

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

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[1] We examine multidecadal changes in surface downward shortwave (SW) radiation flux, total cloud cover, SW cloud effect, and related parameters over Europe during 1965–2004 using monthly gridded data from the Global Energy Balance Archive (GEBA), synoptic cloud reports, and the International Satellite Cloud Climatology Project (ISCCP). One key issue is distinguishing the effects of natural cloud variability from long-term anthropogenic aerosol influences on surface SW flux. Accordingly, we introduce the concept of cloud cover radiative effect (CCRE), defined as the change in downward SW flux produced by a change in cloud cover. The correlation between pan-European time series of CCRE anomalies and GEBA solar radiation anomalies is 0.88, indicating that cloud cover variability and associated changes in cloud albedo dominate SW radiation variability on monthly to decadal timescales. After these weather-related cloud effects are removed by subtracting CCRE anomalies from GEBA solar radiation anomalies via linear regression, a distinct decreasing trend followed by a distinct increasing trend remain in the residual time series. Depending on the method of trend calculation, pan-European residual flux declined by a statistically significant $2.7\text{--}3.5\text{ W m}^{-2}$ per decade during 1971–1986 and rose by a statistically significant $2.0\text{--}2.3\text{ W m}^{-2}$ per decade during 1987–2002. The fact that independent grid boxes exhibit mostly negative trends in the earlier period and mostly positive trends in the later period demonstrates that these long-term variations in SW flux are real and widespread over Europe. Changes in cloud cover cannot account for the trends in surface SW flux since cloud cover actually slightly decreased during 1971–1986 and slightly increased during 1987–2002. The most likely explanation is changes in anthropogenic aerosol emissions that led to more scattering and absorption of SW radiation during the earlier period of solar “dimming” and less scattering and absorption during the later period of solar “brightening.”

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1. Introduction

[2] Solar radiation flux at the surface of the Earth is a key regulator of climate and the primary energy source for life on our planet. Recent evidence suggests that downward solar flux has not been stable over time but instead has experienced substantial decadal variations in many regions of the world. Early studies focusing on changes in downward solar radiation at the surface have found a widespread decrease in this quantity over land regions in the three decades preceding 1990 [e.g., *Ohmura and Lang*, 1989; *Gilgen et al.*, 1998; *Liepert*, 2002; *Stanhill and Cohen*, 2001; and references therein]. More recently, a post-1985 recovery from the previous decline in solar flux has become

apparent at many locations [*Wild et al.*, 2005]. The prior decrease and subsequent increase in surface solar radiation have been popularly called solar “dimming” and “brightening,” respectively.

[3] Cloudiness is the largest modulator of solar radiation in the atmosphere and consequently is a leading candidate for producing multidecadal changes in downward solar flux at the surface. Indeed, some investigators have found that reductions in solar flux from the 1960s to the 1980s at several locations coincide with an observed enhancement of low-level cloud cover [*Abakumova et al.*, 1996; *Russak*, 1990] or an inferred enhancement of cloud optical thickness [*Liepert*, 1997, 2002]. Cloud cover changes cannot be a universal explanation for solar “dimming,” however, because other sites do not exhibit increasing cloud cover despite the occurrence of decreasing solar flux [*Stanhill*, 1998; *Stanhill and Ianetz*, 1997; *Stanhill and Moreshet*, 1994]. In fact, *Qian et al.* [2006] reported that long-term reductions in total and low-level cloud cover accompanied a long-term decline in solar flux over China. At some

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locations, analogous trends in surface solar radiation occurred under both cloudy and clear sky conditions [Abakumova *et al.*, 1996; Liepert, 2002; Russak, 1990; Wild *et al.*, 2005]. Although the latter phenomenon may be widespread, it has been previously difficult to test since most stations lack global radiation measurements with sufficient temporal resolution to screen for clouds or direct beam transmission measurements from which clear-sky solar flux may be inferred.

[4] Changes in the amount and optical properties of anthropogenic aerosol are the most likely cause of clear-sky solar flux trends [e.g., Abakumova *et al.*, 1996; Liepert and Tegen, 2002; Stanhill and Cohen, 2001; Zhang *et al.*, 2004a]. Depending on composition, aerosol particles can absorb solar radiation (preferentially by black carbon) or scatter some of it back to space (preferentially by sulfate), thus reducing either way the downward flux received at the surface [e.g., Charlson *et al.*, 1991; Satheesh and Ramanathan, 2000]. Scattering or absorption by aerosol particles is called the “direct aerosol radiative effect.” The switch from solar “dimming” to “brightening” during recent decades in several regions of the world has been attributed to a reversal from increasing to decreasing anthropogenic sulfur and black carbon emissions [Stern, 2006; Novakov *et al.*, 2003; Wild *et al.*, 2005; Streets *et al.*, 2006]. Although long-term changes in natural aerosols might also have occurred, we cannot investigate this possibility because of lack of observations, aside from the impacts of volcanic eruptions.

[5] In addition to the direct aerosol radiative effect, a greater number of aerosol particles that act as cloud condensation nuclei (CCN) may enhance cloud albedo by increasing the number of cloud droplets and consequently the scattering area [Twomey *et al.*, 1984; Radke *et al.*, 1989]. This is called the “first indirect aerosol radiative effect” or “cloud albedo aerosol effect.” If cloud water content remains constant as CCN and cloud droplet number increase, then the average cloud droplet will become smaller and be less likely to coalesce into a precipitation-size drop. By this mechanism, a greater number of aerosol particles might reduce cloud water loss by precipitation and thereby extend cloud lifetime and average cloud cover [Albrecht, 1989]. This is called the “second indirect aerosol radiative effect” or “cloud lifetime aerosol effect.” Another means by which aerosol particles may possibly affect clouds is through absorption of solar radiation by black carbon that heats and stabilizes the atmosphere, thus evaporating clouds or suppressing their formation [Ackerman *et al.*, 2000; Koren *et al.*, 2004]. This has been called the “semidirect aerosol radiative effect.” Indirect aerosol radiative effects, and especially the cloud albedo aerosol effect, may have contributed to observed solar “dimming” and “brightening” [Wild *et al.*, 2005].

[6] Considering the potential for changes in surface solar radiation to influence the hydrological cycle and partially offset anthropogenic greenhouse warming [e.g., Charlson *et al.*, 1991; Nazarenko and Menon, 2005; Ramanathan *et al.*, 2001; Wild *et al.*, 2004], it is important to rigorously validate surface measurements of downward solar radiation flux, separate solar flux anomalies into cloudy and clear-sky components, quantify long-term changes in these parameters, and identify likely causes of the observed trends. The

present study accomplishes these objectives during 1971–2002 for the region of Europe, which has the longest, densest, and most reliable collection of surface solar flux measurements. Specifically, we compare three independent cloud and radiation data sets to evaluate when and where observations were reliable, and with what confidence interval. In contrast to previous studies, we explicitly quantify the radiative impact of cloud cover anomalies, thus facilitating a computation of how much solar “dimming” and “brightening” was due to cloud cover changes. We also remove the cloud cover radiative impacts from the surface flux anomalies in order to determine the amount of solar “dimming” and “brightening” presumably driven by the combination of direct and first indirect aerosol radiative effects. To overcome the lack of clear-sky measurements or proxies at most stations, we calculate clear-sky flux anomalies by subtracting satellite-derived values of surface short-wave cloud radiative effect anomalies from the monthly mean global radiation anomalies that are reported at all stations. This enables us to distinguish the direct aerosol radiative effect from the first indirect aerosol radiative effect onward from 1983, the beginning of the satellite record. In addition to informing our knowledge of anthropogenic influences on climate, our results provide strong observational constraints that are essential to evaluating the simulation of aerosol processes, cloud microphysics, and their radiative effects in global climate models.

2. Data and Processing

2.1. Global Energy Balance Archive

[7] The Global Energy Balance Archive (GEBA) contains monthly mean values of global (direct + diffuse) downward solar radiation measured at the surface for stations around the world [Gilgen and Ohmura, 1999]. Our investigation focused on Europe since that region has the densest network of stations with the most reliable data. Stations selected for the present study had lengthy records and were not located on isolated headlands or small islands in the North Atlantic. Specifically, we required stations to have at least one monthly value during each 5-year interval within 1970–1994, a time period that encompasses the reported occurrence of both solar “dimming” and “brightening.” 101 GEBA stations satisfied these criteria.

