Aerosol Science and Engineering
https://doi.org/10.1007/s41810-025-00296-2

ORIGINAL PAPER

Impact of Sulphate Aerosols from Human Production and Consumption Activities in Different Regions on the Climate of Asia

Chunjiang Zhou[1] · Gang Huang[2,3] · Su Wang[2] · Ruiqing Li[1] · Min Zhang[1] · Xueyi Xun[1]

Received: 29 September 2024 / Revised: 4 January 2025 / Accepted: 22 January 2025

Abstract

Aerosols of anthropogenic origin exhibit significant spatial variability, leading to localized environmental pollution and climate effects. The increasing international trade has caused extensive cross-border transfer of pollution, rendering the traditional production-based perspective insufficient for assessing the climate impacts of human activities in specific regions. In this paper, using the Earth System Model, five numerical simulation experiments are designed to simulate the impacts of anthropogenic sources of sulfate, associated with both production and consumption activities, on the climate of East and South Asia in different affluent regions. The results show that sulfate associated with consumption activities in developed countries has a greater impact on climate than production activities, whereas the opposite is observed for developing countries. This is because products produced in developing countries are largely consumed by developed countries.

Keywords Sulfate aerosols · Aerosol climate effects · Earth system models · Consumer responsibility principles

1 Introduction

Sulfate aerosol is one of the main types of secondary inorganic aerosols generated by human activities, and its precursor sulfur dioxide (SO_2) is mainly generated by the combustion of industrial energy sources such as coal and petroleum, so sulfate emissions are large in quantity and closely linked to human activities. As an unavoidable concomitant product of fossil energy combustion, anthropogenic aerosols, such as sulfate, are becoming a hot issue considering its impact on the climate and health (Li et al. 2022; Hong et al. 2020; Bai et al. 2018). Whether it is a concomitant reduction under greenhouse gas mitigation or due to pollution control, the concentration of anthropogenic aerosols will be reduced in the future, and their cooling effect will be weakened, which will have a direct impact on the ability to achieve the temperature rise target after greenhouse gas mitigation (Persad et al. 2022; Acosta Navarro et al. 2017; Wang et al. 2023; Yang et al. 2023).

Compared with long-lived greenhouse gases, aerosol particulate matter generally has a shorter lifetime of nearly one week, so its distribution is extremely uneven in space. The rapid development of industry in Europe after the 1850s was accompanied by large increasing of pollutant emissions. With the adjustment of the economic and industrial development of each country, the global SO_2 quantity and spatial distribution also produce huge differences, Europe and North America to reduce the emissions of more than two thirds of the emissions, the Asian region emissions have risen sharply (Zhou et al. 2020). China used to be the largest emitter of SO_2, accounting for about one-third of the world's SO_2, while after strict environmental controls, it’s emissions has declined by 75% since 2007, while India's emissions have increased by 50% (Lu et al. 2011). As a result of these changes, India has now overtaken China as the world's largest emitter of SO_2 from anthropogenic sources.

As the growing demand for pollution abatement within administrative boundaries continues, emissions shifting has also become a critical issue in climate change negotiations on climate equity. The booming trade economy has led to differences in the quantity and spatial distribution of

✉ Gang Huang
hg@mail.iap.ac.cn

[1] School of Ecology and Environment, Inner Mongolia University, Hohhot, China

[2] State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China

both consumption-related and production-related pollutants in the same country/region (Zhao et al. 2015; Wiedmann and Lenzen 2018). If a region simply reduces its production emissions without changing its consumption habits, the corresponding pollutants are borne by other countries (Wang et al. 2017). It is therefore necessary to supplement consumption-based emission inventories with traditional production-based emission inventories (Moran et al. 2013).

Sulfate aerosols have long been recognized as playing an important role in global climate change. Previous scholars proposed that the anthropogenic sulfate-induced radiative forcing (of about – 1 to – 2 W/m^2) is comparable to anthropogenic greenhouse gases in intensity, but is not a simple compensation for geographic and seasonal distribution (Charlson et al. 1992; Volkamer et al. 2006).IPCC AR6 also shows that anthropogenic sources of aerosols have offset about 1 °C of GHG-induced warming since the Industrial Revolution (IPCC: Climate Change 2021). China and India, as large emitters of aerosol pollutants, are also located in the active atmospheric circulation monsoon zone of the Northern Hemisphere, so the impact of aerosols on precipitation in East and South Asia has been a key concern of researchers (Chen et al. 2016; Cowan and Cai 2011; Ganguly et al. 2012). In general, on a continental scale, aerosols can inhibit monsoon development by reducing the radiation reaching the surface and weakening the thermal difference between land and ocean; locally, the radiative effect of aerosols alters the thermodynamic stability and convective potential of the lower atmosphere, leading to lower temperatures, increased atmospheric stability, and weakened winds and atmospheric circulation; and the atmospheric thermodynamic state of cloud formation, convection, and precipitation may be affected by aerosols that act as cloud condensation nuclei or ice nuclei (Li et al. 2018, 2016). Yang et al. (2022) assessed the impact of a large reduction in CO_2 and aerosol particulate matter emissions in China during 2020 on extreme summer precipitation in that year. The simulation results show that the impact of aerosol reduction on precipitation is greater than that of greenhouse gas reduction.

These findings highlight the important role of anthropogenic aerosols on the Asian climate in the context of climate change. In this paper, we will compare the impacts of anthropogenic aerosols of different regional relevance on the climate of East and South Asia from both the production and consumption perspectives. Such a comparison will allow for a more comprehensive and correct understanding of the historical impacts of anthropogenic activities on the global climate, and provide a reference basis for the prediction of the actual effect of carbon neutrality on the regional climate impacts and the response to climate change.

2 Methods

The new version of the Earth System Model Community, CESM2 is a coupled model developed by the National Center for Atmospheric Research (NCAR) to simulate the Earth's climate system (Danabasoglu et al. 2020). The CESM model can be configured in a number of different ways from both a scientific and technical perspective. Users can configure specific model physical properties and parameter settings to change the state and resolution of individual submodels to combine various circles to meet their experimental needs, which is highly flexible. Many experiments have been conducted to evaluate the excellent simulation capability of CESM2 in the atmosphere, ocean and snow circle (Lin et al. 2019; Gettelman et al. 2019).

