

1 Do climate models reproduce observed solar dimming 2 and brightening over China and Japan?

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3 **Abstract.** Previous research indicates that clear-sky downward solar ra-
4 diation measured at the surface over China decreased by about -8.6 W m^{-2}
5 per decade during 1961-1989 and insignificantly increased during 1990-1999.
6 Furthermore, solar radiation over Japan remained relatively constant dur-
7 ing 1971-1989 and substantially increased by $+5.3 \text{ W m}^{-2}$ per decade dur-
8 ing 1990-1999. The present study compares observed solar radiation trends
9 with those from 20th century simulations by fourteen global climate mod-
10 els that contributed to the CMIP3/IPCC-AR4. Since radiative forcing by
11 aerosols is the primary contributor to long-term variations in surface solar
12 radiation, the simulations are expected to resemble the observed trends if
13 the input aerosol histories are realistic. To minimize the confounding impact
14 of different cloud realizations in the observations and models, the radiative
15 effects of cloud cover anomalies are removed from the surface solar radiation
16 anomalies via linear regression. Although all of the models exhibit dimming
17 trends over China before 1990, the largest model trend is -3.4 W m^{-2} per
18 decade, less than half of the magnitude of the observed trend. Models includ-
19 ing black carbon aerosol, however, produce stronger decreasing trends than
20 those that do not. The models also fail to reproduce statistically significant
21 brightening trends during 1990-1999 over Japan, and the largest model trend
22 is $+2.3 \text{ W m}^{-2}$ per decade, only about half of the observed trend. These re-
23 sults suggest that global climate models uniformly underestimate the increase
24 in aerosol radiative forcing over China prior to 1990 and uniformly under-
25 estimate the decrease in aerosol radiative forcing over Japan after 1990.

1. Introduction

Solar radiation at the Earth's surface plays a large role in physical climate and biological life. Measurements in many regions have shown a decrease in the amount of solar radiation reaching the Earth's surface between the 1960's and the 1980's (popularly called solar dimming) followed by an increase during the 1990's and hereafter (solar brightening) [Wild, 2009a, and references therein]. Changes in cloud cover 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]. 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.

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 20th 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 CO₂). Knutti [2008] found that climate models with weak climate sensitivity tended to use a small value of aerosol radiative cooling to reproduce observed 20th century warming, and

47 that models with strong climate sensitivity tended to use a large value of aerosol radiative
48 cooling to reproduce observed warming. If we could better constrain aerosol radiative
49 forcing, we would reduce uncertainty in climate sensitivity and projections of how much
50 warming will occur in the 21st century.

51 Some recent studies to constrain estimates of past aerosol radiative forcing have used
52 multidecadal surface solar radiation measurements to evaluate simulated dimming and
53 brightening in climate models [*Ruckstuhl and Norris*, 2009; *Wild*, 2009b]. Although the
54 timing of the transition from dimming to brightening in models generally does not cor-
55 respond to that seen in observations for Europe, the modeled solar radiation trends are
56 quite consistent with their respective input aerosol emission histories [*Ruckstuhl and Nor-*
57 *ris*, 2009]. This suggests that observed multidecadal variations in surface solar radiation
58 can help determine the most realistic time series of aerosol emissions/burdens in regions
59 of the world where sufficient measurements are available.

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

69 simulated radiation trends are then examined in the context of the input aerosol histories
70 used by particular models.

2. Observations, Model Output, and Input Aerosol Histories

2.1. Observed Solar Irradiance and Cloud Data

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

82 Variations in cloud cover have a large impact on surface solar radiation at monthly to
83 subdecadal time scales but appear to be unrelated to changes in aerosol [*Norris and Wild,*
84 *2007, 2009*]. Clear-sky measurements are therefore more suitable for assessing changes in
85 solar radiation due to anthropogenic aerosol, but they are unfortunately not geographically
86 extensive and lack lengthy records. Using the method described in *Norris and Wild* [2007],
87 we empirically removed the radiative contributions of cloud cover anomalies from global
88 radiation anomalies via linear regression. The resulting “residual” anomalies include both
89 clear-sky solar radiation anomalies and the effects of changes in cloud albedo that are

90 uncorrelated with cloud cover. Dimming and brightening trends are much more distinct
91 in the residual time series than in the original time series.

