Potential impacts of Asian carbon aerosols on future US warming

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[1] This study uses an atmosphere-ocean fully coupled climate model to investigate possible remote impacts of Asian carbonaceous aerosols on US climate change. We took a 21st century mitigation scenario as a reference, and carried out three sets of sensitivity experiments in which the prescribed carbonaceous aerosol concentrations over a selected Asian domain are increased by a factor of two, six, and ten respectively during the period of 2005–2024. The resulting enhancement of atmospheric solar absorption (only the direct effect of aerosols is included) over Asia induces tropospheric heating anomalies that force large-scale circulation changes which, averaged over the twenty-year period, add as much as an additional 0.4°C warming over the eastern US during winter and over most of the US during summer. Such remote impacts are confirmed by an atmosphere stand-alone experiment with specified heating anomalies over Asia that represent the direct effect of the carbon aerosols.
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1. Introduction

[2] Absorbing carbon aerosols such as black and organic carbon can convert sunlight into infrared radiation, heat the atmosphere and reduce surface insolation. On the global scale, black carbon aerosol is considered to be the second largest radiative forcing agent after carbon dioxide [*Ramanathan and Carmichael*, 2008], while carbon aerosols' regional effects may even outweigh those from the greenhouse gases in Asia and Africa. By redistributing solar heating, carbon aerosols can weaken the Asian summer monsoon or change the seasonality and latitudinal distribution of the monsoon rainfall [*Ramanathan and Carmichael*, 2008; *Menon et al.*, 2002; *Lau and Kim*, 2010; *Meehl et al.*, 2008; *Wang et al.*, 2009]. Increased aerosol concentrations may have played a major role in causing the observed drying trends over Africa, South and East Asia in the past 50 years [*Bollasina et al.*, 2011; *Ramanathan and Carmichael*, 2008].

[3] In addition to these regional effects, Asian carbon aerosols, if they continue to increase, could perturb the large-scale circulation [*Chung and Ramanathan*, 2003; *Wang*, 2009] and cause down-stream climate effects. Many previous studies have shown that diabatic heating variability associated with Asian monsoon precipitation can force circumglobal teleconnections [e.g., *Hoskins and Rodwell*, 1995]. Teleconnections may also be produced through the direct effect of the aerosols [*Kim et al.*, 2006], as black carbon can strongly enhance solar heating (*Shindell et al.* [2008] have discussed such effects in the context of global emissions).

[4] Given the potential for Asian carbon aerosols to impact remote regions, and the possibility that their emissions may keep growing in the coming decades, in this study we investigate the possible remote contribution of such aerosols on US climate change. Our basic approach is to compare GCM model solutions for a standard climate mitigation scenario with corresponding solutions in which prescribed carbon aerosol concentrations are increased over Asia.

2. Model and Experiments

[5] We use the Community Climate System Model version 4 (CCSM4) which has fully coupled atmosphere, ocean, land and sea ice components [*Gent et al.*, 2011]. The same version of the model has been used for the Coupled Model Intercomparison Project phase 5 (CMIP5) simulations [*Taylor et al.*, 2012; *Meehl et al.*, 2012]. The anthropogenic forcings in CCSM4 include time-evolving greenhouse gases, as well as prescribed time- and space-evolving concentrations of ozone and the direct effect of sulfate and carbon (black and organic) aerosols. The carbon aerosol concentrations are generated off-line by the chemistry-climate model CAM-chem [*Lamarque et al.*, 2011a] driven by emissions [*Lamarque et al.*, 2010, 2011b]. In the CCSM4 20th century experiment, the global average radiative forcing at the top-of-the atmosphere is estimated as +0.14 Wm^{-2} for black carbon and −0.03 W/m^2 for organic carbon in model year 2000 [*Meehl et al.*, 2012]. As described in *Lamarque et al.* [2011b], this forcing is on the lower end of estimates for present-day forcing.

