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Do climate models reproduce observed solar dimming and brightening over China and Japan?

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[1] Previous research indicates that clear-sky downward solar radiation measured at the surface over China significantly decreased by about -8.6 W m^{-2} per decade during 1961–1989 and insignificantly increased during 1990–1999. Furthermore, solar radiation over Japan remained relatively constant during 1971–1989 and significantly increased by $+5.3$ W m^{-2} per decade during 1990–1999. The present study compares observed trends with those from twentieth century simulations by 14 global climate models in the CMIP3/IPCC-AR4. Since radiative forcing by aerosols is the primary contributor to long-term variations in surface solar radiation, the simulations are expected to resemble the observed trends if the input aerosol histories are realistic. To minimize the confounding impact of different cloud realizations in the observations and models, the radiative effects of cloud cover anomalies are removed from the surface solar radiation anomalies via linear regression. Although all of the models exhibit significant dimming trends over China before 1990, the largest model trend is -3.4 W m^{-2} per decade, less than half the magnitude and significantly different from the observed trend. Models including black carbon aerosol produce stronger decreasing trends than those that do not. The models also fail to reproduce the trend during 1990–1999 over Japan, and the largest model trend is $+2.3$ W m^{-2} per decade, only about half of the observed trend. These results suggest that global climate models uniformly underestimate the increase in aerosol radiative forcing over China prior to 1990 and uniformly underestimate the decrease in aerosol radiative forcing over Japan after 1990.

1. Introduction

[2] Solar radiation at the Earth's surface plays a large role in physical climate and biospheric processes. Measurements in many regions have shown a decrease in the amount of solar radiation reaching the Earth's surface between the 1960s and the 1980s (popularly called solar or global dimming) followed by an increase during the 1990s and hereafter (solar brightening) [*Wild*, 2009a, and references therein]. Changes in cloud cover (the fraction of the sky covered by clouds) do not appear to be the dominant factor driving solar radiation trends for Europe and East Asia [*Norris and Wild*, 2007, 2009; *Ruckstuhl et al.*, 2008; *Rangwala et al.*, 2006]. Instead, increasing and decreasing anthropogenic aerosol emissions are most likely responsible for the observed dimming and brightening, respectively [*Streets et al.*, 2008, 2009]. The direct radiative effect of aerosols includes scattering (primarily by sulfate particles)

and absorption (primarily by black carbon aerosols), both of which reduce incoming solar radiation at the surface. Possible indirect radiative effects of aerosols include enhancement of cloud albedo [*Twomey et al.*, 1984] and a longer cloud lifetime [*Albrecht*, 1989] which also decrease incoming solar radiation at the surface.

[3] Although direct and possibly indirect radiative effects of anthropogenic aerosols have most likely had a substantial impact on the rate of global warming during the twentieth century, it has been difficult to quantify the specific magnitude of anthropogenic aerosol radiative forcing over time [*Solomon et al.*, 2007]. Uncertainty in the amount of aerosol radiative forcing during past decades leads to uncertainty in the value of climate sensitivity (e.g., how much Earth's equilibrium surface temperature will rise with a doubling of CO_2). *Knutti* [2008] found that climate models with weak climate sensitivity tended to use a small value of aerosol radiative cooling to reproduce observed twentieth century warming, and that models with strong climate sensitivity tended to use a large value of aerosol radiative cooling to reproduce observed warming. If we could better constrain aerosol radiative forcing, we would reduce uncertainty in climate sensitivity and projections of how much warming will likely occur in the 21st century.

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[4] Some recent studies to constrain estimates of past aerosol radiative forcing have used multidecadal surface solar radiation measurements to evaluate simulated dimming and brightening in climate models [*Ruckstuhl and Norris*, 2009; *Wild*, 2009b; *Rangwala et al.*, 2006]. Although the timing of the transition from dimming to brightening in models generally does not correspond to that seen in observations for Europe, the modeled solar radiation trends are quite consistent with their respective input aerosol emission histories [*Ruckstuhl and Norris*, 2009]. This suggests that observed multidecadal variations in surface solar radiation can help determine the most realistic time series of aerosol emissions/burdens in regions of the world where sufficient measurements are available.

