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Atmospheric Chemistry and Physics Discussions

Trends and source apportionment of aerosols in Europe during 1980–2018

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Abstract

Aerosols have significantly affected health, environment and climate in Europe. Aerosol concentrations have been declining since 1980s in Europe, mainly owing to the reduction of local aerosol and precursor emissions. Emissions from other source regions of the world, which have been changing rapidly as well, may also perturb the historical and future trends of aerosols and change their radiative impact in Europe. This study examines trends of aerosols in Europe during 1980–2018 and quantify contributions from sixteen source regions using the Community Atmosphere Model version 5 with an Explicit Aerosol Source Tagging technique (CAM5-EAST). The simulated near-surface total mass concentration of sulfate, black carbon and primary organic carbon had a 62% decrease during 1980–2018, of which the majority was contributed by reductions of local emissions in Europe and 8%-9% was induced by the decrease in emissions from Russia-Belarus-Ukraine. With the decreases in the fractional contribution of local emissions, aerosols transported from other source regions are increasingly important to air quality in Europe. During 1980–2018, the decrease in sulfate loading leads to a warming effect of 2.0 W m^{-2} in Europe, with 12% coming from changes in non-European sources, especially from North America and Russia-Belarus-Ukraine. According to the Shared Socioeconomic Pathways (SSP) scenarios, contributions to the sulfate radiative forcing over Europe from both European local emissions and non-European emissions would decrease at a comparable rate in the next three decades, suggesting that future changes in non-

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European emissions are as important as European emissions in causing possible regional climate change associated with aerosols in Europe.

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1. Introduction

Aerosols are main air pollutants that contribute to excess morbidity and premature mortality through damaging cardiovascular and respiratory systems (Lelieveld et al., 2019). They also have adverse effects on atmospheric visibility for road and air traffic (Vautard et al., 2009). During the 1952 London Fog, high fatality associated with extremely high level of aerosols caused thousands of premature deaths (Bell and Davis, 2001), which resulted in a number of air quality legislations for reducing air pollution in Europe (Brimblecombe et al., 2006).

Besides the health and environment effects, aerosols can significantly impact regional and global climate through perturbing the Earth's radiation fluxes and influencing cloud microphysics (Boucher et al., 2013). Globally, anthropogenic aerosols exert a net cooling effect in the Earth system, which have dampened the warming driven by greenhouse gases since the pre-industrial era. Due to a strong surface albedo feedback over polar regions, per unit aerosol emission from western Europe was reported to have the greatest cooling effect than other major source regions of the globe (Persad and Caldeira, 2018), revealing the importance of understanding aerosol variations in Europe.

Significant reductions in near-surface aerosol concentrations and aerosol optical depth (AOD) have been observed in Europe during the last few decades from long-term station measurements and satellite retrievals (de Meij et al., 2012; Tørseth et al., 2012). The decrease in aerosols has been considered as a cause of the increase in surface solar radiation over Europe since the 1980s (Wild, 2009), as well as the

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contributor of the eastern European warming (Vautard et al., 2009), Arctic amplification (Acosta Navarro et al., 2016), and the increased atmospheric visibility over Europe (Stjern et al., 2011) during the past three decades.

The decrease in aerosols over Europe was mainly attributed to the continuous reductions in European local anthropogenic emissions of aerosols and precursor gases since the 1980s (Smith et al., 2011), as a result of legislations for improving air quality. In addition to local emissions, aerosol levels can also be affected by aerosol transport at continental scales (Zhang et al., 2017; Yang et al., 2018a). Aerosol emissions in major economic regions of the world have been changing rapidly during the past few decades owing to economic development and environmental measures. North America has started reducing emissions since the 1980s, and emissions in Russia also showed decreasing trends after the dissolution of the Soviet Union (Smith et al., 2011). In the meantime, aerosol emissions from East Asia and South Asia have largely increased due to economic growth, although emissions in China have been undergoing a remarkable reduction in the most recent years, as a result of strict air quality regulations (Streets et al., 2000; Li et al., 2017). It is important to understand the relative roles of local emissions and regional transport in affecting long-term variation of aerosols in Europe from both air quality and climate perspectives.

Source apportionment is useful for quantifying contributions to aerosols from specific source regions and/or sectors, which is beneficial to the emission control strategies. The traditional method of examining the source-receptor relationship in

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aerosol models is to zero out or perturb a certain percent of emissions from a given source region or sector in parallel sensitivity simulations along with a baseline simulation, which has been used in many studies to examine source contributions of particulate matter (PM) in Europe from different sectors (e.g., Sartelet et al., 2012; Tagaris et al., 2015; Aksoyoglu et al., 2016). Recently, source region contributions to European CO and O_3 levels, as well as global and regional aerosol radiative forcing, were examined under the Hemispheric Transport of Air Pollution model experiment phase 2 (HTAP2) protocol, in which sensitivity simulations were conducted with anthropogenic emissions from different source regions reduced by 20% (Jonson et al., 2018). This method suffers a large computational cost for the excessive model simulations when estimating contributions from a large number of sources, and contributions from all sources do not sum up to 100% of the total concentration in the default simulation (Koo et al., 2009; Wang et al., 2014).

The explicit aerosol tagging method, which simultaneously tracks contributions from many different sources, is a useful tool for assessing source-receptor relationship of aerosols. This method has previous been adopted in regional air quality models such as CAMx (the Comprehensive Air quality Model with Extensions) and CMAQ (the Community Multi-scale Air Quality model). Using regional air quality models with aerosol tagging, contributions from different source sectors and local/regional sources to European PM and its health impact were studied (Brandt et al., 2013; Skyllakou et al., 2014; Karamchandani et al., 2017). However, due to the limitation in domain size of regional air quality models,

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contributions of intercontinental transport from sources outside the domain are difficult to be accounted.

Anthropogenic emissions of aerosols and their precursor gases from different economic regions of the world have changed substantially during the past few decades. Very few studies have examined the source apportionment of aerosols in Europe from sources all over the changing world. In this study, source attrubutions of concentrations, column burden, optical depth of aerosols in four major areas of Europe from sixteen source regions of the globe over 1980–2018 are quantified, which is facilitated by the explicit aerosol source tagging technique that were recently implemented in a global aerosol-climate model (CAM5-EAST). This technique has lately been used to examine source attribution of aerosol trends in China and U.S. during 1980–2014 (Yang et al., 2018a,b). The source apportionment analysis is extended to year 2018 using the Shared Socioeconomic Pathways (SSPs) scenario, with a focus on Europe here.

