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The Influences of the Arctic Troposphere on the Midlatitude Climate Variability and the Recent Eurasian Cooling

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Key Points:
- The Arctic troposphere impacts the large-scale atmospheric circulation and climate variability at midlatitudes
- The modulation of Siberian High by Arctic troposphere impacts the climate variability in south Siberia and East Asia
- The Arctic troposphere is closely associated with the recent cooling trends over Northern Eurasia

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Abstract Understanding the influence of the Arctic troposphere on the climate at midlatitudes is critical for projecting the impacts of ongoing and anticipated Arctic changes such as Arctic amplification and rapid sea ice decline over the Northern Hemisphere. In this study, we analyze a suite of atmospheric model experiments, with and without atmospheric relaxation toward reanalysis data, to study the impacts of the Arctic troposphere on the midlatitude atmospheric circulation and climate variability. The Arctic troposphere is found to strongly impact the interannual variability of the atmospheric circulation and temperature over the midlatitude continents. The major mechanisms for the impacts of Arctic troposphere include the modulation of the large-scale atmospheric circulation, the associated heat transport over the continents, and the impacts on synoptic variations in the North Atlantic-European sector. The impact of the Arctic troposphere on the intensity of the Siberian High is an important factor for how the Arctic can influence temperature variability in south Siberia and East Asia. The trends in the Arctic troposphere in recent decades are closely linked to the recent winter cooling in Northern Eurasia. These recent cooling trends are not driven by the trends in sea surface temperature/sea ice, tropical atmosphere, and the stratosphere. It is argued that the temperature trend pattern of warm Arctic-cold Eurasia is a manifestation of two possibly independent phenomena and the cooling trend is contributed to by the Arctic troposphere through impacting the large-scale atmospheric circulation, the atmospheric blocking frequency, and the intensity of the Siberian High.

1. Introduction

The Arctic is characterized by radiation deficit and extremely harsh climate. The Arctic climate system is a highly complex system in which ocean, sea ice, land, and atmosphere are actively coupled. Changes in this climate system have both local and remote impacts. Thus, understanding of the variability of the Arctic climate system and the components within the system is of paramount importance for the regional and global climate.

The Arctic sea ice and its influences on the Arctic and midlatitude climate have been extensively studied. The local manifestation of the impacts of the Arctic sea ice is clear and commonly agreed. Reduction of sea ice extent leads to enhanced heat transfer toward the overlying atmosphere and warmer surface air temperature (SAT; e.g., Screen & Simmonds, 2010a, 2010b; Serreze et al., 2009). This also increases the atmospheric layer thickness between 1,000 and 500 hPa (Overland & Wang, 2010) and decreases the vertical static stability of the troposphere (e.g., Francis et al., 2009; Jaiser et al., 2012; Overland & Wang, 2010; Stroeve et al., 2011). Modeling evidence of these impacts of Arctic sea ice is also abundant (e.g., Alexander et al., 2004; Strey et al., 2010). In sharp contrast, the remote response to anomalies in Arctic sea ice is far more controversial. The reduction in autumn sea ice extent in Barents and Kara Sea (B/K Sea) is found to drive a stationary Rossby wave in early winter, which contributes to the cold anomalies across a wide area over Northern Eurasia (Honda et al., 2009). Sea ice variability in Barents Sea is also found to modulate the sea level pressure (SLP) and impact the cyclone tracks in the middle to high latitudes, thus affecting the temperature variability over Siberia (Inoue et al., 2012). The reduction in autumn Arctic sea ice is also significantly correlated with the tripole wind pattern, which strongly affects the winter precipitation over part of the Northern Eurasia (B. Wu et al., 2013). The impacts of autumn Arctic sea ice on the wintertime Arctic Oscillation/North Atlantic Oscillation (AO/NAO) are also noted and the dynamical pathways have been investigated in numerous studies (see e.g., Jaiser et al., 2013; Kim et al., 2014; Li & Wang, 2012). However, a wide range of atmospheric responses (including the AO/NAO) to reduction in Arctic sea ice is reported in modeling studies (see Cohen et al., 2014 and references therein), thus highlighting the lack of understanding of dynamic pathways and the remote impacts of Arctic sea ice decline.

The modulation of the variability of AO/NAO by some Arctic processes such as the variations in the Arctic sea ice has both direct and indirect impacts on the climate variability outside the Arctic. Siberian High (SH) is an important climate system during winter in the Northern Hemisphere (NH) and has strong influences on the NH climate variability (Cohen et al., 2001). The relationship between AO and the SH is discussed in various studies (e.g., Gong et al., 2001; Huang et al., 2016, 2017; B. Wu & Wang, 2002). The AO and SH have independent influences on the temperature variability over East Asia while their influences on the temperature variability at high-latitude Asian continent and subarctic ocean often lead to combined response (B. Wu & Wang, 2002). The relationship between AO and SH is also regime-dependent (Huang et al., 2016), highlighting the complex nature of this relationship.

Observations of the past several decades have revealed a downward trend in Arctic sea ice (e.g., Deser & Teng, 2008; Lemke et al., 2007). The negative trend of Arctic sea ice coincides with stronger Arctic warming trend as compared to the other regions, which is termed Arctic amplification (AA; see Cohen et al., 2014 and references therein). The decline in Arctic sea ice is thought to contribute to the AA (e.g., Screen & Simmonds, 2010a). In fact, various mechanisms are proposed to explain the existence of AA (e.g., Serreze & Barry, 2011 and references therein; Pithan & Mauritsen, 2014) and consensus on the cause of AA is still absent. With respect to the impacts of the AA, various mechanisms are also proposed, including changes in storm tracks, the jet stream, and the planetary waves (see Cohen et al., 2014 and references therein). However, as pointed out by Cohen et al. (2014), due to incomplete understanding of the associated processes, limited observations, and imperfect models, large uncertainties in terms of remote impacts of AA still remain.

The emergence of warm Arctic-cold Eurasia pattern with respect to the temperature trends in recent decades has intensified the discussion of the impacts of AA on midlatitude climate and beyond. The cooling trend over midlatitude continents is accompanied by increased cold extremes, with the recent winter of 2013–2014 having broken records (Cohen et al., 2014). The warm Arctic-cold Eurasia temperature pattern is considered in some studies as response to the reduction of Arctic sea ice (e.g., Honda et al., 2009; Liu et al., 2012). The proposed dynamical processes include stationary Rossby wave excitation and the influences on the AO/NAO phase. On the other hand, other studies were not able to confirm the impacts of Arctic sea ice reduction on this well-known temperature trend pattern (e.g., Kumar et al., 2010; Screen et al., 2013; Sun et al., 2016). Therefore, the recent cooling trends over the Eurasian continent may be a result of internal atmospheric variability (Sun et al., 2016). From the existing scientific literature, thus, it is still unclear whether there is any forcing factor that leads to the cooling trend and increased cold extremes in midlatitude continent.

It has been argued that the warming in the Arctic is conducive to the occurrence of the midlatitude atmospheric blocking (Francis & Vavrus, 2015; Walsh, 2014). Midlatitude atmospheric blocking is known to play an important role in the extreme temperature and precipitation events in the Atlantic-European sector and East Asia (e.g., Huang et al., 2018; Sillmann et al., 2011; Sillmann & Croci-Maspoli, 2009; Yang et al., 2018). The role of Ural blocking in contributing to the warm Arctic-cold Eurasia temperature pattern and the association with the reduction of sea ice and the temperature variability over the B/K Sea are highlighted by Luo et al. (2016). However, the correlation between the temperature variability in the B/K Sea and the Eurasian blocking is weak in CMIP5 models (Woollings et al., 2014).

There is no doubt that Arctic phenomena such as the decline in Arctic sea ice and the AA have strong potential to influence the midlatitude weather and climate variability (e.g., Barnes & Screen, 2015). The atmospheric pathway is important for the communication of the impacts of these phenomena to midlatitudes and possibly beyond. To achieve further understanding of the Arctic impacts and the associated atmospheric pathways, we analyze several numerical experiments with the European Center for Medium-Range Weather Forecasts (ECMWF) model in which a relaxation approach is employed (Greatbatch et al., 2012; Jung, Miller, et al., 2010, Jung et al., 2011, 2014; Semmler et al., 2018). The relaxation approach uses reanalysis data to correct the model states and enables a more realistic depiction of the temporal evolution of atmospheric dynamics and thermodynamic state. This approach allows to investigate the pathways through which atmospheric circulation in one area influences that in the other area. Similar analysis of relaxation experiments has been conducted and the strong impacts of Arctic on the subseasonal midlatitude weather are found (Jung et al., 2014). The present study focuses on the impacts of Arctic troposphere on seasonal time scale and the impacts of Arctic troposphere on the winter climate in midlatitudes. Our results should provide insights into the influences of the Arctic troposphere on the midlatitude atmospheric circulation and climate variability. These insights should benefit the further understanding of the seasonal climate variability at midlatitudes and the causes for and impacts of AA on the midlatitudes.

Section 2 describes the model experiments analyzed in this study. Section 3 shows the impacts of the Arctic relaxation and tropical relaxation on the interannual variability of the atmospheric circulation and climate variables. Section 4 investigates the surface temperature pattern that is associated with the interannual variability of the winter Northern Eurasian surface temperature, and the atmospheric circulation patterns are also studied. Both the influences of Arctic troposphere and the extratropical stratosphere on the midlatitude atmospheric circulation and climate variability are studied. Section 5 investigates the warm Arctic-cold Eurasia pattern with respect to the temperature trends in recent decades. Section 6 provides a discussion on the findings and the relevance to current Arctic climate change. Main conclusions are summarized in section 7.

2. Data and Methodology

2.1. ERA-Interim Data

Monthly mean SAT, air temperature at 850 hPa (T850), geopotential height at 500 hPa (Z500) and at 50 hPa (Z50), horizontal winds at 300 hPa, and SLP from the ERA-Interim data are used to describe observed conditions (Berrisford et al., 2011).

2.2. Model Description and Configuration

The atmospheric model of the ECMWF is used in the experiments. The atmospheric model is configured with a horizontal resolution of T_L255 (about 80 km) and 60 vertical levels. Compared to previous studies, this configuration is considered to be of high-resolution, especially in the horizontal. Previous studies have shown that 60 vertical levels are sufficient to represent important stratospheric dynamics including sudden stratospheric warmings (Jung & Leutbecher, 2007).

2.3. Model Relaxation Experiment

The relaxation approach employed in this study can be described by the following equation:

$$dx/dt = F(x) - \alpha (x - x_{ana})$$

where x, α, and x_{ana} denote the state vector of the model, relaxation coefficient, and ERA-Interim data, respectively. F (x) is the model's prognostic equations. The relaxation approach is conducted by adding an extra term (i.e., $-\alpha (x - x_{ana})$) to the equation. The value of α is set to 0.1 in the relaxation area and zero outside the relaxation area with the transition zone being smoothed. The choice of the value of α is based on the consideration of both the strength of the relaxation and the model stability.

The relaxation of the atmospheric variables is carried out using the 6-hourly ERA-Interim reanalysis data as reference data (x_{ana}). The atmospheric variables that are relaxed in each model time step include surface pressure (except for experiments with stratospheric relaxation), temperature, and horizontal winds. Details of the relaxation approach can be found in Jung, Miller, et al., (2010), Jung, Palmer, et al., (2010), and Jung et al., (2014). An evaluation and discussion of this relaxation approach is provided in Jung et al. (2011) and Hoskins et al. (2012). Smoothing is applied over a boundary zone between the areas with and without relaxation being applied. The smoothing is done for a latitude band of about 5° and a pressure layer of about 100 hPa. All the simulations are run from November through February for boreal winters and from May to August for boreal summers for the period 1979/1980–2013/2014. A total of nine ensemble members is used for each experiment using a lagged ensemble approach (forecasts start 6 hr apart). Three experiments with relaxation applied to different areas and two experiments without relaxation are carried out. A summary of these experiments is depicted in Table 1. In the stratospheric relaxation experiment, the relaxation area is north of 30°N to capture aspects associated with variations and changes of the stratospheric polar vortex. Furthermore, we only relax the extratropical stratosphere above approximately 150 hPa. The tropical stratosphere is considered in the tropical relaxation experiment, in which both the troposphere and stratosphere are relaxed. This is also another reason why the relaxation of stratosphere does not extend further south. The relaxation area is quite similar to the one used in Douville (2009). In this study, most of the analyses are based on ensemble-mean, and the ensemble-spread is assessed whenever necessary. Here ensemble-mean is a

Table 1
Summary of the Model Experiments With and Without Relaxation Toward ERA-Interim Reanalysis With the European Center for Medium-Range Weather Forecasts Atmospheric Model

Name of experiment	Boundary conditions	With relaxation	Horizontal area with relaxation	Vertical extent with relaxation
SST-SeaIce-Obs	Observed SST/Sea ice	No	N/A	N/A
SST-SeaIce-Clim	Climatological SST/Sea ice	No	N/A	N/A
Tropical	Climatological SST/Sea ice	Yes	20°S–20°N	Full atmosphere
Arctic	Climatological SST/Sea ice	Yes	70–90°N	Surface to 300 hPa
Stratospheric	Climatological SST/Sea ice	Yes	30–90°N	Above 150 hPa

Note. SST = sea surface temperature.

simple average with each member being treated equally. In both sections 3 and 4, least-squares linear trends in all fields are removed to focus on the interannual variations.

