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Increased Tibetan Plateau Snow Depth: An Indicator of the Connection between Enhanced Winter NAO and Late-Spring Tropospheric Cooling over East Asia

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ABSTRACT

The authors present evidence to suggest that variations in the snow depth over the Tibetan Plateau (TP) are connected with changes of North Atlantic Oscillation (NAO) in winter (JFM). During the positive phase of NAO, the Asian subtropical westerly jet intensifies and the India-Myanmar trough deepens. Both of these processes enhance ascending motion over the TP. The intensified upward motion, together with strengthened southerlies upstream of the India-Myanmar trough, favors stronger snowfall over the TP, which is associated with East Asian tropospheric cooling in the subsequent late spring (April–May). Hence, the decadal increase of winter snow depth over the TP after the late 1970s is proposed to be an indicator of the connection between the enhanced winter NAO and late spring tropospheric cooling over East Asia.

Key words: Tibetan Plateau, snow depth, North Atlantic Oscillation (NAO), tropospheric cooling

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1. Introduction

The North Atlantic Oscillation (NAO) has been identified as an important mode of variability in the climate system with important impacts on the climate of the North Atlantic and surrounding regions, especially Europe (Hurrell, 1995; Marshall et al., 2001). Recently, several studies have found that the winter NAO (W-NAO) may influence the climate in East Asia (Gong et al., 2001; Wu and Wang, 2002; Gong and Wang, 2003; Zhou et al., 2009). Yu et al. (2004) showed that the decadal tropospheric cooling to the east of the Tibetan Plateau (TP) in early spring (March–April) was closely connected with the unprecedented long-term positive phase pattern of the W-NAO that dominated after the late 1970s. The decadal cooling over southwestern China in March was suggested to be induced by increased mid-level stratiform clouds, which were related to the stronger westerlies over the TP during the positive phase of the W-NAO (Li et al., 2005). Xin et al. (2006) found that pronounced decadal cooling dominated in the middle-upper troposphere in late spring, which was highly correlated with the positive NAO in the preceding winter. These studies indicated that the increased W-NAO index in recent decades may be an indicator of the East Asian cooling in the subsequent spring. The cooling in the upper troposphere was associated with a low-level

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*Corresponding author: ZHOU Tianjun, Zhoutj@lasg.iap.ac.cn anticyclone and anomalous descending motion, causing southward movement of the rainbelt in East China (Yu et al., 2004; Xin et al., 2006, 2008; Yu and Zhou, 2007). This implies that the phase of the W-NAO may be an indicator of East China precipitation in the following spring. However, the dynamic processes accounting for the linkage between an enhanced W-NAO and subsequent spring tropospheric cooling over East Asia remain unclear.

The atmosphere itself has a memory of less than two weeks due to the chaotic internal dynamics of atmospheric motion (Lorenz, 1965). The snow pack has a considerably longer memory and can provide conditions allowing the NAO to affect the climate in the subsequent season (Qian and Saunders, 2003; Ogi et al., 2003, 2004). Snowfall is largely controlled by atmospheric conditions, and snow pack/snow cover anomalies may potentially affect the large-scale atmospheric circulation by changing heat and moisture fluxes (Morinaga et al., 2003). Observational and modeling studies suggest that there is a significant reduction in the tropospheric temperature as snow cover increases because of the unique properties of snow cover, including high albedo, high emissivity, high thermal conductivity, and also the fact that it serves as sensible heat sink to the atmosphere (Sankar-Rao et al., 1996; Walland, 1996, 1997). Based on results of regional modeling, Liu et al. (2004) showed that heavier snow cover over the TP resulted in atmospheric cooling in the mid-upper troposphere over the Plateau and its surrounding areas in May and June. Zhao et al. (2007) found that increases in the number of days covered by snow in spring (April–May) were associated with decreases in local tropospheric temperature in the spring and early summer (June). It is inferred that the snowfall over the TP might act as a bridge by linking the winter NAO anomaly and subsequent spring tropospheric temperature in East Asia. Although the relationship between Eurasian snow cover and the NAO has been addressed in many studies (Cohen and Entekhabi, 1999; Bamzai, 2003; Hori and Yasunari, 2003; Vicente-Serrano et al., 2007; Li et al., 2008), the possible connection between the NAO and TP snowfall has been little discussed. In this study, evidence is presented to show that a close relationship exists between snow depth over the TP and the NAO in winter. The associated dynamic mechanisms is explored. The relationship between winter TP snow depth and subsequent spring tropospehric temperatures in East Asia is verified.

