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Supplement of

Regional and global temperature response to anthropogenic SO_2 emissions from China in three climate models

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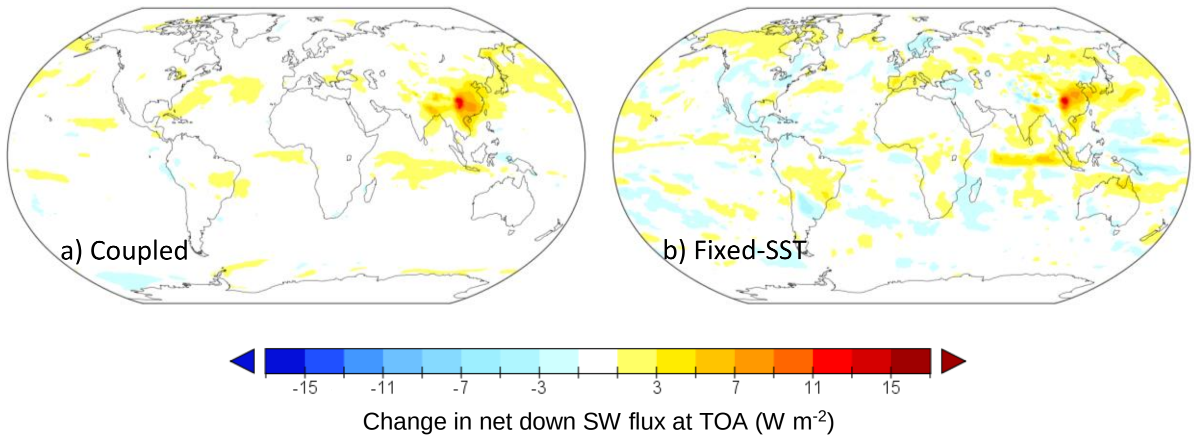
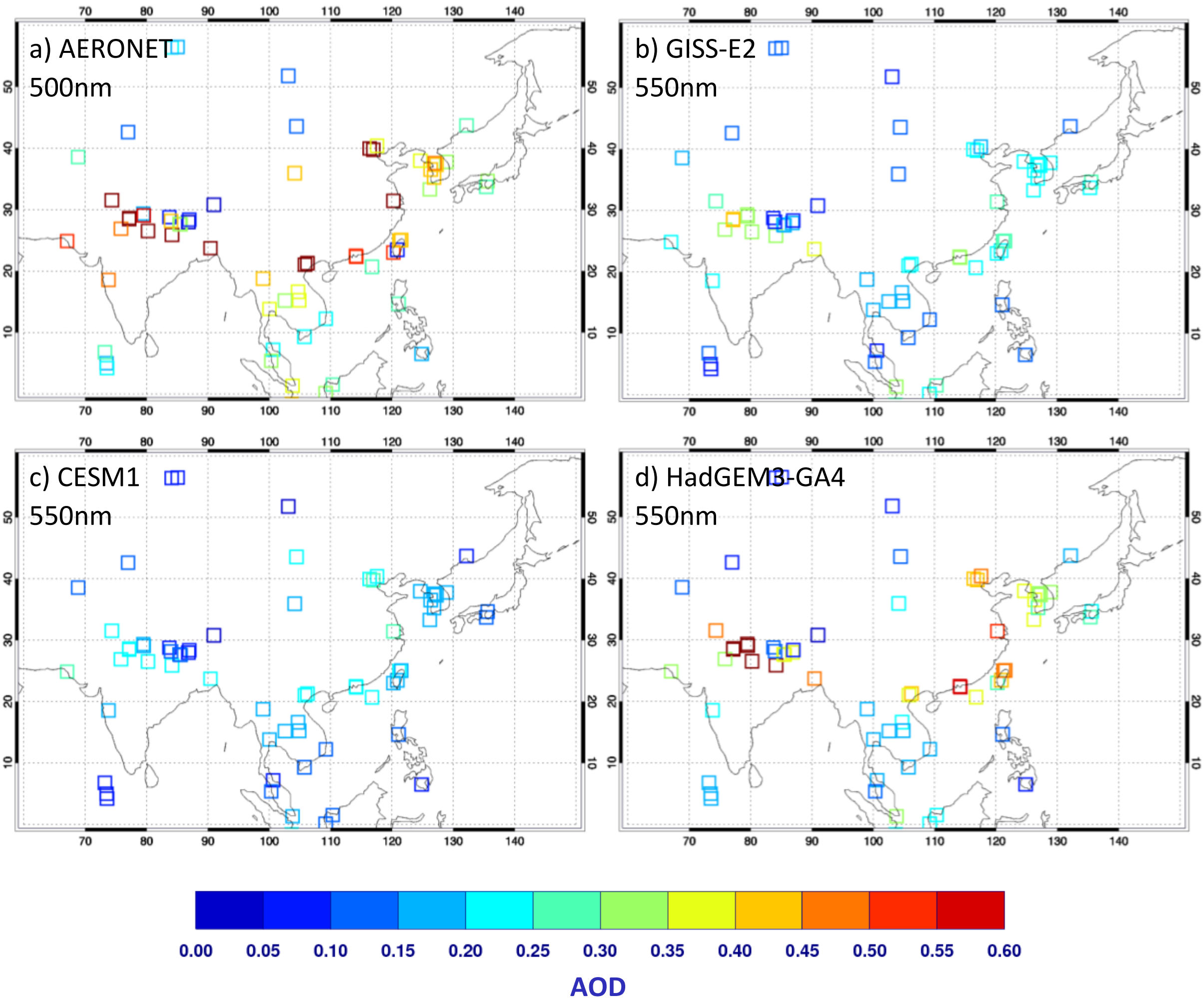
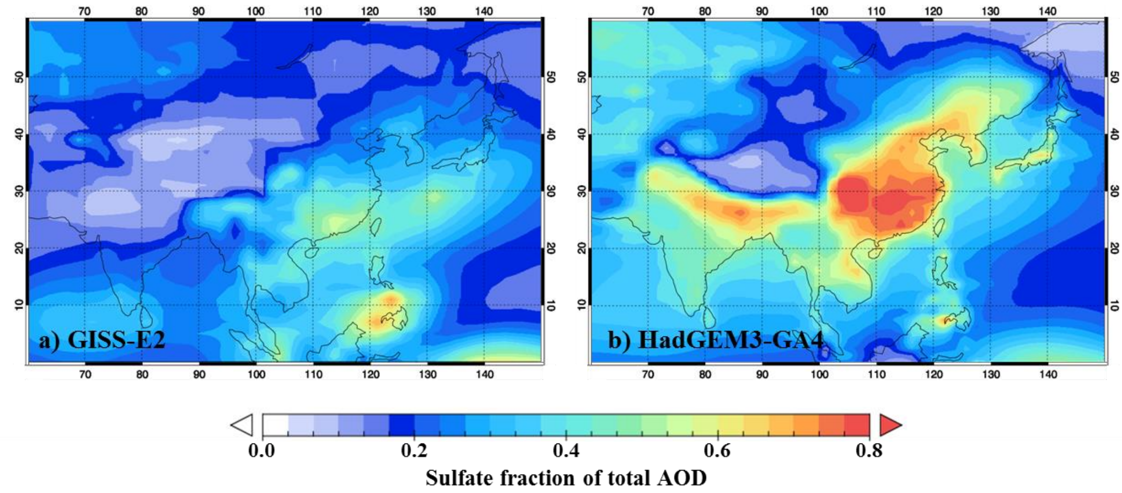


