Regional Arctic Amplification by a Fast Atmospheric Response to Anthropogenic Sulfate Aerosol Forcing in China

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ABSTRACT

It is known that an increase of water vapor over the Arctic is one of most plausible causes driving Arctic amplification. However, debate continues with regard to the explanation of the underlying mechanisms driving the increase of moisture over the Arctic region in the observations. Here, we used the Community Atmosphere Model with prescribed sea surface temperature along with reanalysis datasets to examine the role of fast atmospheric responses to the increase of anthropogenic sulfate aerosol concentrations in China. We found that it plays an additive role in moisture transport from the midlatitudes, resulting in warming of the Arctic region, especially around the Barents–Kara Seas. Specifically, sulfate aerosol forcing in China reduces the meridional temperature gradient and leads to the increase of moisture transport into the Arctic by altering atmospheric circulation. The resulting increase of moisture then leads to surface warming through the enhancement of the downwelling longwave radiation. This implies that Arctic warming around the Barents–Kara Seas has been accelerated, at least in part, by a fast atmospheric response to anthropogenic sulfate aerosol emissions in China in the recent past.

1. Introduction

Global surface air temperature has increased by approximately 1.0°C since the 1880s (IPCC 2013), mainly because of increased concentrations of greenhouse gases in the atmosphere (Bolin and Doos 1986). Most long-lived greenhouse gases, including CO₂, are distributed uniformly around the globe (Rodhe 1990); however, the observed warming trend of surface air temperature is larger in the high northern latitudes than at lower latitudes, which is a phenomenon known as Arctic amplification (Graversen 2006; Graversen et al. 2008; Screen and Simmonds 2010). Furthermore, Arctic

amplification is not spatially uniform (Ding et al. 2014), implying the occurrence of other complex processes in addition to greenhouse gas forcings.

Several processes have been suggested to explain Arctic amplification. These include changes in the snow- and ice-albedo feedback induced by sea ice loss (Screen and Simmonds 2010; Ding et al. 2017), deposits of black carbon on ice and snow cover (Arctic Council 2013), changes in amounts of cloud and water vapor (Schweiger et al. 2008), aerosol-linked indirect longwave warming due to midlatitude pollution (Garrett and Zhao 2006), the lapse rate feedback (Pithan and Mauritsen 2014), and changes in longwave radiation flux (Alexeev et al. 2005; Gong et al. 2017; S. Lee et al. 2017; H.-J. Lee et al. 2017). In addition to those processes local to the Arctic region, global model simulations and observational analyses have also suggested possible influence by remote processes, for example, increased poleward moisture transport from the midlatitudes (Graversen 2006; Graversen and Wang 2009), and poleward-propagating Rossby waves excited

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by tropical convection (Ding et al. 2014; Park et al. 2015). Because of the nonlinearities and complexity in the climate system, there is broad agreement in the science community that a single causal process is unlikely to lead to the Arctic amplification.

Meanwhile, regional aerosol forcing in East Asia has increased considerably over the past several decades (Jeong and Park 2013; Kim et al. 2016; Yeh et al. 2013, 2017) primarily because of increased emissions of anthropogenic aerosols from China, which have shown their highest growth rate since 2000 (Ohara et al. 2007). Although the direct climatic effect of an increase of sulfate aerosols on nearby regions is known to lower temperatures (Charlson et al. 1991), the consequence of a thermal anomaly might cause abnormal atmospheric circulations that could affect remote regions including the Arctic. There is a study that suggested that sulfate aerosol forcing in China can cause not only regional temperature response but also global temperature response (Kasoar et al. 2016). Acosta Navarro et al. (2016) also suggested a reduction of sulfate aerosol in Europe since 1980 contributes a significant fraction of Arctic warming. In this study, we investigate the role of a fast atmospheric response to anthropogenic sulfate aerosol forcing in China on Arctic warming, which has been found to modify the midlatitude atmospheric circulation by changing radiative forcing (Ming et al. 2011). To examine this, we conduct idealized experiments using atmospheric general circulation model simulations in which the role of anthropogenic sulfate aerosol concentration in China is isolated compared with sea surface temperature (SST) forcing. In the present study, we mainly focus on comparing with those model experiments to investigate the role of historical sulfate aerosol concentration on Arctic warming.