[8] Although we excluded all values flagged by GEBA as “suspected error,” this does not guarantee that the remaining data are free from artifacts. Some stations might have spurious variability that could not be cross-checked in the GEBA processing because of lack of neighboring stations with sufficiently overlapping time series. As an alternative means of determining the reliability of GEBA global radiation measurements, we compared time series of GEBA anomalies to time series of surface-observed total cloud cover anomalies from the closest location (usually the same site). Since cloud cover variability dominates month-to-month anomalies in solar radiation flux, it is suspicious when they do not correspond. We calculated linear correlations between GEBA and cloud cover time series after converting cloud cover anomalies to radiation anomalies using the method described in section 2.3. The minimum, median, and maximum values were 0.19, 0.76, and 0.91, respectively. Visual inspection indicated that GEBA time

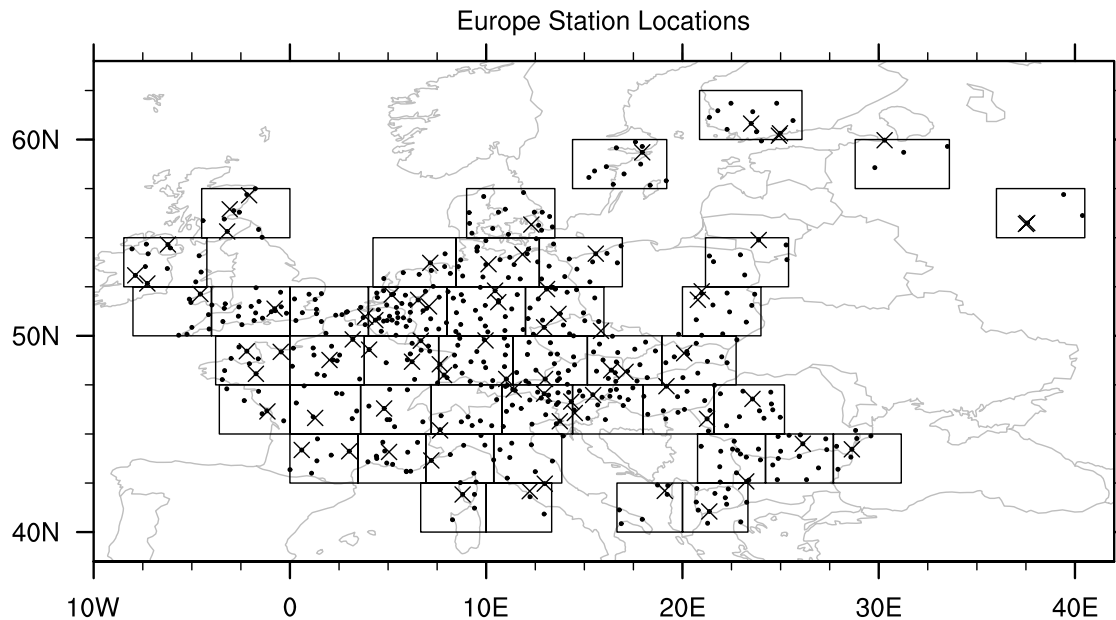


Figure 1. Locations of GEBA stations (crosses), WMO cloud stations (dots), and ISCCP equal-area grid boxes (rectangles) used in this study.

series with a correlation coefficient less than 0.55 with respect to the nearest cloud cover time series typically exhibited unrealistically large multiyear solar radiation anomalies on the order of a few tens of W m^{-2} . To ensure that most spurious variability was removed, we excluded all stations with correlations in the bottom quartile ($r \leq 0.60$). The sensitivity of our results to threshold choice will be discussed in section 3.

[9] Figure 1 shows the locations of the 75 GEBA stations used in this study (corresponding to the top three quartiles of radiation-cloud correlations). These are not distributed uniformly but are instead concentrated in northwestern and central Europe, in part because many stations in southern and eastern Europe were discarded because of the lack of long records of sufficient quality. A simple average of all of the remaining stations would result in a substantial geographic sampling bias, so nearby GEBA stations were first aggregated into 44 grid boxes (demarcated in Figure 1) before the calculation of a pan-European solar radiation anomaly time series. This does not entirely mitigate the sampling bias because there are many areas of Europe with no GEBA stations at all. No interpolation to these empty grid boxes was attempted since in most cases there would be too little information available. To minimize the influence of spurious outliers that might persist in the GEBA data, we determined monthly grid box anomalies according to the median rather than the average of the constituent monthly station anomalies for the 18 grid boxes that had more than one station. Monthly pan-European solar radiation anomalies were similarly determined according to the median of the available grid box anomalies.

2.2. International Satellite Cloud Climatology Project

[10] The International Satellite Cloud Climatology Project (ISCCP) provided monthly mean daytime total cloud amount values [Rossow *et al.*, 1996; Rossow and Schiffer, 1999] for

the 44 equal-area grid boxes demarcated in Figure 1. These grid boxes are the same as those into which the GEBA anomalies were aggregated. In addition to cloud information, the ISCCP Flux Data set (FD) includes values of shortwave (SW) and longwave radiation flux at the top of the atmosphere and at the surface for all-sky (clear + cloudy) and clear-sky conditions [Zhang *et al.*, 2004b]. Note that at the surface, all-sky flux is equivalent to global radiation. These fluxes were calculated by applying a radiative transfer model to cloud properties retrieved by ISCCP with aerosol information provided by other sources [e.g., Lefohn *et al.*, 1999; Tegen *et al.*, 2000]. We obtained pan-European time series of monthly anomalies of ISCCP total cloud amount and downward all-sky and clear-sky SW radiation flux at the surface by choosing the median monthly anomaly for all the grid boxes displayed in Figure 1, irrespective of whether GEBA values were available at that time for the grid box.

[11] It is important to note that the ISCCP radiative transfer model did not incorporate direct measurements of tropospheric aerosol properties since these were not available in most circumstances. The spatiotemporal distribution of tropospheric aerosols during 1983–1990 was instead determined by the aerosol transport model and emission scenarios used by Koch [2001] and Hansen *et al.* [2002]. After 1990, the ISCCP radiative transfer model held the distribution of tropospheric aerosols fixed at 1990 values. The employment of a constant tropospheric aerosol distribution during 1990–2004 obviously precludes the use of ISCCP FD values to investigate possible changes in direct radiative forcing by tropospheric aerosols. Other investigations of surface solar radiation variability based on satellite-derived data have also suffered from an oversimplified treatment of tropospheric aerosol [Pinker and Laszlo, 1992; Pinker *et al.*, 2005]. Any potential indirect effects of aerosols on cloud radiative properties nevertheless re-

main in the ISCCP FD since the radiative transfer model used temporally varying retrieved cloud properties.

[12] Although ISCCP data are currently available from July 1983 to December 2004, we discarded all ISCCP cloud amount values prior to January 1990. The reason for this is that pan-European ISCCP total cloud amount exhibits a suspiciously large multiyear positive anomaly during the 1980s that does not occur in the surface synoptic observations of cloud cover. Previous work by the lead author indicates that artifacts associated with the viewing area of Meteosat, the European geostationary satellite, exist in ISCCP cloud amount data [Norris, 2000], and further evidence for this is presented in Appendix A. Note that these artifacts affect the pan-European time series much more than the individual grid box time series since the latter have relatively greater natural variability. We did use ISCCP FD values from the 1980s since they do not exhibit the spurious variability seen in the total cloud amount data (not shown). The lack of an artifact in ISCCP FD values implies that some pixels near the threshold of cloud detection were identified as cloudy in the 1980s but not thereafter. Such pixels are radiatively insignificant and thus have little impact on the calculation of SW flux, but classifying them as cloudy led to the compensating errors of an overestimation of average cloud amount and an underestimation of average cloud optical thickness.