[5] In the present study, we use the approach of *Ruckstuhl and Norris* [2009] to compare observed multidecadal changes in surface solar radiation over China and Japan with those simulated by the Intergovernmental Panel of Climate Change Fourth Assessment Report IPCC-AR4 models, officially called the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set. Radiative effects of cloud cover variations, predominantly driven by different realizations of weather, are empirically removed from the observational data and model output using the method of *Norris and Wild* [2007] in order to focus on dimming and brightening trends produced by long-term changes in aerosol emissions and burdens. Differences between observed and simulated radiation trends are then examined in the context of the input aerosol histories used by particular models.

2. Observations, Model Output, and Input Aerosol Histories

2.1. Observed Solar Irradiance and Cloud Data

[6] The source of surface solar radiation measurements in this analysis was the Global Energy Budget Archive (GEBA) [*Gilgen and Ohmura*, 1999]. We aggregated monthly global (direct + diffuse) radiation anomalies at each station into 280 km grid boxes over China and Japan. Monthly anomalies of total cloud cover from two collections of surface synoptic reports at weather stations [*Hahn and Warren*, 2003; *Shiyan et al.*, 1997] and the International Satellite Cloud Climatology Project (ISCCP) [*Rossow et al.*, 1996] were combined into the same grid boxes. All major and smaller Japanese islands were represented by gridded data, but some areas of eastern China and all of western China did not have any grid boxes with sufficiently long and reliable time series of GEBA measurements. Further details about the observations and the locations of the stations and grid boxes are given by *Norris and Wild* [2009].

[7] Variations in cloud cover have a large impact on surface solar radiation at monthly to subdecadal time scales but appear to be unrelated to changes in aerosol [*Norris and Wild*, 2007, 2009]. Clear-sky measurements are therefore more suitable for assessing changes in solar radiation due to anthropogenic aerosol, but they are unfortunately not geographically extensive and lack lengthy records. Using the method described by *Norris and Wild* [2007], we empirically removed the radiative contributions of cloud cover anomalies from global radiation anomalies via linear regression. The resulting "residual" anomalies include both clear-sky solar radiation anomalies and the effects of changes in cloud albedo that are uncorrelated with cloud cover. Dimming and brightening trends are much more distinct in the residual time series than in the original time series.

2.2. Model Output

[8] The present study investigated long-term variability in surface solar radiation over China and Japan simulated by 14 climate models listed in Table 1 that had suitable output from the WCRP CMIP3 multimodel data set [*Meehl et al.*, 2007], which is maintained by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). Specifically, we used monthly values of total cloud fraction, all-sky downward surface solar radiation flux, and clear-sky downward surface solar radiation flux during the 1961–1999 time period from the twentieth century simulations (20C3M) that contributed to the IPCC-AR4. A study by *Wild et al.* [2006] of clear-sky downward surface solar radiation flux showed good agreement between AR4 models and surface observations in terms of climatology. Most models participating in the 20C3M did not include any output after 1999. For best comparability to the observations, we employed the method used for the observations to remove radiative impacts of model cloud cover anomalies from model all-sky radiation anomalies. We also analyzed modeled clear-sky fluxes (not shown), which had similar trends as the residual fluxes. In order to avoid geographical biases, we bilinearly interpolated model output from the centers of the model grid boxes to the centers of the observed grid boxes. If a model had multiple runs available we averaged them together.