[6] The mitigation scenario that we use for reference is Representative Concentration Pathway (RCP) 4.5. Both the forcings and the CCSM4 simulation results for this scenario are described in detail in *Meehl et al.* [2012]. For the Asian carbon aerosol sensitivity experiments, we enhance the carbon aerosol concentrations over a rectangular domain at 70°–130° E, 0°–50°N (outlined in Figure 1, top) by three different factors: a) double the black carbon, b) increase both black and organic carbon by 6 times, and c) same as b) but for 10 times. Meanwhile carbon aerosols outside the domain, as well as other external forcings, are kept the same as in RCP4.5. These experiments are referred to as 2×, 6× and 10× respectively. While CCSM4 RCP4.5 projections are

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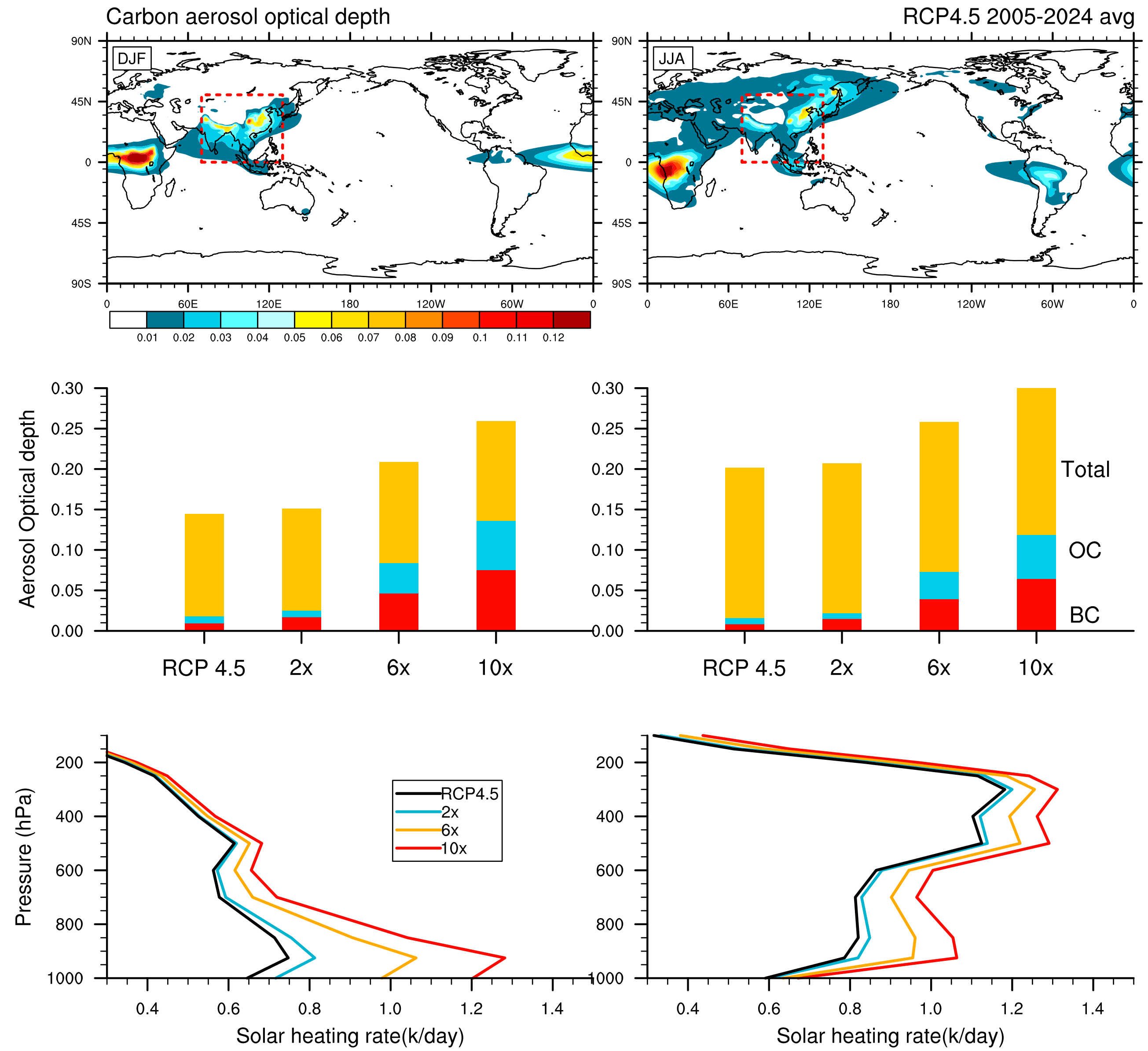