2.3. Surface Synoptic Cloud Cover Observations and Estimated Radiative Effect

[13] Surface synoptic reports of total cloud cover are a useful source of cloud information, especially during the presatellite era. We obtained monthly mean values of surface-observed daytime total cloud cover during 1971–1996 from the NDP026-D [Hahn and Warren, 2003]. For consistency with the GEBA processing, grid box total cloud cover anomalies were determined according to the median of the monthly station anomalies within the grid box, and pan-European anomalies were determined according to the median of the grid box anomalies. Unlike the GEBA station time series, the cloud station time series were almost always available for the entire 1971–1996 period. We screened the synoptic cloud data for potential spurious variability by calculating linear correlations between each station time series and its corresponding grid box time series (representing the neighbors of a station). Stations were excluded if they were both in the bottom quartile of correlations in their grid box and had a lower correlation with the synoptic grid box time series than the ISCCP cloud grid box time series had with the synoptic grid box time series. The median station-grid box correlation value of all excluded stations was 0.65, and the median value of all retained stations was 0.90. Figure 1 displays the locations of the 534 retained synoptic cloud stations.

[14] One disadvantage of synoptic cloud reports is that they do not provide quantitative radiative information, such as SW cloud effect, defined here as the difference between all-sky and clear-sky downward solar radiation flux at the surface. Nevertheless, the radiative impact of surface-observed cloud variability can be reasonably estimated by multiplying monthly grid box cloud cover anomalies by the ratio of climatological cloud effect divided by climatological cloud cover [e.g., Norris, 2005a, 2005b].

We call the resulting parameter a SW “cloud cover” radiative effect anomaly. Specifically,

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

where CCRE is cloud cover radiative effect, CC is cloud cover, $\overline{SW}_{all}$ and $\overline{SW}_{clr}$ are all-sky and clear-sky solar flux at the surface, x is grid box, t is year, m is month, $(\overline{})$ indicates values from the same calendar month averaged over many years, and $()'$ indicates anomalies from the long-term monthly means. For this investigation, we obtained monthly values of $\overline{SW}_{all}$ and $\overline{SW}_{clr}$ from the ISCCP FD and monthly values of $\overline{CC}$ from the gridded synoptic cloud data. $\overline{SW}_{all}$, $\overline{SW}_{clr}$, and $\overline{CC}$ were calculated by averaging over 1983–1996, the period of overlap between the ISCCP FD and the synoptic data. Note that $\overline{SW}_{all} - \overline{SW}_{clr}$ is equivalent to the difference between monthly mean global radiation measured under all conditions and monthly mean global radiation measured only under clear sky conditions.

[15] CCRE anomalies differ from conventional cloud effect anomalies in that the latter take into account all impacts of cloud properties on radiation flux whereas the former take into account only those cloud properties that are linearly related to cloud cover variations. SW cloud effect and SW CCRE anomalies represent a loss of energy to the surface and are consequently negative when cloud cover anomalies are positive.

[16] Figure 2a displays monthly grid box anomalies of surface SW cloud effect ($\overline{SW}_{all} - \overline{SW}_{clr}$) provided by the ISCCP FD versus SW CCRE anomalies estimated from synoptic reports of total cloud cover. Each point represents cloud effect and CCRE anomalies for a particular grid box in a particular month of a particular year during 1983–1996. The linear correlation between them is 0.89, indicating that SW CCRE anomalies explain 80% of the variability in anomalies of SW cloud effect. Estimation of SW CCRE using ISCCP total cloud amount rather than synoptic total cloud cover produces a very similar correlation ($r = 0.87$) and scatterplot (not shown). Were we to compute residuals from the best fit line individually for each calendar month and grid box, the correlation between SW CCRE and SW cloud effect would increase to 0.91. The remaining dispersion around the best fit line is produced by interannual variability in cloud albedo and observational uncertainty. Seasonal and geographical variations in insolation and mean cloud properties are already incorporated into the CCRE calculation.

[17] The amplitude of SW CCRE anomalies estimated from total cloud cover is not the same as the amplitude of the SW cloud effect anomalies provided by the ISCCP FD because the ISCCP FD values incorporate information on cloud optical thickness in addition to cloud amount. The consistent underestimation of SW CCRE relative to SW cloud effect, however, implies that a substantial portion of cloud albedo variability is linearly related to cloud cover variability. Examination of ISCCP grid box anomalies shows that clouds tend to be optically thicker during months with greater than average cloud amount ($r = 0.45$), and this effect can be captured by multiplying the estimated anomalies by 1.7. After this enhancement factor is applied, synoptic-estimated SW CCRE anomalies and ISCCP FD SW cloud effect anomalies lie along the 1:1 line (Figure 2b).

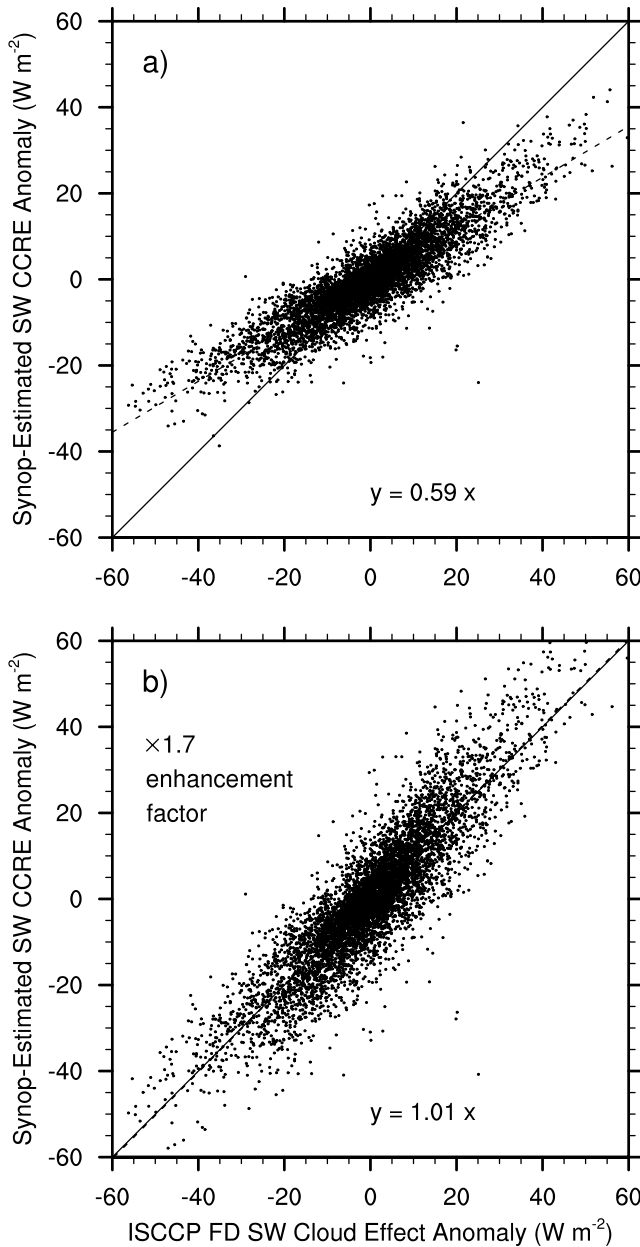


Figure 2. Scatterplot of monthly grid box anomalies of surface SW cloud effect obtained from the ISCCP FD versus anomalies of SW CCRE estimated from synoptic reports of total cloud cover: (a) without modification and (b) multiplied by 1.7. The 1:1 line is solid, and the best fit line is dashed.

Note that such an enhancement factor does not account for all cloud albedo variability but only the portion that is linearly related to cloud cover variations. Although we computed best fit lines in Figure 2 for illustrative purposes, we do not use them in subsequent analysis but instead carry out computations separately for each grid box and calendar month.

2.4. Determination of Observational Uncertainty

[18] Sources of uncertainty in the surface and satellite radiative values include not only measurement imprecision

but also potential problems such as unidentified drifts in instrument calibrations and satellite retrievals, errors in the input parameters to the sophisticated ISCCP radiative transfer model, oversimplifications of the empirical cloud cover radiative effect model, lack of geographical representativeness by point observations, and missing data. Most of these latter issues are poorly quantified, thus rendering infeasible a bottom-up calculation of the total uncertainty. As an alternative, we adopted the top-down approach of assessing uncertainty through intercomparison of corresponding independent data sources. For example, presuming that parameters x and y measure the same quantity and have standard errors ε_x and ε_y , the standard deviation of their differences, σ_{x-y} , equals $\sqrt{\varepsilon_x^2 + \varepsilon_y^2}$. Being ignorant of the true partitioning of uncertainty between x and y , we assumed that $\varepsilon_x = \varepsilon_y = \sigma_{x-y}/\sqrt{2}$. We then approximated the 95% confidence intervals of x and y values as $2\varepsilon_x = \sqrt{2}\sigma_{x-y}$.