2.2. Model Output

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

2.3. Model Aerosol Emission/Burden Histories

106 The 20th century scenarios examined in the present study intended to simulate, as best
107 as possible, the climate response to the actual external forcings experienced by the Earth.
108 Not all models include the same types of external forcings (e.g., black carbon aerosol,
109 volcanic aerosol, indirect radiative effects, etc.), nor do all models use the same input

110 data set for a particular type of external forcing. In some cases, aerosols or precursor
111 species are emitted, transported, and processed within the model, but in other cases,
112 an offline chemistry transport model is used to provide aerosol burdens to the climate
113 model. Table 1 lists references for the input aerosol emission or burden data sets and
114 whether the models include the cloud albedo and cloud lifetime indirect aerosol effects.
115 All models include the direct radiative effect of sulfate aerosols (represented by three
116 emission data sets and three burden data sets), and seven of the fourteen models include
117 the direct radiative effect of black carbon aerosols (represented by two emission data sets
118 and two burden data sets). Half of the models incorporate the cloud albedo indirect effect,
119 only three models incorporate the cloud lifetime indirect effect, and ten models include
120 volcanic forcing. We performed the same interpolation technique for aerosols as we did
121 for the model output.

122 Figure 1 displays the regional mean time series of aerosol emissions and aerosol burdens
123 for China and Japan used in the 20th century simulations. Although emission data sets
124 and burden data sets are not comparable in terms of units and magnitudes, we can
125 nevertheless examine relative changes over time. The aerosol emission histories for China
126 exhibit similar long-term means and rates of increase for sulfate or black carbon aerosol
127 between 1960 and 1990, but they disagree over whether sulfate and black carbon emissions
128 flattened out or declined after 1995 [Smith et al., 2001, 2004; Nozawa et al., 2007] or instead
129 increased [Horowitz, 2006]. The sulfate aerosol burden histories for China contrastingly
130 have much larger differences between long-term means and rates of increase. One of them
131 exhibits a decrease after 1990 [Mitchell and Johns, 1997], and two of them exhibit an
132 increase [Roeckner et al., 1999; Boucher and Pham, 2002]. The black carbon burden

133 data sets for China increase until 1990, after which one continues to increase [*Collins*
134 *et al.*, 2002] and the other decreases [*Novakov et al.*, 2003]. Scaling factors to convert the
135 *Novakov et al.* time series into physical units over China and Japan were unavailable so
136 it is plotted in arbitrary units.

137 The aerosol emission histories for Japan have less consistency in their long-term means
138 and temporal variability. All data sets exhibit increasing emissions during 1960-1970 and
139 nearly flat emissions during 1985-2000, but during 1970-1985 *Nozawa et al.* show slightly
140 decreasing emissions, *Smith et al.* show strongly decreasing emissions, and *Horowitz* shows
141 steady emissions. The aerosol burden histories for Japan cannot be expected to resemble
142 the emission histories since the latter do not take into account transport of aerosol from
143 the climatologically upwind region of China. The Japan sulfate burdens as well as the
144 *Collins et al.* black carbon burden were similar to the respective China histories, albeit
145 with weaker magnitude. The *Novakov et al.* time series are identical for China and Japan
146 because the temporal aerosol variations were assumed to be globally uniform.

3. Results

147 Figure 2a shows the time series of observed and modeled annual anomalies in residual
148 flux for China. Since the radiative effects of cloud cover anomalies were removed from
149 all-sky flux (global radiation) to obtain residual flux, these time series represent variability
150 in clear-sky solar flux and possible changes in cloud albedo. The observed time series,
151 identical to that presented in Figure 2 of *Norris and Wild* [2009], shows significant dim-
152 ming from 1961 to around 1990. While there are year-to-year variations, the long term
153 trend is a strong decline. Residual flux over China began to increase from 1990 onward,
154 perhaps in part due to the recovery from the Mount Pinatubo volcanic eruption in 1991,

155 and the late 1990s values are more positive than the late 1980s values. The post-1990 in-
156 crease, however, is not statistically significant [Norris and Wild, 2009]. All climate models
157 show a mostly steady downward trend from 1961-1990, though their dimming trends are
158 much weaker than that seen in the observations. After 1990, the model ensemble mean
159 continues to decline, but a few models exhibit brightening trends.

