NOTES AND CORRESPONDENCE

Increase in Global Solar Radiation with Total Cloud Amount from 33 Years Observations in Japan

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Abstract

In general, a change in the total cloud amount (TCA) affects the solar irradiance at the surface as a result of on-the-way reflection of solar radiation. The amount of global solar radiation (GSR) increased globally after c.a. 1990, and this increase resulted from a decreases in the TCA and an increases in atmospheric transparency. Here we present the TCA and GSR trends categorized by the TCA for 33 years in Japan (from 1974 through 2006) on the basis of simultaneous observation from 53 weather stations. These trends are calculated using data obtained on a daily basis. The results averaged across Japan show that both GSR and TCA are increasing at the rate of 2.2% and 1.5% per decade, respectively. In most of Japan (regions further north than Kyushu), a high GSR increase rate mostly appears with a large TCA. This fact cannot be accounted for by the increase in the atmospheric transparency alone. There are two possible causes for increases in GSR and TCA in Japan: a change in cloud appearance frequency against the solar zenith angle and a decrease in cloud optical thickness.

1. Introduction

GSR (global solar radiation), which refers to direct and diffused short-wave solar irradiance received at the surface, is a fundamental source for heat balance at the surface. The surface is heated by the GSR and releases heat by sensible and latent heat fluxes. The heated surface and the adjacent atmosphere emit long-wave radiation corresponding to temperatures. These heat fluxes affect not only the daily meteorology, but

also the climate and hydrological cycle. On the other hand, clouds influences the amount of GSR through cloud mass and optical properties. Thus, clouds can impact climate and the hydrological cycle through GSR variation. Furthermore, long-term cloud variation is closely related to global warming because clouds trap the long-wave radiation emitted from the surface and the below-cloud atmosphere.

The amount of GSR increased globally after c.a. 1990 (Wild et al. 2005; Wild 2009). The recent global GSR increase is 6.6 Wm^{-2} per decade, as confirmed by observations made from the Baseline Surface Radiation Network (BSRN) (Wild et al. 2005). Around Japan, two GSR trends were observed: 8 Wm^{-2} per decade from 1990 to 2002 (Norris and Wild 2009) and about 10 Wm^{-2} per decade from the end of 1980s to

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2005 (Ohmura 2009). The factors that cause a variation in the GSR at the surface are, in general, variations in solar irradiance, atmospheric transparency, cloud amount, and cloud optical thickness. Of these, solar irradiance has shown no significant long-term trend recent decades (Foster et al. 2007). Therefore, the remaining factors are considered to affect the GSR at the surface.

Atmospheric transparency has been mostly impacted by aerosols in the atmosphere. Actually, the aerosol optical thickness (this is related to the amount of aerosol in the atmosphere) was found to decrease globally from 1981 to the early 2000s (Mishchenko and Geogdzhayev 2007). However, the situation in East Asia, which is the largest aerosol precursor source in the world (Streets et al. 2006), is different from that in other areas. Emission of sulphur dioxide (SO_2), which is an aerosol precursor, rapidly increased in East Asia during the 1980s (Streets et al. 2008). The SO_2 levels peaked in 1996, but the current emission levels are much higher than those of the 1980s (Streets et al. 2008). SO_2 emitted from East Asia forms aerosols during its transport and hence may affect the atmosphere over Japan, located east of East Asia. The aerosol optical thickness was found to increase over the Asia-Pacific region from 1988 to 2001, as indicated by satellite observation (Sobajima et al. 2004). However, this observation was inconsistent with an observation over Japan: the atmospheric transparency (Feussner-Dubois' turbidity coefficient) averaged for Japan, derived from direct solar radiation observations at 14 stations of the Japan Meteorological Agency (JMA), showed an increasing (clearer) trend from the 1980s to the early 2000s except during the influences of eruptions of Mt. El Chichon and Mt. Pinatubo (Japan Meteorological Agency 2010a). The spatial distribution of aerosol is localised because of emissions from uneven anthropogenic source distributions and transportation by synoptic weather systems. Moreover, natural aerosols with local distribution and short temporal variation (for example, aeolian mineral dust in East Asia) could be superimposed. They may influence regional or temporal differences in the atmospheric transparency trends mentioned above. Furthermore, concerning cloud influence on GSR, aerosols contribute to cloud formation by inducing the formation of cloud condensation nuclei or ice nuclei.

