ATMOSPHERIC AND OCEANIC SCIENCE LETTERS, 2009, VOL. 2, NO. 6, 376–380

Greenland Ice Sheet Elevation Change in Winter and Influence of Atmospheric Teleconnections in the Northern Hemisphere

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Received 17 September 2009; revised 12 November 2009; accepted 13 November 2009; published 16 November 2009

Abstract The relationship between the variability of the surface elevation of the Greenland Ice Sheet (GIS) in winter and sea level pressure is identified through analysis of data from satellite-borne radar altimeters, together with meteorological data fields during 1993–2005. We found that both the North Pacific Oscillation (NPO) and the North Atlantic Oscillation (NAO), the two major teleconnection patterns of the atmospheric surface pressure fields in the Northern Hemisphere, significantly influence the GIS winter elevation change. Further, it is suggested that the NPO may affect the GIS accumulation by influencing the NAO, particularly by changing the intensity and location of the Icelandic Low.

Keywords: Greenland ice sheet, North Pacific Oscillation, North Atlantic Oscillation, atmospheric teleconnection patterns

Citation: Chen, L.-L., O. M. Johannessen, K. Khvorostovsky, et al., 2009: Greenland ice sheet elevation change in winter and influence of atmospheric teleconnection in the Northern Hemisphere, *Atmos. Oceanic Sci. Lett.*, **2**, 376–380.

1 Introduction

The Greenland ice sheet (GIS), one of the important components of the cryosphere, holds enough ice to raise the global sea level about 7 m if fully melted. Even a modest change in ice sheet mass balance could affect future sea level and freshwater flux to the oceans.

The mass balance of the GIS, which is the balance between the mass input to the ice sheet (accumulation) and the mass loss (ablation, iceberg calving), has a complex linkage to climate variability. Many recent studies have addressed the GIS mass balance, but the estimates are highly scattered and are associated with a large uncertainty (Alley et al., 2007; Lemke et al., 2007).

Since the response of the GIS mass balance to climate forcing is not straightforward, several studies have focused on temperature-related ice core oxygen isotopic studies (Rogers et al., 1998) as well as the NAO-related accumulation studies (Mosley-Thompson et al., 2005). Most of such studies have focused on the annual variability of GIS mass balance; however, fewer studies have focused directly on the relationship between atmospheric circulation variability and the mass balance of the GIS in different seasons.

In this paper, we address how the variability of the GIS mass balance is related to two important patterns of the atmospheric circulation in the northern hemisphere: the North Atlantic Oscillation (NAO) (Hurrell et al., 2003) and the North Pacific Oscillation (NPO) (Wallace and Gutzler, 1981; Trenberth and Hurrell, 1994) during the wintertime, because these pressure patterns are known to affect temperature, precipitation, and wind over Greenland (Hurrell et al., 2003; Johannessen et al., 2005). Therefore, we hypothesize that variability of the NAO and the NPO can explain a substantial part of the GIS mass balance.

Section 2 of this paper presents the data and methods. The results are presented and discussed in section 3. Section 4 presents the summary.

2 Data and methods

The ice-sheet elevation data set used here is surface elevation change derived from merged radar altimeter measurements from European Space Agency (ESA) satellites ERS-1, ERS-2, and Envisat for the period 1993–2005, updated after Johannessen et al. (2005). Surface elevation changes can be translated to volume changes, and are an indicator—rather than a direct measure—of changes of mass balance. Because uncertainties exist when converting surface elevation changes to mass balance (Zwally et al., 2005), in this work, we opted to study surface elevation change.

The seasonally averaged time series of surface elevation have been created using a method similar to the one applied in Johannessen et al. (2005). In addition, a correction for the correlation between elevation and backscatter power measurements was determined and applied (Khvorostovsky and Johannessen, 2009).

The meteorological data analyzed to identify the atmospheric circulation variability are monthly sea level pressure (SLP) fields from the National Center for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR) (Source: http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html). The NAO index is updated from Jones et al. (1997) (Source: http://www.esrl.noaa.gov/psd/data/climateindices/ list/#NAOJONES).

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3 Results and discussion

Since the satellite altimeter-derived data set of GIS elevations is presently available only for 1993–2005, it is possible to investigate the GIS elevation change only for a relatively short, decadal-scale period. In this paper, the GIS surface winter elevation change is defined as the elevation differences between December-January-February and September-October-November.