2.4. Model Assessment

The experiments with and without atmospheric relaxation are compared with the ERA-Interim data in terms of the climatological conditions of the atmospheric circulation and climate. Particular emphasis is placed on the winter season. It is found that all model configurations simulate critical atmospheric structures such as the subtropical jets, SH, Subtropical Highs, Aleutian Low, Icelandic Low, and the troughs/ridges at midlevel atmosphere; the temperature distribution is also well captured in all the experiments (not shown). The good performance of the model suggests that model biases do not impact the conclusions of this study.

3. Arctic Versus Tropical Impacts on the Variability of the Seasonal-Mean Climate and Atmospheric Circulation

In this section, the impacts of the Arctic and tropical relaxation on the variability of the seasonal-mean climate and atmospheric circulation are examined. The results highlight the different impacts in different areas between these two experiments. These results can further the understanding of the Arctic influences versus tropical influences on the midlatitudes.

To determine the impacts of the relaxation experiments on the interannual variations of the winter atmospheric circulation and temperature, the temporal correlation coefficients are computed between ensemble mean values from the relaxation experiments and from the ERA-Interim data. Results are shown in Figure 1. Overall, the Arctic relaxation leads to significant correlations in east Canada and Northern Eurasia (left panels). Some moderate correlations are seen in other areas, supporting the notion that the Arctic has the potential to impact climate variability over the NH. In contrast, the tropical relaxation leads to significant correlations in the oceanic areas over subtropics and midlatitudes (right panels). The tropical relaxation also leads to strong correlations over Canada (Figures 1b, 1d, and 1f). However, the correlations over Northern Eurasia are much weaker compared to those in Arctic relaxation. Therefore, the winter climate variability over Northern Eurasia is more strongly related to the Arctic than to the tropical atmospheric circulation. The Arctic represents an important contributing factor for the seasonal climate variability over Northern Eurasia. The dynamic linkages between the Arctic troposphere and the climate variability in Northern Eurasia are studied in more details in section 4.

Corresponding results for boreal summer are shown in Figure 2. The correlation coefficients in summer outside the Arctic are smaller than in winter (left panels), suggesting weaker linkages between Arctic and lower latitudes. In summer, some land surface processes such as soil moisture-atmosphere interaction in the continents in NH may become stronger and this can limit the impacts from the Arctic. The background state (e.g., the prevailing westerlies) of the atmospheric circulation is also much weaker in summer. A weaker background flow may indicate less sensitivity to the changes in Arctic troposphere. Over Northern Eurasia, the correlation coefficients of both SAT and T850 are still much larger in the Arctic relaxation than in the tropical relaxation. For the tropical relaxation, the correlation coefficients outside the tropics are mostly weaker than in winter (right panels). Interestingly, higher correlations of SLP are seen in Northern Eurasia in summer than in winter (Figures 2h versus 1h) in the tropical relaxation. These correlations are also larger than their

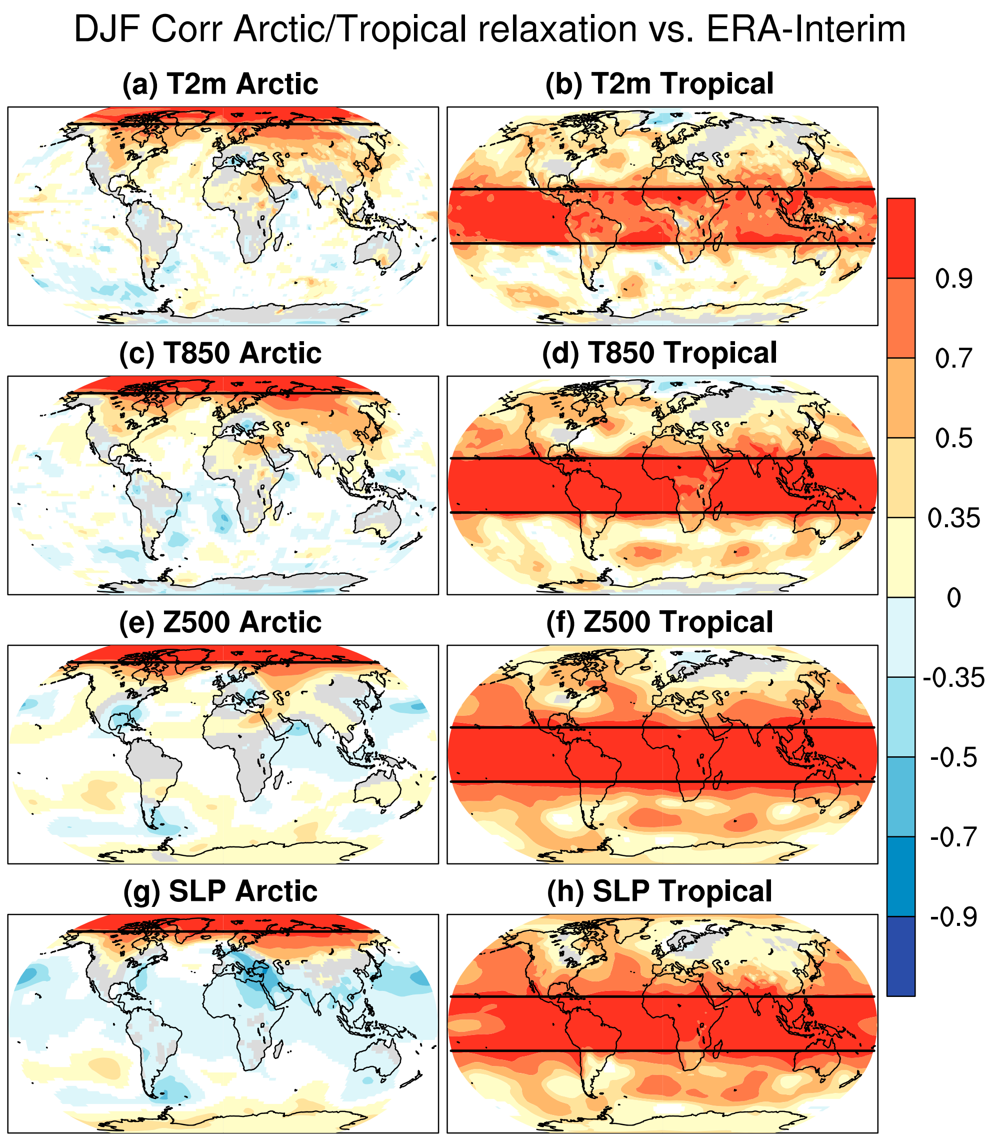

Figure 1. Spatial distribution of the correlation coefficients of winter-mean variables between relaxation experiments and ERA-Interim data for the period 1979–2013. Left panels are for Arctic relaxation experiment and right panels are for tropical relaxation experiment. Correlation coefficients between −0.1 and 0.1 are in white/gray. DJF = December-January-February; SLP = sea level pressure.

counterparts in the Arctic relaxation, suggesting that the variability of the surface circulation in summer (e.g., Asian Low) in the Eurasian continent is more closely related to the tropical atmosphere.

Overall, the influences of Arctic troposphere are more limited in spatial extent and show stronger seasonality as compared to the influences of tropical atmosphere. The winter climate variability over Northern Eurasia is strongly impacted by the Arctic troposphere and the Arctic is a potential source for the seasonal prediction skills in Northern Eurasia. Therefore, study of the thermodynamic and dynamic linkages between Arctic and the Northern Eurasia in the Arctic relaxation experiment is necessary for understanding the pathways for the Arctic troposphere to affect the climate variability in Northern Eurasia.

Further inspection of the patterns of correlation coefficient in stratospheric relaxation and sea surface temperature (SST)-SeaIce-Obs experiments is conducted (not shown). The correlation coefficients of winter-mean variables in stratospheric experiment are less than those in Arctic relaxation experiment over the midlatitude continents but are larger than those in tropical relaxation experiment over the midlatitude continents. The downward impacts of stratosphere on the troposphere during winter are well noted. It is thus indicated

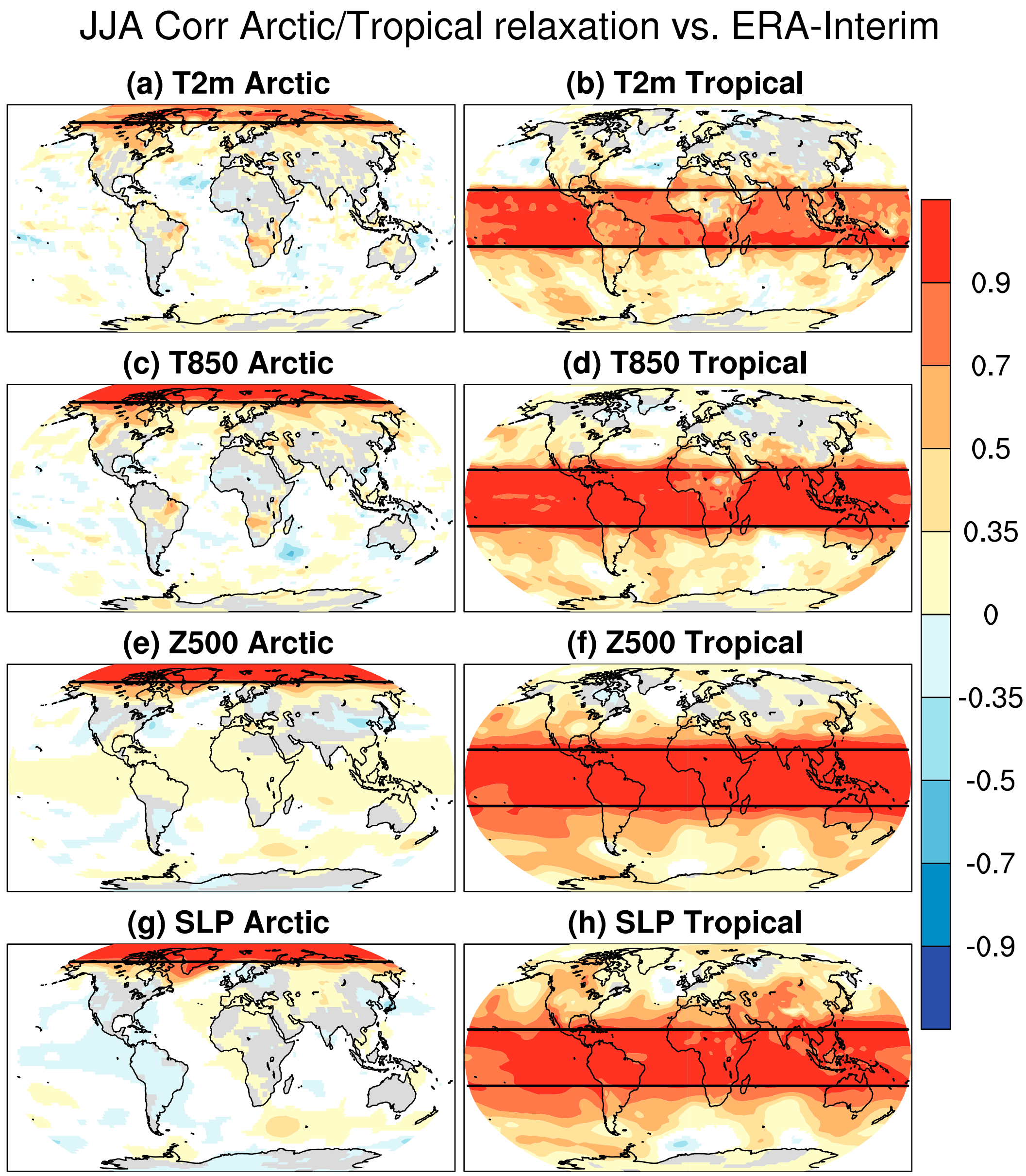

Figure 2. Same as in Figure 1, except for summer-mean variables. JJA = June-July-August; SLP = sea level pressure.

that the impacts of Arctic troposphere in the midlatitudes are forced partly by the stratosphere. It is not surprising that the correlation coefficients are significantly larger over the oceanic areas in SST-SeaIce-Obs experiment as the temperature of the lower atmosphere is strongly affected by the SST. On the other hand, correlation coefficients in SST-SeaIce-Obs experiment are comparable to that in the tropical relaxation experiment over the midlatitude continents. It is noted that the tropical atmosphere is strongly forced by the underlying SST anomalies. On the other hand, it seems that the observed SST/sea ice has no strong impacts on the interannual variations of the climate over the midlatitude continents.

