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The Effect of the Wintertime Arctic Oscillation on Springtime Vegetation over the Northern High Latitude Region

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Abstract: The winter Arctic Oscillation (AO), a major source of climate variability in the Northern Hemisphere, affects winter and the subsequent spring climate over northern high latitude. Such effects are evident even in the 1st eigenmode of the normalized difference vegetation index (NDVI). The impacts of the winter AO is a dipole pattern between Eurasia and North America; positive (negative) values of the winter AO induce warmer (cooler) and high (low) vegetation activity in the following spring over Eurasia (North America). Regarding the time-lagged response of vegetation, the sea surface temperature (SST) and snow cover contribute to maintaining the large-scale circulation anomaly associated with the AO.

Key words: Arctic oscillation, vegetation, NDVI, northern high latitude

1. Introduction

It is very important to understand the response of vegetation greenness to climate variability because vegetation can potentially provide feedback to the climate through albedo, evapotranspiration, and roughness. Furthermore, an understanding of the vegetation greenness response provides insight into carbon cycle issues. Forests in the northern high latitudes, collectively known as the taiga, are mostly located in Siberia and Canada. The taiga represents one of the largest boreal forest areas in the world. The boreal regions play an important role in the global climate system because they are involved in strong feedbacks due to contrasted snow and vegetation energy budgets.

Previous works have stressed the strong impact of the surface air temperature (SAT) on the growth of vegetation over boreal regions (Myneni *et al*., 1997; Tucker *et al*., 2001; Zhou *et al*., 2001; Liu *et al*., 2006). It should be noted that the SAT does not exhibit temporally and spatially homogeneous variations, but instead displays coherent patterns of spatial heterogeneity related to hemisphere-scale circulation features (Thompson and Wallace, 1998). Thus, in addition to forcing meteorological variables, the relationship between vegetation and climate indices has been studied so as to determine inter-annual vegetation variability. For example, over the mid-latitude to high-latitude Northern Hemisphere, the nine most important climate indices explain more than half of the inter-annual variability in the magnitude of the NDVI (Gong and Ho, 2003; Gong and Shi, 2003). Buermann *et al*. (2003) showed that during spring the two predominant hemisphere-scale modes of the covariability between vegetation and temperature are related to teleconnections associated with the El Niño-Southern Oscillation and the AO.

The AO is a natural climate cycle in the Northern Hemisphere (Thompson and Wallace 1998, 2001; Lee, 2014). The positive trend in the winter AO has led to higher winter temperatures, advanced spring (Schaefer *et al*., 2005). The AO or Northern Annular Mode (NAM; Thompson and Wallace, 2001) and the North Atlantic Oscillation (NAO) are closely related and can be largely viewed as expressions of the same phenomenon. Sometimes NAO is thought be a regional counter part of AO. The AO pattern contains the NAO, which may be considered a different view of the same phenomenon (Thompson and Wallace, 2000).

The winter variability of the AO/NAO is known to have a time-lagged influence on the subsequent spring and summer climate (Rigor *et al*., 2002; Ogi *et al*., 2003, 2004; Qian and Saunders, 2003; Yu and Zhou, 2004; Sung *et al*., 2006, Xin *et al*., 2006, 2010; Li *et al*., 2008). The wintertime AO persist through the subsequent spring and autumn SAT (Rigor *et al*., 2002). Specifically, the influence of the AO appears over the Northern hemisphere (Lin *et al*., 2009; Sung *et al*., 2010). When the AO index is in the high and positive phase the atmospheric pressure over the Arctic is lower than average. The persistent cyclonic surface winds over Arctic is related with warming trends over Eurasia with strengthened westerly. This is associated with an increase in winter temperature and amount of precipitation (Hurrell and van Loon, 1997; Thompson and Wallace, 2000; Aanes *et al*., 2004; Yun *et al*., 2014).

