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Homogenized century-long surface incident solar radiation over Japan

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Abstract

Surface incident solar radiation (R_s) plays an essential role in climate change on Earth. R_s can be directly measured, and it shows substantial variability, i.e., global dimming and brightening, on decadal scales. R_s can also be derived from the observed sunshine duration (SunDu) with reliable accuracy. The SunDu-derived R_s was 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 with 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 observations of cloud cover fraction, the detected inhomogeneity was adjusted based on the reference dataset. As a result, a sharp decrease in the observed R_s from 1961 to 1975 caused by instrument displacement was detected and adjusted. Similarly, a gradual decline in SunDu-derived R_s due to steady instrument replacement from 1985 to 1990 was detected and adjusted. After homogenization, the two estimates agree well. R_s was found to have increased at a rate of 0.9 W m^{-2} per decade ($p<0.01$) from 1961 to 2015 based on the homogenized SunDu-derived R_s, which was enhanced by a positive aerosol-related radiative effect (2.2 W m^{-2} per decade) and diminished by a negative

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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).

Key Points:

(1) Surface incident solar radiation (R_s) and sunshine duration over Japan were homogenized.

(2) Homogenized century-long R_s data over Japan were produced, and shows that R_s increased at a rate of ~ 1 W m^{-2} per decade from 1961 to 2015.

(3) Cloud cover modulates R_s variation at monthly and interannual time scales, while aerosols dominate the decadal variation in R_s.

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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; Stanhill and Cohen, 2005). R_s can be measured by either a single pyranometer or the summation of diffuse and direct components. 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). Instrument replacements introduced substantial inhomogeneity into the time series of observed R_s over China during the period of 1990-1993 (Shi et al., 2008; Wang et al., 2015). Instrument changes from the Robitzsch pyranograph to the Kipp & Zonen CM11 pyranometer before 1980 caused no clear dimming in Italy (Manara et al., 2016). However, the possible homogeneity 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;

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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.

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). 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). 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.,

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2015). In Japan, 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 have inhomogeneity issues.

The RHtest-quantile matching (QM) method (Wang, 2008b; Vincent et al., 2012), which first detects the changepoints in a series and then tunes the inhomogeneous data segments to be consistent with other segments in empirical distributions, has been widely used for homogenizing climate variables (Dai et al., 2011; Wang et al., 2010).

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-QM method was applied to homogenize the observed R_s and SunDu-derived R_s, and finally, the homogenized long-term R_s data were derived 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

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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% of R_s stations in 1971, followed by ~24%, 26%, 4% and 32% 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 nearly 50% of SunDu stations in 1986. Before 1990, nearly all of the SunDu stations used new instruments for observations. Less than 5% of SunDu stations before 1985 and more than 10% 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 inhomogeneity problems, which require rigorous data homogenization. RHtest (http://etccdi.pacificclimate.org/software.shtml) is a widely used method to detect and

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adjust multiple changepoints in a data series (Wang, 2008a). Two algorithms were provided to detect changepoints based on the penalized maximal T test and the penalized maximal F test (Wang, 2008b). As the discontinuity dates were recorded on the JMA websites, we artificially treat these observations on those dates as changepoints. To diminish all significant artificial shifts caused by the changepoints, Quantile-Matching (QM) adjustments in the RHtest (Vincent et al., 2012) 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. The homogenization methods were compared in this study and yielded nearly the same SunDu-derived R_s variation, as shown in Figure 3.

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

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observation time for cloud amount has been 08:00-19:00 since 1981 at 10% of cloud amount stations and 08:30-17:00 from 1990 to 1995 at another 10% 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. The Clouds and the Earth's Radiant Energy System (CERES) provides 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).

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):

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

where g is the grid, 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 long-term mean cloud cover 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

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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. 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.

3. Results

3.1 Homogenization of observed R_s and sunshine duration derived R_s

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. Both R_s and SunDu records are available at 105 stations. Figure 4 shows the comparisons between raw data and homogenized data. After QM adjustments, the correlation coefficients between the annual observed R_s and annual SunDu-derived R_s are significant with a 90% confidence interval at 75 stations. The correlation coefficients were improved at 54 of 75 stations after homogenization, including 31 stations that had improvements greater than 0.2. Among the 54 stations, there were 41 stations (marked with red in Table S1) at which the correlation coefficients were greater than 0.5, and the biases and the root mean square errors generally decrease after homogenization.

