Comparable sulfate climate impacts by consumption of developed and developing countries

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Keywords: aerosols, consumption, developing and developed countries

Posted Date: July 12th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-514963/v1>

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Abstract

Regional consumption activities supported by domestic production and international trade have led to substantial amounts of aerosols worldwide, yet the resulting impacts on the global climate system remains unknown. Here we quantify for the first time the climate response to aerosols associated with consumption by developing and developed countries, by integrating a most current-generation fully coupled Earth system model, a recent multi-regional input-output table and an updated emission inventory used for climate change assessment. We find that although consumption associated sulfur dioxide emissions of developed countries are only 60% of those of developing countries, they lead to comparable impacts on the global mean surface air temperature (-0.20 ± 0.09 versus -0.18 ± 0.11 K; with 2 standard deviations) and precipitation (-0.017 ± 0.017 versus -0.019 ± 0.019 mm/day). This is because the emissions of developed countries and resulting forcing are more evenly distributed zonally and located at higher latitudes than the emissions of developing countries. Emissions of both developing and developed countries strongly cool the Northern Hemisphere and cause southward movement of the Intertropical Convergence Zone, while emissions of developing countries have stronger temperature and precipitation impacts over the tropical monsoon regions of China and India. This work serves as the first step of a comprehensive assessment of consumption associated climate impacts in support of global concerted action towards sustainable consumption and stabilized climate.

Main Text

Climate Action and Responsible Consumption and Production are two closely linked Sustainable Development Goals (SDGs) of the United Nations. Consumption activities affect the climate through greenhouse gases and aerosols associated with production to supply consumption. Raw materials extracted to meet global final consumption demands reached 92 billion metric tons in 2017 and will likely increase to 190 billion metric tons by 2060 without concerted action¹; and extraction, processing, use and disposal of these materials often lead to substantial emissions. Many emission pathways of 1.5°C warming require shifts towards sustainable consumption². As international trade allows consumption of any region to be supplied by production worldwide, this affects the magnitude and geographical pattern of consumption associated emissions³⁻⁵. Understanding the climate response to consumption associated emissions offers crucial information to support policymaking and international cooperation in climate change mitigation action from a consumption perspective.

For aerosols, which are short-lived, the spatial distribution of consumption associated emissions determines the distribution of their atmospheric loadings and thus exerts spatially inhomogeneous forcing^{6,7} to the nonlinear climate system. Emerging evidence has suggested strong nonlinearity in the climate response to the magnitude^{8,9} and location¹⁰⁻¹³ of aerosols – for example, one study suggests that a given amount of aerosol emissions released in Western Europe cause 14 times as much global average cooling as when emitted in India¹¹. These studies are solely based on idealized model experiments by scaling the emissions with an arbitrary factor or by putting the same amount of

emissions to different locations. Many studies have analyzed the climate impacts of aerosols associated with each region's own production activities and resulting (realistic) emissions¹⁴⁻¹⁷. The climate response to aerosols associated with the same region's consumption could differ substantially due to the large differences in the magnitude and spatial pattern of emissions and forcing. Yet this consumption induced climate response has never been assessed explicitly. One recent study has estimated the direct radiative forcing of aerosols embedded in trade⁶, but it does not quantify how such forcing affects temperature and precipitation.

Here we provide the first assessment of the effects of aerosols from consumption of developed and developing countries on global temperature and precipitation. We quantify the climate response to sulfate aerosol forcing due to consumption associated emissions of sulfur dioxide (SO₂) in 2014, the latest year for which all data and models are available. Identification of developing and developed countries is based on International Monetary Fund¹⁸. Our results show unexpectedly similar effects of consumption by developed and developing countries on the global average near surface air temperature and precipitation, despite the large difference in the magnitude of consumption-associated SO₂ emissions by a factor of 1.7.

Deriving climate impacts of emissions

Through an interdisciplinary framework, we employ sector-, region- and pollutant-specific anthropogenic emission data from the Community Emissions Data System (CEDS) inventory for the CMIP6 project¹⁹, use the latest Global Trade Analysis Project (GTAP) Multi-Regional Input-Output (MRIO) table (version 10 for 2014)²⁰ to estimate consumption-related emissions of SO₂, and run the fully coupled Community Earth System Model version 2 (CESM2)²¹ to simulate the climate impacts of such sulfur emissions. The widely used^{4,6,22} GTAP MRIO table offers quantitative information on the inter-sectoral and inter-regional economic linkage along the global supply chain, and tracks worldwide production activities in support of consumption of each region. The MRIO table together with the CEDS CMIP6 emission inventory allows for an estimate of consumption-based emissions. Inside the atmospheric component of CESM2, CAM6, the chemical formation of sulfate from emitted SO₂ is represented by the Modal Aerosol Model version 4 (MAM4)²³, following the CESM2 setup for submission to CMIP6.

