Little Influence of Asian Anthropogenic Aerosols on Summer Temperature in Central East Asia Since 1960

Wenjian Hua1, Aiguo Dai2, and Haishan Chen1

1Key Laboratory of Meteorological Disaster, Ministry of Education (KLME), Joint International Research Laboratory of Climate and Environment Change (ILCEC), Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology, Nanjing, China, 2Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, NY, USA

Abstract Recent summer surface air temperature (SAT) variations over Central East Asia (CEA) have been influenced by greenhouse gas and aerosol forcing since 1960. But how CEA SAT responds to contrasting changes in Asian, and European and North American aerosol sources remains unclear. By analyzing observations and model simulations, here we show that aerosol-forced summer SAT changes over CEA since 1960 come mostly from the effects of aerosols outside Asia, with relatively small influences from Asian aerosols. Unlike Europe, where direct and indirect aerosol effects on surface solar radiation drive the SAT long-term trend and decadal variations, over CEA atmospheric circulation response to aerosols outside Asia plays an important role. Aerosol-forced anomalous low-level low pressure in mid-latitude Eurasia may influence the SAT anomalies downstream over mid-latitude Asia, including a warm anomaly around CEA. The results suggest that caution is needed in attributing SAT changes around CEA to anthropogenic aerosols from Asia.

Plain Language Summary Anthropogenic aerosol forcing contributes to the nonuniform surface air temperature (SAT) changes over Eurasia since the 1960s, especially decadal SAT variations over Europe-west Asia and Central East Asia (CEA). However, spatial inhomogeneity of the anthropogenic aerosol forcing could lead to distinct regional temperature responses over Eurasia. Here we explicitly distinguished and separated the contributions from different aerosol emission sources, namely from Europe and North America and from Asia. Our results show that aerosol-forced summer SAT trends and decadal variations over CEA since 1960 are influenced more by aerosols outside Asia than Asian aerosols. Besides the local solar radiation changes in response to aerosol forcing, European and North American aerosols can also affect regional SAT through changes in atmospheric circulation. The decreasing European and North American aerosols could excite an anomalous low-level high pressure center over Northeast China that contributes to warmer SAT around CEA through southerly advection. European and North American aerosols will continue to decrease, whereas global greenhouse gases emissions will continue to increase in the future. These factors, together with decrease in Asian aerosols around 2012, will likely accelerate near-future warming trends over CEA.

1. Introduction

Superimposed on a general warming trend, the surface air temperature (SAT) over Eurasia features a nonuniform pattern during boreal summer (Cohen et al., 2012), with remarkable in-phase decadal variations over Europe-west Asia and Central East Asia (CEA) but small out-of-phase decadal variations over Central Eurasia since the 1960s (Hong et al., 2017; Hua et al., 2021). These decadal SAT variations over Eurasia are thought to result mainly from internal variability (i.e., the Atlantic Multidecadal Oscillation, [AMO]) of the climate system (Hong et al., 2017; Sun et al., 2019; Sutton & Dong, 2012); however, nonlinear external forcing, including decadal changes in greenhouse gases (GHG) and aerosols, may have also contributed to the nonuniform SAT changes over Eurasia (Dong et al., 2016, 2017), especially the decadal SAT variations over Europe-west Asia and CEA since 1950 (Hua et al., 2021).

Recent studies suggest that anthropogenic and volcanic aerosol forcing since 1920 happens to be in phase with the internally-generated AMO (Hua et al., 2019; Qin et al., 2020a, 2020b). Thus, the AMO-like climate variations over Eurasia (e.g., the AMO-associated nonuniform or tripole SAT pattern) may be dominated by the aerosol forcing, rather than the remote influence from the AMO (Hua et al., 2021). However, spatial inhomogeneity of the anthropogenic aerosol forcing could lead to distinct regional temperature responses over Eurasia. For
example, aerosols emitted from Europe and North America have declined due to air quality regulations since the 1980s, while emissions from Asia have continued to increase during the 20th century (Smith & Bond, 2014; Xie et al., 2013). It remains unclear how aerosol-forced SAT variations are reflected in the observed SAT and how SAT responds to time-varying aerosol distributions over Eurasia, that is, the contrasting changes in European and Asian aerosol sources since the 1960s.