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Figure 5 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, which highlights the necessity and feasibility of the RHtest-QM method. The SunDu-derived R_s variation over Japan during recent decades inferred from these "perfect" data at 41 sites (Figure 6) was nearly identical to that from all available data at 156 sites (as shown in Table 1 and Figure 7).

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 8. The regional average cloud amount over Japan in Figure 8 (blue line) increases at a rate of 0.7% per decade from 1960 to 2015, which is consistent with the results (Figure 4) in (Tsutsumi and Murakami, 2012).

3.2 Uncertainties in R_s observations

Figure 7 displays the change in R_s during the last 5 decades, while Figure 8 shows the variation in observed clouds over Japan. The sharp decrease in R_s in 1963 was attributed to the volcanic eruption of Agung in Indonesia in the same year (Witham, 2005). 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 (shown in Figure 8) (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 8. The pronounced R_s decline in 1980 coincides with the significant

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increase in clouds, while the lightening of R_s in 1978 and 1994 encounters abrupt decreases in cloud covers.

As shown in Figure 7, R_s observations change little 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 7). Existing study noted the inaccurate instruments used at the beginning of operation of 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 8, 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

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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 9 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 misleading R_s variation was modified by the RHtest method again using homogenized SunDu-derived R_s as reference data from 1961 to 1970 as shown in Figure 10.

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 8; 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 8, 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 7).

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

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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.

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. In addition, 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.

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 11 and Table 1, which is in

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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) demonstrated that cloud amount categories exert an important effect on R_s variation. R_s enhancement by the increased appearance of large

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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 neighbouring 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 12 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 during 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

Observational data themselves have inherent problems caused by measurement method, instrument replacement and site relocation. Therefore, precautions should be taken when using these data for trend analysis or as validation data. In this study, the RHtest-QM method was introduced to homogenize the direct measurements of R_s and SunDu-derived R_s over Japan using the information in metadata as changepoints. Inhomogeneities in the homogenized raw R_s was 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. The global dimming and brightening over Japan were revisited based on the homogenized SunDu-derived R_s, which diminished the effect of nonclimate signals in the raw observations.

Japan experienced a sudden decline in Rs in 1963, a global brightening of 4.8 W m^{-2} per decade (P<0.01) from 1963 to 1977, a rapid increase in 1978, a sudden decrease in 1980, a global dimming of 5.1 W m^{-2} per decade (P<0.10) from 1981 to 1993, a pronounced increase in 1994, and a nearly 1 W m^{-2} per decade increase from 1995 to 2014. For the last 5 decades, a slight global brightening of 1 W m^{-2} per decade (with a 99% confidence interval) was inferred from the homogenized SunDu-derived R_s. Global brightening since 1961 over Japan is consistent with that in (Stanhill and Cohen,

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2008), except that the magnitude is not as large.

Clouds and aerosols are the two major factors that mediate the transformation of Rs. 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 Rs 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 generally cleaner skies and a reduction in spring Asian dust storms (Wang et al., 2012; Kudo et al., 2012).

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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	-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	-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), 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

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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.

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545 Table 2. Trends of Surface Incident Solar Radiation (R_s) in Japan during Specific Time

546 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**

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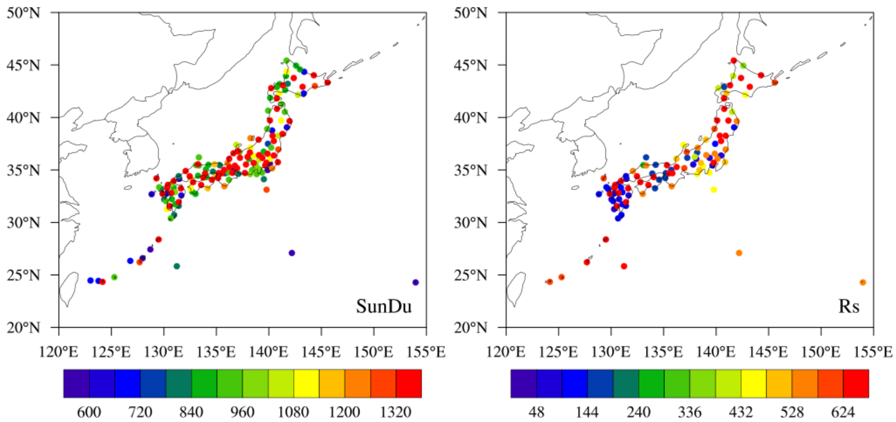