The CAM5-EAST model, along with the aerosol source tagging technique, and aerosol emissions are described in Sect. 2. Section 3 evaluates the model performance in simulating aerosols in Europe. Section 4 show the analysis of source-receptor relationships of aerosols in Europe in climatological mean. Source contributions to long-term variations of European aerosols and their direct radiative forcing (DRF) during 1980–2018, as well as future forcing prediction, are provided in Sect. 5. Section 6 summarizes these results and conclusions.

2. Methods

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2.1 Model Description and Experimental Setup

The global aerosol-climate model CAM5 (Community Atmosphere Model version 5), which was developed as the atmospheric component of CESM (the Community Earth System Model, Hurrell et al., 2013), is applied to simulate aerosols at a spatial resolution of 1.9° latitude × 2.5° longitude and 30 vertical layers from the surface to 3.6 hPa. Aerosol species, including sulfate, black carbon (BC), primary organic aerosol (POA), second organic aerosol (SOA), mineral dust and sea salt, can be simulated in a modal aerosol module of CAM5. The three-mode aerosol module (MAM3) configuration is chosen with the consideration of the computational efficiency of long-term simulation. Details of the MAM3 aerosol representation in CAM5 are described in Liu et al. (2012). On top of the default CAM5, some aerosol-related scheme modifications are utilized to improve the model performance in the aerosol convective transport and wet deposition (Wang et al., 2013).

A 40-year (1979–2018) historical AMIP-type (Atmospheric Model Intercomparison Project) simulation has been performed, following CMIP6 (the Coupled Model Intercomparison Project Phase 6) configurations and forcing conditions. Time-varying sea surface temperatures, sea ice concentrations, solar insolation, greenhouse gas concentrations and aerosol emissions are prescribed in the simulation. To better reproduce large-scale circulation patterns for aerosol transport in the model, wind fields are nudged to the MERRA-2 (Modern Era Retrospective-Analysis for Research and Applications Version 2) reanalysis (Ronald Gelaro et al., 2017).

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Aerosol DRF is defined in this study as the difference in clear-sky radiative fluxes at the top of the atmosphere between two parallel calculations in the radiative transfer scheme with and without specific aerosols accounted, respectively. Historical variation of aerosol DRF due to anthropogenic emissions from Europe and outside Europe are quantified in this study. Future DRF of sulfate aerosol over Europe is also estimated through scaling historical mean (1980–2018) sulfate DRF by the ratio of SSPs future SO_2 emissions to historical emissions assuming a linear response of DRF to AOD and regional emissions. This DRF prediction method has been used to estimate the East Asian contribution to sulfate DRF in U.S. in 2030s (Yang et al., 2018a).

2.2 Aerosol Source Tagging Technique

The Explicit Aerosol Source Tagging (EAST) technique, which was recently implemented in CAM5 (Wang et al., 2014; Yang et al., 2017a, b), is used to examine the long-term source apportionment of aerosols in Europe. Unlike the traditional back-trajectory and emission perturbation methods, EAST has the identical physical, chemical and dynamical processes considered independently for aerosol species (defined as new tracers) emitted from each of the tagged source region and/or sector in the simulation. Sulfate, BC, POA and SOA from pre-defined sources can be explicitly tracked, from emission to deposition, in one CAM5-EAST simulation. Due to the computational constraint and potentially large model bias from the simplified SOA treatment (Yang et al., 2018a; Lou et al., 2019), we focus on sulfate, BC and POA in this study but quantify the potential impact of SOA on the aerosol variation.

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The global aerosol and precursor emissions are decomposed into sixteen source regions defined in the HTAP2 protocol, including Europe (EUR), North America (NAM), Central America (CAM), South America (SAM), North Africa (NAF), South Africa (SAF), the Middle East (MDE), Southeast Asia (SEA), Central Asia (CAS), South Asia (SAS), East Asia (EAS), Russia-Belarus-Ukraine (RBU), Pacific-Australia-New Zealand (PAN), the Arctic (ARC), Antarctic (ANT), and Non-Arctic/Antarctic Ocean (OCN) (Figure 1). Note that sources from marine and volcanic eruptions are included in OCN. The focused receptor region in this study is Europe, which is further divided into Northwestern Europe (NWE or NW Europe), Southwestern Europe (SWE or SW Europe), Eastern Europe (EAE or E. Europe) and Greece-Turkey-Cyprus (GTC) based on the finer source region selection in HTAP2.

2.3 Aerosol and Precursor Emissions

Following the CMIP6-AMIP protocol, historical anthropogenic (Hoesly et al., 2018) and biomass burning (van Marle et al., 2017) emissions of aerosol and precursor gases are used over 1979–2014. For the remaining four years (2015–2018), emissions are interpolated from the SSP2-4.5 forcing scenario, in which aerosol pathways are not as extreme as other SSPs and have been used in many model intercomparison projects for CMIP6 (O'Neill et al., 2016). Figure 2 shows the spatial distribution and time series of anthropogenic emissions of SO_2 (precursor gas of sulfate aerosol), BC and POA from Europe over 1980–2018. High emissions are located over E. Europe and NW Europe, from which the emissions of SO_2, BC and

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POA were reduced by 84–93%, 43–62% and 28–36%, respectively, in 2014–2018 relative to 1980–1984. Although SW Europe had a relatively low total amount of emissions compared to E. Europe and NW Europe, it had significant reductions in SO_2 and BC emissions, 91% and 55%, respectively. Over GTC region, SO_2 and BC emissions were increased by 49% and 48%, respectively. Considering the sub-regions as a whole, SO_2, BC and POA emissions from Europe have decreased by 12.57 Tg yr^{-1} (83%), 0.22 Tg yr^{-1} (46%) and 0.30 Tg yr^{-1} (24%) in 2014–2018 compared to 1980–1984 (Table 1). Historical changes in emissions from other source regions can be found in Hoesly et al. (2018) and Yang et al. (2018b).