160 Figure 2b displays the observed and modeled time series of residual flux over Japan.
161 The observed time series begins in 1971 because cloud cover data were not available prior
162 to that time. There is no significant observed trend prior to 1990, but observed residual
163 flux substantially increases after 1990. All models show weak dimming prior to 1990 and
164 divergent results afterward. Some models produce a small post-1990 increase in residual
165 flux while others produce a small decrease or no change.

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

173 None of the climate models come close to reproducing the strong decrease in residual
174 flux observed for China prior to 1990 (the largest model trend is -3.4 W m^{-2} per decade
175 whereas the observed trend is -8.6 W m^{-2} per decade). This result does not change if
176 we compare modeled clear-sky flux to observed residual flux or modeled all-sky flux to
177 observed all-sky flux (not shown), although there is more scatter in the latter case since the

178 simulations have different realizations of cloud cover variability. Standard tests indicate
179 that all of the models produce a magnitude of dimming that is significantly different from
180 the observations and significantly different from zero at the 95% confidence level.

181 Observed residual flux shows an increasing yet nonsignificant trend during 1990-1999
182 for China. The models exhibit a wide range of behavior: the majority show dimming,
183 some show brightening, and only one has a (dimming) trend that is significantly different
184 from zero (GFDL-CM2.0). No modeled trends are statistically different from the observed
185 trend. The shortness of the time period (only ten years) is probably a contributing factor
186 to the lack of statistical significance. It appears that the recovery from the 1991 Mount
187 Pinatubo eruption did not play a large role in the modeled 1990-1999 brightening since the
188 majority of models that include volcanic aerosol exhibit decreasing residual flux during this
189 time period. A comparison of Figure 1 and Figure 3 suggests that there is anticorrelation
190 between the sign of the residual flux trend and the sign of the aerosol trend during 1990-
191 1999. For example, the strongest positive residual flux trend occurs in a model using the
192 aerosol data set with the strongest decrease during 1990-1999 [*Mitchell and Johns, 1997*]
193 and the strongest negative residual flux trend occurs in a model using the aerosol data
194 set with the strongest increase during 1990-1999 [*Horowitz, 2006*].

195 Unlike China, Japan experienced no dimming or brightening trends during 1971-1989.
196 All models, except for CNRM-CM3, show dimming trends, eight of which are significantly
197 different from zero, but only the GFDL-CM2.1, FGOALS-g1.0, and MRI-CGCM2.3.2
198 are significantly different from the observed trend at the 95% level. During 1990-1999,
199 there is a statistically significant brightening trend during 1990-1999. Most of the models
200 produce a brightening trend, but the only statistically significant trend is dimming (by

201 GFDL-CM2.0). The most positive modeled trend is $+2.3 \text{ W m}^{-2}$ per decade whereas
202 the observed trend is $+5.3 \text{ W m}^{-2}$ per decade. All models except for the CNRM-
203 CM3, MIROC3.2(hires), ECHAM5/MPI-OM, MRI-CGCM2.3.2, and UKMO-HadCM3
204 have trends that are significantly different from the observed trend, suggesting that the
205 simulated aerosol burden over Japan may be unrealistic after 1990. It is difficult to as-
206 sess the degree of correspondence between residual flux trends and aerosol emission trends
207 over Japan due to the confounding impact of aerosol transport from China. No systematic
208 relationship was found between the input aerosol data set used by a model and whether
209 that model had trends different from the observations.

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

217 Only half of the models include processes that enable aerosol particles to potentially
218 modify cloud albedo. This indirect aerosol radiative effect, if operating, would be included
219 in our calculation of modeled residual flux but not in modeled clear-sky flux. Averaged
220 over those models that included a potential cloud albedo indirect effect, we found that the
221 trends for residual flux were no more than 0.1 W m^{-2} per decade greater than the trends
222 for clear-sky flux for both China and Japan and pre-1990 and post-1990 (not shown). If
223 the cloud albedo effect were a substantial contributor to model dimming and brightening

224 over China and Japan, we would expect to see stronger trends in residual flux than in
225 clear-sky flux. Recent observational evidence for Europe suggests that trends in all-sky
226 radiation are primarily driven by the direct radiative effect of aerosol rather than by
227 aerosol modification of cloud albedo [*Ruckstuhl et al.*, 2009].