We conducted a coupled sea-air simulation using CESM2, where the atmospheric module is CAM6, which by default uses the Modal Aerosol Module 4 (MAM4) (Liu et al. 2016) for processing. The standard version of CAM6 has a horizontal resolution of 1.25°longitude and 0.9°latitude, is vertically divided into 32 layers, and has a mode top of 2.26 hPa (~ 40 km). By varying the emission inventory of the sulfate aerosol precursor SO_2, the response of the Asian climate to sulfate is comparatively analyzed. The experimental setup is as follows:

CTL	Global anthropogenic emissions by sources of the sulfate precursor SO_2 fixed in 2014
E_C1	Removal of anthropogenic SO_2 emissions by sources from consumption in 2014 in regions with high economic development, dominated by Europe and the United States
E_C2	Removal of anthropogenic SO_2 emissions by sources from consumption in 2014 in regions with weak economic development, dominated by China and India
E_P1	Removal of anthropogenic SO_2 emissions by sources from production in 2014 in regions with high economic development, mainly in Europe and the United States of America
E_P2	Removal of anthropogenic emissions by sources of SO_2 from production in 2014 in regions with weak economic development, mainly in China and India

SO_2 emissions for 2014 were obtained by combining the production-based CEDS CMIP6 inventory (Hoesly et al. 2018) with the widely used Global Trade Analysis Project (GTAP) input–output table (Multi-Region Input–Output table, MRIO) (Aguiar et al. 2019). The consumption-based SO_2 emission inventory calculation follows previous studies (Lin et al. 2022). Firstly, SO_2 production emission data for the year 2014 on a global scale were obtained from the CEDS CMIP6 emission inventory, which specifies the monthly emissions for 55 sectors on a 0.5°x0.5° horizontal grid. Subsequently, the production and consumption (both calculated in monetary terms) for 141 countries/regions and 57 sectors were calculated based on the 2014 GTAP v10 version MRIO table. The production of each country/region and sector must supply the direct and indirect consumption of all regions and sectors. GTAP provides quantitative information on the connections between sectors and regions along the global supply chain. The correspondence from the 55 sectors in CEDS to the 57 sectors in GTAP was conducted according to Lin et al. (2022). Then, the SO_2 emission intensity for countries and sectors (emissions divided by monetary economic output) was calculated based on the SO_2 production emission inventory and production data. Further, the SO_2 emission data associated with the consumption of individual countries/regions and sectors were calculated by multiplying the sectoral emission intensities with the consumption-related sectoral output. In each country, the spatial and monthly distribution of consumption-related emission data corresponds to the distribution of emission data related to the corresponding production activities.

Before running these five experiments, we perform an additional 300-year pre-simulation Pre_run from the initial 2000 climate state defaulted by the CESM2 fully-coupled present-day simulation (SST, sea ice, and all anthropogenic pollutant emission inventories including SO_2 are fixed to the year 2000). The CTL case then starts with the climate state in the 300th year of the Pre_run and continues for an additional 405 years. Ec1, Ec2, Ep1, and Ep2 each branch off from the CTL in the year 201 for simulation, using the processed sulfur dioxide emission inventory files under different production and consumption scenarios to drive the model. The model runs for 100 years, and data from the last 80 years are used for analysis. Subtract the results of Ec1, Ec2, Ep1, and Ep2 from the CTL results to obtain the concentration differences of sulfate aerosols under different scenarios and their impact on local climate (Figs. 1–8).

3 Results

3.1 Distribution of Sulfate Aerosol Concentration from Anthropogenic Sources Related to Consumption and Production

The spatial distribution of sulfate concentration and its contribution to the optical thickness change (AOD) in the 550 nm, caused by less developed countries and rich countries respectively under the production and consumption perspectives in East Asia and South Asia in 2014, are shown in Figs. 1 and 2.

Under the traditional production perspective, the developing countries, primarily China and India, emit a considerable amount of sulfate aerosols locally (regional average of 117.00 $\mu g/m^2$ and maximum value of 458.96 $\mu g/m^2$). In contrast, the production activities of the developed countries produce less pollutants in these regions (regional average of 12.09 $\mu g/m^2$ and maximum value of 57.97 $\mu g/m^2$). Under the consumption perspective, the developing countries caused a decrease in pollutant emissions (regional average 92.59 $\mu g/m^2$, maximum 393.68 $\mu g/m^2$), especially in East Asia, where consumption-related (regional average 82.97 $\mu g/m^2$) sulfate concentrations produced a significant decrease compared to production-related (regional average 109.23 $\mu g/m^2$). Developed countries, on the other hand, induced an increase in pollutant concentrations in East and South Asia (regional average 35.21 $\mu g/m^2$, maximum value 130.55 $\mu g/m^2$). In terms of average values, the concentration of sulphate aerosols induced by developing countries in East and South Asia was 9.8 times higher than that induced by richer countries in terms of production, and the gap narrowed to 2.6 times in terms of consumption.

Although influenced by other aerosols, such as sand and dust, the changes in AOD in Fig. 2 similarly support the distribution of sulfate concentrations associated with rich versus less developed countries from both perspectives: the changes in AOD due to consumption-related sulfate in developing countries are smaller than the effects of production activities (both in terms of mean values and spatial distribution), and are most pronounced in the regions of China and India. The impact of consumption scenarios in rich countries on AOD in East and South Asia is much larger than that of production scenarios, with a difference of about 2.7 times the regional mean.

3.2 Impacts of Consumption and Production-Related Anthropogenic Sources of Sulfate Aerosols on the Asian Monsoon

The final temperature response exhibits a high degree of nonlinearity due to the complex interactions between the atmospheric and oceanic systems (Westervelt et al. 2020). Figure 3 shows the impact of sulfate associated with production and consumption activities in developing and rich countries on the temperature in East and South Asia in 2014. The cooling effect due to production-related sulfates in developing countries (cooling maximum of – 0.93 K) is stronger than the effect of their consumption-related sulfates, with regional average cooling of – 0.38 K vs – 0.30 K. The cooling effect due to production-related

