Homogenized century-long surface incident solar radiation over Japan

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Abstract

Surface incident solar radiation (R_s) plays a key role in climate change on Earth. R_s can be directly measured, and it shows substantial variability on decadal scales, i.e., global dimming and brightening. R_s can also be derived from the observed sunshine duration (SunDu) with reliable accuracy. The SunDu-derived R_s has been used as a reference to detect and adjust the inhomogeneity in the observed R_s. However, both the observed R_s and SunDu-derived R_s may have inhomogeneity. In Japan, SunDu has been measured since 1890, and R_s has been measured since 1961 at ~100 stations. In this study, the observed R_s and SunDu-derived R_s were first checked for inhomogeneity independently using a statistical software RHtest. If confirmed by the metadata of these observations, the detected inhomogeneity was adjusted based on the RHtest-quantile matching method. Second, the two homogenized time series were compared to detect further possible inhomogeneity. If confirmed by the independent ground-based manual observations of cloud cover fraction, the detected inhomogeneity was adjusted based on the reference dataset. As a result, a sharp decrease of more than 20 W m^{-2} in the observed R_s from 1961 to 1975 caused by instrument displacement was detected and adjusted. Similarly, a decline of about 20 W m^{-2} in SunDu-derived R_s due to steady instrument replacement from 1985 to 1990 was detected and adjusted too. After homogenizations, the two estimates of R_s agree well. The homogenized SunDu-derived R_s show an increased at a rate of 0.9 W m^{-2} per decade ($p<0.01$) from 1961 to 2014, which was caused by a positive aerosol-related radiative effect (2.2 W m^{-2} per decade) and a negative cloud cover radiative effect (-1.4 W m^{-2} per decade). The brightening over Japan was the strongest in spring, likely due to a significant decline in aerosol transported from Asian dust storms. The observed raw R_s data and their homogenized time series used in this study are available at https://doi.org/10.11888/Meteoro.tpdc.271524 (Ma et al., 2021).

1. Introduction

Surface incident solar radiation (R_s) plays a vital role in atmospheric circulation, hydrologic cycling and ecological equilibrium; therefore, its decrease and increase termed as global dimming and brightening (Wild et al., 2005; Shi et al., 2008), have received widespread interest from the public and scientific community (Allen et al., 2013; Xia, 2010; Wang et al., 2013; Tanaka et al., 2016; Ohmura, 2009; He et al., 2018). In addition, the impact factors such as clouds and aerosols on the variation in R_s have been widely studied (Wild et al., 2021; Qian et al., 2006; Feng and Wang, 2021a).

Ground-based observations of R_s are the first recommendation for detecting global dimming and brightening. However, observational data may be inevitably ruined by artificial shifts, which my lead to the variability in R_s with large uncertainties. Wang et al. (2015) point out that instrument replacements and reconstruction of observational network introduced substantial inhomogeneity into the time series of observed R_s over China for 1990-1993. Manara et al. (2016) also show the instrument changes from the Robitzsch pyranograph to the Kipp & Zonen CM11 pyranometer before 1980 caused no clear dimming in Italy. Until recently, Wild et al. (2021) use a well-maintained data series at a site in Germany with long time duration to investigate the dimming and brightening in central Europe under clear sky condition, and point out that the aerosol pollutants are likely major drivers in the R_s variations. Augustine and Hodges (2021) use Surface Radiation Budget (SURFRAD) Network observations to explore the variability in R_s over the U.S. from 1996 to 2019, and find that cloud fraction can explain 62% of the variation of R_s, while aerosol optical depth (AOD) only accounts for 3%. Both studies also indicate the measurement instruments have been changed over the observational time periods, which may introduce non-climatic shifts and inhomogeneity in the raw data series.

Homogenizing the observed R_s has been attempted in China (Wang et al., 2015; Tang et al., 2011; Yang et al., 2018), Italy (Manara et al., 2016), Spain (Sanchez-Lorenzo et al., 2013) and Europe (Sanchez-Lorenzo et al., 2015). It is essential to find a homogeneous reference station to compare with the possible inhomogeneous station to test and adjust the inhomogeneity in the observed time series, as done for the homogenization of air temperature (Du et al., 2020; Zhou et al., 2021). However, this process is difficult for R_s because the instrument replacement of R_s generally occurs nearly simultaneously throughout a country. Therefore, the sunshine duration (SunDu) derived R_s (Yang et al., 2006) has been used as a homogeneous reference dataset to detect and adjust the inhomogeneity of R_s in China (Wang et al., 2015).

The SunDu records the hours of surface direct solar radiation exceeding 120 W m^{-2} and provides an alternative way to estimate R_s (Yang et al., 2006; Stanhill and Cohen, 2008). SunDu-derived R_s is capable of capturing the variability in R_s. He et al. (2018) use the SunDu-derived R_s at ~2600 stations to revisit the global dimming and brightening over different continents, and restate the dimming over China and Europe is consistent with the increasing trends of clouds and aerosols. Feng and Wang (2021b) and Feng and Wang (2021a) merge the satellite retrievals with SunDu-derived R_s to produce a high-resolution long-term solar radiation over China, and indicate cloud fraction could explain approximately 86%–97% of R_s variation. Zeng et al. (2020) demonstrate that SunDu plays a dominant role in determining R_s based on a random forest model framework across China. Stanhill and Cohen (2005) indicate the high correlation between SunDu and R_s at the 26 stations in the United States. Sanchez-Lorenzo et al. (2008) show the variation in SunDu is consistent with that in R_s over western Europe for 1938-2004, and the SunDu time evolution in Spring can partly be explained by clouds and that in Winter can be related to the anthropogenic aerosol emissions. Stanhill and Cohen (2008) establish a simple linear relationship between R_s and SunDu to determine the long-term variation in R_s over Japan. Manara et al. (2017) highlight that the atmospheric turbidity should be considered when using SunDu for investigating multidecadal evolution of R_s.

Artificial shifts in SunDu observations may come from the replacement of instruments. It has been revealed that the Jordan recorder is 10% more sensitive than the Campbell-Stokes recorder for SunDu measurements (Noguchi, 1981). The homogenization of SunDu has been carried out in Iberian Peninsula (Sanchez-Lorenzo et al., 2007), Switzerland (Sanchez-Lorenzo and Wild, 2012), and Italy (Manara et al., 2015).

The measurement of R_s, which started in 1961 in Japan, has a long history (Tanaka et al., 2016), and a data record more than half a century-long has been accumulated.

The dataset has been widely used to study decadal variability (Wild et al., 2005; Stanhill and Cohen, 2008) and to evaluate model simulations (Allen et al., 2013; Dwyer et al., 2010). The Eppley and Robitzsch pyranometers used to measure R_s over Japan were replaced by the Moll-Gorczynski thermopile pyranometers in the early 1970s (Tanaka et al., 2016). However, the possible inhomogeneity of the observed R_s over Japan has not been well quantified, and most existing studies directly used raw R_s data (Wild et al., 2005; Tanaka et al., 2016; Tsutsumi and Murakami, 2012; Allen et al., 2013; Wild and Schmucki, 2011; Kudo et al., 2012; Ohmura, 2009). Some studies have had to abandon data from the early years and focused on only R_s data collected after 1975 (Tsutsumi and Murakami, 2012; Dwyer et al., 2010). Therefore, the observed decadal variability in R_s over Japan is questionable, especially for the 1961-1975 time period.

In Japan, SunDu observations started in 1890, and more than a century-long data were recorded. They cannot be too precious for the climate change detection on a century scale. It is reported that the Jordan recorders used to measure SunDu were replaced by EKO rotating mirror recorders in approximately 1986 (Inoue and Matsumoto, 2003; Stanhill and Cohen, 2008). Therefore, SunDu observations over Japan themselves may suffer inhomogeneity issues.

Non-climatic shifts in the observations may severely influence the climate assessment, therefore rigorous homogenization are required. The world Meterological Organization (WMO) Climate Program guidelines on climate metadata and homogenization list 14 data homogenization assessment techniques developed and applied by different groups/authors (Aguilar et al., 2003). Reeves et al. (2007) compared eight representative homogenization methods and provided guidelines for which procedures work best in different situation, for example the standard normal homogeneity (SNH) test (Alexandersson, 1986) works best if good reference series are available and two-phase regressions of Wang procedure (Wang, 2003) is optimal for good reference series unavailable condition. Based on the comparison work, RHtest method was improved by detecting multiple changepoints in the climate data no matter the reference series are available (Wang, 2008b; Wang et al., 2010; Wang et al., 2007; Wang, 2008a). This method, which first detects the changepoints in a series using penalized maximal tests and then tunes the inhomogeneous data segments to be consistent with other segments in empirical distributions, has been widely used in homogenizing climate variables (Dai et al., 2011; Wang et al., 2010; Du et al., 2020; Zhou et al., 2021).

Discontinuities are inevitably occurred in the long-term observation system which are required to be checked out and adjusted in the raw data. The homogenized series pose a significant role in realistic and reliable assessment of climate trend and variability. The main objective of this study is to detect and adjust the inhomogeneity in R_s estimates over Japan. The metadata were first extracted from website information and related records at each site. The SunDu observations were converted into R_s. The RHtest method was applied to homogenize the observed R_s and SunDu-derived R_s, and finally, the century-long homogenized R_s data were produced over Japan. Furthermore, the impacts of cloud cover and aerosols on R_s variation over Japan in recent decades were explored.