Figure 1. The spatial distribution of stations over Japan with observed sunshine duration (SunDu, 156 stations) and surface incident solar radiation (R_s, 105 stations) data. The colours indicate the data length of the SunDu records from 1890 to 2015 and R_s records from 1961 to 2015. Unit: month.

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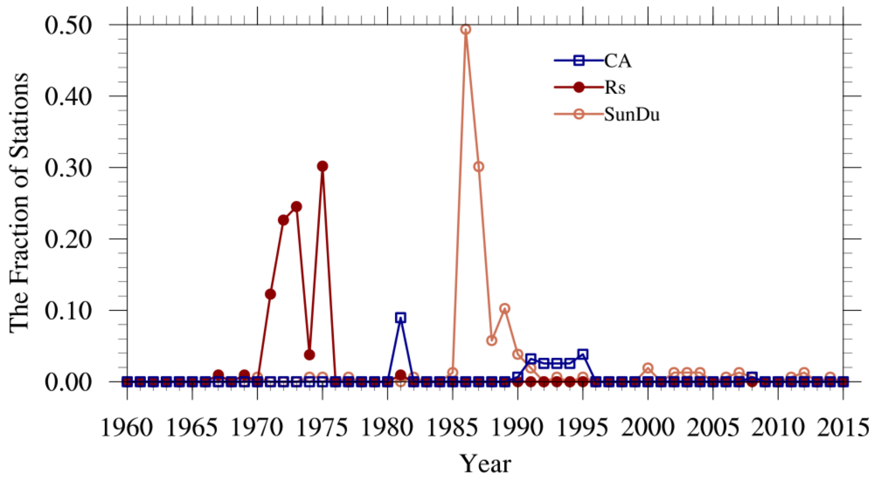

Figure 2. The fraction of stations that suffer from data inhomogeneity due to site relocation, change of instruments and measurement method for sunshine duration (SunDu) records, cloud amount (CA) records and surface incident solar radiation (R_s) records. In total, there were 156 stations with SunDu 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.

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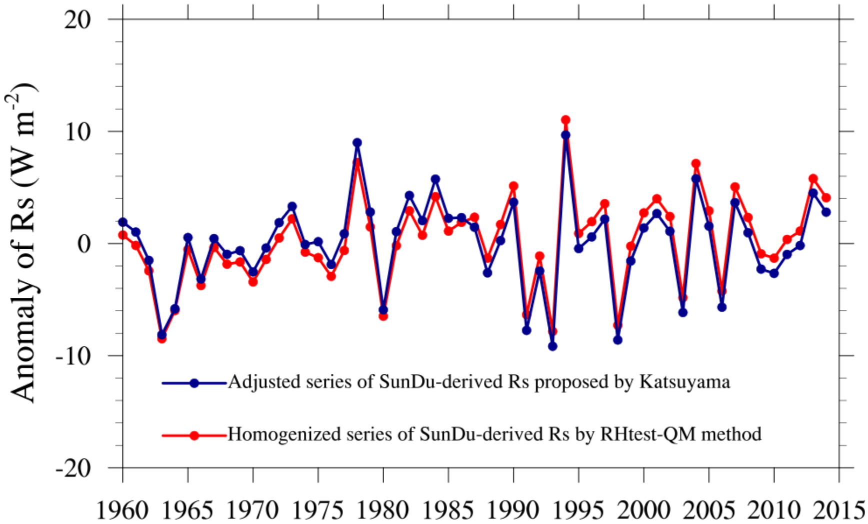

Figure 3. The anomalies of surface incident solar radiation (R_s) derived from homogenized sunshine duration (SunDu) data (red line) by the RHtest-QM method and other independent data (blue line) adjusted by the method in (Katsuyama, 1987). Both of the homogenized datasets yield nearly the same R_s variation.

