

Trends in aerosol radiative effects over China and Japan inferred from observed cloud cover, solar “dimming,” and solar “brightening”

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[1] This study examines multidecadal changes in surface downward shortwave (SW) radiation flux, total cloud cover, SW cloud effect, and related parameters over China and Japan during 1960–2004 using monthly gridded data from the Global Energy Balance Archive, synoptic cloud reports, and the International Satellite Cloud Climatology Project. We use the concept of cloud cover radiative effect, defined as the change in downward SW flux produced by a change in cloud cover, to quantify and remove the impact of cloud cover anomalies on surface solar flux. This will allow radiative effects of long-term changes in anthropogenic aerosol to be more clearly distinguished from natural weather and climate variability. As fit by a linear trend between 1971 and 1989, surface solar flux decreased by a statistically significant 11 W m^{-2} per decade over China and decreased by a nonsignificant 1 W m^{-2} per decade over Japan. The small decline over Japan can be entirely explained by an increase in cloud cover, but changes in cloud cover made negligible contribution to the 1971–1989 solar flux trend over China. Between 1990 and 2002, surface solar flux increased by a statistically significant 8 W m^{-2} per decade over Japan and increased by a nonsignificant 4 W m^{-2} per decade over China. Half of the 1990–2002 solar flux trend over China and one third of the trend over Japan can be attributed to a reduction in cloud cover. The 1971–1989 decrease in surface solar flux over China and the 1990–2002 increase in surface solar flux over Japan are both spatially widespread and exhibit consistent sign across seasons.

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1. Introduction

[2] Solar radiation flux at the surface of the Earth has a large impact on temperature and evaporation, and previous studies have reported the occurrence of substantial changes in downward solar flux at many locations. Between approximately 1960 and 1990, downward solar radiation at the surface decreased over many land areas, particularly in the extratropical Northern Hemisphere [e.g., *Ohmura and Lang*, 1989; *Gilgen et al.*, 1998; *Liepert*, 2002; *Stanhill and Cohen*, 2001, and references therein]. Since 1985, a partial recovery from the previous decline has been observed in many regions [e.g., *Wild et al.*, 2005; *Wild*, 2009, and references therein]. The earlier decrease and following increase in surface solar flux have been popularly called solar (or “global”) “dimming” and “brightening,” respectively.

[3] Variations in cloudiness have a large impact on solar radiation at daily to interannual time scales, and several investigators have examined the possible role of clouds in producing long-term trends in surface solar flux. At several

sites, a correspondence was found between a decrease in downward solar radiation from the 1960s to the 1980s and an increase in inferred cloud optical thickness [*Liepert*, 2002, 1997] or observed low-level cloud cover [*Abakumova et al.*, 1996; *Russak*, 1990]. Some regions, however, do not exhibit trends in cloud cover that have opposite sign from trends in solar flux [*Stanhill*, 1998; *Stanhill and Ianitz*, 1997; *Stanhill and Moreshet*, 1994; *Qian et al.*, 2006; *Norris and Wild*, 2007], indicating that solar “dimming” and “brightening” cannot universally be attributed to changes in cloud cover. Moreover, similar trends in surface solar flux were observed under both cloudy- and clear-sky conditions at some locations [*Abakumova et al.*, 1996; *Liepert*, 2002; *Russak*, 1990; *Wild et al.*, 2005]. It has been difficult to assess the importance of cloud changes to solar “dimming” and “brightening” on a widespread basis owing to the lack of long and geographically extensive records of clear-sky solar radiation measurements. Most stations do not provide global radiation measurements with sufficient temporal sampling to screen for clouds or direct beam transmission measurements from which clear-sky solar flux may be inferred.

[4] The recent study of *Norris and Wild* [2007] (hereafter NW2007) overcame the above shortcomings by quantifying empirically the radiative effect of monthly cloud cover anomalies on surface solar flux over Europe, thus enabling a calculation of the contribution (or opposition) of cloud

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cover trends to solar “dimming” and “brightening.” Furthermore, they statistically removed the radiative effects of monthly cloud cover anomalies from monthly global radiation anomalies over Europe to obtain residual time series comprising variations in clear sky radiation and the radiative effects of changes in cloud albedo. *Ruckstuhl and Norris* [2009] found that the residual time series closely resemble clear sky solar flux time series measured over Switzerland and northern Germany. The pan-European residual time series exhibits more distinct and statistically significant “dimming” and “brightening” trends than does the original surface solar flux time series because strong interannual variations caused by weather-related cloud cover anomalies have been removed. NW2007 attributed multidecadal variations in the residual time series to direct radiative forcing by aerosol and possibly indirect radiative forcing by aerosol through modification of cloud albedo. The time periods of “dimming” and “brightening” generally coincided with time periods when SO₂ and black carbon aerosol emissions were increasing and decreasing, respectively.

[5] Another region of the world that has received considerable attention is east Asia. Many studies have documented decreasing sunshine duration and solar radiation flux over China during the latter half of the 20th century [e.g., *Kaiser and Qian*, 2002; *Zhang et al.*, 2004a; *Che et al.*, 2005; *Qian et al.*, 2006; *Shi et al.*, 2008], although it appears that the decline in radiation may have flattened out or reversed after about 1990 [*Liu et al.*, 2004; *Che et al.*, 2005; *Qian et al.*, 2007; *Xia et al.*, 2006; *Shi et al.*, 2008]. It is unlikely that the decreasing trend in solar radiation was produced by a change in cloudiness since decreasing cloud cover and increasing clear sky frequency was reported for the same time period [*Kaiser*, 2000; *Endo and Yasunari*, 2006; *Qian et al.*, 2006]. A more probable explanation is that anthropogenic aerosol haze increased until around 1990, thus reducing the amount of solar radiation reaching the surface [*Luo et al.*, 2001; *Kaiser and Qian*, 2002].

