The impact of Greenland's deglaciation on the Arctic circulation

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[1] The influence of Greenland's deglaciation on the atmospheric winter and summer circulation of the Arctic have been quantified with the high-resolution regional atmospheric model HIRHAM4. Greenland's deglaciation exerts a pronounced influence on the atmospheric winter circulation of the Arctic. The land areas over Siberia and the Canadian archipelago are warmed by up to 5°C. Parts of the Atlantic and the Arctic Ocean are cooled by up to 3°C. A north-eastward shift of the storm tracks occurs over the North Atlantic as well as an increase of synoptic activity over Alaska. The pronounced P-E changes connected with shifts in the synoptic storm tracks during winter would have important consequences for the atmospheric freshwater input into the Arctic Ocean and the Nordic sea with the potential to cause variability in the Arctic Ocean dynamics on centennial to millennial time scales. The significant differences between simulations with and without Greenland result in a decrease of the geopotential height and a dominant barotropic response of the Arctic atmosphere. These changes correspond to an enhanced winter polar vortex and stratospheric conditions more favorable for large Arctic ozone losses. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1620 Global Change: Climate dynamics (3309); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology. **Citation:** Dethloff, K., W. Dorn, A. Rinke, K. Fraedrich, M. Junge, E. Roeckner, V. Gayler, U. Cubasch, and J. H. Christensen (2004), The impact of Greenland's deglaciation on the Arctic circulation, *Geophys. Res. Lett.*, *31*, L19201, doi:10.1029/2004GL020714.

1. Introduction

[2] The Greenland ice sheet is the largest orographic feature of the Arctic. Mountains of such a scale together with surface heating or cooling anomalies exert a strong influence on the atmospheric circulation of the Northern Hemisphere. The impact of Greenland's ice sheet on the atmospheric circulation is of importance due to its position in vicinity to the North Atlantic storm tracks. The impact of Greenland's deglaciation on cyclone tracks has been investigated in a regional numerical weather prediction model over the North Atlantic by *Kristjánsson and McInnes* [1999] and in global climate models by *Petersen et al.* [2004], *Toniazzo et al.* [2004], and M. Junge (manuscript in preparation, 2004). The primary objective of this study is to obtain a realistic estimate of the regional magnitudes and regional aspects of Arctic climate changes connected with the removal of Greenland's ice sheet by a high-resolution dynamical downscaling of the global simulations of M. Junge (manuscript in preparation, 2004) for the Arctic. *Cuffey and Marshall* [2000] suggested a considerable reduced Greenland ice sheet in consistence with ice core analysis during the Eemian period. *Haug and Tiedemann* [1998] reported the early Pliocene warming of the Northern hemisphere with a fully deglaciated Greenland. These results delivered the motivation and plausibility of our sensitivity experiments concerning Greenland's deglaciation.

[3] A high-resolution regional climate model (RCM) is a powerful tool for improving the simulation of regional effects of the Arctic climate as a result of finer resolved orography and land- sea contrasts, better resolved nonlinear interactions between the large- and meso-scales, improved simulations of hydrodynamic instabilities and synoptic cyclones, and improved description of hydrological and precipitation processes, as discussed by *Lynch et al.* [1999], *Rinke and Dethloff* [2000], *Giorgi et al.* [2001], and *Dorn et al.* [2003]. Information about the changed large-scale atmospheric circulation structures are transferred from the driving global model into the regional model, with the advantage of simulating internal Arctic climate processes closer to reality using higher horizontal resolution. The steep and complex orographic features around Greenland's margins start to become resolved with a horizontal resolution of 50 km, as reported by *Cassano et al.* [2001] and *Kiilsholm et al.* [2003].

