Do Satellites Detect Trends in Surface Solar Radiation?

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Long-term variations in solar radiation at Earth's surface (*S*) can affect our climate, the hydrological cycle, plant photosynthesis, and solar power. Sustained decreases in *S* have been widely reported from about the year 1960 to 1990. Here we present an estimate of global temporal variations in *S* by using the longest available satellite record. We observed an overall increase in *S* from 1983 to 2001 at a rate of 0.16 watts per square meter (0.10%) per year; this change is a combination of a decrease until about 1990, followed by a sustained increase. The global-scale findings are consistent with recent independent satellite observations but differ in sign and magnitude from previously reported ground observations. Unlike ground stations, satellites can uniformly sample the entire globe.

The concept of "global dimming" (*1–3*), which refers to long-term measured decreases in the amount of solar radiation that reaches Earth's surface (*S*), has received prominent attention because of concerns about its possible climatic and environmental implications. An early report on this topic based on surface observations made primarily in Europe (*4*) suggested that *S* declined by more than 10% from 1960 to 1990. On the basis of the analysis of a more comprehensive observational database, it was shown that over land, *S* decreased on the average by 0.23% (*1*) and 0.32% (*2*) per year from 1958 to 1992. The largest decrease was in parts of the former Soviet Union (*5*), where *S* decreased by about 20% between 1960 and 1987. Independent indirect evidence for plausible decreases in *S* has been found in pan evaporation records (*6*, *7*), which show that the rate of evaporation did not increase but rather decreased, in spite of global warming trends evident in records of surface temperatures. When the evaporation data were compared with the global dimming records, the respective tendencies matched, which suggests that these two processes might be linked. Two other studies (*8*, *9*) found that *S* in the Swiss Alps increased between 1995 and 2003 after decreasing from 1981 to 1995 (*8*).

Speculations about possible causes of global dimming include cloud changes, increasing amounts of human-made aerosols, and reduced atmospheric transparency after explosive volcanic eruptions. (Data indicating global dimming could also be produced by instrument deficiencies.) Particles of soot and sulfates absorb and reflect sunlight and facilitate the formation of larger and longer-lasting clouds. The Indian Ocean Experiment (*10*) has clearly documented the large, short-term reduction in solar radiation reaching the surface caused by absorbing aerosols, particularly black carbon and dust. Regionally, the seasonally averaged reduction in the Indian Ocean can reach 10 to 30 W m^{-2}. However, there is some evidence that the reported longer-term

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tendencies might not continue, because of the reduction in the levels of air pollution. For example, global dimming over Germany seems to be decreasing, possibly because of a reduction of pollutants (*11*).

Although the potential climatic effects of a sustained decrease or increase in surface solar radiation require extensive investigation of additional factors, such as the long-wave radiative effects of any associated cloud variations, possible effects on photosynthesis are more direct but will differ by location. In equatorial regions that are sufficiently illuminated, photosynthesis is likely to be limited by carbon dioxide or water, not by radiation. It has been reported (*12*, *13*) that in some cases, photosynthesis could increase slightly with a decrease in solar radiation, because the proportion of diffuse light will increase; diffuse light is absorbed less than the direct beam in the external layers of vegetation, and therefore the diffuse light penetrates deeper into the canopy, reaching a larger fraction of the biomass. At high latitudes, plant growth is light-limited, and a decrease in solar radiation can affect net primary productivity.

In this study, the longest available record of satellite-based estimates of surface solar radiation was used to learn about tendencies in this parameter at spatial scales that otherwise would not be possible. The derived fluxes are based on methodologies that have been critically evaluated and that currently serve as a benchmark for deriving surface short-wave radiative fluxes. Specifically, the International Satellite Cloud Climatology Project (ISCCP) (*14*, *15*) data have been used to derive surface radiative fluxes for about 20 years. An extensive effort was undertaken to address the calibration issue of the various satellite sensors used (*16*, *17*), and it is believed that at present, the best attainable calibration techniques were applied. The homogeneity of the satellite observations was achieved by normalizing all of the geostationary satellites used to the polar orbiting satellites, which enjoy a long history of calibration know-how. Specifically, the Satellite Calibration Center (Centre de Meteorologie Spatiale, Lannion, France) receives special high-resolution imaging data from the Satellite Processing Centers that provide data for ISCCP. These data are used to normalize the calibrations of the geostationary satellites to the polar orbiter, which is taken as the standard, and the resulting coefficients are sent to the processing center or the ISCCP data center (http://isccp.giss.nasa.gov/).