[6] Sulfate aerosol particles scatter solar radiation, some of it back to space, and black carbon aerosol particles absorb solar radiation; both situations reduce the downward solar radiation received at the surface [e.g., *Charlson et al.*, 1991; *Satheesh and Ramanathan*, 2000; *Xia et al.*, 2007]. Black carbon often produces a relatively larger decrease in solar radiation at the surface than does sulfate because it scatters less diffuse radiation toward the surface, but sulfate aerosol nonetheless makes a substantial contribution because it has much greater aerosol optical depth [*Streets et al.*, 2008]. Large areas of China have a retrieved aerosol single scattering albedo that is less than 0.9 [*Lee et al.*, 2007], indicating that black carbon aerosol is prevalent. One attribution of the zero or increasing trend in solar radiation reported after 1990 is a decrease in black carbon and SO₂ emissions since the mid-1990s [*Streets et al.*, 2008]. An alternative explanation is that the overall aerosol burden has actually not declined over China, but rather that the aerosol single scattering albedo has increased (e.g., a smaller proportion of black carbon), thus reducing atmospheric absorption and increasing diffusive transmission of solar radiation [*Qian et al.*, 2007].

[7] Long-term variations in solar radiation over Japan have received less attention. *Sobajima et al.* [2004] found that satellite-retrieved aerosol optical depth increased over

the western North Pacific between 1988 and 2001, principally owing to transport from the Asian continent. This, however, did not apparently lead to a declining trend in solar radiation over Japan since *Wild et al.* [2005] report that annual mean solar radiation has been increasing over Japan since the mid-1980s, according to a polynomial fit to the time series. Possibly discrepant results were obtained by *Wild et al.* [2005], who found a decrease in annual mean solar radiation over Japan from the 1960s to the 1980s, and by *Stanhill and Cohen* [2008], who documented an increase in annual mean sunshine duration during the same period. Annual mean cloud cover over Japan exhibited a rising trend during the 1971–1996 time period [*Warren et al.*, 2007]; presuming no changes in other factors, this would produce a declining trend in solar radiation.

[8] One disadvantage of previous investigations is that the radiative impacts of variations in cloud cover were not quantified. We address this shortcoming in the present study by applying the methods pioneered in NW2007 to China and Japan. Specifically, we use three independent cloud and radiation data sets to document changes in cloud cover, examine how changes in cloud cover may have affected solar “dimming” and “brightening,” and calculate what trends in downward solar radiation occur after cloud cover radiative effects have been removed. Improved understanding of how anthropogenic aerosol influences the climate system in the context of changing cloud cover will be useful for evaluating model simulations of 20th century climate change, constraining the history of aerosol emissions, and narrowing the range of uncertainty for climate sensitivity [e.g., *Ruckstuhl and Norris*, 2009].

2. Data and Processing

2.1. Global Energy Balance Archive

[9] Values of global (direct + diffuse) downward solar radiation measured at the surface for China and Japan were obtained from the Global Energy Balance Archive (GEBA) [*Gilgen and Ohmura*, 1999]. We examined data from 23 stations in China and 60 stations in Japan that had at least one monthly value during each 5-year interval within 1970–2004. As NW2007 noted, the GEBA quality control procedures are insufficient to flag all suspicious data. As a check, we calculated linear correlations between monthly anomalies of GEBA radiation and monthly anomalies of surface-observed cloud cover reported by nearby stations (almost always at the same site). For direct comparability, cloud cover anomalies were converted to radiation anomalies using the method described in section 2.3. GEBA stations with correlations less than 0.60 were excluded from the analysis since it is implausible that nonspurious radiation anomalies would not be dominated by cloud cover variability at month-to-month time scales. NW2007 found that GEBA stations with correlations less than 0.60 exhibited unrealistically large multiyear solar radiation anomalies on the order of a few tens of W m⁻². *Shi et al.* [2008] carried out an independent assessment of long-term solar radiation station data in China and found that long-term regional trends were not affected by poor-quality data. They did identify six stations with erroneous or suspect monthly values, all of which were already excluded from our analysis according to our criteria.

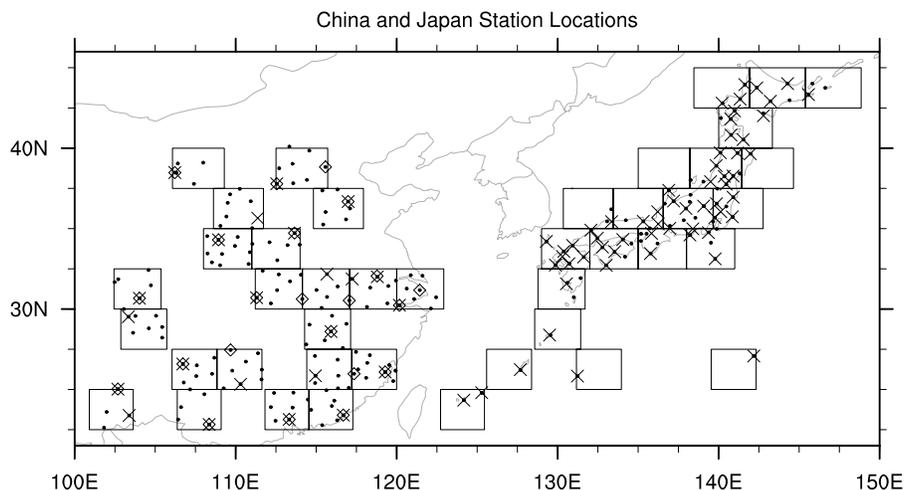


Figure 1. Locations of GEBA stations (crosses), NDP-026D cloud stations (dots), NDP-039 cloud stations (diamonds), and ISCCP equal-area grid boxes (rectangles) used in this study.

[10] Figure 1 shows the locations of the 83 GEBA stations from mainland China and Japanese islands used in this study. In order to avoid geographical sampling bias caused by varying station density, we did not carry out a simple average of the station anomalies but instead first aggregated the data into 21 grid boxes over China and 21 grid boxes over Japanese islands (demarcated in Figure 1). The grid boxes were then aggregated into regional solar radiation anomaly time series for China and Japan. Note that the China time series does not represent the entire country since many areas lacked solar radiation measurements. As was the case for NW2007, we aggregated station anomalies into grid box anomalies and then regional anomalies according to the median rather than the mean. This approach will minimize the influence of possible spurious outliers in the GEBA data that were not identified by the quality control procedures.