A description of the observational datasets and model experiments used in this study is documented in section 2. The main results obtained by comparison with model experiments are described in section 3. A summary is given in the last section.

2. Data and model

a. Data

We used reanalysis datasets and climate model simulations to examine the role of anthropogenic sulfate aerosol forcing in China to polar amplification. We used three different reanalysis datasets to quantify Arctic warming. The datasets in our analysis below include the ECMWF Reanalysis (ERA)-Interim dataset, the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis dataset, and the National Centers for Environmental Prediction (NCEP)–Department of

Energy (DOE) reanalysis II (RA2) datasets for 1985–2010 (Dee et al. 2011; Kanamitsu et al. 2002; Rienecker et al. 2011).

b. Model experiment

To examine the effect of an increase of sulfate aerosols in China on the Arctic climate, we used the Community Atmosphere Model, version 5.1.1 (CAM5). Three CAM5 ensemble simulations with prescribed SSTs were analyzed. We performed model simulations using the NCAR CAM5 model coupled to the Community Land Surface Model, version 4 (CLM4) (Neale et al. 2012). The CAM5 model is based on a finite-volume (FV) dynamical core with $1.9^\circ \times 2.5^\circ$ horizontal resolution and 30 vertical levels. For this experiment, we used prescribed SST and ice fraction as the oceanic surface boundary condition including sea ice fractions over the polar region. The SST and the sea ice fractions comprised time series data constructed by concatenating and interpolating global HadISST data from the Met Office Hadley Centre (Rayner et al. 2003) to the FV core grids of the CAM5. For aerosol simulations, the CAM5 uses a three-mode version of the modal aerosol model (MAM3), which resolves three different modes: the Aitken, accumulation, and coarse modes (Liu et al. 2012). The aerosol species in MAM3 include sulfate, primary organic matter, secondary organic matter, black carbon, soil dust, and sea salt aerosols. The internal mixture between species is considered in the MAM3. For sulfate aerosol simulations, simple gas-phase chemistry is used, including dimethyl sulfide (DMS) oxidation by OH to form SO₂, SO₂ oxidation by OH to form H₂SO₄, H₂O₂ production, and H₂O₂ loss. The total number of transported aerosol tracers in MAM3 is 15. The transported gas species include SO₂, H₂O₂, DMS, H₂SO₄, and a lumped, semivolatile organic species. Oxidant concentrations (O₃, OH, and HO₂) are interpolated from monthly averages taken from simulations by a chemistry–climate model (CAM-chem) (Lamarque et al. 2010). The MAM3 model can reproduce sulfate and other aerosols fast and successfully in previous studies without a significant loss of accuracy (Liu et al. 2012; Mills et al. 2016).

We updated the Asian anthropogenic SO₂ emissions in the CAM5 with the gridded inventory for 2000 over the Asian domain (13°S–54°N, 60°–158°E) to examine the role of accurate sulfate aerosol forcing (Streets et al. 2003). The Asian emission of SO₂ for 2000 was 18.9 Tg yr^{−1}, which is slightly lower than the fixed emission originally applied in CAM5 (19.8 Tg yr^{−1}). Next, we applied annual scale factors of the Regional Emission Inventory in Asia (REAS) (Ohara et al. 2007) for 1985–2010 to the Streets et al. (2003) emissions to impose

FIG. 1. Linear trend of (a) SO_2 emission in the SO_2 run (Gg S yr^{-1}), (b) sulfate concentration at surface ($\mu\text{g m}^{-3} \text{yr}^{-1}$), and (c) sulfate aerosol optical depth (yr^{-1}). Shading denotes a statistically significant region at the 90% confidence level.