2.3. Model Aerosol Emission/Burden Histories

[9] The twentieth century scenarios examined in the present study intended to simulate the climate response to the actual external forcings experienced by the Earth. Not all models include the same types of external forcings (e.g., black carbon aerosol, volcanic aerosol, indirect radiative effects), nor do all models use the same input data set for a particular type of external forcing. In some cases, aerosols or precursor species are emitted, transported, and processed within the model, but in other cases, an off-line chemistry transport model is used to provide aerosol burdens to the climate model. Table 1 lists references for the input aerosol emission or burden data sets and whether the models include the cloud albedo and cloud lifetime indirect aerosol effects. All models include the direct radiative effect of sulfate aerosols (represented by three emission data sets and three burden data sets), and seven of the 14 models include the direct radiative effect of black carbon aerosols (represented by two emission data sets and two burden data sets). Half of the models incorporate the cloud albedo indirect effect, only three models incorporate the cloud lifetime indirect effect, and ten models include volcanic forcing. We performed the same interpolation technique for aerosols as we did for the model output.

[10] Figure 1 displays the regional mean time series of aerosol emissions and aerosol burdens for China and Japan used in the twentieth century simulations. Although emission data sets and burden data sets are not comparable in terms of units and magnitudes, we can nevertheless examine relative changes over time. The aerosol emission histories

