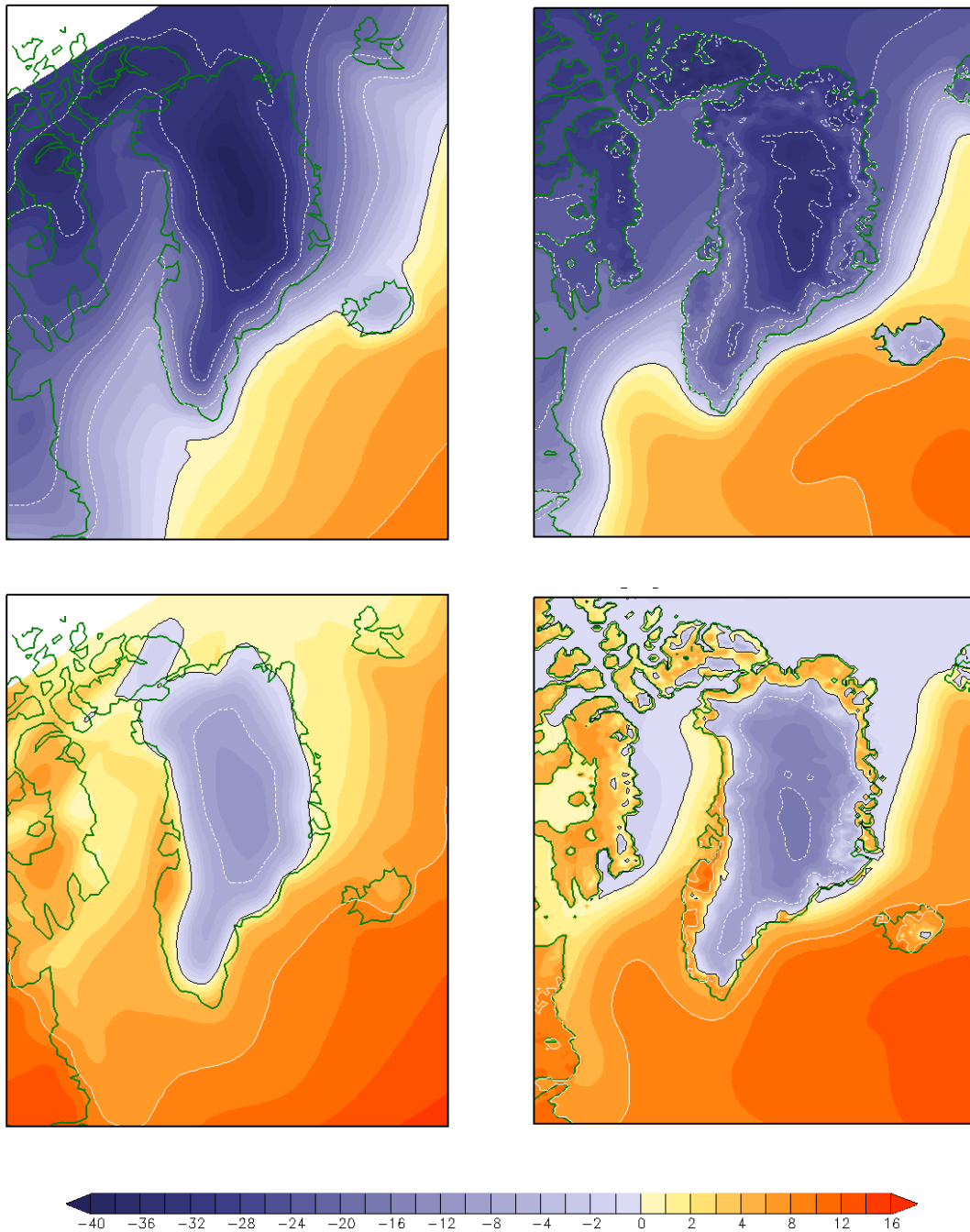


Figure 3: Near-surface temperature [$^{\circ}\text{C}$] for winter (December-February, upper panel) and summer (June-August, lower panel) for the period 1961-1990 in the ERA40 reanalysis and in our simulation. The black line represents the 0°C isotherm, white lines are shown every 8°C .