2. Data and methods

2.1 Surface incident solar radiation and sunshine duration

The monthly observed R_s at 105 stations and SunDu at 156 stations were downloaded from the Japanese Meteorology Agency (JMA) website (see Table S1 and Figure 1). R_s records were available from 1961. During the 1960s, two R_s measurements were conducted in parallel by both Eppley and Robitzsch pyranometers. In the early 1970s (see Figure 2 and Table S2), these instruments were replaced by Moll-Gorczynski thermopile pyranometers. This replacement occurred at approximately 12.4% of R_s stations in 1971, followed by 22.9%, 24.8%, 3.8% and 30.5% in the next four years, which may have caused severe data discontinuity problems (Tanaka et al., 2016).

SunDu has been routinely measured since 1890. Jordan recorders were replaced by EKO rotating mirror recorders at 49.4% of SunDu stations in 1986. Until 1990, nearly all of the SunDu stations used new instruments for observations. 4.5% of SunDu stations before 1985 and 9.0% of SunDu stations after 2000 were moved away from the original sites (see Figure 2 and Table S2) (Stanhill and Cohen, 2008).

In this study, SunDu was used to derive R_s based on the following equation (Yang et al., 2006):

$$R_s / R_c = a_0 + a_1 \cdot n / N + a_2 \cdot (n / N)^2 \quad (1)$$

where n is sunshine duration hours; N is the maximum possible sunshine duration; R_c is surface solar radiation under clear skies; and a_0, a_1 and a_2 are coefficients. This method was recommended in many studies (Wang et al., 2015; Tang et al., 2011).

2.2. Homogenization method

Both R_s and SunDu measurements over Japan suffer severe inhomogeneity problems, which require rigorous data homogenization. RHtest (http://etccdi.pacificclimate.org/software.shtml) is a widely used method to detect and adjust multiple changepoints in a climate data series, such as in surface temperature (Du et al., 2020), radiosonde temperature (Zhou et al., 2021), precipitation (Wang et al., 2010) and surface incident solar radiation (Yang et al., 2018). RHtest provides two algorithms, the penalized maximal T (PMT) test (Wang et al., 2007) and the penalized maximal F (PMF) test (Wang, 2008b), to detect changepoints. The problem of lag-1 autocorrelation in detecting mean shifts in time series was also resolved (Wang, 2008a). The PMT algorithm requires the base time series to be no trend, and hence a reference series is needed. It is invalid when a reference series is not often available or its homogeneity is not sure, also the trend in the base and reference series are probably different. The PMF algorithm allows the time series in a constants trend and thus is applicable without a reference series. Both algorithms have higher detection power and the false alarm rate can be reduced by empirically constructed penalty function.

As the change of instrument in R_s and SunDu observation nearly happened nationwide and simultaneously, it is difficult to find reference data series to match the base data series and hence the PMF algorithm was used to detect the changepoints in this study. Multiple changepoints were detected including climate signals and artificial shifts, and only the ones confirmed by discontinuity information from metadata in Table S2 were left to be adjusted. Then two homogenized series based on direct measurement of R_s and SunDu-derived R_s were obtained.

Large uncertainties may still exist in both homogenized data series as the discontinuities in the raw observations may not be sufficiently and correctly recorded in the metadata. Further changepoints can be detected by considering the impact of the variation of independent climate variables such as clouds and aerosols on the R_s variation. If these uncertainties were found, further changepoint detections were needed based on the PMT or PMF algorithm.

To diminish all significant artificial shifts caused by the changepoints, a newly developed Quantile-Matching (QM) adjustments in the RHtest (Vincent et al., 2012; Wang et al., 2010) were performed to adjust the series so that the empirical distributions of all segments of the detrended base series agree with each other. The corrected values are all based on the empirical frequency of the datum to be adjusted.

Another independent homogenization method proposed by Katsuyama (1987), which was developed due to the replacement of the Jordan recorders with EKO rotating mirror recorder during the late 1980s, is denoted as follows:

$$S_R = 0.8\ S_J\ (S_J < 2.5\ h/day) \quad (2)$$

$$S_R = S_J - 0.5\ h/day\ (S_J \geqslant 2.5\ h/day) \quad (3)$$

where S_J is the daily SunDu observed by the Jordan recorders before replacement; and S_R is the daily SunDu adjusted to be consistent with the values observed with the EKO rotating mirror recorders.

These two homogenization methods were compared in this study and yielded nearly the same SunDu-derived R_s variation, as shown in Figure 3. Although the second method proposed by Katsuyama (1987) is simple and efficient, we just use it to cross validate the accuracy of the RHtest method. Since most artificial shifts in observation system were undocumented worldwide, the statistical methods including RHtest are optimal to identify these non-climatic signals and reduce the discontinuities in the data series. As RHtest can detect the changepoints in the raw data series when the metadata are unavailable while Katsuyama (1987) can't, and RHtest was therefore selected in this study.

2.3 Clouds

Clouds play an important role in R_s variation (Norris and Wild, 2009). Monthly cloud cover observations at 155 stations were also available on the JMA website. The observation time for cloud amount has been 08:00-19:00 since 1981 at 9.0% of cloud amount stations and 08:30-17:00 from 1990 to 1995 at another 15.4% of cloud amount stations (see Figure 2 and Table S2). However, the difference between annual raw and homogenized cloud data is trivial, as cloud data are relatively homogeneous in space compared with R_s and SunDu observations. A site observation of cloud amount can represent the value over a large spatial scale, likely leading to few inhomogeneity issues for cloud data.

To explore the impact of the cloud cover anomaly on the R_s variation, the cloud cover radiative effect (CCRE), defined as the change in R_s produced by a change in cloud cover, was proposed by (Norris and Wild, 2009):

$$CCRE'(lat, lon, y, m) = CC'(lat, lon, y, m) \times CRE(g, m)/\overline{CC}(g, m) \quad (4)$$

where lat is the latitude, lon is the longitude, y is the year, m is the month, $CCRE'$ is the cloud cover radiative effect anomaly, CC' is the cloud cover anomaly, $\overline{CC}$ is the climatology of cloud cover in 12 months and CRE is the cloud radiative effect calculated by the R_s difference under all sky and clear sky conditions.

The residual radiative effect was determined by removing the CCRE anomalies from the R_s anomalies. It is noted that a part of the cloud albedo radiative effect proportional to the cloud amount was contained in the CCRE, as a large cloud amount tends to yield enhanced cloud albedo, whereas another part of the cloud albedo radiative effect due to the aerosol first indirect effect (more aerosols facilitating more cloud condensation nuclei may enhance cloud albedo) may be included in the residual radiative effect, which mainly contains the aerosol radiative effect.

The Clouds and the Earth's Radiant Energy System (CERES) provides a reliable surface incident solar radiation (Ma et al., 2015) primarily based on the Moderate Resolution Imaging Spectroradiometer (MODIS) cloud and aerosol products (Kato et al., 2012). The cloud amount in CERES agrees well with the observations, and the annual CRE in CERES is well correlated with the annual cloud amount in Figure 10.

The regional average cloud amount over Japan in Figure 10 (blue line) increases at a rate of 0.7% per decade from 1960 to 2015, which is consistent with the previous results (Figure 4 in Tsutsumi and Murakami (2012)).

In this study, long-term observations of cloud amount and monthly cloud radiative effect (CRE) data in the CERES EBAF edition were used following Equation (4) to distinguish the cloud cover radiative effect from Rs variation.

2.4 Data Processing

We first interpolated the monthly observational data at sites into 1°×1° grid data, and then calculated the area average of the climate variables. As the brightening and dimming over Japan were the main concern in this study, monthly values were converted into annual values for calculation. If there are missing values in any month in a specific year, the annual value for that year is set to a missing value. The linear regression was used for trend calculation.

3. Results

In this section, we first compared the observed R_s and sunshine duration derived R_s before and after adjustment to demonstrate the necessity and feasibility of the homogenization procedure in Section 3.1. As artificial shifts may not be sufficiently and correctly documented by metadata, uncertainties may still exist in the homogenized series. We then tried to explore these uncertainties by considering the influence of other independent climate variables such as clouds, aerosols on the R_s variation, and ultimately informed a more reasonable homogenized R_s series in Section 3.2. In Section 3.3, we claimed the significant correction in trend analysis of R_s in Japan and quantified the influence of clouds and aerosols on the R_s variation.

3.1 Homogenization of observed R_s and sunshine duration derived R_s

The comparisons between raw data and homogenized data at each site were shown in Figure 4 and their difference were illustrated in Figure 5. Compared with raw data, the absolute values of biases between R_s and SunDu-derived R_s at 74 stations decrease after homogenization, of which the absolute values of biases decrease by more than 4 W m^{-2} at 42 stations and more than 10 W m^{-2} at 8 stations. The root mean square errors at 80 stations were reduced after homogenization, of which reduces are more than 4 W m^{-2} at 40 stations. After adjustments, the correlation coefficients between the annual observed R_s and annual SunDu-derived R_s are improved at 68 stations, including greater than 0.2 improvement at 31 stations. There are 41 stations (marked with red in Table S1, Figure 6) at which the correlation coefficients were greater than 0.5, and the biases and the root mean square errors generally decrease after homogenization.