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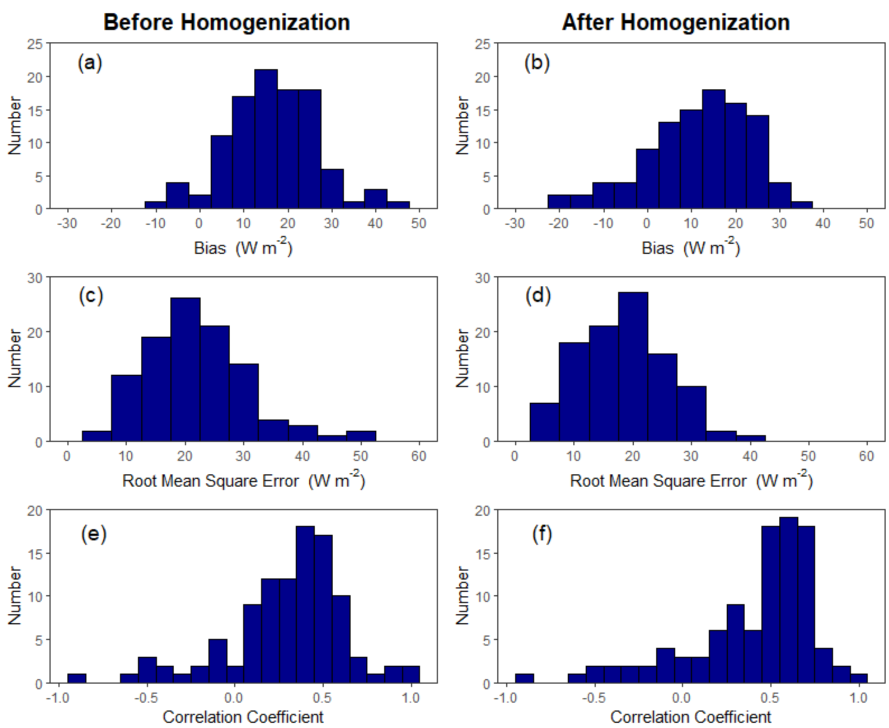

Figure 4. Histograms of bias, root mean square error and correlation coefficient between SunDu-derived surface incident solar radiation (R_s) and observed R_s before (a, c, e) and after (b, d, f) homogenization. Their differences decrease after homogenization.

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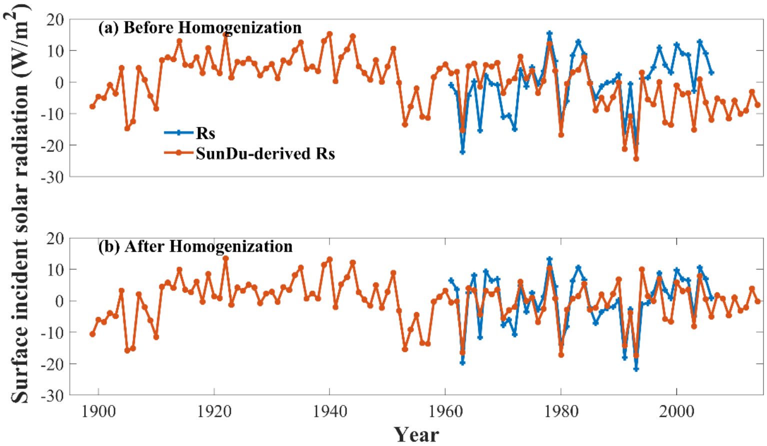

Figure 5. Time series of annual anomalies of observed surface incident solar radiation (R_s) and SunDu-derived R_s at HAMADA site (WMO-ID: 47755, Lat: 34.9°, Lon: 132.07) before and after homogenization.