The rest of the paper is organized as follows. Section 2 describes the data sets and method used in this study. In section 3, the relationship between the NAO and the TP snow depth is investigated and a possible mechanism is proposed. Section 4 verifies the relationship between winter TP snow depth and subsequent late spring tropospheric temperature over East Asia. A summary and concluding remarks are presented in section 5.

2. Data and method

Snow depth data observed at 46 stations (dots in Fig. 1a) with altitude above 2500 m over the TP are used in this study. All the stations have continuous snow depth records for the period 1958–2001, which are archived by the National Meteorological Information Center of the China Meteorological Administration. Note that these stations cover the central and eastern TP. So, "TP" in this study specifically refers to the central and eastern TP. The NAO index used in this study is from Hurrell (1995). We also utilized monthly circulation data from the National Centers for Environmental Prediction–National Center for Atmo-

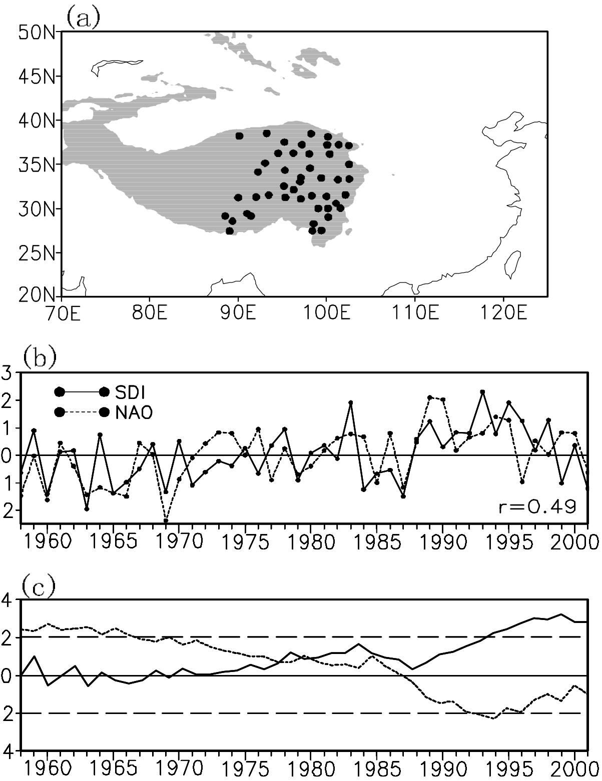

Fig. 1. (a) Distribution of observational stations over the TP. Shaded regions denote where the altitude is above 3000 m. (b) 1958–2001 normalized time series of winter SDI (solid line with filled circle) and NAO index (dashed line with open circle). (c) The forward (solid line) and backward statistic rank series (dashed line) in the Mann-Kendall test of the SDI.

spheric Research (NCEP–NCAR) reanalysis (Kalnay et al., 1996).

Correlation and regression analyses were the main methods used in this study. The statistical significance of the correlations and regressions was examined using Student's t test. The decadal increase of the TP snow depth index was examined with the Mann-Kendall test (Mann, 1945; Kendall, 1975).

3. Relationship between W-NAO and snow depth over the TP

To measure the variability of winter snow depth over the TP, we define a snow depth index (SDI) as the normalized time series of the 46-station averaged observations over the TP for January–March during 1958–2001. Figure 1b shows the time series of SDI along with the winter NAO index. An in-phase relationship is observed between the SDI and the NAO index. The correlation between them is 0.49, statistically significant at better than the 5% level. Note that a coherent covariation of the two indices is also evident on the decadal scale. Both indices show frequent positive anomalies in the 1980s and 1990s, and negative anomalies in the 1960s and 1970s. The decadal increase of the W-NAO after 1980 is well known (Hurrell, 1995). Here, we further verify the decadal changes of the SDI using the Mann-Kendall test. As shown in Fig. 1c, the two (forward and backward progressive) rank series of the test cross during the late 1970s within the 5% significance level zone. This confirms that winter snow depth over the TP also experienced a decadal increase in the late 1970s, which is in accordance with the NAO changes.

To investigate the dynamic mechanisms linking TP snow depth and the NAO in winter, we analyzed the atmospheric circulation changes associated with the winter NAO index. The correlation map between 500 hPa zonal wind and the NAO in winter is shown in Fig. 2. A five-member wave train pattern is apparently observed on the map, ranging from Greenland to the tropical Africa-Arabian Sea region. This pattern is equivalently barotropic in the troposphere, because it is also obvious at 200 hPa (figure not shown). This is consistent with Yang et al. (2004). Note that this five-member wave train pattern still exists if the SDI and 500 hPa zonal wind data are detrended before the analysis (not shown).