2.2. International Satellite Cloud Climatology Project

[11] We obtained monthly mean daytime total cloud amount values for the 21 Chinese and 21 Japanese equal-area grid boxes displayed in Figure 1 from the International Satellite Cloud Climatology Project (ISCCP) [Rossow *et al.*, 1996; Rossow and Schiffer, 1999]. Zhang *et al.* [2004b] applied a radiative transfer model to cloud properties retrieved by ISCCP to create the ISCCP Flux Data set (FD), which contains values of shortwave (SW) and long-wave radiation flux at the surface as well as at the top of the atmosphere for all-sky (clear + cloudy) and clear-sky conditions. Note that global radiation is the same as all-sky flux at the surface. Regional anomaly time series of ISCCP total cloud amount and ISCCP FD downward all-sky and clear-sky SW radiation flux at the surface were calculated by choosing the median anomaly for each month from the Chinese and Japanese grid boxes shown in Figure 1. ISCCP cloud and FD data were available only for July 1983 through December 2004. As will be shown in Figures 2 and 4, strong anomalies in ISCCP cloud amount occurred over China and Japan during 2003 and 2004 that had no parallel anomalies in GEBA global radiation. The lack of correspondence between ISCCP cloud and GEBA radiation

could be caused by the very small number of GEBA stations with data during 2003–2004 or alternatively by an artifact in ISCCP, as sometimes occurs [e.g., Norris, 2000; Norris and Wild, 2007]. Data from 2003 to 2004 were therefore not used in correlation and trend calculations.

[12] One shortcoming of the ISCCP FD is that it did not incorporate direct measurements of tropospheric aerosol properties because these are available only for limited times and places. The radiative transfer model instead employed a tropospheric aerosol distribution produced by an aerosol transport model and emission scenarios used by Koch [2001] and Hansen *et al.* [2002]. These aerosol distributions were temporally varying during 1983–1990 and temporally constant at 1990 values afterward. Xia *et al.* [2006] found that for most regions of China, decadal variability in ISCCP FD surface solar radiation flux was weaker and did not match decadal variability reported by surface solar radiation measurements. This indicates that the aerosol distribution used to derive ISCCP FD fluxes was unrealistic for China, even prior to 1990. The North China region of Xia *et al.*, however, exhibited substantial similarity between ISCCP FD and surface solar measurements. This correspondence must be driven by cloud variations, particularly for the period after 1990. Since cloud properties are directly observed by ISCCP, their radiative effects are much more accurately represented in the ISCCP FD.

2.3. Surface Synoptic Cloud Cover Observations and Estimated Radiative Effect

[13] Surface synoptic cloud reports are the only widespread direct measurement of cloudiness during the presatellite era. The NDP-026D database [Hahn and Warren, 2003] provided monthly mean values of daytime cloud cover during 1971–1996 for the 147 stations in China and 81 stations in Japan displayed in Figure 1. These were supplemented during 1960–1970 for China using 22 stations from the NDP-039 database [Shiyan *et al.*, 1997], the archive used by Kaiser [2000]. The NDP-039 cloud anomalies were taken from 1971 to 1996 long-term calendar month means, and we found very close agreement between regional mean time series averaged from the 22 NDP-039

stations and averaged from the 147 NDP-026D stations during their period of overlap (not shown). No synoptic cloud reports were accessible prior to 1971 for Japan. As was done for the GEBA solar radiation data, monthly total cloud cover anomalies at individual stations were aggregated into grid box anomalies and then regional anomalies according to the median.

[14] Although synoptic cloud reports do not provide quantitative radiative information, NW2007 demonstrated that the radiative impact of surface-observed cloud cover anomalies can nonetheless be estimated with substantial accuracy. This is accomplished by multiplying monthly grid box cloud cover anomalies (CC') by the ratio of long-term mean SW cloud effect ($\overline{SW}_{all} - \overline{SW}_{clr}$) divided by long-term mean cloud cover (CC), i.e.,

$$CCRE'(x, t, m) = CC'(x, t, m) \times \frac{\overline{SW}_{all}(x, m) - \overline{SW}_{clr}(x, m)}{CC(x, m)},$$

where x is grid box, t is year, m is month, and cloud effect is the difference between all-sky and clear-sky downward solar radiation flux at the surface. The resulting values, called SW “cloud cover” radiative effect anomalies ($CCRE'$), differ from conventional SW cloud effect anomalies in that the former include only radiative impacts of changes in cloud properties that are linearly related to cloud cover variations, whereas the latter include radiative impacts of changes in all cloud properties. SW cloud effect and SW CCRE anomalies are negative when cloud cover anomalies are positive because they represent a loss of energy to the surface. The ISCCP FD provided monthly mean values of SW_{all} and SW_{clr} , which together with CC were averaged over 1983–1996 (the period of overlap between ISCCP and synoptic cloud reports) to obtain long-term means.

[15] The linear correlation between monthly grid box anomalies of SW cloud effect ($SW_{all} - SW_{clr}$) from the ISCCP FD and monthly grid box anomalies of SW CCRE derived from synoptic cloud reports is 0.87 for China and 0.77 for Japan. Correlation values are similar if SW CCRE is derived from ISCCP total cloud amount instead of synoptic total cloud cover (0.81 for China and 0.84 for Japan). The majority of variance in SW cloud effect is explained by variability in cloud cover, and the remaining variance is generated by interannual variability in cloud albedo and observational uncertainty. The CCRE calculation already includes geographical and seasonal variations in long-term mean cloud properties and insolation.

[16] As found by NW2007, scatterplots of monthly grid box anomalies indicate that SW cloud effect anomalies are well-correlated with yet consistently larger than SW CCRE anomalies, irrespective of whether they are derived from synoptic or ISCCP cloud cover (not shown). This implies that a substantial portion of variability in cloud albedo is linearly related to variability in cloud cover (i.e., months with larger cloud cover tend to have optically thicker clouds). The best fit line for the scatterplots may be brought to the 1:1 line by multiplying SW CCRE anomalies by a factor of 1.9 for China and a factor of 2.5 for Japan (not shown). These enhancement factors represent the radiative effects of that portion of cloud albedo variability that is linearly related to cloud cover variability. Multiplication of

SW CCRE anomalies by enhancement factors gives SW CCRE anomalies comparable amplitude to cloud effect and all-sky flux anomalies in Figures 2, 3, and 4, but it does not change their temporal patterns.