Here we analyze observations and model simulations to show that the aerosol-forced SAT over CEA during boreal summer is relatively insensitive to local anthropogenic aerosols (AA) over Asia since 1960. Our results suggest that summer SAT trends and decadal variations since 1960 over CEA are dominated by aerosols outside Asia. Our findings should help uncover the nature and cause of the recent amplified summer warming and improve predictions of future summer climate over CEA.

2. Data, Model Simulations, and Methods

2.1. Data and Model Simulations

We used the monthly SAT data from the Climatic Research Unit TS v4.05 (Harris et al., 2020). We also used other SAT data sets to examine the SAT variations, for example, the Berkeley Earth Surface Temperatures (Rohde et al., 2013), and GISS Surface Temperature Analysis version 4 (Lenssen et al., 2019). The results were qualitatively similar and thus not included in the figures shown here. We focus on the period from 1960 to 2020, as SAT observations before around 1960 over East Asia are sparse (Hua et al., 2021).

We analyzed ensemble simulations from 44 coupled climate models participated in the Coupled Model Intercomparison Project Phase 6 (CMIP6) historical all-forcing (ALL) (1850–2014) and Shared Socioeconomic Pathway 5–8.5 (2015–2020) simulations (Table S1 in Supporting Information S1) (Eyring et al., 2016). The effects of different historical external forcing agents were investigated by analyzing simulations from 12 CMIP6 models forced by GHG only and AA only (Table S2 in Supporting Information S1). We also analyzed two single-model large ensembles of fully coupled simulations by the Canadian Earth System Model version 2 (CanESM2, 50 ensemble runs from 1950 to 2100) (Kirchmeier-Young et al., 2017), and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Mark 3.6 (CSIRO-Mk3.6, 30 ensemble runs from 1850 to 2100) (Jeffrey et al., 2013). All these ensemble simulations were forced by historical all-forcing up to 2005 and the Representative Concentration Pathway 8.5 forcing thereafter. In addition to the ALL forcing ensemble, we also used 50-member ensembles of the CanESM2 simulations with AA forcing-only. We also analyzed single-forcing historical simulations (i.e., historicalMisc experiments, Table S3 in Supporting Information S1) by the CSIRO-Mk3.6 model. We chose the large-ensemble CSIRO-Mk3.6 simulations over other available single-model large ensembles of simulations, because this model provides additional experiments (Table S3 in Supporting Information S1) that can help examine contrasting response of SAT to different aerosol sources.

2.2. Methods

We analyzed observed and simulated SAT data over CEA and focused on the 3-month period of June, July and August (JJA). To estimate the internally-generated and externally-forced components in observed SAT, we used the global-mean SAT time series from the multi-model ensemble mean (MMM) of the CMIP6 ALL forcing historical simulations (44 models, Table S1 in Supporting Information S1) as the forced signal and removed it through linear regression from 1960 to 2020 from the observed SAT at each grid point to produce the residual SAT fields that contain primarily internal variability (Dai et al., 2015; Hua et al., 2021). For a given time series, a linear trend was estimated using least squares fitting and a two-tailed Student's t test was used to test whether the trend differs significantly from zero. To examine the decadal SAT variations, we linearly detrended the data and removed the inter-annual to multi-year variations using the 11-year running mean. We emphasize that AA generally cause surface cooling in all years; however, decreasing AA (such as over Europe since 1960) would cause less cooling in recent years than in the earlier period, resulting in an upward (i.e., warming) trend in SAT over the entire period, even though the AA's effect on SAT is always cooling in all years.
3. Results