We conduct three cases of CESM2 simulations by altering anthropogenic SO₂ emissions while keeping everything else unchanged. The reference case GLOBAL includes global anthropogenic emissions of SO₂ in 2014 (see Methods). In Xdeveloping_CE and Xdeveloped_CE, SO₂ emissions associated with consumption activities in developing and developed countries are removed, respectively. The impacts of consumption by developing and developed countries are obtained by subtracting simulation results of Xdeveloping_CE and Xdeveloped_CE from GLOBAL, respectively. Each of Xdeveloping_CE and Xdeveloped_CE contains three ensemble members with different initial conditions (Methods), and the results of these three members, temporally paired with GLOBAL, are averaged for analysis. Uncertainty

estimates for global average results are represented by 2 standard deviations (corresponding to 95% Confidence Interval (CI)), and a paired z-test for statistical significance is used to account for autocorrelation²⁴.

Consumption associated sulfur emissions and loadings

Figure 1 compares the production-based emissions (E_p) and consumption-based emissions (E_c) of SO_2 for both developed and developing countries. The E_c of a region denote worldwide emissions due to production of goods and services to supply consumption by that region. In contrast, the E_p are associated with production by that region to supply global consumption, as recorded in the CEDS CMIP6 inventory. For example, a cell phone sold in the United States may be assembled in China with steel produced in Japan and iron ore extracted in Australia, and all associated emissions are allocated to the United States from the consumption perspective but to these individual countries from the production perspective. The global total E_c of developing countries (67.7 Tg/yr) are about 1.7 times that of developed countries (39.9 Tg/yr). This is in contrast to the factor-of-5 difference in global total E_p (89.7 versus 17.8 Tg/yr). The E_c exhibit much greater spatial coverage than the E_p do, especially for the emissions of developed countries (Fig. 1).

Figure 1 further shows that the E_c of developed countries that are released in developing countries are larger than the E_c of developing countries that are released in developed countries by a factor of 7. These differences are because developed countries are net importers of goods from developing countries, and have much lower emission intensities than the latter^{6,22}. Overall, the E_c of developing countries are more concentrated in Asia low and middle latitudes, whereas the E_c of developed countries more spread out over northern latitudes. These geographical characteristics are further depicted in the zonal average and meridional average emissions in Extended Data Fig. 1. The unique features of regional E_c in magnitude and spatial pattern warrant a detailed assessment of resulting climate impacts to supplement prevailing production-based studies.

Extended Data Fig. 2a,b shows the spatial distribution of sulfate aerosol column densities associated with consumption (S_c) by developed and developing countries. Sulfate is formed in the atmosphere from emitted SO_2 and lost through dry and wet deposition. The spatial pattern of S_c largely follows the E_c due to short atmospheric lifetimes of SO_2 and sulfate, although portions of sulfate are transported from emission source regions to downwind areas³. The global average S_c of developing countries are 1.9 times the S_c of developed countries, consistent with the difference in E_c . The S_c of developing and developed countries are both large in the Northern Hemisphere (NH), but their regional patterns differ. The S_c of developing countries are concentrated over East and South Asia. By comparison, the S_c of developed countries are more evenly distributed in the zonal direction at northern latitudes, with high values over Eurasia and North America. The difference in spatial pattern is also evident for aerosol optical depth (AOD, Extended Data Fig. 2c,d).

Climate responses to sulfur emissions

The E_c of developing and developed countries reduce the global average annual mean 2-m air temperature by 0.18 ± 0.11 K and 0.20 ± 0.09 K, respectively (Table 1). The magnitudes of temperature reduction are both close to the magnitude of observed surface warming (~ 0.2 K) over the past decade². The comparable temperature reductions are despite the global average E_c and S_c of developing countries being 1.7 and 1.9 times those of developed countries. The temperature reduction is most evident in the NH (Fig. 2a,b), by a hemispheric average of 0.23 K driven by the E_c of developing countries and by 0.25 K driven by the E_c of developed countries. The E_c of developed countries causes significant cooling at the NH extratropics (30° – 90° N) with weak effects over tropical East and South Asia. By comparison, the E_c of developing countries cools East and South Asia but less so at higher latitudes of Eurasia (Fig. 2a). The zonal average results in Fig. 3a and 3b further show substantial cooling between 60° S and 60° N by the E_c of each region (by 0.10 – 0.40 K depending on the latitude). The temperature responses in the polar areas are much more uncertain (Fig. 3) due to natural variability^{14,24}, although the Arctic cooling induced by the E_c of developed countries are statistically significant at 68% CI.