[17] We multiplied the 95% confidence intervals for trends by $\sqrt{2.5}$ for China and $\sqrt{1.5}$ for Japan because autocorrelation calculations loosely based upon work by *Zwiers and von Storch* [1995] indicated that residual flux anomalies were typically independent after an interval of 2.5 months for China and 1.5 months for Japan.

3. Results

3.1. China

[18] The top of Figure 2a displays China regional mean time series of monthly anomalies of GEBA global radiation and ISCCP FD all-sky downward solar radiation flux. Figure 2b displays the same time series after application of a 5-year low-pass filter. Independent GEBA and ISCCP FD all-sky flux anomalies exhibit close month-to-month correspondence, providing confidence in the reliability of measured and modeled radiation variability at short time scales. Contrastingly, GEBA and ISCCP FD substantially disagree at multiyear time scales, probably owing to the unrealistic representation of tropospheric aerosol changes in the ISCCP FD. The unfiltered GEBA and ISCCP FD time series have a correlation of 0.76, not including data during 2003–2004.

[19] China regional time series of SW CCRE estimated from synoptic and ISCCP total cloud cover anomalies are shown in the middle of Figures 2a and 2b. These time series are highly correlated at both short and long time scales ($r = 0.85$ for the unfiltered time series), even though the cloud data from which they are derived are completely independent ($r = 0.86$ for unfiltered cloud cover time series). The correspondence between GEBA monthly anomalies and estimated SW CCRE monthly anomalies ($r = 0.72$ for synoptic CCRE and $r = 0.75$ for ISCCP CCRE) indicates that cloud cover variations (and linearly related cloud albedo variations) are primarily responsible for producing variability in solar radiation at monthly to interannual time scales. A positive trend in estimated SW CCRE is apparent between the 1970s and 1990s, which is consistent with a decreasing trend in cloud cover, as reported by previous studies [*Kaiser*, 2000; *Endo and Yasunari*, 2006; *Qian et al.*, 2006].

[20] Variations in GEBA solar flux unrelated to cloud cover can be more distinctly seen if estimated SW CCRE anomalies are removed from GEBA global radiation anomalies. We accomplished this through linear regression applied separately to each grid box and calendar month. The use of linear regression avoids dependence on the quantitative value of any “enhancement factor,” but direct subtraction of regional estimated SW CCRE anomalies from regional GEBA radiation anomalies produced very similar results. At the bottom of Figures 2a and 2b are presented the China regional residual time series produced after estimated synoptic- and ISCCP-derived SW CCRE anomalies are removed from GEBA global radiation anomalies. Interannual variability is considerably muted in the residual time series relative to the original GEBA time series, allowing the low-frequency variations to stand out more clearly, even