4. The Leading Mode of the Variability of the SAT in the Northern Eurasia and the Impacts of the Arctic Troposphere

In the previous section, it is indicated that the Arctic troposphere has strong influences on the winter climate variability in Northern Eurasia. It is thus important to understand the associated mechanisms. In this section,

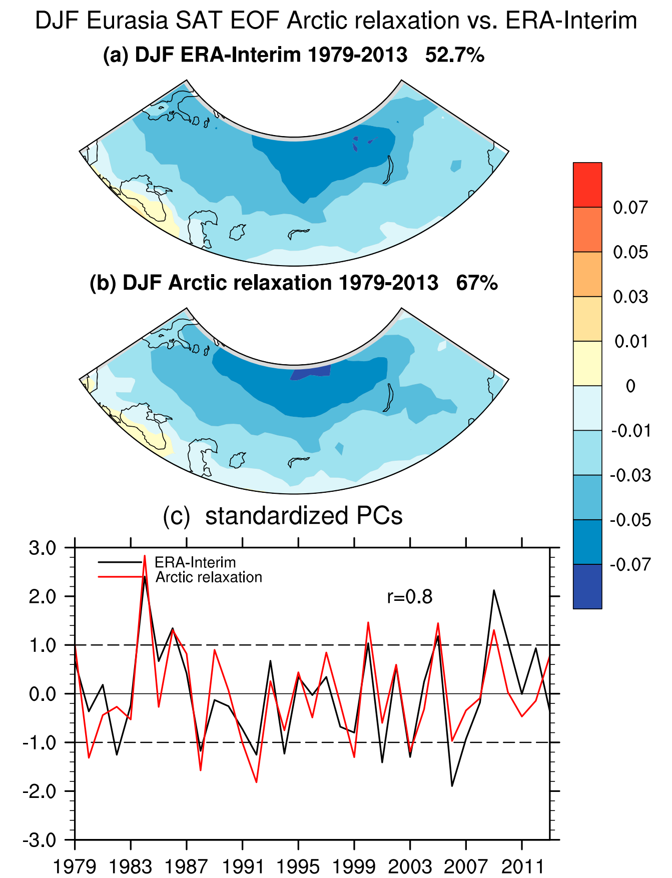

Figure 3. Leading EOF mode of the winter-mean surface air temperature over Northern Eurasia for the period 1979–2013. (a) and (b) are spatial modes of the EOF for ERA-Interim data and Arctic relaxation experiment, respectively. Explained variance by the EOF mode is indicated at top of panels (a) and (b). The principle components are shown in (c). Units: °C. DJF = December-January-February; SAT = surface air temperature; EOF = Empirical Orthogonal Function; PC = principle component.

the analysis is based mostly on the model output from the Arctic relaxation experiment. It is indicated whenever model output from other experiments is used. Results from the stratospheric relaxation experiment are compared to the Arctic relaxation experiment. Trends in all parameters are removed using the linear least squares method.

A similar analysis is performed using the ERA-Interim data (not shown). Results are rather similar to those based on the stratospheric relaxation experiment in terms of the SAT pattern, AO/NAO pattern, and anomaly pattern of the stratospheric polar vortex. The relationship between AO and SH is discussed in section 4.5 for the stratospheric relaxation experiment and ERA-Interim data. As for the Arctic relaxation experiment, the impacts of Arctic SLP on the SAT in Northern Eurasia are concentrated more on high latitudes. The modulation of SH further impacts the SAT in south Siberia and East Asia. The cyclonic-Z500 anomaly pattern is also evident. The associated impacts on the SH intensity are weaker in the ERA-Interim data than in the Arctic relaxation. Note that the SH intensity is impacted by various factors. The experimental setup in the Arctic relaxation experiment singles out the impacts from the Arctic troposphere.

4.1. The Leading Mode Derived From the EOF Analysis and the Associated Temperature Patterns

An Empirical Orthogonal Function (EOF) analysis is used to derive the leading EOF mode of the winter SAT variability in Northern Eurasia. The area for the EOF analysis is 15–135°E and 40–65°N, which is outside the relaxation area in the Arctic relaxation experiment. The spatial mode and principle component (PC) of the leading EOF modes are depicted in Figure 3. For comparison, the EOF mode (Figure 3a and black line in Figure 3c) for the ERA-Interim data is also shown. The spatial mode for ERA-Interim data features a pattern that mostly shows negative signs and is dominated by the loadings over central Russia (Figure 3a). This mode accounts for over half of the total variance. With respect to the spatial mode for the Arctic relaxation experiment, it is similar to that for ERA-Interim data with the large-loading pattern slightly shifted westward (Figure 3b). It accounts for nearly 70% of the total variance, larger than its counterpart. Examination of the temporal evolution of the PCs indicates that both show significant interannual variations, with the correlation between them being 0.8. The similarity of the spatial modes and the high-correlation of the PCs suggest that the implementation of relaxing Arctic troposphere toward ERA-Interim data leads to rather realistic interannual variations of the winter SAT in Northern Eurasia. This is consistent with the results in previous section.

To investigate the association of the winter SAT variability in Northern Eurasia with that in other areas, regression of winter SAT and T850 against the PC of the leading EOF mode of the winter SAT in Northern Eurasia for Arctic relaxation experiment is performed and the results are presented in Figure 4. It is seen that a tripole pattern of SAT anomalies stretches from east Canada, Greenland, and west Arctic to Northern Eurasia and then to the North Africa (Figure 4a). The warming over Canada, Greenland, and west Arctic is in stark contrast to the cooling over Northern Eurasia. Note that the trends were removed prior to the regression analysis. A similar temperature pattern is seen for T850 but with weaker cooling in Northern Eurasia (Figure 4b). The stronger cooling on the surface may indicate the role of some surface processes/climate systems that may amplify the surface cooling.

Similar analysis is also performed using the model output from the control experiment (SST-SeaIce-Clim, not shown). The results show a similar spatial mode of the leading EOF of the winter SAT in Northern Eurasia. However, the correlation between the PC for the control experiment (SST-SeaIce-Clim) and that for the ERA-Interim data is significantly smaller, mostly being zero. Therefore, it can be argued that the leading mode of the winter SAT in Northern Eurasia is driven by the internal atmospheric dynamics but its interannual

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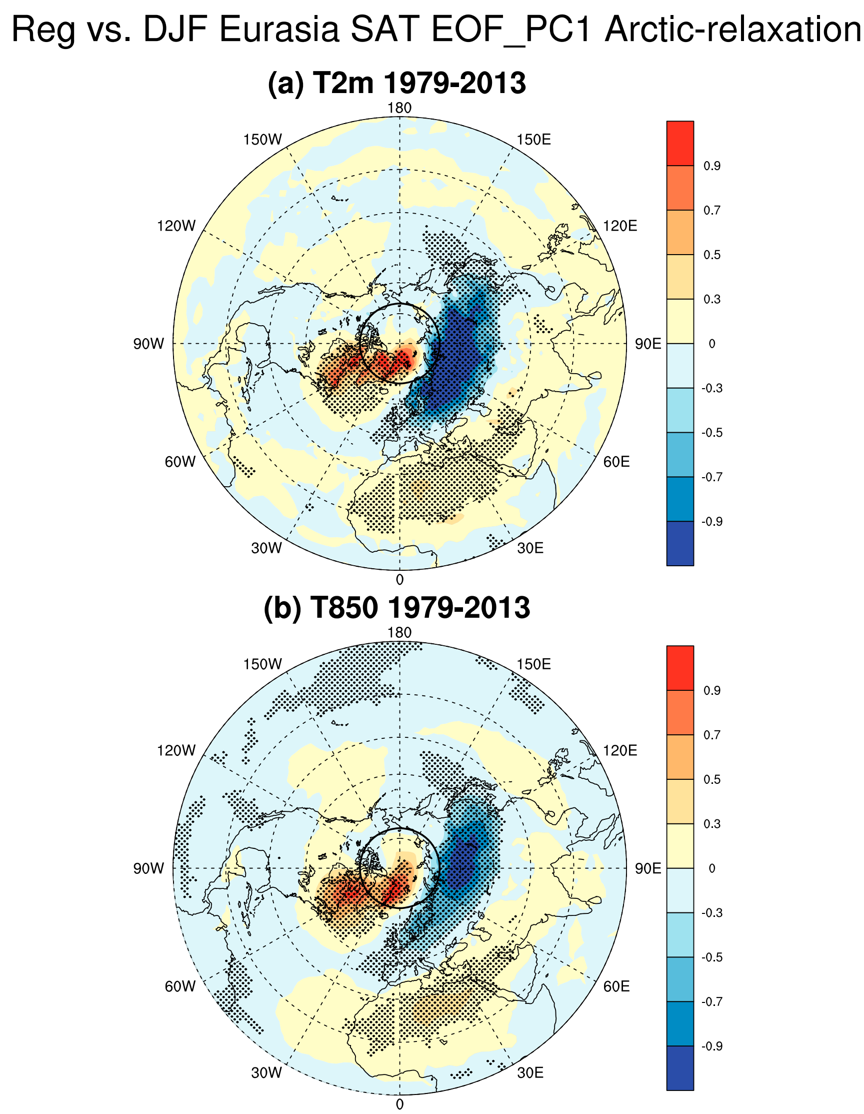

Figure 4. Spatial distribution of the regression coefficients of (a) surface air temperature and (b) air temperature at 850 hPa against leading EOF principle component of the winter-mean surface air temperature over Northern Eurasia based on Arctic relaxation experiment. Stippling indicates significance at 5% level. Units: °C. DJF = December-January-February; SAT = surface air temperature; EOF = Empirical Orthogonal Function; PC = principle component.

variations are strongly affected by the Arctic troposphere. The winter SAT anomalies in Northern Eurasia are also closely correlated with the SAT anomalies in Canada, Arctic, and even the North Africa. In some runs of the control experiment (SST-SeaIce-Clim), the pattern of warming in east Canada, Greenland, and west Arctic and the cooling in Northern Eurasia are clear, indicating that internal atmospheric dynamics is important in generating this temperature pattern. However, relaxing the Arctic toward reanalysis data leads to more realistic interannual variations of the leading winter SAT mode in the Northern Eurasia. It is therefore reasonable to indicate that the Arctic troposphere has strong impacts on the winter climate variability in Northern Eurasia. Large-scale atmospheric circulation pattern is important in linking the temperature anomalies in Arctic to those over Northern Eurasia.