3 Model Evaluation

Compared to the observational data from EMEP (European Monitoring and Evaluation Programme, http://www.emep.int) networks during 2010–2014, CAM5-EAST can well reproduce the spatial distribution and magnitude of aerosol components with normalized mean biases (NMB) of -14%~-23% and correlation coefficients (R) in a range of 0.43~0.62 for sulfate, BC and organic carbon (OC, derived from POA and SOA from the model results) (Figures 3a, b, c). The model underestimates the mean concentration of $PM_{2.5}$ (sum of sulfate, BC, POA and SOA) by 59% relative to EMEP data (Figure 3d), although the spatial distribution has a strong correlation with the observations (R=0.72). It is partially because the model version used in this study does not have the ability to simulate nitrate and ammonium aerosols, which can be the major constituents of $PM_{2.5}$ in some regions,

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and the fine-mode mineral dust and sea salt is not included in the estimated $PM_{2.5}$ either.

Figure 4 shows the time series of annual mean near-surface sulfate, BC, OC and $PM_{2.5}$ concentrations averaged over EMEP sites in Europe and the corresponding model values during 1993–2018. Variations in near-surface sulfate and $PM_{2.5}$ concentrations are consistent between the model and observations, with R values higher than 0.9. $PM_{2.5}$ concentrations are lower in the model simulation than observations in almost all years, confirming the role of the missing aerosol species in contributing to $PM_{2.5}$ as discussed above. The observed variations of BC and OC concentrations in Europe are represented in the simulation, with R values of 0.52 and 0.65, respectively. However, the observed high values of BC and OC concentrations are not captured by the model, probably because very few data were available before 2010 and, therefore, any difference between model and observation cannot be smoothed out through the spatial average. This is also indicated by the large spatial variation of BC and OC concentrations before 2010. Nevertheless, the modeled concentrations are still within the range of observations. Note that the number of sites used for the spatial average in Figure 4 is different from year to year and thus the variation or trend here does not represent that over a sub-region or the entire Europe.

The modeled AOD is evaluated against the AERONET (Aerosol Robotic Network, https://aeronet.gsfc.nasa.gov) data in Figure 8. Both the modeled and observed AOD show decreasing trends during 2001–2018. The model

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underestimates AOD in all four sub-regions of Europe probably due to the lack of nitrate and ammonium aerosols. The variations of AOD in Western Europe (combined NW and SW Europe) are well predicted with R values of about 0.75, but the model barely reproduces the AOD variations in E. Europe and the GTC region (R<0.5). The difference of the interannual variation in AOD between the model simulation and observation can be caused by many factors such as aerosol emissions, aerosol parameterizations in model, aerosol mixing state, inaccurate meteorological fields from reanalysis data, and biases in measurements. However, identifying the contribution of each factor to the difference is beyond the scope of this paper.

4. Source Apportionment of Aerosols in Europe

Based on the tagging technique in CAM5-EAST, near-surface concentrations of total sulfate-BC-POA can be attributed to emissions within and outside Europe, as shown in Figures 5a and 5b, and the relative contributions in percentage are given in Figures 5c and 5d. Averaged over 2010–2018, due to the relatively high local emissions, annual mean sulfate-BC-POA concentrations contributed by European emissions show peak values of 4 μg m^{-3} in E. Europe. The slight increase in SO_2 emission from the GTC region (Figure 2), which is opposite to the decreases in the other three sub-regions of Europe, also leads to high concentrations in GTC, with 2–4 μg m^{-3} contributed by European emissions. Due to the atmospheric transport from surrounding regions including North Africa, the Middle East and RBU, non-European emissions account for 0.5–1 μg m^{-3} over SW Europe, E. Europe and GTC area.

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Overall, European local emissions are the dominant sources of sulfate-BC-POA near-surface concentrations in Europe with contributions larger than 80% (60%) in central areas (most of Europe). Non-European emissions are responsible for 30–50% of the near-surface concentrations near the coastal areas and boundaries of the Europe that are easily influenced by aerosol regional transport.

Figure 6 illustrates the source contributions in percentage of emissions from different regions of the globe to near-surface aerosol concentrations and column burdens over the four sub-regions of Europe averaged over 2010–2018. Different aerosols have fairly different local/remote source attributions depending on the local to remote emission ratio and transport efficiency. European emissions explain 54%–68% of near-surface sulfate concentrations over the four sub-regions of Europe, with the largest local contribution from E. Europe due to the relatively high emission rate. The emissions from Europe dominate BC and POA concentrations in Europe with contributions in the range of 78%–95% and 58%–78%, respectively. The impact of local emissions on near-surface sulfate concentration is smaller than BC and POA. This is partially due to the less efficient gas scavenging than particles and the additional SO_2-to-sulfate conversion process that increases the atmospheric residence time of sulfur. On the other hand, the higher initial injection height of SO_2 emissions from some sources (e.g., industrial sector and power plants) facilitates the lifting of SO_2 and sulfate aerosol into the free atmosphere and, therefore, favors the long-range transport (Yang et al., 2019). The efficient reduction in local SO_2

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emissions in Europe also caused the lower influences of local emissions on sulfate concentrations in recent years.

Anthropogenic emissions over oceans (e.g., international shipping) and natural emissions of oceanic dimethyl sulfide (DMS) and volcanic activities together account for 16%–28% of near-surface sulfate concentrations in the four sub-regions of Europe. About 10% of sulfate and 5%–10% of BC and POA in E. Europe and GTC come from RBU emissions. North Africa contributes to 7% of sulfate, 17% of BC and 24% of POA over SW Europe. The contributions of emissions, from the Middle East, to aerosol concentrations in GTC are between 5% and 10%.

The transboundary and intercontinental transport of aerosols occur most frequently in the free troposphere rather than near the surface, leading to larger relative contributions from non-European sources to aerosol column burdens than to the near-surface concentrations (Figure 6). The European emissions only contribute 32%–47% of column burden of sulfate, 57%–75% of BC and 51%–71% of POA over the four sub-regions of Europe. Over NW Europe and SW Europe, about 10%–15% of the sulfate burden is from East Asia and RBU, respectively. Sources in North Africa are responsible for 27% and 14% of BC and 19% and 11% of POA burden over SW Europe and GTC, respectively. Emissions from North America account for 15% and 10% POA burden over NW Europe and SW Europe, respectively. Emissions from RBU explain 12% and 19% of POA burden over E. Europe and GTC, respectively. Since near-surface aerosol concentrations directly affect air quality and column burden is more relevant to radiative impact, the differences of

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relative contributions between near-surface concentrations and column burden highlight the possible roles of non-local emissions in either air quality or energy balance over Europe.