Figure 7, as an example, shows the time series of surface incident solar radiation (R_s and SunDu-derived R_s) at the HAMADA site (WMO-ID: 47755, Lat: 34.9, Lon: 132.07) before and after homogenization. Details in the improvements after homogenization at most stations can be traced back to Figures 4, 5 and 6. The improved patterns of time series of surface incident solar radiation after homogenization highlights the necessity and feasibility of the RHtest method. The SunDu-derived R_s variation over Japan during recent decades inferred from these "perfect" data at 41 sites (Figure 8) was nearly identical to that from all available data at 156 sites (as shown in Table 1 and Figure 9).

3.2 Uncertainties in R_s observations

Figure 9 displays the change in R_s during the last 5 decades, while Figure 10 shows the variation in observed clouds over Japan. The sharp decrease in R_s in 1963 caused by the volcanic eruption of Agung in Indonesia (Witham, 2005) can be clearly found. The sharp decreases in R_s in 1991 and 1993 are due to the combined effect of the volcanic eruption of Mount Pinatubo in the Philippines in 1991 (Robock, 2000) and the simultaneous significant increases in clouds (Figure 8 in Tsutsumi and Murakami (2012)). The volcanic eruption of El Chichón in Mexico in 1982 exerted little impact on the decline in R_s and may have been compensated by the decrease in clouds, as shown in Figure 10. The pronounced R_s decline in 1980 coincides with the significant increase in clouds, while the lightening of R_s in 1978 and 1994 encounters abrupt decreases in cloud covers.

As shown in Figure 9, no major modifications were found in R_s observations before and after homogenization (comparison between the light blue and dark blue lines). However, the SunDu-derived R_s series are smoother after adjustment by the QM method, as the sharp decrease from 1983 to 1993 caused by the replacement of sunshine duration instruments (Jordan recorders were replaced with EKO rotating mirror recorders) (Stanhill and Cohen, 2008) was repaired (comparison between the light red line and dark red lines). Despite the identical increase in R_s via both the homogenized direct measurements of R_s and the homogenized SunDu-derived R_s during the 1995-2014 period, their variations in R_s from 1961 to 1994 are different (dark red line and dark blue line).

Large discrepancies in R_s variation were found during the time period of 1961-1970, although homogenizations were performed on the direct measurements of R_s and SunDu-derived R_s (dark blue line and dark red line in Figure 9). Existing study noted the inaccurate instruments used at the beginning of operation in the R_s observation network in approximately 1961, and the parallel use of two different types of instruments during the 1960s may result in the large variability in observed R_s (Tanaka et al., 2016). At this time, the clouds fluctuated gently, as shown in Figure 10, and the change in volcanic aerosols from 1965 to 1966 was nearly the same as that from 1962 to 1963 (Table 2 in Sato et al. (1993)), so the sudden decline in the direct observations of R_s from 1965 to 1966, which was twice as large as that from 1962 to 1963, is suspicious. It is inferred that anthropogenic aerosols play a subtle role in the significant reduction in R_s, as this type of phenomenon is common for both polluted and pristine stations in Japan (Figure 22 in (Tanaka et al., 2016)).

Figure 11 shows the correlation coefficients between homogenized R_s (observed and SunDu-derived) and cloud amount. In general, the observed R_s (-0.45) is less correlated than the SunDu-derived R_s (-0.67), particularly from 1961 to 1970, -0.21

compared with -0.64. This in turn supports the reliability of homogenized SunDu-derived R_s, especially during the time period of 1961-1970. The false variability of the observed R_s from 1961 to 1970 was modified by the RHtest method against the homogenized SunDu-derived R_s as shown in Figure 12.

General decreases in stratospheric aerosol optical depth (AOD) were reported in Sato et al. (1993) from 1965 to 1980, and clouds fluctuated slightly, as shown in Figure 10; both of these factors contributed to a brightening of R_s. This is in agreement with the SunDu-derived R_s and contrasts with the direct measurements of R_s.

During the 1985-1990 period, clouds varied slightly, as shown in Figure 10, and the observed atmospheric transmission under cloud-free conditions increased (Wild et al., 2005), which suggests that the large declines in directly observed R_s and SunDu-derived R_s are defective and reinforce the reliability of the adjusted SunDu-derived R_s (dark red line in Figure 9).

From the above analysis, it can be inferred that fewer uncertainties exist in homogenized SunDu-derived R_s, which was confirmed by another work that utilized a different data adjusted method (Stanhill and Cohen, 2008).

3.2 Trends of R_s over Japan

The trends of R_s during specific time periods for different types of datasets are listed in Table 1. Direct measurements of R_s and SunDu-derived R_s from 41 selected stations and all available stations reveal similar variations in R_s over Japan, which demonstrates that the sample number has a subtle impact on the estimation of global brightening and dimming over Japan.

A revisit of global dimming and brightening was list in Table 1. Major differences were found in the time periods of 1961-1980, ranging from -11.2 (-12.0) to -8.4 (-4.8) W m^{-2} per decade before and after R_s homogenizations for all available stations (41 selected stations) over Japan; significant repairs occurred during the 1981-1995 period, ranging from -10.6 (-11.3) to -1.2 (-1.3) W m^{-2} per decade before and after SunDu-derived R_s homogenizations for all available stations (41 selected stations) over Japan. Both corrections were mainly attributed to the homogenization of corrupted raw data caused by the replacement of instruments for R_s and SunDu measurements. After careful checking and adjustment of the SunDu-derived R_s series, the decadal variation in R_s over Japan, which was totally different from former studies (Wild et al., 2005; Norris and Wild, 2009), was remedied. Direct measurements of R_s display nearly zero trend from 1961 to 2014 over Japan, while their homogenization series report a positive change of 0.8-1.6 W m^{-2} per decade; SunDu-derived R_s decrease at a rate of 1.9 W m^{-2} per decade, while its homogenized series reveals a brightening of 0.9 W m^{-2} per decade.

The combined effects of clouds and aerosols on R_s make the global dimming and brightening complicated. The CCRE can explain 70% of global brightening from 1961 to 2014 at monthly and interannual time scales, while the residual radiative effect dominates the decadal variation in R_s, as shown in Figure 13 and Table 1, which is in agreement with Wang et al. (2012). Homogenized SunDu-derived R_s show an increase of 1.6 W m^{-2} per decade from 1961 to 1980; however, persistent increase in cloud amount yields a CCRE decrease of 1.1 W m^{-2} per decade. The residual radiative effect accounts for an increase of 2.4 W m^{-2} per decade for this time period. The cloud radiative effect (-1.4 W m^{-2} per decade) modulates R_s variation of -1.2 W m^{-2} per decade for the 1981-1995 period, while the residual radiative effect (1.2 W m^{-2} per decade) dominates R_s variation of 1.4 W m^{-2} per decade from 1996 to 2014.

Homogenized SunDu-derived R_s shows a slight increase of 0.9 W m^{-2} per decade from 1961 to 2014 with a 90% confidence interval. However, the CCRE accounts for a deceased R_s of 1.4 W m^{-2} per decade, which implies that cloud cover changes are not the primary driving forces for the R_s trend over Japan. Meanwhile, the residual radiative effect exhibits an increase of 2.2 W m^{-2} per decade, which surpasses the negative CCRE.

Several studies demonstrate a generally cleaner sky over Japan from the 1960s to the 2000s (except for the years impacted by volcanic eruptions) based on atmospheric transparency and aerosol optical properties (Wild et al., 2005; Kudo et al., 2012), which supports the dominant role of aerosols in R_s brightening over Japan, as revealed by the residual radiative effect here. Furthermore, the residual radiative effect in this study is stronger than that in Norris and Wild (2009), as raw data were remedied and more accurate satellite data from CERES were adopted to quantify the radiative effect. Tsutsumi and Murakami (2012) demonstrate that cloud amount categories exert an important effect on R_s variation. R_s enhancement by the increased appearance of large cloud amounts is superior to R_s decline by the decreased appearance of small cloud amounts during 1961-2014, which yields increased R_s with increasing total cloud amount. They also pointed out that the decrease in cloud optical thickness due to the large emissions of SO_2 and black carbon from East Asia through the aerosol semi-direct effect (absorption of more energy by aerosols results in the evaporation or suppression of clouds) may have facilitated the increased R_s over Japan.

The decrease in spring dust storms in March-May during the last 5 decades from China (Qian et al., 2002; Zhu et al., 2008), which may travel to neighboring countries(Uno et al., 2008; Choi et al., 2001), could also have triggered the increase in R_s over Japan. The R_s variation and radiative effect in different seasons are categorized in Figure 14 and Table 2, in which an increasing trend of 1.5 W m^{-2} per decade in the homogenized SunDu-derived R_s prevails in spring for the whole time period, dominated by a dramatic increase of 2.8 W m^{-2} per decade in the residual effect and even larger increase for 1961-1980 (3.1 W m^{-2} per decade) and 1996-2014 (3.4 W m^{-2} per decade).

4. Data availability

Monthly observed surface incident solar radiation, sunshine duration and cloud amount data were provided by Japan Meteorological Agency (https://www.data.jma.go.jp/obd/stats/data/en/smp/index.html), and monthly cloud radiative effect (CRE) data were derived from Clouds and the Earth's Radiant Energy System for CERES EBAF data (https://ceres.larc.nasa.gov/order_data.php). The homogenized observed R_s and SunDu-derived R_s used in this study are available at https://doi.org/10.11888/Meteoro.tpdc.271524 (Ma et al., 2021).