4.2. The Atmospheric Circulation Patterns and the Influences of SH

Similar regression analysis is performed for the Z500, Z50, 300 hPa horizontal winds, and SLP and the results are shown in Figure 5. Significant positive anomalies in Z500 are observed in the Arctic, far east of the Eurasian continent, eastern Canada, and high-latitude North Atlantic (Figure 5a). The spatial distribution of

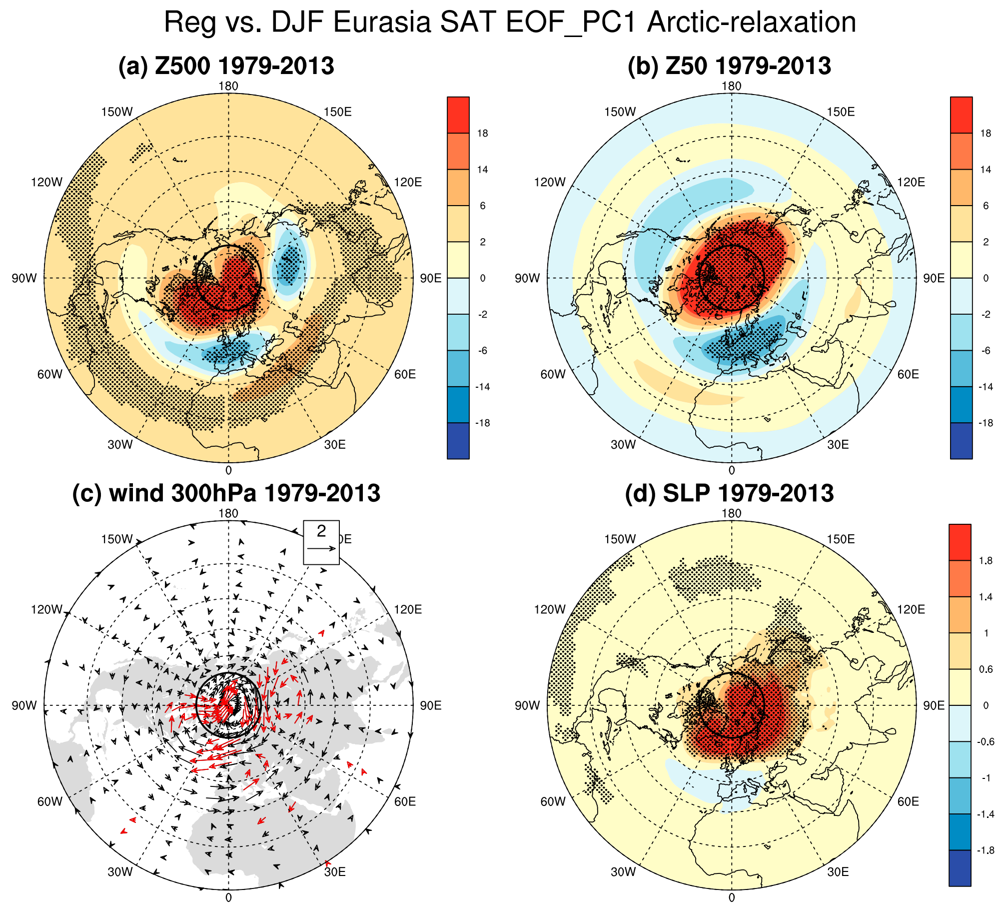

Figure 5. Same as in Figure 4, except for (a) geopotential height at 500 hPa, (b) geopotential height at 50 hPa, (c) horizontal wind, and (d) SLP. Units: geopotential meters, m/s, and hPa for geopotential height, wind, and SLP, respectively. Red vectors in (c) indicate significance at 5% level. DJF = December-January-February; SAT = surface air temperature; EOF = Empirical Orthogonal Function; PC = principle component; SLP = sea level pressure.

the anomalies suggests a weaker North American trough (NAT). Two isolated negative-anomaly areas are centered in Europe and the Lake Baikal, respectively. The pattern of Z500 anomalies over the North Atlantic-European sector resembles the negative phase of NAO. The negative phase of NAO is also seen in the SLP field (Figure 5d). However, the anomalies of both Z500 and SLP in the North Atlantic-European sector are relatively weak, suggesting a relatively weak forcing from the Arctic atmospheric circulation on the south action center of the NAO. Another positive-anomaly Z500 pattern is seen to extend from North Africa to Middle East. Overall, the pattern of Z500 anomalies is consistent with the tripole SAT pattern (Figures 5a versus 4a). Inspection of the Z50 pattern indicates a weaker polar vortex (Figure 5b), which is associated with the forcing of the tropospheric anomalies. The pattern of Z500 anomalies is accompanied by corresponding wind pattern by virtue of the geostrophic balance (Figure 5c). The southeasterly anomalies and southerly anomalies over east Canada weaken the cold flow from the Arctic areas and contribute to the warming (Figures 4a and 4b). The band of easterly anomalies over the sub-Arctic of the Eurasian continent leads to weaker prevailing westerlies and thus weaker warm advection from the west. This contributes to a wide area of cooling (Figures 4a and 4b). Weaker westerly suggests weaker zonal flow and the meridional flow may be enhanced. This is thus a favorable condition for the intrusion of Arctic cold air into Northern Eurasia. Persistence of the weather/climate systems may also be enhanced (Petoukhov et al., 2013; Screen & Simmonds, 2014). In association with the weaker westerlies over the North Atlantic-Northern Europe, the storm activity shows significant decreases over the North Atlantic-Northern Europe (not shown). The storm track is weaker and shifted southward. The storm track activity over the Atlantic is associated with a tripole temperature pattern (Rogers, 1997) that is similar to the one identified in this study. On the one hand, reduced storm activity

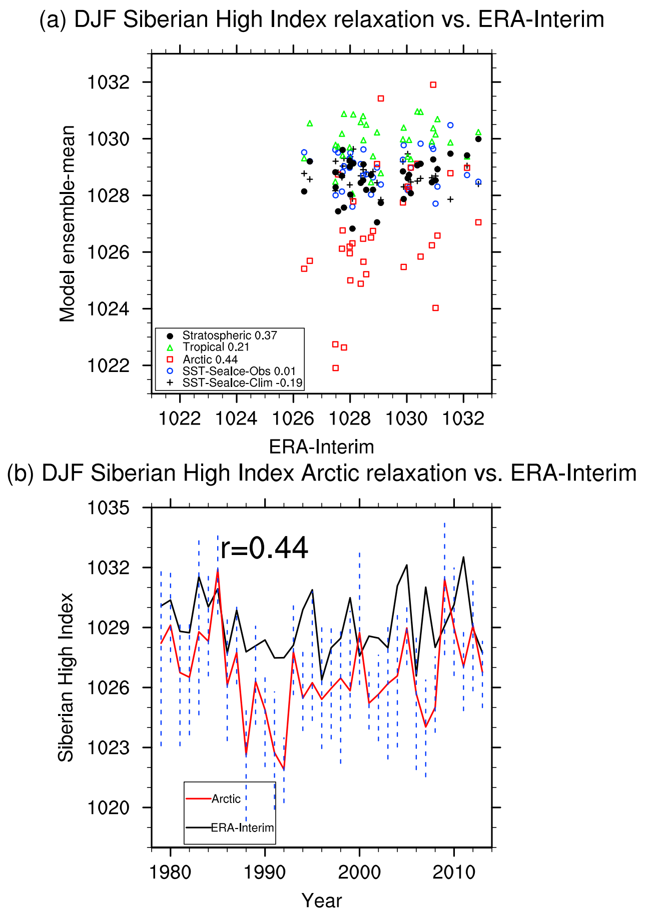

Figure 6. (a) Scatter plot of the intensity of the Siberian High depicted using relaxation experiments versus ERA-Interim data. The correlation coefficients of the intensity of the Siberian High between relaxation experiments and ERA-Interim data are indicated in the legend name. (b) The yearly values of the intensity of the Siberian High for the period 1979–2013. Black (red) line is for ERA-Interim data (Arctic relaxation experiment). Dashed vertical lines indicate ensemble spread. Units: hPa. DJF = December-January-February; SST = sea surface temperature.

weakens the heat advection toward the Northern Europe and Russia. Furthermore, the reduced eddy activity along the weaker storm track may decelerate the prevailing westerly (Lau, 1988), thus contributing to the cold anomalies in Northern Europe and Russia. Westerly anomalies associated with the cyclonic flow pattern centered around Lake Baikal may enhance the cold advection toward the south Siberia and East Asia, impacting the SAT variability over those regions. The southward-extended anomalies in SLP may also have important contributions.

Inspection of the anomalies in SLP shows that a sizable area of large positive SLP anomalies covers the whole Arctic extending to the high-latitude and midlatitude North Atlantic and Northern Eurasia (Figure 5d). This pattern of SLP anomalies even extends into east China and Japan. The increases in SLP over Siberia and its surrounding areas are indicative of a stronger SH, which is an important surface pressure system in winter. Its variability is associated with temperature variations over the Eurasian continent and also the East Asia winter monsoon (e.g., B. Wu & Wang, 2002). Its variability is also associated with the winter cloud cover in Northern Eurasia, particularly around regions of central and southern Siberia and the southern Urals (Chernokulsky et al., 2013).

It seems that the Arctic relaxation has strong impacts on the intensity of SH through the influences on the advection of the warm air mass and of the Arctic cold air mass toward the Siberia and the induction of a midlevel cyclonic-pattern of Z500 over Siberia. The former is indicated by the weaker westerly (Figure 5c) and expansive area of positive SLP anomalies (Figure 5d). Less warm air mass from the west and more cold air from the north contribute to the buildup of cold air mass and larger surface pressure. The latter can enhance the air mass convergence of the atmosphere and thus contributes to larger surface pressure (Figures 5a and 5d). To demonstrate the impacts of Arctic relaxation on the SH as compared to other model experiments, scatter plot of model-generated SH intensity indices versus reanalysis-based SH intensity index is produced and depicted in Figure 6a. The SH intensity index is defined as the weighted area-mean SLP in the domain of 40–60°N, 80–120°E (B. Wu & Wang, 2002). Note that the results are based on the ensemble-average and thus large portion of internal variability may be lost. The Arctic relaxation is in best agreement with the reanalysis in terms of interannual variability of the SH intensity, with the correlation coefficient being 0.44 (red squares). However, the mean-intensity of SH is largely underestimated in Arctic relaxation compared to other experiments, suggesting that the impacts from the internal atmospheric dynamics and also the forcing of SST/sea ice are also important in determining the mean SH intensity. In contrast, the tropical relaxation reproduces stronger mean-intensity of SH with weak correlation coefficient being 0.21 (green triangles). Comparison of SST-SeaIce-Obs and SST-SeaIce-Clim (blue circles and black crosses) indicates that SST and sea ice can to some extent impact the variability of the SH. However, observed SST and sea ice are not the major factors for the interannual variations of SH as the correlation coefficient being nearly zero. The correlation coefficient of SH intensity between stratospheric relaxation experiment and the ERA-Interim data is 0.37, indicating the stratospheric impact on the interannual variability of SH (black solid circle).

In Figure 6b, the temporal evolution of the SH intensity index for both reanalysis (black line) and ensemble-mean of the Arctic relaxation experiment (red line) is depicted. The correlation between them is 0.44, significant at 5% level. It is noted that the mean-intensity of SH is underestimated. The vertical dashed blue lines indicate the ensemble-spread of the SH intensity index. It is clearly shown that the internal variability of the atmospheric dynamics plays an important role in the interannual variability of SH. Overall, the intensity of SH is an important linkage between the Arctic troposphere and the climate variability in Northern Eurasia.

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4.3. The Respective Influences of the SLP Anomalies in the Arctic and of the SH on the Eurasian Temperature Anomalies

The atmospheric circulation anomalies in the Arctic exhibit barotropic structures (Figure 5). To determine the direct and indirect influences of the Arctic tropospheric anomalies on the Eurasian SAT anomalies, the correlations of an Arctic SLP index and the intensity index of SH with the SAT are computed, respectively. Partial correlation of the Arctic SLP index with the SAT adjusted for the intensity index of SH is also computed. The Arctic SLP index is defined as the weighted area-mean SLP north of 65°N. The Arctic SLP index thus faithfully describes the variability of the SLP over the Arctic where relaxation is applied in the Arctic relaxation experiment. The relationship of this index with the SAT in terms of partial correlation adjusted for the SH index can be interpreted as direct impacts of the relaxation. The indirect impacts of the relaxation can be inferred from the relationship between the intensity index of SH and the SAT. The correlation map of the Arctic SLP index (Figure 7a) is similar to Figure 4a, confirming the impacts of the Arctic atmospheric circulation on the SAT variability. The indirect impacts of Arctic relaxation through SH on the Eurasian SAT are concentrated in the area south of 60°N in south Siberia and East Asia (Figure 7b). In contrast, the partial correlation of the Arctic SLP index with the SAT indicates that strong direct impacts are concentrated in the sub-Arctic of the Eurasian continent (Figure 7c). The results highlight the importance of the modulation of the SH and the associated impacts on the SAT variability in south Siberia and East Asia.

4.4. The Impacts of the Stratosphere on the Arctic-Midlatitude Tropospheric Circulation and Climate Variability and the Implications for the Arctic Tropospheric Influences on the Midlatitude Climate Variability

The importance of the interaction between troposphere and stratosphere at the middle to high latitudes is well known; and especially the downward propagation of stratospheric anomalies has been a subject of numerous studies (e.g., Baldwin & Dunkerton, 1999; Christiansen, 2001). In fact, it has been argued that stratospheric variability is an important pathway for the Arctic impacts on the midlatitudes (Nakamura et al., 2016; Y. Wu & Smith, 2016).

Previous subsections reveal the strong impacts of the Arctic troposphere on the midlatitude atmospheric circulation and climate variability. The stratosphere also shows strong impacts on the midlatitude atmospheric circulation and climate variability. It is therefore instructive to investigate the contribution of the stratosphere to the Arctic-midlatitude troposphere circulation and the associated climate variability using a relaxation approach (e.g., see also Douville, 2009). The analysis in sections 4.1 and 4.2 is repeated using the model output from stratospheric relaxation experiment. Similar leading EOF spatial mode of winter SAT in Northern Eurasia is found in stratospheric relaxation experiment, albeit with less explained variance (not shown). The PC has a correlation coefficient of about 0.6 with that based on ERA-Interim data, which is weaker than that between Arctic relaxation and ERA-Interim data. This suggests that the stratosphere has strong impacts on the midlatitude climate and part of the Arctic variability is forced by the stratosphere—keeping in mind, however, that ultimately the stratosphere is forced by tropospheric circulation anomalies in the first place.