Figure 1. (top) Distribution of carbon aerosol optical depth for season (left) DJF and (right) JJA during the period of year 2005–2024 from the CCSM4 RCP4.5 simulations. (middle) Domain (70°–130°E, 0°–50°N, marked by red dotted lines in Figure 1, top) averaged black carbon (red) organic carbon (blue) and total (orange, including carbon, sulfate, sea salt and dust) aerosol optical depth and (bottom) solar heating rate in RCP4.5, 2×, 6× and 10× in DJF and JJA during 2005–2024.

available from year 2005 to 2300, the three carbon sensitivity experiments are only integrated for twenty years from year 2005 to 2024. For each simulation we produced five ensemble members, which are branched from different 20th century simulations [*Gent et al.*, 2011].

[7] Figure 1 (top) shows the geographical distribution of carbon aerosol optical depth for RCP4.5 averaged in DJF and JJA during 2005–2024. By visual inspection, locations of the heavily polluted "hot spots" generally match the satellite-based estimates for the period of 2001–2003 [*Ramanathan et al.*, 2007a, Figure 4], except that CCSM4 seems to overestimate them over Africa during DJF and underestimate them over East Asia during JJA. In addition, *Ramanathan et al.* [2007a, Figure 4] showed an increase of carbon aerosol optical depth from a range of 0.03–0.06 in Dec–Mar to above 0.1 in Jul–Aug over East China, whereas CCSM4 has much smaller seasonal variations.

[8] Averaged aerosol optical depth over the Asian domain from both RCP4.5 and the sensitivity experiments is displayed in Figure 1 (middle). The carbon aerosol optical depth (sum of black and organic) in RCP4.5 is about 0.018 and 0.016 in DJF and JJA respectively, while the total (carbon, sulfate, dust and sea salt) aerosol optical depth is 0.14 and 0.20. These values seem smaller than Ramanathan's estimate (2007a), likely because neglecting the moisture effect on the aerosol optical properties contributes to underestimations in CCSM4 [*Lamarque et al.*, 2011b]. As the carbon aerosol concentrations are increased in the sensitivity experiments, the carbon aerosol optical depth over the Asian box rises to 0.025, 0.074 and 0.14 in 2×, 6× and

