Dominant Modes of Interannual Variability in Eurasian Surface Air Temperature during Boreal Spring

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ABSTRACT

This study investigates interannual variations of surface air temperature (SAT) over mid- and high latitudes of Eurasia during boreal spring and their association with snow, atmospheric circulation, and sea surface temperature (SST) changes. The leading mode of spring SAT variations is featured by same-sign anomalies over most regions. The second mode features a tripole anomaly pattern with anomalies over the central part opposite to those over the eastern and western parts of Eurasia. A diagnosis of surface heat flux anomalies suggests that snow change contributes partly to SAT anomalies in several regions mainly by modulating surface shortwave radiation but cannot explain SAT changes in other regions. Atmospheric circulation anomalies play an important role in spring SAT variability via wind-induced heat advection and cloud-induced surface radiation changes. Positive SAT anomalies are associated with anomalous westerly winds from the North Atlantic Ocean or with anomalous anticyclone and southerly winds. Negative SAT anomalies occur in regions of anomalous cyclone and northerly winds. Atmospheric circulation anomalies associated with the first mode have a close relationship to spring Arctic Oscillation (AO), indicating the impact of the AO on continental-scale spring SAT variations over the mid- and high latitudes of Eurasia. The atmospheric circulation anomalies associated with the second mode feature a wave pattern over the North Atlantic and Eurasia. Such a wave pattern is related to a tripole SST anomaly pattern in the North Atlantic Ocean, signifying the contribution of the North Atlantic Ocean state to the formation of a tripole SAT anomaly pattern over the mid- and high latitudes of Eurasia.

1. Introduction

Surface air temperature (SAT) is a key variable for climate. SAT anomalies have a large impact on the society, economy, and lives of people. For example, a low summer temperature over northeastern China has pronounced influence on regional crop yield (e.g., Sun et al. 1983; Yao 1995). SAT anomalies over Eurasia during boreal spring–summer may influence the Asian summer monsoon through modulating the land–sea thermal contrast. Positive (negative) SAT anomalies over Eurasia may result in an increase (a decrease) in the meridional land–sea temperature gradient, leading to a stronger (weaker) Asian summer monsoon (Liu and Yanai 2001; D’Arrigo et al. 2006). Hence, a better understanding of the Eurasian SAT variability and its factors is of great importance for improving the regional climate prediction.

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Boreal spring surface conditions (e.g., SAT and snow cover) over Eurasia play an important role in linking the preceding winter atmospheric circulation anomalies to the following summer climate anomalies. This is because the atmosphere itself does not have a long memory beyond one month (e.g., Gong and Ho 2003; Ogi et al. 2003). For example, Ogi et al. (2003) indicated that spring surface temperature anomalies over the North Atlantic and Eurasian snow cover anomalies over western Eurasia and central Asia play an important role in linking the boreal wintertime North Atlantic Oscillation (NAO) and the following summertime atmospheric circulation over the subtropics of the Northern Hemisphere. Thus, investigation of Eurasian boreal spring SAT variability and its factors may improve our understanding regarding climate variability in the following summer.

Studies have been conducted on SAT variability over Eurasia. Miyazaki and Yasunari (2008) investigated the dominant interannual variability of winter SAT over Asia and the surrounding oceans. They showed that the first mode of interannual variability of winter SAT, featuring a north–south dipole pattern, has a close relationship to the wintertime Arctic Oscillation (AO). Gamiz-Fortis et al. (2011) examined the dominant patterns of monthly land surface temperature variability over Europe. Chen et al. (2016) analyzed the interannual variation of summer SAT over northeastern Asia and its associated atmospheric circulation anomalies. The first mode, featuring a homogeneous anomaly, has a close connection with the Eurasian teleconnection pattern. Wu et al. (2010, 2011, 2014b) identified interdecadal changes in the influence of El Niño–Southern Oscillation (ENSO), North Atlantic sea surface temperature (SST), and regional snow on northeastern China summer SAT variations. Ye et al. (2015) examined the relationship of interdecadal changes among SAT, snow cover, and atmospheric circulation during boreal winter and spring around the late 1980s. However, few studies have examined the dominant modes of spring SAT anomalies over Eurasia on interannual time scales. One goal of this study is to examine the leading modes of boreal spring Eurasian SAT anomalies on the interannual time scale.

Eurasian snow cover changes may exert significant influences on SAT anomalies via the snow–albedo effect and the snow–hydrological effect (Barnett et al. 1989; Yasunari et al. 1991). Wu et al. (2014a) revealed a good correspondence of spring SAT anomalies with the snow anomaly pattern. However, the correspondence does not distinguish the cause and effect. Surface air temperature change may be a cause for snow anomalies as well. Hence, another goal of this study is to examine whether snow change plays a role in spring SAT variability over Eurasia.

Studies showed that the increasing trend in SAT over mid- and high-latitude Eurasia during the past few decades is attributed mainly to the fact that the AO has a tendency toward the positive polarity (e.g., Thompson and Wallace 1998). On the interannual time scale, SAT anomalies over most parts of Eurasia tend to be positive (negative) when AO is in its positive (negative) phase (Thompson and Wallace 1998, 2000; Gong et al. 2001; Wu and Wang 2002). Previous studies regarding the connection between AO and SAT anomalies primarily focused on boreal winter. Studies indicated that the SAT anomalies over Eurasia are associated with remote SST forcing through the large-scale atmospheric circulation pattern (Wu et al. 2014a; Ye et al. 2015). This indicates that SAT anomalies could be an important factor for spring Eurasian SAT interannual variability. Hence, the third goal of this study is to examine the roles of spring AO and SST anomalies in Eurasian spring SAT variability on the interannual time scale.