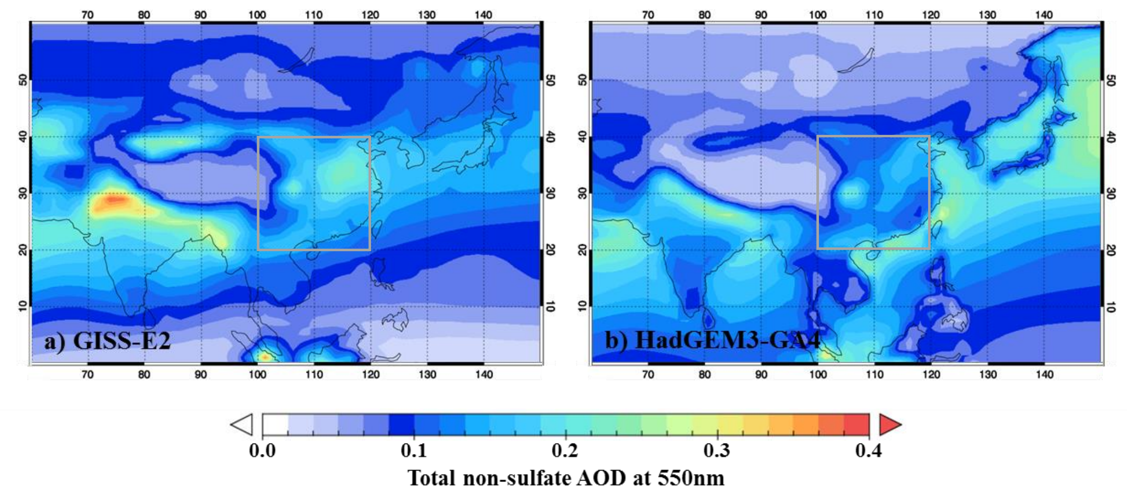
Supplementary Figure S1: Change in TOA SW flux due to removing anthropogenic SO_2 emissions from China in: a) fully-coupled simulations, and b) fixed-SST simulations, with HadGEM3-GA4. Both panels show the difference between the output of the perturbation simulation minus the control simulation; for the coupled simulations the plot shows an average over 150 years, with the first 50 years of the simulations discarded as spin-up. For the fixed-SST simulations, the model was run for 26 years with prescribed year 2000 SSTs and sea-ice, and the plot shows the average over the last 25 years, discarding the first year as spin-up.