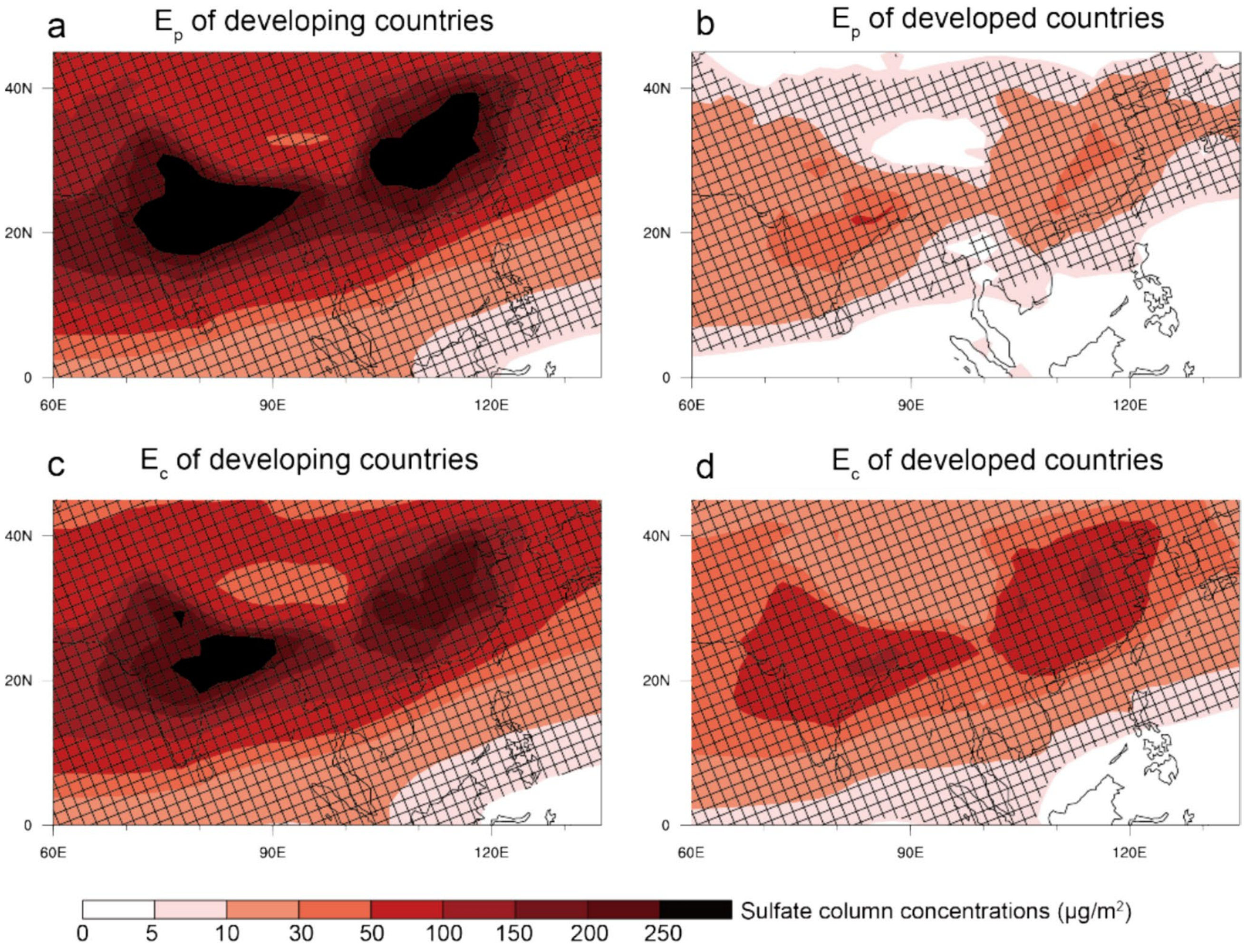

Fig. 1 Distribution of production-related(top) and consumption-related(bottom) sulfate concentrations in developing countries (left) versus developed countries (right). The grid cells with cross lines pass the paired z test at 95% CI. Unit: μg/m^2

sulfates in rich countries is slightly weaker than the cooling effect due to their consumption-related sulfates (− 0.15 K vs − 0.21 K).

Despite the influence cloud uncertainty, the radiative response and temperature changes are both consistent with the perturbation of sulfate concentration. Figure 4a and c show that sulfate emitted by developing countries under both scenarios creates a distinct band of radiative reduction in East and South Asia, with the most pronounced reductions occurring in East Asia. In terms of quantities, the regional average radiative forcing reduction is 1.42 W/m^2 under the production scenario and 1.01 W/m^2 under the consumption scenario. Under the production scenario, sulfate associated with production in the rich countries does not form a large radiatively reduced zone in East and South Asia, only shows radiative reductions in southeastern China and India. However, in the consumption scenario, sulphate associated with rich countries also forms a stable radiatively reduced zone in the region.

Precipitation changes are a comprehensive manifestation influenced by multiple factors such as surface evaporation, atmospheric circulation, humidity, and clouds, among which the change in surface temperature affecting surface evaporation is an important link. Therefore, to a certain extent, the results of aerosol concentration, temperature changes, and precipitation changes are consistent, but the feedback of precipitation on changes in aerosol concentration is highly nonlinear (Stier et al. 2024; Lau and Kim 2006). Generally speaking, there is a negative correlation between aerosol concentration and precipitation. Aerosols affect radiation, causing atmospheric cooling and reducing the energy available for the development of convection, leading to weakened upward motion. At the same time, an increase in aerosol concentration may reduce the effective radius of cloud droplets, causing precipitation to be delayed or suppressed. Figure 5 shows the precipitation response in East Asia and South Asia caused by sulfate aerosols in less developed and wealthy countries under two scenarios. In the

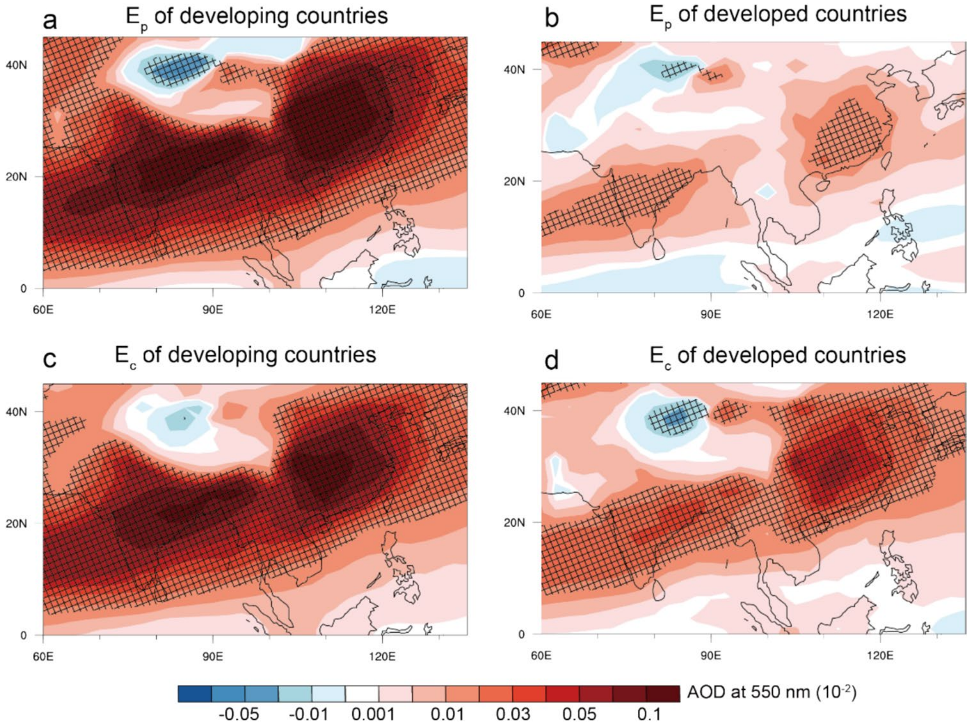

Fig. 2 Distribution of production-related(top) and consumption-related(bottom) AOD in developing countries (left) versus developed countries (right). AOD includes the effect of all aerosol compositions. The grid cells with cross lines pass the paired z test at 95% CI