The rest of the paper is organized as follows. Section 2 describes the datasets and methods used in this study. Section 3 documents the leading modes of interannual variability of spring SAT over the mid- and high latitudes of Eurasia. Section 4 investigates the roles of snow change in the formation of SAT anomalies via analyzing surface heat fluxes. Section 5 analyzes atmospheric circulation anomalies associated with the leading modes of spring SAT anomalies and the impacts of AO and the North Atlantic SST anomalies on spring Eurasian SAT variability. Section 6 gives a summary and discussion.

2. Data and methods

The present study employs monthly mean geopotential height and vertical velocity at 500 hPa, winds at 850 and 200 hPa, surface (10 m) winds, total cloud cover (TCC), and surface heat fluxes (including latent and sensible heat flux and shortwave and longwave radiation) from the National Centers for Environmental Prediction–U.S. Department of Energy (NCEP–DOE) AMIP-II reanalysis (Kanamitsu et al. 2002) from 1979 to the present. Surface winds, TCC, and surface heat fluxes are on T62 Gaussian grids. Winds at 850- and 200-hPa geopotential height and 500-hPa vertical velocity are on a regular 2.5° latitude–longitude grid. We also employ surface heat fluxes from the Japanese 55-year Reanalysis Project (JRA-55) provided by the Japan Meteorological Agency (Kobayashi et al. 2015) to confirm the results obtained from the NCEP–DOE AMIP-II reanalysis.
This study uses monthly mean SAT provided by the University of Delaware for the period 1900–2010 (Matsuura and Willmott 2009). This dataset has a horizontal resolution of $0.5^\circ \times 0.5^\circ$ and is available online (http://www.esrl.noaa.gov/psd/data/gridded/). Monthly mean precipitation data used in this study are derived from the Global Precipitation Climatology Project (GPCP) from 1979 to the present (Adler et al. 2003). This precipitation dataset has a horizontal resolution of $2.5^\circ \times 2.5^\circ$. The monthly mean SST dataset used in this study is obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST, version 3b (http://www.esrl.noaa.gov/psd/data/gridded/). This SST dataset is on a regular 2$^\circ$ latitude–longitude grid from 1854 to the present.

The boreal spring [March–May (MAM)] seasonal mean snow cover data are constructed from the Northern Hemisphere 25-km Equal-Area Scalable Earth Grid (EASE-Grid) weekly Snow Cover and Sea Ice Extent, version 3, product (Brodzik and Armstrong 2013). Note that the original weekly mean snow cover data have been converted into a monthly mean on a regular 1$^\circ \times 1^\circ$ grid. These EASE-Grid snow cover data are available after October 1966 and are obtained from the National Snow and Ice Data Center (NSIDC) through the anonymous ftp at ftp://sidads.colorado.edu/pub/DATASETS. We also use the boreal spring seasonal mean satellite-derived EASE-Grid snow water equivalent (SWE) data on a regular 1$^\circ \times 1^\circ$ grid for the period 1967–2007 provided by the NSIDC.

Present analysis focuses on the interannual variability. The interannual component of anomalies of all variables is obtained by a 9-yr high-pass Lanczos filter (Duchon 1979) applied to original monthly mean anomalies. We examined the percent SAT variance explained by the interannual component of SAT anomalies over Eurasia during boreal spring. Results indicate that the interannual component of SAT anomalies can explain above 70% of original SAT anomalies over most parts of Eurasia (figure not shown).

### 3. Dominant modes of spring SAT anomalies

We perform an empirical orthogonal function (EOF) analysis to obtain the dominant modes of interannual variability of boreal spring (MAM) SAT over the Eurasian continent for the period 1979–2010. The area we chose for EOF analysis extends from 40$^\circ$ to 70$^\circ$N and from 0$^\circ$ to 140$^\circ$E as the land area to the east of 140$^\circ$E is small. Note that SAT anomalies in the EOF analysis are weighted to account for the decrease of area toward the pole (North et al. 1982a). The SAT anomalies associated with EOF1 and EOF2 over areas larger than the domain of EOF analysis are obtained by regression onto the corresponding principal components (PC1 and PC2). Figure 1 shows the distribution of SAT anomalies corresponding to the first two EOF modes and their corresponding PC time series of the MAM Eurasian SAT anomalies on the interannual time scale. The first and second EOF mode explains 39% and 18%, respectively, of the total variance. These two modes are well separated from the other modes based on the method of North et al. (1982b).

The first EOF mode is characterized by same-sign SAT anomalies over Eurasia (Fig. 1a). In the positive EOF1 phase, positive SAT anomalies greater than 1.2$^\circ$C are located to the northwest of Lake Baikal and over the Russian Far East. Relatively small positive SAT anomalies, with a magnitude of generally around 0.4$^\circ$C, are seen over southern Europe (Fig. 1a). By contrary, SAT anomalies over northern Europe are small and insignificant (Fig. 1a). The PC1 time series display large positive values in 1990 and 1997 (Fig. 1c). A large negative value is observed in 1999 (Fig. 1c).