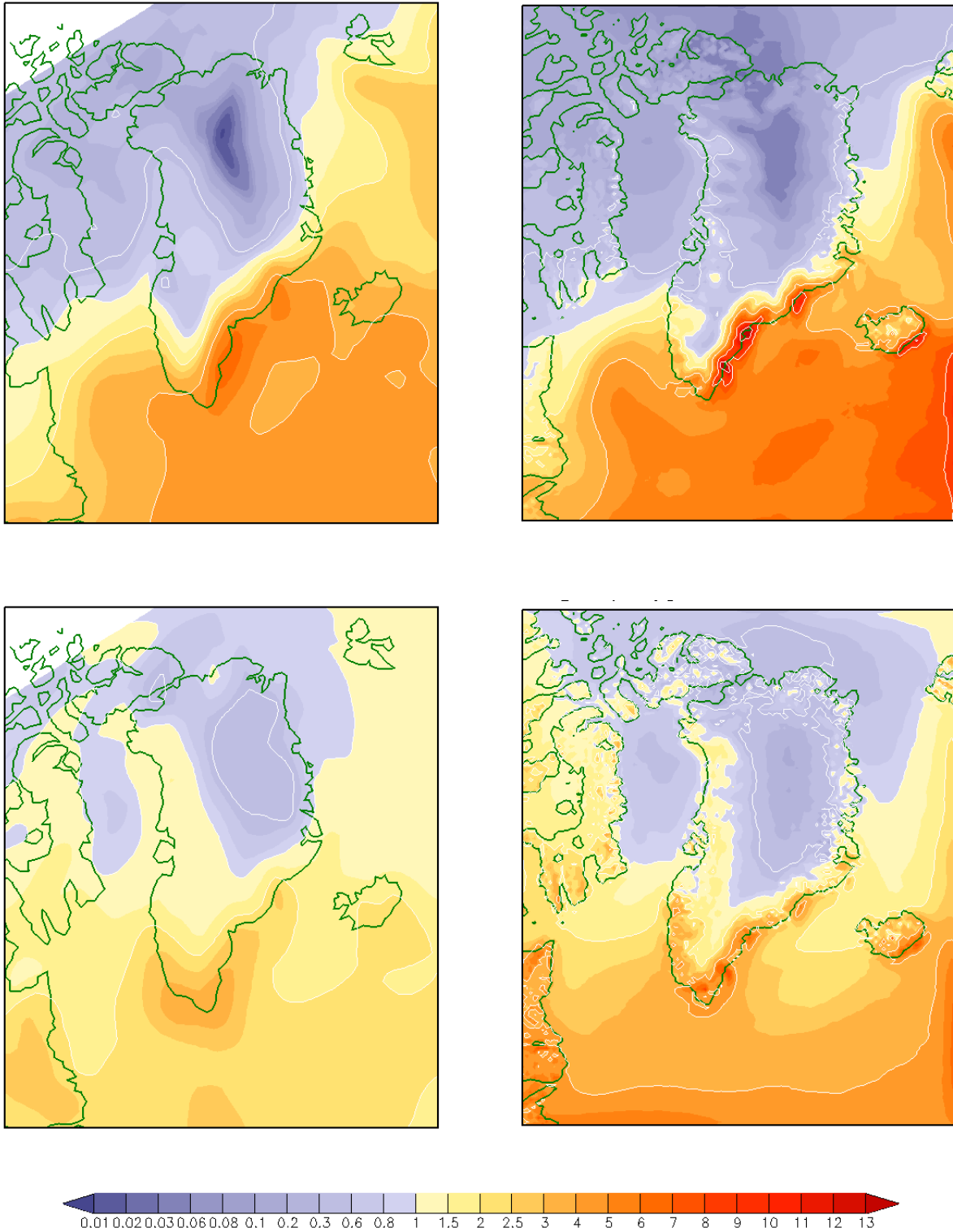


Figure 4: As Figure 3, for precipitation [mm/day]. Isolines at 0.5, 1, 2, 4, 8 and 12 mm/day.