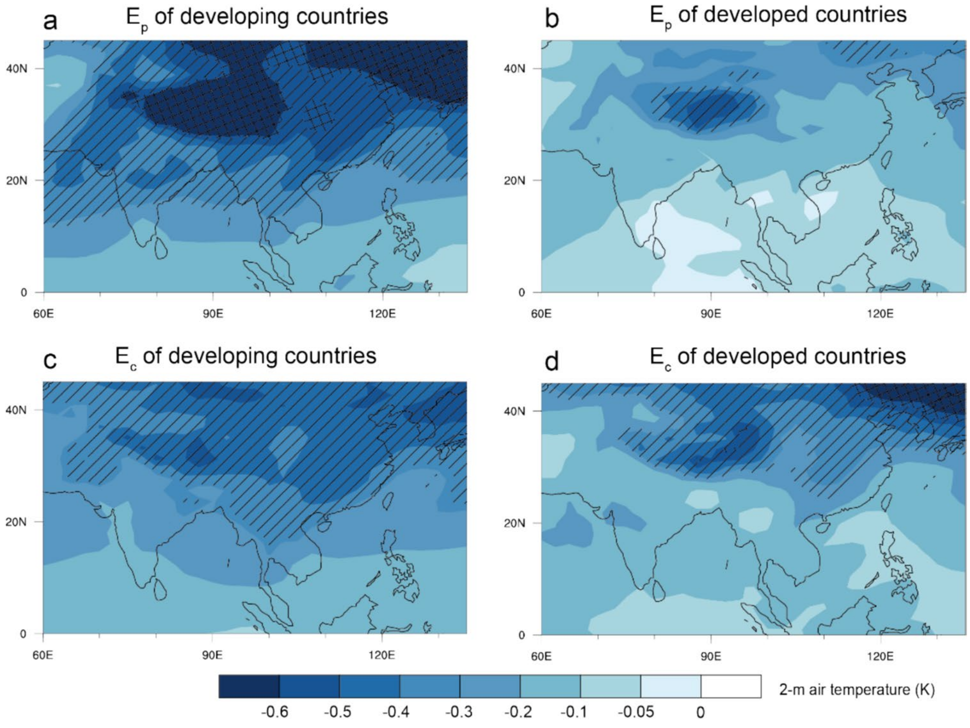

Fig. 3 Global temperature impact of SO2 associated with production(top) and consumption(bottom) activities in developing (left) and developed (right) countries. The grid cells with cross lines pass the paired z test at 95% CI, and those with diagonal lines pass the test at 68% CI. Unit: K

production scenario, the reduction in regional precipitation caused by sulfates associated with less developed countries (-0.19 mm/day) is significantly greater than the impact of wealthy countries (0.009 mm/day), with the latter hardly causing any reduction in Asian monsoon precipitation. In the consumption scenario, the impact of pollutants associated with less developed countries on precipitation decreases (-0.13 mm/day), while the impact of wealthy countries on

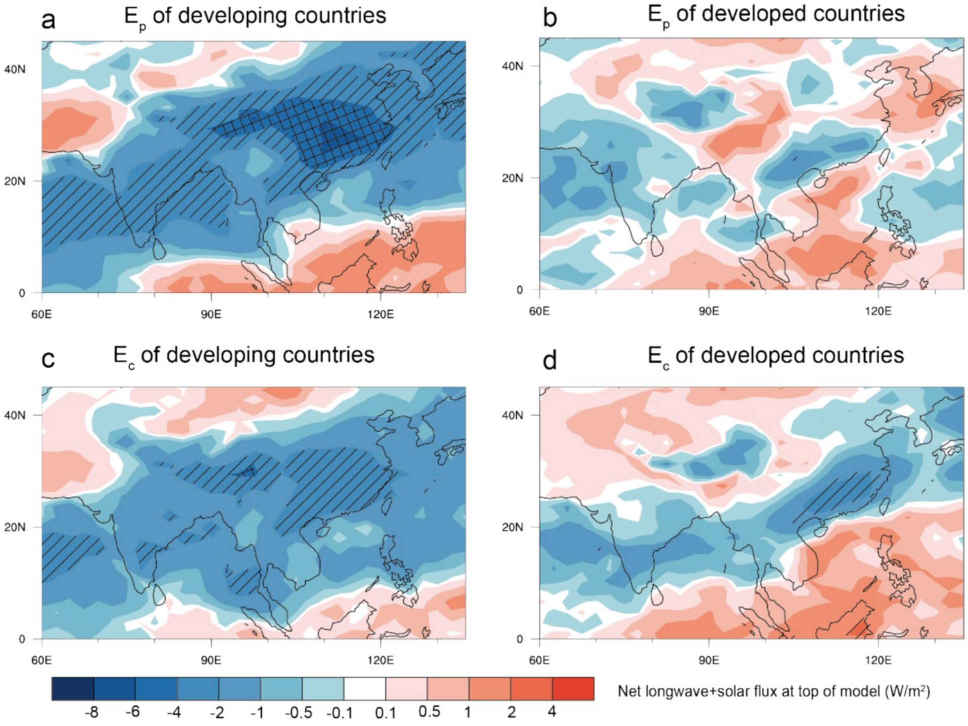

Fig. 4 Changes in production-related (a,b) and consumption-related(c,d) top-of-atmosphere radiative fluxes due to sulfate in developing (left) and developed countries (right). The grid cells with cross lines pass the paired z test at 95% CI, and those with diagonal lines pass the test at 68% CI. Unit: W/m^2