The second EOF mode features a tripole anomaly pattern with same-sign SAT anomalies over western Europe and around 120$^\circ$E extending northward from 40$^\circ$ to 65$^\circ$N and opposite-sign SAT anomalies around 60$^\circ$E extending northward from 40$^\circ$ to 70$^\circ$N (Fig. 1b). In the positive EOF2 phase, negative SAT anomalies reach $-1^\circ$C around 60$^\circ$E. In comparison, positive SAT anomalies are weaker over western Europe (0.4$^\circ$C) than around 120$^\circ$E (0.6$^\circ$C) (Fig. 1b). The PC2 time series show a large negative value in 1995 (Fig. 1d).

The spatial distribution of EOF1 mode appears similar to that of the interdecadal SAT change in the late 1980s shown by Ye et al. (2015). This indicates that the SAT anomaly pattern in EOF1 may be common to both interannual and interdecadal variations. We have applied the EOF analysis to the original SAT anomalies. The obtained EOF1 mode, which explains about 44% of the total variance, displays a spatial distribution similar to Fig. 1a and the corresponding PC1 time series includes both interannual and interdecadal variations (figures not shown). The interannual fluctuation of the PC1 time series is similar to Fig. 1c and an interdecadal change is observed around the late 1980s. The EOF2 mode, which explains about 14% of the total variance, shows a spatial distribution very similar to Fig. 1b and the corresponding PC2 time series is very similar to Fig. 1d.

### 4. Roles of snow change in the SAT anomalies

In this section, we address the possible roles of snow change in the formation of SAT anomalies. We first examine the snow cover extent (SCE) and snow water equivalent anomalies corresponding to the leading two
EOF modes of SAT anomalies. Then, we perform an analysis of surface heat flux anomalies to understand whether and where snow anomalies contribute to the SAT anomalies.

**a. Snow anomalies**

Snow may influence the SAT through the snow–albedo effect and the snow–hydrological effect (Barnett et al. 1989; Yasunari et al. 1991). In the snow–albedo effect, the change in snow cover influences surface temperature through modulating surface net shortwave radiation (SWR). The snow–hydrological effect involves the consumption of heat for melting snow and the moistening of the surface with the melted snow. The increased soil moisture may enhance surface evaporation. These may induce a decrease in surface temperature. Figure 2 shows spring SCE and SWE anomalies associated with EOF1 and EOF2 of the Eurasian spring SAT obtained by regression upon the PC1 and PC2 time series.

Corresponding to EOF1 of Eurasian spring SAT, SCE anomalies over the Eurasian continent display a dipole pattern. Significant positive anomalies around 60°E extend northward from around the Caspian Sea to northern Siberia and significant negative anomalies cover the regions located around and to the southeast of Lake Baikal (Fig. 2b). The distribution of SWE anomalies bears some resemblance to that of SCE anomalies (Figs. 2b,d). In comparison, SWE anomalies cover smaller areas and are located at higher latitudes (Figs. 2b,d), a feature similar to that associated with EOF1 (Figs. 2a,c). Negative SCE and SWE anomalies to the southeast of Lake Baikal may contribute partly to the formation of positive SAT anomalies there as less snow cover may reduce surface albedo and result in an increase in SWR absorbed by the surface and less SWE may increase the amount of heat used to warm the surface (Figs. 1b, 2b, and 2d). Negative SAT anomalies

In comparison, a significant decrease in SWE is located at higher latitudes than the negative SCE anomaly (Figs. 2a,c). This result is consistent with Ye et al. (2015) who documented the interdecadal changes in spring SCE, SWE, and SAT around the late 1980s. The good correspondence between snow and temperature anomalies suggests a role of snow change in the formation of SAT anomalies (Figs. 1a, 2a, and 2c).

**Fig. 1.** Boreal spring (MAM) SAT anomalies (°C) obtained by regression on the normalized PC time series corresponding to (a) EOF1 and (b) EOF2 of the interannual component of Eurasian (40°–70°N, 0°–140°E) MAM SAT anomalies during 1979–2010. (c),(d) The normalized PC time series corresponding to EOF1 and EOF2 of Eurasian MAM SAT, respectively. Stippling denotes anomalies significantly different from zero at the 95% confidence level according to the Student’s $t$ test. The boxes in (a) and (b) denote regions used for constructing area-mean anomalies provided in Figs. 6a–c and 6d–f, respectively.
around 60°E extending from 50° to 65°N may be attributed partly to positive SCE and SWE anomalies there through the snow–albedo effect and modulation of heat consumption for snowmelt (Figs. 1b, 2b, and 2d). Inconsistent changes between snow and SAT are observed over several regions both in the first and second modes. Corresponding to the first mode, significant and positive SAT anomalies over the Russian Far East correspond to insignificant SCE changes (Figs. 1a and 2a). Significant positive SAT anomalies extend to 70°N whereas pronounced negative SCE anomalies are confined to the south of 55°N (Figs. 1a and 2a). The region of significant positive SAT anomalies extends to 40°N where SCE and SWE changes are small (Figs. 1a, 2a, and 2c). Significant increases in SAT over the western part of southern Europe correspond to small SCE and SWE changes (Figs. 1a, 2a, and 2c). Corresponding to the second mode, a significant increase in SAT over western Europe corresponds to insignificant SCE and SWE changes (Figs. 1b, 2b, and 2d). Significant and negative SAT anomalies around 60°E extend to 40°N whereas a significant decrease in SCE (SWE) is confined to the north of 50°N (55°N) (Figs. 1b, 2b, and 2d). A significant decrease in SCE and SWE around 120°E is confined to the regions between 45° and 55°N whereas a large and significant increase in SAT extends northward to 65°N and southward to 40°N (Figs. 1b, 2b, and 2d). The above discrepancies between SAT and snow changes indicate that the snow effect cannot explain the formation of SAT anomalies in many regions.