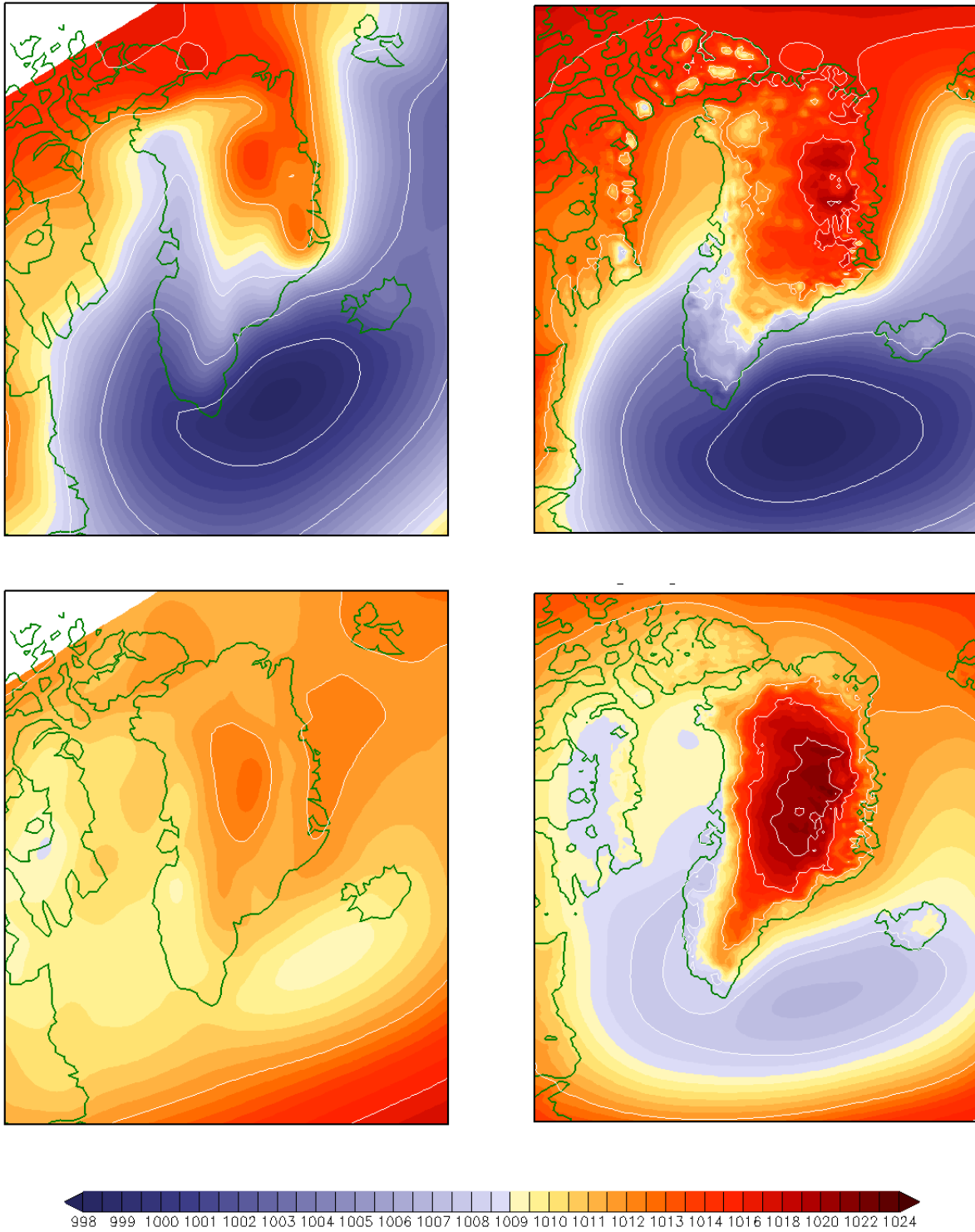


Figure 5: As Figure 3, for sea level pressure [hPa]. Isolines every 4 hPa.



For Upernavik, situated in relatively flat surroundings, the agreement between reanalysis and model simulation is remarkably good. Even the 30 year extreme maxima and minima are captured well, thus further corroborating the ability of HIRHAM to simulate present-day climate and variability. For Ilulissat/Jakobshavn, there is also a good agreement except for the absolute minimum temperature during the winter months, which is underestimated by about 10°C. These and similar differences at the other stations (not shown) can be traced back to the fact that the grid points taken for the comparison are not representative for the respective station. Elevation differences between the stations and the pertinent model grid points have been taken into account by applying a lapse-rate based temperature correction (not shown). Such an analysis thus shows that it is, in principle, possible to simulate local temperature evolution with a reasonable degree of accuracy provided that the resolution is high enough. Judged from this point of view, a 25 km grid may be the coarsest resolution which can be used for such a kind of analysis.

We also note that after the simulation had been finished, it turned out that there was a minor error in the procedure that interpolated orographies from the original high resolution (1 km) digital elevation model data to HIRHAM's 25 km resolution, leading to offsets in elevation on the order of 100-200 m (with isolated maximum values in the north-west of up to 700 m). It was decided that the error introduced by the incorrect heights in general is considerably smaller than the internal variability in the model (i.e., differences between two model runs started from slightly different initial conditions). In addition, one could apply a lapse-rate based correction for temperature (as discussed above), but this has not been done, since the elevation errors at the station location are rather small.