[19] We assigned the 95% confidence intervals for GEBA global radiation anomalies and ISCCP FD all-sky flux solar anomalies as $\sqrt{2}$ times the standard deviation of GEBA-ISCCP differences across all years. Confidence intervals for synoptic-estimated and ISCCP-estimated SW CCRE anomalies were similarly determined as $\sqrt{2}$ times the standard deviation of synoptic-ISCCP differences. Since ISCCP FD SW cloud effect anomalies were very highly correlated with ISCCP all-sky anomalies ($r = 0.98$), we gave them the same confidence intervals as the all-sky data. Confidence intervals for grid box anomalies were derived from differences between grid box time series, and confidence intervals for pan-European anomalies were derived from differences between pan-European time series. Depending on the needs of subsequent processing, confidence intervals were calculated either for individual seasons or in aggregate over all months.

[20] Uncertainties in linear trend analysis come from two sources: the uncertainties of individual values in a time series and the amount of “scatter” around the trend line in a time series. The latter uncertainty is generally a larger factor in meteorological studies because departures from a strict trend line are usually real and not merely the result of observational uncertainty. We took this into account in our determination of trend confidence intervals by multiplying individual uncertainty values by a uniform factor (≥ 1) such that the χ^2 statistic became equal to the number of values in the time series. This happens to be the implicit choice of trend computations that ignore individual uncertainties. In those rare cases where the χ^2 statistic was already larger than the number of values in the time series, the individual uncertainty values were left unchanged. Since autocorrelation calculations loosely based upon Zwiers and von Storch [1995] indicated that radiation flux anomalies were typically independent after an interval of 1.5 months, we multiplied the 95% confidence interval for trends based on monthly data by $\sqrt{1.5}$. A randomness test applied to the trend residuals indicates that this autocorrelation assumption is valid and in fact is conservative in many cases.

3. Results

[21] Figure 3a displays time series of pan-European monthly anomalies of GEBA global radiation and ISCCP

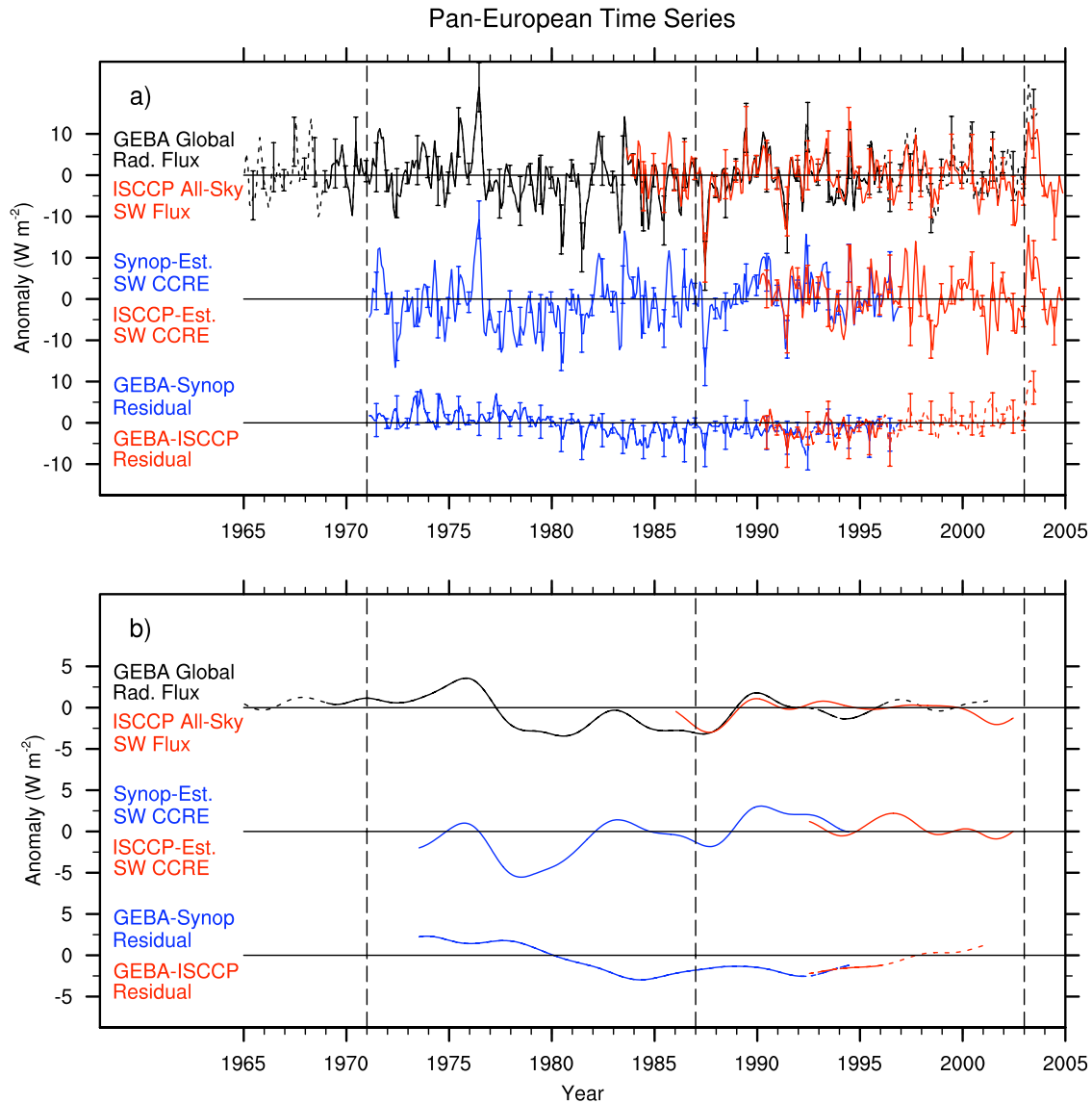


Figure 3. Time series of monthly anomalies averaged over the grid boxes displayed in Figure 1: (a) with 1-2-1 smoothing applied for readability and (b) with the application of a 61-point 5-year Lanczos low-pass filter. The plotted parameters are GEBA global radiation flux (top black), ISCCP all-sky downward SW flux (top red), SW CCRE estimated from synoptic reports of total cloud cover (middle blue), SW CCRE estimated from ISCCP total cloud amount (middle red), residual anomalies after removing synoptic-estimated SW CCRE from GEBA global radiation (bottom blue), and residual anomalies after removing ISCCP-estimated SW CCRE from GEBA global radiation (bottom red). 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 vertical dashed lines mark the starting and ending times for trend calculations in subsequent figures and tables.

FD all-sky downward solar radiation flux (top) and SW CCRE estimated from synoptic and ISCCP total cloud cover (middle). The close agreement between independent values of all-sky flux reported by GEBA and ISCCP ($r = 0.86$) and between independent values of SW CCRE estimated from the synoptic reports and ISCCP ($r = 0.85$) provides confidence in the reliability of the measured and modeled parameters. Moreover, the very high correlation ($r = 0.88$) between GEBA global radiation anomalies and estimated SW CCRE anomalies supports the accuracy of the estimation method and demonstrates that cloud cover variations

(and linearly related cloud albedo variations) are responsible for the large majority of variability in downward solar radiation flux on monthly to subdecadal timescales. We do not expect that GEBA global radiation and ISCCP FD all-sky solar flux will have the same long-term changes since the ISCCP FD assumed constant tropospheric aerosol after 1990. Furthermore, changes in aerosol optical thickness that happen to be included in the ISCCP cloud retrieval will be difficult to detect. This is because variability in aerosol optical thickness is relatively small in comparison to the mean value and variability of cloud optical thickness.

