5.17 SENSITIVITY STUDY OF GREENAND TOPOGRAPHY AND ITS POTENTIAL IMPACT ON THE NORTH ATLANTIC OSCILLATION (NAO)

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1. INTRODUCTION

The North Atlantic Oscillation (NAO) is known to have a variety of important climatic impacts for the North Atlantic basin (Rogers and van Loon 1979). One of its two components, the Icelandic Low (the other is Azores High), is located over Denmark Strait. Therefore cyclone activity, including topographic lee cyclogenesis, over Denmark Strait has a unique climatic significance; the elevation of Greenland Ice Sheet also has an important impact on regional climate.

2. DATA AND METHODS

To reveal this potential impact, we did a sensitivity study with the Greenland Ice Sheet elevation reduced to one tenth of its current height. We ran Polar MM5 version 2 (modifications are based on PSU/NCAR MM5 V3.4) (Li 2003) for the whole month (32 days) continuously without nudging for January 1998 (-NAO month) and January 1999 (+NAO month), discarding the first day's results for model spin-up reasons. The initial and lateral boundary condition are from ECMWF TOGA $2.5^\circ X 2.5^\circ$ 12-hourly global analysis. Sea ice coverages are calculated based on TOGA surface analysis ($1.125^\circ X 1.125^\circ$ resolution). The surface characteristics remain the same as the current Greenland Ice Sheet. The vertical meteorological variables are re-adjusted to the new terrain height when they are interpolated from TOGA pressure levels to the model sigma levels. We call the runs with current ice sheet elevation CT runs, and the runs with reduced ice sheet elevation RT runs.

3. RESULTS

Figure 1 shows the model monthly mean sea level pressure and surface wind using current ice sheet elevation and reduced elevation for January 1998 and 1999. The surface wind over the reduced ice sheet is easterly for both months. In January 1998, the stronger low center moves closer to Iceland in the reduced elevation run with the orientation from southwest to northeast, meaning that the Northern Atlantic is still impacted by frequent storm activity. The significant monthly sea level pressure difference between the current ice sheet elevation and reduced elevation for January 1999 (NAO+) is that the cyclone center near southern Greenland moves to the south of Iceland in RT, therefore southern Greenland cyclogenesis does not exist any more. Because the cyclone center during both the negative NAO month (January 1998) and the positive NAO (January 1999) in reduced elevation runs are both located to the south of Iceland, the North Atlantic Oscillation may not be significant any more. The cyclone paths (not shown) in the reduced elevation runs show that cyclones can move from the southeast coast (Denmark Strait), crossing the ice sheet, to the west coast of Greenland (Baffin Bay). Cyclones along west coast of Greenland in reduced elevation runs maintain their intensity moving northward rather than weakening quickly (due to cut-off of moisture from the underlying sea ice). Along the southeast coast of Greenland, the CT runs display cyclones moving northeastward one after another, while the RT runs show that cyclones sometimes stay over the North Atlantic between Iceland and England for a several days without moving northward, having potentially severe weather effects on England.

Kristjansson and McInnes (1999) did a similar sensitivity study for a 48hour simulation and found that the reduced Greenland Ice Sheet would allow the cold air to enter the rear of the cyclone, increasing the baroclinic instability and eliminating the chance for development of a second cyclone (lee cyclogenesis). The result from this study show similar results, namely the original cyclone gets more and more intense. In northern Greenland, cyclone activity does not exist in the RT runs, which indicates that contemporary cyclonic activity in northern Greenland is also terrain related.

The mean sea level pressure differences between reduced elevation runs and control runs (RT-CT) are shown in Fig. 2. In January 1998 (negative NAO month), the reduced elevation run has a negative pressure deficit over a large area southeast of Greenland, including the North Atlantic. The other pressure deficit area is found over northeastern Canada. Over the west coast of Greenland and northern Greenland, the sea level pressure field from reduced elevation runs is larger than that in control runs. In January 1999 (positive NAO month), a similar sea level pressure difference pattern (-/+/-) is found with different magnitudes and extension. To the east of Greenland, the sea level pressure deficit only covers eastern Denmark Strait and the Greenland Sea. The