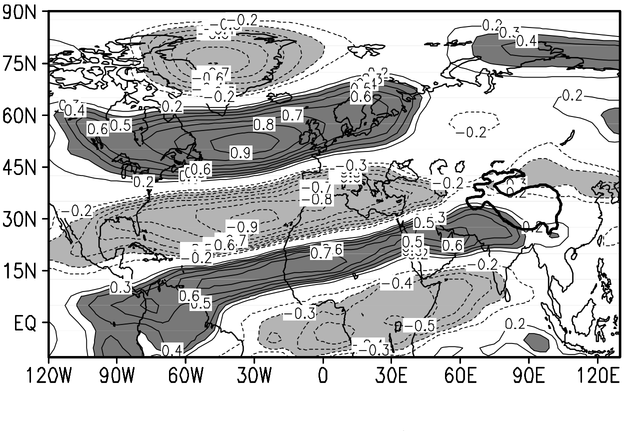

Fig. 2. Correlation between the NAO index and zonal wind at 500 hPa. Shaded regions are statistically significant at the 5% level. The thick black line denotes the location of the Tibetan Plateau (TP).

Among the five-member wave trains, the negative and positive centers in the high latitudes are also typical features of the positive phase of the NAO. Such anomalies associated with the NAO carry warm and moist air to Western Europe, leading to a warm and wet climate there, which has long been recognized (Hurrell, 1995). However, few works have considered the climatic influence of the negative-positive-negative centers of the wave trains extending from the midlatitudes to the tropics associated with the positive NAO. As can be seen, this pattern may be the key factor linking the NAO and the climate in South Asia and eastern Asia. The low-latitude positive band of the wave trains extends from the tropical Atlantic, through North Africa and the Middle East, to the southwestern slope of the TP. The Asian subtropical jet stream prevails from northern Africa to the TP (Yang et al., 2004). Thus, the band of low-latitude positive wind anomalies imply that the Asian subtropical jet stream is strengthened in the positive phase of the W-NAO.

Climatologically, the westerly jet stream over subtropical Asia is deflected by the TP in the lower and middle troposphere, and thereby forms a trough in the India–Myanmar region (Yin, 1949; Wu et al., 1996; Zhang et al., 2001). Since the Asian subtropical jet stream strengthens in the positive phase of the W-NAO, the India–Myanmar trough is inferred to be intensified after 1980, associated with the decadal increase of the W-NAO index. Figure 3 shows the decadal change (1980–2001 mean minus 1958–1979 mean) of the horizontal winds at 500 hPa. Significant changes in the wind vectors are found along the western and eastern flanks of the TP, as well as in the India-Myanmar region. The anomalous airflow indicates that after the anomalously strong jet stream meets the topographic barrier, it flows southeastward, deepens the India-Myanmar trough, and then forms an anomalous cyclonic circulation surrounding the TP. The enhanced southerly wind along the front of the India-Myanmar trough tends to carry more moisture from the Bay of Bengal, favoring excess snowfall over

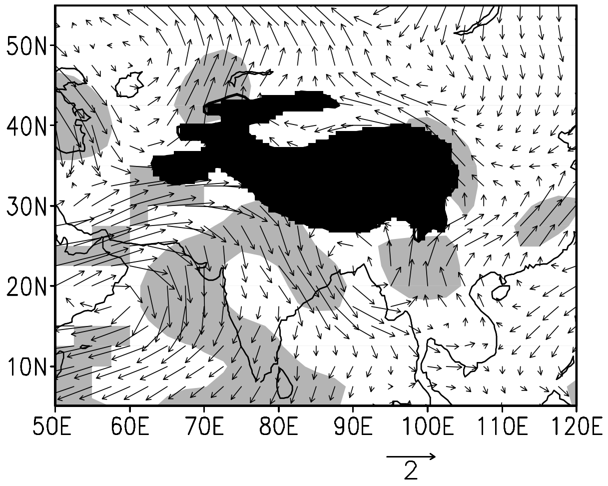

Fig. 3. Decadal changes (1980–2001 mean minus 1958–1979 mean) of winter horizontal winds at 500 hPa. Units of the wind vectors are m s^{-1}. Shaded regions represent changes of the horizontal winds (u or v) are significant at better than the 5% level. The black shaded area denotes the location of the TP.