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

Parameter	1971–1986 Trend		1987–2002 Trend	
	Least Squares	Median Slope	Least Squares	Median Slope
Total cloud cover, % cover decade ⁻¹	-1.0 ± 1.9	-1.5	$+0.9 \pm 1.7$	+0.7
GEBA global radiation, W m ⁻² decade ⁻¹	-3.1 ± 3.3	-2.0	$+1.4 \pm 3.4$	+1.1
Estimated SW CCRE, W m ⁻² decade ⁻¹	$+0.9 \pm 3.5$	+1.7	-0.8 ± 3.2	-0.6
Residual, W m ⁻² decade ⁻¹	-3.5 ± 1.2	-2.7	$+2.3 \pm 1.2$	+2.0
Clear-sky flux, W m ⁻² decade ⁻¹			$+1.7 \pm 1.9$	+1.8
SW cloud effect residual, W m ⁻² decade ⁻¹			$+1.3 \pm 1.3$	+1.0

Moreover, the direct radiative forcing by aerosol is much weaker in the presence of a cloud than in clear sky because many of the incoming solar photons are backscattered by the cloud instead of by aerosol particles.

[22] Previous research has documented a relationship between variations in nimbostratus over Europe and the North Atlantic Oscillation (NAO) during winter [Warren *et al.*, 2007]. We find that the pan-European SW CCRE time series in Figure 3a is uncorrelated with the NAO ($r = 0.05$), in large part because summertime total cloud cover has zero interannual correlation with the NAO yet dominates SW CCRE because of greater insolation. The correlation between SW CCRE and the NAO becomes much larger ($r = 0.89$) after a 5-year low-pass filter is applied, even during summer ($r = 0.52$). Very large positive anomalies in SW CCRE and global radiation occurred during the severe European drought years of 1976 and 2003.

[23] Considering that previous investigations have found no relationship between solar “dimming” and trends in cloud cover at many sites [Qian *et al.*, 2006; Stanhill, 1998; Stanhill and Ianetz, 1997; Stanhill and Moreshet, 1994], it would be useful to calculate the residual time series that remains after estimated SW CCRE anomalies are removed from GEBA global radiation anomalies. Although the simplest removal method would have been straight subtraction, we instead applied linear regression to each grid box and calendar month in order to avoid dependence on the quantitative value of any “enhancement factor.” Both methods produced very similar results. The 95% confidence intervals for the residual anomalies were derived from the standard deviation of the differences between residual time series based on synoptic-estimated CCRE and ISCCP-estimated CCRE.

[24] The most prominent features of the pan-European residual time series, shown at the bottom of Figure 3a, are the decrease from the early 1970s to the mid 1980s, the increase from the early 1990s to the early 2000s, and the relatively flat period in between. Application of a 5-year low-pass filter illustrates these low-frequency changes even more clearly (Figure 3b). The relative minima in 1983–1984 and 1991–1992 correspond to the El Chichón and Mount Pinatubo volcanic eruptions that introduced large amounts of sulfate aerosol into the stratosphere, thus leading to multiyear worldwide reductions in downwelling solar radiation [Abakumova *et al.*, 1996; McCormick *et al.*, 1995; Schwartz, 2005]. Removing the very large interannual and subdecadal surface solar radiation variations caused by cloud cover variations produces a more clear demonstration of solar “dimming” and “brightening” over Europe than is evident in the GEBA global radiation time series.

[25] Linear trends conveniently summarize the change in surface radiation flux associated with solar “dimming” and

“brightening.” We selected 1971–1986 and 1987–2002 as time periods for trend calculations since they divide the available residual time series into equal 16-year intervals with a change point at the transition from “dimming” to “brightening.” Our computed “brightening” trend would have been one third larger had we included the extraordinary drought year of 2003, but we left it out because GEBA data were available only for nine months and only for half of the stations. Trend magnitudes would also have been greater had we chosen as starting or ending points the maximum in 1973 or the volcanic minima in 1983 and 1992.

[26] Table 1 lists all-months pan-European trends calculated using both the method of least squares, which offers a straightforward procedure for determining confidence intervals [von Storch and Zwiers, 2001], and the more robust technique of determining the median of pairwise slopes [e.g., Lanzante, 1996]. Estimated SW CCRE and residual time series derived from synoptic and ISCCP cloud data were averaged together during the period of overlap before computing trends. GEBA global radiation decreased by 2.0–3.1 W m⁻² per decade during 1971–1986 and increased by 1.1–1.4 W m⁻² per decade during 1987–2002. Estimated SW CCRE increased by 0.9–1.7 W m⁻² per decade and decreased by 0.6–0.8 W m⁻² per decade during the same respective time periods, indicating that a 1.0–1.5% cover per decade reduction in cloud cover partially opposed the solar “dimming” and a 0.7–0.9% cover per decade enhancement of cloud cover partially opposed the solar “brightening.” Residual trends are therefore slightly larger than the original global radiation trends, exhibiting a decrease of 2.7–3.5 W m⁻² per decade during 1971–1986 and an increase of 2.0–2.3 W m⁻² per decade during 1987–2002. Out of all of the preceding parameters, only the residual trends are statistically significant. The residual trends have much tighter 95% confidence intervals because of the removal of substantial “scatter” produced by interannual and subdecadal cloud cover variability. As demonstrated by Table 2, residual trends have identical sign across all seasons of the year, albeit with differing magnitudes that

Table 2. Seasonal Pan-European Trends in Residual Flux With 95% Confidence Intervals

Season	1971–1986 Trend, W m ⁻² decade ⁻¹		1987–2002 Trend, W m ⁻² decade ⁻¹	
	Least Squares	Median Slope	Least Squares	Median Slope
May-Jun-Jul	-5.4 ± 3.2	-5.4	$+4.3 \pm 3.3$	+4.1
Aug-Sep-Oct	-4.7 ± 2.4	-3.9	$+1.6 \pm 2.4$	+1.0
Nov-Dec-Jan	-0.7 ± 0.8	-0.6	$+0.5 \pm 1.0$	+0.5
Feb-Mar-Apr	-3.4 ± 2.2	-3.1	$+2.9 \pm 2.2$	+2.9

Table 3. Seasonal Pan-European Relative Trends in Residual Flux With 95% Confidence Intervals

Season	1971–1986 Trend, % decade ⁻¹		1987–2002 Trend, % decade ⁻¹	
	Least Squares	Median Slope	Least Squares	Median Slope
All months	-2.6 ± 0.9	-2.3	$+1.8 \pm 1.1$	+1.8
May-Jun-Jul	-2.4 ± 1.4	-2.3	$+1.9 \pm 1.5$	+1.8
Aug-Sep-Oct	-3.3 ± 1.5	-3.1	$+0.9 \pm 1.9$	+0.9
Nov-Dec-Jan	-1.7 ± 2.0	-1.5	$+1.4 \pm 2.6$	+1.3
Feb-Mar-Apr	-3.0 ± 2.1	-2.7	$+3.2 \pm 2.2$	+2.6

vary according to seasonal insolation. Table 3 lists all-months and seasonal trends in residual radiation expressed as a percentage of climatological global radiation.

[27] We examine the sensitivity of our results to the exclusion of GEBA stations in the lowest quartile of correlations with cloud cover by comparing them to results when no stations are excluded or when all stations below the median are excluded. The 1971–1986 pan-European residual trend is $-4.2 \pm 1.2 \text{ W m}^{-2}$ per decade when no stations are excluded and $-2.7 \pm 1.2 \text{ W m}^{-2}$ per decade when the lower half of the stations are excluded. Both values are within the uncertainty range of the 1971–1986 residual trend listed in Table 1, but the reported solar dimming becomes smaller when GEBA stations less highly correlated with cloud cover are removed. The reported solar brightening conversely becomes larger when more stations are removed, and the 1987–2002 residual trends for all stations and for the upper half of the stations are $+1.9 \pm 1.2 \text{ W m}^{-2}$ per decade and $+2.9 \pm 1.3 \text{ W m}^{-2}$ per decade, respectively. Both of these values are also within the uncertainty range of the 1987–2002 residual trend listed in Table 1.