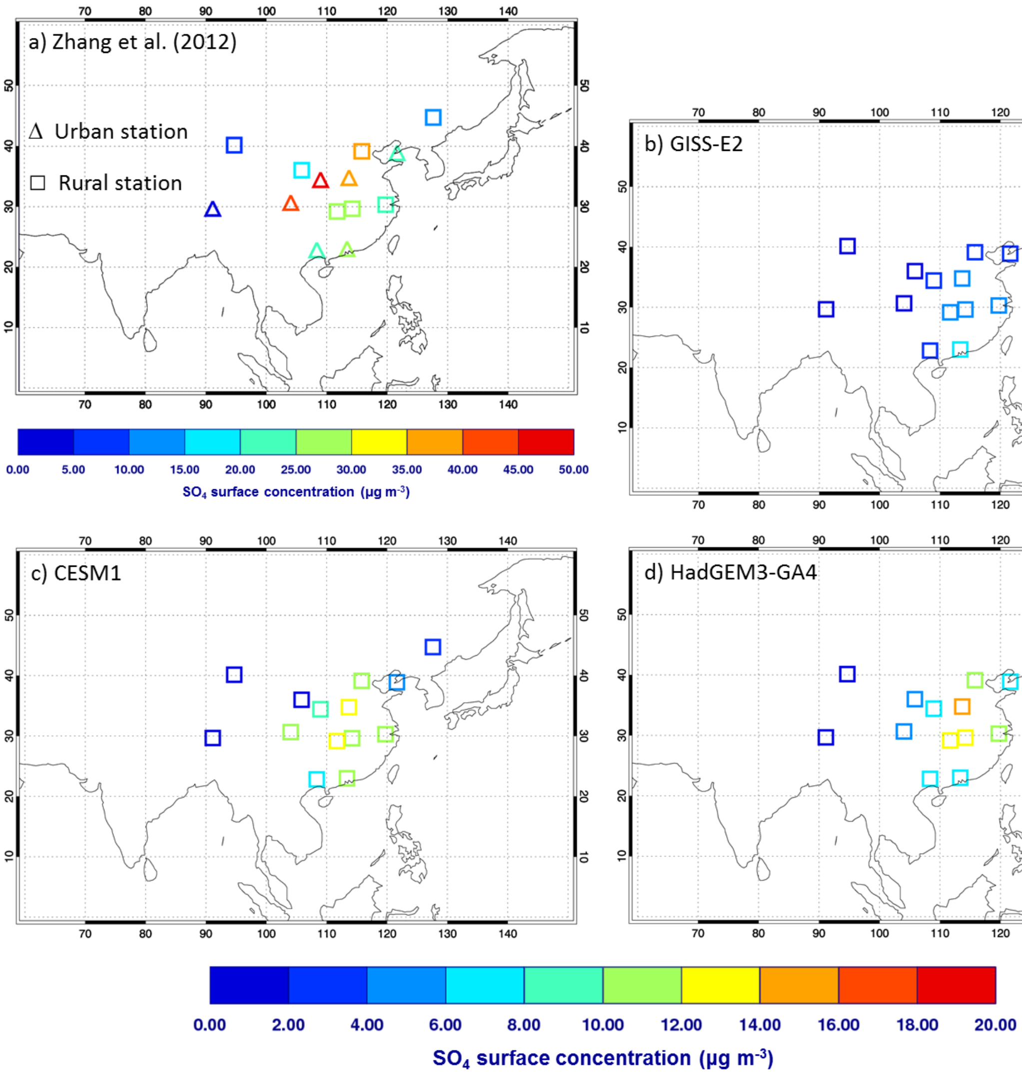
Supplementary Figure S2: Annual mean AOD observed at 500nm by AERONET (a), and diagnosed at 550nm from GISS-E2 (b), CESM1 (c), and HadGEM3-GA4 (d). For AERONET the monthly mean climatology product was used, which for each station provides a value for each month averaged from all years that observations for that month were available. Only stations which could provide a climatological value for all 12 months were then used to calculate an annual mean climatology. For the models, the 150-year mean AOD from each model's control (2000) simulation is masked to the locations of the qualifying AERONET sites by taking the value in the gridbox that each AERONET station is located in. For HadGEM3-GA4 and GISS-E2 the AOD is diagnosed for clear-sky conditions, whereas in CESM1 all-sky AOD is diagnosed, which is expected to be higher than the equivalent clear-sky value. Because most AERONET stations in Asia stared observing more recently than year 2000 (the year the model simulations are based on), the observations may be skewed relative to the models. We assessed the severity of this issue by using MODIS and MISR to see how the same instruments observed AOD changing over China since 2000: For MODIS Terra the E. China average AOD at 550nm was 0.48 for 2001-2003, and 0.54 for 2010-2012. For MISR the E. China average was 0.29 for 2000-2002, and 0.31 for 2012-2014. So, we conclude that it does not appear that there has been a large trend in AOD in E. China over this period, and so the AERONET observations made over this period are likely still reasonably representative of year 2000 conditions.