Table 1. IPCC-AR4 Models Considered in This Study

| Abbreviation	Originating Group(s)	Reference	Number of Runs	Sulfate/Sulfur Dioxide	Black Carbon	Cloud Albedo Indirect Effect	Cloud Lifetime Indirect Effect	Volcanic Forcing
CNRM-CM3	Météo-France/Centre National de Recherches Meteorologiques, France	Salas-Mélia et al. [2005]	1	Boucher and Pham [2002]	Tanré et al. [1984] scaled by Novakov et al. [2003]	no	no	no
GFDL–CM2.0/GFDL–CM2.1	U.S. Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	Delworth et al. [2006]	3/3	Horowitz [2006]	Horowitz [2006]	no	no	Sato et al. [1993], Ramachandran et al. [2000]
FGOALS-g1.0	LASG/Institute of Atmospheric Physics, China	Yu et al. [2004]	3	Boucher and Pham [2002]	none	no	no	no
INM-CM3.0	Institute for Numerical Mathematics, Russia	Galin et al. [2003]	1	Smith et al. [2001, 2004]	none	no	no	Ammann et al. [2003]
IPSL-CM4	Institut Pierre Simon Laplace, France	Marti et al. [2005]	1	Boucher and Pham [2002]	none	yes	no	no
MIROC3.2 (hires)/MIROC3.2 (medres)	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	K-1 Developers [2004]	1/3	Nozawa et al. [2007]	Nozawa et al. [2007]	yes	yes	Sato et al. [1993]
ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group, Germany/Korea	Legutke and Voss [1999]	5	Roeckner et al. [1999]	none	yes	no	Crowley [2000]
ECHAM5/MPI-OM	Max Planck Institute for Meteorology, Germany	Roeckner et al. [2003]	3	Boucher and Pham [2002]	none	yes	no	no
MRI-CGCM2.3.2	Meteorological Research Institute, Japan	Yukimoto et al. [2006]	1	Mitchell and Johns [1997]	none	no	no	Sato et al. [1993]
CCSM3.0	National Center for Atmospheric Research	Collins et al. [2002]	8	Smith et al. [2001, 2004]	Collins et al. [2002] scaled by global population	no	no	Ammann et al. [2003]
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research/Met Office, UK	Johns et al. [2003]	1	Smith et al. [2001, 2004]	none	yes	no	Sato et al. [1993]
KMO-HadGEM1	Hadley Centre for Climate Prediction and Research/Met Office, UK	Martin et al. [2006]	4	Smith et al. [2001, 2004]	Nozawa et al. [2007]	yes	yes	Sato et al. [1993]
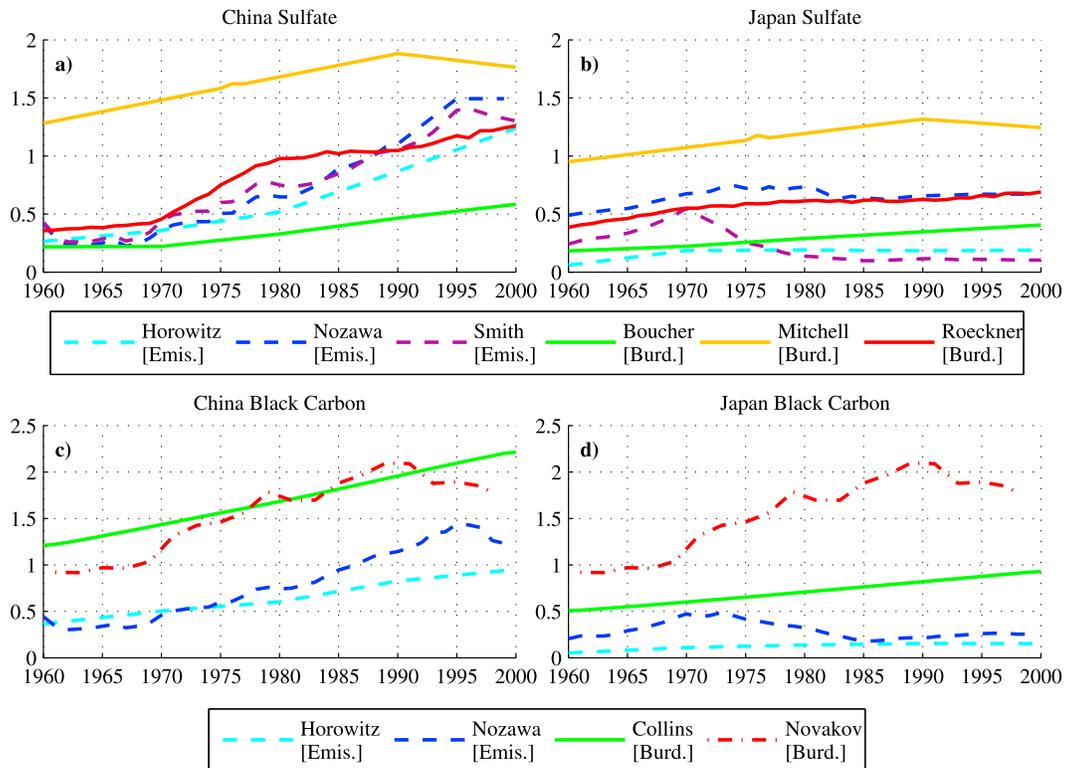
Figure 1. Sulfate emission (dashed lines) and sulfate burden (solid lines) from different data sources used in IPCC-AR4 simulations. Data represent averages for (a) China and (b) Japan. Each plot includes emissions and burdens, though they cannot be directly compared since emissions are plotted in units of 10^5 kg m^{-2} s^{-1} while burdens have units of kg m^{-2}. Black carbon emission (dashed lines) and black carbon burden (solid lines) are shown for (c) China and (d) Japan. The *Novakov et al.* [2003] time series (dash-dotted lines) have identical relative variations over China and Japan and are plotted in arbitrary units since scaling factors for converting to physical units were unavailable.

for China exhibit similar long-term means and rates of increase for sulfate or black carbon aerosol between 1960 and 1990, but they disagree over whether sulfate and black carbon emissions flattened out or declined after 1995 [*Smith et al.*, 2001, 2004; *Nozawa et al.*, 2007] or instead increased [*Horowitz*, 2006]. The sulfate aerosol burden histories for China contrastingly have much larger differences between long-term means and rates of increase. One of them exhibits a decrease after 1990 [*Mitchell and Johns*, 1997], and two of them exhibit an increase [*Roeckner et al.*, 1999; *Boucher and Pham*, 2002]. The black carbon burden data sets for China increase until 1990, after which one continues to increase [*Collins et al.*, 2002] and the other decreases [*Novakov et al.*, 2003]. Scaling factors to convert the *Novakov et al.* [2003] time series into physical units over China and Japan were unavailable so it is plotted in arbitrary units.