The AO has also been linked to phenological measurements of averaged regions around Europe and western Russia (Stöckli and Vidale, 2004). De Beurs and Henebry (2008) noted the widespread influences of the AO and NAO on land surface phenologies across northern Eurasia. Furthermore, it has been reported that the NAO is a predictive index, since the January-February NAO index is strongly correlated with the onset of vegetation that occurs around the month of April in

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Northern Europe (Maignan *et al*., 2008). Gouveia *et al*. (2008) also addressed the strong impact of the winter NAO on vegetation dynamics in spring and summer over the Iberian Peninsula and Northeastern Europe. And for Asia, the impacts of winter NAO on biosphere productivity over China were reported (Wang and You, 2004). Previous results have indicated that the winter AO/NAO could be used as one of the components for estimating vegetation greenness in the coming spring.

Few studies have investigated the lagged influence of the AO/NAO on vegetation over Europe (Maignan *et al*., 2008; Gouveia *et al*., 2008) and over Asia (Wang and You, 2004). Therefore, this study has been conducted on the lagged influence of the winter AO on vegetation activity in the spring over the total boreal forest region. Thus, we investigated the impact of the winter AO on vegetation activity in the following spring over the northern high latitudes. This paper is divided into four sections. Data employed in our work is first described in Section 2. The lagged relationship between the winter AO and spring vegetation is outlined in Section 3. The role of SST and snow cover is discussed in Section 4. Finally, summary and discussion are provided in Section 5.

2. Data and methods

The NDVI data used in this study were taken from the Global Inventory Monitoring and Modeling Studies (GIMMS) group, who derived the data from Advanced Very High Resolution Radiometers (AVHRR) on board the National Oceanic and Atmospheric Administration (NOAA) series of meteorological satellites. Specifically, the data was acquired at a spatial resolution of 8×8 km^2 and a 15-day interval for the period of 1982 to 2006 (Pinzon *et al*., 2005; Tucker *et al*., 2005). Non-vegetation effects are reduced by analyzing only the maximum NDVI value within each month, a process that is termed compositing. For the analysis of atmospheric circulation, which is related to vegetation growth, the NCEP/NCAR reanalysis dataset (Kalnay *et al*., 1996) and the European Centre for Medium Range Weather Forecasts Interim Reanalysis dataset (Dee *et al*., 2011) for the same period from 1982 to 2006 were employed.

Although the AO and the NAO indices are highly correlated, the AO index is used in this study because it captures more of the hemispheric variability in the atmospheric circulation (Thompson and Wallace, 1998). The AO is an index of the dominant pattern of non-seasonal sea-level pressure variations north of 20°N latitude, and is characterized by pressure anomalies of one sign in the Arctic with the opposite anomalies centered about 37°N-45°N (Thompson and Wallace, 2000). We used the AO index from the Climate Prediction Center (source: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html).

Monthly values of the snow cover area were obtained from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/snow). Monthly snow cover frequencies and frequency anomalies are also computed by merging weekly data in monthly values. The snow cover, NOAA's Optimum Interpolation (OI) SST anomalies (Reynolds *et al*., 2002) and ERA-Interim snow depth (Dee *et al*., 2011) were analyzed to determine the lagged relationship between the winter AO and vegetation in the spring.

In order to investigate the spatially coherent patterns of temporal variations of the vegetation over the northern high latitudes, an Empirical Orthogonal Function (EOF) analysis is conducted for the NDVI. We calculate the correlation coefficients and the linear regression coefficients of the spring vegetation with the preceding winter AO index in order to clarify the relationship between them on an inter-annual time scale. The statistical significance is determined by the student *t*-tests under the assumption that the sample data are independent. All of our analyses were carried out using de-trended data. In this study, spring (winter) is defined as the period from April to May (January to March).