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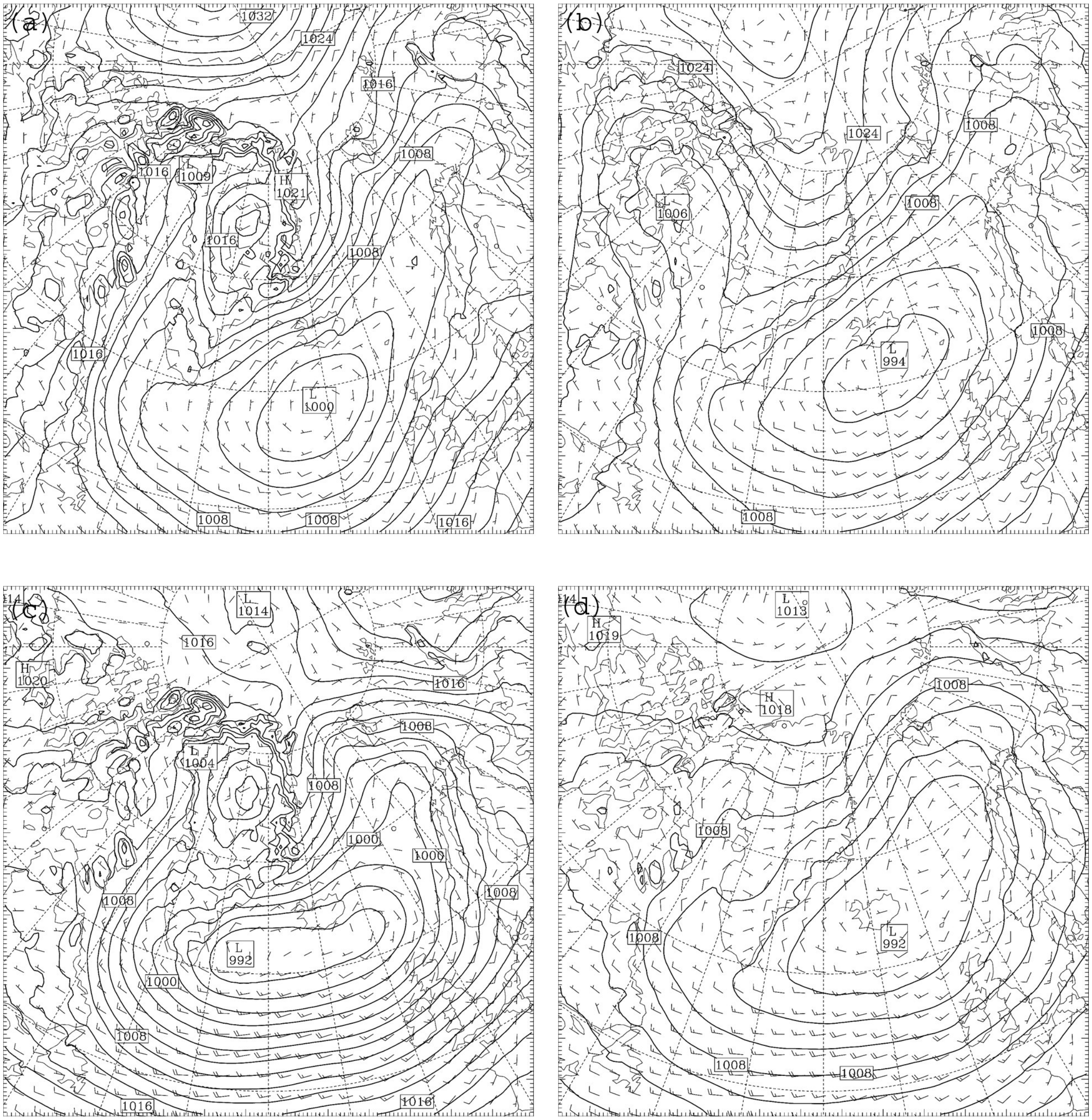

Figure 1 Monthly mean sea level pressure for January 1998 and 1999, respectively. (a): CT run for January 1998, (b): RT run for January 1998, (c): CT run for January 1999, and (d): RT run for January 1999. The contour interval is 2hPa in (a) and (c), and 4hPa in (b) and (d).

northeastern Canadian pressure deficit is very small. In southern Greenland, a large positive pressure difference is found. The differences of sea level pressure field between RT and CT show that in reduced elevation runs, no matter whether it is a negative or positive NAO month, cyclones west of Greenland and to the east of Greenland are stronger, while over the western and northern ice sheet, a strong ridge extends from the Arctic region. The large positive mean sea level pressure difference over the southern tip of the ice sheet demonstrates that the reduced ice sheet leads to less cyclogenesis.