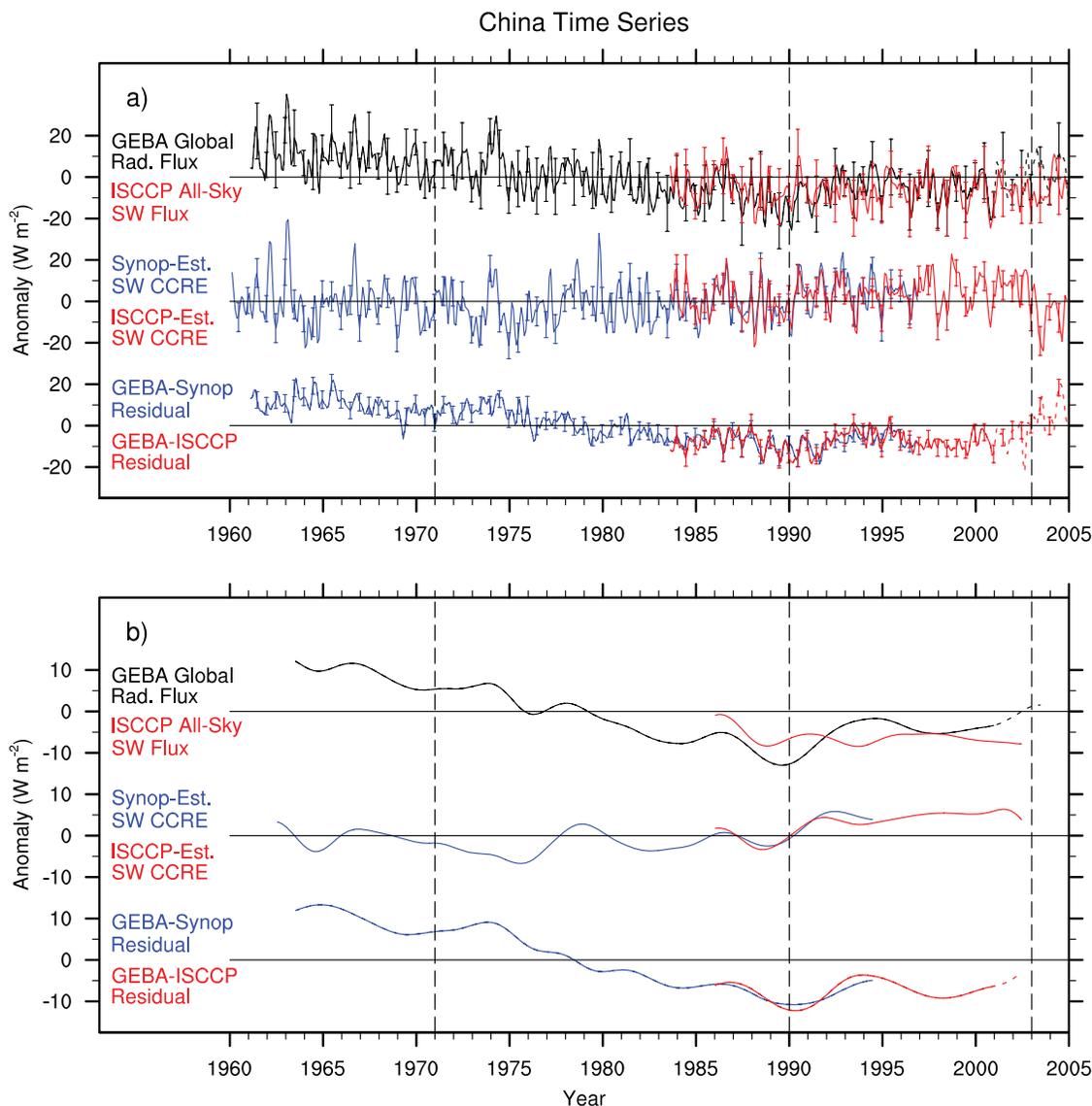


Figure 2. Time series of monthly anomalies averaged over the mainland China grid boxes displayed in Figure 1 (a) with 1-2-1 smoothing applied for readability and (b) with the application of a 61-point 5-year Lanczos low-pass filter. The plotted parameters are GEBA global radiation flux (top, black curve), ISCCP all-sky downward SW flux (top, red curve), SW CCRE estimated from synoptic reports of total cloud cover (middle, blue curve), SW CCRE estimated from ISCCP total cloud amount (middle, red curve), residual anomalies after removing synoptic-estimated SW CCRE from GEBA global radiation (bottom, blue curve), and residual anomalies after removing ISCCP-estimated SW CCRE from GEBA global radiation (bottom, red curve). Dashed values indicate where fewer than 75% of the grid boxes contributed to the GEBA time series. Small vertical bars denote 95% confidence intervals for June and December anomalies and were calculated using the method described in section 2.4 of NW2007. Vertical dashed lines mark the starting and ending times for trend calculations in Figures 2–4 and Tables 1–4.

in the unfiltered time series. The amount of solar radiation reaching the surface substantially decreased in the decades preceding 1990. The faster rate of decreasing solar radiation between the early 1970s and early 1980s corresponds to a faster rate of increasing aerosol optical depth during the same time period [Luo *et al.*, 2001].

[21] After 1990 there was a small increase, followed by a decrease, followed by another increase in the late 1990s. The substantial increase in residual flux in 2003–2004 is probably not real, and a limited number of measurements

suggests that solar radiation over China may actually have declined since 2000 [Wild *et al.*, 2009] owing to a resumption of increasing SO_2 emissions [Streets *et al.*, 2008]. The times of minima in residual flux (~ 1990 and ~ 1998) do not correspond to the time of maximum SO_2 emission by China (~ 1996) or the period of maximum black carbon emission by east Asia (1987–1995) reported by Streets *et al.* [2008]. One possible resolution of the disagreement is that the increasing proportion of sulfate aerosol reduced absorption of solar radiation by aerosol between 1990 and 1994 [Qian

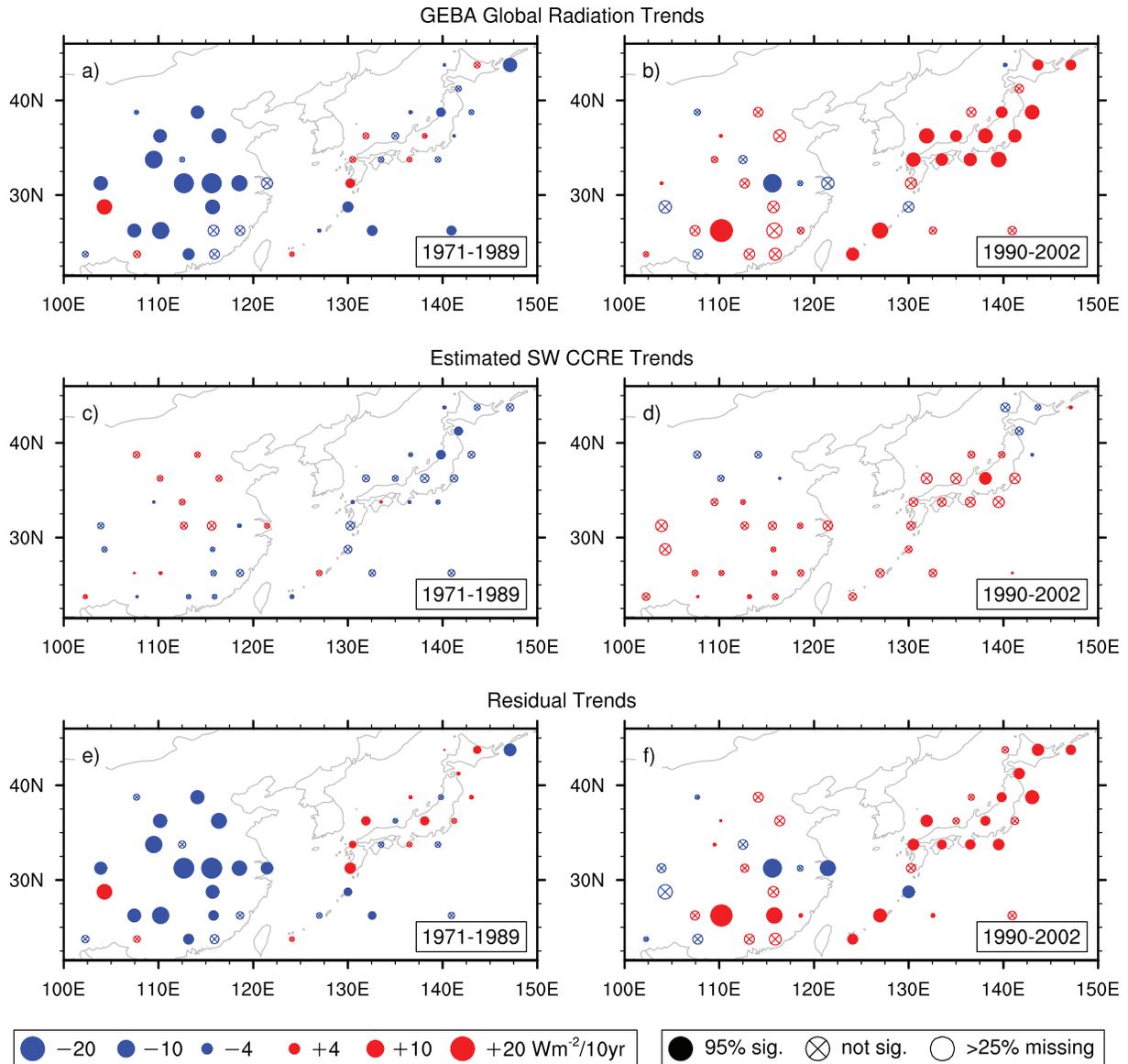


Figure 3. Least squares all-months grid box trends for GEBA global radiation flux anomalies during (a) 1971–1989 and (b) 1990–2002, estimated SW CCRE anomalies during (c) 1971–1989 and (d) 1990–2002, and residual anomalies after removing estimated SW CCRE from GEBA global radiation during (e) 1971–1989 and (f) 1990–2002. Blue and red circles indicate decreasing and increasing trends, respectively, with area proportional to trend magnitude and referenced in legend. Solid circles indicate trends different from zero at the 95% significance level, circles with crosses indicate nonsignificant trends, and open circles indicate that more than 25% of the time series had missing data.

et al., 2007]. Alternative explanations are that the emission histories are somewhat inaccurate or that an artifact was introduced into the solar radiation data when instruments were refitted in the early 1990s [Shi *et al.*, 2008].

