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How Strong Is Influence of the Tropics and Midlatitudes on the Arctic Atmospheric Circulation and Climate Change?

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Key Points:

- The atmospheric circulation in both the tropics and midlatitudes has a strong impact on the Arctic atmospheric circulation
- The midlatitudes play an important role in driving the recent Arctic warming above the atmospheric boundary layer
- Recent summer warming in northeastern Canada-Greenland (northern Europe and western Russia) is strongly driven by SST/sea ice (midlatitudes)

Supporting Information:

- Supporting Information S1

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Abstract

Relaxation experiments with the atmosphere model from European Centre for Medium-range Weather Forecasts are analyzed to understand influence of lower latitudes (south of about 52 °N) on climate variability and change over the Arctic region. Interannual variability of the Arctic troposphere is impacted strongly by both the tropics and the midlatitudes. In general, the link in winter is stronger than that in summer. Furthermore, the tropics and midlatitudes have different preferred pathways by which they influence the Arctic. Trend analysis suggests that winter surface warming trends over the Arctic are driven strongly by the local sea ice-atmospheric interaction. Warming at higher altitudes is strongly tied to remote non-Arctic drivers, with some local amplification. Summer warming trends in northeastern Canada and Greenland are driven strongly by sea surface temperature/sea ice changes and partly by the tropics. The summer warming in northern Europe and western Russia is more strongly driven by the midlatitudes.

Plain Language Summary

This study analyzes model output from relaxation experiments, in which the atmosphere at lower latitudes is nudged toward reanalysis data, to understand influences of tropics and midlatitudes on the Arctic atmosphere in terms of variability and trends. Our results demonstrate that the Arctic atmospheric circulation in terms of interannual variability can be relatively well constrained by lower latitudes. Generally, lower-latitude forcing of the Arctic is stronger in winter than in summer. However, the Arctic temperature variability is less well constrained, owning possibly to poorly constrained local cloud/radiation feedback. In terms of the recent warming trends in the Arctic region, the surface warming is more strongly related to the local sea ice-atmosphere interaction during winter. The warming at higher altitudes is strongly driven by remote processes. The summer warming is located mainly over the land areas and the driving factors are region dependent.

1. Introduction

The Arctic climate system is a coupled system in which ocean, sea ice, land, and atmosphere interact with each other. The Arctic climate system also interacts with lower latitudes (tropics, subtropics, and midlatitudes). The impact of Arctic sea ice on the local and remote atmospheric circulation has been extensively studied (e.g., Alexander et al., 2004; Wu et al., 2013). The Arctic sea ice has experienced a strong declining trend in the recent decades (e.g., Deser & Teng, 2008; Lemke et al., 2007; Stroeve et al., 2012, 2014). At the same time, the Arctic has also been warming at a much faster rate compared to the rest of the globe, a phenomenon known as Arctic amplification (AA; see Cohen et al., 2014, and references therein). The decline in Arctic sea ice has been considered as a strong contributing factor for AA (e.g., Screen & Simmonds, 2010a, 2010b). However, AA has also been explained by various other factors, including poleward transport of moisture and heat and local cloud-radiation/temperature feedbacks (e.g., Serreze & Barry, 2011, and references therein; Pithan & Mauritsen, 2014; Gong et al., 2017). A general consensus on the relative importance of local versus remote processes in explaining AA is still missing.

The impacts of AA on the large-scale atmospheric circulation include changes in storm tracks, jet stream, and planetary waves (see Cohen et al., 2014, and references therein). In fact, the decline in Arctic sea ice has been considered a major driver of the recent warm Arctic-cold Eurasia temperature pattern (e.g., Honda et al., 2009; Liu et al., 2012). At the same time, this linkage has been questioned in some other recent studies (e.g., Kumar et al., 2010; Perlwitz et al., 2015; Screen et al., 2013; Sun et al., 2016), highlighting that our understanding of the climate variability and change in the Arctic and its potential impacts on lower latitudes is still limited.