Figure 1 shows a time series of spatially-averaged surface elevation changes in winter, with several exemplary years of positive (e.g., 1996, 1997, 2002, and 2003) and negative (e.g., 1993, 1995, 2001, 2004, and 2005) elevation change. The elevation change represents primarily the difference between added mass due to snow accumulation and loss of mass due to surface melting and ice flow. Here, ice flow can be seen as a constant for the major part of GIS because of the short time scale, while melting and firn compaction are negligible in winter. Thus, the time series in Fig. 1 effectively show the variations in winter snow accumulation. The positive elevation change values indicate that ice sheet growth due to snow accumulation is larger than surface elevation lowering caused by ice flow, whereas negative values imply that snow accumulation does not compensate for ice flow-induced ice sheet volume decreases. The exemplary positive (1996) and negative (1993 and 1995) elevation change years are consistent with the high and low accumulation years (firn and ice core data) from the Program for Arctic Regional Climate Assessment (PARCA) (McConnell et al., 2001; Rogers et al., 2004). Therefore, the time series in Fig. 1 reasonably describes the variations in winter snow accumulation.

In order to understand the relationship between the GIS surface elevation change and atmospheric circulation, a lagged correlation analysis has been performed between the winter elevation change time series (Fig. 1) and the SLP fields in the Northern Hemisphere. This was performed for four three-month averages of SLP: September-October-November (SON), October-November-December (OND), November-December-January (NDJ), and December-January-February (DJF).

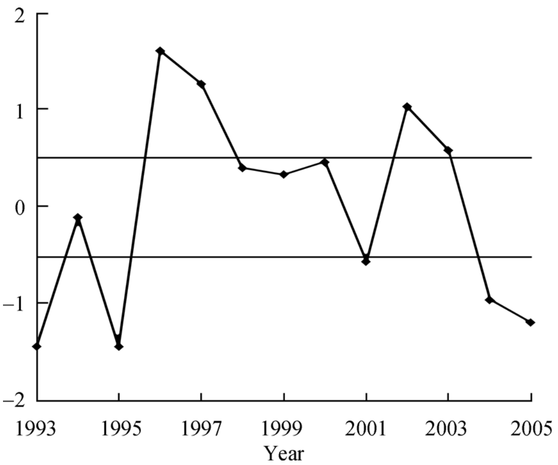

Figure 1 Standardized spatially-averaged changes (linear trend removed) in the winter GIS elevation, 1993–2005. The 1/2 standard deviations are indicated as solid horizontal lines. The values greater than 1/2 absolute standard deviations are defined as the exemplary years of changes.

The significant correlations for all four periods are located mostly in the Arctic, North Pacific, and North Atlantic Oceans (Fig. 2). In the SON period, the signifycant negative correlation ($r \sim -0.6$) areas are in the Pacific Ocean, and the significant positive correlation ($r \sim 0.8$) areas are in northern Canada and the Arctic Ocean. This phenomenon is probably related to the changes of the Aleutian Low and the Polar High. In the OND period, the significant positive correlation area mentioned above has moved to the Beaufort Sea and the northeast of Russia. Another significant positive correlation area, which appears in the Iceland region, is probably related to the changes of the Icelandic Low. In addition, two significant negative correlation areas remain in Northern Pacific Ocean. Furthermore, in the NDJ period, the significant positive correlation ($r \sim 0.8$) area in the Iceland region has increased as compared with that during the OND period, and the significant negative correlation ($r \sim -0.6$) area still exists in the western Pacific. Note that a new significant negative correlation ($r \sim -0.6$) area appears in the southern part of the North Atlantic Ocean. The latter correlation area might be related to the changes of the Azores High. Finally, in the DJF period, there are much fewer systematic significant correlation areas are present.

These correlation analyses show a possible in-phase relationship (positive correlation) between the winter elevation change of GIS and pressure changes of the Polar High and Icelandic Low as well as an out-of-phase relationship (negative correlation) with pressure changes of the Aleutian Low and Azores High. Thus, Fig. 2 reveals that during the SON, OND, and NDJ periods, the pressure variations of the Aleutian Low and Polar High, which are both related to the NPO, may impact the winter elevation change of the GIS. In contrast, during the NDJ period, the pressure variations of the Icelandic Low and Azores High, which are related to the NAO, are the main factor impacting the GIS winter elevation change, as also shown by Johannessen et al. (2005). During the DJF period (Fig. 2d), the NAO still influences the elevation change, but the influence is much weaker than that during the NDJ period. Based on the above analysis, it is suggested that both the NPO and the NAO pattern have a significant impact on the winter surface elevation change of the GIS.