3. Winter AO and spring vegetation

The lagged response in climate is reflected in the regression field of the NDVI with the winter AO over a particular northern high latitude region (Fig. 1). The horizontal pattern of the spring NDVI related to the winter AO shows a dipole pattern between Eurasia and North America that does not have the same sign over the circumpolar region, though so many researchers reported positive trend of vegetation over the total boreal region during recent decades (Myneni *et al*., 1997;

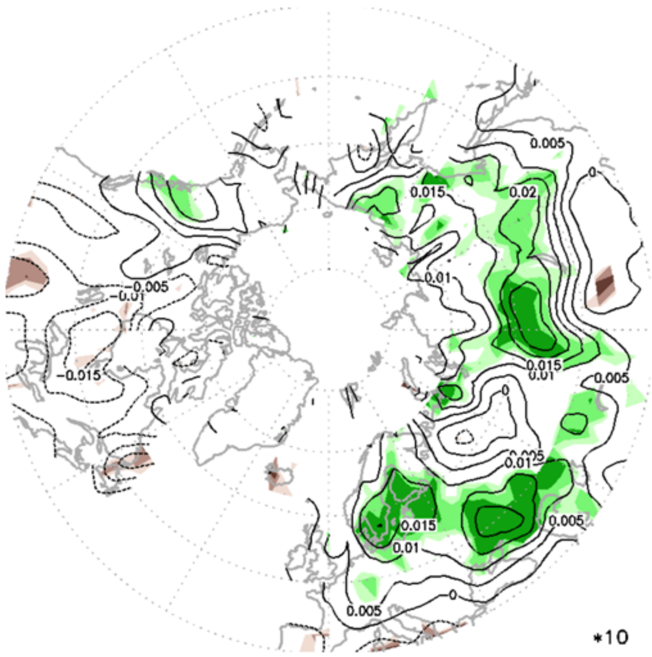

Fig. 1. Maps for the regression coefficients of the spring NDVI with the AO in the previous winter for the area above 40°N. The shaded regions are the statistical confidence levels; light, middle light, and heavy shadings indicate that the regression coefficients exceed the 90%, 95%, and 99% confidence levels, respectively.

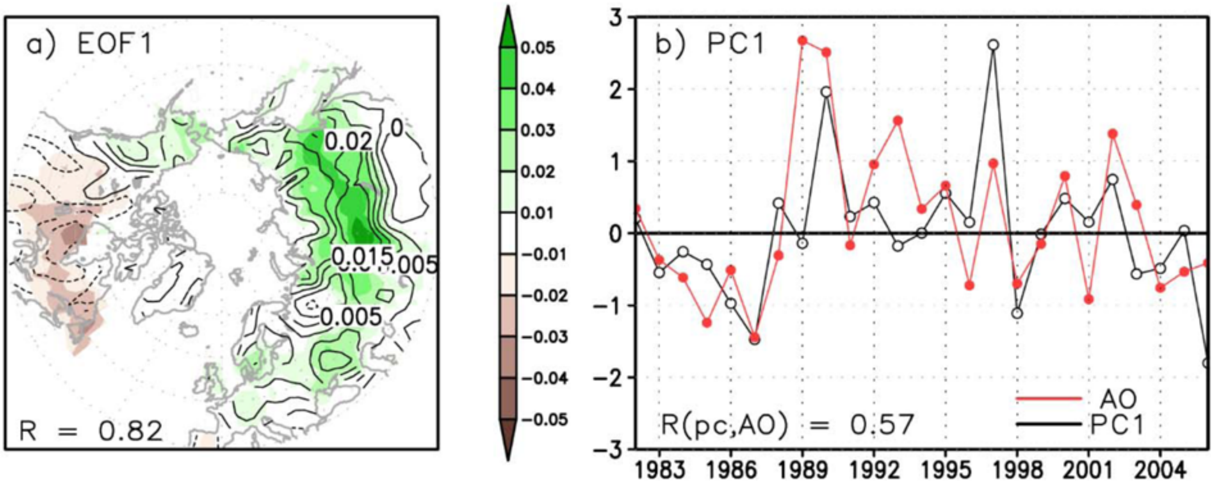

Fig. 2. (a) First leading eigenvectors of the NDVI (shadings) and regression coefficients of the NDVI with the AO in the previous winter (contours). (b) Principal component obtained from the EOF analysis of spring NDVI anomalies over the northern high latitudes above 40°N and the winter AO index.