5. Source Apportionment of Long-term Trends

Total sulfate-BC-POA concentrations decreased during 1980–2018 over all of the four sub-regions of Europe (Figure 7), since that near-surface aerosol concentrations in Europe are dominated by its local emissions and the European anthropogenic emissions have significantly decreased during this time period. Averaged over the entire Europe, near-surface concentrations of sulfate, BC and POA decreased by 70%, 43% and 23%, respectively, between 1980–1984 and 2014–2018, which is consistent with the decreases in local emissions (Table 1). The total sulfate-BC-POA concentrations decreased by 62%. With SOA included, this value does not have a substantial change (from 62% to 59%) and the decreasing trends in the four sub-regions of the Europe are not largely affected either. The column burden of sulfate, BC, POA and the sum of these three decreased by 60%, 28%, 4% and 55%, respectively, which is less than the decrease in corresponding near-surface concentration. It is because non-local emissions have larger influences at high altitudes than at the surface, which partly dampened the contribution of near-surface aerosol decrease (induced by reductions in location emissions) to the column integration.

The decrease in European local emissions explains 93% of the reduced concentration and 91% of the reduced burden in Europe between the first and last

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five-year period of 1980–2018, while 8%–9% is contributed by the reduction in emissions from RBU (Table 2). The decrease in emissions from North America also explains 10% of the reduced column burden of sulfate-BC-POA in Europe from 1980–1984 to 2014–2018. Along with the decreases in local emission contributions to near-surface sulfate-BC-POA concentrations in Europe, the fraction of non-European emission contributions increased from 10%–30% to 30%–50% during 1980–2018 (Figure 7), indicating that aerosols from foreign emissions through long-range transport have become increasingly important to air quality in Europe. Regulations for further improvement of air quality in Europe in the near future need to take changes in non-European emissions into account.

Similar to the declining trend in column burden, simulated total AOD also decreased from 0.12–0.16 to 0.06–0.08 in NW Europe and SW Europe and from 0.19–0.21 to 0.09–0.13 in E. Europe and GTC region during the past four decades (Figure 8). Sulfate AOD accounts for the largest portion of total combustion AOD (sum of sulfate, BC, POA and SOA) over the four sub-regions of Europe. The combustion AOD has decreased by 0.065 from 1980–1984 to 2014–2018 (Table 1), with 0.059 (91%) contributed by the decrease in sulfate AOD. Therefore, we focus on sulfate aerosol when examining the decadal changes in AOD and DRF in Europe below.

The decreased sulfate AOD can also be decomposed into different contributions from individual source regions in CAM5-EAST. European local emissions contribute to 89% of the decrease, followed by 9% and 7% attributed to changes in emissions

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from RBU and North America, respectively, with the residual offset by other source regions (Table 2). Over the last four decades, model simulated sulfate AOD decreased at a rate of 0.017, 0.017, 0.026 and 0.012 decade^{-1}, respectively, over NW Europe, SW Europe, E. Europe and GTC. Decreases in European local SO_2 emissions result in 78% of the sulfate AOD decreases over GTC and about 90% over the other three sub-regions (Figure 9). For the remote sources, emission changes in North America explain 5%–10% of the European sulfate AOD decrease, while RBU sources contribute 29% of the sulfate AOD decrease over GTC and 6%–8% over NW Europe and E. Europe, indicating a possible warming enhancement effect of changes in emissions from North America and RBU.

Averaged over 1980–2018, sulfate imposed a cooling effect over Europe with the maximum negative DRF at the top of the atmosphere (TOA) exceeding –3 W m^{-2} in E. Europe (Figure 10). Compared to 1980–1984, the magnitude of sulfate DRF decreased in 2014–2018, leading to a 1–3 W m^{-2} warming mainly in E. Europe. The warming effect mostly came from local SO_2 emission reduction, while non-European emission changes only contributed less than 0.4 W m^{-2} over most regions of the Europe. Considering Europe as a whole, the decrease in sulfate DRF caused a warming effect of 2.0 W m^{-2}, with 88% and 12% coming from reductions European local emissions and changes in non-European emissions, respectively (Tables 1 and 2).

Future changes in sulfate DRF associated with European and non-European emissions based on eight SSP scenarios are also estimated and shown in Figure 11.

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Sulfate DRF contributed by both European and non-European emissions would decrease in the near future but has large variabilities between different SSPs. The sulfate DRF (cooling) over Europe contributed from European local emissions shows a decrease from -0.48 W m^{-2} in year 2015 to -0.18 (-0.08 ~ -0.33) W m^{-2} in year 2030 and -0.14 (-0.05 ~ -0.29) W m^{-2} in year 2050. Unlike their contributions to the historical (1980–2018) change, non-European emissions have an increasingly significant impact on the future sulfate DRF changes in Europe. The contributions of non-European emissions decrease from -0.68 W m^{-2} in year 2015 to -0.39 (-0.13 ~ -0.64) W m^{-2} in year 2030 and -0.26 (-0.08 ~ -0.63) W m^{-2} in year 2050, with the changes in a magnitude similar to that of European local emissions. It suggests that future changes in non-European emissions are as important as European emissions to radiative balance and associated regional climate change in Europe.

6. Conclusions

Using a global aerosol-climate model with an explicit aerosol source tagging technique (CAM5-EAST), we examine the long-term trends and source apportionment of aerosols in Europe over 1980-2018 from sixteen source regions covering the globe in this study. CAM5-EAST can well capture the spatial distribution and temporal variation of aerosol species in Europe during this time period, although it underestimates $PM_{2.5}$ concentration and total AOD due in part to the lack of representation of nitrate and ammonium aerosols in the model.

Averaged over 2010–2018, European emissions account for 54%–68%, 78%–95% and 58%–78% of near-surface sulfate, BC, and POA concentrations over

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Europe, respectively. RBU emissions explain 10% of sulfate in E. Europe and GTC. North Africa contributes to 17% of BC and 24% of POA over SW Europe. Anthropogenic emissions over oceans (e.g., from international shipping) and natural emissions from marine and volcanic activities together account for 16%–28% of sulfate near-surface concentrations in Europe. European emissions only account for 32%–47%, 57%–75% and 51%–71% of column burden of sulfate, BC and POA, respectively, in Europe, with the rest contributed by emissions from East Asia, RBU, North Africa and North America.