Clouds also have an important influence on the GSR (Dutton et al. 2006). Around Japan, the decrease in cloud coverage is thought to have contributed to one-third of the GSR increase from 1990 to 2002 (Norris and Wild 2009). Thus, to account for the GSR increase

in Japan, it is necessary to take into account the effect of clouds in addition to the degree of atmospheric transparency. Satellite measurement of radiance from the earth can detect the presence of clouds all over the globe. However, the total cloud amount (TCA) trend determined using long-term satellite data, such as data from the International Satellite Cloud Climatology Project (ISCCP), could be unreliable because of the potential inclusion of satellite-viewing geometry artefacts (Evan et al. 2007). TCA observations from the ground suggest that the TCA increased over some continents after 1950 (Forster et al. 2007). Globally, the TCA trend is insignificant because the increasing trend over the ocean (Norris 1999) is offset by the decreasing trend over land (Warren et al. 2007). The signs of regional TCA trends vary in the regions (Forster et al. 2007). For example, in China, the TCA decreased after 1950 (Qian et al. 2006), but around Japan, it increased from 1971 to 1996 (Warren et al. 2007). Because of the difficulty involved in carrying out observations, regional studies on long-term cloud trends are limited.

From a global point of view, the increasing GSR trend is obvious, but the TCA trend is insignificant. We investigate the TCA trend in Japan and its relationship with the increasing GSR trend. We used the observation data for 33 years in Japan (from 1974 through 2006). Their quality was controlled under the JMA guidelines as described following section. In the previous studies on the GSR-cloud relationship, regional (or grid box) averages of GSR and TCA recorded at different stations located in the same area were used (e.g., Norris and Wild 2009). Since cloud and GSR distributions are localized, measurements comparisons obtained from different stations may be insufficient to show the exact cloud-GSR relationship. In this study, we calculate the GSR and TCA trends using data from simultaneous observations at the same weather station in Japan. Furthermore, the GSR trends are classified by cloud amount categories.

2. Experimental

2.1 GSR observation

GSR observation in the JMA was initially performed using bimetallic pyranometers, which were replaced by thermopile pyranometers after 1970. The JMA closed some stations after 2006 and stopped GSR measurements in those places. In this study, we used daily-accumulated GSR data and daily-mean TCA data observed at 53 stations in Japan from 1974 through 2006. The station data are grouped into six regions (Hokkaido, Tohoku, Kanto-Chubu, Nishinippon, Kyushu, and Okinawa) (Fig. 1). Each pyranometer in

Fig. 1. Map of the 53 stations (open circles) and the six regions defined for this study.

the JMA has been calibrated every five years according to the World Radiometric Reference maintained at the World Radiation Center (WRC), since the World Meteorological Organization (WMO) International Pyrheliometer Comparison-III at the WRC in 1970 (Sekine et al. 1973; Japan Meteorological Agency 2010a).

2.2 Visual cloud observation

Visual TCA observations are performed eight times (3:00, 6:00, 9:00, 12:00, 15:00, 18:00, 21:00, 24:00 Japan Standard Time (JST)) (7 times after March, 1995; midnight observation was discontinued) per day at 46 stations and four times per day at seven stations (3:00, 9:00, 15:00, 21:00 JST) by trained technicians based on the guidelines of the JMA. For overcast skies, the cloud amount is 10. In this study, we classify the

daily-mean TCA into six categories (CC0: 0.0–1.9, CC2: 2.0–3.9, CC4: 4.0–5.9, CC6: 6.0–7.9, CC8: 8.0–9.9, CC10: 10.0).