Figure 8 is similar to Figure 5 except that it is based on stratospheric relaxation experiment. The temperature patterns that are similar to that in Figure 4 are also seen in the stratospheric relaxation experiment (not shown). A weaker polar vortex is seen in the stratosphere (Figure 8a). The anomaly pattern of Z500 indicates a pattern that clearly resembles a negative AO/NAO phase (Figure 8b). The impacts on the tropospheric circulation in the Pacific sector are weak, consistent with the findings in Greatbatch et al. (2012). The anomaly pattern of 300 hPa wind is consistent with that of the Z500 as determined by the geostrophic relation (Figure 8c). Inspection of the SLP anomaly pattern also shows a significant negative phase of AO/NAO (Figure 8d). Comparison of Figures 8 and 5 suggests that the patterns of stratospheric circulation and tropospheric circulation are somewhat similar between the stratospheric and Arctic relaxation experiments. The AO/NAO anomaly pattern is much more evident in the stratospheric relaxation experiment, while the impacts on the SLP (thus on the SH intensity) in the Northern Eurasia are stronger in the Arctic relaxation experiment. It is thus suggested that *part* of the influences of the Arctic troposphere on the midlatitude (particularly over the North Atlantic-European sector) are controlled by the downward propagation of the stratospheric anomalies into the Arctic troposphere. This suggests the importance of the stratospheric pathway for Arctic impacts on the midlatitudes, consistent with previous studies (e.g., Nakamura et al., 2016; Y. Wu & Smith, 2016). As the stratospheric circulation is subjected to the impacts of various factors, including the

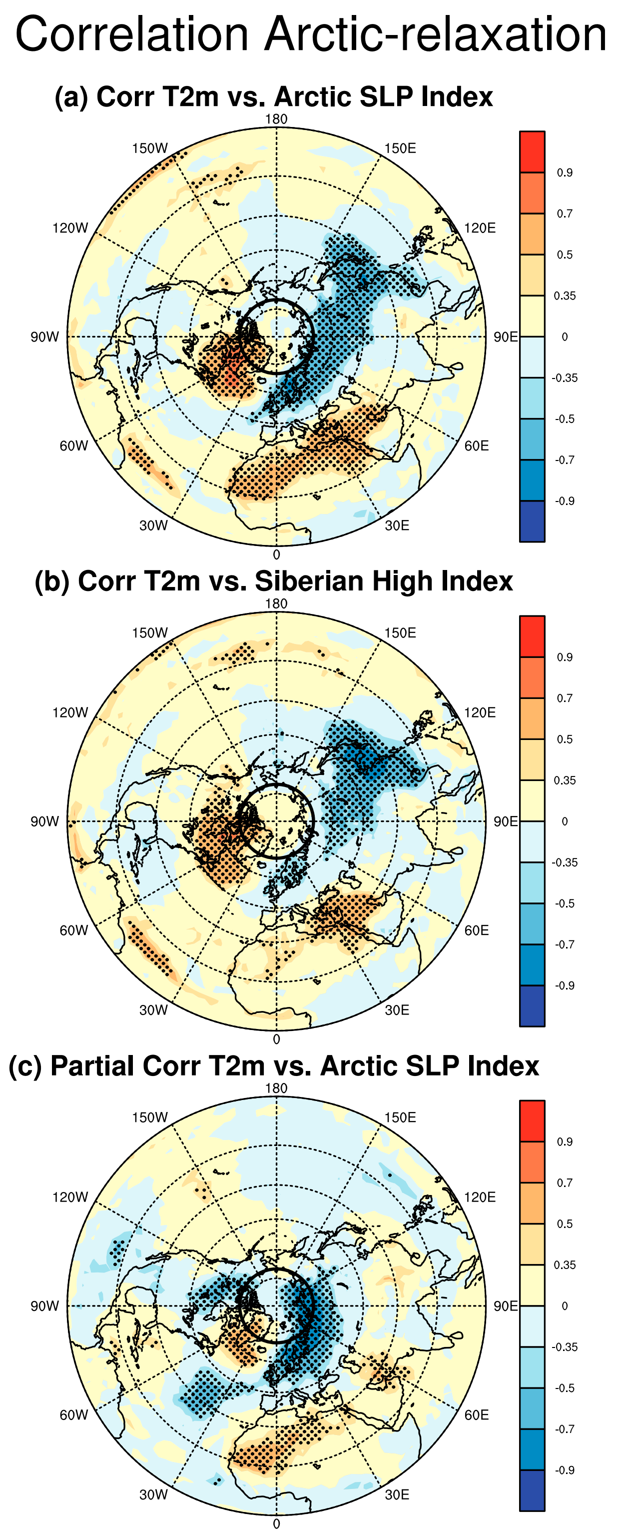

Figure 7. (a) Spatial distribution of the correlation coefficients of surface air temperature and the Arctic SLP index based on Arctic relaxation experiment. (b) Same as in (a) but for Siberian High index. (c) Spatial distribution of the partial correlation coefficients of surface air temperature and the Arctic SLP index adjusted for the Siberian High index. See text for the definition of the Arctic SLP index and the Siberian High index. Stippling indicates significance at 5% level. SLP = sea level pressure.

troposphere, improved understanding of some slowly varying climate components such as Arctic sea ice and Eurasian snow may enhance the seasonal prediction skills over the midlatitudes.

The positive SLP anomalies in the stratospheric relaxation are confined to the sub-Arctic. This is in contrast to the positive SLP anomaly pattern in the Arctic relaxation, which extends further south and east. In both relaxation experiments, the easterly anomalies at the high latitudes in Northern Eurasia contribute to the cooling over those areas by weakening the westerly winds. In both relaxation experiments, cyclone-like anomalies in Z500 and horizontal winds are seen over Siberia. The cyclonic Z500 anomaly is stronger in the stratospheric relaxation experiment. This indicates that this cyclonic Z500 anomaly is also strongly forced by the stratospheric variability. The modulation of SH intensity in the Arctic relaxation is important for impacting the SAT in south Siberia and East Asia. This mechanism is not important in the stratospheric relaxation. The roles of the cyclone-like circulation anomalies over Siberia may be multiple. In both relaxation experiments, the enhanced northwesterly winds over the south frank of cyclone-like circulation anomalies intensify cold air intrusion into the south Siberia and East Asia, directly affecting the temperature variability in those regions. In fact, the East Asian trough is more westward-tilted in the stratospheric relaxation experiment, which has important implications for the cold air intrusion into south Siberia and East Asia. In the Arctic relaxation, the intensity of SH may be enhanced by the midlevel cyclone-like circulation anomalies through impacting the convergence of air flow.

Comparison of Figures 5 and 8 shows that the SLP anomalies over the Arctic and its surrounding areas are stronger in the Arctic relaxation experiment. In contrast, the AO/NAO pattern is more pronounced in the stratospheric relaxation experiment. The SLP variability over the Arctic is associated primarily with the AO pattern in the stratospheric relaxation experiment. However, in the Arctic relaxation experiment, the SLP over the Arctic is directly controlled by the relaxation. Thus, the variability of SLP over the Arctic is also influenced much by other non-AO factors. This explains the larger impacts on the SLP in the Arctic relaxation experiment. The AO/NAO anomaly pattern is the dominant feature in the stratospheric experiment. The AO variability is not forced much by the tropospheric variability in the Arctic as shown in the Arctic relaxation. However, the downward impacts of AO by stratospheric variability is strong, as demonstrated in many other studies.

4.5. The Relationship Between AO and SH Inferred From the Stratospheric Relaxation Experiment

In the stratospheric relaxation experiment, the simulated SH index shows moderate correlation with that based on ERA-Interim data. It is evident that the variability of SH is influenced by various factors, including the potential impacts of AO. We perform EOF analysis of the winter-mean SLP north of 20°N for the stratospheric relaxation experiment and the ERA-Interim data (not shown). As the AO structure is not strong in the Arctic relaxation experiment, we only discuss the relationship between AO and SH in the stratospheric relaxation experiment. The leading spatial EOF modes and their PCs are defined as the AO patterns and indexes. The leading EOF in the stratospheric relaxation experiment explains much larger variance than in the ERA-Interim data (about 70% versus about 50%). The AO structure in the stratospheric relaxation experiment is

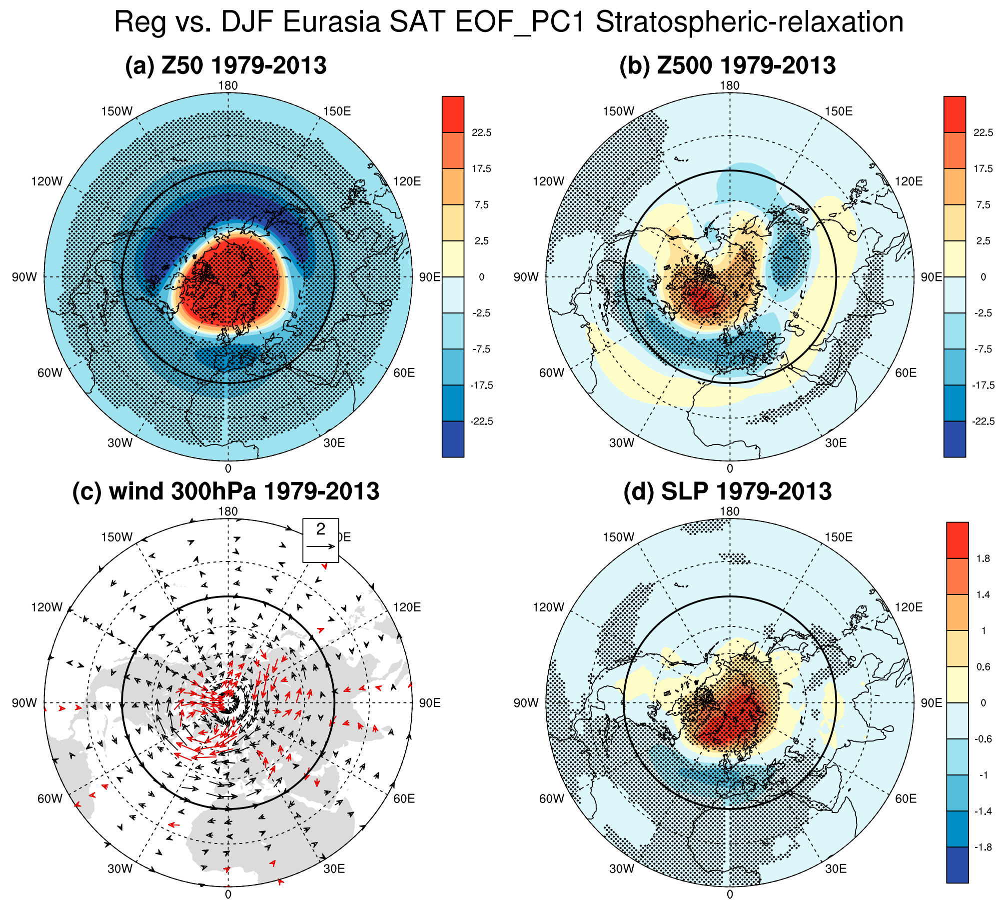

Figure 8. Same as in Figure 5, except for stratospheric relaxation experiment. DJF = December-January-February; SAT = surface air temperature; EOF = Empirical Orthogonal Function; PC = principle component; SLP = sea level pressure.

dominated by the anomalies over the Arctic and North Atlantic-European sector. The AO index in the stratospheric relaxation has a correlation coefficient of 0.6 with that based on ERA-Interim data, suggesting that forcing from the stratosphere does affects the variability of AO.

The AO index is weakly correlated with the intensity index of SH in the ERA-Interim data, with a correlation coefficient being about −0.11. The correlation is about 0.21 in the stratospheric relaxation experiment. Both relationships are weak and show opposite signs for the period 1979–2013. The weak relationship between AO and the SH intensity in the stratospheric relaxation experiment explains the weak impacts on the SLP anomalies in Siberia and its surrounding areas. Further inspection of the 15-year moving-window correlations suggests highly varying and unstable relationship between AO and SH. Their relationship is characterized by strong interdecadal changes. The exact correlation coefficients range from −0.53 (−0.51) to 0.31 (0.56) for ERA-Interim data (stratospheric relaxation experiment). In both the stratospheric relaxation experiment and ERA-Interim data, the relationships between AO and SH are opposite roughly between the first and second half periods during 1979–2013, with negative and positive correlations found for respective periods. The AO variability as forced by the stratospheric variability exerts some influences on the SH variability but these influences might be rather weak in some periods compared to other influencing factors for the SH variability.