b. Surface heat flux anomalies

Snow changes may induce SAT anomalies through the snow–albedo effect and the snow–hydrological effect (Barnett et al. 1989; Yasunari et al. 1991). On the other hand, positive (negative) SAT anomalies may, in turn, provide a favorable thermal condition for snow consumption (accumulation). This makes it difficult to separate the snow effect on the SAT anomalies. The effect of snow on temperature is through surface heat flux changes. Thus, in this subsection, we analyze surface heat flux anomalies to identify possible contributions of snow changes to SAT variability.

Snow changes can modulate surface heat fluxes in different ways. Snow anomalies affect SWR through changing surface albedo. More (less) snow cover may lead to less (more) SWR absorbed by the surface and result in a decrease (increase) in SAT. Snow amount influences the consumption of heat for snow melting. Less (more) snow reduces (increases) the part of heat for snow melting. Consequently, more (less) heat is used for
surface warming given the same heat input. This may lead to an increase (decrease) in SAT because the thermal condition in the snow surface can be communicated to the surface air quickly. This effect can be captured by the change in surface sensible heat flux (SH) through the temperature difference between surface air and ground surface and is also reflected in the change in surface upward longwave radiation (LWR) that depends on ground surface temperature. Less (more) snow is accompanied by an increase (decrease) in upward SH as the land–air temperature difference may increase (decrease) and is associated with an increase (decrease) in upward LWR because the ground surface temperature is higher (lower). More (less) snow increases (decreases) soil moisture when snow melts. This leads to an increase (decrease) in upward surface latent heat flux (LH) through the humidity difference between ground surface and surface air. The SWR and LWR may be influenced by cloud. An increase in cloudiness may lead to a decrease in downward SWR and an increase in downward LWR. Hence, to understand SWR and LWR anomalies, we also need to examine the total cloud cover changes.

Figures 3 and 4 show anomalies of spring surface net heat flux (NHF), SH, LH, SWR, and LWR as obtained by regression on the normalized PC1 and PC2, respectively, of Eurasian spring SAT. In addition, anomalies of spring TCC anomalies related to EOF1 and EOF2 of Eurasian spring SAT are shown in Fig. 5. In the
following, positive surface heat flux anomalies denote they are downward, acting to warm the surface. Note that surface heat flux anomalies obtained from JRA-55 (figures not shown) are in good agreement with those of NCEP–DOE AMIP-II reanalysis. Hence, in the following, we only present the results derived from the NCEP–DOE AMIP-II reanalysis.

Corresponding to EOF1 of the spring SAT, a significant increase in NHF is observed from northern Europe through eastern Siberia (Fig. 3a). Over southern Europe, the Russian Far East, Mongolia, and northern China, a change in NHF is weak and insignificant (Fig. 3a). The increase in NHF is dominated by SH over northern Europe, the eastern European Plain, and northern Siberia (Figs. 3a,b). The LH has a negative contribution to NHF over most regions north of 50°N (Figs. 3a,c). A significant increase in SH is also observed over the Russian Far East where an increase in NHF is insignificant (Figs. 3a,b). An increase in SH over northern Europe cannot be explained by the SWE decrease (Figs. 3b and 2c). A decrease in LH over northern Europe, the eastern European Plain, and western Siberia (Fig. 3c) cannot be explained by a decrease in SCE and SWE (Figs. 2a,c). A significant increase in SWR is observed over western Europe (Fig. 3d). An increase in SWR over the southern part of western Europe cannot be explained by the SCE change, but may be attributed to a decrease in cloudiness (Figs. 2a, 3d, and 5a). An increase in SWR over the northern part of western Europe is related to a decrease in SCE (Figs. 2a and 3d) and an increase in cloudiness has a negative effect (Figs. 3d and 5a). An increase in SWR is weak and insignificant over eastern Siberia (Fig. 3d) possibly because the snow–albedo effect related to decreases in SCE and

![Fig. 4](image-url)
SWE is compensated by the cloud–albedo effect associated with an increase in TCC (Figs. 2a, 2c, and 5a). In the cloud–albedo effect, more TCC reflects more downward shortwave radiation, leading to a decrease in downward shortwave radiation reaching the surface and thus a smaller SWR. An increase in SWR around and to the east of Lake Baikal may be related to the decrease in TCC (Figs. 3d and 5a). The spatial pattern of LWR and SWR changes. Significant LH anomalies are mainly observed in the region of 50°–65°N and 40°–60°E (Fig. 4c), which appears to be partly attributed to an increase in SWE (Fig. 2d).