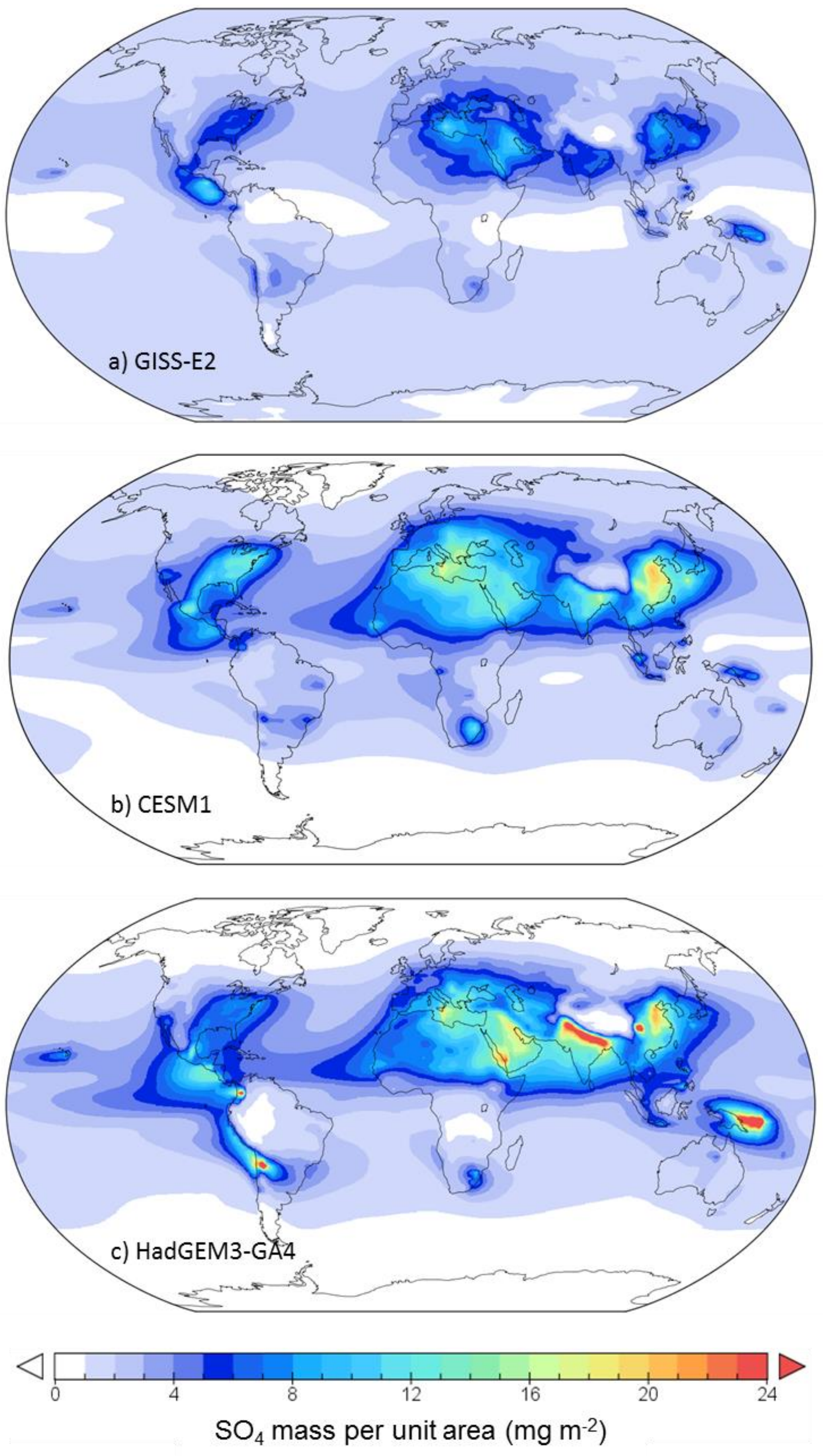
Supplementary Figure S3: Fraction of total AOD at 550nm made up by sulfate in GISS-E2 (a), and HadGEM3-GA4 (b), over the Asia region. Calculated in each case as the ratio of SO_4 clear-sky optical depth to total clear-sky AOD in the 150-year mean from each model's control run.



Supplementary Figure S4: Non-sulfate clear-sky AOD at 550nm over Asia in GISS-E2 (a), and HadGEM3-GA4 (b). Calculated in each case by subtracting the clear-sky sulfate optical depth from total clear-sky AOD in the 150-year mean from each model's control run. The average within the E. China region (100°E-120°E, 20°N-40°N, indicated by grey box) is 0.15 for GISS-E2 and 0.19 for HadGEM3-GA4.



Supplementary Figure S5: Surface SO_4 concentrations in China as reported for 2006-2007 by Zhang et al. (2012) (a), and in GISS-E2 (b), CESM1 (c), and HadGEM3-GA4 (d). For the Zhang et al. dataset, a monthly climatology is calculated by averaging values for each month from both 2006 and 2007 (where available), and then all twelve months are averaged to calculate an annual mean. Stations located in urban areas are denoted by triangles. For the models, the SO_4 concentration in the lowest model level of the control (2000) simulation of each model is used, and the data is masked to the locations of the observations by taking the value from the gridbox that each station is located in. For GISS-E2 and HadGEM3-GA4 a 150-year annual mean is used, whilst for CESM1 the mean surface SO_4 is taken from a 30-year extension to the original control simulation. For the models, all points are denoted with squares to indicate that the model resolutions are too coarse (~200 km) to make an urban-rural distinction. Note the colour scale for the models is 2.5 times smaller than for the observations.