interannual variation of SO_2 emission in the model. The increasing trend of annual SO_2 emission, its concentration, and sulfate aerosol optical depth is significant in China and Southeast Asia for 1985–2010 (Fig. 1). For SO_2 emissions outside of Asia, national emission inventories are used for anthropogenic species where available, including the European Monitoring and Evaluation Program (EMEP) inventory for Europe and the U.S. Environmental Protection Agency (EPA) 1999 National Emissions Inventory

(NEI99) for the United States, and otherwise default values are used from the Global Emission Inventory Activity (GEIA) in 2000. Other emissions follow default emissions of MAM3, which is described in Gent et al. (2011). The generation of desert dust particles is calculated based on the Dust Entrainment and Deposition Model (DEAD), which varied the meteorological field (Mahowald et al. 2006; Yoshioka et al. 2007).

Three CAM5 model experiments were performed to isolate the effects of anthropogenic sulfate aerosol emissions in China on regional Arctic amplification. The first experiment prescribed a historical SST and sea ice from 1985 to 2010 (i.e., 26 years) without SO_2 (a precursor gas of sulfate aerosols) emissions over Asia (referred to as the SST run). The second experiment prescribed a climatological (1985–2010) SST and sea ice but included time-varying SO_2 emissions over Asia (referred to as the SO_2 run). The third experiment prescribed a historical SST and sea ice with time-varying SO_2 emissions over Asia (referred to as the SST- SO_2 run). Each experiment consisted of four ensemble members, the ensemble mean values of which are mainly used in the present study.

In all experiments, CO_2 concentration was fixed to 387 ppmv. Furthermore, CH_4 , N_2O , and CFC concentrations were also fixed to their values in the 2000s to exclude possible effects of increases of greenhouse gas concentrations on Arctic amplification. Unless stated otherwise, the results derived from observations and model experiments are presented only for boreal winter, that is, the December–February mean. Table 1 describes all experiments conducted in this study.

3. Results

Figures 2a–c display the spatial pattern of the linear trend of surface air temperature in boreal winter to the north of 60°N (1985–2010), obtained from the ERA-Interim dataset, MERRA reanalysis dataset, and NCEP DOE RA2 dataset, respectively. Pronounced warming is shown across the Arctic with two maxima: one over the Barents–Kara (B–K) Seas and the other over northeastern Canada, including Greenland and Baffin Bay. The magnitude of the former is greater than the

TABLE 1. Description of model experiments conducted in this study.

Name of model expt	Simulation period	Boundary SST	SO_2 emission	CO_2 concentration	Note
SST run	1985–2010	Historical SST	Zero in Asia	387 ppmv	Ensemble member 4
SO_2 run	1985–2010	Climatological (1985–2010) SST	Asia	387 ppmv	Ensemble member 4
SST- SO_2 run	1985–2010	Historical SST	Asia	387 ppmv	Ensemble member 4

FIG. 2. Spatial distribution of mean surface air temperature trend (K yr^{-1}) for 1985–2010 during boreal winter in the reanalysis datasets: (a) ERA, (b) MERRA, and (c) NCEP DOE RA2. Shading denotes a statistically significant region at the 90% confidence level. The dotted boxes indicate the domains of the northeastern Canada sector (60° – 80°N , 45° – 75°W) and B–K Seas (70° – 85°N , 10° – 100°E).

latter in all three datasets (Table 2). In addition to the significant warming trend in both of these regions, evident interannual variability is also prominent (Fig. 1 in the online supplemental material). Note that the significance levels of all figures are calculated using the

ratios between the linear trend and its standard error of dataset at 90% confidence level. However, correlation coefficients between the time series of surface air temperature of the two regions are found not statistically significant in all three datasets (Table 3). This indicates

TABLE 2. Linear trends of surface air temperature averaged over the northeastern Canada sector and the B–K Seas in the three different reanalysis datasets.