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

4. Summary and Conclusion

236 This study compared long-term variations in observed and modeled downward solar
237 radiation at the surface over China and Japan during 1961-1999. Simulated surface radia-
238 tion and cloud output were obtained from 20th century simulations carried out by fourteen
239 global climate models. For both observations and models, the cloud cover anomalies were
240 empirically removed from the solar flux anomalies via linear regression to minimize the
241 confounding impact of different realizations of cloudiness. The resulting residual flux more
242 distinctly showed radiative impacts of long-term changes in aerosols. All models included
243 as input the history of sulfate emissions or sulfate burdens, and seven models included
244 the history of black carbon emissions or black carbon burden. The correspondence in

245 observed and modeled residual flux trends can be used to assess the realism of the various
246 aerosol histories used by different models.

247 The preceding results describe a predominant tendency for models to underestimate
248 the magnitude of observed long-term regional changes in surface solar radiation over
249 East Asia, whether they are decreasing (over China during 1961-1989) or increasing (over
250 Japan during 1990-1999). These errors may be caused by the underestimation of long-
251 term changes in aerosol emissions used as input to 20th century climate simulations, errors
252 in the processing, transport, and removal of aerosols by the models, or an underestimation
253 of the radiative impact of aerosol changes in the models. While we found no systematic
254 relationship between the magnitude of modeled trends in residual flux and the inclusion of
255 a cloud albedo aerosol indirect effect by the model, the average dimming trend of models
256 with black carbon aerosol was larger than the trend of those without.

257 Because surface cooling by aerosols has partially compensated surface warming due to
258 increased greenhouse gases over the past century, it is essential to accurately quantify
259 how different types of aerosols and their radiative effects have been changing around the
260 world. In this study, we used observed dimming and brightening trends over China and
261 Japan to assess the realism of input aerosol data sets and their impact on downward
262 surface radiation in 20th century simulations by global climate models. The results of
263 this investigation and those for other regions will help constrain aerosol radiative forcing
264 and thereby estimated climate sensitivity, thus narrowing the range of projected global
265 warming during the 21st century.

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Figure 1. Sulfate emission (dashed lines) and sulfate burden (solid lines) from different data sources used in IPCC-AR4 simulations. Data represent averages for China (a) and Japan (b). Each plot includes emissions and burdens, though they cannot be directly compared since emissions are plotted in units of $10^5 \text{ kg m}^{-2} \text{ s}^{-1}$ while burdens have units of kg m^{-2} . Black carbon emission (dashed lines) and black carbon burden (solid lines) are shown for China (c) and Japan (d). The *Novakov et al.* time series (dot-dashed 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.

Figure 2. Time series of annual residual flux anomalies averaged over China (a) and Japan (b). The red line is observational data, other colors are fourteen IPCC-AR4 20C3M simulations, and the black line is the ensemble average over the fourteen models.

Figure 3. Scatterplots of residual flux linear trends over China for 1961-1989 versus 1990-1999 (a) and over Japan for 1971-1989 versus 1990-1999 (b). 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.