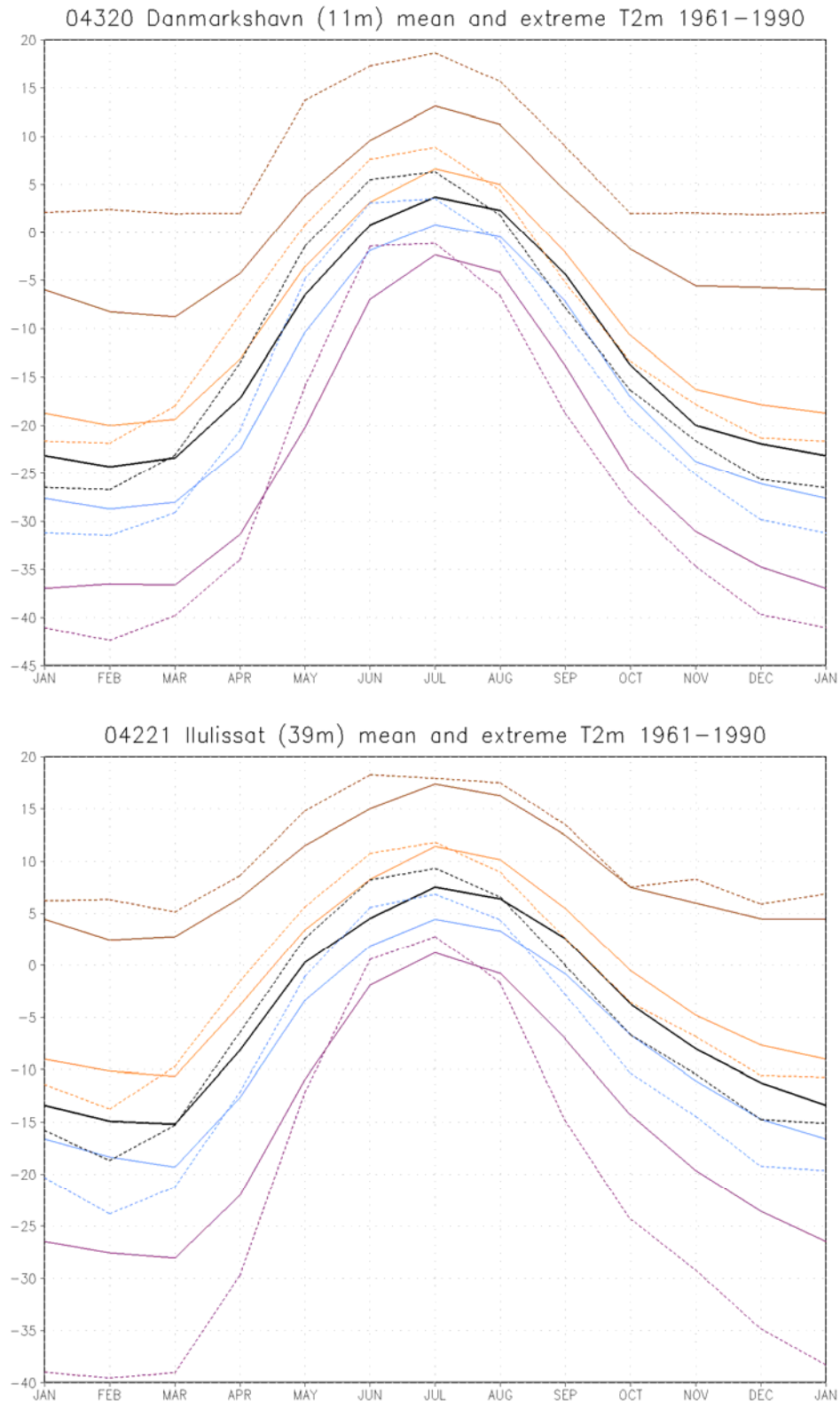


Figure 6: Mean and extreme 2m temperatures [°C] for the period 1961-1990 in Danmarkshavn (top panel) and Ilulissat/Jakobshavn (lower panel). Solid lines: ERA40, stippled lines: HIRHAM. From top: absolute maximum temperature (brown), mean maximum temperature (orange), mean temperature (black), mean minimum temperature (blue) and absolute minimum temperature (violet).

4. Future Climate Evolution

As outlined above, the driving model for the 25 km HIRHAM simulation is a coupled atmosphere-ocean model, i.e. the atmosphere is not forced by observed SSTs and sea ice concentrations, but rather by modelled ones. This implies that in order to obtain meaningful statements on variability and change, the considered periods need to be long enough, in particular in the Arctic owing to its large internal variability. This is often not possible using time slices of future climate evolution. Here we have chosen to compare two thirty year averages for periods in the 21st century (2021–2050 and 2051–2080) with modelled present-day conditions (1961–1990).

Figure 7 shows seasonal changes in 2 m temperature for the two future periods in Greenland. For 2021–2050, a general temperature increase of 3°C in winter, 4°C in spring and of 2°C in summer and autumn is found. In winter, locally larger values up to 6°C along the west coast (between Sisimiut / Holsteinsborg and Upernavik) and 4°C along the east coast (between Tasiilaq / Ammassalik and Ittoqqortoormiit / Scoresbysund) and further northeast to Svalbard are found. These are adjacent to regions covered with sea ice under present-day conditions, but not in future climate. On the ice sheet, the model projects an increase by 2°C throughout the year. For the later period (2051–2080), winter temperature increases accelerate considerably, reaching 7–8°C throughout the Arctic and 12°C along the east coast, culminating in a more than 18°C increase at Svalbard's northeast coast, which is a region prone also to large recent temperature anomalies. On the ice sheet, a temperature increase of 5–6°C in winter and spring and 3–4°C in summer and autumn is projected. The comparatively large temperature increase over the northern section of the ice sheet in spring is related to an increase in cloudiness and wind velocity (not shown) so that less low-level inversions can form. Summer temperature changes are small and more uniform as long as temperature remains near 0°C due to the presence of melting ice. The small temperature decrease along Greenland's north coast is related to changes in lower tropospheric wind (not shown). Generally, a large decrease in the number of extremely cold days (with an average temperature below –20°C) is projected.