	ERA-Interim	MERRA	NCEP DOE RA2
Northeastern Canada (60° – 80°N , 45° – 75°W)	$0.15^{\circ}\text{C yr}^{-1}$	$0.17^{\circ}\text{C yr}^{-1}$	$0.16^{\circ}\text{C yr}^{-1}$
Barents–Kara Seas (70° – 85°N , 10° – 100°E)	$0.20^{\circ}\text{C yr}^{-1}$	$0.18^{\circ}\text{C yr}^{-1}$	$0.20^{\circ}\text{C yr}^{-1}$

TABLE 3. Simultaneous correlation coefficients between the time series of surface air temperature over northeastern Canada (60° – 80° N, 45° – 75° W) and the B–K Seas (70° – 85° N, 10° – 100° E) in the three reanalysis datasets.

	ERA-Interim	MERRA	NCEP DOE RA2
Correlation coef	0.10	0.18	0.39

that Arctic amplification is not spatially uniform and that the mechanisms driving the warming, as well as its variations, might differ between the two regions (Bader 2014).

A recent study has suggested that the warming in northeastern Canada and Greenland is strongly associated with a negative trend in the North Atlantic Oscillation, in conjunction with a response to anomalous Rossby wave train activity originating from the tropical Pacific, which is considered the result of natural climate variability due to SST forcing (Ding et al. 2014). In

contrast, the surface warming over the B–K Seas might be associated with a local process caused by a significant reduction of sea ice extent (supplementary Fig. 2) (Woods and Caballero 2016). An increase of downward longwave radiation due to an increase of water vapor is recognized as an essential factor in the warming in the B–K Seas (Woods and Caballero 2016; H.-J. Lee et al. 2017), although possible causes remain ambiguous. Recent studies have emphasized dynamical connections between the midlatitude atmospheric circulation and sea ice loss in the B–K Seas (Barnes and Screen 2015; Yang et al. 2016; Luo et al. 2017). Figure 2 also indicates that there exists a large contrast of the cooling in northern Eurasian and the warming in the B–K Seas, which is prominent in the ERA-Interim and MERRA reanalysis datasets. Inspired by these surface temperature contrasts, we investigated the role of anthropogenic sulfate aerosol forcing in China.

FIG. 3. Spatial distribution of the surface air temperature trend to 60° N (K yr^{-1}) simulated in the atmosphere model in the (a) SST- SO_2 , (b) SST, and (c) SO_2 runs. Also shown is the (d) difference between the SST- SO_2 run and the SST run (SST- SO_2 run minus SST run).

FIG. 4. Time series of modeled surface air temperature averaged over the (left) northeastern Canada sector (60° – 80° N, 45° – 75° W) and (right) B–K Seas (70° – 85° N, 10° – 100° E) for the (a),(d) SST– SO_2 , (b),(e) SST, and (c),(f) SO_2 runs. Dashed lines denote the linear trends. Note that the thin lines indicate the time series of surface temperature simulated in each ensemble member.

Figures 3a–c displays the spatial pattern of the linear trend of surface air temperature to the north of 60° N (1985–2010) produced by the SST– SO_2 , SST, and SO_2 runs, respectively. There are some similarities and differences in comparison with the reanalysis datasets (Fig. 2). The most striking feature is that the warming trend is not apparent over northeastern Canada and Greenland in the SO_2 run (0.004 K yr^{-1}) (Fig. 3c), which is in contrast with both the SST– SO_2 run (0.05 K yr^{-1}) and the SST run (0.07 K yr^{-1}) (Figs. 3a,b). These features are also shown in the time series of surface air temperature averaged in the northeastern Canada and Greenland sector (1985–2010) in the SST– SO_2 run, SST run, and SO_2 run, respectively (Fig. 4). These results suggest that the warming in the northeastern Canada and Greenland sector is caused partly by SST forcing, consistent with the result in previous study (Ding et al. 2014). However, over the B–K Seas, linear trends of surface warming of 0.11, 0.07, and 0.06 K yr^{-1} are shown in the SST– SO_2 run, SST run, and SO_2 run, respectively (Fig. 4), which are all statistically significant at the 90% confidence level. The linear trend of surface warming in SST– SO_2 run is similar to the sum of those in SST run and SO_2 run over the B–K Seas, although the warming in the SST– SO_2 run and SST run is much more localized in the western part of the B–K area compared with that in the SO_2 run. This indicates