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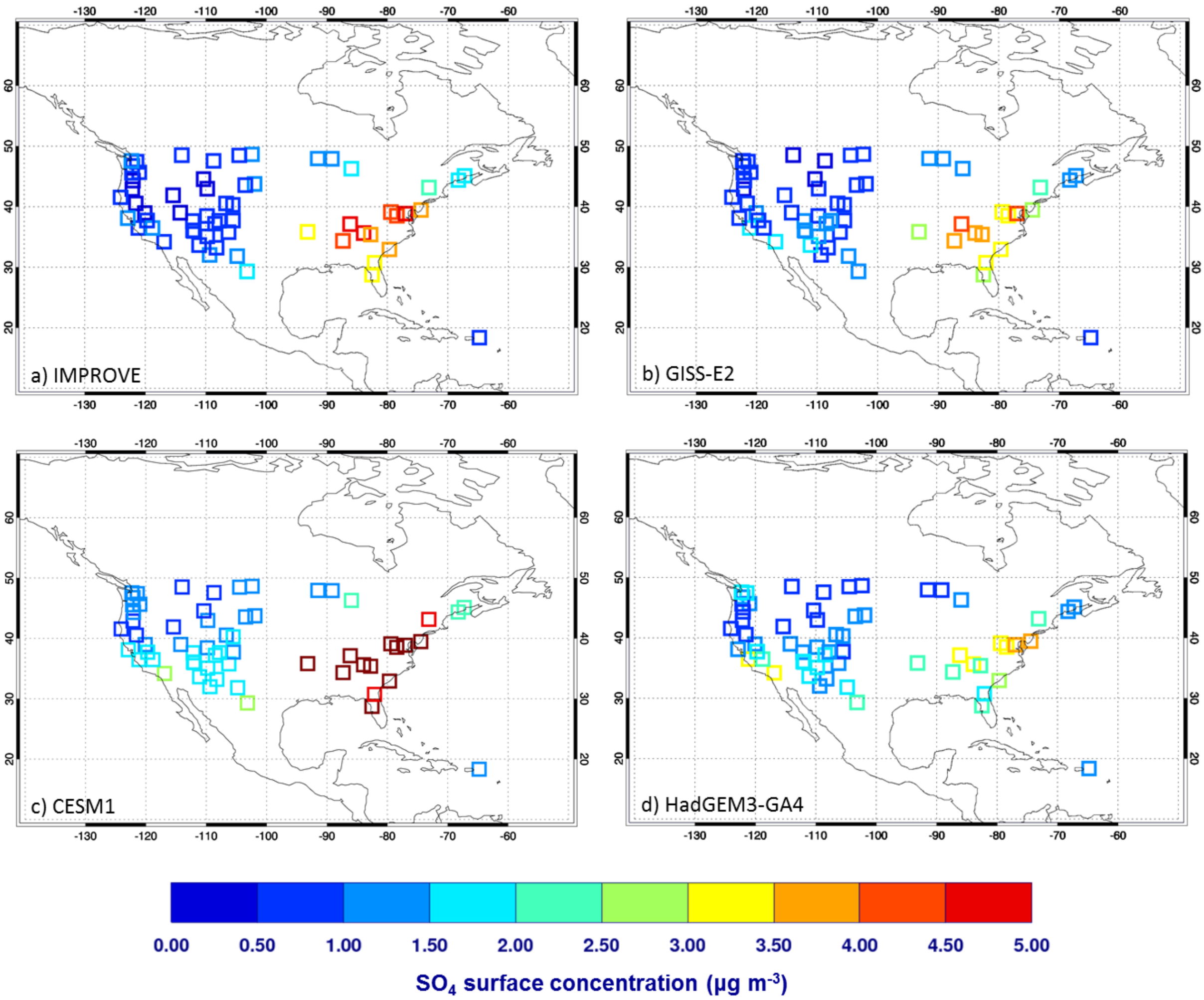
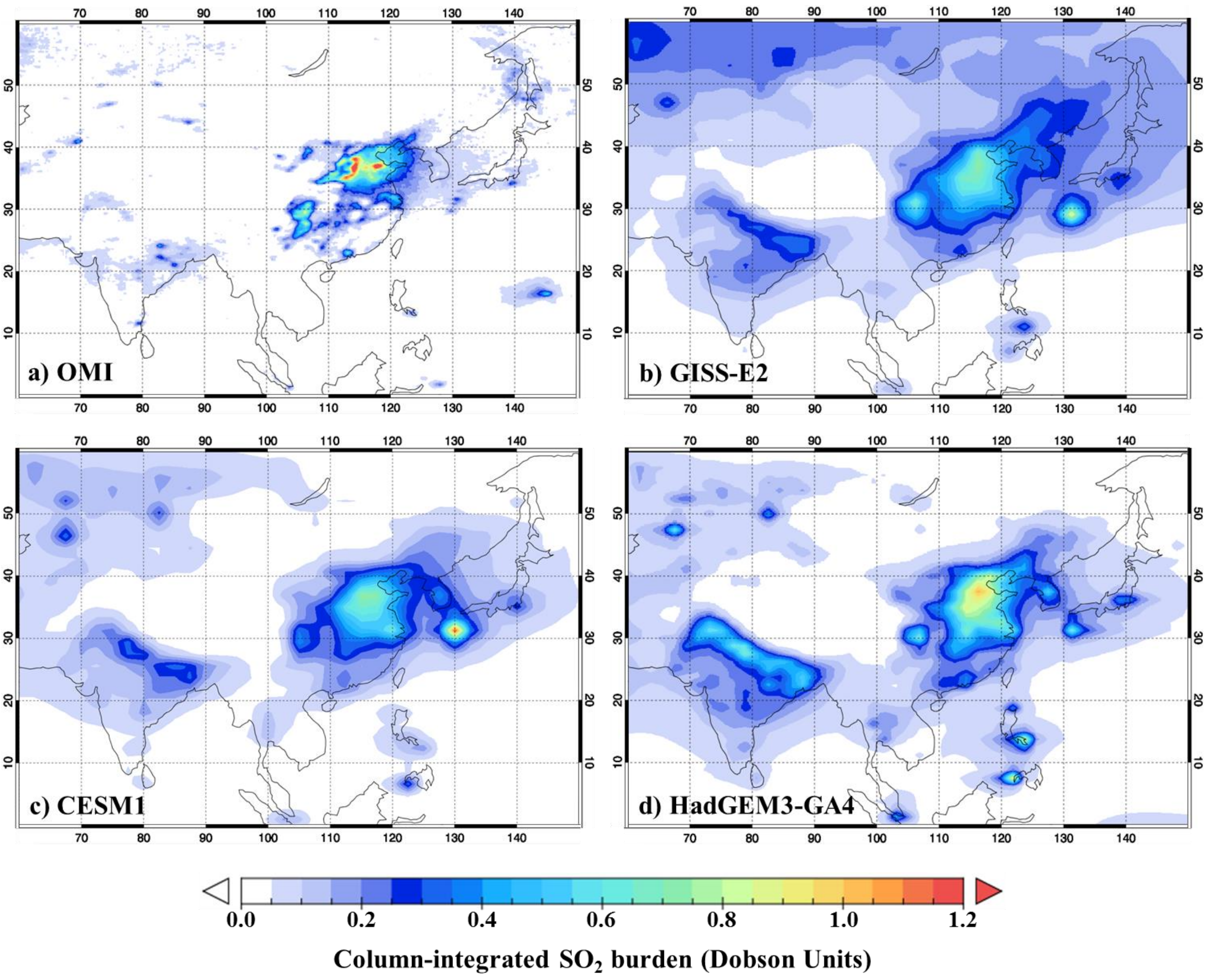
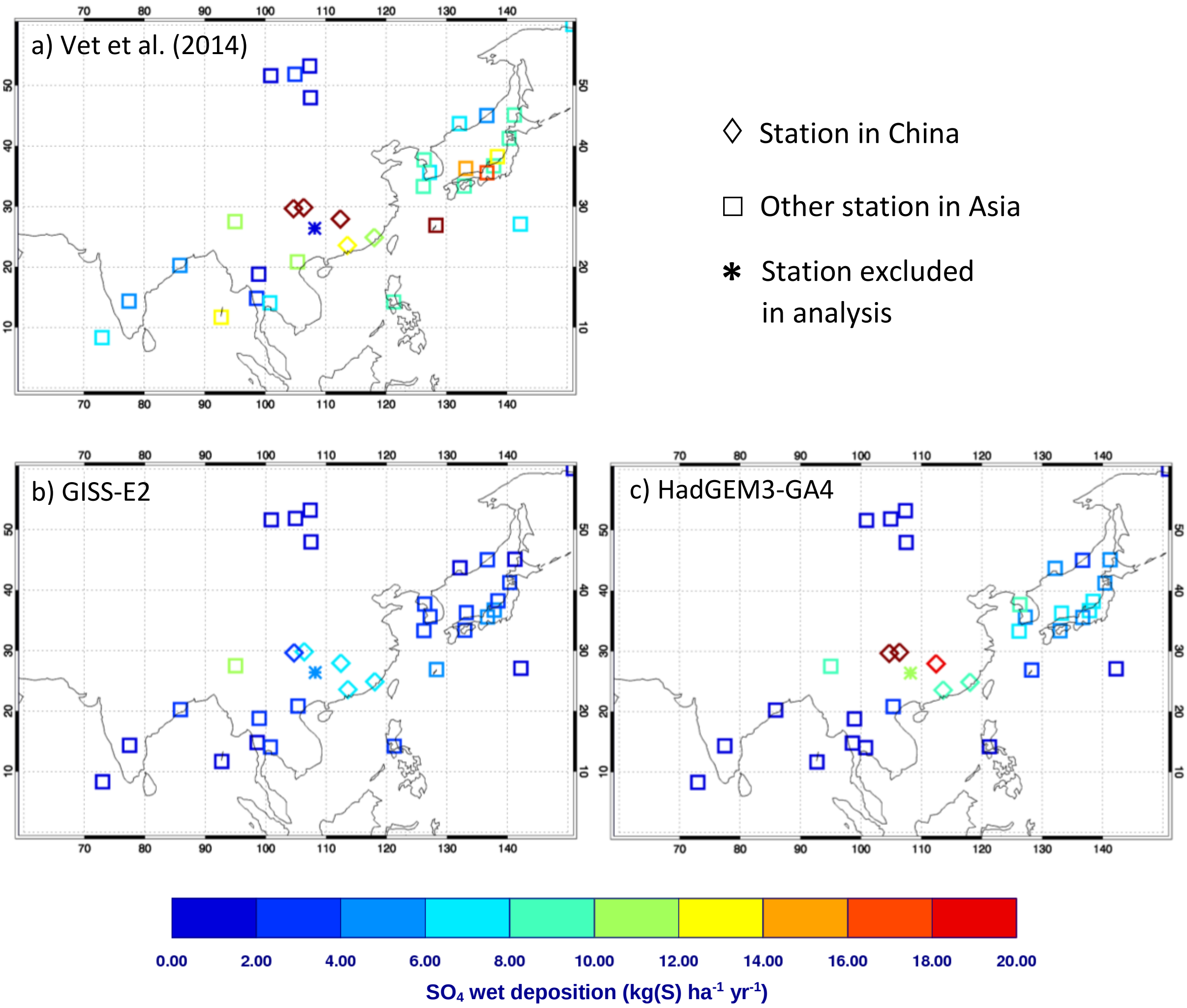
2 Supplementary Figure S6: Climatological column-integrated SO_4 burden in a) GISS-E2, b)
3 CESM1, and c) HadGEM3-GA4. In each case a 150-year average in taken from the control
4 simulation of the model.