Figure 1

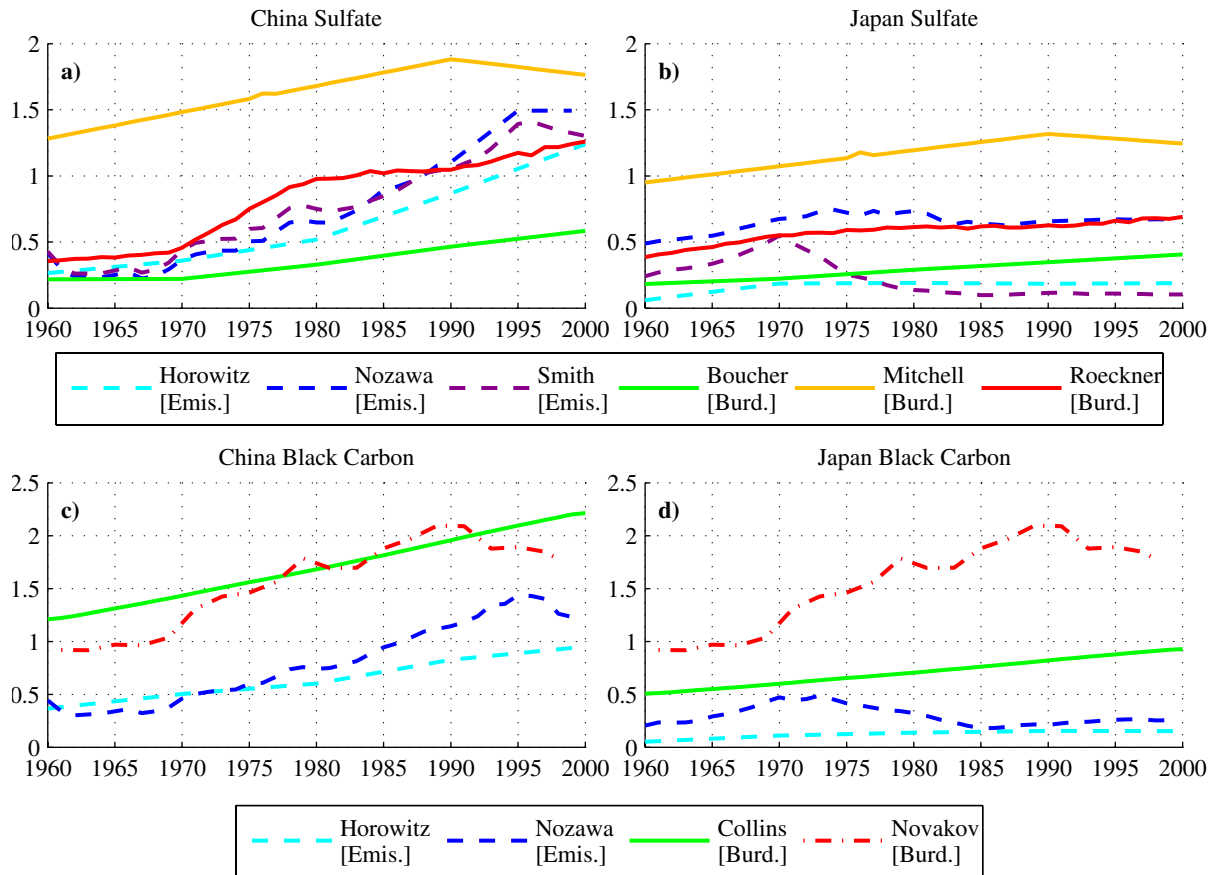


Figure 2

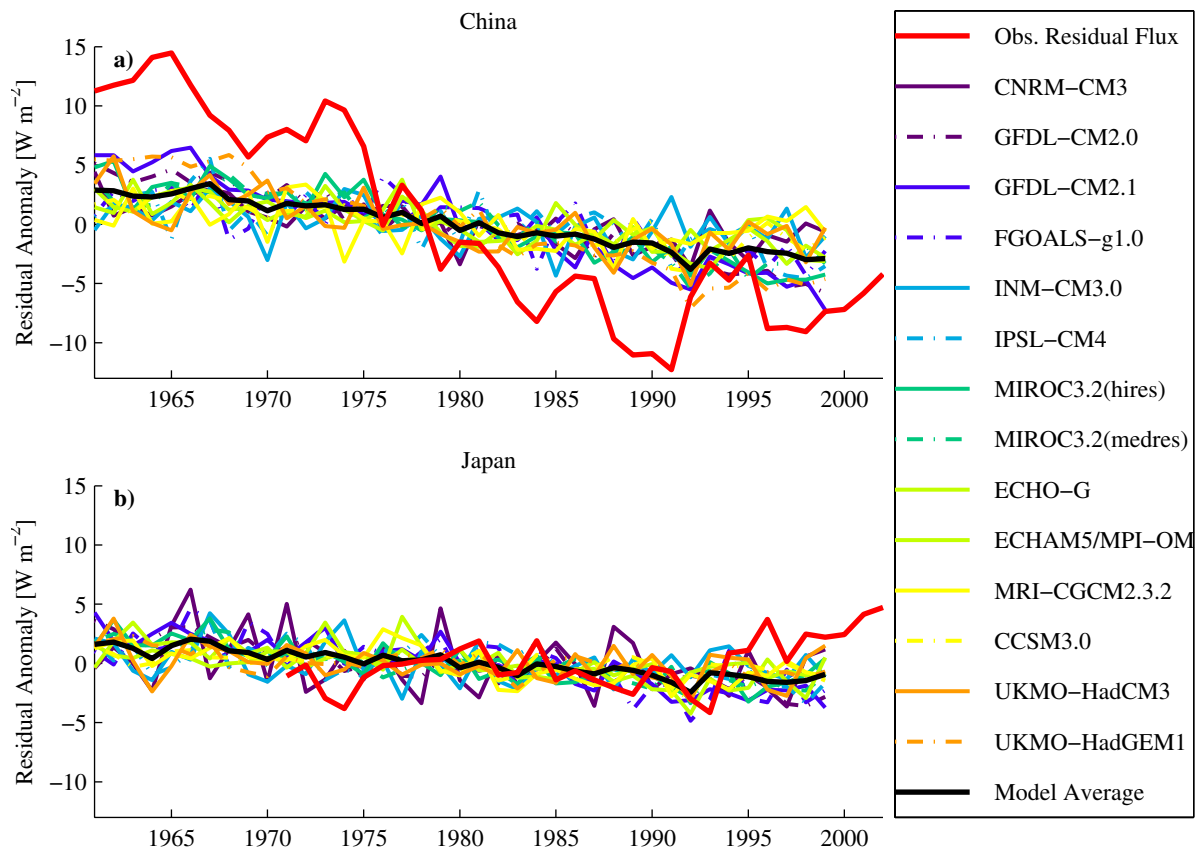


Figure 3

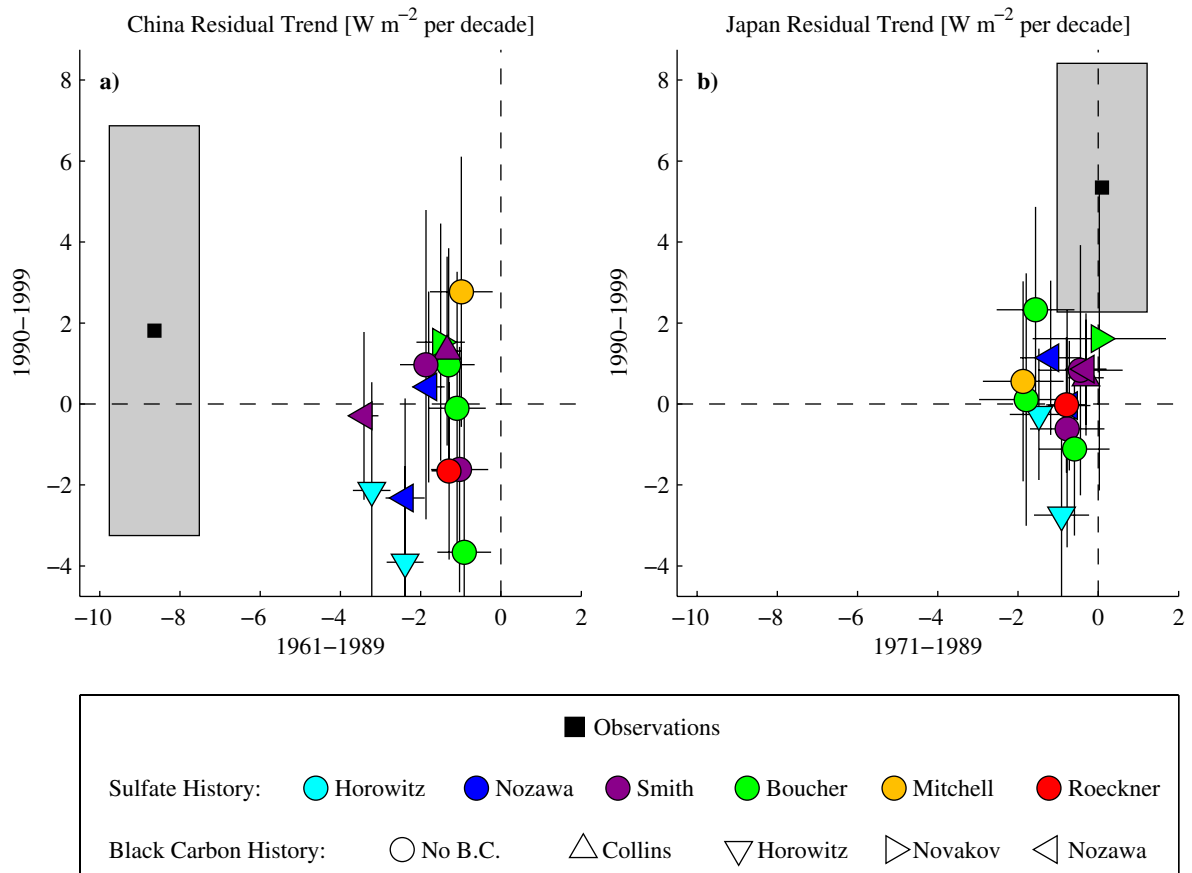


Table 1. IPCC-AR4 models considered in this study

Abbreviation	Originating Group(s)	Reference	# 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	<i>Salas-Méla et al.</i> [2005]	1	<i>Boucher and Pham</i> [2002]	<i>Tarré et al.</i> [1984] scaled by <i>Novakov et al.</i> [2003]	no	no	no
GFDL-CM2.0 GFDL-CM2.1	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	<i>Delworth et al.</i> [2006]	3/3	<i>Horowitz</i> [2006]	<i>Horowitz</i> [2006]	no	no	[<i>Sato et al.</i> , 1993; <i>Ramachandran et al.</i> , 2000]
FGOALS-g1.0	LASG / Institute of Atmospheric Physics, China	<i>Yu et al.</i> [2004]	3	<i>Boucher and Pham</i> [2002]	none	no	no	no