Tucker *et al*., 2001; Zhou *et al*., 2001). The field shows positive areas over Eurasia and Alaska, and negative areas over North America. That is, when the winter AO is in a positive phase, the vegetation activity in the coming spring tends to be stronger in Eurasia and weaker in North America, although the statistically significant area is smaller in North America than in Eurasia.

The lagged relationship between the NDVI and AO in Fig. 1 is considerably similar to the 1st mode of the NDVI in the EOF analysis. Using EOF analysis, spatially coherent patterns of the temporal variations of vegetation are extracted over the northern high latitudes. The eigenvectors and associated principle components (PCs) for the first leading EOF mode of NDVI, which explains about 17% of the total variance, is shown in Fig. 2. A clear dipolar structure with positive values over Eurasia and negative values over North America is evident. That is, when the greenness of vegetation for Eurasia is compared with that of North America on an inter-annual time scale, there are seesaw like variation between Eurasia and North America (Fig. 2a). An examination of the regression coefficients of the NDVI with the winter AO (contour) and eigenvectors (shading) revealed that their patterns are well-matched with a spatial correlation coefficient value of 0.82. Temporarily, the correlation coefficient between the principle components and the winter AO index is 0.57 at the 1% significance level (Fig. 2b). Therefore, it seems possible that the AO is the origin of the dipolar pattern of vegetation activity between the two continents. The winter AO can explain 17% of the variability in the greenness in subsequent spring over the northern high latitude region, which is almost entirely covered with natural forest, namely the taiga.

Here, we explore the question of how the winter AO modulates the vegetation greenness in the subsequent spring and induces a dipole pattern between two continents. Because the SAT and precipitation are key factors that influence vegetation growth, we have calculated correlation coefficients among those climate variables and the NDVI. The correlation coefficients between the SAT and NDVI in spring are shown in Fig. 3a. On both continents, the NDVI is positively correlated with the temperature anomaly in the spring at the 1% significance level. There is a marked dependence of vegetation greenness on the SAT in spring over the northern high latitudes. In contrast to the SAT, precipitation has little impact on the greenness in spring over the boreal forest (not shown). This is consistent with the results of numerous studies, where the SAT was described as an important determinant of the biological activity over the northern high latitudes (Myneni *et al*., 1997; Tucker *et al*., 2001; Zhou *et al*., 2001; Liu *et al*., 2006). The winter AO modulates the vegetation greenness (as shown in Figs. 1 and 2), and the growth of vegetation is highly dependent on SAT anomalies (Fig. 3a). The SAT is therefore expected to be the link connecting the winter atmospheric variability (AO) and spring vegetation.

Accordingly, we have calculated the regression field of the spring SAT anomaly with the previous winter AO; the results are shown in Fig. 3b. As expected, the horizontal pattern of the spring SAT related to the winter AO exhibited a dipole pattern between Eurasia and North America. The field shows a seesaw effect between the warm area over Eurasia and the cool area over North America. This is an indicator that, when the winter AO is in a positive phase, in subsequent spring Eurasia tends to be warmer and greener, while North America tends to be cooler and less green in the subsequent spring; the situation is reversed in the negative phase.