[22] A simple way to summarize long-term variations in surface radiation flux is through linear trends. Since solar “dimming” over China occurred prior to 1990, we chose the 1971–1989 and 1990–2002 time periods for trend calculations. The earlier period begins in 1971 instead of 1961 for comparability with results for Japan, but GEBA and residual trend values for 1961–1989 are quite similar to those for 1971–1989. The years of 2003 and 2004 were left out owing to the questionable data, but had they been

included, the post-1990 increasing trend in residual flux would have been 3 times larger. Trends were computed using not only the least squares method, which makes calculation of confidence intervals straightforward [von Storch and Zwiers, 2001], but also by the median of pairwise slopes method [e.g., Lanzante, 1996], which is more robust to outliers and end point effects. Before computing trends, the synoptic- and ISCCP-derived time series were averaged together during their period of overlap.

[23] Table 1 lists all-months China regional trends for various radiation and cloud parameters, and Figure 3 displays all-months trends for each grid box. Regional mean GEBA global radiation and residual flux both declined by

Table 1. All-Months China Regional Trends in Cloud and Surface Solar Radiation Parameters With 95% Confidence Intervals

Parameter	1971–1989 Trend		1990–2002 Trend	
	Least Squares	Median Slope	Least Squares	Median Slope
Total cloud cover (%-cover decade ⁻¹)	-0.5 ± 2.5	-0.6	-0.6 ± 3.8	-0.8
GEBA global radiation (W m ⁻² decade ⁻¹)	-10.7 ± 4.5	-10.8	+4.0 ± 7.4	+2.9
Estimated SW CCRE (W m ⁻² decade ⁻¹)	+0.9 ± 5.6	+0.9	+2.6 ± 8.6	+2.3
Residual (W m ⁻² decade ⁻¹)	-10.9 ± 2.1	-10.8	+2.3 ± 4.1	+2.3

about 11 W m⁻² per decade during 1971–1989 (Table 1). This rate is twice as large as that reported by some previous studies [e.g., *Che et al.*, 2005], probably because our trend interval ended at 1990 rather than 2000 and consequently did not include any of post-“dimming” period. The uncertainty range for the residual trend is much smaller than the uncertainty range for the GEBA trend because the substantial “scatter” contributed by interannual cloud cover variability has been removed. As noted by previous studies [e.g., *Che et al.*, 2005; *Qian et al.*, 2007; *Shi et al.*, 2008], the “dimming” prior to 1990 was spatially widespread, and 19 out of 21 mainland China grid boxes reported reductions in solar radiation, most of which were large and statistically significant (Figures 3a and 3e). Changes in cloud cover appear to have had relatively little impact on radiation trends over China during 1971–1989 (Figure 3c). The most likely explanation for the observed decrease in solar radiation is a rise in aerosol optical thickness [*Luo et al.*, 2001; *Kaiser and Qian*, 2002].

[24] China regional mean GEBA global radiation exhibits an increasing trend during 1990–2002 [*Liu et al.*, 2004; *Xia et al.*, 2006; *Shi et al.*, 2008], but this is not statistically significant according to our analysis (Table 1). A comparison of the GEBA trend values with the SW CCRE and residual trend values indicates that half of the post-1990 “brightening” comes from reduced cloud cover and consequently cannot be completely attributed to decreasing aerosol. Decreasing cloud cover is widespread over China after 1990, and 17 out of 21 grid boxes report a positive trend in estimated SW CCRE (Figure 3d). Most grid boxes in mainland China have nonsignificant trends in radiation flux during 1990–2002, and once the cloud cover contribution is removed, they are nearly evenly divided between positive and negative changes (Figure 3f). This suggests that there was no substantial, spatially uniform, and monotonic change in aerosol optical thickness over China during the 1990s.

[25] Table 2 provides China regional mean seasonal trends in residual flux. During the 1971–1989 interval, residual trends are most negative during the time of year when insolation is largest and least negative during the time of year when insolation is smallest. This relationship to insolation does not exist for trends in residual flux during the 1990–2002 interval, which instead exhibit inconsistent

magnitudes and signs across the seasons and generally lack statistical significance.

3.2. Japan

[26] Regional mean time series of monthly anomalies averaged over Japanese islands are shown in Figure 4. The unfiltered GEBA global radiation and ISCCP FD all-sky flux time series have a correlation of 0.76, and the estimated synoptic- and ISCCP-derived SW CCRE time series have a correlation of 0.83. GEBA anomalies and estimated SW CCRE anomalies have closer correspondence than existed for China ($r = 0.83$ for synoptic CCRE and $r = 0.80$ for ISCCP CCRE). As was the case for China, GEBA and ISCCP FD solar fluxes substantially disagree over long-term trends, presumably owing to lack of realistic low-frequency aerosol variability in the ISCCP FD.

[27] Unlike the case for China, a strong decline in Japanese GEBA global radiation occurs only before the mid-1960s. GEBA radiation slightly increases during the 1970s, slightly decreases during the 1980s, and then strongly increases after the early 1990s (Figure 4). This pattern appears more clearly in the residual fluxes, especially when low-pass filtered, owing to the removal of the radiative contribution of sub-decadal variations in cloud cover. It may be possible to attribute the low-frequency variability of residual flux to changes in aerosol burden. According to *Smith et al.* [2001], SO₂ emissions by Japan declined from 2.7 TgS a⁻¹ in 1970 to 0.7 TgS a⁻¹ in 1980. This would reduce sulfate aerosol haze and allow increasingly more solar radiation to reach the surface, as seen in Figure 4 for the 1970s. SO₂ emissions by China, however, were increasing at this time to a value of 7.8 TgS a⁻¹ in 1980. The transport of increasingly more sulfate aerosol from China would oppose the local reduction in SO₂ emission and eventually overwhelm it. This explains the decline in surface solar radiation occurring between 1980 and the early 1990s shown in Figure 4. The increase in solar radiation after the early 1990s may be explained by decreased emissions from China [*Streets et al.*, 2008] or a decrease in the fraction of absorbing aerosol from China [*Qian et al.*, 2007]. A sophisticated model for aerosol processing and transport is needed to clarify why the post-1990 increase in solar flux for China is smaller than the increase for Japan.