2. The Global Model Setup and the Regional Atmospheric Model HIRHAM4

[4] The 20 year long AGCM simulations with and without Greenland's topography have been downscaled for the pan-Arctic domain with the high-resolution RCM HIRHAM4 for an ensemble of 20 January and 20 July months. The AGCM used is the ECHAM4 [*Roeckner et al.*, 1996] at T42 resolution and with 19 vertical layers. Two simulations have been performed, a control and a perturbed integration, where the orography ist set to zero at all grid points representing Greenland. These points are considered as land points with a surface type corresponding to tundra areas in computing the surface energy balance. Changes in the land sea mask due to the raise of the mean sea level by 7 meters, following the deglaciation of Greenland are not

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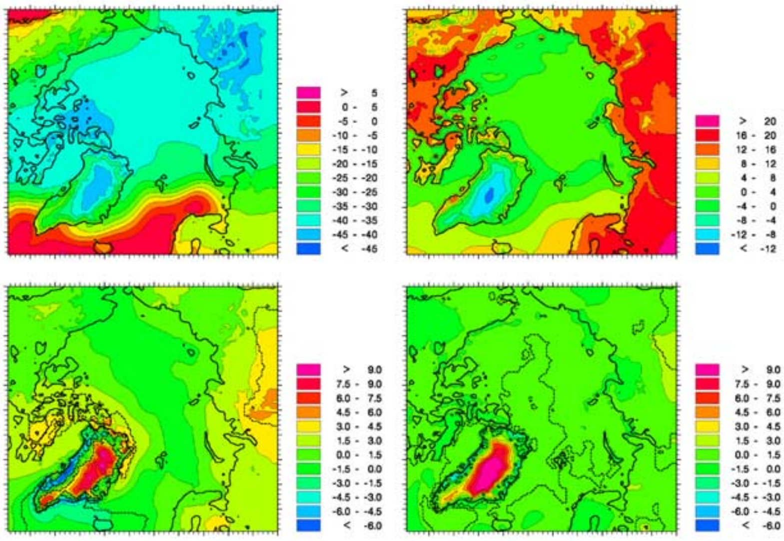

Figure 1. Mean Arctic 2 m temperature (°C) in January (left column) and July (right column), downscaled with HIRHAM4, top) control run, bottom) difference "Deglaciated Greenland run minus control run". Dashed contours represent the lower limit for 95% significance.

considered, since they are of marginal influence for Greenlands topography. For both experiments, the model is forced with climatological sea surface temperatures. The AGCM climate has been compared against the ERA15 data set and shown that the observations of the sea level pressure and other fields are sufficiently reproduced (M. Junge, manuscript in preparation, 2004).

[5] The ability of HIRHAM4 to simulate present-day Arctic conditions realistically has been documented, and in particular the accumulation rates over Greenland have been found quite realistic [*Dethloff et al.*, 2002; *Box and Rinke*, 2003]. HIRHAM4 has been described by *Dethloff et al.* [1996]. The dynamical part of the model is based on the hydrostatic limited area model HIRLAM, documented by *Machenhauer* [1988]. HIRHAM4 uses the physical parameterization package of the AGCM ECHAM4. These parameterizations include radiation, land surface processes, sea surface and sea-ice processes, planetary boundary layer, gravity wave drag, cumulus convection and stratiform clouds. The integration domain covers the whole Arctic north of about 65°N with 110 by 100 grid points and a horizontal resolution of 0.5 by 0.5°. The vertical discretization consists of 19 unequally spaced levels in hybrid sigma-pressure coordinates from the surface up to 10 hPa. The model calculations have been carried out with a time step of 300 s. At the lower boundaries, sea surface temperature and sea-ice fraction from the global climate simulations, described by M. Junge (manuscript in preparation, 2004), are updated twice per day to drive HIRHAM4. Between these times a linear interpolation takes place. The lateral forcing includes all prognostic variables except the cloud water. The information from the boundaries was transferred into the interior of the RCM by a boundary relaxation in a 10 point wide boundary zone with boundary data updated also two times per day. The parameterization packages of the global and the regional model are physically consistent which avoids inconsistencies in the process of dynamical downscaling. The influence of a larger Arctic integration domain down to about 40°N has been studied by *Jürrens* [1999] and a smaller subdomain was investigated by *Rinke and Dethloff* [2000].