The unexpectedly comparable cooling effects by the E_c of developing and developed countries are because the E_c of developed countries, although smaller in magnitude, have a stronger per emission capability to induce forcing. To demonstrate this point, we calculate the effective radiative forcing (ERF) of E_c with additional CAM6 simulations (Methods). The ERF represents the change in the top-of-atmosphere net (shortwave + longwave) radiative flux due to emission perturbations and fast adjustments of the atmosphere and land surface, with sea surface temperature and sea ice unchanged. The global mean ERFs due to the E_c of developing and developed countries are comparable (-0.48 ± 0.64 versus -0.42 ± 0.64 W/m²), consistent with the similar temperature changes. The ERF per emission of SO₂ for these two regions are -0.0071 ± 0.0094 and -0.011 ± 0.016 W/m²/(Tg/yr), respectively, with the latter higher by about 50%.

Extended Data Fig. 3a,b further shows the horizontal distribution of ERF. The E_c of developed countries lead to significant negative ERF throughout the NH middle and high latitudes, whereas the E_c of developing countries result in the greatest ERF at the low and middle latitudes around China and India. The negative ERF caused by E_c of developing countries is statistically significant at 95% CI over South Asia, East Asia and the downwind northern Pacific, significant at 68% CI over the majority of the NH, but insignificant over the Contiguous United States (Fig. 3a). The negative ERF by E_c of developed countries is statistically significant at 95% CI over parts of East Asia, the northern Pacific, northern Eurasia and North America, and significant at 68% CI over many other NH areas (Fig. 3b).

Decomposition of the ERF by using radiative kernels²⁵ shows major contributions from the direct radiative forcing of sulfate and fast adjustment of clouds, with minor effects from fast adjustments of other climate variables (Extended Data Table 1). The spatial distribution of sulfate direct radiative forcing

(Extended Data Fig. 3c,d) follows those of S_c and AOD (Extended Data Fig. 2), with the global average sulfate forcing induced by the E_c of developing countries 2.5 times that of developed countries (-0.16 ± 0.061 versus -0.066 ± 0.035 W/m²). The E_c of developing and developed countries exert similar global average radiative effects via fast cloud adjustment (-0.32 ± 0.22 versus -0.32 ± 0.28 W/m², Extended Data Table 1). The fast cloud adjustment corresponds to the overall increase in clouds coverage (statistically significant at 95% or 68% CI over large regions; Extended Data Fig. 4).

Extended Data Table 2 shows radiative kernel decomposition²⁵ for the top-of-atmosphere (TOA) net radiative flux resulting from E_c perturbation, as averaged over the last 110 years of fully coupled CEMS2 simulations. Contributors to the net flux include ERF and the resulting responses of water vapor, surface albedo, temperature and clouds. The contributions of all non-ERF factors are in addition to the radiative effects of their fast adjustments presented in Extended Data Table 1. The 110-year average net fluxes due to the E_c of developing and developed countries are much smaller than the respective values of ERF. Over the 110 years, the net flux is varying but with no trends (Extended Data Fig.11). The net flux is not zero because the response of deep ocean to ERF (which may take thousands of years) has not been fully realized – this is evident from the imbalance in surface energy flux over the oceans (Extended Data Fig. 3e,f).

Extended Data Table 2 shows that the ERF induced reduction in surface temperature (i.e., in addition to the small fast adjustment) leads to a large positive radiative effect, whereas the corresponding reduction in water vapor leads to a negative radiative effect. The ERF induced change in clouds (in addition to the fast adjustment) leads to a small radiative effect. The total radiative effect of clouds change induced by E_c of each region is negative (-0.23 ± 0.37 W/m² for developing countries and -0.26 ± 0.43 W/m² for developed countries), calculated as the sum of the respective values in Extended Data Tables 1 and 2. This is consistent with the overall enhancement in clouds coverage simulated by fully coupled CESM2 (statistically significant at 95% or 68% CI over vast areas; Extended Data Fig. 5).