The estimated surface-downward solar radiative fluxes were derived with the University of Maryland version of the Global Energy and Water Cycle Experiment (GEWEX) Surface Radiation Budget algorithm (*18*), and the ISCCP D1 satellite data at a spatial resolution of 2.5° was used as input. The monthly mean fluxes were obtained by averaging the daily mean values that were obtained by integration of three hourly instantaneous fluxes. The model allows the computing of upward fluxes at the surface and net solar fluxes at the top of the atmosphere by using satellites observations of clear and cloudy radiances, cloud cover fraction, and independent information on the total amount of water vapor, ozone, and snow cover.

Extensive evaluation of the satellite-estimated monthly mean downward fluxes at the surface against ground measurements has been performed (*19*, *20*). Monthly averaged, hemispheric, broadband, solar-surface measurements from the World Radiation Data Center, the Global Energy Budget Archive, and the Canadian Network were used. These measurements provide a continuous, long, time series that is clustered in regions with similar climatological surface types (such as Europe, southeast Africa, East Africa, and south Australia) that are used in the evaluation. The range of the root mean square (RMS) errors at a spatial resolution of 2.5° was found to be between 11.7 and 31.5 W m^{-2} (*19*); the best results were found over Europe, Australia, eastern Canada, and western Canada (known for good quality of ground data); the worst were found over central Africa and Pakistan/India. In an updated evaluation at 1° resolution based on ISCCP DX data (*20*, *21*), the range of the RMS errors was reduced to about 7.5 to 27.0 W m^{-2} (excluding African stations). On the basis of results of evaluation against Surface Radiation (SURFRAD) (*22*) ground observations at a spatial resolution of 0.5° over the United States, it was found that the average RMS error on a monthly time scale was about 20 W m^{-2} (*23*).

Two independent approaches were used to determine tendencies of the data: linear and second-order fits. The confidence levels of the derived tendencies were calculated according to the Student's *t*-test distribution with $n - 2$ degrees of freedom

$$t = r_{xy}\sqrt{\frac{n-2}{1-r_{xy}^2}}$$

Here r_{xy} is the correlation coefficient between the original time series and the linear and second-order fitted time series (*24*), and *n* is the number of observations.

Figure 1 presents linear and second-order least-squares fits to the original satellite-derived time series of surface solar irradiance (1983 to 2001) after removal of the mean annual cycle. On a global scale, the linear slope (solid line) in the surface solar radiation is positive at 0.16 W m^{-2} $year^{-1}$. The second-order polynomial (broken line) indicates a small decrease during the time period from 1983 to 1992, with a reversal around 1992. Both the linear and the second-order fits are significant at a 99% level of confidence.

Results from similar analyses are presented in Fig. 2, which were computed from the following: satellite-based observations over the Arctic (60° to 90°N) (Fig. 2A); satellite-based observations over a local point in the Arctic (Barrow, Alaska) (Fig. 2B); and ground observations at Barrow, Alaska (Fig. 2C). To be consistent with the analysis for American Samoa (Fig. 3), adjacent satellite grid points were averaged over the ground location for Fig. 2B. The ground observations are from the National Oceanic and Atmospheric Administration, Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL) (*25*) and are considered to be the highest quality available for long-term ground observations. Analysis of the satellite-based observations shows a small decrease in solar radiation over the 60° to 90°N Arctic region from 1983 to 2001. The linear slopes for all three cases in Fig. 2 are slightly negative. However, the second-order fits show a decrease in solar radiation from 1983 to about 1992 to 1993 that is followed by a reversal in tendency. This is the first time that consistency in long-term temporal variations between satellite observations and ground observations has been documented. These results also indicate that the radiative conditions at the Barrow site behave similarly to those over the latitudinal belt of 60° to 90°N. The results are consistent with independent findings that report warming in the Arctic from 1982 to 1999 and an increase in