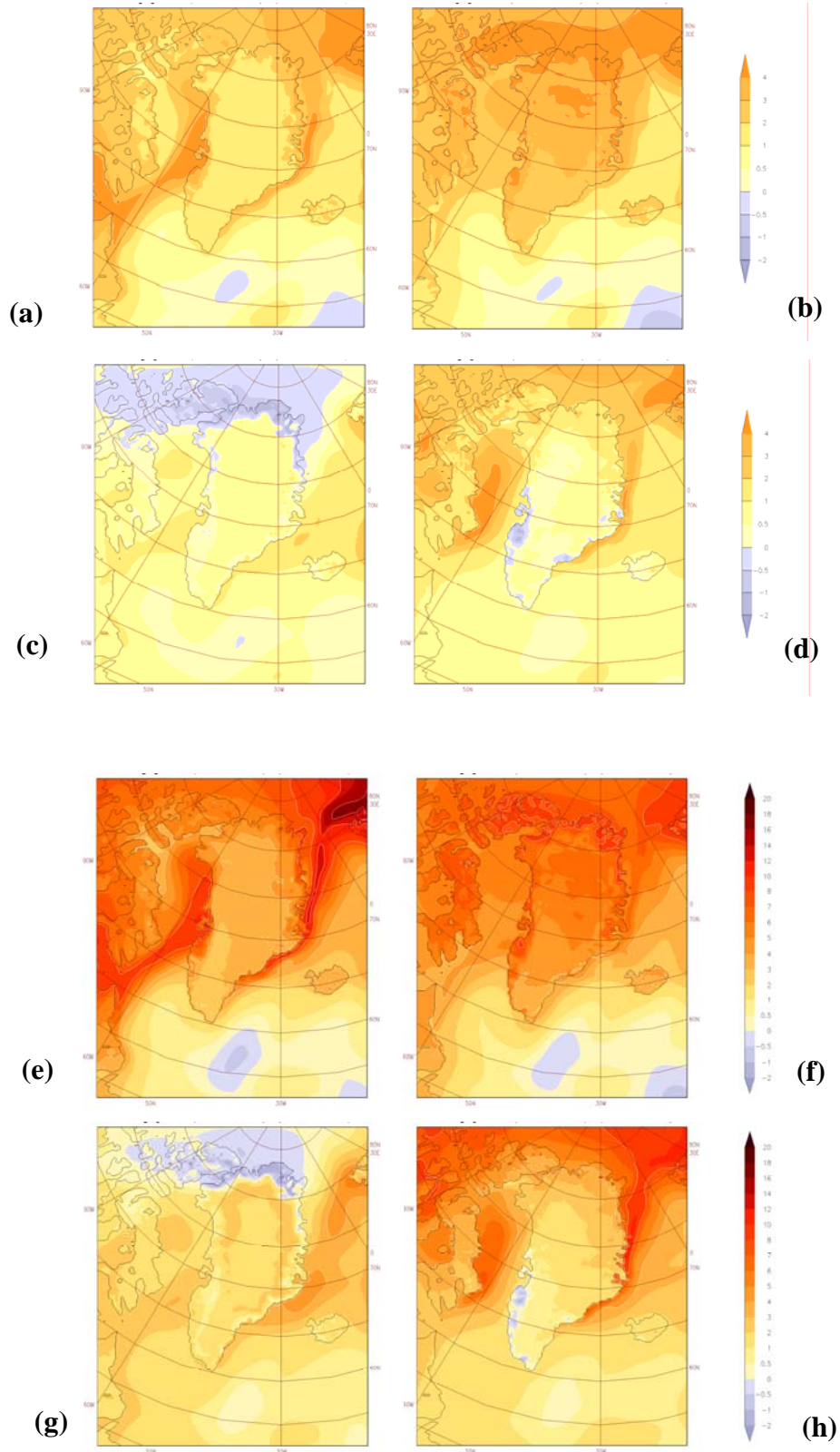


Figure 7 Simulated mean near surface (2 m) temperature change in HIRHAM4 for the difference between the two 30 year periods 2021–2050 and 1961–1990 for (a) winter (December-February), (b) spring (March-May), (c) summer (June-August) and (d) autumn. (e)-(h) Same as (a)-(d), for 2051–2080 minus 1961–1990.