5. Conclusions

The homogenization of raw observations related to R_s can significantly improve the accuracy of global dimming and brightening estimation and provide a reliable assessment of climate trends and variability. In this study, we for the first time homogenized the raw R_s observations and obtained a more reliable R_s data series over Japan for century-long.

Documented artificial shifts in metadata play an important role in regulating the raw observations. If changepoints were confirmed by metadata or other independent climate variables, RHtest method was applied to remove the discontinuities. In this study, shifts in the homogenized raw R_s were further checked by exploring the relationship with the ground-based cloud amount and tuned again using homogenized SunDu-derived R_s as the reference data. By comparing the variations in independent climate variables of cloud and aerosol, the homogenized SunDu-derived R_s were proved to be more reliable in detecting R_s variability over Japan.

A revisit of global dimming and brightening is made based on the homogenized R_s series. R_s over Japan increases at a rate of 1.6 W m^{-2} per decade for 1961-1980, which is contrary to the trend (-4.8~-12.0 W m^{-2} per decade) in the unreasonable R_s observation. A slight decrease of 1.2 W m^{-2} per decade for 1981-1995 in homogenized SunDu-derived R_s accounts for only 1/10 of the trend in its unadjusted series. This directly contributes a brightening of 0.9 W m^{-2} per decade (with a 99% confidence interval) for the last 5 decade in homogenized series, which is totally contrary to the variation in its original series. Global brightening since 1961 over Japan is consistent with that in Stanhill and Cohen (2008), except that the magnitude is not as large.

We also explored how the clouds and aerosols mediate the transformation of R_s. The brightening in Japan for 1961-1980 was the combined effect of cloud cover (negative effect) and aerosols (positive effect). The dimming for 1981-1995 was governed by reduced cloud amounts, while the increase in R_s for 1996-2014 was controlled by decreased aerosols. These results are different from those in Norris and Wild (2009), as homogenization was performed on the raw data and more accurate cloud radiative effect data series from CERES were utilized in our study. During the entire period of 1961-2014, cloud amounts dominated seasonal and interannual R_s variations, while aerosols (including aerosol-cloud interactions) drove decadal R_s variations over Japan, noted by other studies, in response to general cleaner skies and a reduction in spring Asian dust storms (Wang et al., 2012; Kudo et al., 2012).

Author contributions

QM and KW designed the research and wrote the paper. LS collected the raw data. YH homogenized the raw data. QW provided the technical support. YZ and HL checked the data.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1. Trends of Surface Incident Solar Radiation (R_s) in Japan during Specific Time Periods for Different Types of Datasets[a]. Unit: W m^{-2} per decade

Case[b]	Datasets[c]	1961-1980	1981-1995	1996-2014	1961-2014
Selected 41 Stations	OBS-raw	-12.0**	-2.1	2.4	-0.3
	OBS_HM	-4.8*	-2.1	2.4	1.5**
	OBS_2HM	-0.8*	-2.1	2.4*	0.9**
	SunDu-derived	1.4	-11.3**	1.4	-2.1**
	SunDu-derived_HM	1.4	-1.3*	1.5	0.9**
All Stations	OBS-raw	-11.2**	-1.3	2.2	0.2
	OBS_HM	-8.4**	-1.3	2.2	0.8
	OBS_2HM	0.7	-1.3	2.2	1.6**
	SunDu-derived	2.3*	-10.6**	1.2	-1.9**
	SunDu-derived_HM	1.6	-1.2	1.4	0.9*
Radiative Effect	CCRE series	-1.1	-1.4	-0.0	-1.4**
	Residual series	2.4**	-0.1	1.2*	2.2**

[a]The trend calculations were based on the linear regression method. Values with two asterisks (**) imply p <0.01, and those with one asterisk (*) imply 0.01<p<0.1.

[b]Rs trends were calculated by different numbers of observations, including all stations that are available on the JMA website and 41 stations (marked with red in Table S1, detailed in Section 3.1) that are significantly improved after homogenization. This implies that the sample number has a subtle impact on the trend calculation over Japan. Radiative effects from clouds and aerosols were also explored.

[c]Trend calculations were based on the raw measurements of surface incident solar radiation (OBS-raw), their homogenized series (OBS_HM), derived incident solar radiation from sunshine duration hours (SunDu-derived) and their homogenized series (SunDu-derived_HM). OBS_HM from 1961 to 1970 was further homogenized by using SunDu-derived_HM as reference data, termed OBS_2HM. It is found that

homogenized SunDu-derived Rs have the lowest uncertainties among these five datasets in Section 3.1. The cloud cover radiative effect (CCRE) was denoted as the change in Rs produced by a change in cloud cover, and the CCRE calculations were performed following Equation (4) by observed cloud amounts and the cloud radiative effect (CRE) from CERES satellite retrieval. Residual effect series were obtained by removing the CCRE from homogenized SunDu-derived Rs anomalies.

Table 2. Trends of Surface Incident Solar Radiation (R_s) in Japan during Specific Time Periods for Different Types of Datasets for All Seasons. Unit: W m^{-2} per decade

Season	Datasets	1961-1980	1981-1995	1996-2014	1961-2014
Spring	SunDu-derived_HM	3.1	-1.5	3.4*	1.5
	CCRE series	-0.7	-1.6	-1.6	-0.9
	Residual series	4.9**	-0.5**	2.2**	2.8*
Summer	SunDu-derived_HM	1.4	-3.4	0.6	0.4
	CCRE series	-1.9	-2.1	-4.4**	-2.7
	Residual series	2.0**	-1.8	1.5**	2.8
Autumn	SunDu-derived_HM	0.6	1.5	3.3**	1.0*
	CCRE series	-1.3**	1.6	1.6	-0.9
	Residual series	1.8**	0.8**	2.1**	2.0*
Winter	SunDu-derived_HM	0.6	-1.5	-1.6	0.5
	CCRE series	-0.6	-3.3	-0.6	-0.7
	Residual series	1.1**	0.9**	-0.9**	1.2**

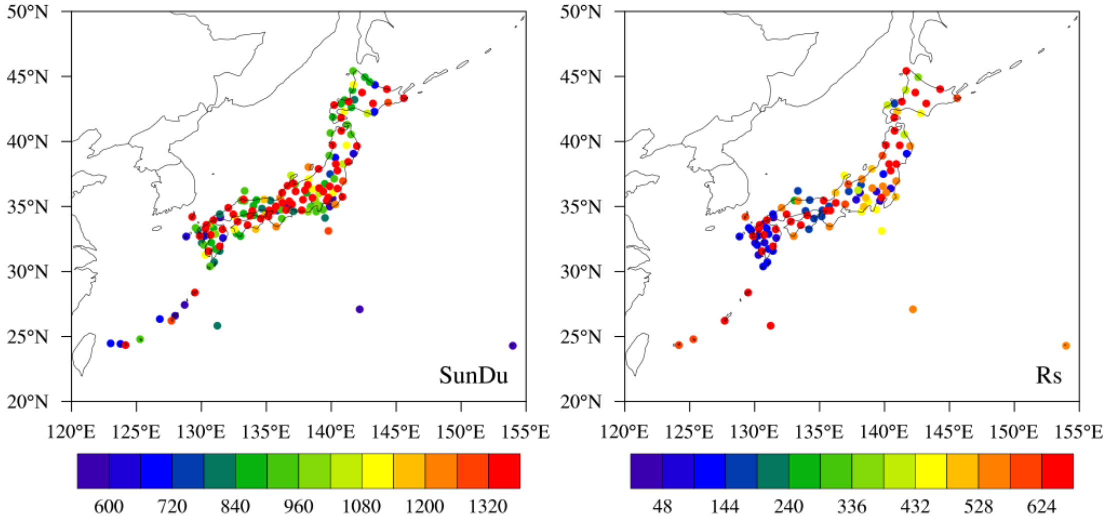

Figure 1. The spatial distribution of stations over Japan with observed sunshine duration (SunDu, 156 stations) and surface incident solar radiation (R_s, 105 stations) data. The colours indicate the data length of the SunDu records from 1890 to 2015 and R_s records from 1961 to 2015. Unit: month.

