The Long-term Variation in Surface Shortwave Irradiance in China and Japan: A Review

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(Manuscript received 20 August 2015, in final form 2 July 2016)

Abstract

We reviewed the long-term trends and inter-annual variations in the surface shortwave irradiance in China and Japan. Pyranometer observations revealed decreases followed by increases in the shortwave irradiance in China and Japan between the 1960s and 2000s, while obvious long-term trends were not evident in the satellite observations after 1983. In China, surface shortwave irradiance decreased from 1961 until around 1990, but then began to increase. In Japan, on the contrary, the decreasing trend stopped in the 1960s, with little inter-annual variation during the 1970s and 1980s, and an increase began around 1990. The causes of the differences between the shortwave irradiance trends in China and Japan were ascribed to an increase in light-absorbing aerosols in China that began in the 1960s and a decrease in absorbing aerosols in Japan that began in the late 1970s. Absorbing aerosols decrease both direct and diffuse radiation, while non-absorbing aerosols decrease direct radiation but increase diffuse radiation. Although these aerosol influences are generally found under clear sky conditions, absorbing aerosols could have direct effects even under cloudy sky conditions. The trends of surface shortwave irradiance in China and Japan are in line with the so-called global dimming and brightening dimming processes, although the phases of the minimum periods in the two regions slightly differed. An increase in anthropogenic aerosol was responsible for the variation in the shortwave irradiance through the direct radiative effect of aerosol in the polluted area, while indirect radiative effects, i.e., changes in cloud cover due to an increase in cloud condensation nuclei, dominated in pristine areas. The effects of other factors, such as variations in water vapor and natural aerosol levels, appear to be small compared to the effects of cloud and anthropogenic aerosols.

Keywords shortwave irradiance; long-term variation; China and Japan

1. Introduction

Shortwave radiation from the sun plays an important role in the climate system of the earth. Shortwave radiation drives dynamical and thermo-dynamical processes in the atmosphere as well as dynamics in the ocean. Because surface shortwave radiation affects the evaporation process at the earth’s surface and the transport of water, it is linked with the earth’s water cycle. Shortwave radiation also drives photosynthesis in plants; thus, it is important for the whole biosphere. Spatial and temporal variations in the surface shortwave radiation budget are closely related to the amount of available solar energy, which is likely to become an important energy source in the future. Accordingly, shortwave radiation is extremely important for humans and ecosystems in various ways.

Despite its importance, quantitative evaluation of radiation budgets in the surface–atmosphere system has not yet been performed. The annual mean global
energy balance was slightly revised in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) from the value given in the IPCC’s Fourth Assessment Report (IPCC 2007, 2013; Trenberth et al. 2009). Over the past two decades, owing to a reassessment of the role of light-absorbing aerosols, the absorption of shortwave radiation by the atmosphere has been revised from 67 W m$^{-2}$ to 79 W m$^{-2}$, with an uncertainty range of 74–91 W m$^{-2}$ (Kiehl and Trenberth 1997; Wild et al. 2013). Estimates of the downward shortwave irradiance at the surface have decreased from 198 W m$^{-2}$ to 185 W m$^{-2}$, while estimates of the incoming shortwave irradiance at the top of the atmosphere (TOA) have remained almost the same. Raschke et al. (2005) also evaluated the radiation budget of the atmosphere–surface system and the role that clouds play in it. They mainly used an International Satellite Cloud Climatology Project (ISCCP) data set and estimated the shortwave irradiance at the surface to be 189 W m$^{-2}$ and the shortwave absorption by the atmosphere to be 71 W m$^{-2}$. Thus, the radiation budget and energy flux of the earth’s atmosphere and surface are still not known with sufficient accuracy, while radiative forcing due to greenhouse gases and other anthropogenic emissions since the industrial revolution are considered to have had a radiative effect of a few Watts per square meter.

The incident solar radiation at the TOA has been measured using a well-calibrated radiometer onboard a satellite, and the total solar irradiance at a distance of 1 AU from the sun is now estimated to be 1361–1362 W m$^{-2}$, with variation in an 11 year cycle (Kopp et al. 2005a, b; Fröhlich 2010). The reflected shortwave irradiance at the TOA has also been directly measured at the global scale using a broadband radiometer onboard a satellite (Barkstrom 1984; Wielicki et al. 1996). In addition, as a result of calculations based on satellite-derived cloud data, such as ISCCP and meteorological data, the shortwave irradiance at the surface and the TOA can be globally estimated and have been reported, for example, in the ISCCP-Flux Data (ISCCP-FD: Zhang et al. 1995, 2004) and the Global Energy and Water Cycle Experiment-Surface Radiation Budget (GEWEX-SRB: Gupta et al. 1999, 2006). The number of surface observation sites is limited; thus, evaluating surface downward shortwave irradiance on a global scale is difficult. However, surface radiation measurements can provide long-term data for a period of more than 50 years, which is approximately three decades longer than the period for which satellite observation records are available.