[11] The aerosol emission histories for Japan have less consistency in their long-term means and temporal variability. All data sets exhibit increasing emissions during 1960–1970 and nearly flat emissions during 1985–2000, but during 1970–1985 *Nozawa et al.* [2007] show slightly decreasing emissions, *Smith et al.* [2004] show strongly decreasing emissions, and *Horowitz* [2006] shows steady emissions. The aerosol burden histories for Japan cannot be expected to resemble the emission histories since the latter

do not take into account transport of aerosol from the climatologically upwind region of China. The Japan sulfate burdens as well as the *Collins et al.* [2002] black carbon burden were similar to the respective China histories, albeit with weaker magnitude. The *Novakov et al.* [2003] time series are identical for China and Japan because the temporal aerosol variations were assumed to be globally uniform.

3. Results

[12] Figure 2a shows the time series of observed and modeled annual anomalies in residual flux for China. Since the radiative effects of cloud cover anomalies were removed from all-sky flux (global radiation) to obtain residual flux, these time series represent variability in clear-sky solar flux and possible changes in cloud albedo. The observed time series, identical to that presented in Figure 2 of *Norris and Wild* [2009], shows significant dimming from 1961 to around 1990. While there are year-to-year variations, the long-term trend is a strong decline. Residual flux over China began to increase from 1990 onward, perhaps in part due to the recovery from the Mount Pinatubo volcanic eruption in 1991, and the late 1990s values are more positive than the late 1980s values. The post-1990 increase, however, is not statistically significant [*Norris and Wild*, 2009]. All climate models show a mostly steady downward trend during 1961–
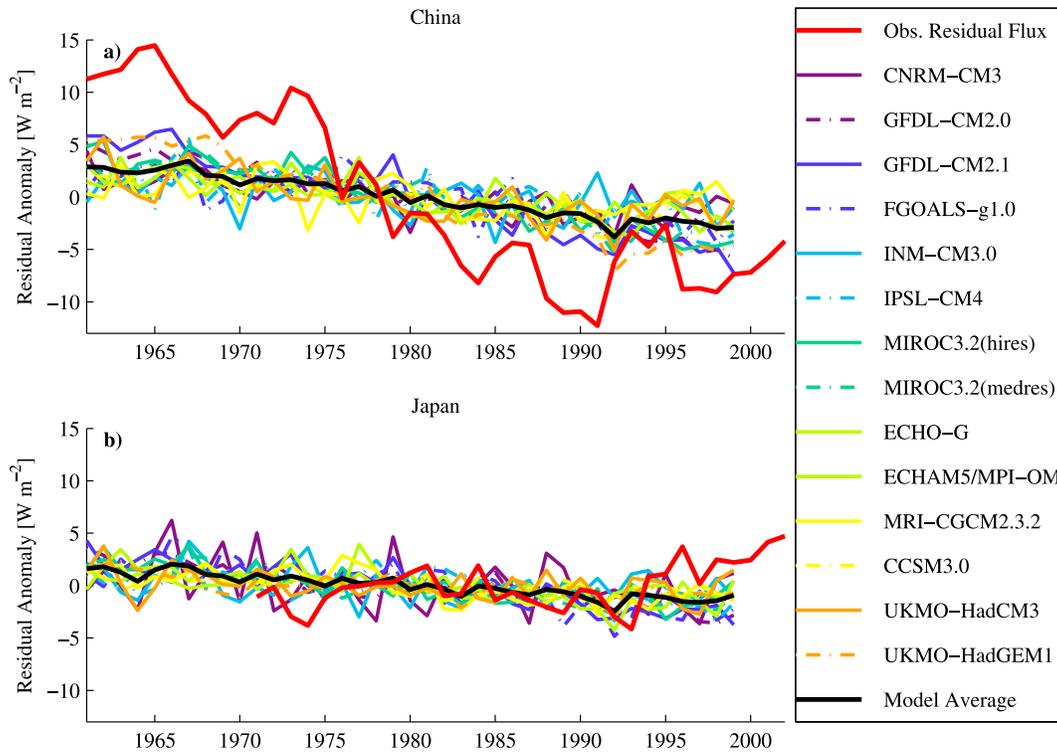
Figure 2. Time series of annual residual flux anomalies averaged over (a) China and (b) Japan. The red line is observational data, other colors are 14 IPCC-AR4 20C3M simulations, and the black line is the ensemble average over the 14 models.