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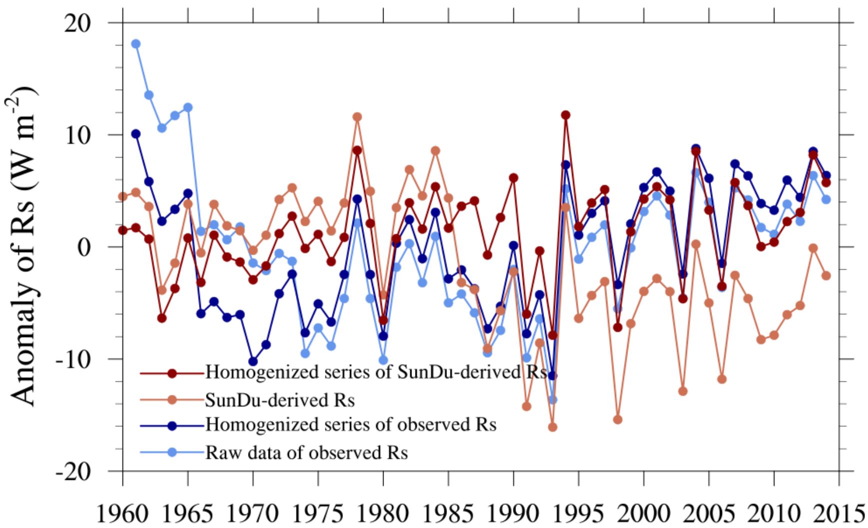

Figure 6. Time series of annual anomalies of surface incident solar radiation (R_s) based on direct R_s observations (light blue line) and their homogenized series (dark blue line) and sunshine duration (SunDu) derived R_s (light red line) and their homogenized series (dark red line). All of the lines 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.

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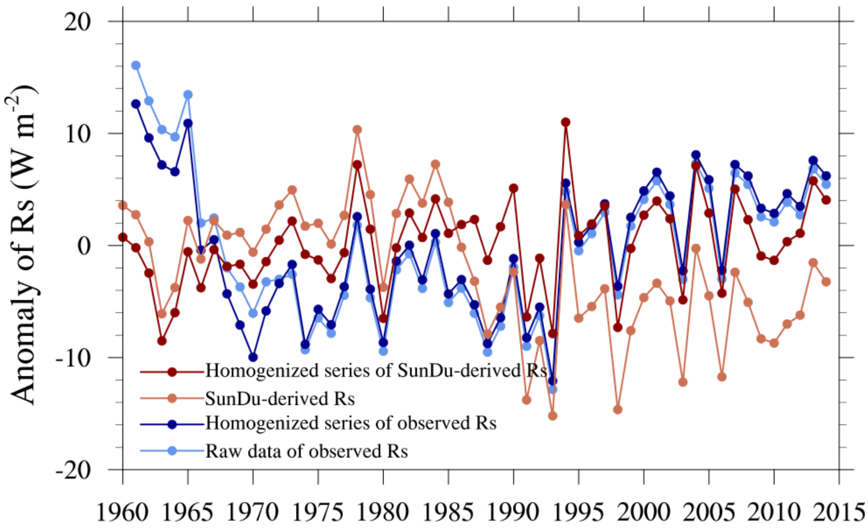

Figure 7. Time series of annual anomalies of the surface incident solar radiation (R_s) based on direct observations (light blue line) and their homogenized series (dark blue line) and sunshine duration (SunDu) derived R_s (light red line) and their homogenized series (dark red line). All of the lines 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).

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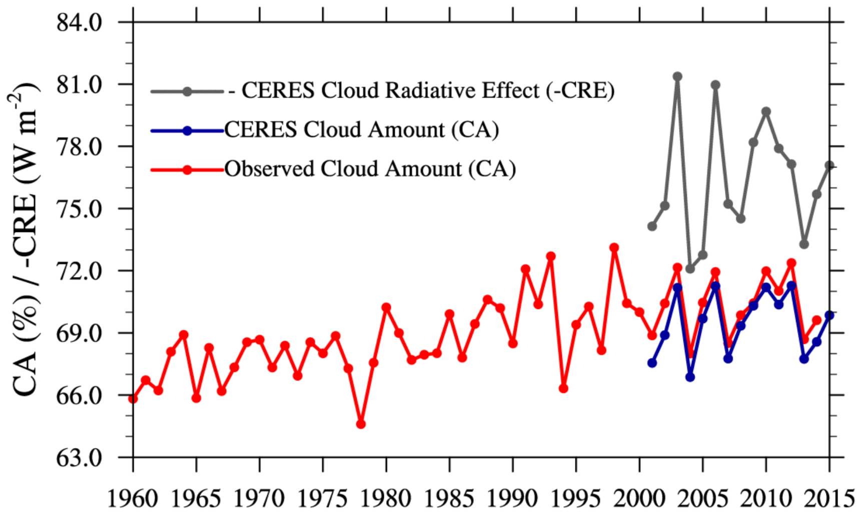

Figure 8. The cloud amount (CA) from CERES (blue line) agrees well with that derived from surface observations (red line) over Japan. At the annual time scale, the negative cloud radiative effect (-CRE, grey line) in CERES correlated well with the cloud amount.