It has been argued that the Arctic climate is strongly forced by the lower latitudes (e.g., Baggett & Lee, 2015; Garrett & Zhao, 2006; Gong et al., 2017; Vavrus, 2004). Poleward transport of energy is important for climate variability in the Arctic and is dominated by the atmospheric transport at the middle-high latitudes. There is some evidence that anthropogenic aerosols transported from the midlatitudes enhance the longwave emissivity of Arctic clouds (Garrett & Zhao, 2006). Understanding possible tropical impacts on Arctic climate is also an area of active research. It has been argued that a Rossby wave anomaly, driven by sea surface temperature (SST) anomalies in the tropical Pacific, has led to the recent warming in northeastern Canada and Greenland through contributing to the negative trend in the North Atlantic oscillation (NAO; Ding et al., 2014). In fact, various studies have attributed the Arctic warming to tropical convection, which in turn is strongly associated with the tropical SSTs (Flournoy et al., 2016; Goss et al., 2016; Lee, 2012; Lee et al., 2011) or the Madden-Julian Oscillation (Yoo et al., 2011). These studies, together with the studies emphasizing the Arctic local processes such as sea ice-albedo and radiation feedbacks, highlight the complex nature of the Arctic climate variability and change. So far, compared to the extensive on-going research on the impacts of the changing Arctic on lower latitudes, relatively little attention has been paid to the lower-latitude forcings of the Arctic climate. In this paper, we analyze numerical experiments with the European Center for Medium-range Weather Forecasts (ECMWF) atmospheric model in which a relaxation approach is employed (Greatbatch et al., 2012; Jung et al., 2010; Jung et al., 2011, 2014; Semmler et al., 2018). This approach allows quantifying the impacts of the lower latitudes on the variability and change of the Arctic troposphere (north of 60 °N). In particular, the relative importance of the tropics compared to midlatitudes are considered. We quantify the impact of remote drivers in terms of interannual variability and recent trends. The results provide insights on understanding the driving factors of the Arctic climate variability and change.

2. Data and Methodology

2.1. ERA Interim Data

For comparison of the model results with observations, monthly mean surface air temperature (SAT), air temperature at 500 hPa (T500) and at 850 hPa (T850), specific humidity at 850 hPa (Q850), geopotential height at 500 hPa (Z500), sea level pressure (SLP) and surface downward thermal radiation (SDTR) were taken from the ERA Interim (Berrisford et al., 2011).

2.2. Model Relaxation Experiments

The ECMWF atmospheric model is used in the experiments. In this study, a horizontal resolution of T_L255 (about 80 km) and a vertical resolution of 60 levels are employed. Specific atmospheric variables, including surface pressure (not for the tropical relaxation), temperature, and horizontal winds, are relaxed in each model time step toward the ERA Interim reanalysis data, which is available at the same resolution. Details of the relaxation approach can be found in Jung, Miller, & Palmer, 2010, Jung et al., 2010, Jung et al., 2011 and 2014) and Hoskins et al. (2012). In the lower latitude relaxation experiment (TropMidlat), atmospheric variables below 300 hPa in the area between 52.5 °S and 52.5 °N are relaxed. In the tropics relaxation experiment (Trop) atmospheric variables over the troposphere and stratosphere in the area between 20 °S and 20 °N are relaxed. Both relaxation experiments are run with climatological SST/sea ice concentration (SIC) conditions. Inclusion of the stratospheric relaxation in the Trop experiment is not expected to have significant implications for the results in this study (see supporting information for more discussions). Assuming linearity, the impacts of midlatitudes on the Arctic regions can be obtained by taking the differences between the two experiments (TropMidlat-Trop; see supporting information for further details). Similar analyses of relaxation experiments were carried out by Jung et al. (2014) and Ye et al. (2018), with the goal to study the impacts of the Arctic on midlatitude weather and climate. Two additional experiments without relaxation were run with climatological SST/SIC ($CLIM_{SST,SI}$, reference experiment) and with observed SST/SIC conditions ($OBS_{SST,SI}$), respectively. A total of nine ensemble members were run from November through February for boreal winters of the period 1979/80–2013/14 as well as from May to August for boreal summers for the period 1980–2014. The lagged ensemble was generated by initializing the simulations from ERA-Interim fields that are 6 hr apart.

3. Results

3.1. Impacts of the Tropics Versus Midlatitudes on Interannual Variability of the Arctic Troposphere

The strength of the influence of the tropics and midlatitudes on climate variability of the Arctic troposphere is quantified in terms of temporal correlation coefficients (Figure 1). The interannual variability of atmospheric variables from these relaxation experiments is displayed in the supplementary figures and discussion of the results is provided in the supporting information. All fields were detrended before the analysis.

The impacts of the tropics on the circulation in terms of SLP and Z500 are relatively strong only over the western sector of the Arctic (Figures 1a and 1c). This suggests that the key pathway for the influence of the tropics on the Arctic circulation may be over the North American sector. In contrast, the impacts of the midlatitudes on the Arctic circulation are stronger over most other parts of the Arctic (Figures 1b and 1d), particularly over the North Atlantic-European sector. Thus, the North Atlantic-European sector is seemingly a preferred pathway for the midlatitudes to impact the Arctic circulation. In terms of interannual variability of the Arctic circulation, our results indicate that separating the influences of the midlatitudes from those of tropics may be necessary.