The measurement of direct solar radiation at the surface has a long history (Fröhlich 1991). In 1837, Pouillet developed a pyrheliometer for evaluating the solar constant based on so-called water calorimetry, i.e., measurement of the temperature of water heated by solar radiation. He made the first evaluation of the solar constant as 1228 W m$^{-2}$, whereas it is now estimated to be 1361 W m$^{-2}$. In the 18th and 19th centuries, solar radiation measurements were mainly conducted to obtain the solar constant. To improve the measurement accuracy of this constant, Ångström used two detectors, which were alternately shaded from and illuminated by solar radiation. He replaced the calorimeters by electrically calibrated detectors in the famous compensation pyrheliometer. Sunshine duration measurement also has a long history. Measurements started in Japan in the late 19th century, and the currently available records cover more than 100 years (Bennett 1964). Sunshine duration data can be used to estimate the downward shortwave irradiance by the parameterization method, as described in Section 3.

Long-term observations of the surface shortwave irradiance using pyranometers have been conducted globally since the International Geophysical Year (IGY) 1957/1958, although their geographical distribution is limited. The IGY was originally established to study the influence of the sun on the earth (Martin 1958; Landsberg 1961). Many meteorological observatories around the world took this opportunity to begin pyranometer observations. The global surface shortwave irradiance map has been investigated using pyranometer measurements as well as sunshine duration measurements (Löf et al. 1966). More recently, studies on surface shortwave irradiance have focused mainly not on decadal or secular variations but on a global map, i.e., the geographical distribution of the downward shortwave irradiance.

Pyranometer measurements of the downward shortwave irradiance also started in China and Japan after the IGY. In China, two types of instruments were used at meteorological observatories. One type was a copy of a former Soviet Union instrument, and the other was manufactured in China. The former was substituted with the latter during the period 1990–1993, and the procedures involved in making observations were improved. A solar radiation observation network was established in China in 1957. In Japan, sunshine duration measurements have been made for more than 100 years and are used as a proxy for the downward shortwave irradiance.

As part of the Global Energy Balance Archive
(GEBA), long-term radiation data have been archived at the Swiss Federal Institute of Technology in Zurich (Ohmura et al. 1989). Data sources used by GEBA include the World Radiation Data Center, national weather services, the Baseline Surface Radiation Network (BSRN: McArthur 2005) facilities, and other institutions that perform pyranometer measurements (Gilgen et al. 2009). Ohmura and Lang (1989) first reported that shortwave irradiance at the surface has undergone significant decadal variations and has highlighted the decreasing trend in Europe between the late 1950s and late 1970s. Since then, similar trends have been reported for other regions, such as the United States, the former Soviet Union, and Antarctica (Abakumova et al. 1996; Stanhill and Cohen 1997, 2001; Liepert 2002; Liepert and Tegen 2002). The decreasing trends since the 1950s became increasing trends in many regions around the 1980s. This pattern is now referred to as “global dimming and brightening” (Wild et al. 2005). Although the factors that cause global dimming and brightening have been investigated over the past decade, firm conclusions have not yet been obtained. The variation of total solar irradiance at the TOA was less than 0.1 %, including an 11-year sunspot cycle, for the period from 1978 until 2005 (Foukal et al. 2006). Therefore, the surface shortwave irradiance change is attributable to the atmosphere–surface system of the earth. Wild (2009) produced a comprehensive review of this issue, with a huge number of references, taking into account both observations and general circulation model (GCM) simulations. He suggested that the factors affecting surface shortwave irradiance differ between regions. The downward shortwave irradiance is obviously affected by the indirect aerosol effect in pristine regions, whereas the direct effect is more important than the indirect effect in polluted regions. The number of cloud condensation nuclei (CCN) in polluted regions is sufficient; hence, the additional anthropogenic aerosols acting as CCN lead to saturation and act as a direct effect. However, the mechanism of dimming and brightening is not fully understood. For example, GCM simulations have not succeeded in quantitatively reproducing the dimming and brightening trend (Wild and Schmucki 2011).

In this review, an assessment of the data quality of pyranometer measurements is made in Section 2. Sections 3 and 4 provide estimates of the surface shortwave irradiance based on parameterization and satellite observations. After these technical sections, the long-term trends and inter-annual variations in the downward shortwave irradiance at the surface are reviewed and discussed for China and Japan.