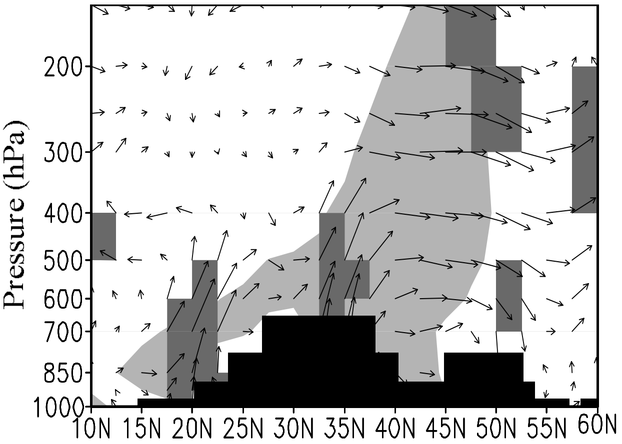

Fig. 4. Latitude–height cross sections of the regression coefficients of winter meridional wind and vertical velocity averaged between 92.5°E and 102.5°E upon the W-NAO index (1958–2001). Light (heavy) gray shaded regions indicate that the regression coefficients of the meridional (vertical) wind component upon the W-NAO index are significant at better than the 5% level. The black shaded area denotes the location of the TP.

the TP.

To further validate the relationship between the atmospheric circulation over the TP and the W-NAO, the winter meridional wind and vertical velocity averaged between 92.5°E and 102.5°E are regressed upon the W-NAO index, respectively. As shown in Fig. 4, following the positive phase of the W-NAO, southerly winds prevail through the whole troposphere and anomalous ascending motions appear over the TP. Both the strengthened southerly winds and the ascending motion favor excess snowfall over the TP. This suggests that the strong positive phase of the W-NAO which dominated after the late 1970s may have been responsible for the increase in snow depth over the TP.

4. Relationship between winter TP snow depth and subsequent late spring tropospheric temperature over East Asia

In this section, the relationship between the winter SDI over the TP and late spring temperatures (April–May, hereafter AM) is examined. Figure 5a shows the regression map of late spring 300 hPa temperature upon winter TP SDI. A significant negative temperature anomaly appears over East Asia associated with the increase of winter SDI. An increase of one standard deviation in the winter SDI corresponds to a reduction of the temperature by about 0.5°C in East Asia. This regression pattern is similar to the decadal change of 300 hPa temperature in late spring shown in Fig. 5b, which demonstrates that the mean temperature over the last two decades was reduced by about 1.5°C in East Asia. The longitude–height section of the regression map of AM temperature along 30°–45°N upon winter TP SDI is shown in Fig. 5c. Associated with the increased SDI, the temperature decreases in East Asia between 500 hPa and 200 hPa, with a center around 300 hPa, which is consistent with the vertical distribution of the decadal change of AM temperature. So it is suggested that the decadal increase of winter snow depth over the TP partly explains the tropospheric cooling over East Asia in AM.

The mechanisms accounting for the linkage between winter TP snow depth and East Asian temperatures in the following season have been explored by many previous studies (Vernekar et al., 1995; Ose, 1996; Zhang and Tao, 2001; Wu and Kirtman, 2007). Wu and Kirtman (2007) found that the TP snow cover and ENSO work cooperatively to enhance spring rainfall in southern China. We also calculated the partial correlation between the winter SDI and late spring tropospheric temperatures after removing the ENSO signal. The partial correlation coefficients are around −0.35 over central China, a result which is significant at better than the 5% level, implying little influence of ENSO on the late spring tropospheric cooling.

5. Summary and concluding remarks

In this study, the relationship between the winter NAO and snow depth over the TP, and the possible mechanisms for their linkage, are investigated using