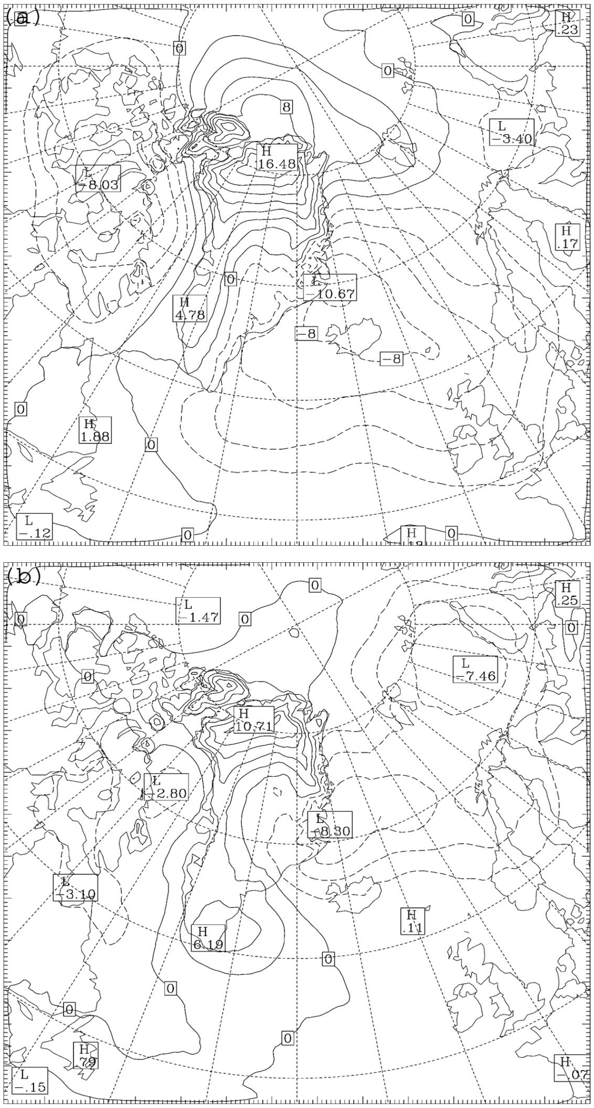

Figure 2 The monthly mean sea level pressure difference between CT and RT for January 1998 (a) and 1999 (b). The dashed lines are negative values. Contour interval is 2hPa.

Upper level geopotential heights and jets also show significant changes from current ice sheet elevation runs to reduced elevation runs (not shown). In the run with current Greenland elevation, a 500hPa trough is located to the west of Greenland in January 1998. In January 1999, this trough is across Greenland's southern tip. In both cases, there is a southerly jet over the Greenland Ice Sheet at 500hPa. In the reduced elevation runs for both January 1998 and January 1999, the 500hPa trough (not shown) moves northward, overlying southern Greenland. A new ridge forms over northern Greenland, destroying the southerly jet crossing the ice sheet. The formation of a ridge over northern Greenland and destruction of the jet crossing the ice sheet are also displayed at 250hPa in the RT runs (not shown). It is not surprising to see that negative values are mainly located over the ice sheet due to the fact that the reduced ice sheet elevation lowers the upper level heights.