INM-CM3.0	Institute for Numerical Mathematics, Russia	<i>Galim et al.</i> [2003]	1	<i>Smith et al.</i> [2001, 2004]	none	no	no	[<i>Ammann et al.</i> , 2003]
IPSL-CM4	Institut Pierre Simon Laplace, France	<i>Marti et al.</i> [2005]	1	<i>Boucher and Pham</i> [2002]	none	yes	no	no
MIROC3.2(hires) / MIROC3.2(medres)	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	<i>K-1 Developers</i> [2004]	1/3	<i>Nozawa et al.</i> [2007]	<i>Nozawa et al.</i> [2007]	yes	yes	[<i>Sato et al.</i> , 1993]
ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group, Germany / Korea	<i>Legutke and Voss</i> [1999]	5	<i>Roeckner et al.</i> [1999]	none	yes	no	[<i>Crowley</i> , 2000]
ECHAM5/MPI-OM	Max Planck Institute for Meteorology, Germany	<i>Roeckner et al.</i> [2003]	3	<i>Boucher and Pham</i> [2002]	none	yes	no	no
MRI-CGCM2.3.2	Meteorological Research Institute, Japan	<i>Yukimoto et al.</i> [2006]	1	<i>Mitchell and Johns</i> [1997]	none	no	no	[<i>Sato et al.</i> , 1993]
CCSM3.0	National Center for Atmospheric Research, USA	<i>Collins et al.</i> [2002]	8	<i>Smith et al.</i> [2001, 2004]	<i>Collins et al.</i> [2002] scaled by global population	no	no	[<i>Ammann et al.</i> , 2003]
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research / Met Office, UK	<i>Johns et al.</i> [2003]	1	<i>Smith et al.</i> [2001, 2004]	none	yes	no	[<i>Sato et al.</i> , 1993]
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research / Met Office, UK	<i>Martin et al.</i> [2006]	4	<i>Smith et al.</i> [2001, 2004]	<i>Nozawa et al.</i> [2007]	yes	yes	[<i>Sato et al.</i> , 1993]