2. Pyranometer and pyrheliometer measurements

2.1 Instruments

The instrument that has most commonly been used to measure the surface shortwave irradiance, including direct and diffuse radiation, is the pyranometer. Pyranometers are based on the principle of thermopiles, wherein changes in radiant energy are converted into changes in the temperature difference between the detector and a heat sink. The response time is generally in the order of several seconds. Pyranometer evaluation methods were established around the middle 1970s, at the latest (e.g., Thekaekara 1976). A pyranometer directly measures the incident radiation from a 2π hemispherical solid angle, i.e., the irradiance on a horizontal plane. The irradiance \( S_\lambda \) at wavelength \( \lambda \) can be calculated using

\[
S_\lambda = \int_{0}^{2\pi} \int_{0}^{\pi} I_\lambda(\mu, \varphi) \mu \, d\mu \, d\varphi,
\]

where \( I_\lambda \) is the radiance at \( \lambda \), \( \mu \) is the cosine of the zenith angle \( \theta \), and \( \varphi \) is the azimuthal angle. The total energy of shortwave irradiance \( S \) is obtained by integrating \( S_\lambda \) over the whole wavelength range of the solar radiation spectrum. A glass dome covers the detector for protection; hence, the actual spectral range of the pyranometer does not cover the true solar spectrum. For example, the World Meteorological Organization (WMO) first-class standard pyranometer, CM-22, (Kipp & Zonen Co., Delft, the Netherlands) covers a spectral range of 200–3600 nm, while the second-class standard pyranometer, CM-21, only covers a range of 310–2800 nm. The spectral ranges of the CM-22 and CM-21 correspond to 98.7 % and 95.8 % of the total solar spectrum, respectively (Thekaekara 1976).

As mentioned above, a pyranometer uses a thermopile so that the response time is not too short. The surface of the detector is expected to have 100 % absorption for any wavelength of radiation; however, it is quite difficult to achieve this expected value. In addition, the detector absorption property must be independent of the incident angle of radiation. Performing measurements for the whole incident angle range from 0° to 90° is also difficult. This uncertainty due to the incident angle is referred to as the cosine response error and can exceed several percent at incident zenith angles larger than 70° in the pyranometers used in recent decades (Nast 1983). These errors need to be taken into account for...
obtaining accurate measurements of the total shortwave irradiance. The direct component of the shortwave irradiance is affected by the cosine response error more than the diffuse component. To avoid this issue, it is recommended that the direct and diffuse components of the shortwave irradiance be independently measured by using a pyrheliometer and by shading the pyranometer from direct radiation, respectively. The direct component of the shortwave irradiance is much larger than the diffuse component under clear sky conditions; thus, accurate measurement of the direct solar radiation reduces the error in global shortwave irradiance estimations. The BSRN program has been conducting these operations since the 1990s (Ohmura et al. 1998). However, most of the long records of shortwave irradiance measurements at meteorological observatories have been obtained using single pyranometers, which have been employed to measure combinations of direct and diffuse radiation.

2.2 Calibration and accuracy

Pyranometer calibration at a meteorological observatory is generally performed by comparison with a reference pyranometer, which in turn is calibrated using a pyrheliometer. The pyrheliometer is absolutely calibrated by comparison with reference active cavity radiometers at the World Radiation Center (WRC), Davos, Switzerland. It has been reported that several of the WRC reference active cavity radiometers are quite stable, with variabilities of 0.002 % for the past three decades (WRC 2010). It is referred to as the World Radiometric Reference (WRR). Most pyrheliometers that are used for calibration worldwide are compared with the standard WRC instrument and can then be used for pyranometer calibration. The accuracy of the total shortwave irradiance measured using a pyranometer was estimated to be 15 W m$^{-2}$ even for the uppermost value of measurements with high solar elevation under the clear sky condition in 1991, while the accuracy of measurements performed using a pyrheliometer and a pyranometer with a shading disc in the BSRN is now within 5 W m$^{-2}$ or 2 % (McArthur 2005).

To analyze long-term trends, radiation reference traces are important. Two pyrheliometer measurement references existed: the Ångström scale and the Smithsonian scale. In 1956, WMO unified these two scales into International Pyrheliometer Scale 1956 (IPS-1956). The Japan Meteorological Agency (JMA) referred to the Smithsonian scale before 1957 and changed its reference to IPS-1956. Direct component of the shortwave irradiance obtained by a pyranometer was calibrated by a pyrheliometer using IPS-1956. Since 1981, JMA has been using the WRR. When JMA changed its reference to WRR from IPS-1956, inter-comparison was performed, and the old data were adjusted to the WRR scale with a correction factor of 1.022, while the factor recommended by WMO is 1.026 (WMO 2008).

In Japan, JMA has played the role of Regional Radiation Center since 1965. The JMA standard pyrheliometer is compared with the WRC standard radiometers every five years. Pyranometers are calibrated with the JMA standard pyrheliometer using a shadowing disc, which obstructs direct solar radiation. For long-term analysis of the surface shortwave irradiance, the pyranometer accuracy is estimated to be comparable to the above standard. Furthermore, five observatories in the JMA network have been designated as the BSRN sites: Tateno, Sapporo, Fukuoka, Ishigakijima, and Minanitorishima.