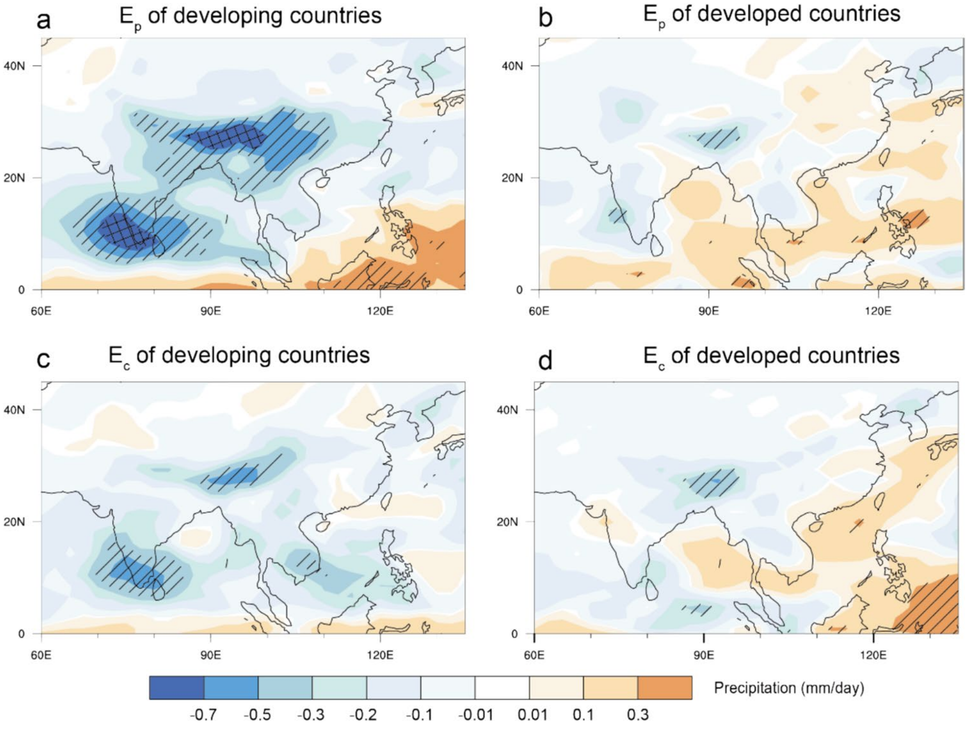

Fig. 5 Global precipitation impact of SO2 associated with production(top) and consumption(bottom) activities in developing (left) and developed (right) countries. The grid cells with cross lines pass the paired z test at 95% CI, and those with diagonal lines pass the test at 68% CI. Unit: mm/day

precipitation increases (– 0.03 mm/day). It is worth noting that in all scenarios, there is an increase in precipitation over the ocean to varying degrees, which is related to the adjustment of tropical circulation.

3.3 Impact of Anthropogenic Sulfate Aerosols on Atmospheric Circulation

The advection and vertical motion of the atmosphere are determined by circulation, which is driven by solar radiation. Changes in sulfate aerosol concentration can affect the Earth's surface radiation balance. After the heat source changes, the intensity of high and low-pressure systems on the ground will adjust accordingly, affecting the pressure gradient force between the ocean and land, which in turn affects wind direction and speed. The increase in sulfate aerosol concentration in East Asia and South Asia leads to a reduction in solar radiation reaching the ground, while the radiative cooling effect of anthropogenic sulfate aerosols in the Southern Hemisphere is weaker, leading to an energy imbalance between the Northern and Southern Hemispheres. In the tropics, the upward branch of the Northern Hemisphere Hadley circulation weakens, while the Southern Hemisphere Hadley circulation strengthens. Correspondingly, the Intertropical Convergence Zone (ITCZ) shifts towards the Southern Hemisphere, increasing oceanic precipitation and presenting the phenomenon of "warmer places being wetter." (Xie et al. 2013; Hwang et al. 2013).

Figure 6 illustrates the changes in atmospheric vertical motion following perturbations in sulfate aerosol concentration. As shown, the subsidence motion in the region of 0 ~ 30°N is significantly enhanced, corresponding to an increase in surface pressure and a strengthening of the anticyclonic circulation in the lower troposphere (Fig. 7). Concurrently, the surface moisture flux along the coasts of East Asia and South Asia weakens, leading to reduced precipitation. The decrease in precipitation results in a reduction of condensation latent heat (Fig. 8), cooling the air above the continents and similarly reducing the land-sea thermal contrast, which in turn weakens the East Asian summer monsoon, forming a positive feedback loop. This feedback mechanism is most pronounced in scenarios of production in less developed countries, where the enhancement of subsidence motion in the 0 ~ 20°N range is very evident and the most extensive (Fig. 6a). Additionally, the