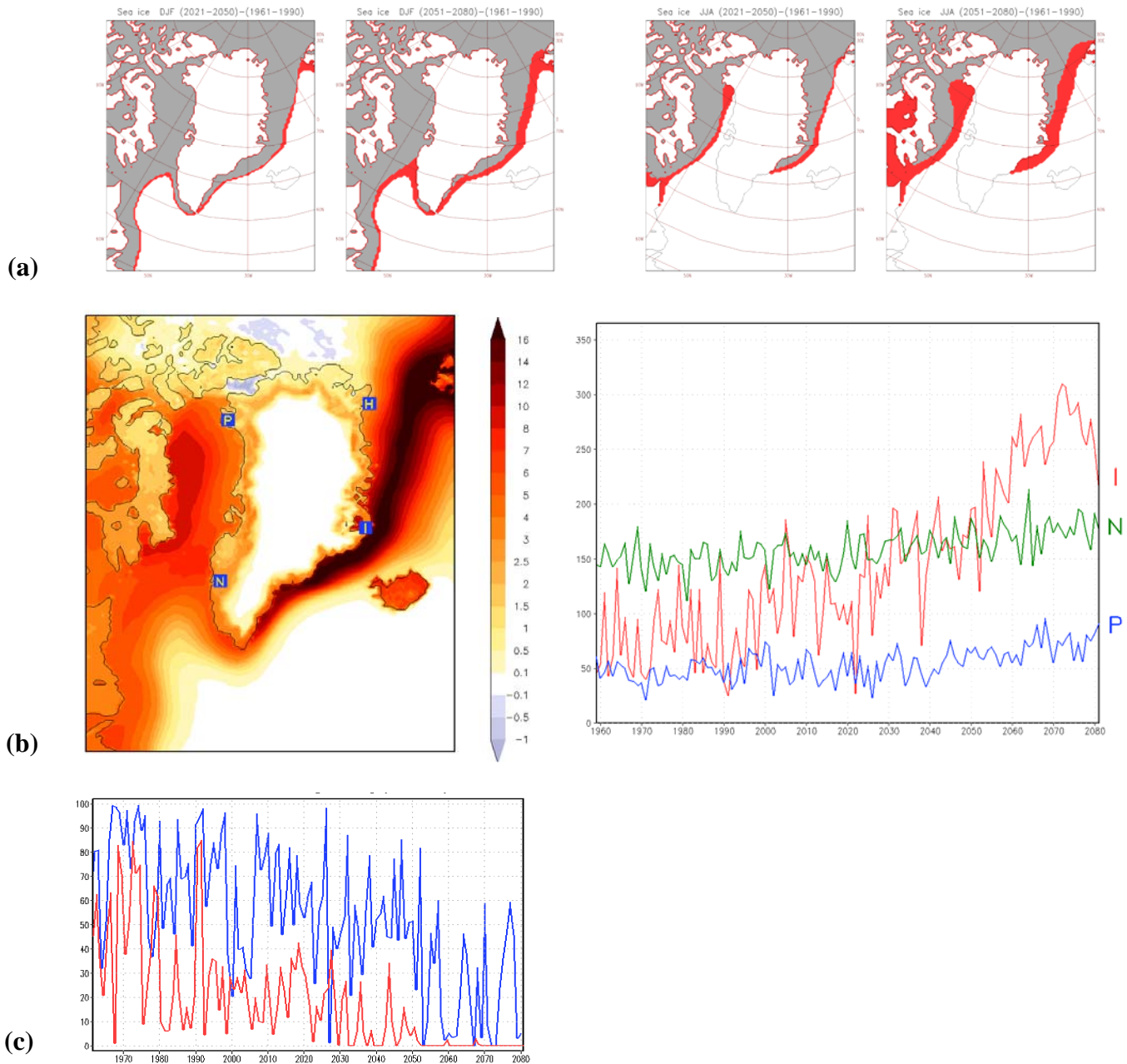


Figure 8 (a) Changes in winter (left) and summer (right) sea ice cover for the periods 2021–2050 minus 1961–1990 (left panels) and 2051–2080 minus 1961–1990 (right panels). Grey shading denotes areas with sea ice (i.e., ice concentration in a grid cell is greater than 0) both under present-day and future conditions, white means no sea ice. Red shading denotes areas which have sea ice under present-day, but not under future conditions. No attempt is made to assess ice thickness. (b) Left: Linear trend (days/decade) in the number of thawing days for the period 1961–2080. A thawing day is defined as days with an average temperature above 0°C. Right: Time series 1961–2080 of the number of thawing days for model grid points near three selected locations: Nuuk/Godthåb (green line, denoted with “N”), Pituffik/Thule Air Base (blue line, denoted with “P”) and Ittoqqortormiit/Scoresbysund (red line, denoted with “I”). (c) Sea ice concentration (in %) in March (blue curve) and September (red curve) for a grid point near Holm Land (81°N, 15°W, denoted with “H”).

The climate simulation projects a retreat of sea ice by about 100 km for 2021–2050 compared to present-day conditions and by a further 300–400 km by 2051–2080 (Figure 8a and b). Particularly large changes are projected along the east coast. This is further elucidated by investigating the annual number of thawing days (Figure 8c and d), here defined as days with positive average temperature. Linear trends of more than 20 days per decade are visible along most of the east coast. Other stations in the southwest and northwest also show increases in the number of thawing days, though considerably smaller. In accordance to the huge winter temperature increase near Svalbard discussed above, several winters with no sea ice at all are projected for this region towards the end of the period (not shown).

Holland *et al.* (2006) discuss the possibility of abrupt transitions in September sea ice cover. In our simulation, there is a clear downward trend both for late winter (March) and late summer (September) ice cover. There are no indications of abrupt changes along the southern and western parts of Greenland's coast. For the north-eastern part of Greenland, we find indications for transitions (Figure 8e), but more gradual than described in Holland *et al.* (2006).

In agreement with findings in ACIA (2005) and Christensen *et al.* (2007a), most of the Arctic region north of about 60°N is projected to gain an increase in precipitation, especially Siberia, Scandinavia (not shown) and the north-eastern part of Greenland (Figure 9, top panel). For 2021–2050, a precipitation increase by 15% over western and 40% over interior and eastern Greenland is projected. For 2051–2080, there is further increase by 30–40% over western and interior and about 60% over eastern Greenland. Looking more in detail, we find that there is a distinct decrease in both snow-fall amount and frequency along the southern parts of Greenland's coast, whereas more snow is projected on the lower parts of the ice sheet, in particular along the east coast (not shown). An investigation of snow-fall exceeding certain thresholds (Figure 9, lower two panels) reveals that there will be a modest increase in extreme snow-fall events by 2021–2050. For 2051–2080, this will only be the case in regions with an elevation of more than 1500 m due to the enhanced temperatures. In particular, there will be more extreme snow-fall events on the ice sheet according to the model simulation. The hydrological cycle is expected to intensify, as an increase in temperatures allows for a higher absolute humidity in the atmosphere. This increased humidity leads to an enhanced occurrence of orographic precipitation (not shown). This as well as an increased run-off contribution (roughly a third from land in the few areas with bare land points) will contribute to an enhanced freshwater supply in general.

In the Arctic, the length of the growing season is one of the important factors impacting ecosystem processes. The timing of snowmelt in spring is determined by temperatures and snow depth. Even the most recent generation of GCMs allows only limited insight into changes in Greenland snow-cover, since in most models the ice sheet is treated as passive. Taking ECHAM5 as an example, this means that snow is allowed to accumulate on the ice sheet until a predefined maximum snow-cover of 10 m is reached. Since no ablation takes place, this means in practice that the ice sheet is covered by 10 m of snow throughout the year. Similarly, no thawing from the ice cap is considered. Other models behave similarly. The coastal region where snow is allowed to accumulate in the models is rather narrow over most of Greenland, which means that present-day GCMs generally are of little use to assess changes in snow-cover over Greenland due to the coarse resolution. On the other hand, the high-resolution RCM simulation allows limited insight into the evolution of snow-cover outside the ice sheet (not shown). In all seasons, there is an increase of snow depth compared to the period 1961–1990 over the northern half of Greenland, and a decrease along the south-western, southern and south-eastern coasts. The construction of coupled atmosphere-ice-ocean RCMs including three-dimensional thermo-mechanically coupled ice sheet models is a recent development, which will allow to quantify the response of the ice sheet to climate change and feedback mechanisms.