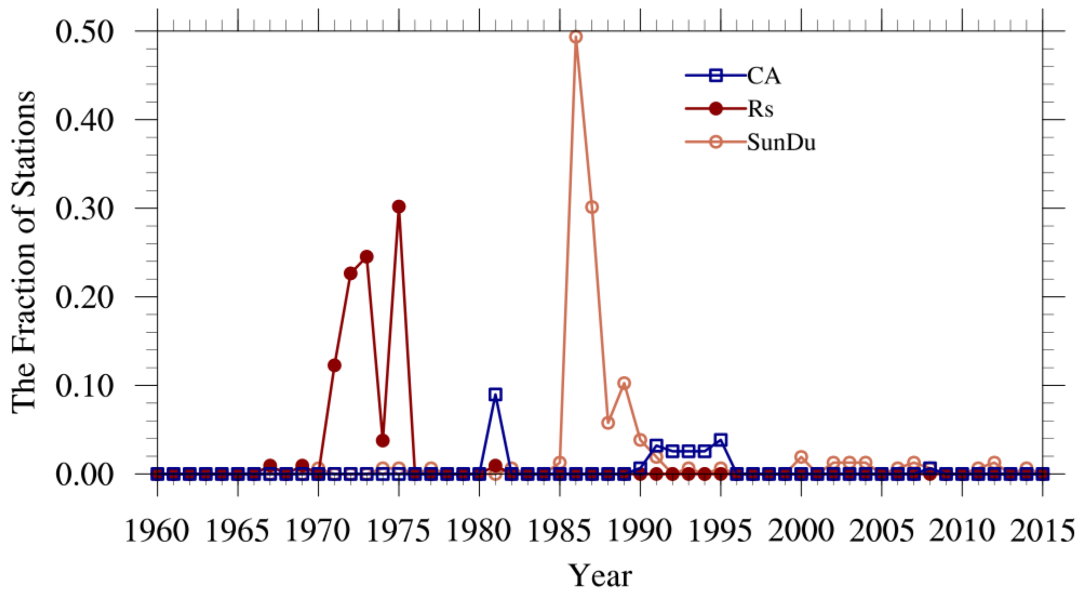

Figure 2. The fraction of stations that suffer from data inhomogeneity due to site relocation, change of instruments and measurement method for sunshine duration (SunDu) records, cloud amount (CA) records and surface incident solar radiation (R_s) records. In total, there were 156 stations with SunDu records, 105 of which had R_s records and 155 of which had CA records. The inhomogeneity information shown here was derived from metadata from https://www.data.jma.go.jp/obd/stats/data/en/smp/index.html, and was used as primary information to perform the inhomogeneity adjustment in the RHtest method detailed in Section 2.2.

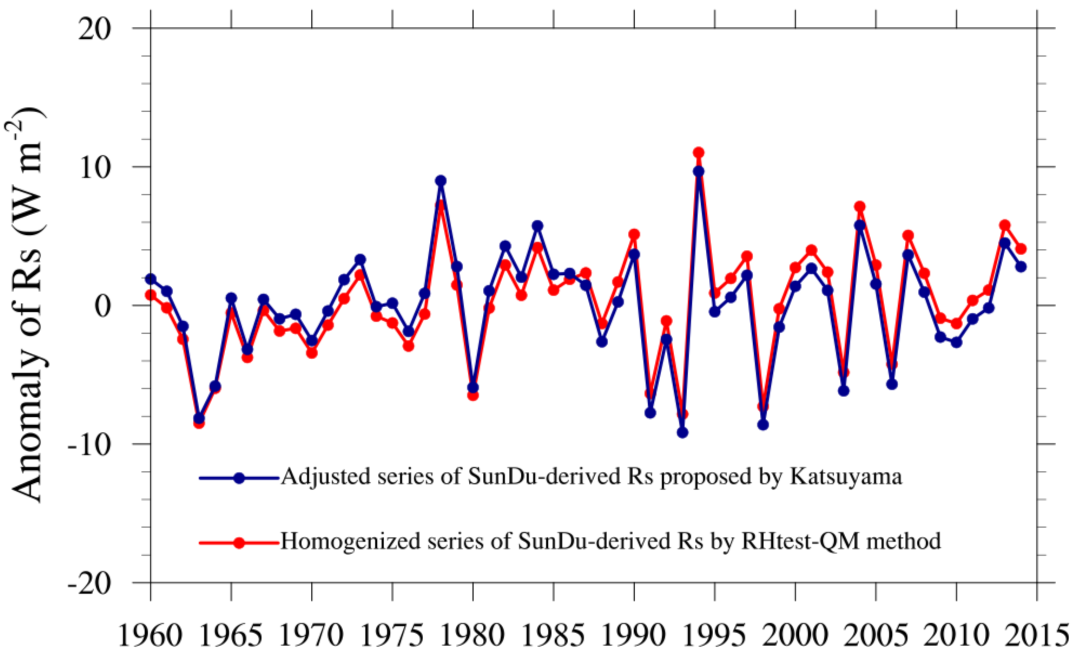

Figure 3. The anomalies of surface incident solar radiation (R_s) derived from homogenized sunshine duration (SunDu) data (red line) by the RHtest-QM method and other independent data (blue line) adjusted by the method in (Katsuyama, 1987). Both of the homogenized datasets yield nearly the same R_s variation.

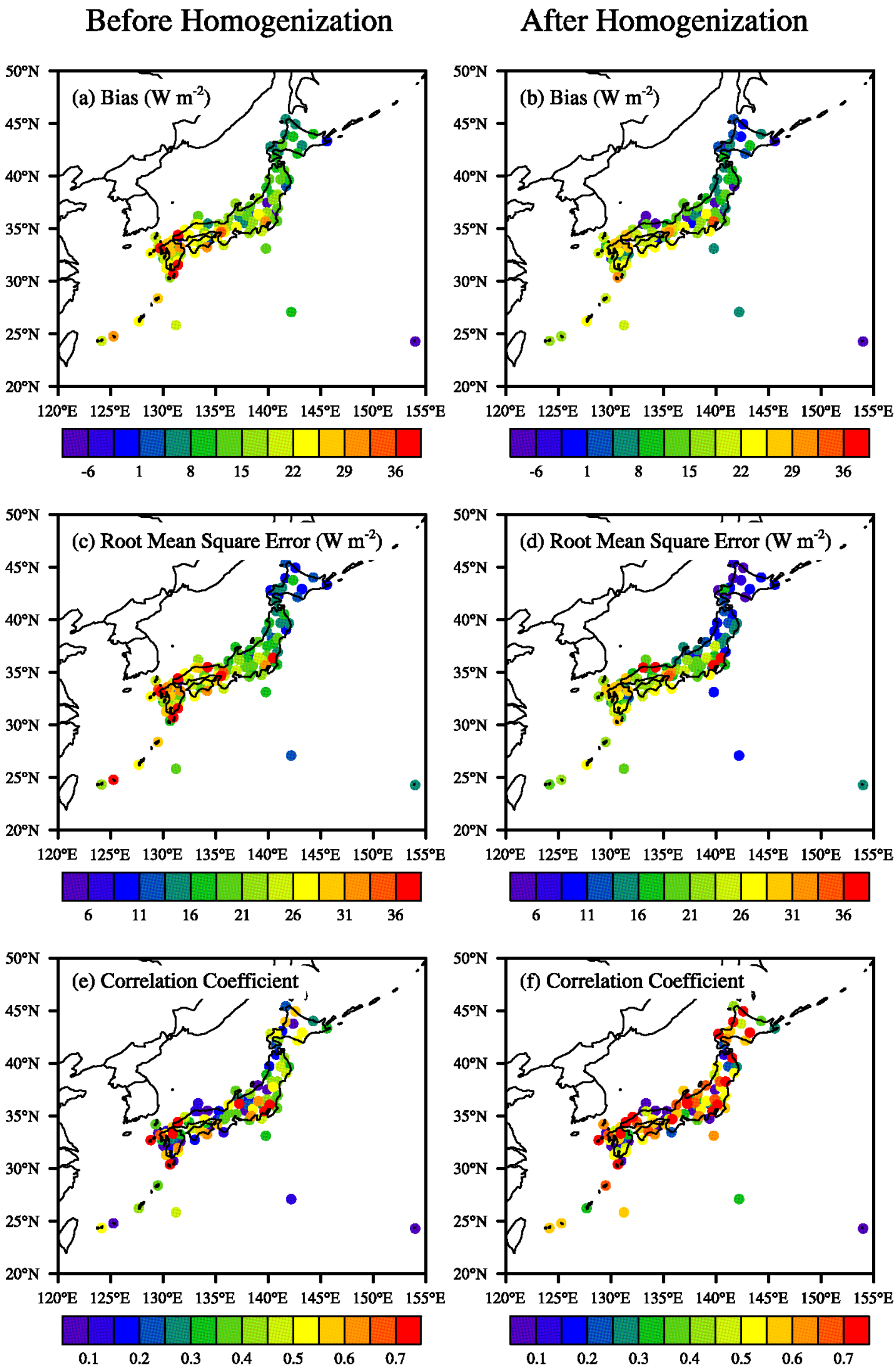

Figure 4. The spatial distribution of bias, root mean square error and correlation coefficient between SunDu-derived surface incident solar radiation (R_s) and observed

R_s before (a, c, e) and after (b, d, f) homogenization. Improvements were made at most sites after homogenization.