[28] Tables 3 and 4 show no linear trend in Japan regional mean residual flux during 1971–1989, either for individual

Table 2. Seasonal China Regional Trends in Residual Flux With 95% Confidence Intervals

Season	1971–1989 Trend (W m ⁻² decade ⁻¹)		1990–2002 Trend (W m ⁻² decade ⁻¹)	
	Least Squares	Median Slope	Least Squares	Median Slope
May–Jun–Jul	-14.9 ± 4.2	-14.9	+3.5 ± 9.7	+4.3
Aug–Sep–Oct	-12.6 ± 3.8	-12.7	-2.6 ± 8.5	-3.4
Nov–Dec–Jan	-7.4 ± 3.7	-7.6	+2.3 ± 6.7	+2.2
Feb–Mar–Apr	-8.8 ± 4.5	-9.0	+5.9 ± 7.8	+5.2

Japan Time Series

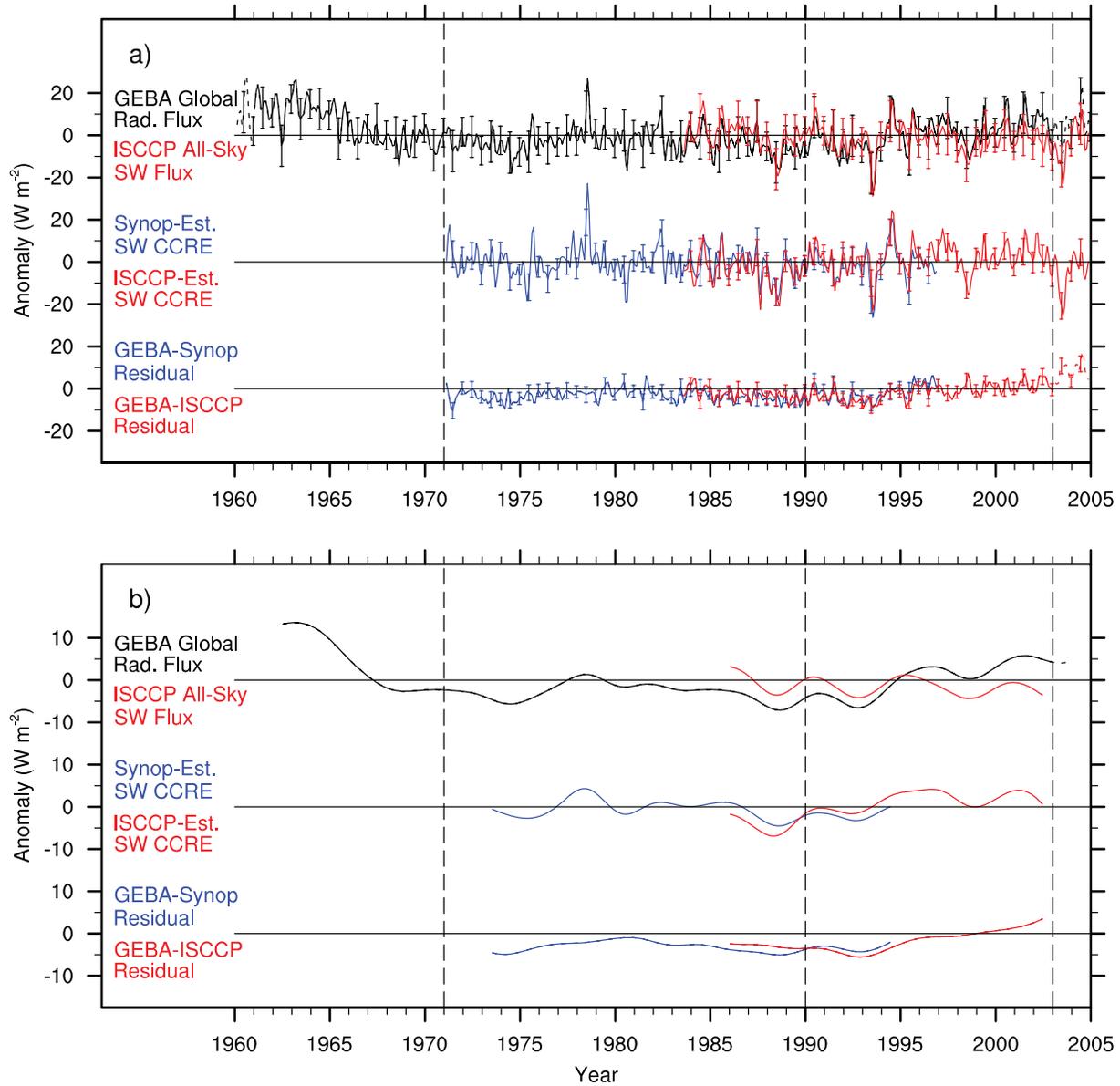


Figure 4. As in Figure 2 but for monthly anomalies averaged over the Japanese island grid boxes displayed in Figure 1.

seasons or all months together. A small and statistically insignificant decline in GEBA global radiation did occur during 1971–1989, but this can completely be attributed to an increase in cloud cover (Table 3) (also noted by *Warren et al.* [2007]). The enhancement of cloud cover was spatially widespread, as demonstrated by the 19 out of 21 grid boxes

over Japanese islands that have negative trends in estimated SW CCRE for 1971–1989 (Figure 3c).