We also calculated the correlation coefficients among the winter AO, SAT anomalies, and NDVI anomalies with spatially averaged fields, and compared the interrelationships between North America and Eurasia (Figs. 3c-f). We have selected two regions, Eurasia (50°N-70°N, 0°E-180°E) and North America (40°N-70°N, 60°W-120°W). The taiga, the vast forest area

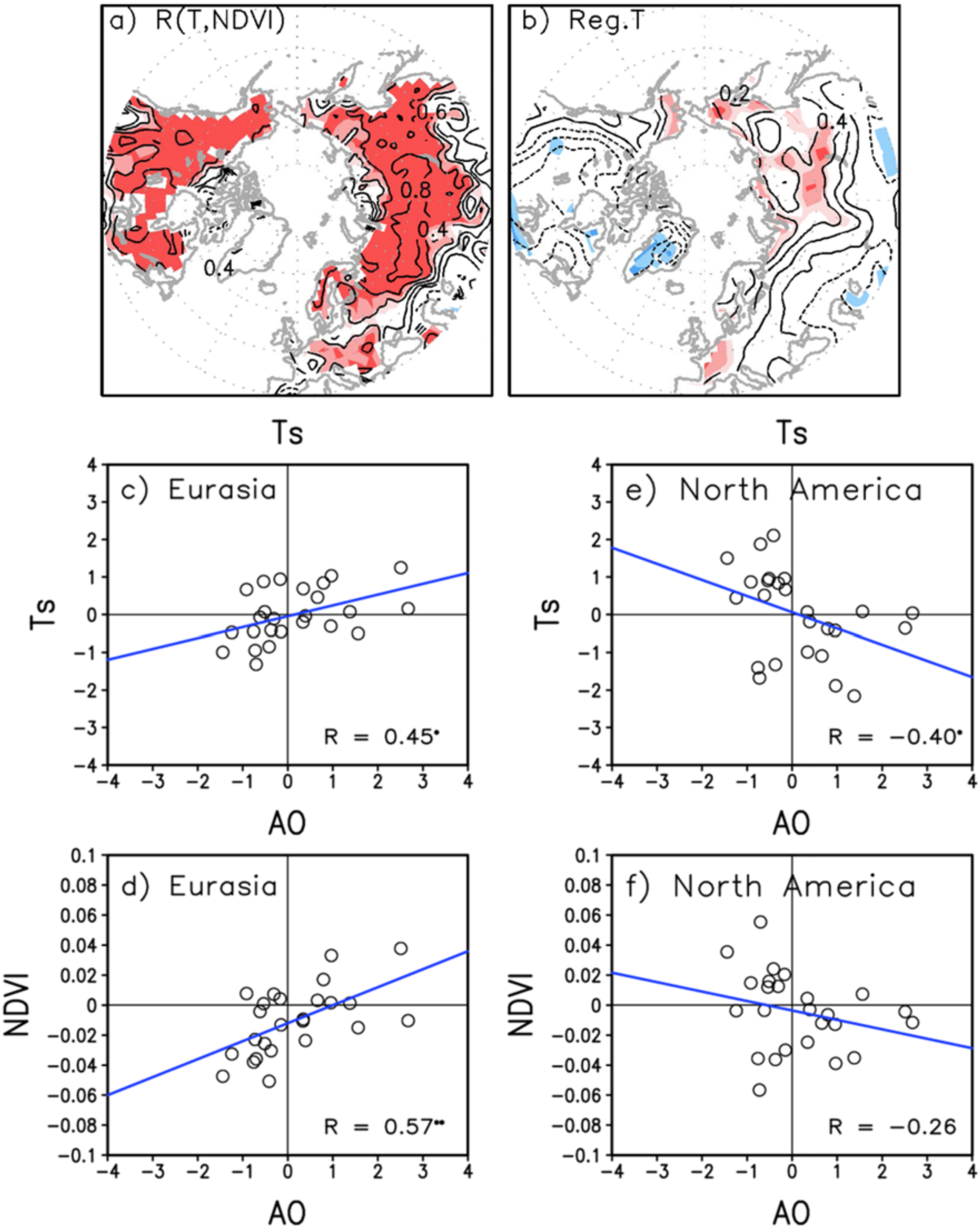

Fig. 3. Maps for the correlation coefficients of (a) the spring SAT and (b) the regression coefficients of the spring SAT with the AO in the previous winter for the area above 40°N. (c-f) Scatterplots of the spatially averaged spring NDVI and the SAT anomaly against the AO in the previous winter is shown over (c, d) Eurasia and (e, f) North America; "R" is the correlation coefficient. The double (single) asterisk denotes that the statistical confidence exceeds the 99% (95%) level. The shading convention is the same as that employed in Fig. 1.