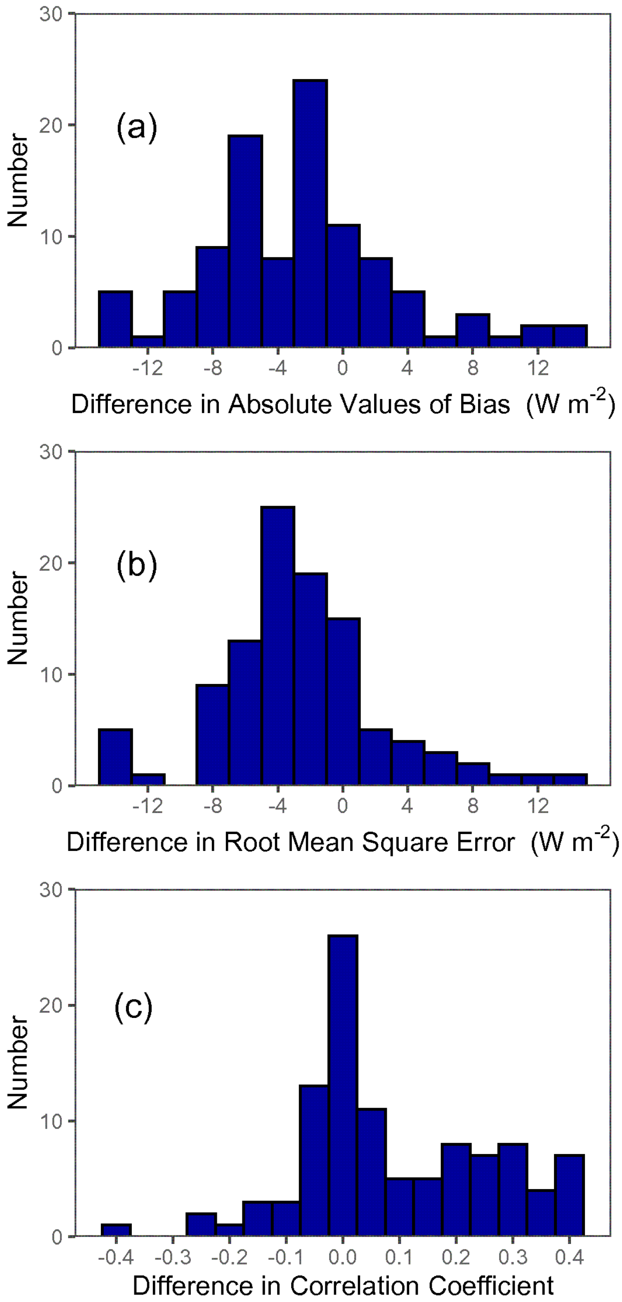

Figure 5. Histograms of the difference in absolute values of bias, root mean square error and correlation coefficient between SunDu-derived surface incident solar radiation (R_s) and observed R_s before and after homogenization. Their differences decrease after homogenization.

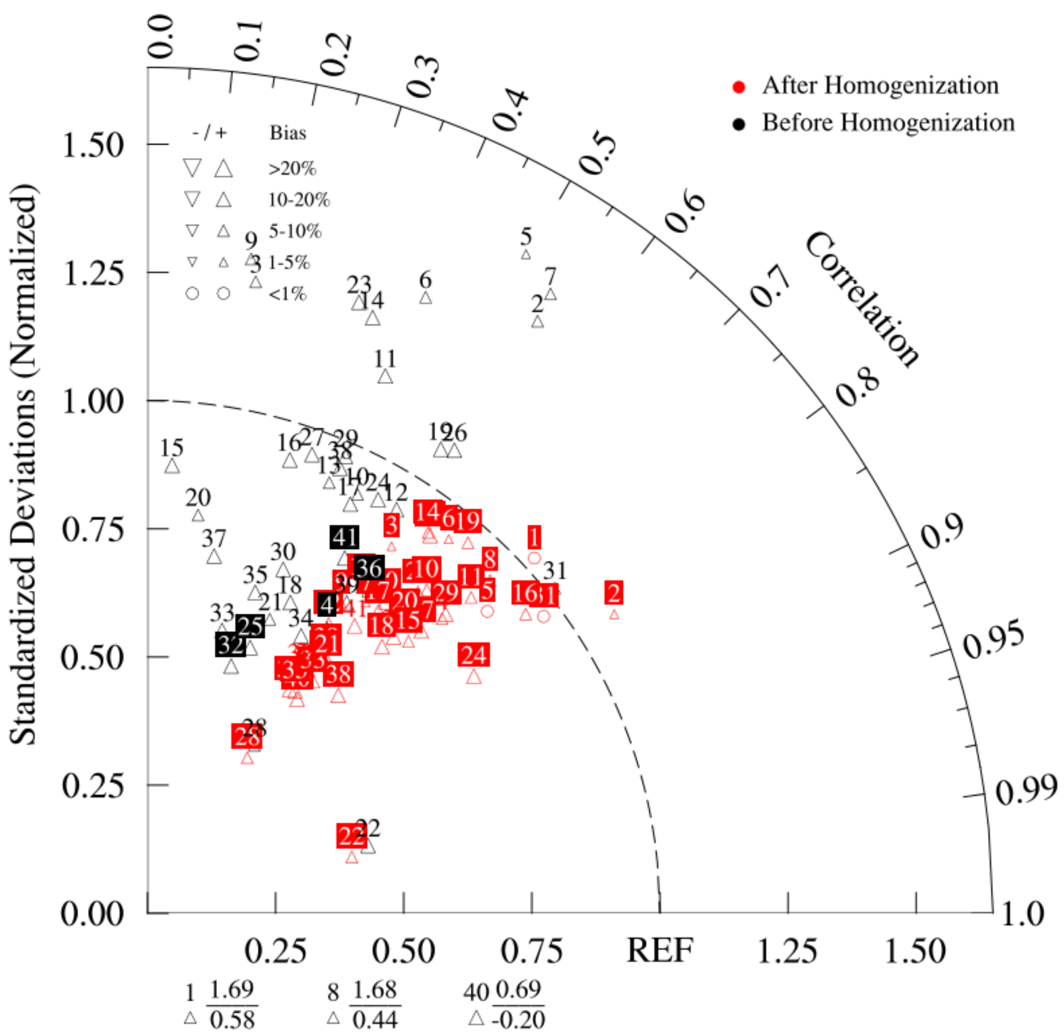

Figure 6. Taylor diagram describing the relative biases, standardized deviations and correlation coefficients between the annual observed surface incident shortwave radiation (Rs) and annual sunshine duration (SunDu) derived Rs before and after homogenization at 41 selected stations (Numbered 1-41 here). “REF” can be treated as the perfect point, where values the closer to this point indicate a better evaluation. The

size and direction of the triangles denote the magnitude and negative or positive of biases, respectively. The boxes indicate the smaller bias in Raw (black color) or HM (red color) series. This figure shows that biases decrease at most sites (in red boxes) after homogenization, except for the 5 stations numbered 4, 25, 32, 36 and 41 (in black boxes). Three stations (numbered 1, 8 and 40 in black color) listed below the panel are beyond the scope of the figure, with bias (triangle), ratio of standardized deviation (above the “---” line) and correlation coefficient (below the “---” line) shown. In addition to the improvements in the correlation coefficients after homogenization, the biases and the standard deviations generally become small in this Taylor diagram.

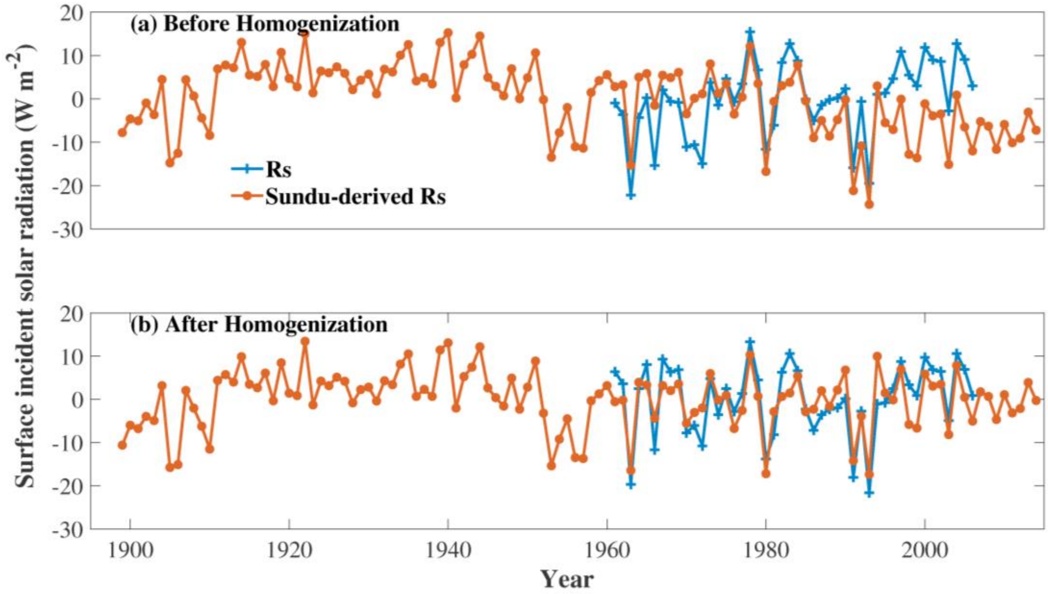

Figure 7. Time series of annual anomalies of observed surface incident solar radiation (R_s) and SunDu-derived R_s at HAMADA site (WMO-ID: 47755, Lat: 34.9°, Lon: 132.07) before and after homogenization.