Is Arctic temperature variability impacted in a similar way? Inspection of the correlation maps of temperature parameters like SAT (Figures 1e and 1f), T850 (Figures 1g and 1h), and T500 (Figures S8a and S8b) reveals similar patterns to that of SLP and Z500. Such similarity suggests that control of dynamical processes on thermodynamics over the Arctic region is strong. However, the influences on temperature are seemingly weaker for both tropics and midlatitudes. This suggests that some nondynamic local processes are also important in the temperature variability in the Arctic. In fact, perpetual seasonal cycle of climatological SST/SIC is prescribed in the relaxation experiments, thus limiting the feedback of SST/SIC variability onto the temperature variability particularly over the oceanic areas. This may partially account for the weaker influences on temperature variability over the oceanic areas. Relatively strong influences of the SST/SIC on the interannual variability of the temperature in $OBS_{SST,SI}$ experiment are confined to surface and sea ice-edge areas (Figures S7a, S7c, and S7e). We propose that local thermodynamic/radiative processes are also important for explaining the interannual temperature variability particularly over the Arctic ocean. Preliminary analysis will be provided below to support such hypothesis but further detailed analysis is necessary.

Variability of winter SAT in the Arctic region is strongly driven by downward atmospheric radiation, which is closely associated with the poleward transport of heat and moisture (e.g., Gong et al., 2017; Lee et al., 2017; Woods et al., 2013). Correlation between the winter SAT and SDTR is actually strong both in the reanalysis and the relaxation experiments (not shown). Arctic surface climate is also strongly influenced by cloud feedback processes (Vavrus, 2004). For example, mixed-phase clouds over the Arctic contribute strongly to the Arctic surface climate through affecting the radiative flux (Morrison et al., 2012). However, climate models still exhibit relatively poor skills in simulating the Arctic mixed-phase clouds (Morrison et al., 2011). Here we choose to examine the influences of the middle-low latitudes in terms of changes in downward radiation and specific humidity to support our argument. The processes leading to the relatively poor constrains on the temperature is beyond the scope of this study. In fact, the correlation patterns of Q850 (Figures S8c and S8d) and SDTR (Figures S8e and S8f) resemble well those of the temperature. The weak influences on SDTR explains well the weak influences on SAT (Figures 1e and 1f vs. S8e and S8f). Both poorly constrained SDTR and specific humidity are possibly related to the poorly constrained local radiative/cloud processes. The detailed reasons merit further research.

In summer, the influence of the tropics in terms of surface circulation is remarkable mainly over North America (Figure 2a) and is mostly weak in terms of midlevel circulation (Figure 2c). Overall, the influence of the tropics on the Arctic circulation is much weaker during summer. The midlatitudes still exhibit relatively strong impacts on the circulation particularly over the sub-Arctic (Figures 2b and 2d). However, the impact of midlatitudes is much weaker over the North Atlantic-European sector during summer than during winter. The impacts on temperature mimic that on the circulation (Figures 2e–2h). The relatively small influences on the surface temperature over the oceanic areas are also accounted for partly by the use of perpetual seasonal cycle of SST/SIC in the relaxation experiments, which can be supported by inspecting the results in $OBS_{SST,SI}$ experiment (Figures S7b, S7d, and S7f).