Compared to 1980–1984, simulated total sulfate-BC-POA near-surface concentration and column burden over 2014–2018 had a decrease of 62% and 55%, respectively, the majority of which was contributed by reductions in European local emissions. The decrease in emissions from RBU contributed 8%–9% of the near-surface concentration decrease, while the decrease in emissions from North America accounted for 10% of the reduced column burden. With the large decrease in local emission contribution, aerosols from foreign sources became increasingly important to air quality in Europe. The decrease in sulfate led to a 2.0 W m^{-2} warming in Europe, with 12% coming from changes in non-European emissions, especially in North America and RBU. Based on the SSP scenarios and the assumed relationship between DRF and emissions, we estimated that sulfate DRF over Europe contributed from European emissions and non-European emissions would decrease at a comparable rate in the near future. This suggests that future changes in non-European emissions are as important as European emissions in affecting regional

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climate change associated with aerosols in Europe. It should also be noted that the model currently does not have the ability to simulate nitrate and ammonium aerosols and, therefore, the conclusions may not hold with all aerosols.

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Data availability.

The default CAM5 model is publicly available at http://www.cesm.ucar.edu/models/cesm1.2/ (last access: 16 August 2019). Our CAM5-EAST model code and results can be made available through the National Energy Research Scientific Computing Center (NERSC) servers upon request.

Competing interests.

The authors declare that they have no conflict of interest.

Author contribution.

YY, SL, and HW designed the research; YY performed the model simulations; YY, and SL analyzed the data. All the authors discussed the results and wrote the paper.

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Table 1. Annual emissions (Tg yr^{-1}), concentrations (μg m^{-3}), column burden (mg m^{-2}), AOD (scaled up by a factor of 100) and DRF (W m^{-2}) of Sulfate, BC, POA, SBP (sulfate-BC-POA) and $PM_{2.5}$ (sulfate-BC-POA-SOA) in Europe averaged over 1980–1984 and 2014–2018, as well as the differences between 1980–1984 and 2014–2018. Differences in percentage relative to mean values in 1980–1984 are presented in parentheses.

		Emis.	Conc.	Burden	AOD*100	DRF
Sulfate	1980–1984	15.10	6.00	14.35	9.13	-3.27
	2014–2018	2.53	1.80	5.79	3.24	-1.24
	Δ	-12.57 (-83.2)	-4.20 (-70.0)	-8.55 (-59.6)	-5.89 (-64.6)	2.04 (-62.2)
BC	1980–1984	0.47	0.4	0.38	0.7	--
	2014–2018	0.25	0.23	0.28	0.5	--
	Δ	-0.22 (-45.8)	-0.17 (-43.0)	-0.11 (-27.6)	-0.21 (-29.2)	--
POA	1980–1984	1.24	1.12	1.12	0.63	--
	2014–2018	0.94	0.86	1.08	0.58	--
	Δ	-0.30 (-24.4)	-0.26 (-23.2)	-0.04 (-3.8)	-0.05 (-7.5)	--
Sulfate-BC-POA	1980–1984	--	7.52	15.85	10.46	--
	2014–2018	--	2.89	7.15	4.32	--
	Δ	--	-4.63 (-61.6)	-8.70 (-54.9)	-6.15 (-58.7)	--
$PM_{2.5}$	1980–1984	--	10.48	19.58	11.92	--
	2014–2018	--	4.34	8.55	5.44	--
	Δ	--	-6.14 (-58.6)	-11.03 (-56.3)	-6.48 (-54.37)	--

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Table 2. Relative contributions (%) of emissions from major source regions to the changes in near-surface concentrations, column burden, AOD and DRF in Europe between 1980–1984 and 2014–2018.

	Sulfate-BC-POA			
	Δ Conc.	Δ Burden	Δ AOD	
EUR	92.8	91.2	91.2	
NAM	1.8	10.0	6.5	
NAF	-1.0	-1.5	-1.6	
MDE	-0.9	-1.9	-1.5	
EAS	-0.3	-3.1	-1.7	
RBU	8.0	9.2	8.5	
OTH	-0.1	-4.2	-2.0	
OCN	-0.3	0.2	0.6	
	Sulfate			
	Δ Conc.	Δ Burden	Δ AOD	Δ DRF
EUR	91.3	89.2	88.9	88.2
NAM	2.1	10.5	6.9	
NAF	-0.6	-0.9	-0.8	
MDE	-0.8	-1.7	-1.3	
EAS	-0.3	-2.8	-1.4	11.8
RBU	8.6	9.5	8.7	
OTH	-0.1	-4.0	-1.8	
OCN	-0.3	0.3	0.7	

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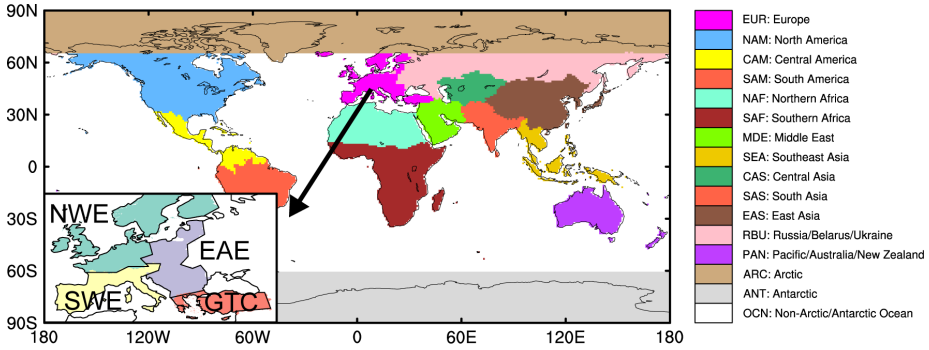

Figure 1. Source regions that are selected for the Explicit Aerosol Source Tagging (EAST) in this study, including Europe (EUR), North America (NAM), Central America (CAM), South America (SAM), North Africa (NAF), South Africa (SAF), the Middle East (MDE), Southeast Asia (SEA), Central Asia (CAS), South Asia (SAS), East Asia (EAS), Russia-Belarus-Ukraine (RBU), Pacific-Australia-New Zealand (PAN), the Arctic (ARC), Antarctic (ANT), and Non-Arctic/Antarctic Ocean (OCN). The embedded panel (at bottom left) is Europe, as the receptor region, which is further divided to Northwestern Europe (NWE), Southwestern Europe (SWE), Eastern Europe (EAE) and Greece-Turkey-Cyprus (GTC).