1990, though their dimming trends are much weaker than that seen in the observations. After 1990, the model ensemble mean continues to decline, but a few models exhibit brightening trends.

[13] Figure 2b displays the observed and modeled time series of residual flux over Japan. The observed time series begins in 1971 because cloud cover data were not available prior to that time. There is no significant observed trend prior to 1990, but observed residual flux substantially increases after 1990. These results are generally consistent with the findings of *Wang et al.* [2009], who report a large decline in visibility over China but not over Japan during 1973–2007. All models show weak dimming for Japan prior to 1990 and divergent results afterward. Some models produce a small post-1990 increase in residual flux while others produce a small decrease or no change.

[14] For a more convenient comparison of dimming and brightening in the observed and modeled time series, we calculated least squares linear trends on monthly residual flux anomalies during 1961–1989 (China), 1971–1989 (Japan), and 1990–1999 (China and Japan). We found that the results were not sensitive to a several-year shift in the starting and ending points. Following *Norris and Wild* [2007, 2009], our calculation of the 95% confidence interval of trend values took into account the autocorrelation in the time series. The results are presented in Figure 3a for China and Figure 3b for Japan.

[15] None of the climate models come close to reproducing the strong decrease in residual flux observed for China prior to 1990 (the largest model trend is -3.4 W m^{-2} per decade with a 95% confidence interval of ± 0.5 W m^{-2} per

decade whereas the observed trend is -8.6 ± 1.1 W m^{-2} per decade). This lack of consistency remains if we compare modeled clear-sky flux to observed residual flux or modeled all-sky flux to observed all-sky flux (not shown), although there is more scatter in the latter case since the simulations have different realizations of cloud cover variability. Standard tests indicate that all of the models produce a magnitude of dimming that is significantly different from the observations and significantly different from zero at the 95% confidence level.