In the Arctic areas, the E_c of developed countries lead to an increase in sea ice coverage (Extended Data Fig. 6b) and a deepened polar vortex (as manifested in the geopotential height and wind field at 500 hPa, Extended Data Fig. 7b). The increase in sea ice coincides with the strong surface cooling there (Fig. 2b). The change in polar vortex is consistent with the widespread cooling over the northern middle and high latitudes (Fig. 2b). By comparison, the E_c of developing countries lead to weaker Arctic responses (Extended Data Fig. 6a and 7a) because the emissions are located at lower latitudes.

The E_c of developing and developed countries each result in warming along the coasts of Greenland. The temperature change is consistent with the reduction in sea ice coverage (Extended Data Fig. 6a,b) and the increase in the surface (latent + sensible) heat flux to the atmosphere (Extended Data Fig. 6e,f). Correspondingly, the change in surface winds reduces the sea ice drift to these locations (Extended Data Fig. 6c,d).

In the tropics, the Southern Hemisphere (SH) Hadley Cell circulation strengthens and the NH Hadley Cell weakens, and the associated Intertropical Convergence Zone (ITCZ) shifts southward, as manifested in the weakened rising in the NH tropics and enhanced rising in the SH tropics (Extended Data Fig. 8). These tropical responses are because the sulfate induced cooling is stronger in the NH than in the SH, resulting in reduced hemispheric temperature asymmetry (because the NH is warmer than the SH climatologically) and less atmospheric cross-equator energy transport to the SH by the Hadley Cell^{26,27}. The tropical circulation change is associated with weakened precipitation^{28,29} in South and East Asian monsoon areas (Fig. 2c,d), which has a warming effect³⁰ that partly offsets the radiative cooling effect. Since the magnitude of ERF by developing countries is large in East and South Asia (Extended Data Fig. 3a), the sinking enhancement at 0-20°N is strong (Extended Data Fig. 8a). The ERF by developed countries occurs at higher latitudes and is zonally even. The resulting effect on the Hadley Cell is weaker in magnitude (Extended Data Fig. 8b versus 8a), as also reflected in the weaker change in meridional winds in tropical Asian monsoon areas at 850 hPa (Extended Data Fig. 7d versus 7c).

The E_c of developing and developed countries result in similar reductions in global average annual mean precipitation (-0.019 ± 0.019 versus -0.017 ± 0.017 mm/day, Fig. 2c,d), since the response of precipitation is strongly constrained by radiative energy balance³¹. The calculated changes in precipitation are statistically significant at 68% CI over the majority of tropical oceans. The precipitation changes are even statistically significant at 95% over parts of the tropical regions of China, India, the Indian Ocean and the western Pacific due to the E_c of developing countries (Fig. 2c), and over parts of the tropical Pacific due to the E_c of developed countries (Fig. 2d). The E_c of developing countries results in the greatest reduction (by up to -0.57 mm/day, statistically significant at 95% CI; Fig. 2c) over tropical Asian continental monsoon areas (India, IndoChina Peninsula and south China), whereas the E_c of developed countries does not cause such a strong reduction (Fig. 2c,d). The zonal average results also show the strongest precipitation changes in the tropics (by up to about ± 0.1 mm/day), with a reduction in the NH and an enhancement in the SH (Fig. 3c,d), consistent with the changes in the Hadley Cell and ITCZ (Extended Data Fig. 8). The peak zonal average precipitation enhancement over the SH tropics are statistically significant at 68% CI.

Discussion

For each region, there exist substantial differences between its E_c and E_p in the magnitude and geographical pattern. The climate response to emissions associated with regional consumption presented in this study is very different from inferred from prevailing production-based studies. For example, applying the global average temperature change per unit of E_p suggested by Lewinschal et al.⁹ would mean a factor-of-5 difference in the temperature response to the E_p of developing and developed countries, in contrast to the comparable temperature effects by their E_c shown here. This suggests that a picture of the regional contribution to climate change drawn from both production and consumption perspectives will be more complete in supporting regional efforts to combat climate change.