that the regional Arctic warming around the B–K Seas is likely due to the combined effects of SST forcing and sulfate aerosol forcing in China. Therefore, we argue that the increase of anthropogenic sulfate aerosols in China plays an additive role in the warming around the B–K Seas. It is noteworthy that the difference of warming trend between the SST– SO_2 run and SST run shows a wide warming around the B–K Seas (Fig. 3d), which is quite similar to the warming trend in the SO_2 run (Fig. 3c), which is indicative of an additive role of a fast atmospheric response to the increase of anthropogenic sulfate aerosols in China (Fig. 3d). It is also noteworthy that each ensemble member also shows a consistent warming trend, indicating that such a warming trend is not due to internal variability (Fig. 4). On the other hand, all trends obtained from three runs are weaker than the observations (i.e., 0.16 K yr^{-1} in northeastern Canada and Greenland, and 0.20 K yr^{-1} in the B–K Seas). This might be associated with the fact that the forcing of increasing CO_2 concentration for 1985–2010 is missed in three experiments (figure not shown). The warming trend of surface air temperature is the largest in the B–K Seas in the SST– SO_2 run, whereas that in northeastern Canada and Greenland is the largest in the SST run. Therefore, the response to sulfate forcing is not additive in all regions of the Arctic.

FIG. 5. Spatial distribution of surface air temperature trend (K yr^{-1}) over Eurasia continent: (a) SST- SO_2 run, (b) SST run, (c) SO_2 run, (d) difference between SST- SO_2 run and the SST run (SST- SO_2 run minus SST run), and (e) the ensemble mean of three reanalysis datasets (ERA, MERRA, and NCEP-DOE RA2) datasets. Shading denotes a statistically significant region at the 90% confidence level. The box denotes the central Eurasian region ($35^\circ\text{--}55^\circ\text{N}$, $10^\circ\text{--}100^\circ\text{E}$).

To explore how sulfate aerosol forcing in China might influence regional Arctic warming via a fast atmospheric response, we consider the linear trend of surface air temperature in the midlatitudes ($20^\circ\text{--}60^\circ\text{N}$) produced by reanalysis datasets and the model (Fig. 5). While a cooling trend of surface air temperature in central Eurasia ($35^\circ\text{--}55^\circ\text{N}$, $10^\circ\text{--}100^\circ\text{E}$) is dominant in the SO_2 run (Fig. 5c), it is not significant in the SST- SO_2 run and the SST run (Figs. 5a,b). Note that the difference of cooling trend between the SST- SO_2 run and the SST run (SST- SO_2 run minus SST run) (Fig. 5d) is similar to the cooling trend in central Eurasia simulated in the SO_2 run except its magnitude (Fig. 5c). This indicates that a fast atmospheric response to the sulfate aerosol forcing in China plays a linear additive role on the cooling in central Eurasia. The cooling trend in central Eurasia is also shown in reanalysis datasets except the western part of Eurasia (Fig. 5e). A mismatch

in the trends of central Eurasian temperature between the SST- SO_2 run and the reanalysis is mainly from the SST run, that is, SST forcing (Fig. 5b). We argue that the SST forcing overwhelmed the cooling of surface air temperature in central Eurasia continent, indicating that part of the cooling trend in central Eurasia might be attributable to sulfate aerosol forcing in China. On the other hand, while the surface temperature trend in the reanalysis dataset is similar to that in the SST run below 35°N , it is similar to the region above 35°N in the SO_2 run. This indicates that the role of SST forcing and sulfate aerosol forcing differs from region to region, which may cause large temperature differences between the SST- SO_2 run and the reanalysis dataset (Figs. 5a,e). In addition, note that the reality of radiative forcings including the CO_2 forcing is missed in the SST- SO_2 run when compared with the reanalysis dataset.