[28] One possible reason for the occurrence of a stronger negative trend and weaker positive trend when stations with relatively low correlations with cloud cover are included is that these stations are less reliable in general and suffer from sensor degradation in particular such that they report a spurious decrease in global radiation over time. Another possible reason for the change in trend value with station selection is that the geographical sampling is different. The number of grid boxes contributing to the pan-European time series decreases from 53 to 44 to 30 when stations in the lower quartile and lower half of correlations with cloud cover are excluded, and almost all of the lost grid boxes are in southern and eastern Europe.

[29] Figures 4a and 4b display all-months trends in GEBA global radiation anomalies during 1971–1986 and 1987–2002 at each grid box. We used the least squares method to determine trends because it provided convenient calculations of statistical significance, but the median slopes technique produced very similar patterns (not shown). Examination of particular grid box trends in Figure 4a verified that their distribution of negative and positive values matched those documented in earlier studies for specific stations, despite being computed over somewhat differing time periods [Abakumova *et al.*, 1996; Liepert and Kukla, 1997; Stanhill, 1998; Stanhill and Cohen, 2001; Stanhill and Moreshet, 1994]. The predominance of negative trends over positive trends during 1971–1986 (40 versus 4) and positive trends over negative trends during

1987–2002 (28 versus 16) in Figures 4a and 4b demonstrate that the decline in global radiation prior to the mid 1980s and recovery thereafter are regional phenomena and not merely the result of erroneous measurements at a few stations. The grid box trends have less frequent statistical significance than the pan-European trends because their interannual and sub-decadal variations are relatively larger.

[30] The grid box trends in estimated SW CCRE presented in Figures 4c and 4d exhibit different spatial patterns than do the global radiation trends in Figures 4a and 4b, providing substantial support that changes in cloud cover are not the primary cause of solar “dimming” and “brightening” in Europe. Unlike the case for global radiation, trends in SW CCRE are organized into definite centers of action, suggesting that cloud cover changes are likely driven by shifts in atmospheric circulation. Congruent to the pan-European trend results listed in Table 1, the removal of estimated SW CCRE anomalies from global radiation anomalies generates grid box residual trends that have much more frequent statistical significance than the original trends.

[31] One limitation of the residual anomalies is that they combine variations in clear-sky solar radiation flux with variations in cloud optical thickness that are unrelated to cloud cover, whereas it would be useful to distinguish the clear-sky and cloudy-sky contributions due to their possible correspondence to the direct and first indirect aerosol radiative effects. Unfortunately, most GEBA stations lack direct measurements or proxies for clear-sky solar radiation flux and the ISCCP FD cannot accurately represent clear-sky flux since it does not include temporally varying tropospheric aerosol. Using the fact that SW cloud effect equals all-sky solar flux minus clear-sky solar flux and the equivalence between ISCCP all-sky flux and GEBA global radiation, we obtained monthly grid box clear-sky flux anomalies by subtracting ISCCP FD SW cloud effect anomalies from GEBA global radiation anomalies. This procedure presupposes that temporal variations in SW cloud effect are identical in both data sets. Confidence intervals for the clear-sky flux parameters were calculated as the square root of the sum of the squared confidence intervals of GEBA global radiation and ISCCP SW cloud effect.

[32] The cloudy-sky contribution to residual anomalies was furthermore obtained by removing estimated SW CCRE anomalies from ISCCP FD SW cloud effect anomalies via linear regression at each grid box. These “SW cloud effect residual” anomalies thus represent variations in SW cloud effect that are not linearly related to variations in cloud cover. Specifically, only the portion of cloud albedo variability that is uncorrelated with cloud cover remains in the SW cloud effect residual.

[33] Figure 5 displays time series of pan-European monthly anomalies clear-sky solar flux (middle), and SW cloud effect residual anomalies (bottom). Their sum is very similar to the main residual time series (Figure 5, top), which is reproduced from the bottom of Figure 3a. The former two parameters are available only from July 1983 onward since their calculation required SW cloud effect provided by the ISCCP FD. Although the clear-sky flux time series and the SW cloud effect residual time series exhibit substantial interannual variability, they both generally increase from the mid 1980s to the early 2000s. As

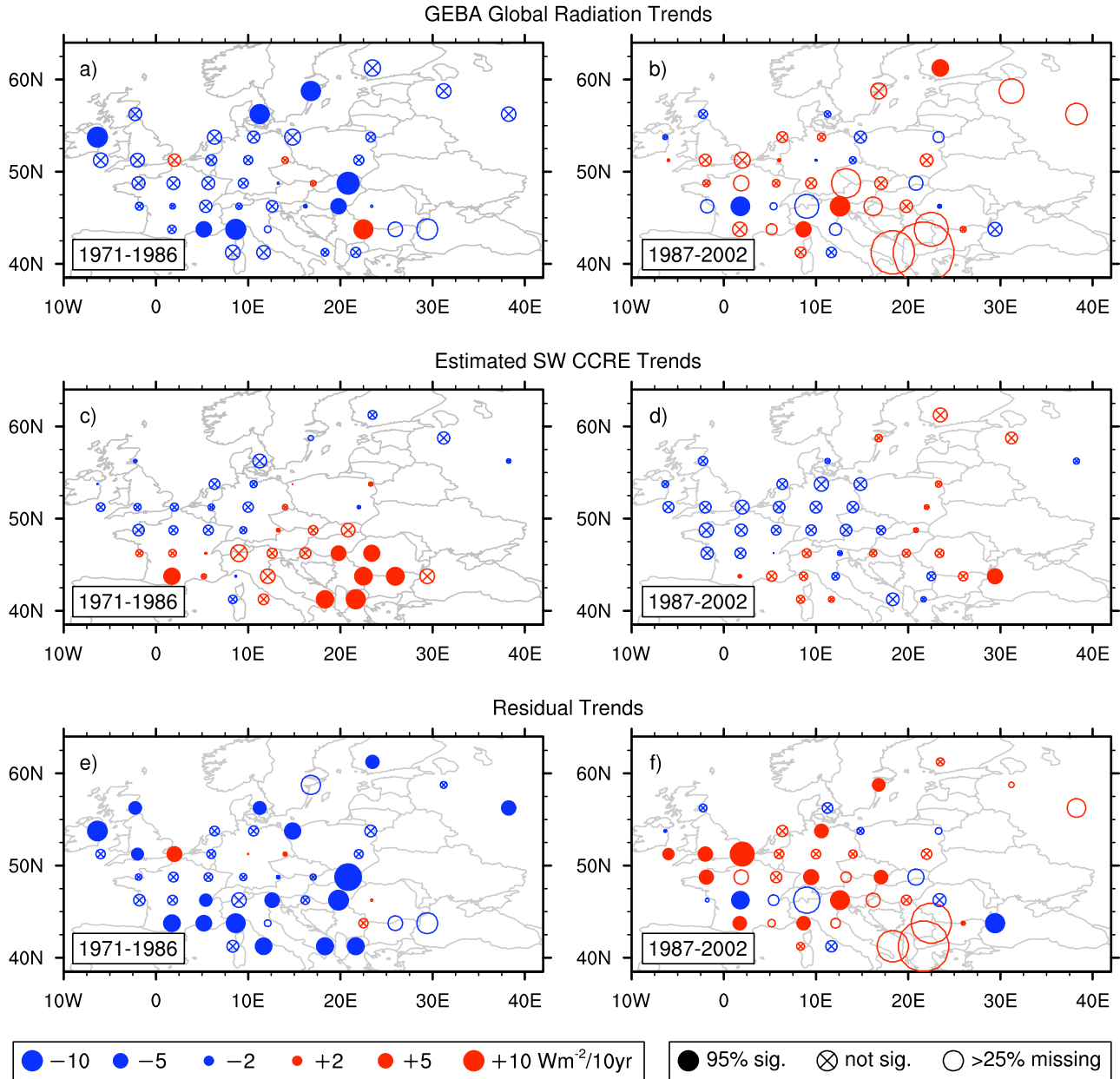


Figure 4. Least squares all-months grid box trends for GEBA global radiation flux anomalies during (a) 1971–1986 and (b) 1987–2002, estimated SW CCRE anomalies during (c) 1971–1986 and (d) 1987–2002, and residual anomalies after removing estimated SW CCRE from GEBA global radiation during (e) 1971–1986 and (f) 1987–2002. 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.

listed in Table 1, clear-sky flux increased by $1.7\text{--}1.8 \text{ W m}^{-2}$ per decade and SW cloud effect residual flux increased by $1.0\text{--}1.3 \text{ W m}^{-2}$ per decade between 1987 and 2002. Neither of these trends is statistically significant, but we nonetheless show them because they are the only geographically widespread information available on clear-sky and cloudy-sky contributions to the main residual time series. When all GEBA stations with cloud cover correlations less than the median are excluded, the clear-sky flux trend becomes $+2.1 \pm 1.9 \text{ W m}^{-2}$ per decade, and when no stations are excluded,

the clear-sky flux trend becomes $+1.1 \pm 1.8 \text{ W m}^{-2}$ per decade. The value of SW cloud effect residual trend does not vary with the selection of GEBA stations.