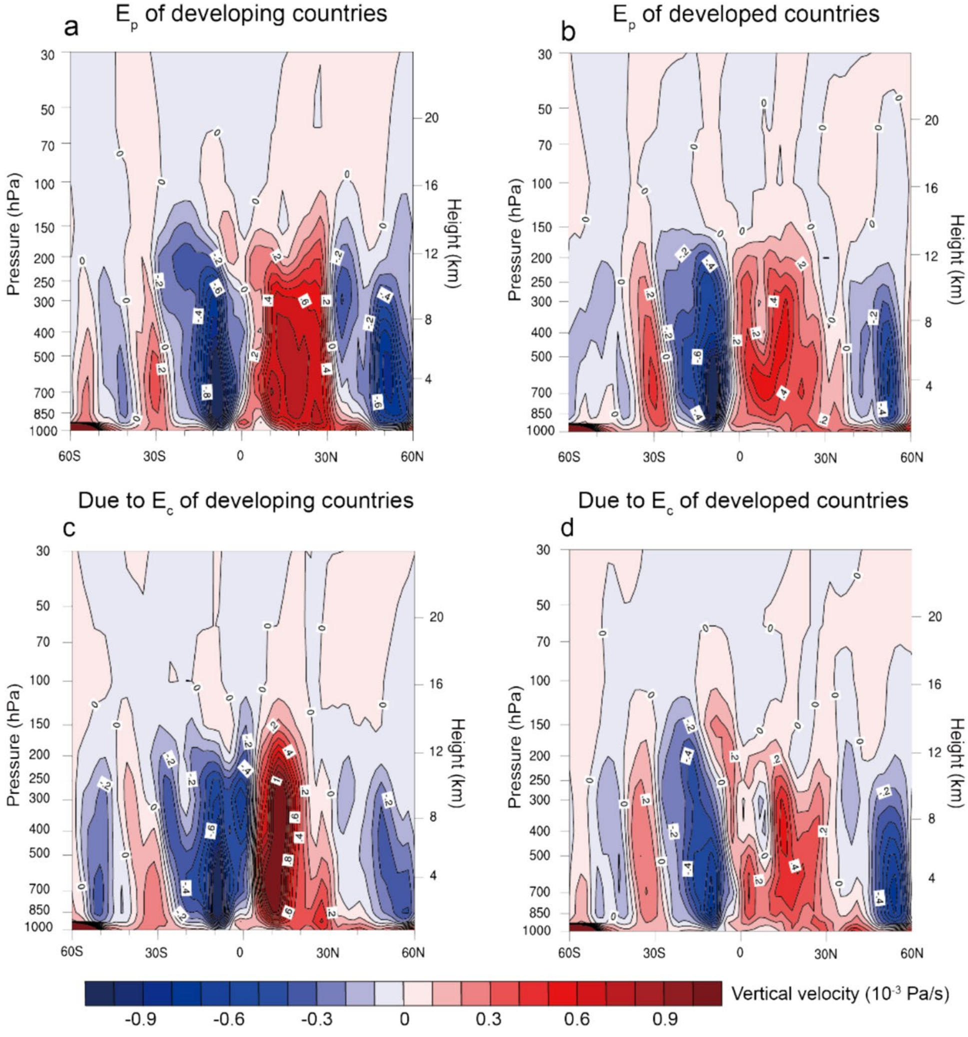

Fig. 6 Meridional circulation response to production-based(top) and consumption-based(bottom) emissions. Zonal average changes in vertical velocity ($\omega = dp/dt$) due to developing (left) and developed (right) countries. Negative values represent rising air. Unit:10^{-3} Pa/s

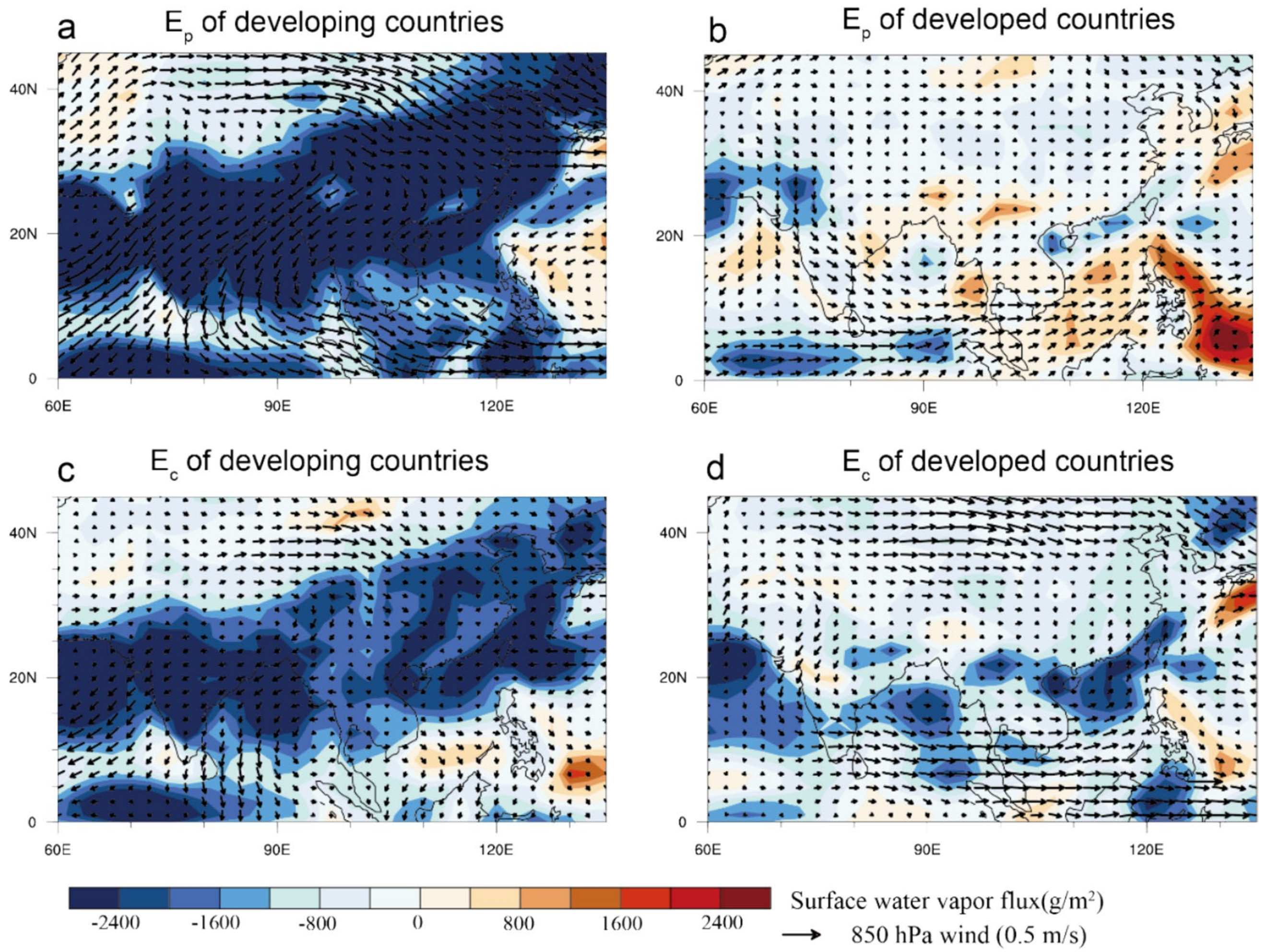

Fig. 7 Changes in surface water flux (the color-coded graph, Unit: g/m^2) and 850 hPa wind field after perturbation of production-related(top) and consumption-related(bottom) sulfate concentration in developing countries (left) and developed countries (right). The arrow shows the change in wind field. Unit: m/s

Hadley circulation in the Southern Hemisphere is strengthened, with a very noticeable cross-equatorial wind from the Northern Hemisphere at 850 hPa in the Pacific region south of the equator. The impact from the consumption perspective of less developed countries is secondary. The influence of sulfate related to production and consumption in developed countries on vertical motion and surface sensible and latent heat in the equatorial region is relatively weaker and does not lead to such a strong reduction in precipitation in the Asian monsoon region.

4 Discussion

Climate action and responsible consumption and production are two closely linked United Nations Sustainable Development Goals. The development of international trade means that consumption in one region can be supplied by production from other parts of the world, thus constituting a second way of transboundary pollution transport beyond atmospheric transport. However, previous studies on the climate effects of aerosols have all been conducted from the perspective of production emissions, and there is currently no work that assesses the impact of pollutant emissions from human activities on the climate from the perspective of consumption. Analyzing the pollutant emissions related to different regions and their impact on the climate from a consumption perspective can provide new information and different insights to support policy formulation and international cooperation in mitigating climate change actions (United Nations 2019; Zhang et al. 2017; Waldhoff and Fawcett 2011).