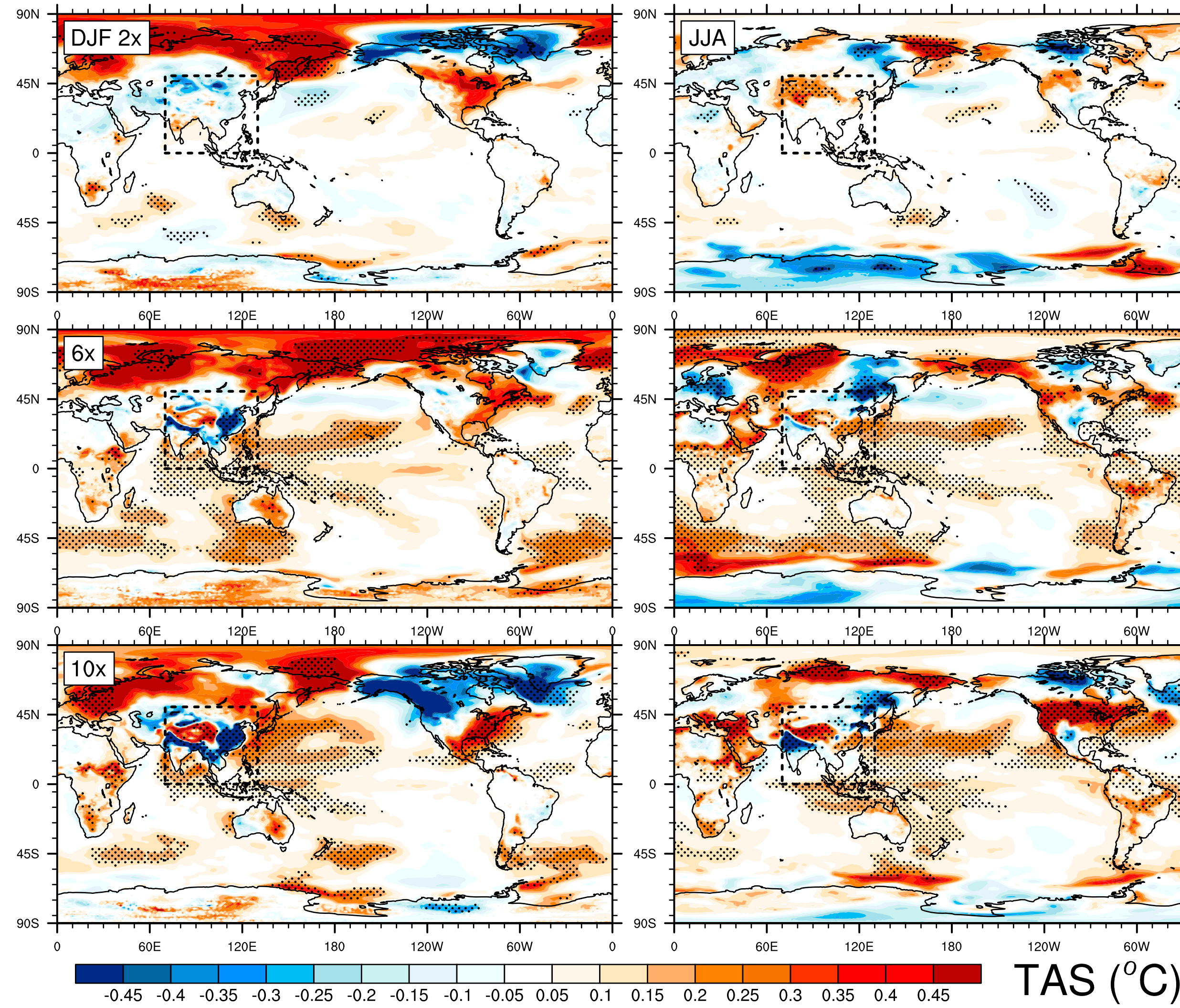

Figure 2. Surface air temperature (TAS) differences resulting from increased carbon aerosol concentration at the Asia domain (marked by the black dotted lines). The anomalies are computed from five-member ensemble (top) 2×, (middle) 6× and (bottom) 10× relative to RCP4.5 averaged in (left) DJF and (right) JJA during 2005–2024. Stippling indicates areas where the anomalies are significant at the 90% level from a Student's t-test.

10× respectively in DJF, and to 0.022, 0.072 and 0.12 in JJA, while the corresponding total aerosol optical depth is 0.15, 0.21, 0.26 during DJF, and 0.21, 0.26 and 0.30 in JJA respectively. If we follow the definition for "hot spots" used by *Ramanathan et al.* [2007a], which have a threshold of 0.03 and 0.3 for carbon and anthropogenic aerosol optical depth, respectively, our 6× and 10× experiments depict extreme scenarios in which almost the entire extent of South and East Asia have turned into "hot spots".

[9] As a result of the added carbon aerosols, the Asian domain-averaged solar heating rate in the lower troposphere increases systematically from RCP4.5 to 10× (Figure 1, bottom). During DJF, the solar heating rate in the lower troposphere is in the range of 0.6–0.8 K/day for RCP4.5, and it approximately doubles in 10×. The heating anomalies in the sensitivity experiments relative to RCP4.5 are generally smaller in JJA (about 0.2 K/day for 10×) than in DJF, but they penetrate higher, with large amplitude values up to 300 hPa. Observations of solar heating profiles are scarce, but data collected by unmanned aerial vehicles over a tropical island in the Indian Ocean during March 2006 suggest solar heating in the lower troposphere is about 1–2 K/day and 50% of that may come from black carbon [*Ramanathan et al.*, 2007b]. Based on these estimates, we think that neither the solar heating rates in RCP4.5 nor the anomalies added by the sensitivity experiments are overly unrealistic. Changes in both global and regional mean radiative forcing in 6× and 10× are presented in auxiliary material.[1]

3. Results

[10] In terms of global annual mean surface air temperature (TAS) over the twenty-year period, the effect of the enhanced Asian aerosols in our experiments is weak. There is no significant change in 2× compared with the RCP4.5 result, while there is a weak warming of about 0.1°C in both 6× and 10×. More pronounced anomalies are found in seasonal means on regional scales (Figure 2). During DJF, except over Tibet, there is surface dimming in the Asian box.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051723.