Visual cloud observation from ground stations is known to be effective for climate studies (Warren et al. 2007; Dai et al. 2006). However, an investigation into the reliability of the visual TCA observation is necessary. Clouds can reduce the daily maximum temperature by reflecting sunlight and increase daily minimum temperature by enhancing downward long-wave radiation. Therefore, variation in the diurnal temperature range (DTR) generally anti-correlates with that in the TCA (Dai et al. 1999). Additionally, comparison of the annual-mean TCA and DTR also shows anti-correlation (Fig. 2). The average correlation coefficient for Japan is -0.66 , and the value obtained when Okinawa, which is a group of small islands, is

Fig. 2. Annual variations of total cloud amount (TCA, overcast sky equals to 10) and diurnal temperature range (DTR, °C) in Japan.

excluded is -0.71 . The consistency between the visual TCA observation and the instrumental temperature measurement indicates the reliability of the TCA data.

Poor night visibility could affect visual TCA observation, particularly on nights without moon light (Hahn et al. 1995). In Japan, the night TCA trend in no moonlight cases was found to be 1% per decade higher than that in moonlight cases (Fujibe et al. 2005). Furthermore, an increase in ground illumination because of urbanization around the station could affect TCA trends at night. However, the TCA trends vary greatly by region as shown in the results, although urban development is almost uniform across Japan. Therefore, the TCA bias from ground illumination is considered to be much smaller than that from meteorological factors. On the other hand, the discontinuance of the midnight TCA observation after March 1995 may affect the TCA trends.

2.3 Trend calculation

The GSR and TCA variations are not monotonic in Japan. In particular, the sign of the global GSR trend has changed from negative to positive since about 1990, as mentioned in the Introduction, and the situation is similar in Japan (Ohmura 2009). This implies that the linear GSR trend is sensitive to the analysis period. In our analyses, the slope of the GSR trend during the period 1974–2006 shows a monotonic increase (the differential value is always positive) when a curve is fitted using second-degree polynomials. In this study, we emphasize the relative comparison of the GSR and TCA trends. Thus, we discuss both GSR and TCA by using the linear trends observed from 1974 through

Fig. 3. Global solar radiation (GSR) and TCA trends for the period 1974–2006 in Japan. Bars indicate ranges at 95% confidence level.

2006.

In this study, trend statistics are calculated using the Mann-Kendall test for trend and Sen's slope estimates (MAKESSENS) (Sirois 1998). The annual means used in MAKESSENS are averaged from the monthly means calculated from the daily-accumulated GSR and the daily-mean TCA.

3. Results and discussion

The GSR trend averaged over six regions is 3.25 (1.40 – 4.77) Wm^{-2} per decade. In this paper, the values in parentheses indicate the range at the 95% confidence level. The corresponding relative trend is 2.2% (1.0–3.3%) per decade. Our result is comparable to other results for Japan (8 Wm^{-2} per decade for the period 1990–2002) (Norris and Wild 2009). The TCA trend averaged over six regions is also positive (0.10 (0.04 – 0.16) per decade), and the corresponding relative trend is 1.5% (0.7 – 2.3 %) per decade. This trend is somewhat larger than the grid-box results (0.2 – 1.4 % per decade) for Japan for the period 1971–1996 (Warren et al., 2007).

The regional GSR trends range between 0.8 and 3.3% per decade, and they are statistically significant at the 95% level in all regions except Tohoku (Fig. 3). The signs of the regional TCA trend are positive except

in Okinawa, and increase with latitude (Fig. 3). The largest regional TCA trends are observed in Hokkaido and Tohoku (2.6% per decade), and the trends in the regions further north than Nishinippon (Hokkaido, Tohoku, Kanto-Chubu) are statistically significant at the 95% level. At the 90% significance level, both GSR and TCA increase trends are statistically significant in the regions further north than Kyushu.

Do the GSR trends depend on the daily-mean TCA categories? In other words, is the GSR trend for clear-sky conditions different from that for overcast-sky conditions? Two observations can be obtained from the GSR trends categorized by daily-mean TCA (Fig. 4). The first is that the signs of the GSR trends are all positive, although some are insignificant at the 95% level. The second is that, in the regions further north than Kyushu, the GSR relative trends mostly increase with an increase in the daily mean TCAs.