3.1. SAT Trends and Decadal Variations Over Eurasia

The SAT records show amplified summer warming trend over CEA, central and southern Europe, and the dry regions in northern Africa and the Arabian Peninsula, while the warming is weak over South and Central Asia and northern Europe since 1960 (Figure 1a). Although internal variability leads to some regional trends (Figure 1b), most of the observed SAT trends over Eurasia result from external forcing during 1960–2020 (Figure 1c). The observed SAT trends (Figure 1a) are strongly correlated spatially with the externally forced SAT trends (Figure 1c, $r = 0.99$), but the correlation is relatively weaker ($r = 0.34$) with the trends caused by internal variability only (Figure 1b). Over CEA, almost all of the observed warming trend (0.3°C decade$^{-1}$) from 1960 to 2020 results from external forcing (Figure S1 in Supporting Information S1). CMIP6 multimodel ensemble and single-model large ensemble of all-forcing simulations (e.g., CSIRO-Mk3.6) reproduce this warming trend over CEA (0.32–0.38°C decade$^{-1}$), although the forced warming trends in CMIP6 are noticeably stronger than in observations over most Eurasia (Figures 1c and 1d).
To identify the key forcing agents of the local warming trend over CEA, we further analyzed additional model simulations that were forced by GHG and AA only. The increases in global GHGs produce widespread warming across Eurasia in the CMIP6 GHG forcing-only simulations, with enhanced warming over the dry regions such as northern Africa, the Arabian Peninsula and northwestern China (Figure 1e), consistent with previous findings (Zhou, 2016; Zhou et al., 2016). Furthermore, the observed strong warming in northern western-central Russia (Figures 1a and 1c) can be largely attributed to the GHG forcing (Figure 1e), which causes sea-ice melting in the adjacent Barents-Kara Seas that can amplify surface warming around the region (Dai et al., 2019). In contrast, from 1960 to 2020 AA causes a cooling trend over northern western-central Russia and South Asia but a strong warming trend (recovering from its strong cooling in 1960) over Europe and a moderate warming trend downstream over mid-latitude Asia, including CEA (Figure 1f). This AA-induced mid-latitude nonuniform change pattern (relative to the strong cooling in 1960) contributes to the regional warming patterns in the CMIP6 ALL simulations (Figure 1d), and to some degree it also resembles the observed nonuniform warming pattern in mid-latitude Eurasia (Figures 1a and 1c). This indicates that AA may have contributed to the nonuniform warming pattern in mid-latitude Eurasia during 1960–2020, especially over Europe and CEA (Figure S1 in Supporting Information S1). Such a spatial pattern is also evident in other single-model large ensemble simulations with AA forcing-only, although it differs slightly in the exact locations (Figure S2 in Supporting Information S1). Consistent with the AA-induced nonuniform warming trends (relative to 1960) in mid-latitude Eurasia (Figure 1f), decadal changes in AA also contribute to the observed nonuniform SAT decadal variations over Eurasia since 1960 (Figure 2). In observations, the decadal warm (cold) anomaly during 2000–2020 (1975–1995) is strongest over eastern Europe and around CEA, while it is the opposite over central Eurasia (Figure 2a). Decadal warm (cold) anomaly from about 2000 to 2020 (1975–1995) has occurred around CEA and eastern Europe in the AA forcing-only simulations (Figures 2b and 2c and S3 in Supporting Information S1), although the magnitude of the local responses varies slightly among the models. These results suggest a nonuniform warming pattern over Eurasia due to AA forcing, with enhanced warming around CEA and eastern Europe. The AA-induced SAT over
CEA shows decadal variations from 1960 to 2020, with negative anomalies from the 1970s to 1990s and positive anomalies after the late 1990s (Figure 2d).

In summary, recent changes in aerosol forcing caused zonally varying SAT changes in mid-latitude Eurasia, especially over CEA and eastern Europe, that have contributed to the enhanced summer warming there since 1960 seen in observations.

3.2. SAT Response to Evolving Aerosol Distributions

The above analyzes suggest that anthropogenic aerosol forcing may have contributed to the SAT warming trend and decadal variations since 1960 around CEA, mainly due to the decreasing aerosol emissions from Europe (and possibly also from North America) since 1960 (Figures 1f and 2d). However, we should note that global emissions of AA have increased through the 20th century; in particular, aerosol emissions from Asia have increased steadily since the 1950s, which may produce a cooling trend around East Asia including CEA. How do the local and remote AA contribute to the SAT trend over CEA?