[29] Contrastingly, Japan regional mean GEBA global radiation increased by a statistically significant 8 W m^{-2} per decade during 1990–2002 (Table 3). It appears that about a third of this “brightening” can be attributed to a reduction

Table 3. All-Months Japan Regional Trends in Cloud and Surface Solar Radiation Parameters With 95% Confidence Intervals

Parameter	1971–1989 Trend		1990–2002 Trend	
	Least Squares	Median Slope	Least Squares	Median Slope
Total cloud cover (%-cover decade ⁻¹)	+0.8 ± 1.1	+0.7	-1.2 ± 1.9	-1.0
GEBA global radiation (W m ⁻² decade ⁻¹)	-1.3 ± 2.6	-1.0	+8.9 ± 4.9	+7.8
Estimated SW CCRE (W m ⁻² decade ⁻¹)	-2.6 ± 3.3	-1.8	+3.1 ± 5.1	+2.6
Residual (W m ⁻² decade ⁻¹)	+0.1 ± 1.2	+0.0	+5.5 ± 2.3	+5.1

Table 4. Seasonal Japan Regional Trends in Residual Flux With 95% Confidence Intervals

Season	1971–1989 Trend ($\text{W m}^{-2} \text{ decade}^{-1}$)		1990–2002 Trend ($\text{W m}^{-2} \text{ decade}^{-1}$)	
	Least Squares	Median Slope	Least Squares	Median Slope
May–Jun–Jul	+0.6 ± 2.9	+0.4	+3.4 ± 5.1	+3.8
Aug–Sep–Oct	−0.1 ± 2.2	−0.2	+6.9 ± 4.6	+6.8
Nov–Dec–Jan	−0.1 ± 1.4	−0.1	+3.3 ± 2.5	+3.0
Feb–Mar–Apr	−0.1 ± 2.8	+0.5	+8.1 ± 5.6	+7.1

of cloud cover since the linear trend in residual flux is only about 5 W m^{-2} per decade, although still statistically significant. Were the questionable years of 2003 and 2004 to be included in the calculation, the post-1990 residual flux trend would be a third larger. Table 4 indicates that the seasonal pattern of residual flux trend magnitude for 1990–2002 does not vary with the seasonal cycle of insolation; it is instead produced by differing seasonal cloud cover trends (not shown). Positive all-months estimated SW CCRE trends occur in 17 out of 21 grid boxes over Japanese islands (Figure 3d), and positive all-months residual flux trends occur in 20 out of 21 grid boxes, the majority of which are statistically significant (Figure 3f).

4. Summary

[30] The radiative impact of cloud cover anomalies, called SW CCRE anomalies in the present study, can quantitatively be estimated as proportional to the ratio of climatological cloud radiative effect divided by climatological cloud cover. Estimated SW CCRE anomalies and linearly related changes in cloud albedo are the most important contributors to anomalies in surface solar radiation flux on monthly to interannual time scales. This variability is presumably mostly driven by natural weather and seasonal climate variations, and its presence makes it more difficult to discern more slowly changing anthropogenic influences on downward solar radiation at the surface. When estimated SW CCRE anomalies are removed from all-sky flux (or global radiation) anomalies via linear regression to produce what this study calls residual flux anomalies, low-frequency variations in surface solar radiation become much more distinct.

[31] Regional mean residual flux over China decreased at a rate of 11 W m^{-2} per decade prior to 1990. Because there was near-zero change in cloud cover and SW CCRE during this period, the most plausible explanation for the solar “dimming” is a large increase in the number of anthropogenic aerosol particles that either directly scattered and absorbed radiation or possibly also indirectly enhanced cloud albedo by increasing the number of cloud condensation nuclei and cloud droplets [e.g., Twomey *et al.*, 1984; Radke *et al.*, 1989]. Although Zhai and Eskridge [1997] report that precipitable water increased over China by about 1 mm per decade between 1970 and 1990, a change of this magnitude is too small to be a substantial contributor to the observed solar “dimming” (e.g., Ohvri *et al.* [2009] and a simple calculation using the method of Lacis and Hansen [1974]).

[32] The decline in solar radiation over China reverses around 1990, and between 1990 and 2002, all-sky flux rises at a rate of about 4 W m^{-2} per decade. This enhancement is not statistically significant, and a 2 W m^{-2} per decade

positive trend in estimated SW CCRE indicates that half of the observed increase in all-sky solar flux is actually produced by a decrease in cloud cover. Unlike the case for 1971–1989, the geographical and seasonal pattern of residual flux trends over China for 1990–2002 is not consistent, suggesting that there was not a strong, widespread, and monotonic decrease in anthropogenic aerosol burden during that time period. Recent results indicate that SO_2 emission has been increasing and surface solar radiation has been decreasing since 2000 [Streets *et al.*, 2008; Wild *et al.*, 2009].

[33] Regional mean all-sky flux for Japan exhibited a small and statistically insignificant decreasing trend during 1971–1989 that appears to be solely driven by an increase in cloud cover. Although small decadal variations are present, the long-term trend in residual flux between 1971 and 1989 is zero, possibly because decreasing aerosol emissions by Japan were offset by the transport of increasing aerosol emissions by China. Contrastingly, all-sky flux rose at a statistically significant rate of 8 W m^{-2} per decade between 1990 and 2002. One third of this increase is actually produced by a decrease in cloud cover, as indicated by a 3 W m^{-2} per decade positive trend in SW CCRE. The post-1990 increase in surface solar radiation over Japanese islands is spatially widespread and has consistent sign across seasons. Like many other regions of the world [Wild *et al.*, 2005], this solar “brightening” is presumably caused by decreasing anthropogenic aerosol over the Japan, but it is not yet clear how this can be reconciled with the lack of correspondingly strong brightening over China.

[34] Taken together, the results for China and Japan suggest that East Asia on average experienced a period of about 5 W m^{-2} per decade solar “dimming” prior to 1990 followed by a period of about 4 W m^{-2} per decade solar “brightening.” This temporal pattern resembles that reported by NW2007 for Europe, although East Asia trends have greater magnitude. Anthropogenic aerosol cooling may have partially offset greenhouse warming over much of Eurasia and North America during the 1960s through the 1980s [e.g., Charlson *et al.*, 1991], but the subsequent reduction in aerosol burden since that time is likely to have been responsible for more rapid warming [e.g., Liu *et al.*, 2004; Wild *et al.*, 2007; Ruckstuhl *et al.*, 2008]. As was done for Europe [Ruckstuhl and Norris, 2009], these results can be used to constrain aerosol emission histories provided to global climate models and thus reduce uncertainties in anthropogenic forcing of 20th century climate.

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