In order to further test the above hypothesis, correlation analysis has been performed between the time series of the winter surface elevation change and both the NAO and NPO indices. The NAO index used here is updated from (Jones et al., 1997) and is based on the normalized SLP series from Gibraltar and Reykjavík. The NPO index is defined as the SLP difference between (65°N, 170°E) and (45°N, 150°W) and is consistent with the definition in Wallace and Gutzler (1981) and Trenberth and Hurrell (1994). As shown in Table 1, the strongest positive ($r \sim 0.88$) and negative ($r \sim -0.77$) correlation coefficients are found, respectively, between the winter GIS elevation change and the NPO index during the preceding OND and

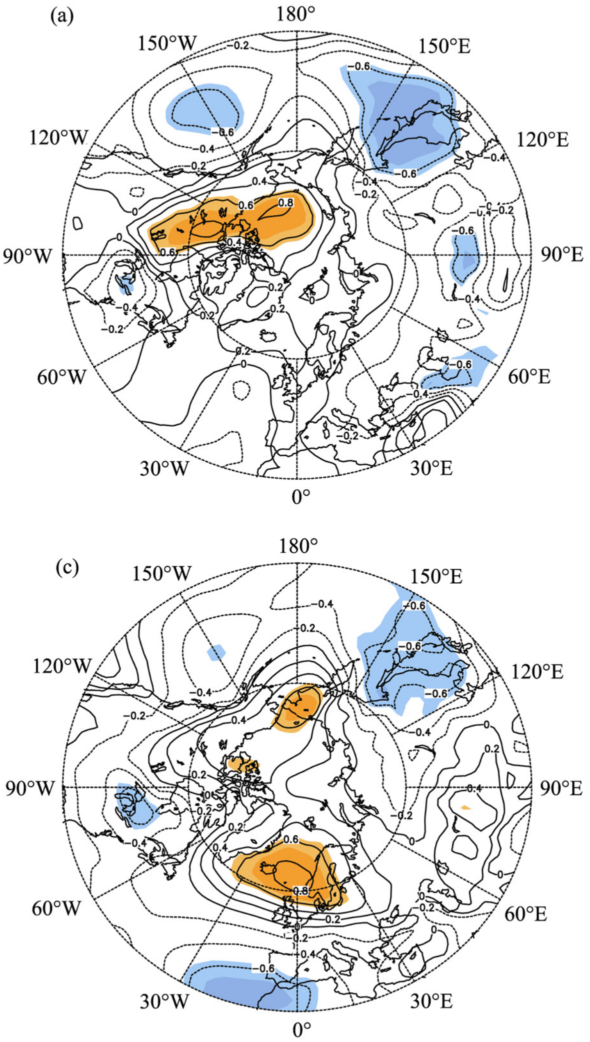

Figure 2 The correlation coefficients between the winter GIS elevation change and SLP fields in the Northern Hemisphere (linear trends removed) for (a) SON, (b) OND, (c) NDJ, and (d) DJF, during 1992/93–2004/05. Dashed lines (blue shadows) show contours below zero and solid lines (yellow shadows) show contours above zero, with only values above the 0.05 significance level shaded.

NAO index during the preceding NDJ. This result is consistent with the spatial distribution of the correlation coefficients between the winter GIS elevation change and the SLP shown in Fig. 2, and therefore supports our original hypothesis that both the NAO and the NPO pattern influence the winter surface elevation change of the GIS. The result is also consistent with the results described by Johannessen et al. (2005), where it was found that the NAO pattern strongly affects the GIS surface elevation change, but without addressing the influence of the NPO. This is the first time that the influence of the NPO pattern on the GIS surface elevation change has been shown.

Table 1 Correlation coefficients between the winter elevation change of GIS and NAO/NPO indices for the period 1992/93–2004/05. The *r* value of the 0.05 significance level is ±0.55.

Climate indices	Correlation coefficient
NAO (SON)	−0.41
NAO (OND)	−0.45
NAO (NDJ)	−0.77
NAO (DJF)	−0.45
NPO (SON)	0.62
NPO (OND)	0.88
NPO (NDJ)	0.82
NPO (DJF)	0.24

However, the NAO and the NPO pattern are not independent because they are both connected in the framework of the Arctic Oscillation (AO) (Thompson and Wallace, 1998) or Northern Annular Mode (NAM) (Thompson and Wallace, 2001). The NPO index during the OND period and the NAO index during the NDJ period (shown in Fig. 3) displayed a strong negative correlation ($r \sim -0.68$) during our observation period. Honda et al. (2001) also estimated that there is an interannual seesaw-like oscillation between the intensities of the surface Aleutian Low and the Icelandic Low, which are the main centers of action of the NPO and the NAO. This seesaw oscillation (Honda et al., 2001) is initiated by the ampli-