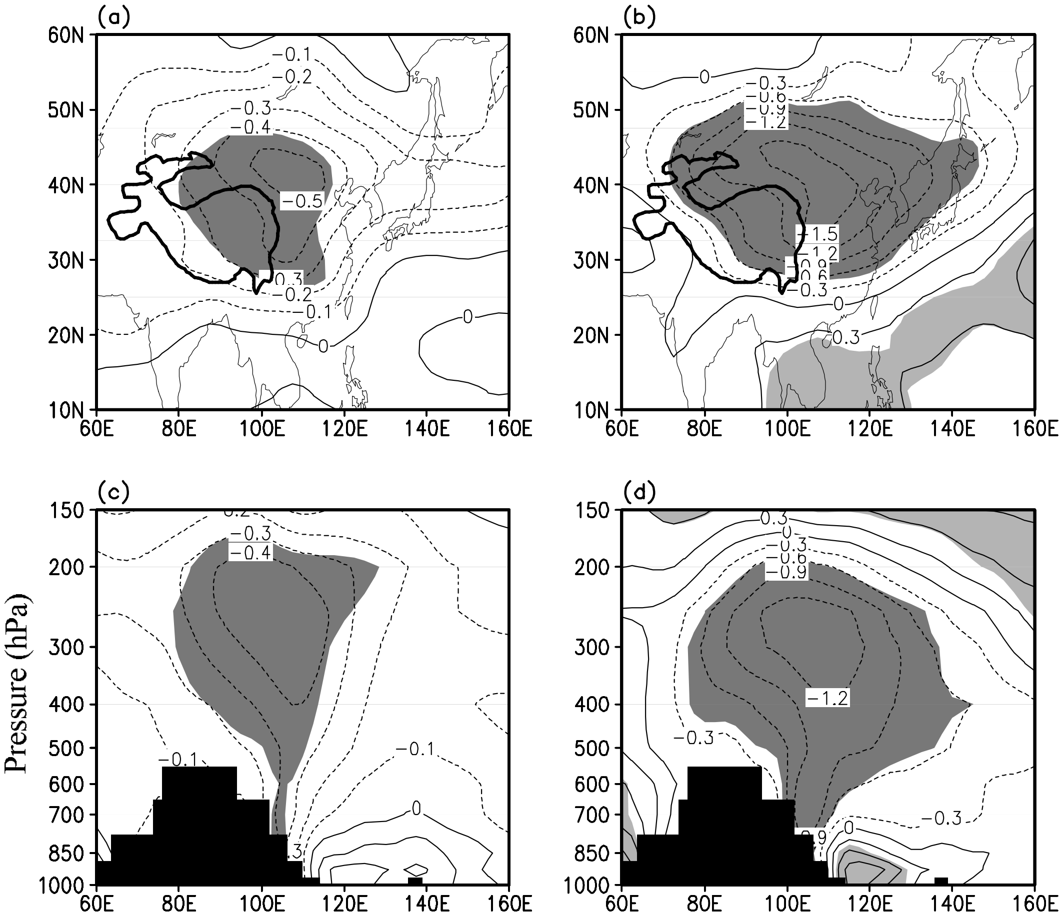

Fig. 5. (a) April–May (AM) air temperature at 300 hPa regressed upon winter TP SDI (1958–2001). (b) Decadal change of AM air temperature at 300 hPa. (c) Zonal–height cross section of the regression coefficients of AM air temperature averaged between 30°N and 45°N upon winter TP SDI (1958–2001). (d) Decadal change of AM air temperature averaged between 30°N and 45°N. Shaded regions are significant at better than the 5% level. The black shaded area denotes the location of the TP. Units are °C per standard deviation of SDI index.

snow depth data and NCEP/NCAR reanalysis data. The relationship between winter snow depth over the TP and the subsequent late spring tropospheric temperature is also examined. Analysis demonstrates that the winter snow depth over the TP underwent a distinct decadal increase after the late 1970s. The increased winter snow depth over the TP was found to be closely associated with the enhanced W-NAO index. During the positive phase of the W-NAO, the Asian subtropical westerly jet is stronger, which deepens the India-Myanmar trough. Thus, more moisture is transported to the TP from the Bay of Bengal in that phase. Meanwhile, low-level convergence appears around the TP, which induces anomalous ascending motion over the plateau. Both the ample moisture supply and the ascending motion are favorable for greater snow accumulation over the TP.

The variation of winter snow depth over the TP is negatively correlated with the subsequent late spring tropospheric temperatures over East Asia. The increased TP snow depth after the late 1970s may have been one important factor resulting in the cooling of the troposphere over East Asia in late spring. Therefore, these decadal scale increases in snow depth are suggested to act as a bridge linking the enhanced positive W-NAO pattern and the late spring tropospheric cooling over East Asia in recent decades.

This study is mainly based on statistical analysis, and thus the suggested causal relationships need to be confirmed by numerical experiments. Further work is also necessary to understand the physical processes linking increased winter snow depth over the TP and late spring tropospheric cooling over East Asia. The present analysis still does not explain why the maximum cooling appears at 300 hPa.

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