The above results indicate that snow change contributes to SAT anomalies in several regions primarily through modulating SWR. SHF anomalies over many parts of Eurasia cannot be explained by changes in SCE or SWE. In addition, SWR and LWR changes over many parts of Eurasia follow anomalies of TCC more closely than those of SCE and SWE. As such, other factors may play an important role in spring SAT anomalies over Eurasia, which will be addressed in section 5.

c. Comparison of area mean anomalies

To further examine the contribution of snow changes to SAT anomalies, in the following, we calculated anomalies of surface heat fluxes, SCE, SWE, and TCC averaged over several selected regions, which are outlined in Fig. 1. The three regions selected for the EOF1 mode are located in southern Europe (45°–55°N, 5°–50°E), the central part of Eurasia (45°–68°N, 70°–120°E), and the Russian Far East (60°–70°N, 130°–175°E) (Fig. 1a). The three regions selected for the EOF2 mode are located in western Europe (45°–65°N, 5°–25°E), western Siberia (45°–65°N, 50°–80°E), and eastern Siberia (45°–65°N, 100°–130°E) (Fig. 1b). The three regions for the EOF1 mode show the same-sign SAT anomalies, but with different impacts of snow and atmospheric circulation changes, which will be shown later. The results are shown in Figs. 6a–c for the EOF1 mode and Figs. 6d–f for the EOF2 mode.

For EOF1 of the spring SAT, in southern Europe (Fig. 4b), a large SWR increase is nearly cancelled by a decrease in LWR, LH, and SH, leading to a small increase in NHF. An increase in SWR is mainly attributed to a decrease in snow. In the central part of Eurasia (Fig. 4c), significant LH anomalies are mainly observed in the region of 50°–65°N and 40°–60°E (Fig. 4c), which appears to be partly attributed to an increase in SWE (Fig. 2d).
increase in SH and a decrease in LH cannot be explained by SWE and SCE decreases. In the Russian Far East (Fig. 6c), an increase in NHF is mainly attributed to an increase in SH that is inconsistent with the SAT increase. An increase in SH in this region cannot be explained by a decrease in SWE and SCE.

Overall, changes in SH associated with EOF1 of the Eurasian spring SAT in the three selected regions are not related to SCE and SWE anomalies. In southern Europe, SWR is the main contributor to the SAT increase. In the central part of Eurasia, an increase in SAT is attributed to increases in SH and SWR. In the Russian Far East, an increase in SAT is mainly attributed to an increase in SH.

For EOF2 of the Eurasian spring SAT, in western Europe (Fig. 6d), increases in LH and SH have a positive contribution to the NHF increase. An increase in SWR is small possibly because of a cancellation between the cloud–albedo effect and the snow–albedo effect. In western Siberia (Fig. 6e), SWR is the main contributor to the NHF decrease. The LH has a negative effect on the NHF change. The decrease in SWR is attributed to an increase in SCE and SWE. The LH increase cannot be explained by an increase in SCE and SWE. In eastern Siberia (Fig. 6f), an increase in SWR is mostly canceled by decreases in SH and LWR, leading to a small change in NHF.
5. Atmospheric circulation changes and roles of AO and North Atlantic SST anomalies

Results in the previous section show that surface heat flux anomalies over several regions cannot be explained by the snow effect. In these regions, atmospheric circulation anomalies may play an important role in SAT changes. Atmospheric circulation anomalies influence SH via wind-induced heat advection and SWR through the cloud–albedo effect. In this section, we examine large-scale atmospheric circulation anomalies and the factors for the development of the anomalous atmospheric circulation pattern.

a. Surface wind anomalies

Notable surface wind anomalies are observed over Eurasia corresponding to the first two EOF modes of spring SAT variability. Figure 7 displays surface (10 m) wind anomalies associated with EOF1 and EOF2 of the Eurasian spring SAT, respectively, obtained by regression upon the corresponding PC time series. Comparison of the spatial patterns of SAT anomalies and the corresponding surface wind anomalies reveals a good match between them for both modes, as described below.

Corresponding to the first mode, a significant cyclonic wind anomaly is observed over northern Europe, accompanied by significant westerly wind anomalies over Europe and significant southerly wind anomalies over western Siberia (Fig. 7a). A significant anticyclonic wind anomaly covers the regions of western and eastern Siberia. Located to the west of an anomalous anticyclone over the North Pacific, significant southerly wind anomalies extend from the Sea of Okhotsk to the Russian Far East. Westerly wind anomalies over the western coast of Europe bring warmer and moister air from the North Atlantic Ocean to Europe. This may contribute to positive SAT anomalies there (Figs. 1a and 7a). Southerly wind anomalies over midlatitude Eurasia and the Russian Far East bring warmer air from lower latitudes, which may contribute to positive SAT anomalies there (Figs. 1a and 7a). It should be noted that cyclonic wind anomalies over northern Europe may result in a decrease in downward shortwave radiation through the enhancement of upward motion and increasing cloudiness. Therefore, this may lead to relatively small SAT anomalies there (Fig. 1a).