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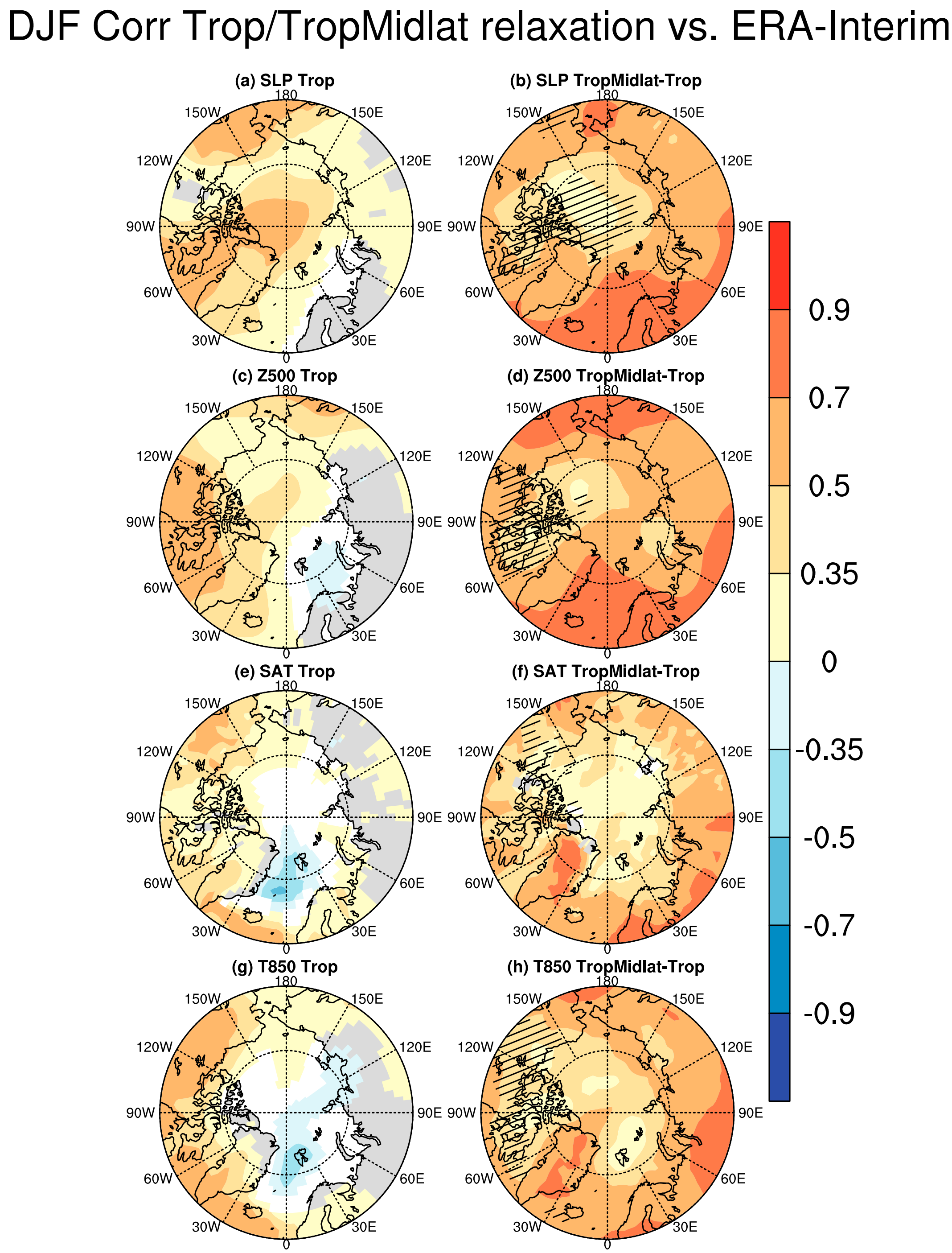

Figure 1. Spatial distribution of the correlation coefficients of winter-mean variables between relaxation experiments and ERA-Interim data for the period 1979–2013. Left panels and right panels are for Trop and TropMidlat-Trop (midlatitudes only) experiments, respectively. Hatching on the right panels indicates smaller correlation coefficients than on the left panels. Correlation coefficients between −0.1 and 0.1 are in white/grey. The threshold value for the correlation coefficient at 5% significance level is ±0.35. SLP = sea level pressure; Z500 = geopotential height at 500 hPa; SAT = 2-m air temperature; T850 = air temperature at 850 hPa. DJF = December–February.