surrounding the globe which contains a third of all trees on Earth, is distributed over these regions. Because Alaska has a few vegetation, this region was excluded. A significant positive correlation between the SAT (NDVI) in spring and AO in the previous winter is observed in Eurasia (Figs. 3c, d). Eurasia shows a strong vegetation response to the AO index at the 1% significance level, which means an increase (decrease) in vegetation greenness in spring for the previous positive (negative) AO winter. It is shown that the correlation between AO and NDVI is higher than that between AO and SAT. Over

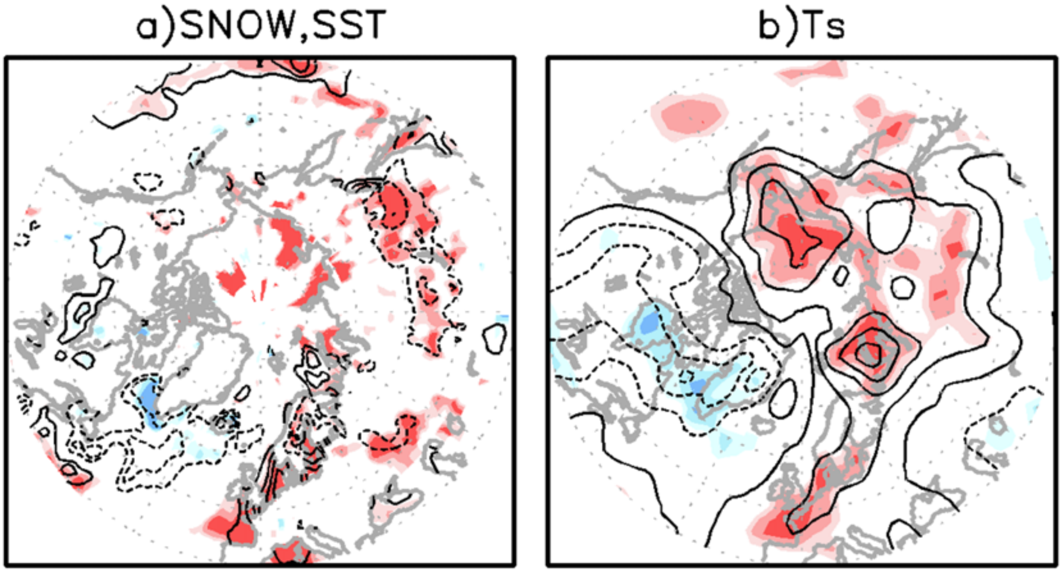

Fig. 4. Maps for the regression coefficients of the spring (a) SST and snow cover with the AO in the previous winter (40^{o}N-90^{o}N). Contours over the oceans are regression values of the SST, while contours over land are regression values of the snow cover. The spring (b) SAT regressed against the winter AO is shown. The shading convention is the same as that employed in Fig. 1.

the boreal forest, the onset of vegetation could be influenced by snow melt as a moisture supply. Earlier snow melts induced from higher SAT and positive AO could bring higher vegetation activity, therefore the higher correlation between AO and NDVI. On the other hand, negative correlations of the SAT and NDVI against the AO index are observed over North America (Figs. 3e, f). The correlation coefficient between the SAT and AO index is −0.4, which is significant at the 5% significance level.