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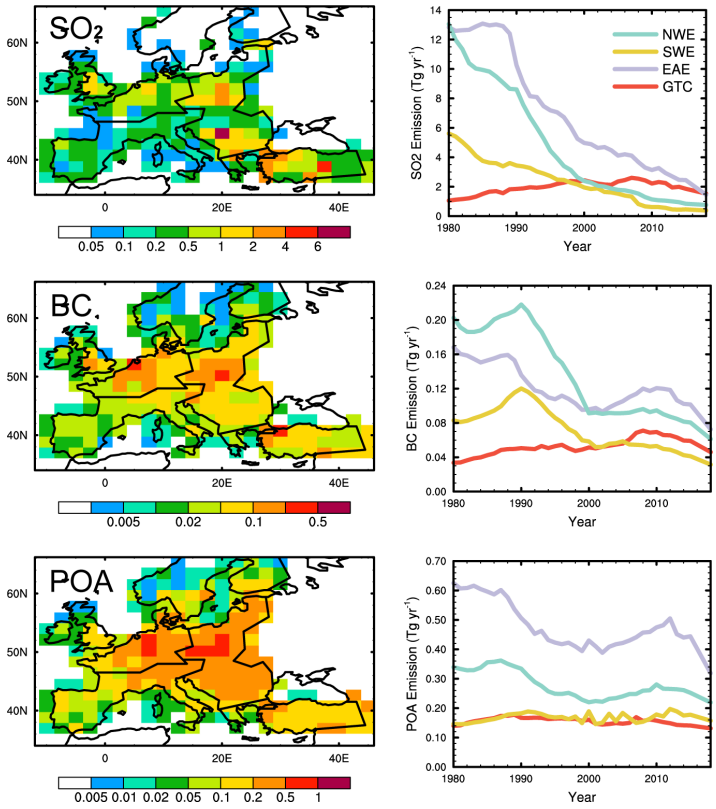

Figure 2. Spatial distribution (left) of annual mean (1980–2018) SO_2 (top), BC (middle) and POA (bottom) emissions (Tg m^{-2} yr^{-1}) over Europe. Time series (1980–2018) of annual total SO_2, BC and POA emissions (Tg yr^{-1}) from the four sub-regions of Europe.

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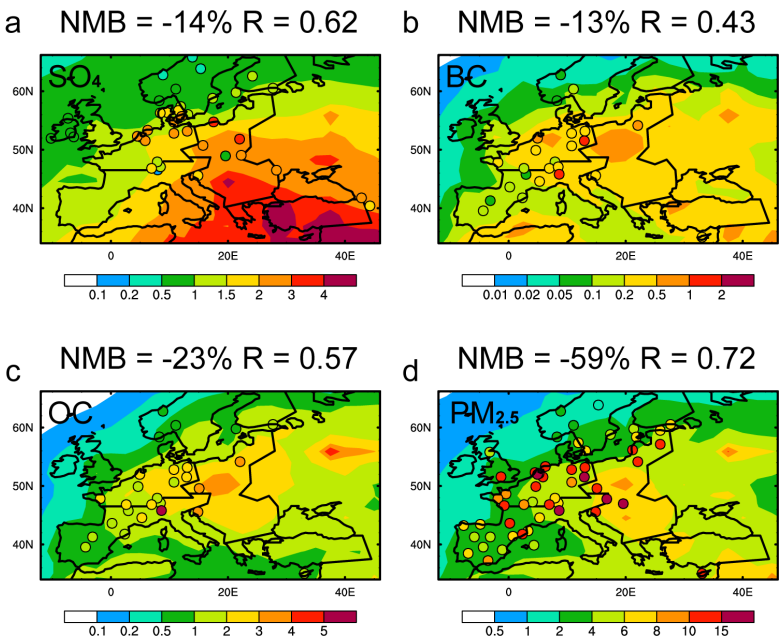

Figure 3. Spatial distribution of simulated (contour) and observed (color-filled circles) annual mean near-surface (a) sulfate, (b) BC, (c) OC (derived as (POA+SOA)/1.4 in model) and (d) $PM_{2.5}$ (sulfate+BC+POA+SOA in model) concentrations (μg m^{-3}) over 2010–2014. Observations are from EMEP (European Monitoring and Evaluation Programme) networks. Normalized mean bias (NMB = 100%× $\sum(Model_{site} - Observation_{site}) / \sum Observation_{site}$) and correlation coefficient (R) between observed and simulated concentrations are noted at the top of each panel.

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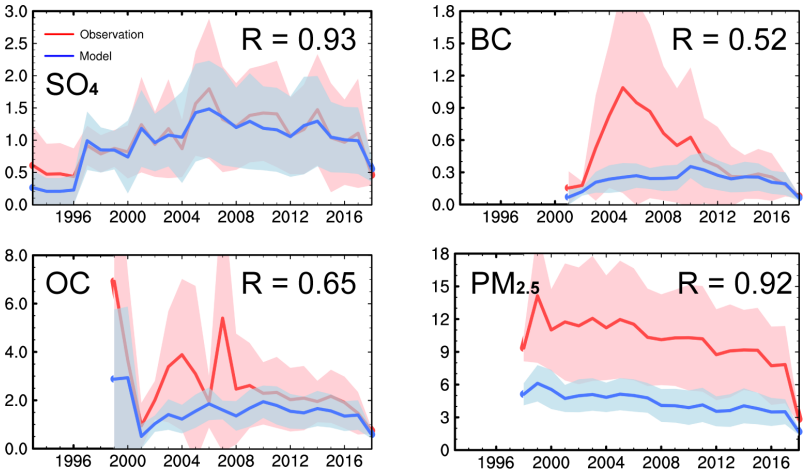

Figure 4. Time series (1993–2018) of spatial and annual mean near-surface sulfate, BC, OC and $PM_{2.5}$ concentrations (μg m^{-3}) in Europe from model simulation (blue lines) and observations (red lines). Model results are plotted only when EMEP observational data are available. Shaded areas represent 1-σ spatial standard deviation of annual mean concentrations for each year. Temporal correlation coefficients (R) between observed and simulated spatially averaged concentrations are noted on the top-right corner of each panel.