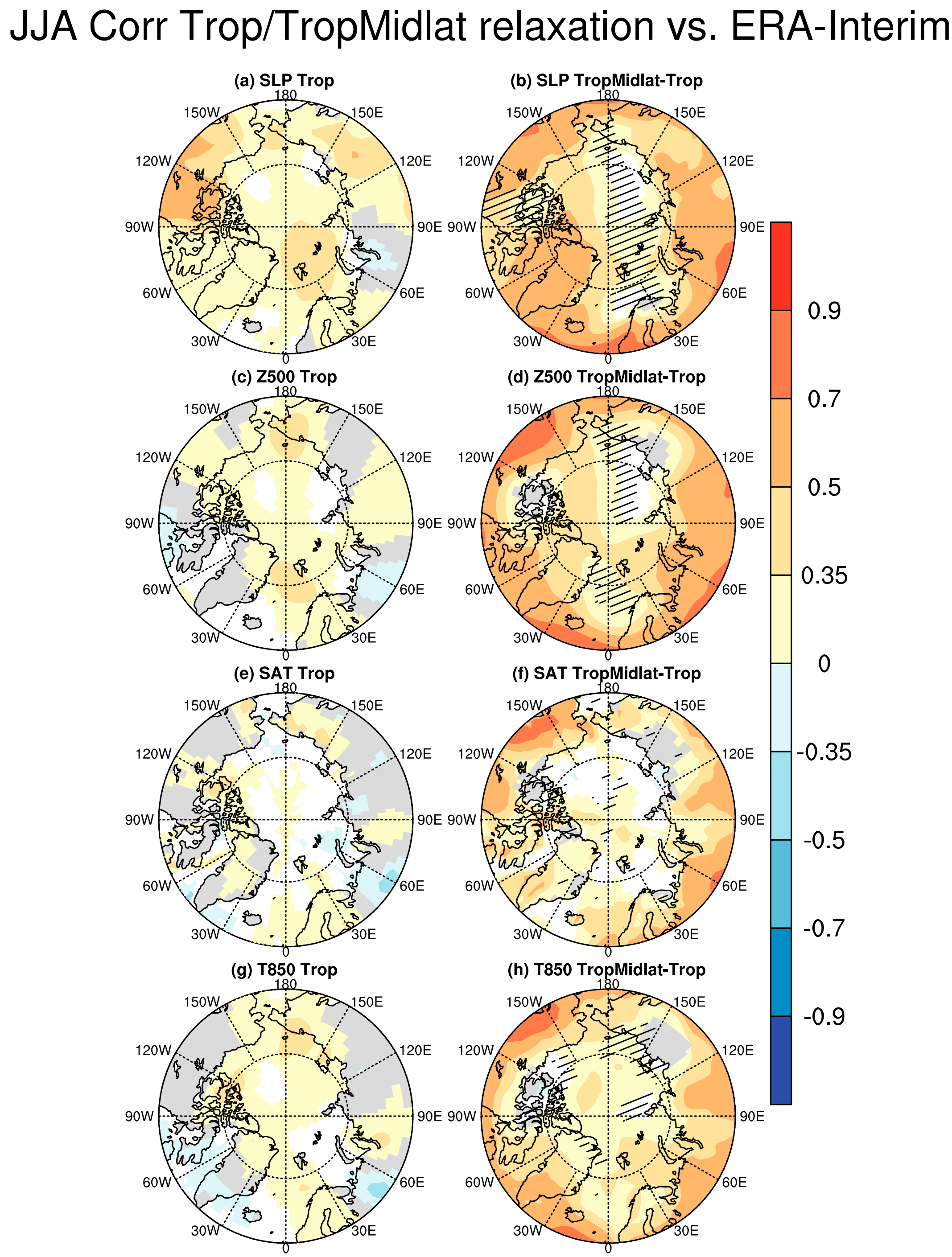

Figure 2. Same as in Figure 1 but for summer during the period 1980–2014. JJA = June–August.

3.2. Impacts of Lower Latitudes on the Recent Trends of the Arctic Climate and Tropospheric Circulation

The recent warming trend in the Arctic is still a subject for active research and scientific discussions. It has been argued that the strengthening of the poleward transport of moisture and heat is a key process contributing to the recent Arctic warming trends in winter and that the transport enhancement is driven primarily by the circulation anomaly (e.g., Gong et al., 2017). We focus on the most recent period 1990–2013 to study the possible role of the tropics and midlatitudes in driving the Arctic warming. Trends are estimated using the Theil–Sen estimator and their significance is evaluated using the nonparametric Mann-Kendall test (see Mondal et al., 2012). The Theil–Sen estimator is insensitive to outliers.

In the reanalysis, surface warming is observed over most of the Arctic oceanic area, with strongest warming seen over the Baffin Bay, the Barents-Kara Sea and the adjacent seas. (Figure 3a). The low-level (Figure 3b) and midlevel (Figure S9a) warming is different from that close to the surface in that it mainly stretches from northeastern Canada to the Laptev/Kara Seas. There is a significant upward trend in low-level humidity (i.e., Q850) mainly over south and west of Greenland over the Arctic ocean (Figure S9b), and the trend pattern seems to resemble that of the low-mid level but not the surface temperature. In contrast, an upward trend in SDTR is notable over most of the Arctic ocean (Figure S9c), rather similar to that of SAT. The accompanied pattern of circulation trend features some salient structures (Figure 3c). The first is the recent downward trend of NAO (e.g., Iles & Hegerl, 2017). In addition, the strong ridge over western Russia is seemingly part of a stationary Rossby wave that extends from the North Atlantic to Asia. Such an enhanced atmospheric ridge is concurrent with increases in atmospheric blocking frequency over the Ural region (e.g., Luo et al., 2016). A significant increase in the geopotential height is also seen over the Arctic and North Pacific.

The Arctic warming seems to be forced partially by the midlatitudes (Figures 3d, 3e, S9d, S10a, S10d, and S10g), particularly for the low-level and midlevel temperature trends. The tropics contributes partly to the temperature trend over the Arctic, albeit with weaker magnitude (Figures 3g, 3h, S9g, S10b, S10e, and S10h). An upward trend in Z500, similar to that in the reanalysis, is seen over most of the Arctic in the TropMidlat-Trop relaxation experiment (Figures 3f and S10j). Such a Z500 trend pattern is not found in the Trop relaxation experiment except over the North Pacific (Figures 3i and S10k). This suggests that a substantial portion of the circulation trend over the Arctic during recent decades is forced by the midlatitudes, which in turn is strongly associated with the negative trend of NAO and an enhanced ridge near Ural region.