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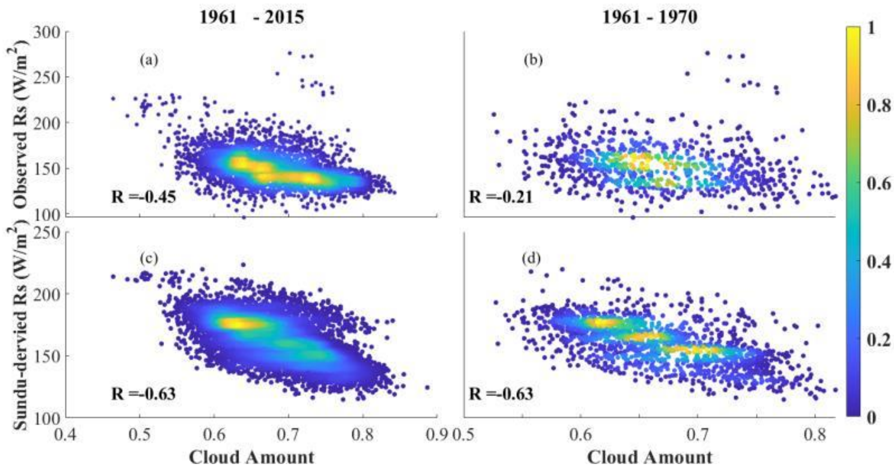

Figure 9. Scatter plot of homogenized monthly surface incident solar radiation (R_s) (observed and SunDu-derived solar radiation) as a function of ground-based observations of cloud amount over Japan at all stations only when both cloud amount data and observed R_s data are available. (a) and (c) for 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.

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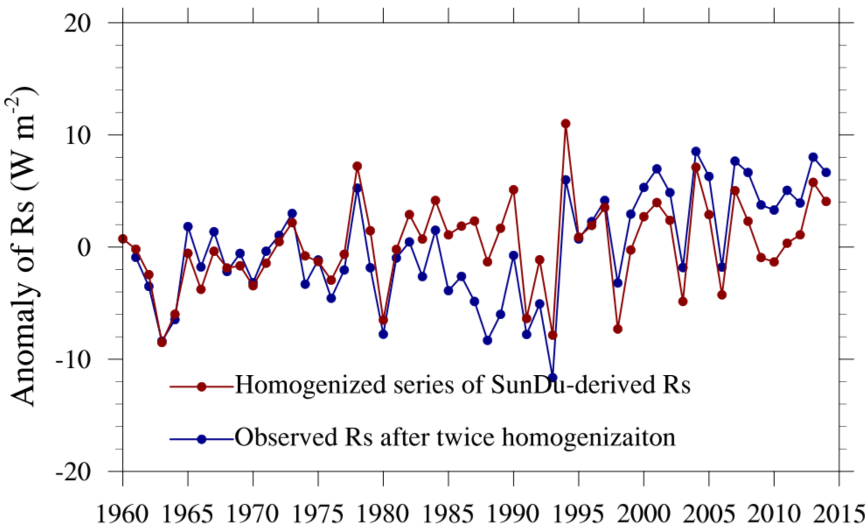

Figure 10. Time series of annual anomalies of the surface incident solar radiation (R_s) based on R_s observations after two homogenizations (dark blue line). The homogenized series of observed R_s from 1961 to 1970 shown in Figure 7 was tuned by RHtest method again using the homogenized series of SunDu-derived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