The pyranometers used in China are calibrated at least once per month at the stations with reference instruments. Reference radiometer calibration is performed against the regional reference instrument, which in turn is calibrated every two years against the Chinese reference instrument. The pyrheliometers are regularly calibrated against reference pyrheliometers at the Regional Radiation Center in Tokyo, Japan, or Pune, India. The pyranometers and pyrheliometers used for measurements in China changed in 1990. Before 1990, the instruments used to measure solar irradiance in China were modeled on those used in the former Soviet Union. After 1990, instruments manufactured in China replaced the old instruments. It is inferred that the errors in the solar irradiance measurements performed before 1990 do not exceed 5 % and 3 % for pyranometers and pyrheliometers, respectively. After 1990, the errors associated with the pyranometers and pyrheliometers do not exceed 5 % and 2%, respectively (Shi et al. 2008).

2.3 Operation

Most pyranometers and pyrheliometers are operated at meteorological observatories around the world, where technicians maintain the instruments. Pyranometers are generally fixed with level adjustment, and it is currently recommended to clean their glass dome covers once a day (WMO 2008). Pyrheliometer used to require manual operation to track the sun, but this process is now automatically performed by sun-tracking systems. Pyranometer can be operated in any weather conditions, though these conditions
should be taken into account.

We performed simple experiments to determine the influence of precipitation on the surface shortwave irradiance on November 11, November 30, and December 21, 2012. A CM-22 pyranometer (Kipp & Zonen Co.) was operated on the top of a 12-floor building at the Graduate School of Science, Tohoku University, Sendai, Japan. An artificial rain shower was provided several times each day under overcast sky conditions. Figure 1 shows a time series of the downward shortwave irradiance on December 21, 2011. After three days of experiments, no remarkable biases due to the artificial rain showers were found. It is likely that snowfall and snow cover have significant effects on downward shortwave irradiance measurements, although we did not investigate these effects. Therefore, it should be noted that winter pyranometer data obtained in regions where snow falls are common may contain large uncertainties.

3. Parameterization with sunshine duration data

3.1 Parameterization method

The downward shortwave irradiance at the surface can be estimated using a parameterization formula with other climatic or meteorological parameters, such as sunshine duration, cloud cover, atmospheric turbidity, humidity, and temperature (e.g., Yang et al. 2006; Miller et al. 2008; Xu et al. 2011). The parameterization method can easily be used to estimate the shortwave irradiance without pyranometer measurements; thus, it is used in various research fields, such as agriculture and ecology, as well as in the solar energy industry (e.g., Bakirci 2009; Matzarakis et al. 2010). Meteorological data, including sunshine duration data, have been measured at many observatories for more than 100 years, which is much longer than the period during which direct shortwave irradiance measurements have been made using pyranometers. Shortwave irradiance used to be estimated by parameterization under clear sky conditions more than half a century ago at the latest (Houghton 1954). Using Houghton’s parameterization, Davies et al. (1975) reported that the uncertainty in the daily shortwave irradiance estimates obtained under a clear sky was at most 27.5 % and was mainly the result of atmospheric turbidity due to dust aerosols. The agreement between parameterization and pyranometer measurements is much better under cloudy sky conditions than under clear sky conditions. The effect of multiple reflections between clouds and the surface is taken into account. Total cloud cover is used and the uncertainty is several percent.

A more sophisticated version of the Davies et al. (1975) method has been used in recent decades. For example, the daily mean surface shortwave irradiance under clear sky conditions can be estimated using the following formulae (Kondo 1994; Xu et al. 2011):
\[
\frac{S}{S_0} = (C_i + 0.7 \times 10^{-m_d}) (1 - i) (1 + j),
\]
where
\[
C_i = 0.21 - 0.2 \beta_{DUST} \quad \text{for} \quad \beta_{DUST} < 0.3,
\]
\[
= 0.15 \quad \text{for} \quad \beta_{DUST} \geq 0.3,
\]
\[
F_i = 0.056 + 0.16 (\beta_{DUST})^{0.5},
\]
\[
i = 0.014 (m_d + 7 + 2 \log_{10} w) \log_{10} w,
\]
\[
j = [0.066 + 0.34 (\beta_{DUST})^{0.5}] (ref - 0.15).
\]

In the above formulae, \( S \) is the daily mean downward shortwave irradiance at the surface, \( S_0 \) is the shortwave irradiance at the TOA, \( \beta_{DUST} \) is the turbidity factor, \( m_d \) is the daily mean optical air mass (equivalent path-length of direct solar radiation in the atmosphere relative to that at solar zenith position), \( w \) is the amount of precipitable water (cm), and \( ref \) is the surface albedo. The amount of precipitable water is generally estimated from the water vapor pressure at the surface.