4. DISCUSSION

Initial sensitivity study shows that the reduced Greenland Ice Sheet elevation has a significant impact on the regional climate over the North Atlantic, which is very important for the current climate change study because global warming may melt the Greenland Ice Sheet, reducing the ice sheet elevation. The latest IPCC report (2001) points out that if $3.3^{\circ}C$ warmer temperatures are sustained, it will take a million years to melt the Greenland Ice Sheet completely. Higher temperatures will take less time to melt the Ice Sheet. It is likely that consideration of the impact of surface melting on ice flow (Zwally et al. 2002) would result in a much faster ice sheet elevation decrease. In this numerical regional climate change study, we assume that the inflow and outflow boundaries are the same as current ones. The only difference is the reduced ice sheet elevation and meteorological variable re-adjustment over the reduced ice sheet. Because most parts of Greenland are located in the Arctic region, the change of Greenland Ice Sheet height will certainly change the pattern of the polar vortex in the Northern Hemisphere. Consequently it will change the inflow and outflow boundaries for any limited area model. Therefore further Greenland topographic sensitivity study needs more careful design (i.e. needs to include the Azores High to capture the NAO change).

The debate as to whether the NAO and Arctic Oscillation (AO) are the same phenomenon is continuing. The AO is the leading mode of circulation variability with deep, barotropic, zonally symmetric structure in the Northern Hemisphere (Thompson and Wallace 1998). It features a seesaw in atmospheric mass between Arctic and mid-latitudes. As mentioned by Rogers (1984) and others, the NAO is a mass oscillation between the subpolar northern Atlantic and the lower mid-latitudes. By comparing the correlations between different indices and monthly winter season United Kingdom Meteorological Office sea level pressure data, Thompson and Wallace (2000) argue that the NAO and AO are essentially one phenomenon with different names. Despite the inseparability of winter season NAO and AO patterns, Rogers and McHugh (2002) point that the non-winter main AO center is confined to the Eurasian side of the Arctic Ocean basin, which is separate from the non-winter NAO pattern. The inseparability of winter season NAO and AO patterns may be due to their sharing storm tracks in the northern Atlantic and Arctic regions. From the monthly mean sea level pressure field from the sensitivity runs with reduced ice sheet elevation, it is noticeable that the Icelandic Low center is shifted to the south of Iceland, for both positive NAO and negative NAO months. Also remembering that the winter NAO is the most pronounced among all four seasons, we may conclude that the topographic effect of the Greenland ice sheet not only changes the path of cyclone tracks, but also 'creates' the NAO and 'characterizes' the winter AO pattern. Figure 1 can be used to demonstrate the possible NAO change. We list the NAO index from Roger's (1984) raw monthly values for January 1998 and 1999, and associated monthly mean sea level pressure at Akureyri, Iceland ($66^\circ N, 18^\circ W$) from CT and RT runs in Table 1. The station Ponta Delgada, Azores ($38^\circ N, 26^\circ W$) is not listed because it is out of the domain. We can see that the monthly sea level pressure in current positive NAO month (January 1999) remains almost the same value (997.2hPa vs 997.6hPa) in CT and RT runs. For the negative NAO month (January 1998), the monthly sea level pressure depression increases by 4hPa from CT to RT, making the NAO index less negative. Because the station at the Azores is out of the domain, we cannot compare the monthly sea level pressure change at Ponta Delgada, Azores at the present time. It is feasible to study the relationship between winter NAO and AO pattern by using a global climate model such as CCM3 or a coarse limited area model such as MM5, coupled with a limited area mesoscale model (i.e., Polar MM5), to carry out a series of sensitivity studies of the impact of Greenland ice sheet elevation. The domain could cover the entire Northern Hemisphere. The broadscale model will provide better initial fields and inflow/outflow boundary conditions for the limited area mesoscale model. The changed nature of the polar vortex and the positioning of synoptic-scale trough along the east coast of North America will alter the amount of air mass exchange, if not the direction, between high and low latitudes. In this way, we may be able to distinguish the difference between the NAO and AO.

Table 1 Roger's (1984) raw monthly NAO index for January 1998 and 1999, and monthly mean sea level pressure (hPa) at Akureyri, Iceland.

	CT (1998)	RT (1998)	CT (1999)	RT (1999)
Akureyri, Iceland	1006.9	1003.0	997.2	997.6
Roger's NAO index	-6.3		9.8	
MSLP (RT-CT)	-3.9		0.4	

5. ACKNOWLEDGMENTS

This study was sponsored by NSF under grants OPP-9707557 and OPP-0112486

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