4. The role of SST and snow cover

In this section, we consider how the lagged influence of the AO is possible. Generally, it is known that, when compared with ocean, sea ice and snow, the atmosphere does not have a long memory beyond one month. Therefore, many previous studies have suggested that sea ice, snow cover extent, and SST contribute to allowing the winter variability of the AO/NAO to affect the climate of the subsequent spring (Rodwell *et al*., 1999; Rigor *et al*., 2002; Peng *et al*., 2002, 2003; Ogi *et al*., 2003, 2004). The role of the SST and snow cover is reflected in the regressed maps of the SST and snow cover over land in spring against the AO in the previous winter (Figs. 4a, b). In Fig. 4, the contours over oceans (land) are regression values of the SST (snow cover); the shadings denote the statistical significance level. Red colors in Fig. 4 denote a warmer SST and less snow cover over land for the positive AO index in the previous winter. Specific features are evident over Eurasia and the North Pacific. Blue colors in Fig. 4 indicate a cooler SST and more snow cover for the positive AO index in the previous winter. Such features appear over the North America and the North Atlantic. These anomalous SST patterns related with AO/NAO are consistent with the results of several previous studies (Rodwell *et al*., 1999; Peng *et al*., 2002; Ogi *et al*., 2003; Rimbu *et al*., 2003). This indicates that the influence of the wintertime AO is attributed to the role of the ocean in maintaining the AO effect.

In addition to the SST anomalies, less snow cover in the spring is observed in conjunction with the positive AO in the previous winter over Eurasia. In contrast to the Eurasian continent, North America appeared to have more snow cover in the spring following the positive AO in the winter. This is consistent with a previous study; the timing of thawing over Siberia is controlled by the winter NAO due to its strong influence on the SAT (Livingstone, 1999). When snow melts over the forest, the change in albedo is large and may enhance the warming process. As a result, there is positive feedback between temperature and snow. A positive SAT anomaly, caused by the positive AO polarity, leads to thinner and more fractured snow, lower albedo, earlier spring snow melt, an earlier spring SAT rise, and a positive spring SAT anomaly; the consequences of the negative winter SAT anomaly are opposite. To explore the relationship between temperature and snow, we examine the variations of monthly-mean SAT and snow depth anomalies in association with the AO index. To help delineate the signal from the noise, we have focused that exceed one standard deviation as being high or low AO index. The Fig. 5 depicts the monthly SAT and snow depth anomaly composite for that exceed one standard deviation of AO index; 1989, 1990, 1993, 2002 for high AO index and 1985, 1987, 2001 for low AO index. There is a positive SAT anomaly and negative snow depth anomaly from winter to early spring over Eurasia and vice versa over North America.