With respect to cloudy sky conditions, sunshine duration data are generally used in addition to the meteorological data employed to perform estimations under clear sky conditions. In line with the clear sky conditions mentioned above, the daily shortwave irradiance under cloudy sky conditions can be obtained using the following formulae (Kondo 1994; Xu et al. 2011):

\[
\frac{S}{S_0} = a + b \frac{N + \Delta N}{N_0} \quad \text{for} \quad 0 < \frac{N}{N_0} \leq 1,
\]
\[
= c \quad \text{for} \quad \frac{N}{N_0} = 0,
\]
where the coefficients \( a, b, \) and \( c \) are dependent on the surface pressure \( p_s \) as follows:

\[
a = 0.179 + 0.32 \left(1 - \frac{p_s}{1000}\right),
\]
\[
b = 0.55,
\]
\[
c = 0.114 + 0.32 \left(1 - \frac{p_s}{1000}\right).
\]

\( N \) and \( N_0 \) are the observed and possible sunshine durations in hours, respectively. \( \Delta N \) is a supplementary value according to the instrument type and season. \( \Delta N = 0 \sim 1.5 \) (h) for a new solar-cell-type instrument and is not necessary for Jordan-type, rotating-mirror-type, and old solar-cell-type instruments (Kondo et al. 1991). In this regard, because sunshine duration observations are influenced by topography, an adjustment procedure is needed when the absolute value is studied (Xu et al. 2011).

Xu et al. (2011) applied the above parameterization method to the estimation of the shortwave irradiance in China. Shortwave irradiance estimated by the parameterization method was compared with pyranometer observations at Beijing and Lhasa, China. The maximum differences between the parameterization estimations and the observations were less than 10% at Beijing and Lhasa.

3.2 Sunshine duration measurements
Sunshine duration is used not only as a proxy for cloud cover, but also to provide information on the irradiance due to direct solar radiation. The observation of sunshine duration has a long history. It started in Tokyo and Osaka, Japan in 1890, whereas shortwave irradiance observations using pyranometers started in 1957. Jordan-type sunshine recorders were used in Japan and China until the 1970s. Since then, sunshine observations have been recorded by electric instruments with photo sensors or solar cells. In 2003, the WMO defined sunshine duration as the period during which direct solar radiation exceeds a threshold value of 120 W m\(^{-2}\) (WMO 2003). This threshold value was developed for clear sky conditions with light and moderately turbid atmospheres.

In most cities of China, 120 W m\(^{-2}\) may be too large because of heavy air pollution. Direct solar radiation is less than 120 W m\(^{-2}\) even under clear sky conditions. It has been shown that sunshine duration has decreased over the period 1954–1998 in China (Kaiser and Qian 2002), although cloud cover also decreased over a similar period, 1951–1994 (Kaiser 1998). The cloud cover trend is not consistent with the sunshine duration trend because sunshine duration is a proxy for cloud cover. The direct solar radiation at low solar elevation angles is likely to be less than 120 W m\(^{-2}\), and an increase in aerosol optical thickness caused a decrease in sunshine duration over this period.

4. Estimation of surface shortwave irradiance from satellite measurements
Satellite remote sensing has been used to estimate the surface shortwave irradiance. In the early days of satellite observations, a statistical method was used that correlated the downward shortwave irradiance at the surface with the reflected radiance measured from space. Following progress in radiative transfer theory and computer facilities, a physical method was later developed using cloud and meteorological data.
Fritz et al. (1964) were the first to show the quantitative relation between the downward shortwave irradiance at the surface and the reflected irradiance at the TOA observed by satellites. They found a correlation coefficient of −0.9 between the albedo at the TOA measured by TIROS-III radiometer channel 3 (0.2–6 μm) and the atmospheric transmittance obtained by surface pyrheliometer measurements (here, “pyrheliometer” refers to a pyranometer). The albedo was obtained from the radiance with a full view angle of 5° by applying an isotropic scattering assumption. By using a large field-of-view radiometer on board the TIROS-IV satellite, Hanson et al. (1967) estimated the downward shortwave irradiance. Since then, satellite radiance data have been used to estimate downward shortwave irradiance at the surface by applying statistical methods (Schmetz 1989; Pinker et al. 1995, and references therein). Recently, a much-improved and more sophisticated method of obtaining the downward shortwave irradiance based on radiation measurements at the TOA has been applied to Clouds and the Earth’s Radiant Energy System (CERES) data. The algorithms for obtaining the downward shortwave irradiance at the surface from CERES can be classified as methods to relate CERES TOA radiative fluxes to the surface irradiance directly and methods based on the best information on cloud, surface, and atmosphere properties, which are used to calculate the surface irradiance, while constraining the radiative model solution to agree with CERES TOA flux observations (Wielicki et al. 1998).