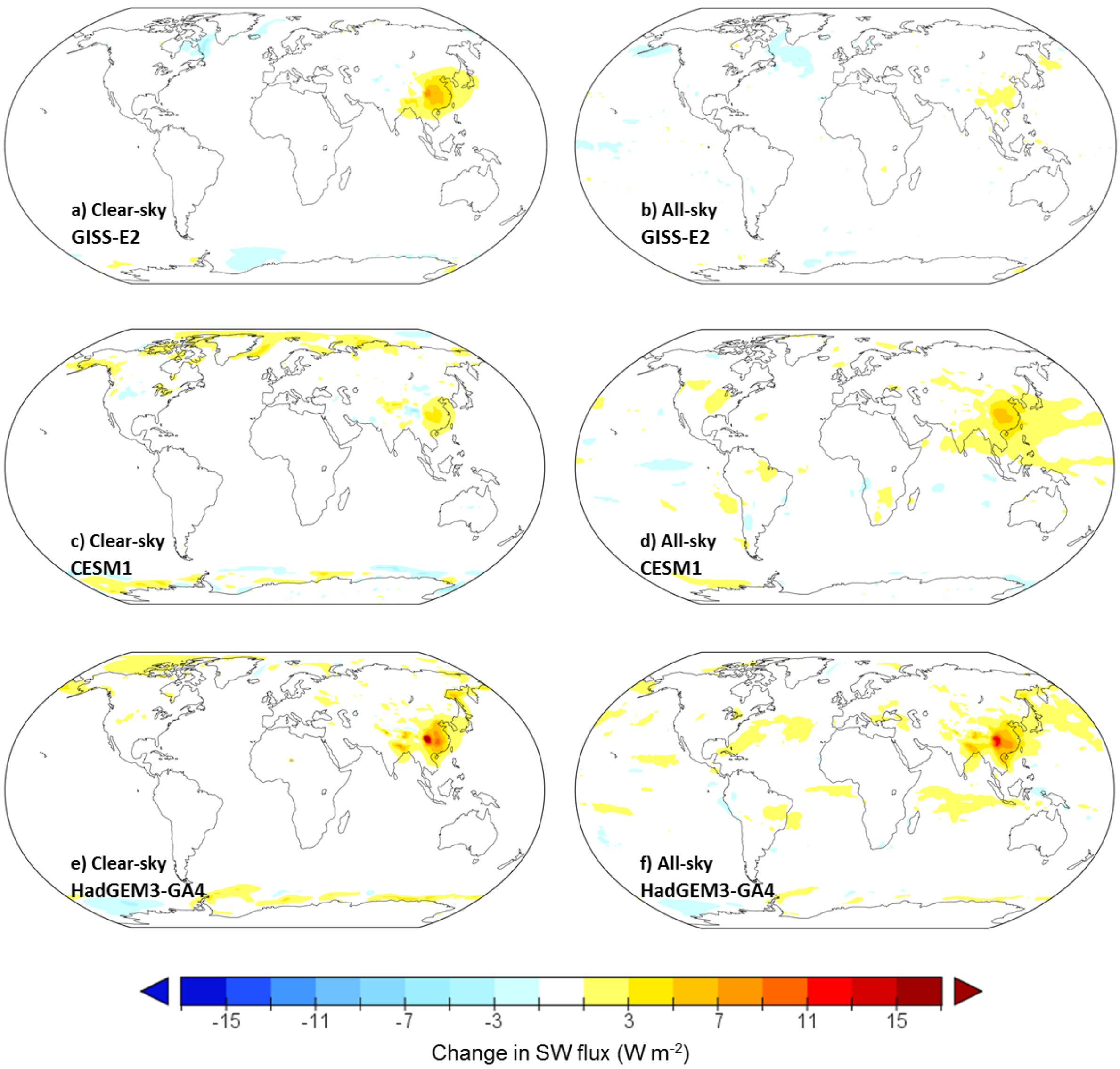
Supplementary Figure S7: Annual mean surface SO_4 concentrations over the US as observed by the IMPROVE monitoring network (a), and as diagnosed in GISS-E2 (b), CESM1 (c), and HadGEM3-GA4 (d). For the IMPROVE data we calculate monthly climatologies between 1995-2005 for all stations with data for each month from at least 6 years within this range, and average over months to calculate an annual mean climatology for each station. For the models, the mean surface SO_4 from each model's control (2000) simulations is masked to the location of the qualifying IMPROVE sites by using the value at the gridbox each site is located in. For GISS-E2 and HadGEM3-GA4 a 150-year annual mean is used, whilst for CESM1 the mean surface SO_4 is taken from a 30-year extension to the original control simulation.