To answer this question, we first examine the spatial and temporal characteristics of the AA forcing, measured by the ambient aerosol optical depth at wavelength of 550 nm (AOD550), from the CMIP6 AA forcing-only simulations (Figure S4 in Supporting Information S1). AA emissions from East and South Asia (and also the global mean) have increased steadily from 1920 to around 2012, and then declined sharply thereafter, while the emissions from Europe and North America peaked around 1979 (Figure S4 in Supporting Information S1). Such different aerosol emission patterns lead to evolving aerosol distributions (i.e., shifted from Europe and North America before the 1980 to Asia thereafter) (Qin et al., 2020a; Smith & Bond, 2014). In particular, from 1960 to 2020 the AA emissions from Asia are dominated by an upward trend (with some decreases after 2012), whereas the emissions from Europe and North America contain mainly decadal variations.

To illustrate the SAT’s response to different aerosol emission sources, here we analyze an idealized experiment by the CSIRO-Mk3.6 model (Table S3 in Supporting Information S1) that is the same as the all-forcing simulations except that historical aerosol forcing is prescribed only in Asia (10°S–45°N; 65°E−150°E). As expected, significant cooling trends from 1960 to 2012 are widespread across Eurasia in response to the Asian AA forcing (Figure 3a), except for northern western-central Russia, where there exists moderate warming that may result from the nonlinearity in the response to the GHG and AA forcing (Figures 1c and 1f) (Deng et al., 2020). We notice that the cooling trend over CEA is only modest in response to Asian aerosols (Figure 3a). In contrast, the AA forcing from outside Asia leads to recovering warming trends during 1960–2012 in mid-latitude Eurasia including CEA (Figure 3a). The combination of these AA effects results in warming trends over most mid-latitude Eurasia, including CEA (Figure S2a in Supporting Information S1), which is consistent with Figure 1f and enhances the GHG-induced warming over mid-latitude Eurasia (Figures 1d and 1e). Thus, the locally enhanced warming since 1960 over CEA in observations (Figures 1a and 1c) and model simulations (Figure 1d) is mainly caused by increasing GHG and decreasing aerosol emissions from Europe and North America, while increasing Asian aerosols slightly weaken the warming there. Consistent with the warming trends, the decadal changes in aerosol emissions from Europe and North America also produce decadal SAT variations from 1975–1995 to 1996–2012 over Eurasia, including CEA, with relatively small contributions from Asian aerosols (Figures 3c and 3d).

3.3. How Do Anthropogenic Aerosols Affect SAT?

Climate response to aerosol forcing through aerosol-radiation and aerosol-cloud interactions has received much attention (Boucher et al., 2013; Dong et al., 2019). Aerosol forcing excluding Asian AA (mostly AA from Europe and North America, Figures 4a, S4, and S5 in Supporting Information S1) shows a decrease from 1960 to 2012 over Europe (Figure S6 in Supporting Information S1). Local decreases in AA loadings over Europe lead to significant increases in surface absorbed shortwave radiation under both all-sky and clear-sky conditions (Figures 4b and 4c), through aerosols’ direct and indirect effects and water vapor and other feedbacks (Figure 4d) (Boucher et al., 2013). Furthermore, the trends of the all-sky and clear-sky net surface shortwave radiations show similar magnitudes and patterns (Figures 4b and 4c), indicating a relatively small effect of clouds through the indirect aerosol effect. The indirect aerosol effect comes mainly from slightly reduced cloud fraction over Europe (Figure 4d). As expected, the aerosol forcing over Asia from Europe and North America and the associated
responses in net surface solar radiation and cloudiness are relatively weak, except for India, South and East China where increased cloudiness leads to decreased all-sky net surface solar radiation (Figures 4a–4d).