The above result prompts the question of how a fast atmospheric response to sulfate aerosol forcing in China could cause the cooling trend in central Eurasia in the SO_2 run. We suggest both direct and indirect processes to explain this phenomenon. First, the gradual increase in concentration of sulfate aerosols in central Eurasia (supplementary Fig. 3a) is associated with a reduction of net surface shortwave radiation in each ensemble model (supplementary Fig. 3b), which leads to cooling in central Eurasia in the SO_2 run. Second, an increase of sulfate aerosol concentration in China in the SO_2 run (see Fig. 1), which is associated with perturbing the precipitation anomalies through both the indirect and direct effect of sulfate aerosol (supplementary Figs. 4a,b), is associated with the reduction of dust mobilization (Fig. 6a) through the modulation of the atmospheric circulation (supplementary Figs. 4c,d) (Wang et al. 2008). The anomalous circulation in central and northern Eurasia acts to reduce the wind speed over the Gobi and Taklimakan Deserts in the SO_2 run (supplementary Figs. 4c,d). Therefore, the resulting decrease in dust concentration leads to a cooling of central Eurasia via the reduction of the absorption and radiative forcing at surface of solar and terrestrial radiation by dust aerosols in the SO_2 run (Figs. 6b,c). Several studies based on the observations reported that dust storms over the Eurasian continent have decreased in recent decades (Wu et al. 2011; Zhu et al. 2008). In addition, Yue et al. (2011) suggested that dust aerosol plays a role to warm in Eurasia continent owing to their light absorbing effect. These results indicate that the decreases in dust concentration play a role to lead to the central Eurasian cooling in the SO_2 run. Note that the spatial structures of precipitation and the wind speed associated with the variability of sulfate concentration in China are not much different among all ensemble members in the SO_2 run (supplementary Figs. 5 and 6).

Cooling in the central Eurasian continent acts to change the meridional temperature gradient from the surface to the midtroposphere (Fig. 7a) in the SO_2 run. This leads to regional Arctic warming via modification of the tropospheric atmospheric circulation. Specifically, the change of meridional temperature gradient causes the change in the position of the jet stream (Kim et al. 2007). It is found that the jet stream is slightly shifted to the south (supplementary Fig. 7), which is mainly associated with the change in the meridional temperature gradient due to a cooling in the Eurasian continent (Fig. 5c). A southward shift of the jet stream causes to change the position of descending motion as well as the atmospheric circulation (Sanders and Hoskins 1990), which is found in central Eurasia around the entrance of the jet stream (Fig. 8 and supplementary Fig. 7). Note

FIG. 6. Spatial patterns of surface dust concentration and aerosol absorption (1985–2010) during boreal winter in the SO_2 run: (a) linear trend of surface dust concentration ($\mu\text{g yr}^{-1}$), (b) trend of atmospheric shortwave absorption (shortwave radiative forcing at the top of the atmosphere minus shortwave radiative forcing at surface; $\text{W m}^{-2} \text{yr}^{-1}$), and (c) trend of atmospheric shortwave radiative forcing at surface ($\text{W m}^{-2} \text{yr}^{-1}$). Shading denotes statistical significance at the 90% confidence level.

that the zonal wind is averaged in 60° – 130°E to correctly present the secondary circulation associated with a jet stream shift. The anticyclonic circulation induced by a southward shift of the jet stream acts to provide a favorable condition for supplying moisture into the low-level Arctic (Fig. 8 and supplementary Fig. 8). These processes result in the enhancement of the poleward moisture transport into the Arctic region around the B–K Seas in the low-level atmosphere in the SO_2 run (Fig. 7b), which is also found in the reanalysis dataset (Fig. 9a). Subsequently, the increase of water vapor (Fig. 7c) might partly cause enhanced downward longwave radiation