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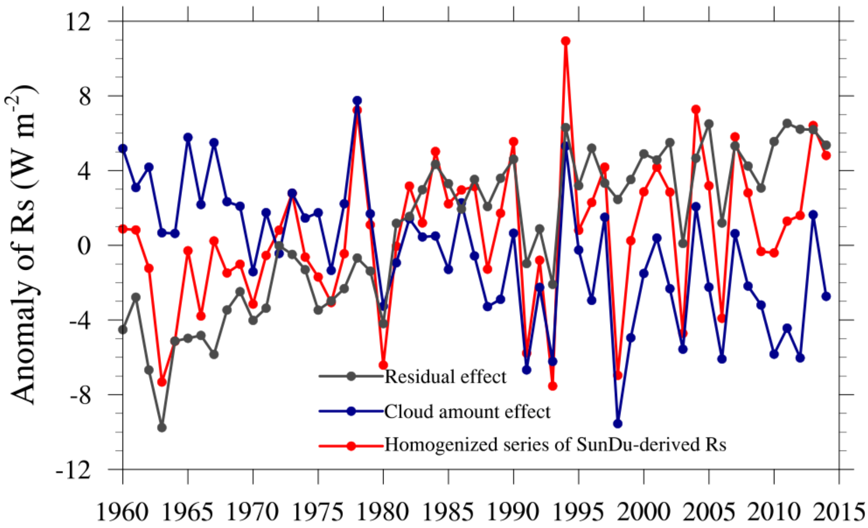
626 

627 Figure 11. Area-averaged anomalies of homogenized SunDu-derived R_s (red line) over
628 Japan. The cloud cover radiative effect (CCRE, blue line) was denoted as the change in
629 R_s produced by a change in cloud cover and calculated following Equation (4) by
630 observed cloud amounts and cloud radiative effect (CRE) from the CERES satellite
631 retrieval. The residual effect (grey line) was obtained by removing the cloud cover
632 radiative effect (CCRE) from the homogenized SunDu-derived R_s anomalies.
633

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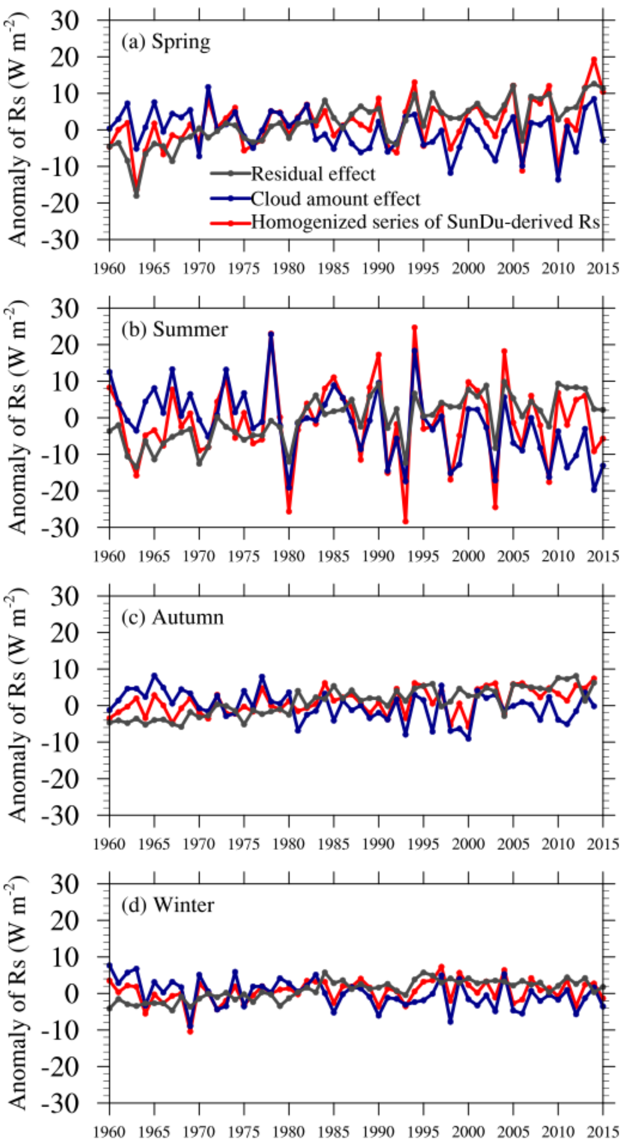

Figure 12. Same as Figure 10 but for the four seasons. The decrease in Asian spring dust may have triggered the brightening over Japan for 1961-2015, as the R_s in spring increases most among the seasons.