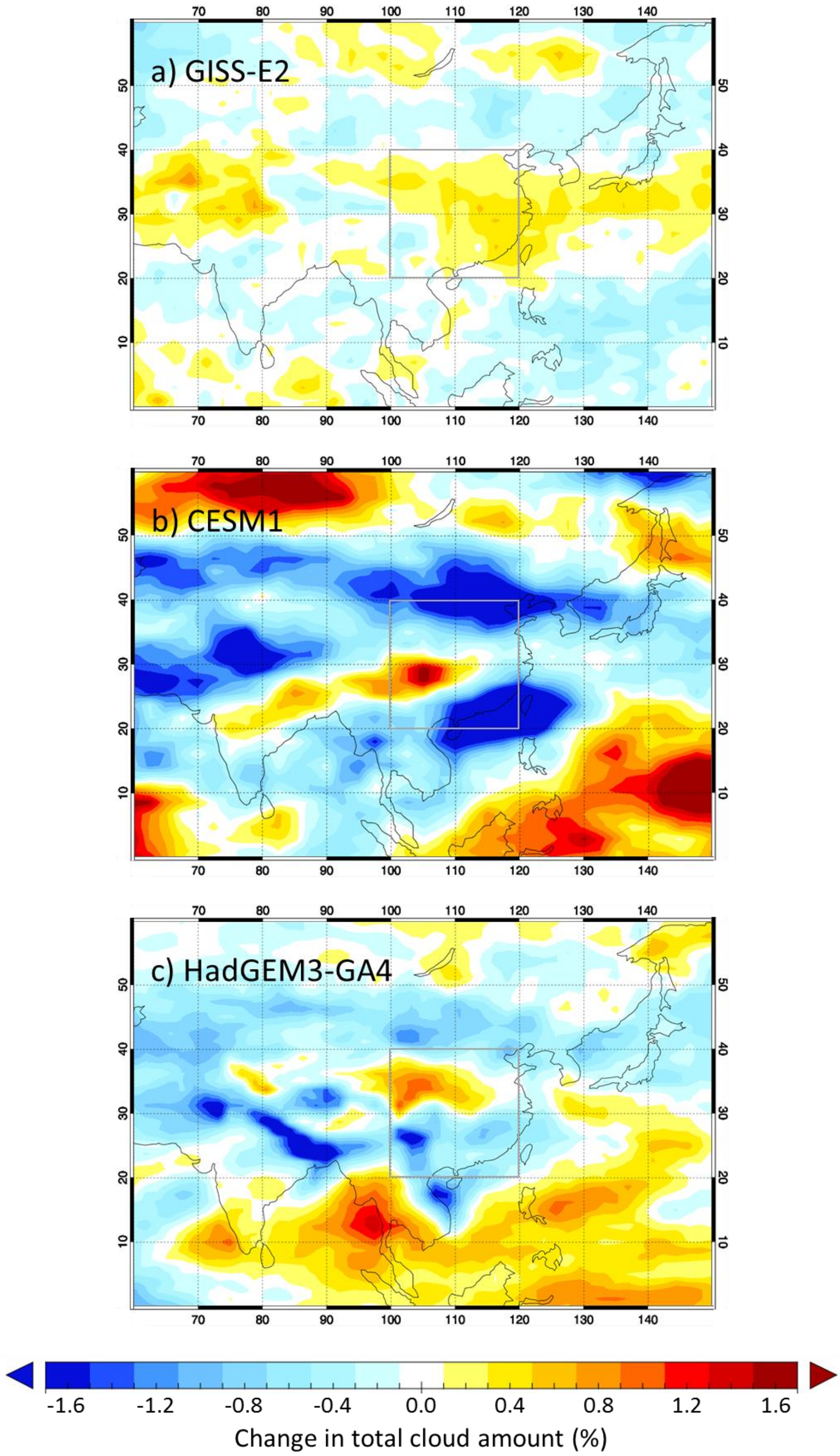
Supplementary Figure S8: Column-integrated sulphur dioxide burdens over Asia as observed by the OMI satellite instrument (a), and simulated in GISS-E2 (b), CESM1 (c), and HadGEM3-GA4 (d). For OMI SO_2 we calculate a climatology by averaging gridded monthly data to create annual means, and then averaging over all years from 2005-2012. Model data for GISS-E2 and HadGEM3-GA4 are 150-year means from the control simulation of each model, whilst for CESM the data is a 30-year average from an extension to the control simulation.