FIG. 7. Temperature, moisture transport, and downward longwave radiative flux in the SO_2 run: (a) trend of zonally (10° – 100°E) averaged temperature (K yr^{-1}), (b) trend of zonally (10° – 100°E) averaged northward moisture transport ($Q \times v$; $\text{m s}^{-1} \text{yr}^{-1}$), (c) trend of integrated specific humidity from 850 to 1000 hPa ($\text{g kg}^{-1} \text{yr}^{-1}$), and (d) trend of downward longwave radiation at the surface ($\text{W m}^{-2} \text{yr}^{-1}$). Shading denotes statistical significance at the 90% confidence level.

(Fig. 7d). This results in Arctic warming around the B–K Seas, which is also found in the reanalysis datasets (Figs. 9b,c). All of the model experiments suggest that a fast atmospheric response to the sulfate aerosol forcing in

China plays an additive role in regional Arctic warming by increasing moisture transport through modulation of the atmospheric circulation.

4. Summary and discussion

Global surface air temperature has increased since the mid-1800s. The observed warming trend of surface air temperature is larger in the high latitudes than that at lower latitudes, which is a phenomenon known as Arctic amplification. While there are several hypotheses, an increase of downward longwave radiation due to an increase of water vapor is found as an essential factor of Arctic amplification. We examined the role of a fast atmospheric response to the anthropogenic sulfate aerosol forcing in China on Arctic amplification using the reanalysis datasets and idealized model experiments.

A set of model experiments indicated that a fast atmospheric response to the increase of anthropogenic sulfate aerosols in China plays an additive role in the warming around the B–K Seas despite some discrepancies between the simulation and the reanalysis. We

FIG. 8. Linear trends of wind fields, showing climatological zonally averaged (60° – 130°E) zonal wind (contours; m s^{-1}) and trend of zonally averaged (60° – 130°E) zonal wind with meridional circulation [shading: zonal wind ($\text{m s}^{-1} \text{yr}^{-1}$); vector: v ($\text{m s}^{-1} \text{yr}^{-1}$); $\omega \times -30$] in the SO_2 run. Shading denotes statistical significance at the 90% confidence level.

FIG. 9. Moisture transport and downward longwave radiative flux in the ERA-Interim: (a) linear trend of zonally averaged northward moisture transport ($Q \times v$; $\text{m s}^{-1} \text{yr}^{-1}$), (b) linear trend of integrated specific humidity from 850 to 1000 hPa ($\text{g kg}^{-1} \text{yr}^{-1}$), and (c) trend of downward longwave radiative flux at the surface ($\text{W m}^{-2} \text{yr}^{-1}$). Shading denotes statistical significance at the 90% confidence level.

suggested the mechanism associated with moisture transport into the Arctic as the cause. Specifically, a fast atmospheric response to sulfate aerosol forcing in China reduces the meridional temperature gradient and leads to the increase of moisture transport into the Arctic by altering atmospheric circulation. The resulting increase of moisture then leads to surface warming through the enhancement of the downwelling longwave radiation. Therefore, increased aerosol forcing in China might exacerbate Arctic warming.

Previous studies examined the effect of sulfate aerosol forcing in East Asia on temperature using a fully coupled climate model (Liu et al. 2018; Kasoar et al. 2016). Their studies reported that sulfate aerosol forcing in

East Asia induces a cooling globally including the Arctic region. Our study focused the effect of a fast atmospheric response on the regional Arctic amplification due to the sulfate aerosol forcing in China. The total effects of sulfate aerosol forcing in China including feedback processes of aerosol forcing and a slow SST forcing may be completely different or even opposite from previous studies suggested (Liu et al. 2018; Kasoar et al. 2016). Therefore, these results may imply that the regional Arctic warming by a fast atmospheric response to the increase of sulfate aerosol in China is quite different from that due to the total climate responses including SST changes and its feedback processes with aerosol forcing.

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