Corresponding to the second mode, significant anticyclonic wind anomalies are observed over Europe and eastern Eurasia and a significant cyclonic wind anomaly is seen around 60°E over western Siberia (Fig. 7b). In correspondence, there are significant southerly wind anomalies over western Europe and around 120°E extending from 40° to 70°N and significant northerly wind anomalies over Eurasia along 60°E (Fig. 7b). Southerly wind anomalies over western Europe and around 120°E bring warmer air from lower latitudes, contributing to positive SAT anomalies there (Figs. 1b and 7b). By contrary, northerly wind anomalies around 60°E carry colder air from higher latitudes, contributing to negative SAT anomalies there (Figs. 1b and 7b). In addition, anomalous anticyclones over Europe and eastern Eurasia may result in enhancement of SWR through suppressing upward motion and reducing cloudiness. This may contribute partly to the positive SAT anomalies there (Fig. 1b). The negative SAT anomalies around 60°E may be partly attributed to the presence of an anomalous cyclone. Cyclonic wind anomalies may lead to the enhancement of upward motion and an increase in cloudiness. This could result in a reduction of SWR and contribute to negative SAT anomalies (Fig. 1b).

The above results indicate that atmospheric circulation anomalies play an important role in Eurasian spring SAT variability via wind-induced heat advection and cloud-induced surface radiation changes. We have examined the two leading modes of spring Eurasian geopotential height anomalies at 500 hPa. Figures 8a and 8b show 500-hPa geopotential height
anomalies corresponding to the two modes. The EOF1 mode displays positive anomalies over southern Europe and eastern Siberia and negative anomalies over the northern part of western Siberia (Fig. 8a). The EOF2 mode is characterized by a wave pattern extending eastward from northern Europe to East Asia (Fig. 8b). The geopotential height anomalies at 500 hPa related to the two leading modes of the Eurasian spring SAT (Figs. 8c,d) display spatial distributions very similar to those corresponding to EOF1 (EOF2) of the Eurasian spring 500-hPa geopotential height (Figs. 8a,b). The correlation coefficient between PC1 (PC2) of the Eurasian spring SAT anomalies and PC1 (PC2) of the Eurasian spring 500-hPa geopotential height reaches 0.70 (0.73), significantly over the 95% confidence level according to the Student’s t test. This confirms that the Eurasian spring SAT anomaly pattern is largely controlled by atmospheric processes. In section 5b, we discuss possible reasons for the formation of the atmospheric circulation anomalies associated with the leading modes of the Eurasian spring SAT variability.

b. Roles of AO and North Atlantic SST anomalies

The leading modes of Eurasian spring SAT variability appear to be related to large-scale atmospheric circulation changes over and beyond Eurasia. Figure 9 shows anomalies of winds at 850 and 200 hPa in association with EOF1 and EOF2 of the Eurasian spring SAT. Corresponding to EOF1, significant westerly wind anomalies at 850 hPa are observed to cover northern Europe through Siberia to the Russian Far East (Fig. 9a). To the south are two anomalous anticyclones centered over southern Europe and Lake Baikal. Wind anomalies at 200 hPa bear a close resemblance to those at 850 hPa (Figs. 9a,c), indicative of a barotropic vertical structure. Corresponding to EOF2, wind anomalies at 850 hPa display a wave train over the North Atlantic Ocean and Eurasia, with three anticyclones over the midlatitudes of the North Atlantic Ocean, western Europe, and northeastern China, and two cyclones over the high latitudes of the North Atlantic Ocean and western Siberia, respectively (Fig. 9b). A similar wave train is present at 200 hPa (Fig. 9d).

What is the possible reason for the formation of atmospheric circulation anomalies related to EOF1 of the Eurasian spring SAT? Previous studies have demonstrated that the AO is a dominant mode of atmospheric circulation anomalies over the extratropics of the Northern Hemisphere (Thompson and Wallace 1998, 2000). These studies have demonstrated that the variability of AO can
exert a significant influence on surface temperature anomalies over Eurasia. Specifically, in the positive AO phase, anomalous westerly winds are observed over the high latitudes of Eurasia. This prevents the cold surge from the Arctic to invade into Eurasia, thus leading to an SAT increase. The correlation coefficient between PC1 of the spring SAT and the spring AO index during 1979–2010 reaches 0.49, which is significant at the 5% level. Geopotential height anomalies at 500 hPa associated with EOF1 of the Eurasian spring SAT display opposite signs between the Arctic region and the midlatitudes of the Northern Hemisphere (Fig. 10). The distribution generally resembles the springtime AO pattern (Chen et al. 2014). The above results indicate that the AO may be an important factor for continent-wide SAT changes over mid- and high-latitude Eurasia during spring through modulating atmospheric circulation anomalies.

The North Atlantic SST anomalies may induce atmospheric circulation changes over Eurasia. To examine whether SST anomalies in the North Atlantic Ocean play a role in the formation of atmospheric circulation anomalies related to EOF1 of the spring SAT, we show SST anomalies in Fig. 11a as obtained by regression on the normalized PC1 of the spring SAT. SST anomalies are weak and insignificant over most of the North Atlantic Ocean except for the coastal regions of Europe. This implies that atmospheric circulation anomalies associated with EOF1 of the Eurasian spring SAT cannot be explained by the North Atlantic SST variability.