Although the E_c of SO_2 by developing and developed countries differ by a factor of 1.7, they result in comparable changes in the global average surface air temperature and precipitation. This highlights the complex response of the nonlinear climate system to not only the magnitude but also the spatial pattern of aerosols. This finding is broadly consistent with previous E_p based, idealized model simulations⁸⁻¹³, although our results are based on realistic E_c emissions. For climate policy considerations and international negotiations, a climate change attribution assessment based on fully coupled model simulations driven by realistic, regionally detailed emissions is important. Such an assessment will also offer a reference to validate and correct results based on simplified metrics (e.g., global average radiative forcing and global warming potential) in situations where these metrics are used to save computational resources and time.

Our study is based on emissions in a recent year. Along with the economic globalization and trade liberation, the world has experienced rapid changes in regional E_p and E_c . The E_p of developed countries have continued to decline for decades¹⁹, but their E_c have declined at much weaker rates^{3,32}. Over the recent few years, the E_p of China have been reduced substantially³³, whereas the E_p of many developing countries have continued to grow or changed little³⁴ (except for the temporary disruption by COVID-19), and the resulting changes in E_c remain unclear. Future changes in E_p and E_c will depend on the pathway of socioeconomic development and emission control. Many future scenarios assume transition in the energy-industrial sector at a scale not been experienced in the past^{2,35}. A few ongoing events such as the Sino-US trade war²², Brexit and COVID-19 have disrupted the global trade, but the duration of these events and their direct and indirect emissions impacts are less clear. Also not clear are whether the world will embrace continuous globalization – regional rivalry is one of the few plausible Shared Socioeconomic Pathways projected for this century³⁶ – and how this will affect the magnitude and distribution of regional E_c . These pose important questions of how the continuously changing E_c of each region has been affecting and will affect the climate system.

Our study is focused on the effect of sulfate. However, consumption activities also affect other aerosols (e.g., black carbon) and greenhouse gases. Given the importance of responsible consumption to the success of climate change mitigation and environmental protection^{1,2}, it will be very beneficial to conduct a comprehensive assessment of the climate response to the whole suite of climate-relevant constituents associated with regional consumption. A multi-model assessment will help reduce the intrinsic uncertainty in model simulations. This, of which our sulfate study serves as the first step, will complement prevailing production-based analyses to help understand how human activities affect the climate system more thoroughly. As much of the E_c of any region are released in other regions, such a consumption based assessment will also provide a basis for international cooperation to act towards sustainable consumption and climate change mitigation, which will have substantial co-benefits for public health⁴.

Methods

The CESM2 Model

We use fully coupled CESM2 in this study. CESM2 is the most current-generation Earth system model developed by the National Center for Atmospheric Research (NCAR) and other institutions. CESM2 is built upon many successes of its predecessor, CESM1.2, which is one of the best models in the CMIP5 set of model simulations according to a pattern distance metric of present-day precipitation and temperature^{37,38}. CESM1.2 captures the spatial pattern of climatic surface temperature at a country scale in the meteorological reanalysis data, with a high correlation coefficient and a low normalized mean deviation³⁹. CESM2 contains many updates upon CESM1.2 and results in an improved historical simulation, including a better representation of low latitude precipitation and shortwave cloud forcing²¹. An overview of CESM2 can be found elsewhere²¹.

CAM6 is the atmospheric component of CESM2 with a fully interactive aerosol scheme, the modal aerosol model with four modes (MAM4)²³. The main difference between MAM4 and the MAM3 scheme used in CESM1.2 is the representation of carbonaceous aerosols²³. SO₂ is oxidized by the hydroxyl radical, hydrogen peroxide and ozone to form sulfate (SO₄), and sulfate size distributions are simulated prognostically in three lognormal modes: Aitken, accumulation, and coarse^{40,41}. Both MAM4 and MAM3 provide aerosol simulations with reasonable agreement with observations^{42,43}; and they have been used widely to simulate the effects of sulfate on global temperature, precipitation and local climate^{11,14,24,44-50}. In this study, CAM6 is run at a horizontal resolution of 1.9° × 2.5° with 32 vertical levels.

CESM2 includes an interactive land surface model (the Community Land Model version 5, CLM5)⁵¹ run at the same horizontal resolution as CAM6, with an extensive suite of new and updated processes and parameterizations upon previous versions. The ocean component of CESM2 adopts the Parallel Ocean Program version 2 (POP2)⁵² with several physics and numerical improvements²¹, and is run at an equivalent resolution of 1°. CESM2 uses the Los Alamos sea ice model version 5.1.2 (CICE5)⁵³ as its sea-ice component, and CICE5 shares the same horizontal grid with POP2.