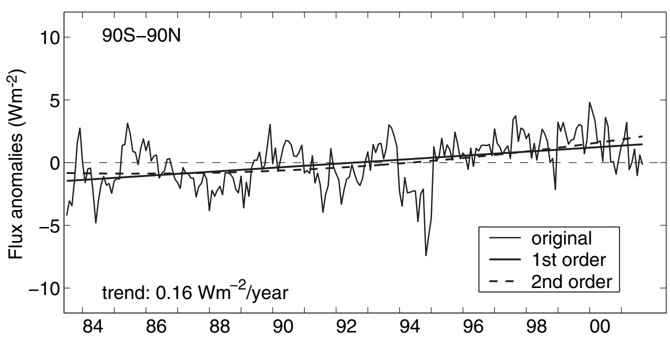

Fig. 1. Linear and second-order least-squares fits to the original satellite-derived time series of *S* (from 1983 to 2001) averaged over the globe, after removal of the mean annual cycle. The linear slope (solid line) of the surface solar radiation is positive at 0.16 W m^{-2} $year^{-1}$. The second-order polynomial (dashed line) indicates a small decrease from 1983 to 1992, with a reversal around 1992. Both the linear and the 2nd-order fits are significant at the 99% level of confidence.

cloudiness during the spring and summer (*26*), when most of the radiation in this region is received. Correlations between the actual ground observations at Barrow with the satellite estimates were computed and found to be 0.97 (fig. S1). A similar experiment has been performed at American Samoa, a site where high-quality observations are available (*25*) and which represents oceanic conditions (Fig. 3). Observed tendencies from satellite estimates of the surface solar fluxes are shown (Fig. 3A), and Fig. 3B represents the same, using the CMDL ground observations. Because local cloud effects caused by land/water boundaries affect the observations at the Samoa site, the satellite estimates were averaged over grid cells adjacent to the one centered over the ground site. Here, the linear slopes are positive and the second-order fit indicates a decrease in radiation from 1983 to about 1992 to 1993 that is followed by an increase thereafter. Correlations between the actual ground observations at this site with the satellite estimates were also computed and found to be 0.86 (fig. S1). We investigated the tendencies of the surface solar radiation in the tropical belt of 20°S to 20°N (Fig. 4A) and at the top of the atmosphere (ToA) (Fig. 4B). It was found that at the surface, there is a positive linear increase of about 0.18 W m^{-2} $year^{-1}$, which indicates an increase in the surface radiation. At the ToA, the situation is reversed and the decease is about –0.17 W m^{-2} $year^{-1}$. The tendencies from the second-order fit are similar to the linear ones. A decreasing tendency is also reported at the ToA's reflected solar radiation (*27*), which is observed by a combined data set based on observations from the Clouds and the Earth's Radiant Energy System (CERES) (*28*) and from the Earth Radiation Budget Satellite (ERBE) (*29*). It is claimed that the observed changes in radiation budget are caused by changes in the mean tropical cloudiness, which is detected in the satellite observations but fails to be predicted by several current climate models.

The studies that reported dimming were conducted over land; therefore, a separate analysis of tendencies over the land and oceans was performed (Fig. 5). A land mask as described in (*30*) was used. We considered sea ice–covered oceans as ocean. The tendencies over land global domain from 90°S to 90°N have been found to be slightly negative at about –0.05 W m^{-2} $year^{-1}$, and over the oceans, the tendency was positive at 0.24 W m^{-2} $year^{-1}$. For the