5. The Impacts of Arctic Troposphere on Recent Trends in Winter SAT Over Northern Eurasia

The cooling trend of temperature in recent decades is a departure from the long-term warming trend of temperature in Northern Eurasia. This cooling trend in Northern Eurasia is in sharp contrast to the continuous warming trend in the Arctic, which leads to a temperature pattern referred to as warm Arctic-cold Eurasia pattern (e.g., Mori et al., 2014). As discussed in section 1, both the decline in Arctic sea ice and internal atmospheric variability are proposed to explain the recent cooling in Northern Eurasia. In this section, various experiments are analyzed to understand the impacts of the model relaxation as well as observed SST/sea ice on this temperature pattern. The important role of Arctic troposphere in contributing to the cooling trend of temperature in Northern Eurasia is highlighted in the following analysis.

5.1. The Warm Arctic-Cold Eurasia Temperature Pattern in Recent Decades

Figure 9 displays the SAT trends for the period 1990–2013 as computed from the ERA-Interim data and model output of various model experiments. In ERA-Interim data, warming trends are seen in Arctic and east Canada with maxima exceeding 2.4 °C per decade in some areas (Figure 9a). The warming trends are accompanied by cooling trends in northern Europe, central Russia, Mongolia, and Siberia. Inspection of the three relaxation experiments (Figures 9b–9d) indicates that only the Arctic relaxation experiment (Figure 9b) reproduces a similar warm Arctic-cold Eurasia pattern as seen in ERA-Interim data. Indeed, the trends are quite different and rather weak in both tropical and stratospheric relaxation experiments (Figures 9c and 9d). Therefore, it can be argued that both the warming trends and the cooling trends as seen in ERA-Interim data are not strongly associated with the atmospheric circulation in the tropics and the stratosphere. Relaxing the stratosphere toward reanalysis is also found to fail to capture the trends in the winter atmospheric circulation in Greatbatch et al. (2012). It is also noted that the trends in east Canada and central Russia in Arctic relaxation experiment are weaker than those in ERA-Interim.

In SST-SeaIce-Obs experiment (Figure 9e), the warming trends are seen in the Arctic, east Canada, and Northern Eurasia and cooling trends are seen in Northeast Pacific. The warming trends in Arctic Ocean and oceanic areas of east Canada are much stronger than both the cooling and warming trends in other areas. This suggests that the warming trends of SAT in Arctic and east Canada in recent decades are driven strongly by the local SST/sea ice trends. This assertion is also supported by the observation of weaker temperature trends at 850 hPa over these two areas (not shown). The bottom-heavy temperature response to the anomalies in Arctic sea ice/SST is widely noted. The warming trends in Northern Eurasia are in direct contrast to the cooling trends as seen in ERA-Interim data. Therefore, the cooling trends in Northern Eurasia as seen in ERA-Interim data are not driven by the SST/sea ice trends. This is consistent with previous studies (e.g., Sun et al., 2016).

We argue that the cooling trends of temperature in recent decades in Northern Eurasia are more closely associated with tropospheric circulation in the Arctic. The cooling trends are not driven by SST/sea ice trends and tropical/stratospheric circulation trends. However, some forcing factors such as Eurasian snow, internal atmospheric dynamics in the midlatitudes, and ocean-atmosphere interaction may also contribute to the cooling trends in Northern Eurasia.

5.2. The Atmospheric Circulation Trends in Recent Decades and the Role of SST and Sea Ice Forcing

The above analysis leads to two important questions. One is about the atmospheric circulation that communicates the impacts of the Arctic influences on the midlatitude in the Arctic relaxation experiment. The other is about the warming trends in temperature over both Arctic and Northern Eurasia as seen in the SST-SeaIce-Obs experiment. The warming trends in Arctic are well defined in both Arctic relaxation experiment and ERA-Interim data. However, the cooling trends in Northern Eurasia are absent in the SST-SeaIce-Obs experiment. Therefore, it remains to be seen how similar warming patterns in Arctic are associated with different trend patterns of temperature in Northern Eurasia. To address these two questions, trends in atmospheric circulation are studied below.

Figure 10 is similar to Figure 9 except for Z500. An expansive area of significantly positive trends in Z500 is located in the Arctic, extending south to east Canada, west Russia, and central Asia in ERA-Interim data (Figure 10a). The meandering of the pattern is strong, which is an important feature. Positive trends are also seen in North Pacific. The pattern of positive trends indicates a weaker NAT and an enhanced ridge over west Russia. Negative trends in Z500 are centered in northeastern America, Europe, and Mongolia, respectively. The belt of contrasting trends in the North Atlantic-Europe and west Arctic indicates a negative trend of NAO in recent decades. The negative NAO trend in the extended winter is shown in Iles and Hegerl (2017). The pattern of Z500 trends including the magnitude is well reproduced in Arctic relaxation experiment,

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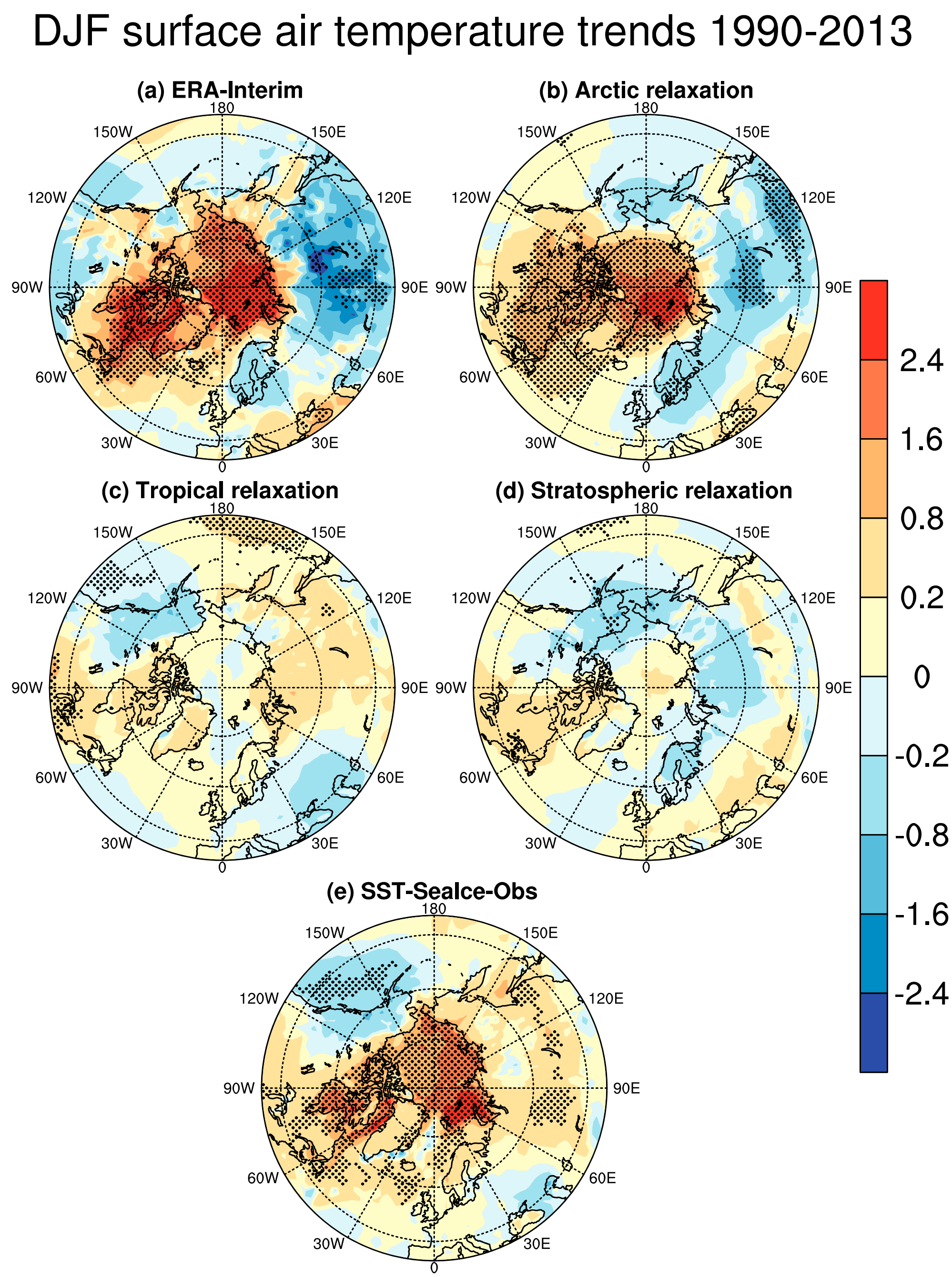

Figure 9. The spatial distribution of the linear trends in winter-mean surface air temperature for the period 1990–2013 as computed for (a) ERA-Interim data, (b) Arctic relaxation, (c) tropical relaxation, (d) stratospheric relaxation, and (e) SST-SeaIce-Obs experiments. Stippling indicates significance at 5% level. Units: °C per decade. DJF = December-January-February; SST = sea surface temperature.

except the negative trends in the North Atlantic-Europe (Figure 10b). The negative trends of Z500 in recent decades are basically missing over North Atlantic-Europe in the Arctic relaxation experiment. This suggests that the recent negative trend of NAO is not forced by the Arctic tropospheric circulation. The pattern of Z500 trends as seen in the ERA-Interim data is not found in both tropical relaxation and SST-SeaIce-Obs experiments (Figures 10c and 10e). Although similar spatial pattern as in the ERA-Interim data is seen in the stratospheric relaxation, the magnitudes of trends are rather weak and insignificant (Figure 10d). Trends in Z50 feature a similar pattern as in Z500 in ERA-Interim data, albeit with weak statistical

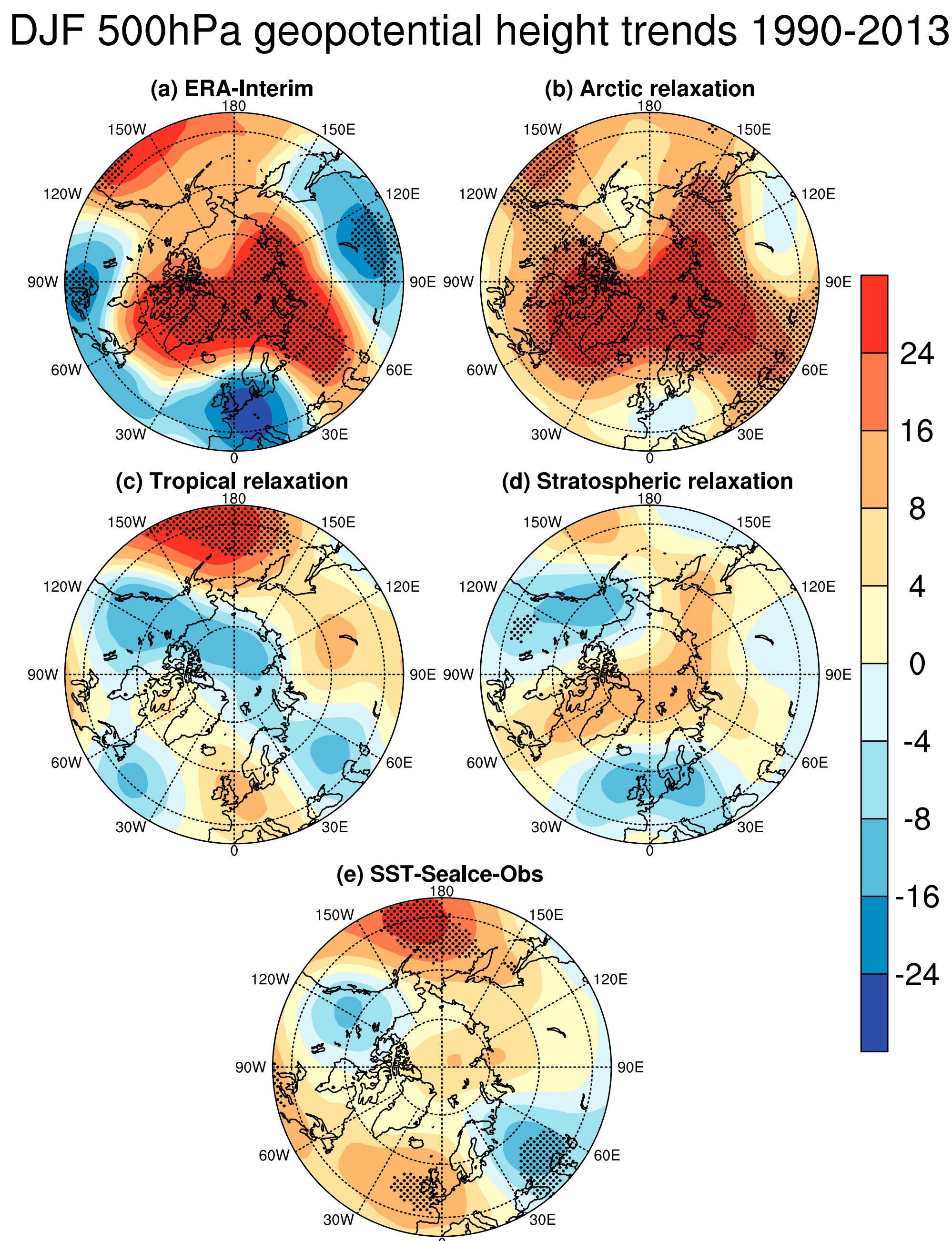

Figure 10. Same as in Figure 9, except for geopotential height at 500 hPa. Units: geopotential meters per decade. DJF = December-January-February; SST = sea surface temperature.