What is the role of local Arctic processes in contributing to the temperature trends in the Arctic? The tropical atmospheric circulation is known to be well coupled to the underlying SSTs. Figures 3g–3i and 3j–3l are rather similar outside the Arctic. A comparison of Figures 3g–3i and 3j–3l suggests that the forced atmospheric circulation pattern outside the Arctic region by the SST/SIC is primarily due to the tropical atmospheric circulation response to the SST/SIC and its poleward influences. Therefore, the different responses in the Arctic between the Trop relaxation and $OBS_{SST,SI}$ experiments can be roughly attributable to the influences of the local SST/SIC variability in the Arctic. Inspection of the trend patterns (Figures 3a, 3d, 3g, and 3j) and the ratio of trend by the relaxation experiments to that by the ERA-Interim data (Figures S10a–S10c) suggests that the leading contributing factor for the Arctic surface warming during winter is the local SST/SIC trend over the Arctic. This is consistent with the central role of local sea ice in contributing to the surface warming trends in the Arctic (e.g., Screen & Simmonds, 2010a). In the $OBS_{SST,SI}$ experiment, the upward trends in Q850 and particularly SDTR (Figures S9k and S9l) resemble well that of SAT (Figure 3j). Comparing Figures 3h and 3k suggests that the positive trend in specific humidity is likely driven by the local processes. The enhanced SDTR potentially amplifies the surface warming by emitting back the radiation that is trapped in the low layer by the enhanced humidity. Such water vapor/radiation feedback seems to be more important over the Nordic Sea, the Barents Sea, and the adjacent seas in both the reanalysis (Figures S9b and S9c) and $OBS_{SST,SI}$ experiment (Figures S9k and S9l). The trends in both Q850 and SDTR (Figures S9e, S9f, S9h, and S9i) are relatively small in both the relaxation experiments (i.e., Trop and TropMidlat-Trop). Thus, the lack of local radiative feedback/forcing in some of the experiments may be an important reason for the relatively small impacts of lower latit+udes on the surface temperature. On the other hand, the local sea ice is not a major factor for the warming trend at lower (Figures 3k and S10f) and particularly midlevel (Figures S9j and S10i) Arctic troposphere over the region stretching from northeastern Canada to the Laptev/Kara Seas. The influence of midlatitudes seems to be become important in terms of warming trends at low-level (Figures 3e and S10d) and midlevel (Figures S9d and S10g) atmosphere over the region stretching from northeastern Canada to the Laptev/Kara Seas. These results are somewhat similar to the conclusions in Perlwitz et al. (2015), which suggests that significant impacts of the local Arctic sea ice on the Arctic temperature are limited to the surface. The inferred local sea ice feedback has