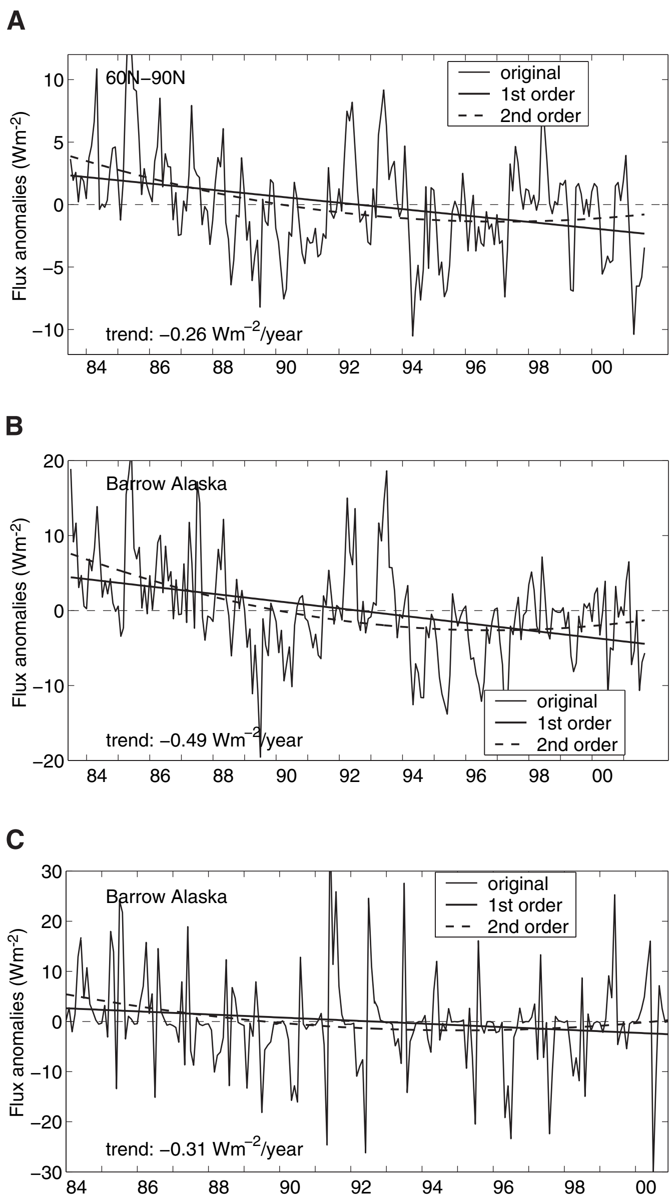

Fig. 2. Linear and second-order least-squares fits over (**A**) the Arctic 60° to 90°N, (**B**) over Barrow Alaska from satellites, and (**C**) at Barrow from ground observations.

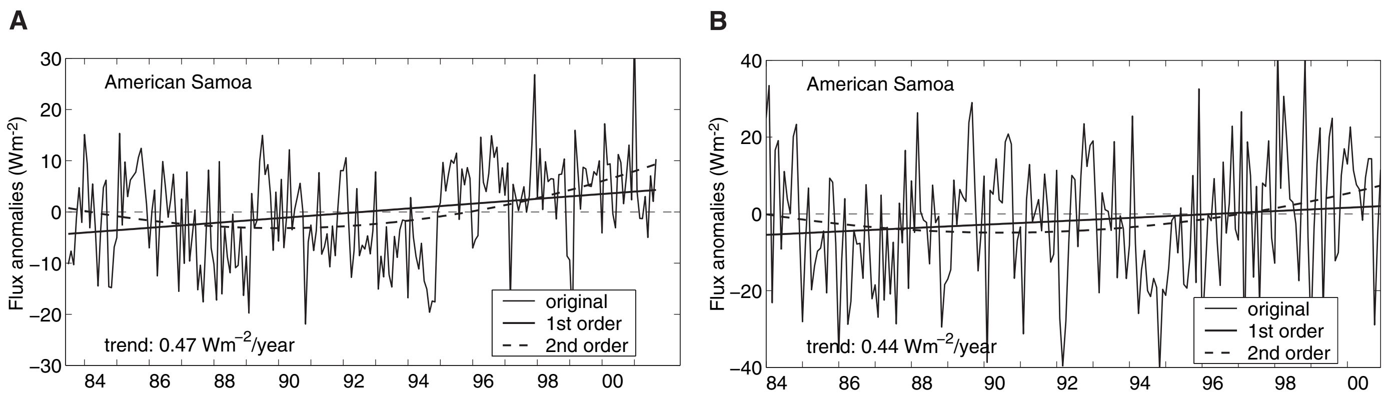

Fig. 3. Linear and second-order least-squares fits over (**A**) American Samoa from satellites and (**B**) at American Samoa from ground observations.

land case, the trend is not statistically significant; however, for the ocean, it is significant with a confidence level of 99%. Because long-term ground observations are available mostly from land sites, it is possible that land-based observations are not representative of Earth as a whole, and therefore brightening at a global scale is possible. For the land-alone case, although the overall slope is negative, there is a small increase after 1993.