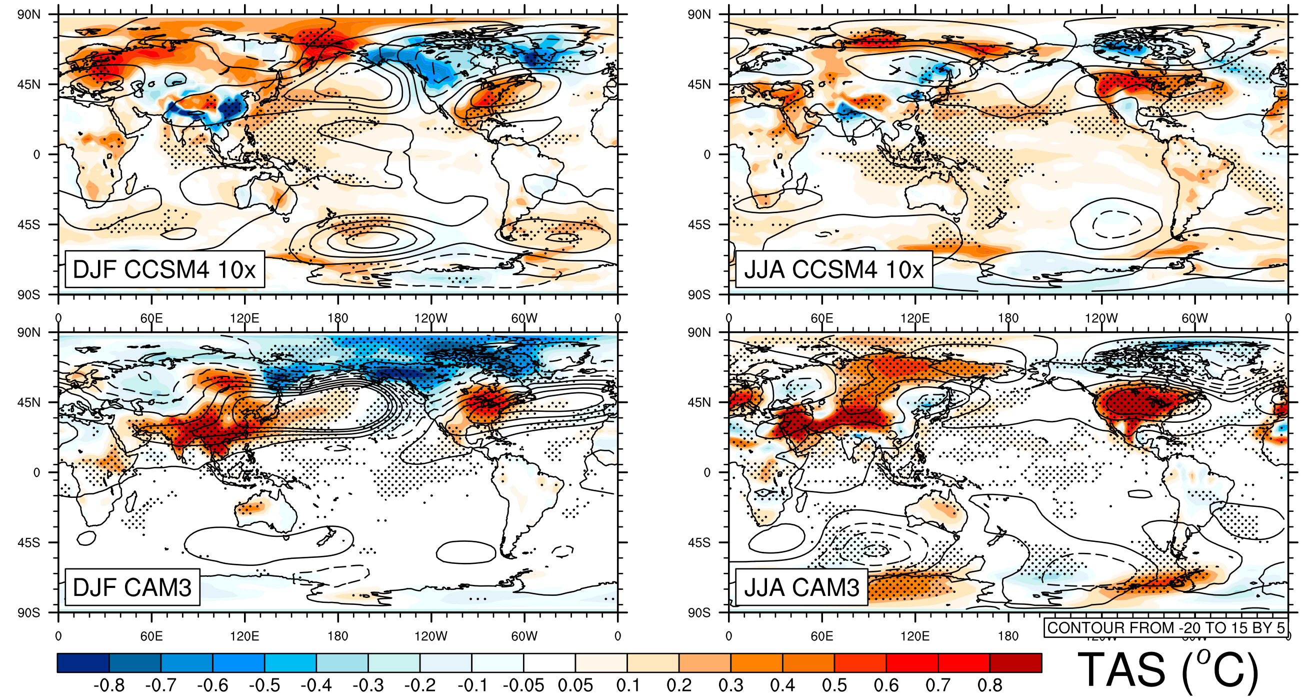

Figure 3. (top) Surface air temperature (TAS, shading) and 500 hPa geopotential height (Z500, contours) anomalies in (left) DJF and (right) JJA during 2005–2024 in 10×. (bottom) TAS and Z500 anomalies from the CAM3 specified heating experiment. Stippling indicates areas where the TAS anomalies are significant at the 90% level from a Student's t-test.

Surface dimming is less clear in JJA with cooling only occurring over North India and the northeast corner of our Asian domain.

[11] Both 6× and 10× produce consistent warm anomalies over the western Pacific. In addition, there is a roughly 0.4°C warming on average over the US East Coast (85°–70°W, 30°–50°N) during winter and over the entire US (125°–70°W, 30°–50°N) during summer. The warming is more significant in summer than in winter because there is smaller ensemble spread and more consistency across the three experiments. Other regions that have consistent temperature responses in 6× and 10× include the Eurasian region at high latitudes in DJF and the Near East and Brazil in JJA.

[12] In order to further verify that Asian heating anomalies like those produced in 2×, 6× and 10× can produce US temperature anomalies, we used a technique similar to *Meehl et al.* [2006] and specified diabatic heating anomalies in a T42 version of the atmospheric component of CCSM3 (CAM3 [*Collins et al.*, 2006]). (We did not use the atmospheric component of CCSM4 because such a capacity was still under development.)