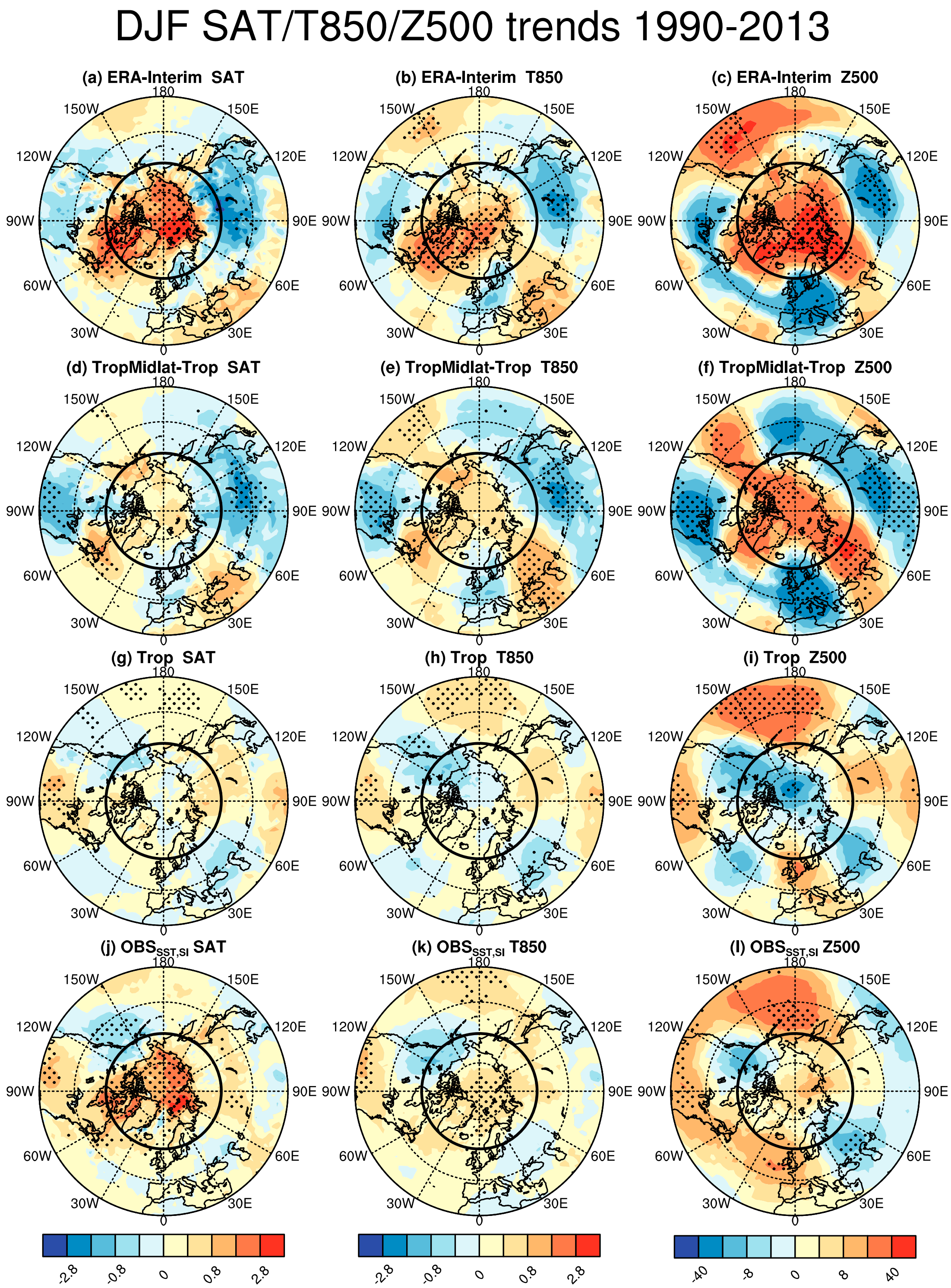

Figure 3. The spatial distribution of the linear trends in (left) winter mean SAT, (middle) T850 and (right) Z500 for the period 1990–2013 as computed for (a, b, and c) ERA-Interim data, (d, e, and f) TropMidlat-Trop, (g, h, and i) Trop relaxation, and (j, k, and l) OBS$_{SST,SI}$ experiments. Stippling indicates significance at 5% level. Units: °C/decade and gpm/decade.

some contribution to the recent Arctic circulation changes (Figure 3l versus 3c; Figure S10l). However, the contribution is much weaker than the midlatitudes over northeastern Canada, Greenland, the Nordic Seas, and the Barents-Kara Sea, where strongest circulation trends in the reanalysis data are observed (Figure 3c).