About 20 years (from 1983 to 2001) of *S* fluxes at Earth's surface that were derived from satellite observations were analyzed. (The annual mean surface solar radiation in W/m^2 from 1983 to 2001, as distributed over the globe at 2.5° spatial resolution estimated from the ISCCP D1 data, is illustrated in fig. S2.) The analysis was conducted at a global scale as well as over regions of special climatic significance. Our findings at the global scale as well as those in the tropical belt and in the Arctic are consistent with the findings of independent satellite studies (*26*–*28*). For example, a global-scale decrease in cloudiness (*31*) based on ISCCP D1 data was found, which is consistent with an increase in surface solar radiation found in this study, because clouds are the major modulators of the solar radiation that reaches the surface. Warming in the Arctic from1982 to 1999 and an increase in cloudiness during the spring and summer (*26*) is reported, which is also consistent with our findings in this region. Moreover, since the mid-1960s, the melt date in northern Alaska has advanced by 8 days (*32*) as a result of a decrease in snowfall in winter, followed by a warmer spring, which are believed to be caused by variations in regional circulation patterns. A significant variation in photosynthetic activity and growing season length at latitudes above 35°N from 1982 to 1999 was also reported, which is indicated by the Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very-High Resolution Radiometer (AVHHR) onboard the polar-orbiting NOAA meteorological satellites (*33*). Two distinct periods of increasing plant growth are apparent: 1982 to 1991 and 1992 to 1999, which are separated by a reduction from 1991 to 1992 that is associated with the volcanic eruption of Mt. Pinatubo in June 1991. The average May to September NDVI from 45° to 75°N increased by 9% from 1982 to 1991, decreased by 5% from 1991 to 1992, and increased by 8% from 1992 to 1999. In an independent study based on the AVHRR data for the period from 1982 to 2000. it was found that in the Northern Hemisphere, the area with an increasing trend of the annual sum of NDVI was approximately 12 times larger than the area with a decreasing trend. Although these areas are located over a large range of geographical regions, they include Siberia, northeastern Europe, and the northern part of North America (*34*). At high latitudes, plant growth is light-limited, and therefore a decrease in solar radiation would not be conducive to an increase in the vegetation index. On the basis of on observations made from CERES (*28*) and a 16-year record from the ERBS mission (*29*), a decrease in reflected short-wave flux at the ToA (*27*) was found. This could result in an increase in *S* (assuming no variations in the solar output or in atmospheric absorption).

On the basis of earthshine measurements (*35*) of Earth's reflectance carried out at the Big Bear Solar Observatory since 1998 and satellite observations of global cloud properties for earlier years, a proxy measure of Earth's global short-wave reflectance was constructed. A steady decrease in Earth's reflectance from 1984 to 2000 was shown, with a strong drop during the 1990s. During 2001 to 2003, only earthshine data are available, and they indicate a reversal of the decline. It should be noted that the earthshine measurements are available for only a short time period, and the extension to a longer period is achieved by using ISCCP data.

We report here on an attempt to use long-term satellite observations as obtained under the World Climate Research Programme GEWEX ISCCP initiative to study possible trends in the *S*. Averaged over the entire period of available record and at a global scale, a small increase in *S* was observed rather than