Supplementary Figure S9: SO_4 wet deposition in Asia, reported for 2000-2002 in Vet et al. (2014) (a), and in GISS-E2 (b) and HadGEM3-GA4 (c). For the Vet et al. (2014) dataset, we use the 3-year mean values provided by the data product. For the models we use the 150-year mean from the models' control (2000) simulations, masked to the location of the observation stations by taking the value from the gridbox each station is located in. Diamonds indicate stations in China, and the asterisk indicates the station that was excluded from the analysis in the main manuscript, as both models had unusually large biases at this one station.



Supplementary Figure S10: Changes in net TOA clear-sky (a, c, e) and all-sky (b, d, f) SW flux due to removing SO_2 emissions from China in GISS-E2 (a, b), CESM1(c, d), and HadGEM3-GA4 (e, f). GISS-E2 and HadGEM3-GA4 plots are calculated from 150-year means of the perturbation minus control simulations. Clear-sky diagnostics were not available for the full 150-year period for CESM1, and so for this model the mean is calculated from a 30-year extension to both perturbation and control simulations. Comparing the left column (clear-sky) with the right (all-sky) over China, GISS-E2 has much larger clear-sky flux changes, HadGEM3-GA4 has very similar clear-sky and all-sky flux changes, and CESM1 has larger all-sky flux changes (see Section 4.2 of main text for discussion).



Supplementary Figure S11: Change in annual mean total cloud cover over Asia in a) GISS-E2, b) CESM1, and c) HadGEM3-GA4, following removal of SO_2 emissions from China. GISS-E2 and HadGEM3-GA4 plots are calculated from 150-year means of the perturbation minus control simulations. This diagnostic was not available for the full 150-year period for CESM1, and so for this model the mean is calculated from a 30-year extension to both perturbation and control simulations. Consequently, the apparently larger responses in (b) may be partly the result of the much shorter averaging period, which will result in a poorer signal/noise ratio.

References

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