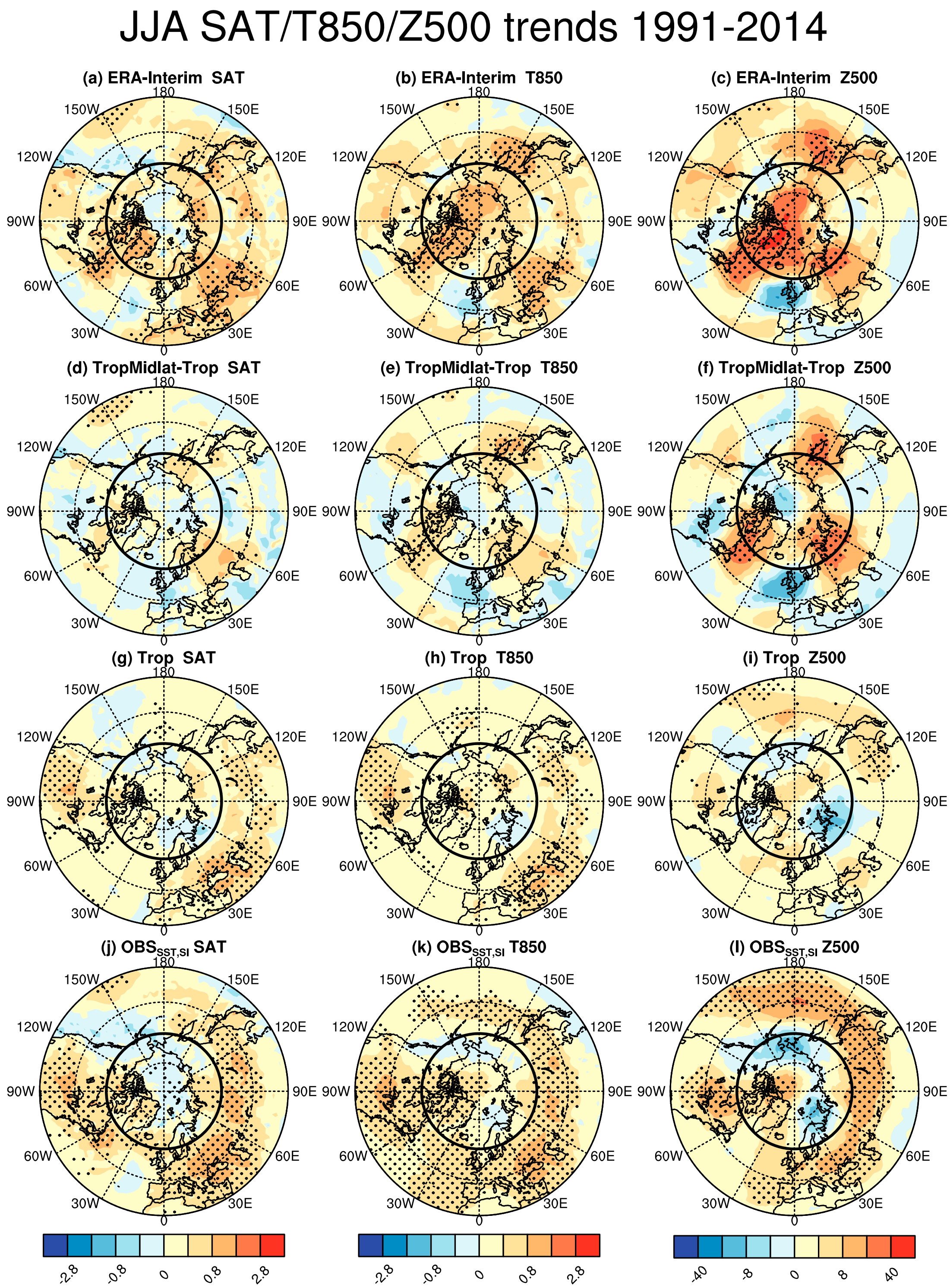

Figure 4. Same as in Fig. 3 except for summer during the period 1991–2014.

The Arctic surface warming during summer is located mainly over the land areas in the reanalysis (Figure 4a). The warming pattern at low-level (Figure 4b) and midlevel (not shown) atmosphere is more extensive. The warming in northeastern Canada and Greenland is driven strongly by SST/SIC (100 °W-0 °W, 60 °N-90 °N; Figures 4j and S11a) and contributed partly by the tropics (Figures 4g, 4h, and S11a). In contrast, the temperature and circulation trends over northern Europe and western Russia are driven strongly by the midlatitudes (15 °E-70 °E, 60 °N-67 °N; Figures 4a–4c versus 4d–4f; Figure S11b).

4. Discussion and Conclusions

In terms of the interannual variability of the Arctic troposphere, our results suggest that the Arctic atmospheric circulation is strongly constrained by lower latitudes; this is especially true during boreal winter with the summer season also having a strong internal component. The preferred pathways for tropical and midlatitude influences during winter are different: The western (eastern) Arctic is more strongly influence by the tropics (midlatitudes). Compared to the atmospheric circulation, the impacts on temperatures and radiative fluxes are relatively less pronounced in the Arctic. This may hint at the importance of local radiative/cloud feedback processes for explaining such a difference.

In terms of the recent trends, the lower latitudes are found to account for a relatively small portion of the Arctic surface warming during winter. The contribution of midlatitudes to the warming trends seems to be larger at low-middle levels. This may suggest that local sea ice feedback is a leading cause for the recent Arctic surface warming and the local radiation feedback possibly amplifies such warming. Importantly, the winter Arctic circulation trends are mainly driven by the midlatitudes. The temperature and circulation trends during summer in northeastern Canada and Greenland are strongly influenced by the SST/SIC with some contribution from the tropics. The midlatitudes play an important role in driving the temperature and circulation trends in northern Europe and western Russia during summer.

This study focuses on the impacts of the lower latitudes on the Arctic climate variability and change. The Arctic driving of lower-latitude weather and climate is also of great interest. It would be interesting to compare the relative strength of these "teleconnections" based on model relaxation experiments, complementing the observational analysis by Cohen (2016). In fact, the results of this study can be qualitatively compared to that of Jung et al. (2014) and especially that of Ye et al. (2018).

The use of the atmosphere-only model in the relaxation experiments is admittedly a limitation when it comes to studying the local feedback processes in the Arctic. Such a configuration cannot account for the important two-way feedback processes of SST/sea ice and the atmosphere. In fact, coupled regional model experiments conducted for the Arctic, which are somewhat similar to the TropMidlat relaxation experiment, have demonstrated the importance of the feedbacks between atmospheric circulation and the sea ice over the Arctic Ocean (e.g., Dorn et al., 2009; Rinke et al., 2013). In the present study, the direct influences of the lower latitudes on the Arctic surface temperature are not strong without the two-way feedback of SST/sea ice and the atmosphere. The active interaction between the atmospheric circulation and the sea ice over the Arctic Ocean along with a good representation of the feedback processes may be a key to understanding the Arctic surface climate change.

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