[34] Figure 6a presents trends in clear-sky solar flux anomalies during 1987–2002 at each grid box. We found qualitative agreement between particular grid box trends in Figure 6a and those few stations with clear-sky global radiation or direct beam (atmospheric clear sky transmission) measurements during this time period [Wild *et al.*, 2005]. The predominance of positive trends over negative

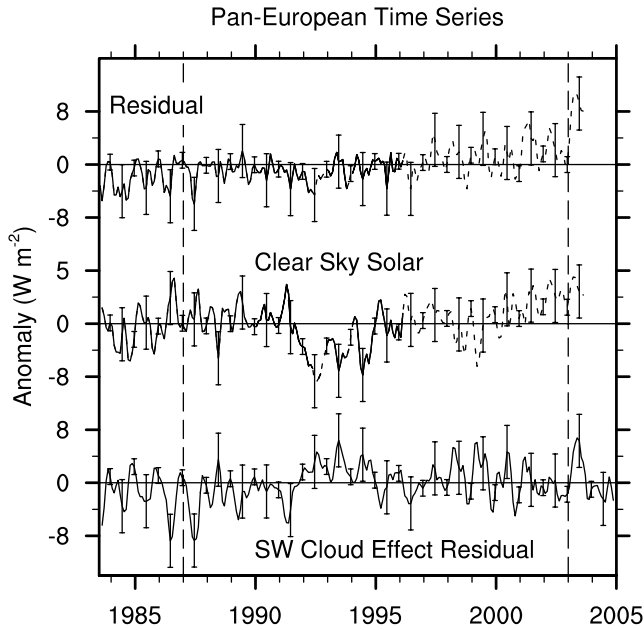


Figure 5. As in Figure 3a except for (top) residual anomalies after removing estimated SW CCRE from GEBA global radiation, (middle) clear-sky SW flux, and (bottom) residual anomalies after removing estimated SW CCRE from ISCCP FD SW cloud effect. Residuals derived from synoptic cloud cover and from ISCCP cloud amount were averaged together into a single time series for greater clarity.

trends (28 versus 16) demonstrates the widespread nature of the enhancement of downward clear-sky solar flux after the mid 1980s. Figure 6b shows that positive trends are even more prevalent than negative trends for SW cloud effect residual anomalies (39 versus 5).

4. Discussion and Conclusions

[35] Radiative effects of cloud cover anomalies and linearly related changes in cloud albedo, called SW CCRE anomalies in this study, are the greatest contributors to

variability in surface global radiation (also called all-sky SW flux) at monthly to subdecadal timescales (top and middle of Figure 3). Considering that large positive SW CCRE anomalies occurred during noteworthy drought years and that low-frequency variability in SW CCRE is highly correlated with the NAO ($r = 0.89$), we believe that the SW CCRE time series displayed in Figure 3 represents the radiative effects of natural weather and climate variability. The fact that multidecadal trends in cloud cover and SW CCRE are weak and not statistically different from zero (Table 1) is consistent with the attribution to natural variability.

[36] Removal of SW CCRE anomalies from GEBA global radiation anomalies generated a residual time series collectively composed of variations in clear-sky solar flux and the radiative effects of cloud albedo changes that were not linearly related to cloud cover (Figure 3b and Figure 5, top). Depending on the method used to compute the trend, this residual decreased by a statistically significant $2.7\text{--}3.5\text{ W m}^{-2}$ per decade between 1971 and 1986 and increased by a statistically significant $2.0\text{--}2.3\text{ W m}^{-2}$ per decade between 1987 and 2002 (Table 1). Trend magnitudes were greatest during months of the year with the most insolation (Table 2), although this was not when the largest relative changes occurred (Table 3).

[37] The availability of satellite-derived surface SW cloud effect values, the sum of all cloud radiative effects, enabled us to distinguish clear-sky anomalies from cloudy-sky anomalies in the main residual time series from 1983 onward. We calculated clear-sky flux by subtracting the SW cloud effect from GEBA global radiation (Figure 5, middle) and obtained the contributions of cloud albedo changes unrelated to cloud cover as another residual time series after removing SW CCRE anomalies from SW cloud effect anomalies (Figure 5, bottom). Between 1987 and 2002, the clear-sky flux increased by $1.7\text{--}1.8\text{ W m}^{-2}$ per decade and the SW cloud effect residual increased by $1.0\text{--}1.3\text{ W m}^{-2}$ per decade (Table 1). Since the trends were determined separately for each time series, we cannot expect that the sum of the clear-sky and SW cloud effect residual trends will exactly equal the main residual trend;

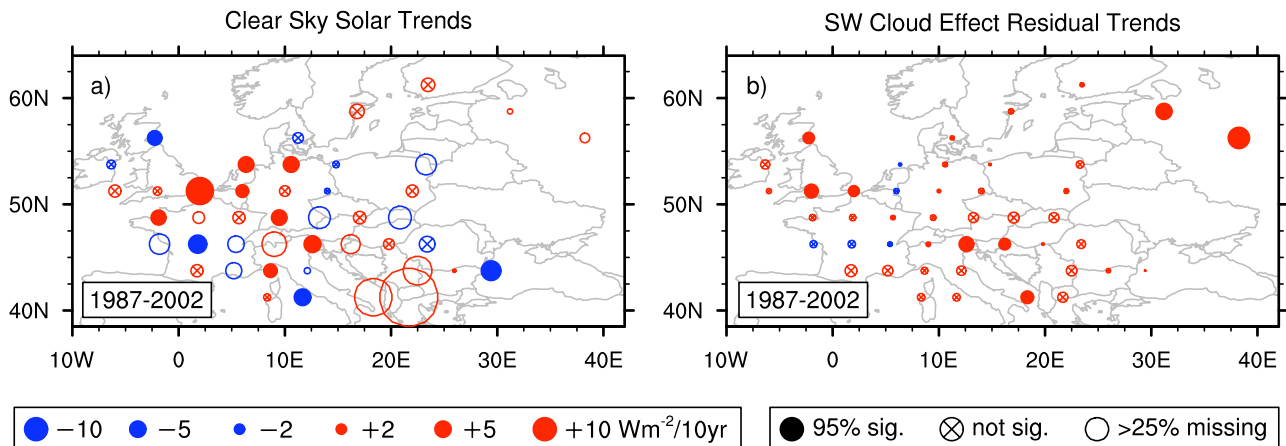


Figure 6. As in Figure 4 except for (a) clear-sky downward SW radiation flux anomalies during 1987–2002 and (b) residual anomalies after removing estimated SW CCRE from ISCCP FD SW cloud effect during 1987–2002.

nevertheless, the three trends agree well within the limit of their confidence intervals.

[38] One crucial question is whether these trends are real or spurious. Although no other independent data set is available to corroborate multidecadal variations in GEBA global radiation, the fact that ISCCP FD all-sky flux agrees very well with GEBA on interannual timescales provides confidence that GEBA is also accurate on longer timescales. Additional assurance is supplied by spatial commonality of negative trends in the earlier period and positive trends in the later period, since it is unlikely that independent GEBA stations across many different nations would all suffer from the same bias (Figure 4). Another possibility is that the reported trends are real but only valid for the immediate area of the stations, which are often located near large population centers [Alpert *et al.*, 2005]. This issue is not likely to be a substantial problem for our European region since Alpert *et al.* found that long-term variations at rural sites were no less than those at urban sites within the 40–70°N latitude zone. Although the identification of artifacts in ISCCP cloud amount during 1983–1989 (Figure A1) raises the possibility that multiyear variations in ISCCP FD cloud effect may be spurious, that would not undermine the validity of the solar “dimming” and “brightening” reported by the main residual time series. Any unreliability of ISCCP FD cloud effect would instead only eliminate our ability to distinguish between clear-sky and cloudy-sky contributions to the main residual.