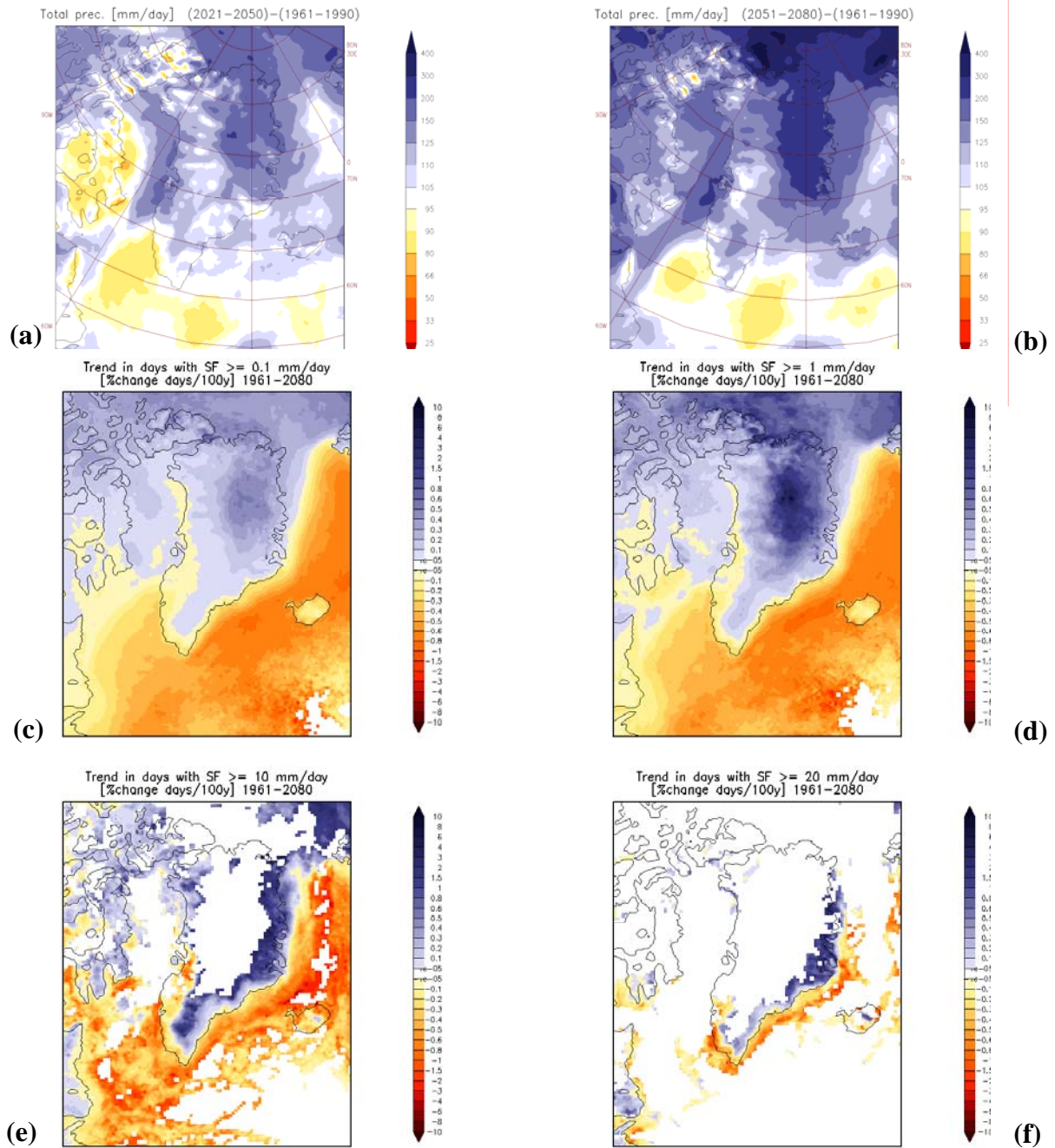


Fig. 9 Top row: Change in annual precipitation, expressed as a percentage of present-day (1961–1990) precipitation for (a) 2021–2050 and (b) 2051–2080. Bottom rows: Linear trend in the number of days (expressed as a percentage change per 100 years compared to present-day) with snow-fall exceeding thresholds of (c) 0.1, (d) 1, (e) 10 and (f) 20 mm/day, respectively. White areas over the ice sheet denote regions where no such precipitation events are simulated under present-day conditions.

5. Local climate change in Greenland - the Zackenberg region as an example

The Zackenberg Research Station is situated at 74.5°N and 21°W in the southern part of north-eastern Greenland 25 km north-west of the “Daneborg” weather station. This high Arctic region is characterised by continental climate with very cold winters and generally dry conditions even though the region is located near the coast, since under present-day conditions the sea is frozen most of the time in a belt several 100 km wide. Changes in sea ice-cover will therefore be decisive for local climate changes in the Zackenberg area. Zackenberg is also located near the region where the largest temperature changes are projected according to Fig. 9.