What is the possible factor for the formation of atmospheric circulation anomalies related to EOF2 of the Eurasian spring SAT? Using observational data and model simulations, previous studies have indicated that a tripole North Atlantic SST anomaly pattern can excite a wave train extending eastward from the North Atlantic to East Asia along the westerly jet waveguide (e.g., Z. Wu et al. 2009; R. Wu et al. 2010, 2011; Z. Wu et al. 2012). Such a wave train bears some resemblance to the atmospheric circulation anomalies shown in Figs. 9b and 9d. This implies that SST anomalies over the North Atlantic Ocean may contribute to atmospheric circulation anomalies related to EOF2 of the Eurasian spring SAT variability.

To verify this hypothesis, we show in Fig. 11b the SST anomalies in the North Atlantic Ocean obtained by a regression on the normalized PC2 of the spring SAT. From Fig. 11b, a tripole (or horseshoe) SST anomaly pattern is observed in the North Atlantic Ocean, with significant negative SST anomalies in the tropical and midlatitude North Atlantic Ocean and significant positive SST anomalies in the western subtropical North Atlantic Ocean. The anomalous anticyclone over the midlatitude North Atlantic Ocean is located to the northwest of negative SST anomalies (Figs. 9b, 9d, and 11b). This spatial relationship indicates a Rossby

![Fig. 9. Anomalies of MAM wind anomalies at 850 hPa (m s$^{-1}$; vectors, scale at upper-right corner) obtained by regression on the normalized (a) PC1 and (b) PC2 of MAM SAT during 1979–2010. (c),(d) As in (a),(b), but for wind anomalies at 200 hPa. The shading denotes regions where either component of the wind anomalies is significantly different from zero at the 95% confidence level according to the Student’s $t$ test.](image-url)
wave–type response of atmospheric circulation to the North Atlantic SST anomalies, consistent with the results obtained by Czaja and Frankignoul (1999). It should be mentioned that atmospheric circulation anomalies over the North Atlantic Ocean may have a feedback on the tripole SST anomaly pattern via modulating surface heat fluxes. The anomalous northeasterly winds along the southeastern flank of the anomalous anticyclone enhance surface wind speed and evaporation, favoring negative SST anomalies. Anomalous descent accompanying the anomalous anticyclone leads to less cloud and more downward shortwave radiation, which favors positive SST anomalies. Such ocean–atmosphere interaction processes may favor the maintenance of the tripole SST and the atmospheric circulation anomaly over the North Atlantic (Figs. 9b, 9d, and 11b).

We have further examined the precipitation and vertical motion anomalies. Figure 12 displays anomalies of spring precipitation and vertical velocity at 500 hPa associated with EOF2 of the spring SAT. Significant decreases in precipitation and suppression in vertical motion are observed over the midlatitude North Atlantic Ocean (Figs. 12a,b). Comparison of Figs. 12 and 11b shows that the anomalous descent and decreased precipitation are located to the northwest of negative SST anomalies over the subtropical North Atlantic Ocean. The spatial phase relationship may be associated with the above-mentioned ocean–atmosphere interaction processes. The anomalous anticyclone located to the northwest of negative SST anomalies (Figs. 9b,d) induces anomalous descent and suppresses precipitation via accompanied anomalous divergence. Hence, anomalous descent and suppressed precipitation are observed to the northwest of negative SST anomalies (Fig. 12). Further, the atmospheric heating anomaly pattern over the North Atlantic may contribute to the formation of the wave train from the North Atlantic to East Asia.

The role of North Atlantic convection in the formation of atmospheric circulation anomalies related to...
EOF2 of the Eurasian spring SAT is further investigated by experiments with a barotropic model (Sardeshmukh and Hoskins 1988). As suggested by Sardeshmukh and Hoskins (1988), the barotropic model can well separate the essential dynamics of atmospheric response to the prescribed convective heating. In addition, the barotropic model is computationally efficient. The barotropic model employed in this study is spectral with the truncation at rhomboidal wavenumber 40. We perform two experiments: one with climatological spring mean divergence (EXPA) and the other with climatological spring mean divergence plus prescribed convergence anomaly (EXPB). The convergence anomaly in EXPB is prescribed over the midlatitude North Atlantic with a maximum intensity of $2.7\times10^{-6}\text{ s}^{-1}$ at $40^\circ\text{N}, 40^\circ\text{W}$. The location for this convergence anomaly is selected according to a significant downward motion anomaly over the midlatitude North Atlantic in Fig. 12b. The barotropic model is integrated for 40 days in the two experiments. Figure 13a shows the difference of response between the above-mentioned two experiments (i.e., EXPB minus EXPA) averaged over model days 31–40 with red contours representing the imposed convergence anomaly. A wave pattern of height anomalies is observed over the North Atlantic extending southeastward to East Asia. This wave pattern of height anomalies is located more southward compared to the wave train in association with EOF2 of the Eurasian spring SAT (Figs. 9b,d). This difference suggests an impact of atmospheric heating anomaly in other regions.