Following the development of radiative transfer theory and computer facilities, physical methods have been developed. Cloud data obtained from satellite remote sensing as well as other meteorological data are used to calculate the radiation at the earth’s surface. With the development of radiative transfer code for plane parallel atmospheres, it has become possible to calculate the surface shortwave irradiance using cloud data obtained by satellite remote sensing. Geostationary meteorological satellites have radiometers with visible and infrared channels, which provide cloud information with high temporal resolution, although the observed areas are limited according to the satellites’ positions. Lu et al. (2010) estimated the surface shortwave irradiance over China using a lookup table approach from the TOA reflectance of the visible channel. Comparison between satellite retrieval and ground-based observations showed that the mean bias and root-mean-square error were 0.6 % and 17.7 %, respectively, for daily data under all sky conditions. Differences between types of aerosols can result in large errors in surface shortwave irradiance estimates. The three-dimensional radiative effects of clouds also cause large errors in the retrieval of surface shortwave irradiance using satellite data, particularly for hourly retrievals. Deneke et al. (2008) also compared the surface shortwave irradiance in the Netherlands estimated from satellite observations with ground-based pyranometer observations. The comparison indicated that the hourly, daily, and monthly root-mean-square errors were 17.0 %, 10.8 %, and 4.2 %, respectively.

Long-term, quality-controlled cloud and meteorological data are required to assess the long-term variation in the surface shortwave irradiance. The ISCCP commenced in 1983 to provide quality-controlled homogeneous cloud data using visible and infrared radiometer measurements onboard polar orbital and geostationary meteorological satellites. The instruments included the Advanced Very High Resolution Radiometer/National Oceanic and Atmospheric Administration (AVHRR/NOAA) and the Visible and Infrared Spin-Scan Radiometer/Geostationary Meteorological Satellite (VISSR/GMS; Rossow and Schiffer 1999). We provide two shortwave irradiance analyses based on ISCCP data in the following section: ISCCP-FD and GEWEX-SRB data.

4.1 ISCCP-FD

The ISCCP provides various products, not only for cloud properties, such as cloud cover, cloud top height, and cloud optical thickness, but also those derived from cloud data, i.e., radiative properties in atmosphere–surface systems. Cloud data from the ISCCP D1 and D2 datasets, as well as ancillary meteorological datasets, were applied to the radiative transfer code of the NASA Goddard Institute for Space Studies General Circulation Model (GISS GCM) to produce the radiation dataset ISCCP-FD (Zhang et al. 1995, 2004). The ISCCP-FD data included both shortwave and longwave radiative irradiances at the surface and the TOA, with a spatial resolution of 280 km × 280 km and an original temporal resolution of 3 h.

The performance of the ISCCP-FD data was evaluated by comparing it with surface pyranometer observations. Monthly average values of the shortwave irradiance were usually used. The uncertainty of the monthly average shortwave irradiance at the surface of the ISCCP-FD was previously estimated to be 10–15 W m\(^{-2}\) from a comparison with BSRN observations (Zhang et al. 2004). A comparison with
monthly averaged pyranometer measurements in China also showed that the ISCCP-FD data tended to overestimate the downward shortwave irradiance at the surface, particularly in urban areas, by 16–17 W m$^{-2}$ (Hayasaka et al. 2006). The reason for the overestimation was attributed to the aerosol model used in the radiative transfer calculation to produce the ISCCP-FD data. These data were based on the monthly mean climatology of aerosol vertical profiles, with 18 different size and composition combinations, as in the GISS GCM (Hansen et al. 2002). This aerosol model was not consistent with that present in China. Zhang et al. (2010) compared the diurnal variation in the shortwave irradiance between the ISCCP-FD data and surface measurements, such as BSRN, Atmospheric Radiation Measurements (ARM: Ackerman and Stokes 2003), and the Surface Radiation Budget Network (SURFRAD: Augustine et al. 2008), and suggested that the climatological aerosols were not consistent with those in the surface observations.

4.2 GEWEX-SRB

The GEWEX-SRB products are provided by NASA Langley Research Center (Stackhouse et al. 2004). The spatial and temporal resolutions are $1^\circ \times 1^\circ$ and 3 h, respectively. These products are computed using an algorithm based on Pinker and Laszlo (1992). The algorithm estimates the downward shortwave irradiance at the surface from the reflected shortwave irradiance at the TOA. The reflected irradiance is obtained from the relation between the narrow-band radiance and the broadband irradiance. The surface shortwave irradiance is obtained on the basis of the cloud fraction, atmospheric composition, and background aerosol and assumes a surface spectral albedo shape, with cloudy and clear sky radiances at the TOA acting as constraints. The ISCCP DX dataset (Rossow and Schiffer 1999) was used to obtain cloud properties.