From the viewpoint of the total energy received from the GSR at the surface, the appearance frequency is as important as the daily GSR amount. The appearances of small TCA are decreasing (trends are negative) and those of large TCA are increasing (trends are positive) in the regions further north than Kyushu (Fig. 5), which brings about increasing trends in the uncategorized daily-mean TCA in these regions (Fig. 3). Thus, in the case of small daily-mean TCAs, the annual-total GSRs, which refer to the annual solar energy received at the surface, decrease to greater extent in all the regions further north than Kyushu (Fig. 6); this is because the GSR decrease amount caused by the appearance decrease is greater than the daily GSR increase. On the other hand, for large daily-mean TCAs, the annual-total GSRs increase because of the increase in daily GSRs and appearance (Fig. 6). Note that the daily GSRs (and the annual-total GSRs) averaged for all TCA categories are increasing in all regions as mentioned above (Fig. 3).

As mentioned in Introduction, there are four potential factors that could influence the GSR increase at the surface. Of these, variations in solar irradiance are not so large as to affect GSR. As described in Introduction, it was found that the degree of atmospheric transparency was increasing (clearer) in Japan during the analysis period, and this was considered one of the reasons for the GSR increase. However, the fact that the GSR relative trends mostly become larger with an increase in the mean TCAs in the regions further north than Kyushu (Fig. 4) cannot be accounted for by the increase in the degree of atmospheric transparency alone. Two possible causes are proposed. One is a change of cloud appearance frequency against solar zenith angle. This

Fig. 4. GSR trends for TCA categories for the period 1974–2006 in Japan. Bars indicate ranges at 95% confidence level. TCA categories are referred in the Subsection 2.2.

Fig. 5. Trends in TCA appearance frequency for TCA categories for the period 1974–2006 in Japan. Bars indicate ranges at 95% confidence level.

could result in an increase in GSR even if daily mean TCAs increase. The other possible cause is a decrease of cloud optical thickness. Large emissions of SO_2 and black carbon from East Asia (e.g., Streets et al. 2003) could bring about a decrease in cloud optical thickness (viz. semi-direct effect) and prolonged cloud lifetime

Fig. 6. Trends in annual-total GSR for TCA categories for the period 1974–2006 in Japan. Bars indicate ranges at 95% confidence level.

(viz. cloud lifetime effect) by gas-to-particle conversion during the SO_2 transport. However, identifying the causes is not possible only from our observations. As shown in Fig. 7, the TCA trends are clearly smaller for lower latitudes, particularly in spring and autumn. As described in Introduction, the TCA trends in China decreased after 1950. In the mid-latitudes of East Asia ($30\text{--}40^\circ\text{N}$), the monsoon, which enhances the meridional atmospheric circulation (the flow between north and south), weakens in spring and autumn and weather systems (high and low pressures) frequently move from west to east in the southern Japan, carrying an East Asian air mass. Thus we suggest that the TCA trends over Japan could partially originate in East Asia, particularly in these seasons.

4. Summary and remarks

Our results show that both GSR and TCA across Japan are increasing at the rate of 2.2% and 1.5% per decade, respectively. In most of Japan (regions further north than Kyushu), a high GSR increase rate mostly appears with a large TCA. This fact cannot be accounted for by the increase in the degree of atmospheric transparency alone. There are two possible causes of increasing in GSR and TCA in Japan: a change in cloud appearance frequency against the solar zenith angle and a decrease in cloud optical thickness. In Japan, temperatures have increased rapidly since the late 1980s (Japan Meteorological Agency, 2010b). The increases in GSR and TCA could impact warming in Japan. Furthermore, they can affect not only the local

Fig. 7. Seasonal trends in daily-mean TCA for the period 1974–2006 in Japan. Bars indicate ranges at 95% confidence level.

weather but also the global climate and hydrological cycles. A better understanding of TCA and GSR variations could contribute to the understanding of the climate change mechanism. This may contribute to the reduction of future uncertainties in climate projections for the mitigation of and adaptation to global warming.

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