significance (not shown). Similar patterns of Z50 trends are also seen in Arctic and stratospheric relaxation experiments, with the former being more significant (not shown). In sharp contrast, nearly opposite patterns of Z50 trends are seen in tropical relaxation and SST-Sealce-Obs experiments (not shown). The results of trend analysis suggest that the Arctic troposphere in the Arctic relaxation experiment has strong impacts on the stratosphere. In contrast, the stratosphere in the stratospheric relaxation experiment has relatively weak impacts on the Arctic-midlatitude troposphere in terms of trends. The tropospheric circulation and states over the Arctic are therefore key factors for the impacts of Arctic on the midlatitude in terms of the temperature trends. Therefore, the warm Arctic-cold Eurasia pattern of temperature trends are not forced by the stratospheric/tropical circulation and the associated atmospheric states.

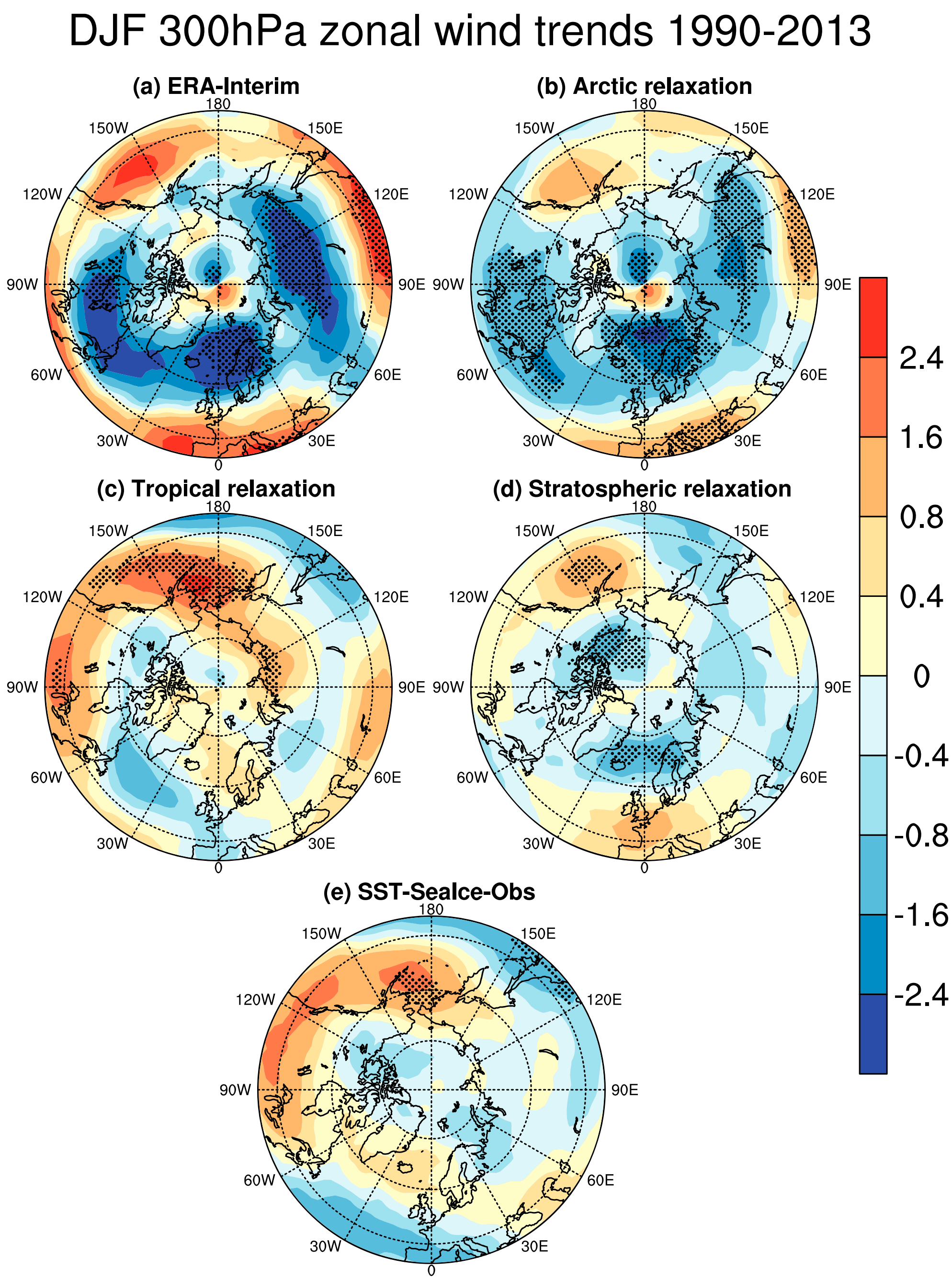

Figure 11. Same as in Figure 9, except for zonal wind at 300 hPa. Units: m/s per decade. DJF = December-January-February; SST = sea surface temperature.

The lack of proper trends in atmospheric circulation in both troposphere and stratosphere also explains the absence of cooling trends in temperature over Northern Eurasia in SST-SeaIce-Obs experiment (Figure 9e). In other words, our results suggest that the trends in atmospheric circulation over the Arctic and its surrounding areas are not forced by the local and remote SST/sea ice trends. It is also indicated that the warming trends in the Arctic and its surrounding areas are not the cause for the trends in the troposphere in the Arctic and its surrounding areas. This suggests that the warming trends in the Arctic are not physically linked to the cooling trends in the Northern Eurasia in recent decades. The decline in Arctic sea ice is coincident with warming in the Arctic and is also suggested in some studies as the cause for the cooling trends in Northern Eurasia. Although the warming trend in the Arctic is reproduced in SST-SeaIce-Obs experiment, the lack of the correspondingly correct trends in both atmospheric circulation and the temperature in Northern Eurasia raises some doubts on the widely proposed influences of the declining Arctic sea ice on the Eurasian cooling trends.

The patterns of trends in zonal wind at 300 hPa are consistent with the patterns of trends in Z500 by virtue of the geostrophic relation (Figure 11). The observation of negative trends over northern Europe and the Norwegian Sea indicates downward trends in heat advection toward northern Europe, which accounts partly for the cooling trends in northern Europe in ERA-Interim data (Figure 11a). Negative trends in zonal winds are also seen in west-central Russia and Siberia, which contribute to the cooling trends in temperature. There are several plausible reasons for such contribution. First, weaker zonal wind may lead to weaker heat advection toward Russia and Siberia. Second, weaker zonal wind may enhance equatorward intrusion of Arctic cold air. Third, weaker zonal wind may favor more blocking activity, which contributes to extreme events. Similar trends in zonal wind at 300 hPa are seen in Arctic relaxation experiment with weaker magnitudes (Figure 11b). As expected, significant trends in meridional wind at 300 hPa are also evident in both experiments (not shown). In particular, the positive trends over east Canada indicate weakening of the NAT and the associated weakening of the southward advection of cold air mass is in agreement with the observation of positive temperature trends. These patterns of trends in 300 hPa wind are not seen in tropical relaxation and SST-SeaIce-Obs experiments (Figures 11c and 11e). They are weak in stratospheric relaxation experiment (Figure 11d). Trends in SLP are also examined to understand the associated changes in the surface circulation. Significant positive trends in SLP are evident in the Arctic and Northern Eurasia in ERA-Interim data, with significant negative trends off the east coast of North America and over the Mediterranean Sea (Figure 12a). Similar pattern of positive trends is found for Arctic relaxation experiment, with the pattern of negative trends missing (Figure 12b). A similar situation is found in Z500 trends (Figure 10b). It is thus suggested that the Arctic tropospheric circulation trends in recent decades have weak impacts on the atmospheric circulation trends over the North Atlantic-European sector. The area with significant positive trends is much larger in Arctic relaxation experiment, extending well southward to the subtropics. The trends in SLP over Siberia in both Figures 12a and 12b suggest upward trends in the intensity of SH in recent decades. The intensity of SH had been decreasing from 1970s to 1990s but has been increasing starting from early to mid-1990s (Jeong et al., 2011). Therefore, the upward trend in SH intensity during recent decades is a potential contributing factor for the cooling trend in temperature over Northern Eurasia. The patterns of SLP trend in tropical relaxation and SST-SeaIce-Obs experiments are different from ERA-Interim data (Figures 12c and 12e). The pattern of SLP trend in stratospheric relaxation experiment is somewhat similar to ERA-Interim data (Figure 12d). However, the trends are weak and insignificant. It is thus indicated that the recent upward trend in SH intensity is closely associated with the changes in the Arctic troposphere and is not related much to the trends in SST/sea ice, the tropical, and the stratospheric circulation.

5.3. The Trends in the Winter Atmospheric Blocking Frequency and the Roles of Arctic Tropospheric Circulation, SST, and Sea Ice Forcing

The atmospheric blocking frequency (see the method in Lejenäs & Økland, 1983; Tibaldi & Molteni, 1990) during winter shows upward trends over the west-central Northern Eurasia in the ERA-Interim data (Figure 13a, black curve). The upward trends in blocking frequency are particularly strong near the Ural area (around 60°E). These upward trends in the blocking frequency might have contributed to the recent Eurasian cooling, as demonstrated in previous studies (e.g., Luo et al., 2016). Therefore, we are particularly interested in these upward trends. Downward trends in blocking frequency are seen over Europe (0–45°E) and Asia-Pacific sector (130–180°E). The longitudinal distribution of the blocking frequency trends is quite different in SST-SeaIce-Obs experiments (red versus black curves). It is thus argued that the recent upward trends in blocking frequency over west-central Northern Eurasia are not driven much by SST or sea ice changes. Rather, the ensemble-spread in the SST-SeaIce-Clim experiment (blue open triangles) suggests that these upward trends in the blocking frequency may be generated by internal atmospheric dynamics.