Besides the local solar radiation changes, aerosols can also affect SAT through changes in atmospheric circulation in response to nonuniform aerosol forcing. The zonally-varying SAT changes are associated with decreasing (increasing) geopotential height over western Europe and northern Asia (northern Europe and Northeast China), which led to enhanced southerly warm air into CEA and northerly cold air into central Eurasia (Figure 4e). These anomaly winds should contribute to the relatively large (small) warming over CEA (central Eurasia). That is, the nonuniform diabatic heating induced by decreasing aerosol loadings from Europe and North America could produce anomalous low-level low and high pressure centers over mid-latitude Eurasia, which enhance (weaken) the warming over CEA (central Eurasia) induced by the decreasing AA from Europe and North America. Consistent with the trends, the decadal changes in aerosols mainly from Europe and North America also contribute to significant decadal variations in surface shortwave radiation under both clear- and all-sky conditions (Figures S7a–S7d in Supporting Information S1), leading to large decadal SAT variations over Europe (Figure 3d). However, the radiation and SAT responses are weak downstream. Associated with the SAT variations, there is a high pressure center over northern Europe and Northeast China, leading to southerly winds into CEA and northwesterly winds into central Eurasia (Figure S7e in Supporting Information S1), which should contribute to the SAT changes there.

4. Summary and Discussion

We have analyzed observations and historical simulations by CMIP6 and CSIRO-Mk3.6 models to show that anthropogenic aerosol forcing contributes to the observed warming trend and decadal SAT variations over CEA since 1960. We further explicitly distinguished and separated the contributions from different aerosol emission sources, namely from Europe and North America and from Asia. Our results suggest that SAT trends and decadal variations since 1960 over CEA are influenced by aerosols outside Asia. The decreasing European and North

Figure 3. (a) Linear trends during 1960–2012 in June, July and August (JJA) surface air temperature (SAT) (°C decade−1) due to aerosol forcing over Asia. Shown is the SAT trend difference between the AsiaAA (Asian aerosol forcing) and NoAA (nonaerosol forcing) simulations by the Commonwealth Scientific and Industrial Research Organisation Mark 3.6 (CSIRO-Mk3.6) model (Table S3 in Supporting Information S1), which represents the response to aerosol forcing over Asia assuming linearity in the response. (b) Same as (a), but for the difference between the ALL and AsiaAA simulations, which represents the response to aerosol forcing outside Asia (i.e., from Europe and North America) under the linearity assumption. The stippling indicates that the trends are statistically significant at the 5% level. (c and d) Same as (a and b), but for JJA-mean SAT anomalies (°C) for the warm period (1996–2012) relative to the cold period (1975–1995) from the CSIRO-Mk3.6 ensemble simulations. The model simulations were linearly detrended before calculating the anomalies.
American aerosols since \sim 1979 not only cause a warming trend near the surface through increased surface solar radiation due to reduced reflection by decreasing aerosols and decreasing cloudiness, but also excite an anomalous low-level high pressure center over Northeast China that contributes to warmer SAT around CEA through southerly advection. The aerosol-forced change patterns help explain the enhanced warming trend and decadal SAT variations over CEA during 1960–2020. European and North American aerosols will continue to decrease, whereas GHGs will continue to increase in the future. These factors, together with continued decreases in Asian aerosols since 2012, will likely accelerate near-future warming trends over CEA.

Here we only examined aerosols’ impacts on the mean SAT trends and decadal variations during the boreal summer over Eurasia. Further analyses are needed to quantify aerosols’ impacts on precipitation and other climate fields over mid-latitude Eurasia. Climate response to evolving aerosol emissions (i.e., anthropogenic aerosol emission sources shifted from the western to eastern hemisphere around the 1980s) has been examined in some recent studies (Diao et al., 2021; Kang et al., 2021; Wang et al., 2021). For example, different responses in atmospheric (or oceanic) energy transport, SST and atmospheric circulation to the changed aerosol emissions have been noticed (Kang et al., 2021). Thus, the evolving geographical distributions of aerosol emissions may be important for understanding regional climate changes, as shown here for summer surface warming patterns over Eurasia.
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