3. Arctic Climate Changes Following Greenland's Deglaciation

[6] Figure 1 shows the mean January and July 2 m temperature from the control run and the difference between the run with removed Greenland orography and the control run. In both months, the control run reproduces the regional temperature minimum over central Greenland. The strongest temperature response due to Greenland's deglaciation appears in the Greenland region itself, but a significant remote temperature increase is in evidence over western Siberia. The dashed contours present the lower limit of 95% significance and indicate regions where the differences are statistically significant. Compared to the control run, the western and southern sides of Greenland and the northern part of the Atlantic Ocean are cooled by up to 6°C, whereas the interior of Greenland is warmed by up to 9°C. These changes are connected with elevation changes, but also with a shift in the cyclonic storm tracks, resolved owing to the high- resolution model and presented in Figure 3. Parts of the Canadian Arctic and the Arctic Ocean are warmer too, potentially influencing the sea-ice cover in that area. The July 2 m temperature changes after deglaciation are mainly notable over Greenland and uniformly distributed over most of the Arctic area being up to 2°C higher.

[7] Figure 2 shows the January and July "precipitation minus evaporation" P-E pattern from the control run and from the run with removed Greenland orography. Over the Labrador and the Barents Seas, evaporation exceeds precipitation during January in both runs, whereas only in the run without Greenland, evaporation is also higher than precipitation between Greenland and Iceland. The strongest P-E changes due to a reduction of precipitation occur at

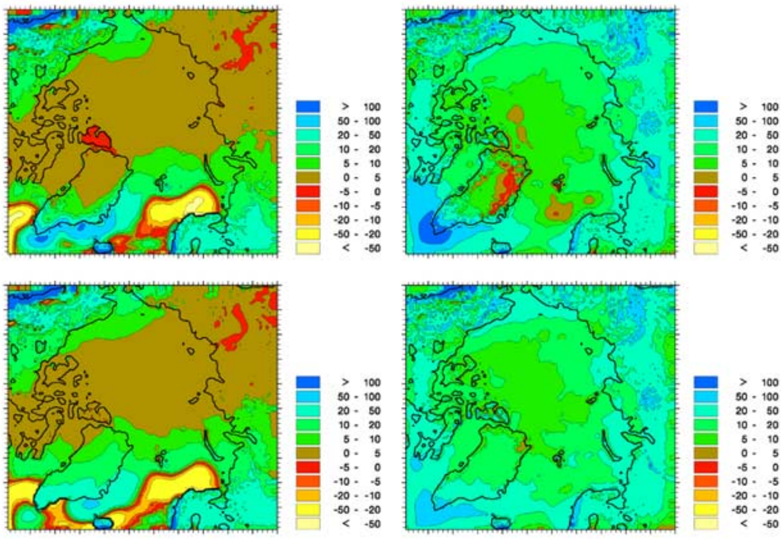

Figure 2. Mean Arctic ‘‘Precipitation minus Evaporation’’ P-E (mm) in January (left column) and July (right column), downscaled with HIRHAM4, top) control run, bottom) deglaciated Greenland run.

Greenland's south coast and over Alaska. These changes are a result of north-eastward shifts in the storm tracks, presented in Figure 3. Such P-E changes would have important consequences for the freshwater input into the Arctic Ocean. *Cubasch et al.* [2000, 2001] reported that changes in the Arctic freshwater forcing have the potential to cause variability in the Arctic Ocean dynamics on centennial to millennial time scales, which indicates the need for analyzing these feedbacks in a coupled atmosphere-ocean-sea-ice system. In the July control run, precipitation exceeds evaporation at the south coast of Greenland and over most parts of the Arctic.