There has been considerable multidecadal variability in the strength of the Arctic Oscillation in recent times, and many models suggest an increase of the positive phase of the NAO for the 21st century (Christensen *et al.*, 2007a). These changes will also affect Greenland. Positive indices of the NAO result in warmer, moister and windier conditions than normal over most of northern Europe and Northeast Greenland, whereas it is colder and drier than normal over the western part of Greenland. Even though the local effect of the NAO on temperatures at Zackenberg is rather small (see e.g. Jones *et al.*, 2003 and Hanssen-Bauer, 2007), an increase in its strength will favour a northward retreat of sea ice in the Zackenberg region, so that continentality will decrease in North-east Greenland in general and in the Zackenberg area in particular. This goes along with an increase in both temperature and precipitation, especially in winter. Consequently, climate conditions will change towards those in the Low Arctic with deeper snow-cover, lengthening of the melting season and increased variability including extended thaw periods during winter.

Table 1 shows the monthly mean temperatures for Zackenberg for the three periods 1961-1990, 2021-2050 and 2051-2080 as an average of the nearest two grid points, one of which is located over sea, whereas the other has a height of 560 m above sea level. To compare with local measurement, the lower tropospheric lapse rate (approximated by the quotient of temperature differences and geopotential differences between the pressure levels of 1000 and 850 hPa) needs to be accounted for. In summer, temperature typically decreases by 0.5°C/100m height change, whereas in winter and spring the vertical temperature decrease is small or temperature is even rising with height due to shallow inversions, while autumn lies in between. With the projected increase in windiness, such inversions will become less frequent, resulting in an additional warming of about 1°C in winter and spring of 2051-2080 caused by changes in the stratification of the lower troposphere.

| | DJF | MAM | JJA | SON | Year |
|---------------------------|-------|-------|------|-------|------|
| Observed | -15.6 | -11.4 | 4.4 | -8.9 | -7.8 |
| 1961-90 | -19.9 | -11.0 | 4.5 | -11.2 | -9.4 |
| 2021-50 | -16.7 | -6.4 | 3.9 | -10.1 | -7.3 |
| (2021-2050) – (1961-1990) | 3.2 | 4.6 | -0.6 | 1.1 | 2.1 |
| 2051-80 | -13.3 | -3.6 | 4.5 | -8.8 | -5.3 |
| (2051-2080) – (1961-1990) | 6.6 | 7.4 | 0.0 | 2.4 | 4.1 |

Table 1: Observed and modelled temperatures at Zackenberg for winter (DJF), spring (MAM), summer (JJA), autumn (SON) and the annual mean. The model data is an average of the two nearest points to Zackenberg. Changes in lapse rate and the different orography of model and station data have been taken into account.

While only minor changes are projected in summer, Table 1 shows that largest temperature changes can be expected in winter and spring, in particular (not shown) in March and April. Further evidence for these changes can be seen in Figure 8b, which elucidates that the annual number of thawing days (positive daily mean temperature) for the model grid point representing Zackenberg is projected to increase from about 80 for 1961–1990 to almost 250 for the period 2051–2080. According to these simulations, there will be more than 300 such days in individual years, so that the climate at the end of the 21st century even as far north as nearly 75°N hardly any longer can be characterized as “high-Arctic”.

6. Conclusions

Climate and climate change over the Arctic in general and Greenland in particular have recently attained much attention. Using the most recent (IPCC AR4) models and a rather large ensemble, there is growing confidence that the climate change signal can be separated from noise in the early 21st century despite the large natural variability (Christensen *et al.*, 2007a). Such a statement was not possible in ACIA (2005) due to the considerably smaller ensemble size, lack in spatial resolution and model deficiencies such as flux corrections. With few exceptions, the AR4 models project modest warming on the order of 2–3°C in the southern and larger warming (around 7°C) for the northern part of Greenland.

We report results from a transient climate simulation at an (for Greenland) unprecedented horizontal resolution of 25 km, which has been forced with a rather high resolution (T63, i.e. roughly 1.8 degrees in latitude and longitude) coupled GCM. The regional model shows considerably stronger temperature increase in regions where sea ice retreats than the driving global model. An assessment of extreme events reveals considerably less cold (and warmer) days than under present-day conditions. Largest changes can be expected along the east coast, in particular in the Zackenberg region, where days with a positive average temperature are projected to become the rule rather than the exception. Most of Greenland, especially the northeast, will experience more precipitation. At lower elevations, an increasing percentage of this precipitation can be expected to fall as rain instead of as snow as under present-day conditions. On the other hand, more extreme snow fall events than at present are projected on the ice sheet. Higher temperatures and increased precipitation will have a profound effect on the hydrological budget of the region.

Arctic sea ice is responding sensitively to global warming (Meehl *et al.*, 2007). Most AR4 models and also our regional simulation show significant, but smaller changes of sea ice in winter (at least to the middle of the 21st century) than in late summer, when sea ice is projected to disappear towards the end of the 21st century due to the ice-albedo feedback and the advection of warmer waters into the Arctic. In the HIRHAM4 simulation, late summer sea ice around Greenland disappears everywhere except in the far north where, however, it is substantially reduced.

While most models agree in a substantial decrease in sea ice cover during the 21st century, there are remaining uncertainties. Recently, Dethloff *et al.* (2006) showed that quite minor improvements in the parameterization of arctic sea ice and snow-cover exert a strong influence on arctic albedo and (via changes in mid-latitude storm tracks) on the climate of most of the Northern Hemisphere. These changes lead to an initial increase in sea ice for high latitudes under present-day conditions and therefore lower arctic temperatures. But for future conditions (Stendel and Christensen, in preparation), a considerably faster temperature increase and sea-ice decrease during the mid-21st century in the Arctic in general and around Greenland in particular is triggered compared to the standard ECHAM parameterization. It would therefore be highly desirable to extend the present investigation by including other models.

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