Extended Data Fig. 9a describes the suite of model simulations in this study. We conduct three cases of fully coupled CESM2 simulations, including GLOBAL, Xdeveloping_CE and Xdeveloped_CE. The three cases differ only in anthropogenic SO₂ emissions, with global emissions in GLOBAL, removal of E_c of developing countries in Xdeveloping_CE, and removal of E_c of developed countries in Xdeveloped_CE. Prior to running the three cases, we conduct an additional fully coupled simulation Pre_run for 300 years from an initial climate state in the year of 2000. The GLOBAL case then starts from the climate state in the 300th year of the Pre_run, and continues for an additional 407 years; Extended Data Fig. 10 shows that the climate has reached quasi-equilibrium state at this time. Xdeveloping_CE contains three ensemble members branched from the 201st, 211th and 265th year of GLOBAL, respectively. Xdeveloped_CE contains three ensemble members branched from the 201st, 235th and 247th year of GLOBAL, respectively. Each ensemble member of Xdeveloping_CE and Xdeveloped_CE are run for 140

years, with the last 110 years used for analysis. Depending on the years of each ensemble member of Xdeveloping_CE and X_developed_CE, results from GLOBAL are paired temporally for comparison.

Each simulation outputs monthly mean values for temperature, precipitation and other variables. For Xdeveloping_CE or X_developed_CE, each of the three ensemble member provides a monthly time series of paired difference relative to GLOBAL, and the three resulting time series are averaged to obtain an ensemble mean time series. The 110-year average and standard deviation for the ensemble mean time series is analyzed. To correct for the model autocorrelation, we apply the paired z-test²⁴ to the monthly time series and focus the analysis on areas where the climate response passes the significance test with respect to 95% or 68% CI.

Effective radiative forcing calculations

To calculate the ERF, we conduct three additional simulations of CAM6 with specified sea surface temperature and sea ice, following Conley et al.²⁴. Here, the ERF is computed from individual simulations with SO₂ emissions identical to GLOBAL, Xdeveloping_CE or X_developed_CE. An all-emission CAM6 simulation is run for 199 years. Other simulations branch from the 5th year of the all-emission simulation and are run for 195 years. The last 190 years of all simulations are used to calculate the ERF.

Radiative kernel decomposition

We calculate the TOA radiative feedbacks using the radiative kernel method introduced by Huang, et al.⁵⁴, which has been widely used in decomposition of radiative effects for climate change analysis⁵⁵⁻⁶¹. The radiative kernel, K_X , is pre-calculated by a partial perturbation method using the radiative transfer model RRTM⁶² for temperature (T), water vapor (q), and surface albedo (a). Then, for non-cloud climate variables, the radiative feedback is computed as

$$\Delta_X R = K_X \Delta X,$$

for $X = T, q, \text{ or } a$. The direct radiative forcing (G) from sulfate is calculated based on CAM6 simulations, as determined by contrasting the TOA radiative flux (calculated at each time step but outputted every month) from CAM6 simulations with and without the E_c (GLOBAL versus Xdeveloping_CE, or GLOBAL versus X_developed_CE). The cloud feedback is then obtained from the residual of the radiation budget

$$\Delta_{clld} R = \Delta R - G - K_T \Delta T - K_q \Delta q - K_a \Delta a,$$

where ΔR is the response of the net TOA radiative flux.

Emissions

Anthropogenic emissions of all species but SO_2 represent the year of 2000, as taken from the CESM2 present-day simulations. Emissions of SO_2 for the year of 2014 are obtained by combining the (production-based) CEDS CMIP6 inventory¹⁹ and the latest version (v10, for 2014) of the widely used^{4,6,22} GTAP MRIO table²⁰.

The GTAP MRIO table is a result of an internationally collaborative effort to produce a regionally and sectorally harmonized, high-quality input-output database for global trade analysis. It has been widely used as a core dataset in general equilibrium models. The disaggregation details of regions and sectors in the GTAP v10 table are compatible with those in CEDS, with sectoral and regional mapping established in previous work^{22,63}.