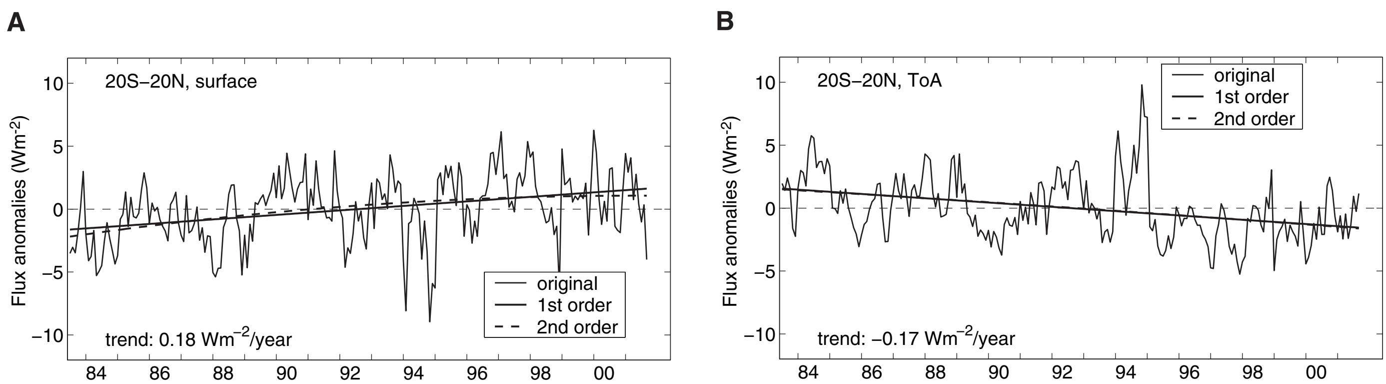

Fig. 4. Linear and second-order least-squares fits over (**A**) the tropical belt of 20°S to 20°N at the surface and (**B**) at ToA.

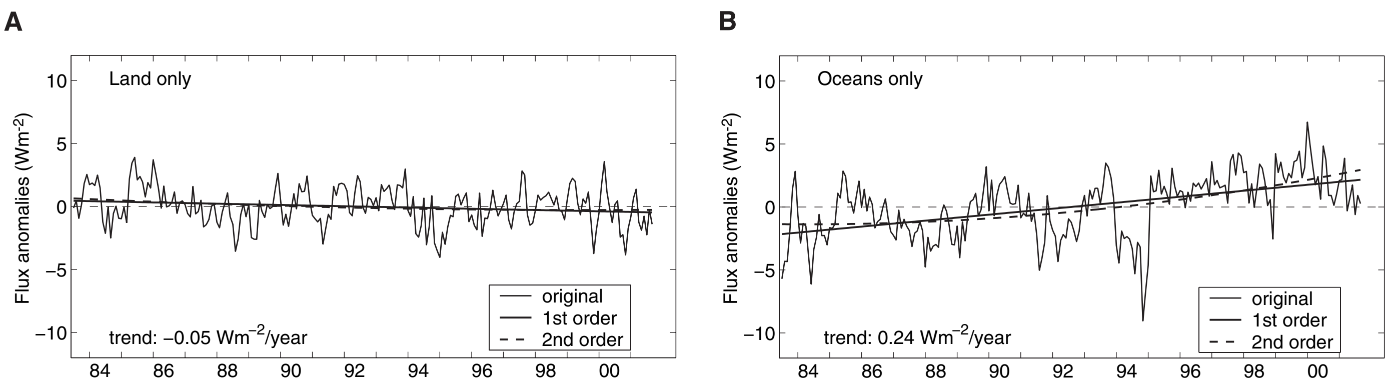

Fig. 5. Linear and second-order trends for (**A**) land areas only and (**B**) for oceans only.

a dimming. This increase has been found to be significant at the 99% level of confidence. The satellite-based record of surface solar fluxes from 1983 until 1992 does suggest some dimming, followed by an increase after 1992, as seen in numerous ground observations. It was also shown that tendencies over land and over ocean can differ in sign and magnitude, and that in order to obtain a global view of the dimming phenomena, there is a need for comprehensive and global observations that are possible only from satellites. There is a need to be aware of calibration issues regarding both ground-based and satellite data that might affect the interpretation of long-term observations. The best available approach to calibration was used to produce the satellite observations used in this study, and the most comprehensive global coverage achievable by combining geostationary and polar-orbiting satellites was used. The magnitudes of the observed tendencies in S at a global scale were much smaller in magnitude than those reported from ground observations.

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Supporting Online Material
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Figs. S1 and S2

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