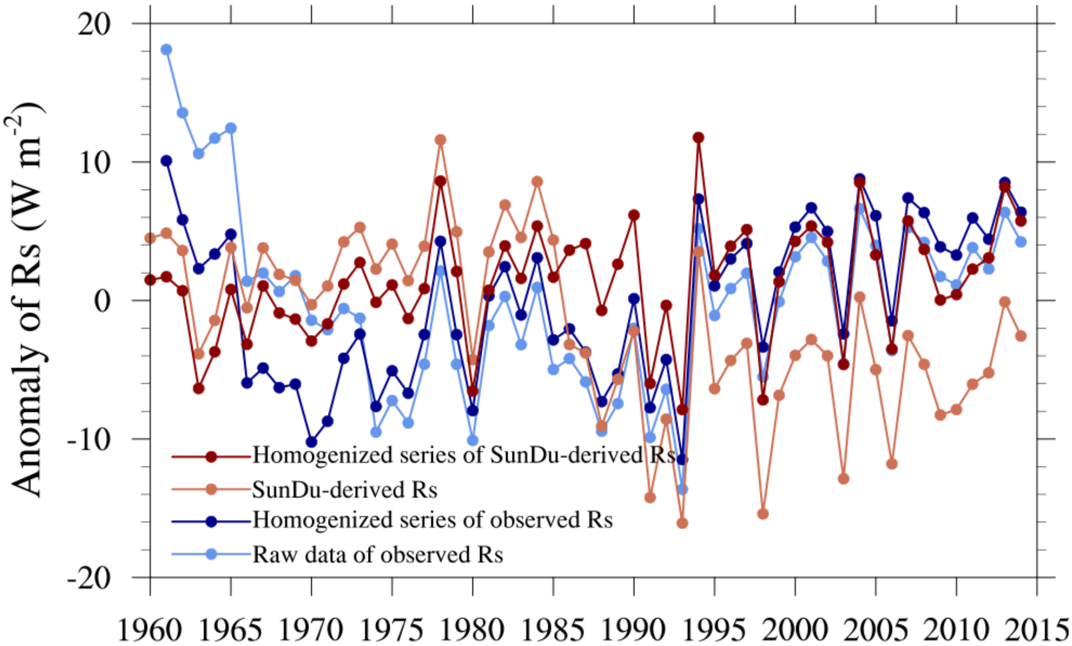

Figure 8. Time series of annual anomalies of surface incident solar radiation (R_s) based on direct R_s observations (light blue line) and their homogenized series (dark blue line) and sunshine duration (SunDu) derived R_s (light red line) and their homogenized series (dark red line). All of the lines were calculated based on observations at 41 sites. Details on how these 41 sites were selected are given in Section 3.1. The R_s variations are nearly the same as those shown in Figure 7, which were calculated based on all available observations.

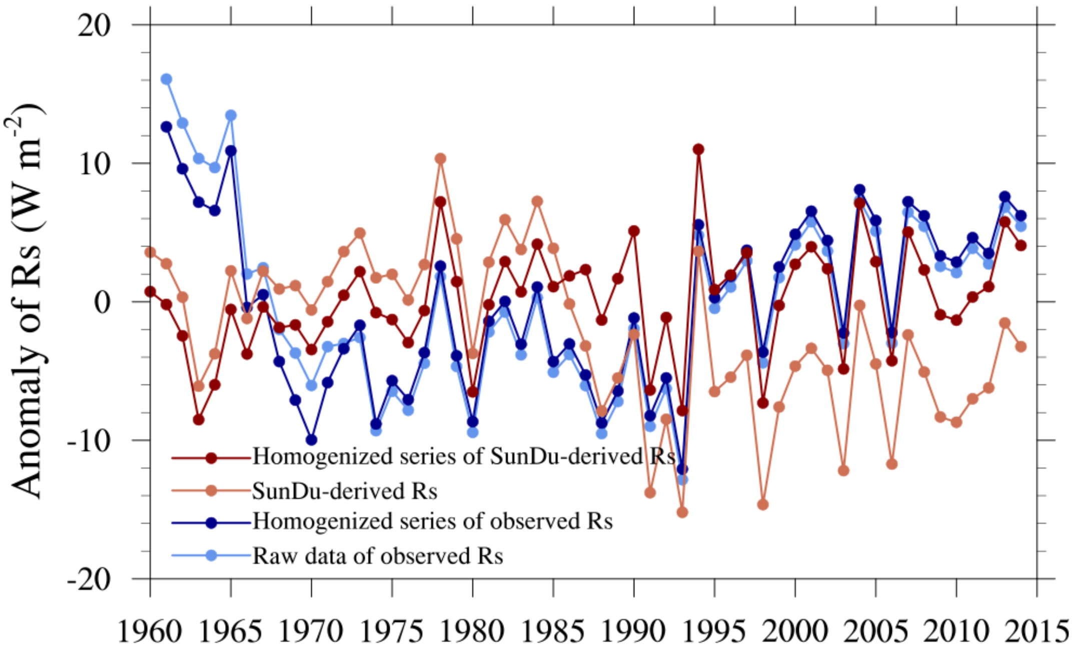

Figure 9. Time series of annual anomalies of the surface incident solar radiation (R_s) based on direct observations (light blue line) and their homogenized series (dark blue line) and sunshine duration (SunDu) derived R_s (light red line) and their homogenized series (dark red line). All of the lines were calculated based on as many observations as possible. The light blue line and dark blue line were calculated from the R_s observations at 105 sites, while the light red line and dark red line were derived from the SunDu-derived Rs at 156 sites. The R_s variations are nearly the same as those shown in Figure 6, which were calculated based on the 41 selected sites in Section 3.1. Large discrepancies were found in the homogenized data series (dark blue and dark red lines).

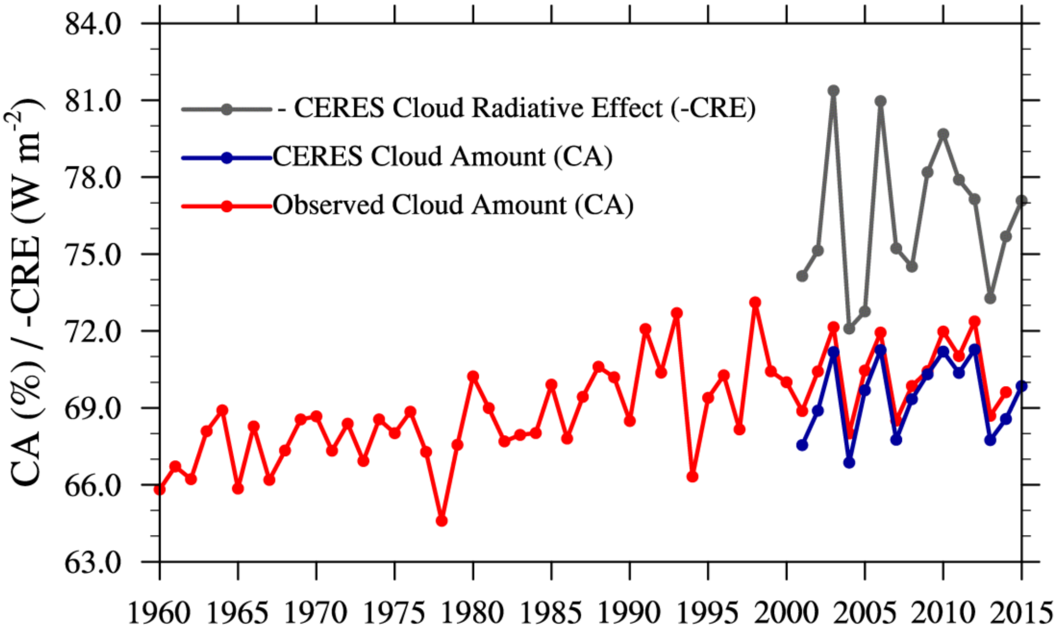

Figure 10. The cloud amount (CA) from CERES (blue line) agrees well with that derived from surface observations (red line) over Japan. At the annual time scale, the negative cloud radiative effect (-CRE, grey line) in CERES correlated well with the cloud amount.

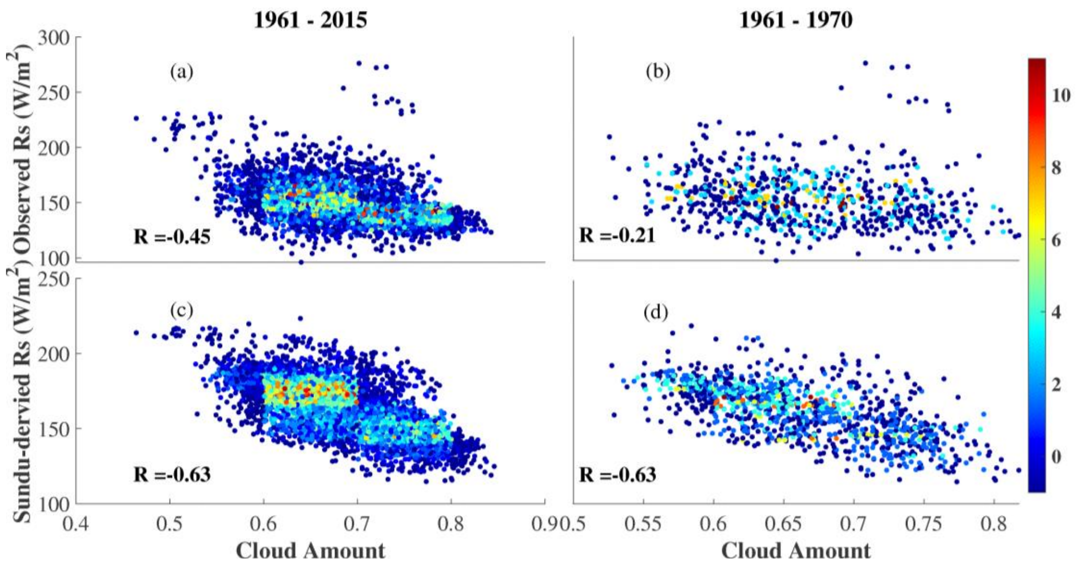

Figure 11. Scatter plot of homogenized monthly surface incident solar radiation (R_s) (observed and SunDu-derived solar radiation) as a function of ground-based observations of cloud amount over Japan at all stations only when both cloud amount data and observed R_s data are available. (a) and (c) for 1961-2015, (b) and (d) for 1961-1970. The smallest correlation coefficient in (b) indicates that the observed R_s data are spurious for 1961-1970, and SunDu-derived R_s are more convincing.