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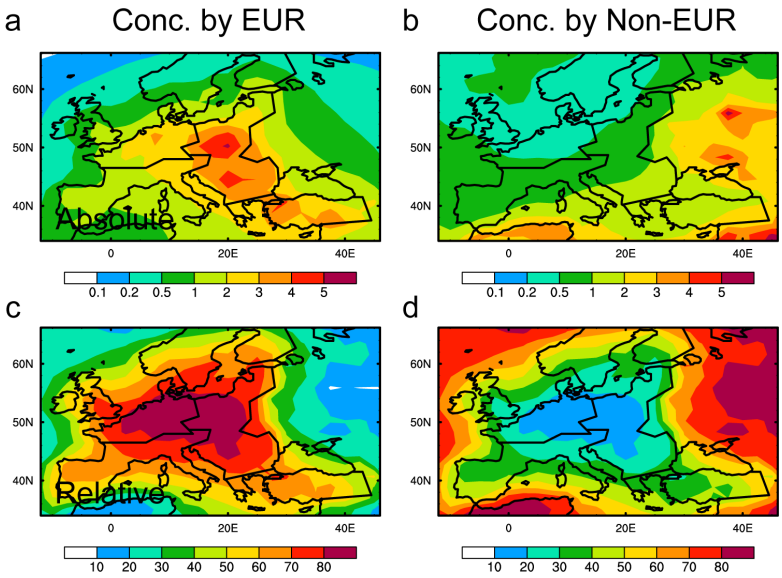

Figure 5. (a,b) Absolute (μg m^{-3}) and (c,d) relative contributions (%) to annual mean near-surface concentrations of sulfate-BC-POA from European local emissions and emissions outside the Europe, respectively, averaged over 2010–2018.

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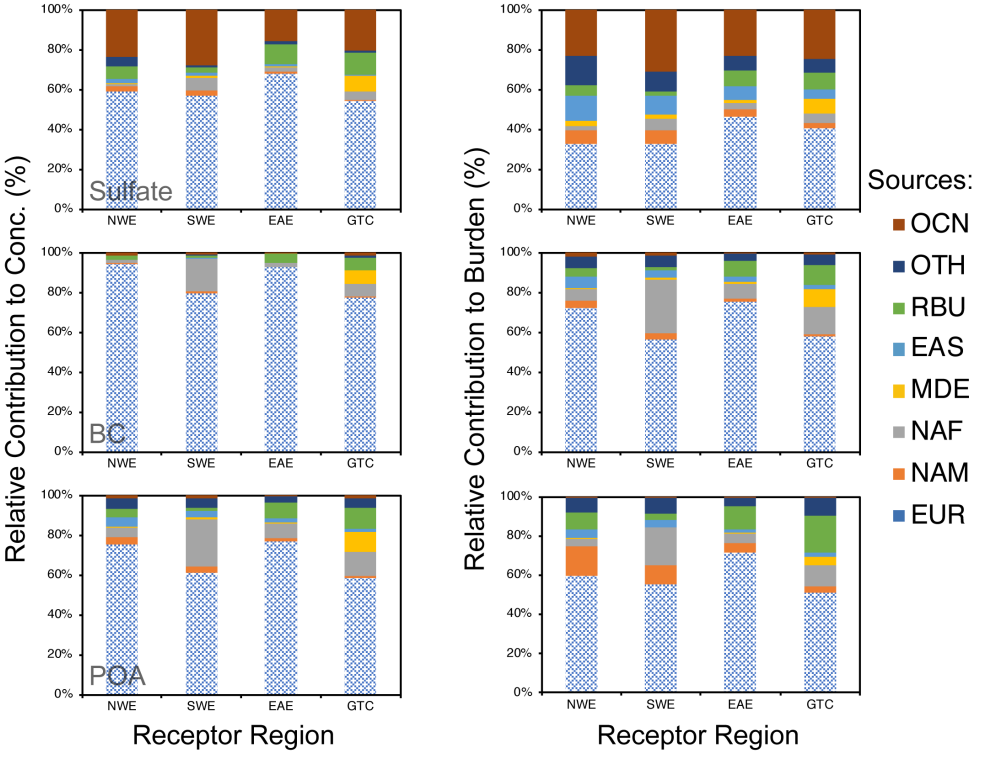

Figure 6. Relative contributions (%) by emissions from major tagged source regions (EUR, NAM, NAF,MDE, EAS, RBU, OCN) and other regions (OTH=CAM+SAM+SAF+SEA+CAS+SAS+PAN+ARC+ANT) to near-surface concentrations (left) and column burdens (right) of sulfate, BC and POA (from top to bottom) in the four sub-regions of Europe averaged over 2010–2018. Patterned areas represent EUR local contributions.

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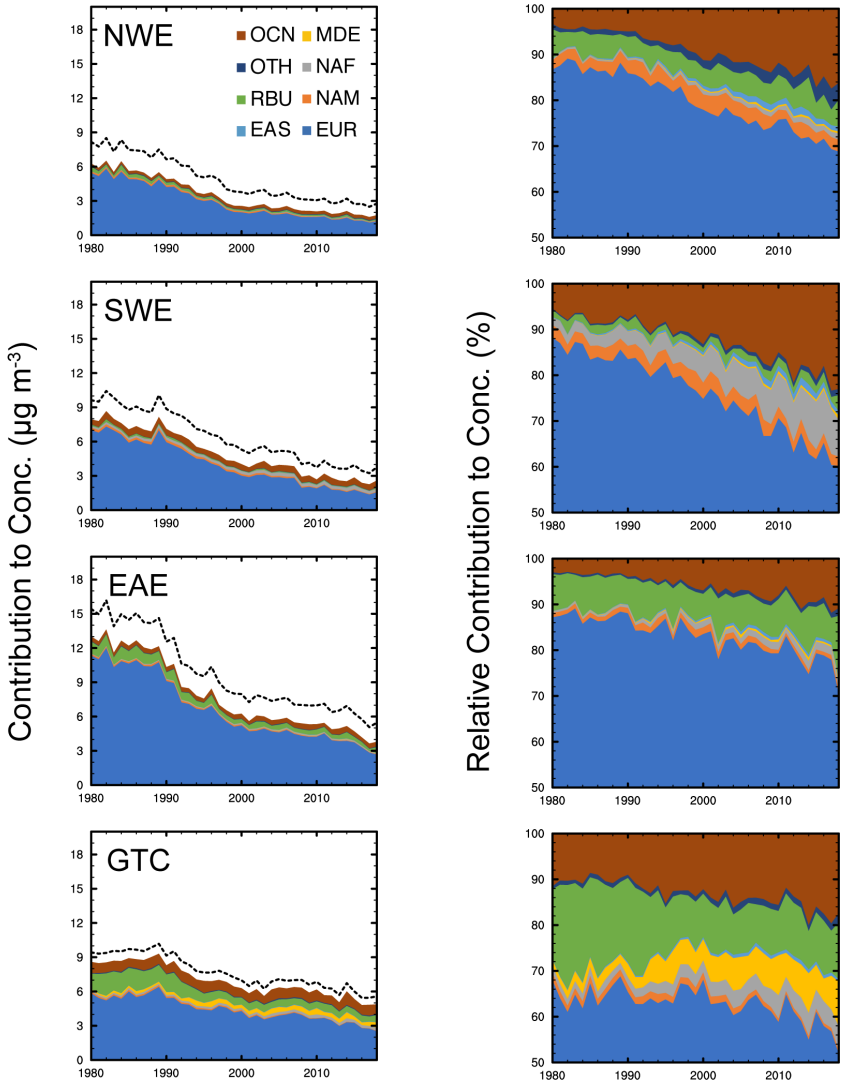