[16] Observed residual flux shows an increasing yet nonsignificant trend during 1990–1999 for China. The models exhibit a wide range of behavior: the majority show dimming, some show brightening, and only one has a (dimming) trend that is significantly different from zero (GFDL-CM2.0). No modeled trends are statistically different from the observed trend. The shortness of the time period (only 10 years) is probably a contributing factor to the lack of statistical significance. It appears that the recovery from the 1991 Mount Pinatubo eruption did not play a large role in the modeled 1990–1999 brightening since the majority of models that include volcanic aerosol exhibit decreasing residual flux during this time period. A comparison of Figure 1 and Figure 3 suggests that there is anticorrelation between the sign of the residual flux trend and the sign of the aerosol trend during 1990–1999. For example, the strongest positive residual flux trend occurs in a model using the aerosol data set with the strongest decrease during 1990–1999 [*Mitchell and Johns*, 1997] and the strongest negative residual flux trend occurs in a model using the aerosol data set with the strongest increase during 1990–1999 [*Horowitz*, 2006].
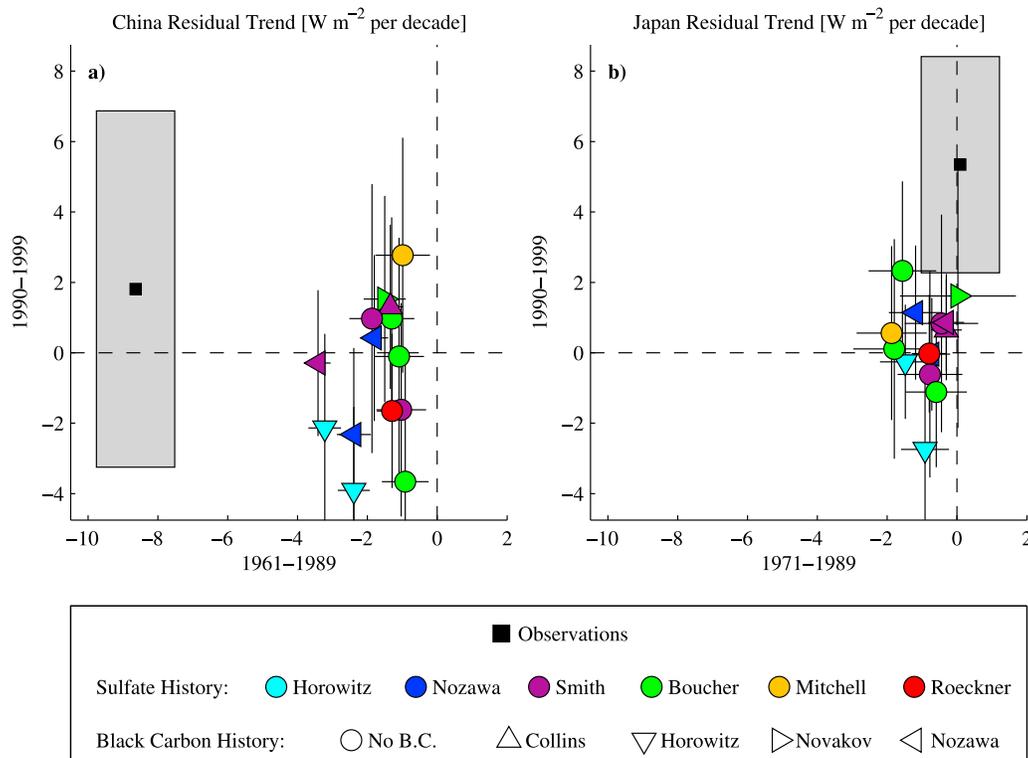
Figure 3. Scatterplots of residual flux linear trends (a) over China for 1961–1989 versus 1990–1999 and (b) over Japan for 1971–1989 versus 1990–1999. Observations are located in the center of the gray rectangles, where the edges represent the 95% confidence interval of the trend in fitting to observed data. The marker colors indicate the sulfate emission or sulfate burden data set used in the simulations, and the marker shape indicates the black carbon data set. Error bars denote the 95% confidence interval of the linear trends for the respective period.

[17] Unlike China, Japan experienced no dimming or brightening trends during 1971–1989. All models, except for CNRM-CM3, show dimming trends, eight of which are significantly different from zero, but only the GFDL-CM2.1, FGOALS-g1.0, and MRI-CGCM2.3.2 are significantly different from the observed trend at the 95% level. During 1990–1999, there is a statistically significant brightening trend during 1990–1999. Most of the models produce a brightening trend, but the only statistically significant trend is dimming (by GFDL-CM2.0). The most positive modeled trend is +2.3 ± 2.5 W m^{-2} per decade whereas the observed trend is +5.3 ± 3.1 W m^{-2} per decade. All models except for the CNRM-CM3, MIROC3.2(hires), ECHAM5/MPI-OM, MRI-CGCM2.3.2, and UKMO-HadCM3 have trends that are significantly different from the observed trend, suggesting that the simulated aerosol burden over Japan may be unrealistic after 1990. It is difficult to assess the degree of correspondence between residual flux trends and aerosol emission trends over Japan due to the confounding impact of aerosol transport from China. No systematic relationship was found between the input aerosol data set used by a model and whether that model had trends different from the observations.