Using the state of consumption and production activities of individual countries in 2014 as the context of today's international trade environment, we selected representatives of two groups of countries according to their economic

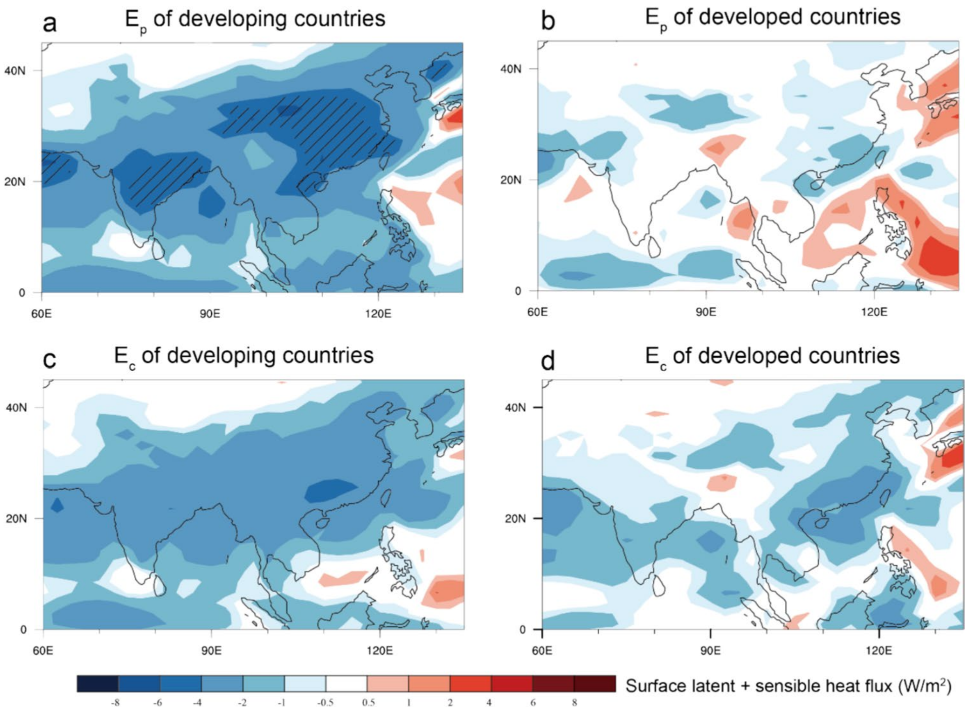

Fig. 8 Changes in surface heat flux (latent + sensible) due to production-based(top) and consumption-based(bottom) emissions of developing(left) and developed(right) countries. The grid cells with diagonal lines pass the test at 68% CI. Unit: W/m^2

affluence, and quantified the impact of anthropogenic sources of sulfate aerosols associated with production and consumption activities on the East and South Asian climate for the two groups of countries, using the latest generation of the fully coupled earth system model (CESM2).

The affluent countries have substantial sulfate emission reductions from a production perspective, resulting in minimal changes in pollutant concentrations, temperature, and precipitation in East and South Asia through atmospheric transport. Sulfate concentrations associated with their consumption activities are significantly higher in these two regions, exerting a greater impact on temperature and precipitation. In contrast, the developing countries, particularly China and India, generate large amounts of sulfate aerosols locally as a result of their extensive production activities, causing a decrease in local temperature and precipitation. However, from a consumption point of view, the local pollutant concentrations and their impact on climate are reduced to different degrees. At the same time, the simulation results show a highly nonlinear response of the climate system to the spatial pattern of aerosol forcing.

International trade is now unprecedented in scale and complexity, and in recent years the global supply chain has shifted to developing countries (Lenzen et al. 2012; Liang et al. 2017). Improvements in environmental and working conditions in developed countries are often achieved through transfers to other countries, resulting in stronger impacts from consumption activities compared with their production activities. In developing countries, although sulphate concentrations and impacts associated with consumption activities have declined to some extent compared with production activities, they remain substantial. The effectiveness of the response to climate change depends not only on the control of pollutant generation by production emission sources, but also on the reduction of pollution-related consumption of final goods and services, which requires the efforts of all.

Acknowledgements The work was supported by the Inner Mongolia Central guidance of local science and technology development funds (2022ZY0178, 2022ZY0163) awarded to Dr. Chunjiang Zhou and Dr. Min Zhang; a Special Programs for Research in First-Class Disciplines (YLXKZX-ND-049), awarded to Dr. Ruiqing Li; the National Natural Science Foundation of China (42141019, 42261144687) awarded to Dr. Gang Huang; and the Project of Creating Ordos National Sustainable Development Agenda Innovation Demonstration Zone(2022EEDSKJXM005), awarded to Dr. Xueyi Xun.

Data availability The authors declare that datasets for this research are available in the following online repository. The CESM is available at http://www.cesm.ucar.edu/models/cesm2/. All computer codes generated during this study are available from the corresponding authors upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests. All the authors admitted that they have contributed to the study.

References

Acosta Navarro JC, Ekman AML, Pausata FSR et al (2017) Future Response of Temperature and Precipitation to Reduced Aerosol

Emissions as Compared with Increased Greenhouse Gas Concentrations. J Clim 30(3):939–954. https://doi.org/10.1175/JCLI-D-16-0466.1

Aguiar A, Chepeliev M, Corong EL, McDougall R, van der Mensbrugghe D (2019) The GTAP Data Base:Version 10. J Global Econ Anal 4(1):1–27. https://doi.org/10.21642/JGEA.040101AF

Bai R, Lam JCK, Li VOK (2018) A review on health cost accounting of air pollution in China. Environ Int 120:279–294

Charlson RJ, Schwartz SE, Hales JM et al (1992) Climate forcing by anthropogenic aerosols. Science 255(5043):423–430. https://doi.org/10.1126/science.255.5043.423

Chen J-P, Chen IJ, Tsai IC (2016) Dynamic feedback of aerosol effects on the east Asian summer monsoon. J Clim 29(17):6137–6149

Cowan T, Cai W (2011) The impact of Asian and non-Asian anthropogenic aerosols on 20th century Asian summer monsoon. Geophys Res Lett 38(11):L11703

Danabasoglu G, Lamarque JF, Bacmeister J et al (2020) The community earth system model version 2 (CESM2). J Adv Model Earth Syst. 12(2):e2019MS001916. https://doi.org/10.1029/2019MS001916