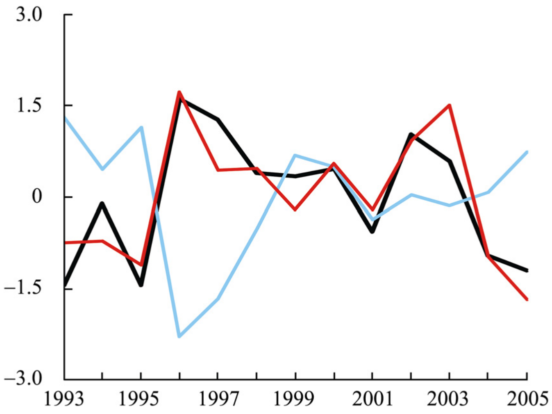

Figure 3 Standardized time series of the GIS winter elevation change (black line), the NAO index (blue line) during the NDJ 1993–2005 period, and the NPO index (red line) during the OND 1992–2004 period.

fication of the Aleutian Low through midwinter and causes the amplification of the Icelandic Low with different signs. This supports our results that the strongest positive correlation ($r \sim 0.88$) between the NPO and the GIS winter elevation is found during the OND period, but the strongest negative correlation ($r \sim -0.77$) with the NAO is found during the NDJ period. Thus, it is suggested that the NPO impacts the winter elevation change of the GIS by influencing the NAO with an approximately 1-month lead.

Figure 4 shows the SLP spatial distribution in the North Atlantic Area during the positive and negative phases of NPO during our observation period. During the significant positive/negative NPO index years, NAO is weaker/stronger than normal. Particularly during the significant positive NPO index years (Fig. 4a), the Icelandic Low splits across the north of Iceland, and the southern low pressure center moves to the south of Greenland, which increases the precipitation in southern part of Greenland (Bromwich et al., 1999; Johannessen et al., 2005).

4 Summary

The GIS winter elevation change has been investigated using merged radar altimeter measurements from the ESA satellites ERS-1, ERS-2, and Envisat during the period from 1993 to 2005. With this new time series, together with NCEP/NCAR reanalysis data, we investigated the relationship between the winter GIS elevation change and the SLP fields during recent years. The results revealed that the NPO during the OND period and the NAO during the NDJ period cause changes in GIS winter elevation. As has been noted previously, the NAO impacts the GIS elevation change by influencing the precipitation via NAO-linked cyclone activity. The current study also indicates that the NPO can affect the GIS elevation change by influencing the intensity and location of the Icelandic Low with an approximately 1-month lead. However, in order to better understand the seasonal variations of the surface elevation change of the GIS, we should directly compare the surface elevation change with accumulation and temperature patterns over Greenland—a study which is underway.

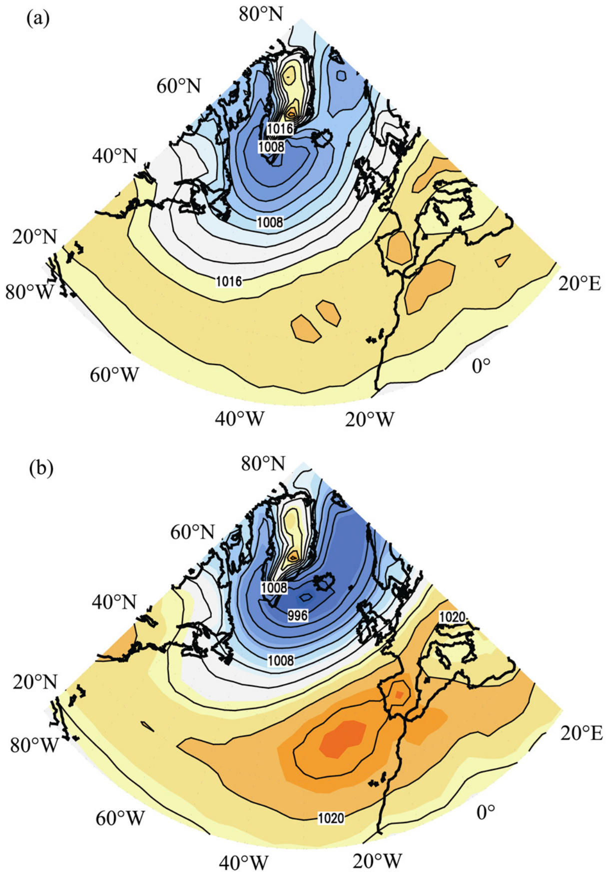

Figure 4 Spatial patterns of SLP fields during the exemplary (a) positive and (b) negative NPO index (shown in Fig. 3) years, October-November-December for the NPO index and November-December-January for the SLP fields. The definition of the exemplary years is the same as in Fig. 1.

Acknowledgements. This research was supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. KZCX2-YW-Q1-02), the National Basic Research Program of China (973 Program, Grant No. 2009CB421406) and the Nansen Scientific Society in Norway.

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