Figure 7. Time series (1980–2018) of absolute (left, μg m^{-3}) and relative (right, %) contributions of emissions from major source regions to the simulated annual mean near-surface sulfate-BC-POA concentrations averaged over the four sub-regions of Europe. Dashed lines in left panels represent simulated aerosol concentrations including SOA.

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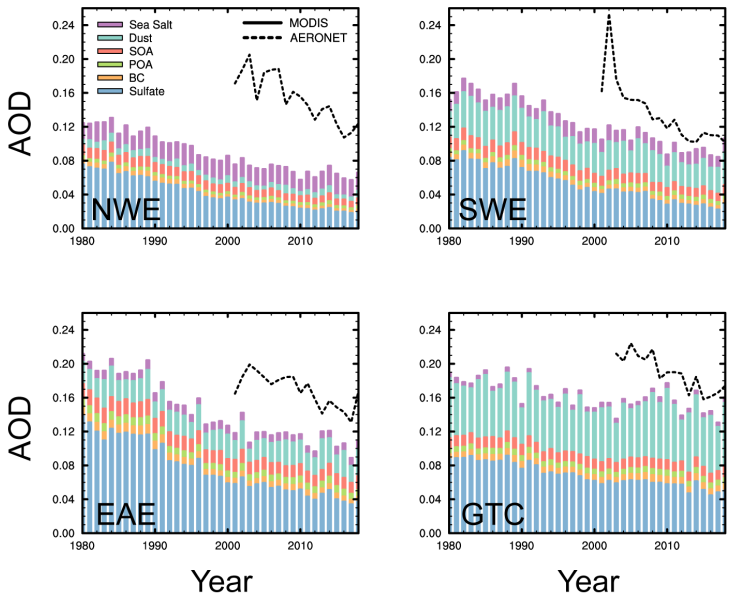

Figure 8. Time series (1980–2018) of simulated annual mean AOD for sulfate, BC, POA, SOA, dust and sea salt averaged over the four sub-regions of Europe. Dashed lines represent AOD from AERONET measurements.

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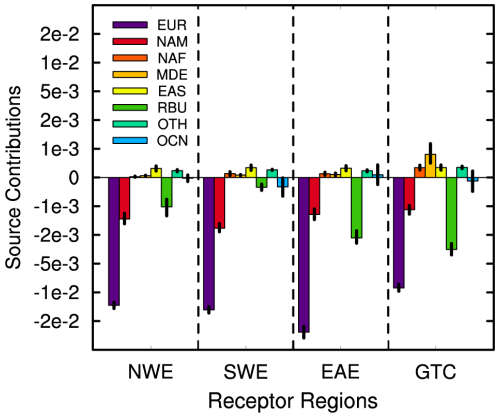

Figure 9. Absolute contributions (decade^{-1}) of the emissions from major source regions to the trends of sulfate AOD over the four sub-regions of Europe. Error bars represent 95% confidence intervals of the linear regression.

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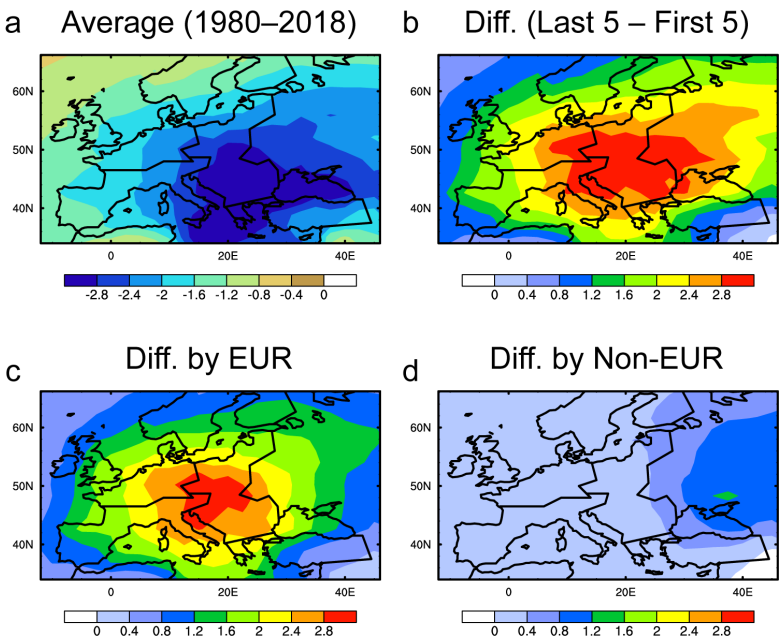

Figure 10. (a) Simulated annual mean DRF (W m^{-2}) of sulfate averaged over 1980–2018 and (b) the difference in sulfate DRF between 1980–1984 and 2014–2018. The contributions of European and non-European emissions to the difference are given in (c) and (d), respectively.

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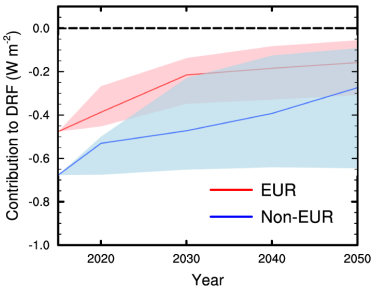

Figure 11. Time series (2015–2050) of estimated annual mean sulfate DRF over Europe contributed by European and non-European emissions. Lines and areas represent median values and minimum-to-maximum ranges of the estimated sulfate DRF from eight SSP scenarios, including SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, SSP5-3.4, and SSP5-8.5. Future DRF of sulfate aerosol over Europe is estimated by scaling historical mean (1980–2018) sulfate DRF using the ratio of SSPs future SO_2 emissions to historical emissions assuming a linear response of DRF to regional emissions.