[39] We believe that the most likely causes for the prior decline and subsequent recovery in residual radiation are aerosol radiative effects. Although this hypothesis cannot be tested in a straightforward manner because long-term explicit measurements of the distribution and properties of anthropogenic aerosol particles and their influences on clear-sky transmission and cloud properties do not exist, the available sulfur and black carbon emission records are generally consistent with our conclusions. The solar “dimming” evident in the residual time series prior to the mid 1980s (Figures 3 and 4e) is consistent with the increasing sulfur and black carbon emissions reported for eastern Europe and the former Soviet Union during the same time period, although not with the flat or slightly declining emissions reported for western Europe [Smith *et al.*, 2001; Stern, 2006; Novakov *et al.*, 2003]. It may be possible to reconcile the latter discrepancy if substantial transport to western Europe of aerosol particles and precursors from eastern Europe and elsewhere has occurred, or it may be the case that the estimated emission records or GEBA are in error. The solar “brightening” after the mid 1980s seen in Figures 3 and 4f is consistent with the decline in sulfur and black carbon emissions reported for both western and eastern Europe as a response to “clean air” laws and the closure of dirty factories and power plants in formerly communist countries [Novakov *et al.*, 2003; Smith *et al.*, 2001; Stern, 2006; Streets *et al.*, 2006]. We do not attempt to use the emission records to interpret the spatial pattern of trends displayed in Figures 4 and 6 because the emissions data were averaged over whole or multiple nations and do not include the essential processes of transportation and deposition.

[40] In addition to changing the amount of solar radiation reaching the surface through direct scattering and absorption, aerosols can affect cloud properties by altering cloud

droplet number and hence scattering area and cloud albedo. Recalling that low-frequency cloud cover variability is closely associated with the NAO and that any variability linearly related to cloud cover anomalies was removed via linear regression from SW cloud effect anomalies, we ascribe the decrease in the SW cloud effect residual to aerosol influence on cloud albedo. Krüger and Graßl [2002] found that NOAA/NASA Pathfinder satellite-retrieved cloud albedo declined by 2.5% from 1985–1989 to 1996–1999 over central Europe and attributed it to a weakening of the cloud albedo aerosol effect, or alternatively a reduction in absorption by black carbon particles within and below the cloud. They estimated that the reduction in cloud albedo corresponded to a 1.5 W m^{-2} change in top-of-atmosphere SW cloud radiative forcing between the late 1980s and the late 1990s, which is comparable to the trend in surface SW cloud effect residual radiation listed in Table 1. We believe that alternative explanations for decreasing cloud albedo, such as a long-term reduction in cloud water path since the mid 1980s, are unconvincing since it is unlikely that natural or anthropogenic processes would produce a multidecadal decline in cloud water path at the same time as a multidecadal enhancement of cloud cover (Table 1).

[41] The fact that the observed long-term increase in cloud cover occurred at the same time as a long-term decrease in anthropogenic sulfate aerosol argues against a substantive operation of the second indirect effect, otherwise known as the cloud lifetime effect. While it is possible that the slight enhancement of cloud cover since the mid 1980s could be attributed to a decline in black carbon aerosol and a hypothetical weakening of the semidirect aerosol radiative effect, we believe that this is unlikely since the semidirect effect probably has not been an important process over Europe during the past several decades. The suppression of cloudiness by aerosol absorption of solar radiation has only been demonstrated for extreme smoke conditions [Koren *et al.*, 2004], whereas the relative proportion of black carbon aerosol over Europe has been small, especially when compared to India and China. Moreover, previous studies have not found a link between black carbon aerosol and cloud cover either for interannual variations [Warren *et al.*, 2007] or for long-term trends [Norris, 2001].

[42] Although the results we describe for the Europe are not applicable globally, the temporal pattern of “solar dimming” followed by “solar brightening” is consistent with the hypothesis that anthropogenic aerosol cooling partially offset greenhouse warming over much of Eurasia and North America during the 1960s through the 1980s [e.g., Charlson *et al.*, 1991] and continues to offset greenhouse warming in developing areas of the world [Nazarenko and Menon, 2005; Ramanathan *et al.*, 2001]. A comparison of these results to equivalent output from a global climate model for the region of Europe would be a good test of the model aerosol and cloud microphysical parameterizations and the aerosol emission history provided to the model as an external parameter.

Appendix A

[43] We discarded ISCCP total cloud amount values prior to January 1990 because the pan-European total cloud

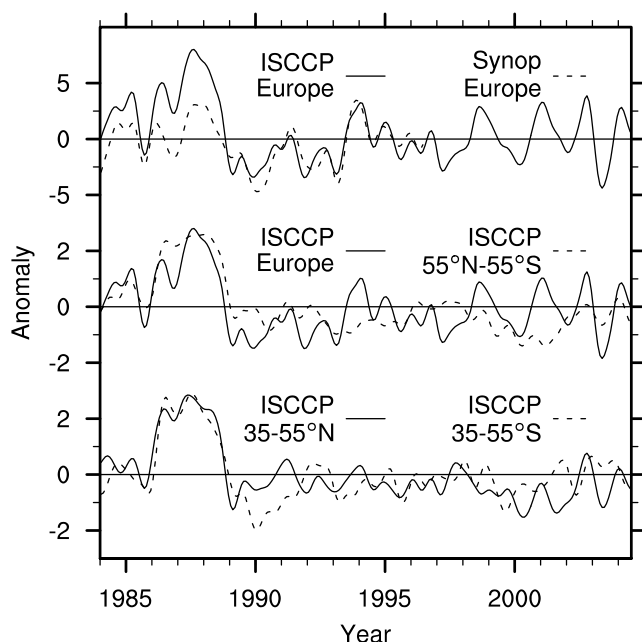


Figure A1. Time series of monthly anomalies of surface synoptic total cloud cover averaged over Europe (top dashed) with time series of monthly anomalies of ISCCP total cloud amount averaged over Europe (top solid and middle solid), over 55°S – 55°N , 37°W – 41°E (middle dashed), over 35 – 55°N , 37°W – 41°E (bottom solid), and over 35 – 55°S , 37°W – 41°E (bottom dashed). A 13-point 1-year Lanczos low-pass filter was applied for readability. The top time series have units of % cloud cover, and the middle and bottom time series have been normalized for better comparability.

amount time series exhibits a suspiciously large multiyear positive anomaly during the 1980s. This large anomaly does not occur in the surface-observed total cloud cover time series, which otherwise agrees well with the ISCCP time series (Figure A1, top). The time series of ISCCP total cloud amount averaged over the primary view area of Meteosat (55°S – 55°N , 37°W – 41°E) [Rossow *et al.*, 1996] also shows a large multiyear positive anomaly during the 1980s (Figure A1, middle), implying that an unknown artifact affecting the whole geostationary satellite view area is the cause of the pan-European anomaly [Norris, 2000]. This hypothesis is confirmed by comparing the linear correlations between the pan-European and whole-geostationary time series calculated for 1983–1989 and for 1990–2004. The value for the former period is 0.58, whereas the value for the latter period is only 0.16. Further support is provided by correlations between time series of total cloud amount anomalies averaged over northern (35 – 55°N) and southern (35 – 55°S) midlatitude regions (Figure A1, bottom). The 1983–1989 value is 0.64, whereas the 1990–2004 value is only 0.06. Considering that these regions are far apart and experience opposite seasons, we argue that their time series could be so highly correlated during the 1980s only if they were jointly affected by some spurious factor.

[44] The ISCCP FD values do not exhibit correlations that are larger in 1983–1989 than in 1990–2004 or other obviously unrealistic features (not shown). This implies that

the total cloud amount artifact is predominantly caused by spurious variations in the least radiatively significant clouds. Such clouds are near the threshold of detection, and factors influencing the ease of detection may cause very optically thin clouds or partially filled pixels to be identified as cloud at some times but not other times.

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