The GEWEX-SRB monthly averaged shortwave irradiance data were evaluated using the geographically corresponding GEBA and BSRN data (Hinkelman et al. 2009). It has been suggested that the quality of the GEWEX-SRB data depends on the region investigated. It has been shown that the GEWEX-SRB data are consistent with both the GEBA and BSRN datasets, with a bias of less than 10 W m$^{-2}$, except in the polar regions, while the standard deviation is larger than 20 W m$^{-2}$. A comparison of the GEWEX-SRB data with surface pyranometer measurements in China suggested that the bias of the GEWEX-SRB data is 8–9 W m$^{-2}$, which is smaller than that of the ISCCP-FD data (Hayasaka et al. 2006), although the version of the dataset is different from that used by Hinkelman et al. (2009). Because GEWEX-SRB uses ISCCP reflected radiance at visible wavelengths, the calibration of the radiometer on board the satellite is also taken into account. The ISCCP uses an afternoon polar orbital NOAA series satellite as a calibration reference for the other polar orbital satellites and geostationary satellites. The dates of transition from one reference satellite to the next cause small discontinuities in the SRB products, particularly in areas with high surface albedos, such as the polar regions.

4.3 Assessment of ISCCP-FD and GEWEX-SRB datasets

With respect to the evaluation of the long-term trend in surface shortwave irradiance, it has been reported that an artificial edge effect in the view from geostationary satellites affects the estimation of cloud cover (Evan et al. 2007). Although a decreasing trend in global cloud cover has been observed from ISCCP data, it has been shown that the viewing edge of the observation area of a geostationary satellite artificially causes a decreasing trend. According to an analysis by Evan et al. (2007), ISCCP cloud cover data for China and Japan are not influenced by this effect. Doelling et al. (2013) also pointed out calibration issues of a geostationary satellite Multi-functional Transport Satellite (MTSAT) for 2005–2010. Although MTSAT-1R overestimates dark scenes that neighbor very bright clouds, the influence on the ISCCP data is not obvious. Moreover, in general, cloud inhomogeneity (3D) radiative effects and multi-layer vertical profile of cloud cause uncertainties in cloud retrieval and calculation of shortwave irradiance.

Raschke et al. (2006) compared the ISCCP-FD and GEWEX-SRB zonal average monthly data and showed that the difference between the surface shortwave irradiances in the two datasets was more than 40 W m$^{-2}$, particularly in relatively high-latitude regions. The difference was attributed to various complex factors, for example, solar insolation at the TOA, daylight period due to the lowest sun angle above the horizon, and ancillary meteorological dataset. Raschke et al. (2006) also suggested that cloud data used in the ISCCP-FD appeared to represent optically thinner clouds than those in the GEWEX-SRB, although both datasets use cloud characteristics provided by the ISCCP. As a result, the difference between the two datasets was $-6.3 \pm 7.5$ W m$^{-2}$.
for 60°S–60°N; therefore, these datasets seem to have sufficient accuracy for studies of the long-term surface shortwave irradiance trends in China and Japan.

5. Inter-annual variation in downward shortwave irradiance in China and Japan

A decreasing trend in the downward shortwave irradiance in Europe was reported for the first time by Ohmura and Lang (1989), and since then numerous papers have been published reporting the long-term variation. Studies in the East Asia region have been conducted following the studies in other regions of the world. Some of these studies, showing linear trends in the shortwave irradiance in China and Japan, are summarized in Table 1. Because these studies have generally been based on the same data obtained by the Chinese Meteorological Administration (CMA) and JMA, the differences are ascribed to quality control, analysis period, and the numbers of observation sites used for analysis. For example, quality assessment was conducted for the daily pyranometer data by Shi et al. (2008), based on Ohmura et al. (1989) and Younes et al. (2004). Many studies may not have considered quality control assessment. Nevertheless, the trends of the downward shortwave irradiance shown in Table 1 are similar to each other, indicating decreasing trends before 1990, which then changed to increasing trends in both China and Japan. Figure 2 is based on several studies and shows the long-term variations in the surface shortwave irradiance averaged over China and Japan, respectively. Figure 2 indicates that a recovery in the shortwave irradiance occurred earlier in Japan than in China. The decreasing trend changed around 1990 in China, while the long-term trend was not evident during the 1970s and 1980s in Japan. The details of the long-term trends and inter-annual variations in China and Japan are discussed in the following sections.