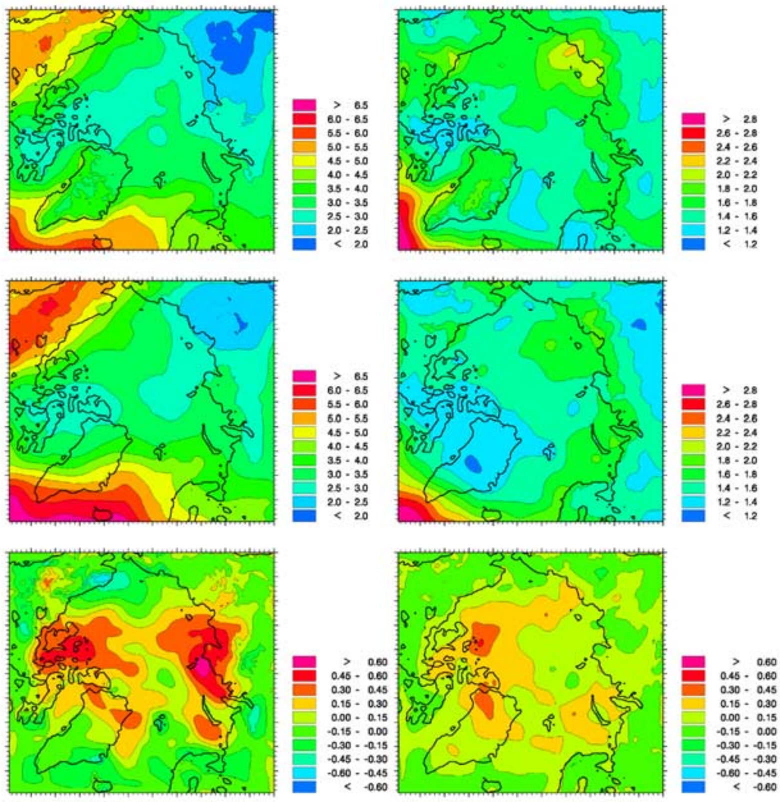

Figure 3. Mean synoptic scale variability (2–6 days) of sea level pressure (hPa) in January (left column) and July (right column), top) downscaled control run with HIRHAM4, middle) deglaciated Greenland run downscaled with HIRHAM4, bottom) Difference (HIRHAM4- AGCM) for the deglaciated Greenland run.

[8] Figure 3 shows as a measure for the synoptic storm activity, the standard deviation of the January and July 2–6 day band-pass-filtered sea level pressure from the control run, from the run with removed Greenland orography and the difference between the RCM HIRHAM4 and the driving AGCM. Greenland's orography, is responsible for the storm tracks around Greenland, described by *Chen et al.* [1997] and simulated by *Dethloff et al.* [2002]. In January, the sensitivity run with removed Greenland orography shows a north-eastward shift of the storm tracks over the North Atlantic as well as an increase of synoptic activity over Alaska connected with a shift of the Pacific storm tracks. The synoptic-scale variability increases over the southern and eastern parts of Greenland and decreases at Greenland's west coast. Stronger synoptic activity appears from the Atlantic Ocean across the Barents and Kara Seas towards Siberia. This could explain why Siberia is warmed and the Siberian high is reduced during winter. The increased synoptic-scale variability at the east coast of Greenland is associated with a mean sea level pressure decrease in this area and a shift of the Islandic low to the north-east. At the same time, the decreased synoptic-scale variability along the north-west coast of Greenland is connected with an increase of the mean sea level pressure, and an enhanced winter polar vortex with conditions more favorable for large stratospheric ozone losses in the Arctic, as reported by *Rex et al.* [2004]. During summer, the storm tracks are generally weaker than during winter, and one main storm track in the Baffin Bay, causing precipitation over the north coastal regions of Greenland [*Chen et al.*, 1997] disappears.

[9] Compared to the driving AGCM the synoptic-scale variability in the RCM shows an enhanced winter cyclonic activity over the Arctic Ocean following the increased resolution and a dipole structure with variability maxima over the Kara Sea and the Canadian Archipelago. Stronger synoptic variability over the Arctic Ocean connected with the development of baroclinic disturbances in the high-resolution experiments occurs also during summer.

4. Conclusions

[10] Greenland's deglaciation exerts a strong influence on the regional circulation structures and storm tracks of the Arctic. The high horizontal resolution leads to substantial changes of regional circulation features compared to the coarse resolution driving AGCM. A north-eastward shift of the storm tracks occurs over the North Atlantic as well as an increase of synoptic activity over Alaska. The strong P-E changes, connected with these shifts in the synoptic storm tracks, would have important consequences for the fresh-water input into the Arctic Ocean and the Nordic Sea with the potential to cause variability in the Arctic Ocean dynamics on centennial to millennial time scales. The significant differences between simulations with and without Greenland are linked to the blocking of cold air masses west of Greenland that result in a decrease of the geopotential height on the upstream side of the mountain during winter and a dominant barotropic response of the Arctic atmosphere. These changes correspond to an enhanced winter polar vortex and stratospheric conditions more favorable for Arctic ozone losses.

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