Ganguly D, Rasch PJ, Wang H et al (2012) Climate response of the south Asian monsoon system to anthropogenic aerosols. J Geophys Res 117:D13209

Gettelman A, Hannay C, Bacmeister JT, Neale RB et al (2019) High climate sensitivity in the Community Earth System Model version 2 (CESM2). Geophys Res Lett 46:8329–8337. https://doi.org/10.1029/2019gl083978

Gtap v10 data base (pre-released version). [EB/OL]. (2019) https://www.gtap. agecon.purdue.edu/about/project.asp

Hoesly RM, Smith SJ, Feng L et al (2018) 2018) Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS. Geosci Model Dev 11(1):369–408. https://doi.org/10.5194/gmd-11-369-2018

Hong C, Zhang Q, Zhang Y et al (2020) Weakening aerosol direct radiative effects mitigate climate penalty on Chinese air quality. Nat Clim Chang 10:845–850. https://doi.org/10.1038/s41558-020-0840-y

Hwang Y-T, Frierson DMW, Kang SM (2013) Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century[J]. Geophys Res Lett 40(11):2845–2850

IPCC: Climate Change 2021 (2021) The Physical Science Basis. In: Masson-Delmotte, V. et al. (eds) Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Lau KM, Kim KM (2006) Observational relationships between aerosol and Asian monsoon rainfall, and circulation. Geophys Res Lett. https://doi.org/10.1029/2006GL027546

Lenzen M, Moran D, Kanemoto K et al (2012) International trade drives biodiversity threats in developing nations. Nature 486(7401):109–112

Li Z, Lau WKM, Ramanathan V et al (2016) Aerosol and monsoon climate interactions over Asia. Rev Geophys 54(4):866–929. https://doi.org/10.1002/2015RG000500

Li X, Ting M, Lee DE (2018) Fast adjustments of the Asian summer monsoon to anthropogenic aerosols. Geophys Res Lett 45(2):1001–1010. https://doi.org/10.1002/2017GL076667

Li J, Carlson BE, Yung YL et al (2022) Scattering and absorbing aerosols in the climate system. Nat Rev Earth Environ 3:363–379. https://doi.org/10.1038/s43017-022-00296-7

Liang S, Stylianou KS, Jolliet O et al (2017) Consumption-based human health impacts of primary PM2.5: The hidden burden of international trade. J Clean Prod. 167(133):139

Lin L, Gettelman A, Xu Y et al (2019) CAM6 simulation of mean and extreme precipitation over Asia: sensitivity to upgraded physical parameterizations and higher horizontal resolution. Geosci Model Dev 12(8):3773–3793. https://doi.org/10.5194/gmd-12-3773-2019

Lin J, Zhou C, Chen L et al (2022) Sulfur emissions from consumption by developed and developing countries produce comparable climate impacts. Nat Geosci 15:184–189. https://doi.org/10.1038/s41561-022-00898-2

Liu X, Ma PL, Wang H et al (2016) Description and evaluation of a new four-mode version of the Modal Aerosol Module (MAM4) within version 5.3 of the Community Atmosphere Model. Geosci. Model Dev. 9(2):505–522. https://doi.org/10.5194/gmd-9-505-2016

Lu Z, Zhang Q, Streets DG (2011) Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010. Atmos Chem Phys 11(18):9839–9864. https://doi.org/10.5194/acp-11-9839-2011

Moran DD, Lenzen M, Kanemoto K et al (2013) Does ecologically unequal exchange occur? Ecol Econ 89:177–186. https://doi.org/10.1016/j.ecolecon.2013.02.013

Persad GG, Samset BH, Wilcox LJ (2022) Aerosols must be included in climate risk assessments. Nature 611:662–664

Stier P, van den Heever SC, Christensen MW et al (2024) Multifaceted aerosol effects on precipitation. Nat Geosci 17:719–732. https://doi.org/10.1038/s41561-024-01482-6

United Nations. The sustainable development goals report[J/OL]. 2019, https://unstats.un.org/sdgs/report/2019

Volkamer R, Jimenez JL, Martini S et al (2006) Secondary organic aerosol formation from anthropogenic air pollution: Rapid and higher than expected. Geophys Res Lett 33(17):L17811. https://doi.org/10.1029/2006GL026899

Waldhoff ST, Fawcett AA (2011) Can developed economies combat dangerous anthropogenic climate change without near-term reductions from developing economies? Clim Change 107(3–4):635–641. https://doi.org/10.1007/s10584-011-0132-7

Wang H, Zhang Y, Zhao H et al (2017) Trade-driven relocation of air pollution and health impacts in China. Nat Commun 8(1):738. https://doi.org/10.1038/s41467-017-00918-5

Wang P, Yang Y, Xue D et al (2023) Aerosols overtake greenhouse gases causing a warmer climate and more weather extremes toward carbon neutrality. Nat Commun 14:7257. https://doi.org/10.1038/s41467-023-42891-2

Westervelt DM, Mascioli NR, Fiore AM et al (2020) Local and remote mean and extreme temperature response to regional aerosol emissions reductions. Atmos Chem Phys 20(5):3009–3027. https://doi.org/10.5194/acp-20-3009-2020

Wiedmann T, Lenzen M (2018) Environmental and social footprints of international trade. Nat Geosci 11(5):314–321. https://doi.org/10.1038/s41561-018-0113-9

Xie S-P, Lu B, Xiang B (2013) Similar spatial patterns of climate responses to aerosol and greenhouse gas changes. Nat Geosci 6(10):828–832. https://doi.org/10.1038/ngeo1931

Yang Y et al (2022) Abrupt emissions reductions during COVID-19 contributed to record summer rainfall in China. Nat Commun 13:959. https://doi.org/10.1038/s41467-022-28537-9

Yang Y, Zeng L, Wang H, Wang P, Liao H (2023) Climate effects of future aerosol reductions for achieving carbon neutrality in China. Sci Bull 68:S2095–S9273. https://doi.org/10.1016/j.scib.2023.03.048

Zhang Q, Jiang X, Tong D et al (2017) Transboundary health impacts of transported global air pollution and international trade. Nature 543(7647):705–709. https://doi.org/10.1038/nature21712

Zhao HY, Zhang Q, Guan DB et al (2015) Assessment of China's virtual air pollution transport embodied in trade by using a consumption-based emission inventory. Atmos Chem Phys 15(10):5443–5456. https://doi.org/10.5194/acp-15-5443-2015

Zhou C, Liu P, Huang G et al (2020) The impact of secondary inorganic aerosol emissions change on surface air temperature in the northern hemisphere. Theor Appl Climatol 141:857–868. https://doi.org/10.1007/s00704-020-03249-6