The anomalous snow cover signals appear when snow melts

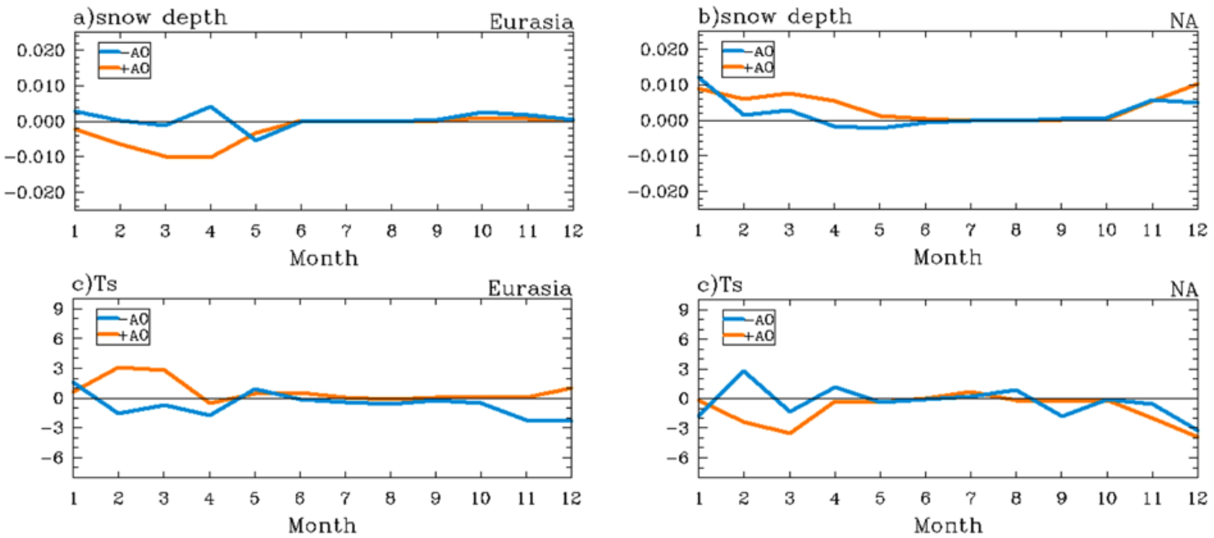

Fig. 5. The spatially averaged monthly SAT and snow depth anomaly composite for that exceed one standard deviation of AO index is shown over (a, c) Eurasia and (b, d) North America.

in spring over Eurasia between 50ºN and 60ºN (Fig. 4a). As mentioned above, snow cover affects local atmospheric heating through snow-albedo feedback during the melting season. Warming occurs over Eurasia, the Arctic Ocean, the North Pacific, and Alaska, while cooling takes place over North America and the North Atlantic Ocean. The local heating signal is more distinctive over Chukchi Sea, Barents Sea and Norwegian Sea (Fig. 4b).

As shown in Figs. 4 and 5, the lagged response is widespread over the northern high latitude lands, indicating that the lasting memory may reside in some large scale forcing like the SST and snow cover. It seems possible that the indirect lagging influence of the winter AO on the spring SAT and vegetation activity is manifested through the duration of the period of high surface albedo, provided by snow and ice, and through a portion of solar heat absorbed by melting snow and ice.

5. Summary

In this study, we investigated the effect of AO-induced climate variability on vegetation greenness. The winter variability of the AO/NAO is known to have a lagged influence on the subsequent spring and summer climate (Ogi *et al*., 2003; Qian and Saunders, 2003; Sung *et al*., 2006). We examined the time lagged vegetation response induced by the AO, one of the major sources of climate variability in the Northern Hemisphere. The relationship documented here may enable the AO index to serve as a predictor for spring vegetation greenness over the northern high latitudes. Some 17% of the spring vegetation variance is explained by the previous winter's AO variations. Though previous studies (Wang and You, 2004; Gouveia *et al*., 2008; Maignan *et al*., 2008) stated that the AO has predictive characteristics for specific region, in this study, we suggest the winter AO as one of the predictive components of vegetation greenness or dynamics in subsequent spring over the total northern high latitudes.

The AO atmospheric mode in the winter was found to modulate the vegetation activity (anomalous NDVI) in the subsequent spring over the northern high latitudes. The time-lagged response of the vegetation corresponds to the 1st mode of the NDVI. The pattern correlation between the 1st mode eigenvector of the NDVI and the regression coefficient is considerably high with the value 0.82, while the correlation coefficient between the PCs and the AO index time series is 0.57. Such results indicate that the winter AO controls vegetation activity. Vegetation responses related to the AO appear as a dipole pattern between Eurasia and North America. The positive (negative) values of the winter AO induce high (low) vegetation activity in the following spring in Eurasia and vice versa in North America.

The time lagged influence of the AO is related to the SST and snow cover. Ogi *et al*. (2003) suggested that the SST and snow cover act to maintain the impact of the AO. In this study, the surface temperature associated with the AO mode primarily contributes to the dipole pattern of vegetation greenness in the high latitudes. As consistent with the findings of Ogi *et al*. (2003), the persistence of the preceding winter temperature in Eurasia and North America is related to the SST and snow cover, which maintain the atmospheric surface temperature conditions into the spring season.

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