The calculation of SO_2 E_c follows our previous studies^{4,6,22} and is briefly described here; see the flowchart in Extended Data Fig. 9b. We first obtain the worldwide E_p of SO_2 in 2014 from the CEDS CMIP6 emissions inventory, which specifies monthly emissions for 55 sectors on a $0.5^\circ \times 0.5^\circ$ horizontal grid. We also calculate the production and consumption (each in monetary quantity) in 57 sectors of 141 countries/regions based on the GTAP v10 MRIO table for 2014. Production of each country/region and sector is to supply direct and indirect consumption by all regions and sectors. GTAP provides quantitative information of the linkages between sectors and regions along the global supply chain. The mapping from 55 sectors in CEDS to 57 sectors in GTAP follows Lin et al.²² (see their Supplementary Data 6). We then calculate country- and sector-specific emission intensities (emission divided by monetary economic output) of SO_2 based on the E_p and production data. We further calculate the E_c of individual countries/regions and sectors by multiplying the sectoral emission intensities with consumption-associated sectoral output. Within each country, the spatial and monthly distributions of E_c follow the distributions of the corresponding E_p . For example, the E_c of the United States that are released in China (due to Chinese production for the US consumption) follow the spatial and monthly distributions of the E_p of China. For consumption activities not associated with monetary economic output such as residential use and private vehicle driving (and thus not shown in the GTAP MRIO table), emissions are taken from the CEDS CMIP6 dataset directly, following Lin et al.²².

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Declarations

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Acknowledgements

We thank Mike Mills, Hailong Wang, Xichen Li and Zheng Lu for help with model setup at the beginning of the project, and Yonggang Liu for discussion. This work is funded by NSFC (41775115, 41831175, and 91937302) and MOST (2019QZKK0604). Jingxu Wang is in part supported by the Fundamental Research Funds for the Central Universities (842113005).

Author contributions

J.Lin and G.H. conceived the study. J.Lin and C.Z. designed the research. L.C. calculated the emissions. C.Z. conducted the CAM and CESM simulations. P.L., J.W. and Y.Y. contributed to the experiments. Y.X. conducted radiative kernel calculations. J.Lin, C.Z., G.H., J.Lamarque, J.N., J.Y. and K.H. analyzed the results. J.Lin and C.Z. wrote the paper with comments from J.Lamarque, J.N., J.Y., K.H. and Y.H.

Data availability

The GTAP data are available at <https://www.gtap.agecon.purdue.edu/>. The CEDS CMIP6 emissions are available at <https://esgf-node.llnl.gov/search/input4mips/>. Source data for figures are included in the paper. Raw model simulation results generated during this study are large in size and are available upon reasonable request.

Code availability

The CESM is available at <http://www.cesm.ucar.edu/models/cesm2/>. The codes for kernel calculation is available at <http://www.meteo.mcgill.ca/~huang/>. All computer codes generated during this study are available from the corresponding authors upon reasonable request.

Competing interests

The authors declare no competing interests.

Tables

Table 1. Climate response to E_c of SO_2 . Included are the changes in global average annual mean S_o , AOD, ERF, 2-m air temperature (T) and precipitation (P). The values in brackets represent 2 standard deviations.

	Due to E_c of Developing countries	Due to E_c of Developed countries
E_c (SO_2 $10^4 \mu\text{g}/\text{m}^2/\text{yr}$)	13.3	7.9
S_c (SO_4 $\mu\text{g}/\text{m}^2$)	17.5 (± 0.83)	9.1 (± 0.89)
ΔAOD (10^{-2})	0.50 (± 0.32)	0.32 (± 0.36)
ERF (W/m^2)	-0.48 (± 0.64)	-0.42 (± 0.64)
ΔT (K)	-0.18 (± 0.11)	-0.20 (± 0.09)
ΔP (mm/day)	-0.019 (± 0.019)	-0.017 (± 0.017)

Figures

Figure 1

Contrasting consumption-based and production-based emissions. Anthropogenic SO_2 emissions associated with consumption (a, b) and production (c, d) activities of developing (a, c) and developed (b,

d) countries in 2014. The Ec data are derived here, and the Ep data are taken directly from the CEDS CMIP6 inventory. The global average is shown in each panel.

Figure 2

Climate response to consumption-based emissions. The changes in annual mean 2-m air temperature (a, b) and precipitation (c, d) due to Ec of developing (a, c) and developed countries (b, d). 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. The global average is shown in each panel.

Figure 3

Zonal average responses of temperature and precipitation to consumption-based emissions. Changes in zonal average annual mean 2-m air temperature (a, b) and precipitation (c, d) in response to E_c of developing (a, c) and developed (b, d) countries. The light shading indicates 2 standard deviations of the 110-year time series and the dark shading indicates 1 standard deviation. The global average value is shown in each panel.

Supplementary Files

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