[18] Half of the 14 models examined in this study do not include a radiative effect due to black carbon. Although it is not possible to make a direct connection between the aerosol time series displayed in Figure 1 and the residual flux time series in Figure 2, we do note that all seven models that include black carbon effects are among the eight models with the largest dimming trends over China during 1961–1989. The average dimming for models with black carbon is −2.3 ± 0.2 W m^{-2} per decade compared to −1.2 ± 0.3 W m^{-2} per decade for those without.

[19] Only half of the models include processes that enable aerosol particles to potentially modify cloud albedo. This indirect aerosol radiative effect, if operating, would be included in our calculation of modeled residual flux but not in modeled clear-sky flux. Averaged over those models that included a potential cloud albedo indirect effect, we found that the trends for residual flux were no more than 0.1 W m^{-2} per decade greater than the trends for clear-sky flux for both China and Japan and pre-1990 and post-1990 (not shown). If the cloud albedo effect were a substantial contributor to model dimming and brightening over China and Japan, we would expect to see stronger trends in residual flux than in clear-sky flux. Recent observational evidence for Europe suggests that trends in all-sky radiation are primarily driven by the direct radiative effect of aerosol rather than by aerosol modification of cloud albedo [*Ruckstuhl et al.*, 2010]. It is also expected that the aerosol indirect effects will have a smaller influence on cloud characteristics in polluted regions than in pristine regions [*Wild*, 2009a]. The IPCC-AR4 model simulations are consistent with a larger impact of

aerosol direct radiative effects on surface radiation in East Asia.

[20] Three models allow aerosols to interact with precipitation processes and thereby potentially modify cloud lifetime and cloud cover. We found no consistency in the sign of trends in cloud cover over China and Japan produced by these three models, nor was there any evidence for systematic differences between cloud trends produced by models that did and models that did not incorporate a cloud lifetime aerosol indirect effect (not shown). There is no observational evidence that aerosol modification of precipitation has produced systematic changes in cloud cover over Europe, China, or Japan [*Norris and Wild*, 2007, 2009].

4. Summary and Conclusion

[21] This study compared long-term variations in observed and modeled downward solar radiation at the surface over China and Japan during 1961–1999. Simulated surface radiation and cloud output were obtained from twentieth century simulations carried out by 14 global climate models. For both observations and models, the cloud cover anomalies were empirically removed from the solar flux anomalies via linear regression to minimize the confounding impact of different realizations of cloudiness. The resulting residual flux more distinctly showed radiative impacts of long-term changes in aerosols. All models included as input the history of sulfate emissions or sulfate burdens, and seven models included the history of black carbon emissions or black carbon burden. The correspondence in observed and modeled residual flux trends can be used to assess the realism of the various aerosol histories used by different models.

[22] The preceding results describe a predominant tendency for models to underestimate the magnitude of observed long-term regional changes in surface solar radiation over East Asia, whether they are decreasing (over China during 1961–1989) or increasing (over Japan during 1990–1999). These errors may be caused by the underestimation of long-term changes in aerosol emissions used as input to twentieth century climate simulations, errors in the processing, transport, and removal of aerosols by the models, or an underestimation of the radiative impact of aerosol changes in the models. While we found no systematic relationship between the magnitude of modeled trends in residual flux and the inclusion of a cloud albedo aerosol indirect effect by the model, the average dimming trend of models with black carbon aerosol was larger than the trend of those without.

[23] Because surface cooling by aerosols has partially compensated surface warming due to increased greenhouse gases over the past century, it is essential to accurately quantify how different types of aerosols and their radiative effects have been changing around the world. In this study, we used observed dimming and brightening trends over China and Japan to assess the realism of input aerosol data sets and their impact on downward surface radiation in twentieth century simulations by global climate models. The results of this investigation and those for other regions will help constrain aerosol radiative forcing and thereby estimated climate sensitivity, thus narrowing the range of projected global warming during the 21st century.

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