[13] Two CAM3 experiments were carried out. One was a 1000-year control experiment with both sea surface temperature (SST) and external forcings fixed at present-day levels. The other was a 200-year experiment with a similar model setup except that a steady heat source centered in our Asian domain was added to the model's thermodynamic energy equation. To include this added source, the vertical heating profile was calculated from the solar heating anomalies in 10× relative to RCP4.5 with the following approximations: a) the heating profile did not have seasonal variations; b) the vertical distribution of the heating profile at the center of the Asian domain was approximated by an exponential function derived from a least square fit to the 10× solar heating anomalies averaged over the domain, while the heating rate decreased linearly to zero towards the borders of the domain.

[14] With these approximations, the heating profile at the center of the Asia domain is calculated as $H = 0.019 * \exp(0.00355 * p)$, where H and p stand for the heating rate in K/day and pressure in hPa, respectively. H has values of 0.04, 0.1, 0.4, 0.7 K/day at 200, 500, 850 hPa and the surface, respectively. Neglecting the annual cycle causes an overestimate in DJF and an underestimate in JJA in the mid to upper troposphere, both on the order of about 0.05 K/day, and a much bigger overestimate in JJA in the lower atmosphere (~0.2 K/day at 900 hPa and 0.5 K/day at surface).

[15] Despite these approximations, as well as the large differences in the formulation of the two atmosphere models and the lack of an interactive ocean in CAM3, the TAS anomalies in the specified heating experiment show a striking resemblance to those in 10× over North America in both DJF and JJA (shading in Figure 3). These matching anomalies in regions far from Asia indicate that the Asian carbon aerosols in CCSM4 and the specified heating in CAM3 are producing similar large-scale remote responses.

[16] We use 500 hPa geopotential height (Z500) anomalies to represent the circulation change in our experiments (contours in Figure 3). In both seasons, positive anomalies occur above the warm US TAS anomalies. In DJF in both models these features are associated with a three-lobed feature downstream of the Asian source that is reminiscent of the Pacific/North America (PNA) pattern. Although PNA with this sign is often forced from the tropical Pacific by rainfall deficits, as during La Nina events, it is also an intrinsic pattern of the atmosphere variability, which means it can be easily excited. Here the Z500 anomalies do not

have negative anomalies with comparable amplitudes over Hawaii as would occur during such events if they were excited from the equatorial Pacific. Lack of significant equatorial precipitation anomalies in 10× (Figure S2) also support that the DJF Z500 anomalies in Figure 3 are not tropically excited. Moreover, in the CAM3 experiment there are no SST anomalies to sustain forcing from the tropics.

[17] Earlier we hypothesized that aerosol induced changes in either the monsoon hydrological cycle or in radiative heating in Asia could cause large-scale circulation changes. We find the solar heating anomalies in the Asian box in 10× are at least an order of magnitude larger than the latent heat anomalies in the same region as well as in the Tropics. Thus we think the US warming and high pressure anomalies in 6× and 10× are likely caused by aerosol direct effects, rather than by changes in the hydrological cycle. The similarity of the Z500 patterns but disagreement in the Asian precipitation anomalies in the CCSM4 and CAM3 experiments also support this conjecture.

4. Summary and Discussion

[18] Our experiments with CCSM4 indicate that if Asian carbon aerosol concentrations are greatly increased in the 21st century, the induced large-scale circulation may add 0.4°C TAS warming on average over the eastern US during winter and over almost the entire US during summer. This warming is in addition to the anthropogenically-induced TAS warming over the same US domain found in the CCSM4 RCP4.5 experiment [*Meehl et al.*, 2012], which during 2005–2024 is about 0.9°C and 0.7°C in DJF and JJA, respectively. Hence the US warming is amplified by roughly 50% by the remote effects of the enhanced carbon aerosols over Asia in the 6× and 10× experiments.

[19] These remote impacts on the US are largely reproduced by a CAM3 specified heating experiment, providing additional evidence that the increased tropospheric heating from solar absorption due to greater concentrations of carbon aerosols over Asia can directly affect US climate. This is in spite of the differences in the formulation of the two atmospheric models and the many approximations in the heating profile used in the CAM3 experiment. The agreement not only adds more confidence to our results, it suggests that the remote impacts may not be very sensitive to the fine structure of the heating profile. However, we must add the caveat that there are large uncertainties in black carbon aerosol emission data and aerosol indirect effects are not represented in the model we have employed.

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