The blocking frequency trends based on the relaxation experiments are shown in Figure 13b. A relatively good resemblance between the Arctic relaxation experiment and the ERA-Interim data is noted in terms of the longitudinal distribution (red versus black curves). This is not true for both the stratospheric and tropical relaxation experiments (blue and green curves). Generally, the internal atmospheric variability is strong as seen from the ensemble spread. However, the ensemble-spread in the Arctic relaxation experiment for the longitudes from about 45 to 105°E is narrower, which is due to the fact that the lower limits

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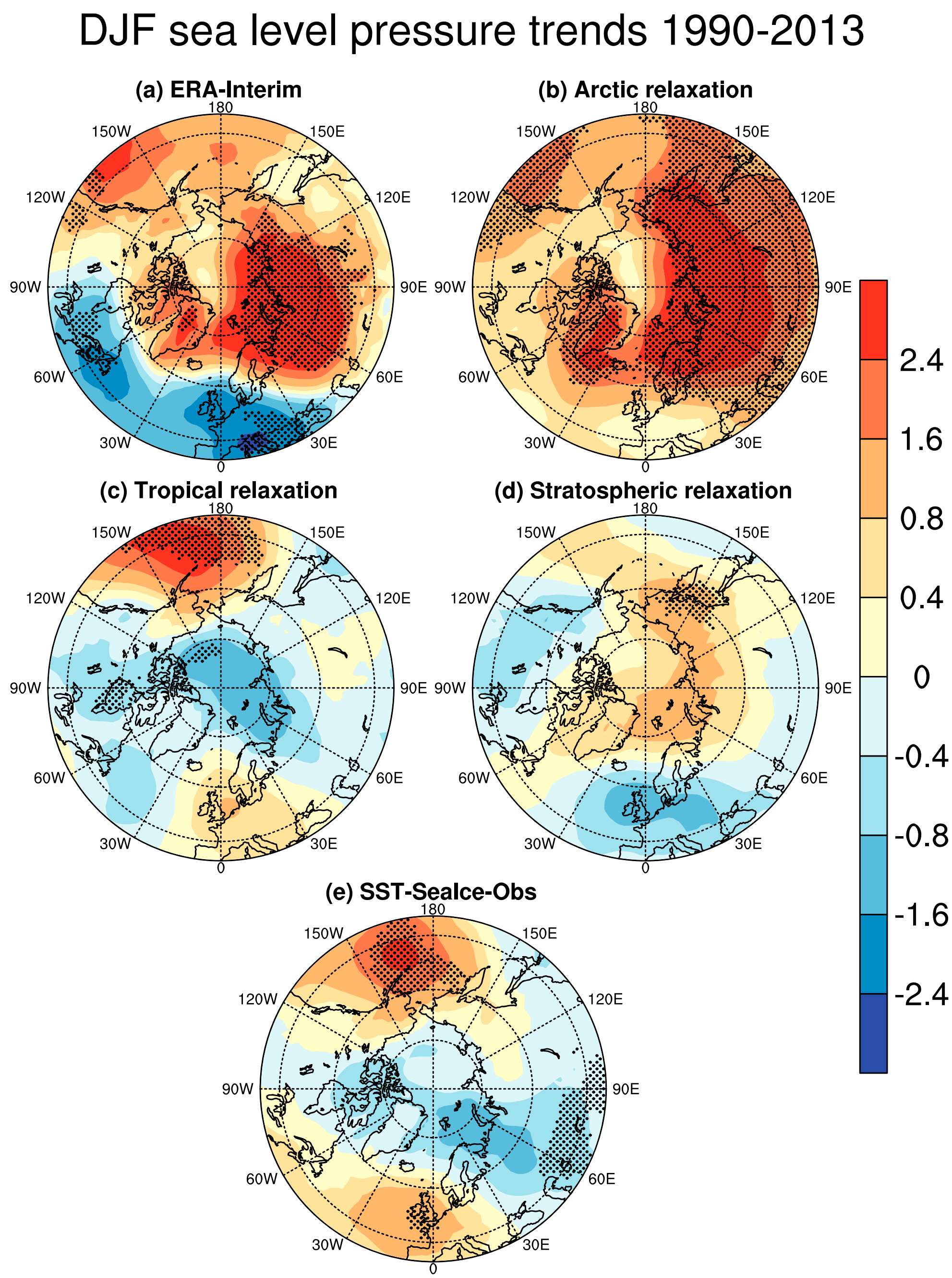

Figure 12. Same as in Figure 9, except for sea level pressure. Units: hPa per decade. DJF = December-January-February; SST = sea surface temperature.

(red open triangles) are strongly shifted *upward*. In other words, the Arctic relaxation forces the trends in the blocking frequency toward positive sign in the Ural and central Russia areas. Thus, relaxation of the Arctic troposphere does constrain the blocking frequency trends in those regions, at least to a certain degree. It can be argued therefore that the Arctic tropospheric circulation in recent decades favors upward trends in the atmospheric blocking frequency in Ural and central Russia area. However, the ensemble-mean trends and the most pronounced positive trends in the ensemble members over the Ural and central Russia area in Arctic relaxation experiment are still relatively small compared to what is observed in the ERA-Interim data. This suggests that other mechanisms are more important for explaining atmospheric blocking trends in the Ural area.

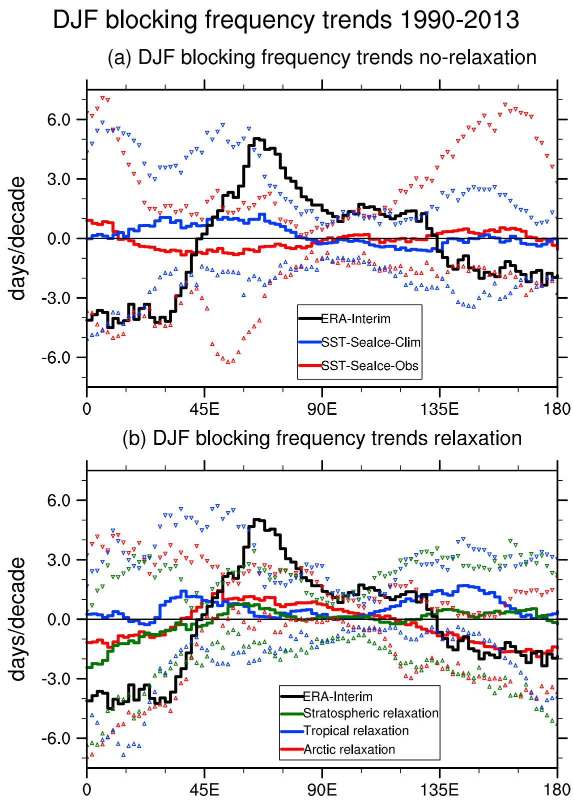

Figure 13. The longitudinal distribution of the trends in atmospheric blocking frequency during winter for the period 1990–2013. (a) SST-SeaIce-Clim and SST-SeaIce-Obs experiments without relaxation. (b) Arctic, tropical, and stratospheric relaxation experiments. Black curves are for ERA-Interim data. Inverted open triangles (open triangles) indicate the upper (lower) limits of the ensemble spread. Units: days per decade. The triangles use corresponding colors to indicate the model ensemble-spread of the experiments. DJF = December-January-February; SST = sea surface temperature.

Results in this section suggest that the warm Arctic-cold Eurasia pattern of temperature trends is a manifestation of two possibly independent phenomena. The warming in the Arctic areas is contributed partly by the local SST/sea ice trends. However, the trends of tropospheric circulation in the Arctic and its surrounding areas are not forced by the local or remote SST/sea ice trends. They are also not forced by the tropical/stratospheric circulation. The Arctic troposphere is found to modulate the midlatitude zonal and meridional winds and impact the heat advection over the midlatitude continents. It also contributes to the upward trend in the SH intensity. The upward trends in SH intensity contribute to the cooling trends in temperature over Northern Eurasia. The Arctic troposphere also seemingly contributes to the increasing atmospheric blocking frequency in recent decades over the Ural and central-Russia areas.

6. Discussion

The strong impacts of Arctic troposphere on the midlatitude atmospheric circulation and climate are noted in this study. The impacts are particularly significant in Northern Eurasia. These impacts are mainly communicated through the modulation of the large-scale atmospheric circulation and the associated heat transport. The influences of Arctic troposphere on the midlatitude are centered on specific regions, with the strong modulation of synoptic activities over North Atlantic-European sector being one such example. In the Arctic relaxation experiment, relaxing the model states in the Arctic troposphere toward ERA-Interim data forces the model to represent the observed development. One question regarding this is about the sources for the Arctic tropospheric variability. On interannual timescales, variations of Arctic sea ice, seasonal snow, SST variability, poleward forcing of atmospheric circulation and energy transport, stratospheric forcing, and internal atmospheric variability are important candidates. As indicated in section 4.4, relaxing the stratosphere shows similar impacts on the midlatitudes as compared to relaxing the Arctic troposphere. The stratospheric relaxation leads to stronger AO circulation patterns but weaker SLP pattern in Northern Eurasia. This is accounted for by the weak forcing of the Arctic tropospheric circulation on the center of action of the AO/NAO outside the Arctic. In the Arctic relaxation, SLP is relaxed toward ERA-Interim data and thus the SLP variability related to both stratospheric variability and the tropospheric variability is well captured. This explains the greater impacts on the SLP in Northern Eurasia by the Arctic relaxation. The Arctic tropospheric impacts on the midlatitudes might be partly contributed to by the stratospheric circulation variability. The Arctic sea ice and Eurasian snow are two influencing factors for the stratospheric variability as suggested in many studies. Thus, understanding of the impacts of the Arctic sea ice and Eurasian snow on the stratospheric variability is important. In the Arctic relaxation experiment, the intensity of SH is strongly modulated by the Arctic troposphere, which contributes strongly to the climate variability in the Asian continent. Further research into the correlation between Arctic troposphere and the variability of SH is important for the study of the climate variability in Northern Eurasia, particularly southeastern part of the Asian continent.

The recent warm Arctic-cold Eurasia pattern of temperature is faithfully reproduced only in the Arctic relaxation experiment. Warming of the Arctic areas is due in part to the trends in SST/sea ice. However, the trends in the Arctic troposphere are not driven by the trends in SST/sea ice. Trends in both surface warming and tropospheric circulation in the Arctic are also not influenced much by the trends in the stratospheric/tropical circulation. These results explain the fact that only Arctic relaxation experiment reproduces the recent warm Arctic-cold Eurasia pattern of temperature. By inference, the trends in Arctic sea ice is not a contributing factor for the recent cooling trends in Northern Eurasia. Overall, the results in this study confirm the strong impacts of Arctic troposphere on the cooling trends and the associated atmospheric circulation trends in Northern Eurasia. In view of the rapid temperature rise, continuous decrease in Arctic sea ice and the associated climate changes in the Arctic, understanding of the changes and variability of the Arctic troposphere has important implications for the climate variability in the midlatitude region and beyond. On the other hand, the impacts of midlatitudes on the Arctic troposphere and stratosphere are highlighted in numerous studies (e.g., Jung & Leutbecher, 2007). The interaction between Arctic atmosphere and midlatitude atmosphere is thus important for understanding the climate variability in the NH middle to high latitudes.

Limitations of this study are outlined below. Results in this study are based on the output from one model with small ensemble size. However, this is taken into account when interpreting the results. Further, some important processes such as the atmospheric responses to forcing of Arctic sea ice and the interaction between troposphere and stratosphere may be model-dependent and are affected by the physical considerations used in different models. Therefore, multimodel-ensemble studies may prove useful in this sense. The water vapor is not a relaxed variable in all the experiments. This may limit the impacts of the water vapor transport and the moist dynamic processes. For example, the impacts of transport of lower-latitude water vapor on the climate variability at middle to high latitudes might be underestimated. The diagnosis used in this study is also weighted heavily toward large-scale atmospheric dynamics and thermodynamics. The forcing of the transient eddies in terms of momentum, heat, and moisture transport is not studied. As atmosphere-only model is used to carry out the experiments, sea ice/ocean-atmospheric interaction processes are suppressed and these interaction processes may be important.

7. Conclusions

A suite of model experiments with and without atmospheric relaxation is analyzed to study the impacts of the Arctic troposphere on the midlatitude atmospheric circulation and climate variability. The main outcomes from the analysis are summarized below.

Compared to the tropical atmosphere and the stratosphere, the Arctic troposphere has stronger influences on the SAT and atmospheric circulation in the midlatitude continents, particularly over Northern Eurasia. However, some of the impacts of the Arctic troposphere on the midlatitudes are seemingly controlled by the downward propagation of the stratospheric forcing. The stratospheric circulation is also forced from below. Further analysis is conducted to understand the linkage between Arctic troposphere variability and the winter SAT variability in Northern Eurasia. It is indicated that a temperature pattern of warming in the east Canada, Greenland, and west Arctic and cooling in Eurasia emerges in the Arctic-Eurasian sector. The Arctic troposphere modulates the large-scale midlatitude atmospheric circulation and the associated heat advection over Northern Eurasia. The synoptic activity over North Atlantic-European sector is also strongly impacted. In addition, the direct impacts of the Arctic troposphere on the climate variability in Northern Eurasia are concentrated on the high latitudes. The indirect impacts are communicated by the variability of SH. The intensity of SH is a strong linkage between the variability of Arctic troposphere and the winter SAT variability in south Siberia and East Asia.

The warm Arctic-cold Eurasia pattern of temperature trends can be found in observations in recent decades. The cooling trends in Northern Eurasia in recent decades are closely associated with the trends in Arctic troposphere. The downward trends in the zonal wind indicate weakening westerlies and reduced heat transport toward Northern Eurasia. The increases in atmospheric blocking frequency over the Ural and central Russia area are associated with the cooling trends. The intensity of SH shows an increasing trend in recent decades, which contributes to the surface cooling. Both the warming trend in the Arctic and the cooling trend in Northern Eurasia are not associated with trends in the tropical atmosphere and the stratosphere. The trends in SST/sea ice seemingly contribute partly to the warming trends in the Arctic areas but is not the cause for the recent cooling trends in Northern Eurasia. Therefore, improved understanding of the variability of the Arctic troposphere may represent a key to delineating the causes of the warm Arctic-cold Eurasia pattern of temperature trends and also to projecting the future evolutions of the temperature trends in Northern Eurasia.

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