From Fig. 12b, a significant upward motion anomaly is observed around the subtropical western North Atlantic. This implies that the upward motion anomaly over the subtropical western North Atlantic and the downward motion anomaly over the midlatitude North Atlantic may both contribute to the formation of atmospheric circulation anomalies associated with EOF2 of the Eurasian spring SAT. To verify this speculation, we have performed another experiment (i.e., EXPC) with climatological spring mean divergence plus a convergence anomaly prescribed over the midlatitude North Atlantic with a maximum intensity of $-7\times10^{-6}\text{ s}^{-1}$ at $40^\circ\text{N}, 40^\circ\text{W}$ and a
A divergence anomaly prescribed over the subtropical western North Atlantic with a maximum intensity of $-7 \times 10^{-6}$ s$^{-1}$ at $35^\circ$N, $70^\circ$W. The location for the divergence anomaly is selected based on the significant upward motion anomaly over the subtropical western North Atlantic in Fig. 12b. Figure 13b displays the difference of response between EXPC and EXP A averaged over model days 31–40 with thick red contours denoting the imposed divergence and convergence anomalies. From Fig. 13b, a wave train pattern of height anomalies is observed over the North Atlantic and Eurasia, which bears a close resemblance to the atmospheric circulation anomalies related to EOF2 of the Eurasian spring SAT (Figs. 9b,d). This confirms that the formation of atmospheric circulation anomalies associated with EOF2 of the Eurasian spring SAT may be contributed by atmospheric heating anomalies over both the midlatitude North Atlantic and the subtropical western North Atlantic.

The results in this subsection demonstrate the roles of the AO and the North Atlantic SST anomalies in the Eurasian spring SAT variability through large-scale atmospheric circulation changes. The AO has a large impact on continental SAT variations. The North Atlantic SST anomalies induce a tripole Eurasian spring SAT anomaly pattern through exciting a wave pattern over the North Atlantic and Eurasia.

6. Summary and discussion

The present study investigates the interannual variations of boreal spring SAT over mid- and high-latitude Eurasia and the plausible factors during 1979–2010. The first mode of spring SAT variations is featured by same-sign SAT anomalies over most of Eurasia to the north of $40^\circ$N. The second mode is characterized by a tripole pattern with same-sign SAT anomalies over the eastern and western part of Eurasia and opposite-sign anomalies over the central part of Eurasia.
Analysis shows that snow change contributes to the formation of SAT anomalies in several regions by modulating surface heat flux changes. Corresponding to EOF1, a decrease in SCE and SWE over the western part of southern Europe contributes partly to an increase in SAT by increasing SWR. Corresponding to EOF2, SCE and SWE increases over the northern part of western Siberia may contribute partly to a decrease in SAT via decreasing SWR, and SCE and SWE decreases around Lake Baikal favor positive SAT anomalies through increasing SWR. However, SAT anomalies over many regions cannot be explained by the SCE or SWE change. Comparison of the spatial distribution of SCE, SWE, SWR, LWR, and cloud cover anomalies indicates that SWR and SLR changes over Eurasia follow more closely the TCC change than the snow cover change. The SH changes over many parts of Eurasia are not related to the snow change.

Analysis shows that surface wind anomalies may contribute largely to the formation of SAT anomalies over most parts of Eurasia in both EOF1 and EOF2. For EOF1, positive SAT anomalies over Siberia and the Russian Far East are related to anomalous southerly winds that transport warmer air from lower latitudes, and positive SAT anomalies over western Europe may be attributed to westerly wind anomalies that transport warmer and moist air from the North Atlantic Ocean. In addition, anomalous anticyclones over midlatitudes reduce clouds and increase downward SWR reaching the surface, contributing to positive SAT anomalies. For EOF2, positive SAT anomalies over western and eastern Eurasia are related to southerly wind anomalies that transport warmer air from lower latitudes, and negative SAT anomalies over central Eurasia may be due to the northerly wind anomalies that transport colder air from higher latitudes. Further, the anomalous anticyclone over western and eastern Eurasia and the anomalous cyclone over central Eurasia contribute to the SAT anomalies by modulating cloud and SWR.

Corresponding to EOF1, the atmospheric circulation anomaly over Eurasia has a close relationship with spring AO. This suggests an important role of the AO in the formation of continent-wide SAT anomalies over mid- and high-latitude Eurasia. Corresponding to EOF2, atmospheric circulation anomalies feature a wave train over the North Atlantic Ocean and Eurasia, with three anticyclones over the midlatitudes of the North Atlantic Ocean, western Europe, and northeastern China, and two cyclones over the high latitudes of the North Atlantic Ocean and western Siberia, respectively. Further analysis indicates that the formation of wave train–like atmospheric circulation anomalies may be attributed to a North Atlantic tripole SST anomaly pattern. This suggests the role of the North Atlantic SST anomalies in the formation of tripole SAT anomalies over mid- and high-latitude Eurasia. In addition, results obtained from barotropic model experiments indicate that North Atlantic SST-related atmospheric heating anomalies over the midlatitude North Atlantic and the subtropical western North Atlantic both contribute to the formation of atmospheric circulation anomalies over the North Atlantic and Eurasia in association with EOF2 of the Eurasian spring SAT.

In several regions, snow and atmospheric circulation changes both contribute to SAT anomalies by modulating surface heat fluxes. However, it is hard to determine the relative contribution of snow and atmospheric circulation changes to the formation of SAT anomalies in observational and reanalysis data. To understand the relative contribution of snow changes and atmospheric circulation anomalies, a carefully designed numerical model experiment may be needed in the future.

In addition, coupled climate models capture the leading mode of the boreal spring SAT and their association with snow and atmospheric circulation changes obtained in this study? What are the dominant modes of boreal spring SAT over the mid- and high latitudes of Eurasia on an interdecadal time scale? What are the dominant modes of Eurasian SAT during boreal summer and autumn? These issues will be further pursued in the future.

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