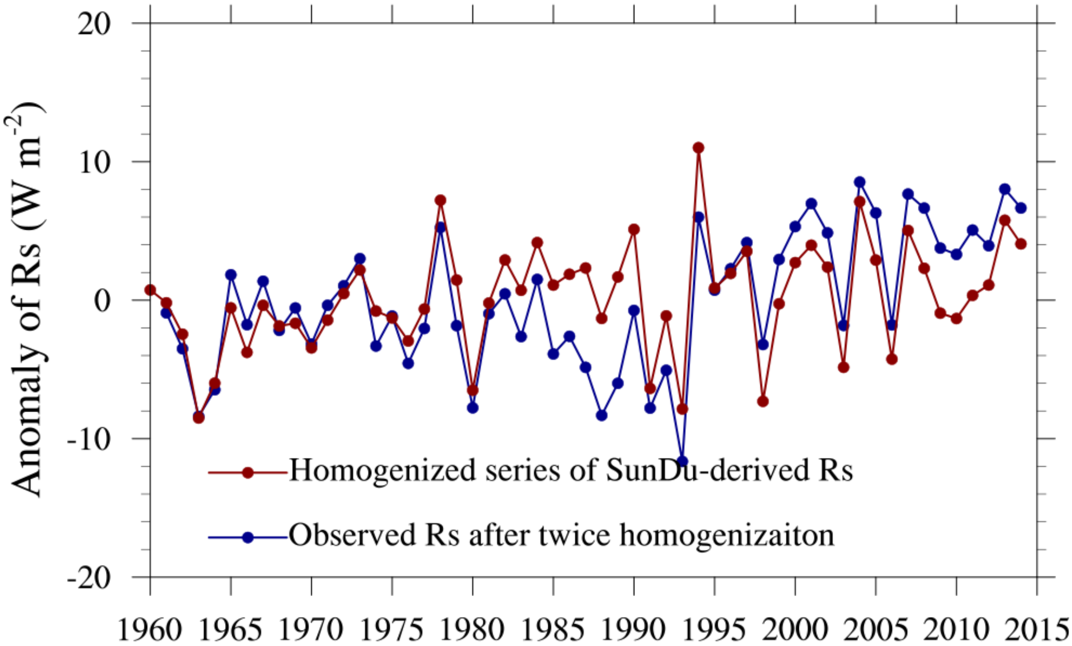

Figure 12. Time series of annual anomalies of the surface incident solar radiation (R_s) based on R_s observations after two homogenizations (dark blue line). The homogenized series of observed R_s from 1961 to 1970 shown in Figure 7 was tuned by RHtest method again using the homogenized series of SunDu-derived R_s (dark red line in Figure 7 and Figure 10) as a reference.

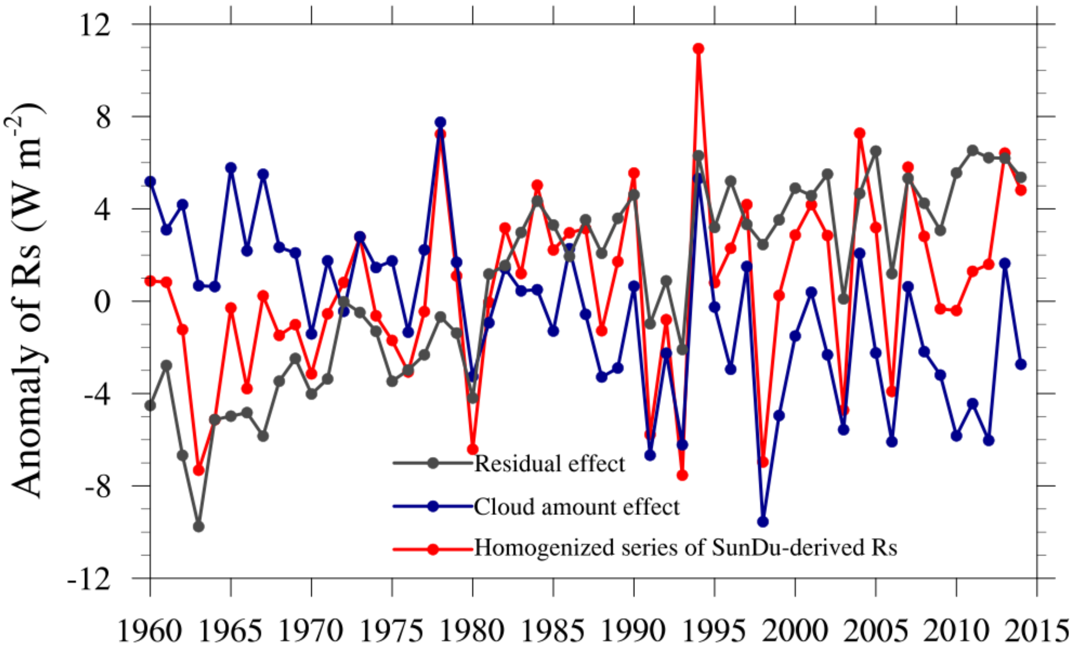

Figure 13. Area-averaged anomalies of homogenized SunDu-derived R_s (red line) over Japan. The cloud cover radiative effect (CCRE, blue line) was denoted as the change in R_s produced by a change in cloud cover and calculated following Equation (4) by observed cloud amounts and cloud radiative effect (CRE) from the CERES satellite retrieval. The residual effect (grey line) was obtained by removing the cloud cover radiative effect (CCRE) from the homogenized SunDu-derived R_s anomalies.

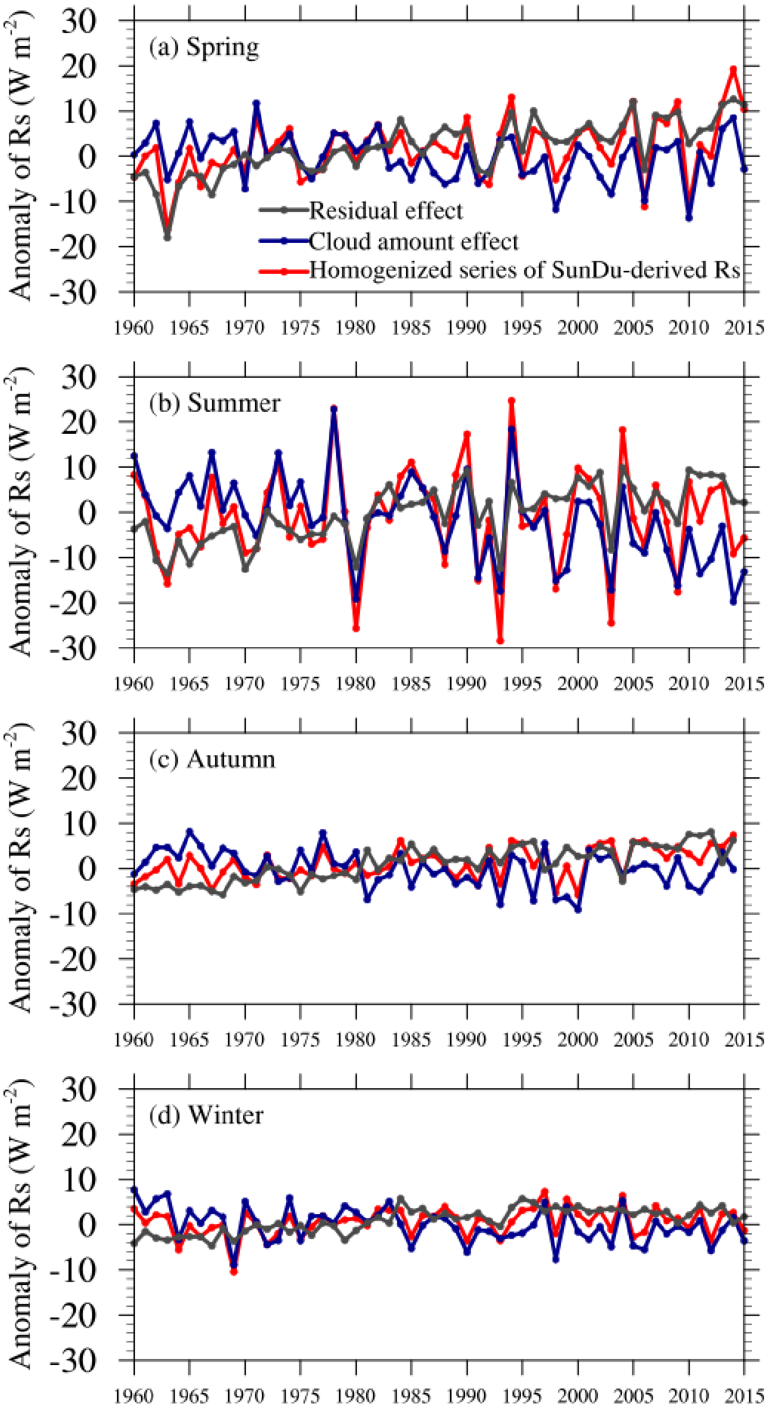

Figure 14. Same as Figure 12 but for the four seasons. The decrease in Asian spring dust may have triggered the brightening over Japan for 1961-2015, as the R_s in spring increases most among the seasons.