5.1 China
a. Observed downward shortwave irradiance in China

In China, observations of solar radiation by the CMA began in 1957 (i.e., the IGY) at 122 sites; both the global and diffuse irradiances were measured at 78 stations, and only the global irradiance was measured at 44 stations. The daily radiation data were digitized, the long-term variation in the downward shortwave irradiance was analyzed, and the dimming and brightening phenomenon was found across almost all of China. Liang and Xia (2005) observed a decreasing trend in the shortwave irradiance from the 1960s until around 1990 using pyranometer measurements at 42 first-class stations, where standardized calibration and careful maintenance are undertaken regularly. Che et al. (2005) and Shi et al. (2008) also reported that downward shortwave irradiance decreased from 1961 to around 1990, but then began to increase in most regions of China. Although both studies used the same data, Shi et al. (2008) conducted a data quality assessment based on GEBA (Ohmura et al. 1989; Younes et al. 2004), while Che et al. (2005) did not check the data quality. They used three criteria for quality assessment; (1) physical correctness, (2) consistency with sunshine duration data, and (3) climatological consistency with individual latitudes. According to Shi et al. (2008), the quality of the shortwave irradiance data provided by the CMA is sufficient for long-term trend analysis, except at a few stations on the Tibetan Plateau.

Additional quality assessment was performed for the same dataset by Tang et al. (2010, 2011). It has been reported that there were some discontinuities in the shortwave irradiance data around 1993, due to the replacement of instruments, so the quality of some data may not be sufficient for long-term analysis (Tan et al. 2010). Wang et al. (2012) also reported this discontinuity from a comparison of pyranometer measurements and sunshine duration measurements. However, they concluded that only a small number of sites were affected by the replacement and that most of the pyranometer measurements were consistent with the sunshine duration measurements before 1990 and after 1993.

As an alternative to pyranometer measurements, Tang et al. (2011) developed an artificial neural network (ANN) model using meteorological data for 71 stations and a hybrid method based on sunshine duration data and meteorological data at 459 stations. The results indicated that the mean shortwave irradiance decreased for the period 1961–1989 and leveled off after 1990. The linear trends in the shortwave irradiances obtained by the ANN model and the hybrid method for 1961–2000 were smaller than the direct measurements performed using pyranometers. Nevertheless, the studies referred to above consistently show that the downward shortwave irradiance decreased from 1961 until 1990 and then increased or leveled off in most regions of China. The above-mentioned decreasing trend in the shortwave irradiance until 1990 is also consistent with a reported decreasing trend in pan evaporation, which indirectly supports the decreasing trend in the shortwave irradi-
There have been several studies of the shortwave irradiance trend in China, although the geographical areas analyzed have been limited. For example, Ohmura (2006) showed that there was a nearly linear decrease in the shortwave irradiance in the northwest region of China for 1961–2000, while in the southeast region of China the decreasing trend became an increasing trend after the late 1980s. In the northwest region, Zhou (2011) analyzed pyranometer data for 1961–2000 that were obtained from 16 CMA sites, taking into account seasonal changes. In all seasons, the surface shortwave irradiance initially decreased, but then began to increase around the late 1980s, with a decrease again around 2000, although the inter-annual variations differed between the seasons. Zhang et al. (2004) also reported a decreasing trend from the 1960s until the 1980s at Shanghai, Nanjing, and Hangzhou in the southeast region of China. At these three stations, the decreasing trends appeared to level off around 1980, which is earlier than reported elsewhere in China (e.g., Shi et al. 2008). They suggested that the shortwave irradiance trends observed at these stations were affected by the rapidly increasing levels of air pollution. Therefore, the periods of decrease and increase in the shortwave irradiance might differ among regions because their meteorological and air pollution conditions differ.

Stanhill and Kalma (1995) revealed a large decrease in the shortwave irradiance in Hong Kong. Hong Kong is one of the most polluted areas, and urbanization appears to affect changes in irradiance. Because many of the meteorological observatories in China are located in cities, it has been considered that the decreasing trend in the shortwave irradiance might reflect local air pollution (Wang et al. 2011). Satellite observations of aerosols over China show the influence of urbanization around mega-cities and industrial areas, with these observations suggesting that the spatial distributions of aerosols are wider than just cities and industrial regions. Surface observations of aerosols are also consistent with satellite observations.

Table 1. Summary of long-term trends in surface shortwave irradiance in China and Japan.

<table>
<thead>
<tr>
<th>Region</th>
<th>Data</th>
<th>Period</th>
<th>Number of Sites</th>
<th>Absolute Trend (W m⁻² decade⁻¹)</th>
<th>Relative Trend (%) decade⁻¹</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Pyranometer</td>
<td>1961–2000</td>
<td>64</td>
<td>−4.5</td>
<td>−3</td>
<td>Che et al. [2005]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1960–2000</td>
<td>42</td>
<td>−4.9</td>
<td>−3.3</td>
<td>Liang and Xia [2005]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1961–2000</td>
<td>57</td>
<td>−3.2</td>
<td>−2.1</td>
<td>Qian et al. [2007]</td>
<td>Clear sky only</td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1961–2000</td>
<td>72</td>
<td>−3.8</td>
<td>−2.54</td>
<td>Shi et al. [2008]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1961–1989</td>
<td>72</td>
<td>−7</td>
<td>−4.61</td>
<td>Shi et al. [2008]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1990–2000</td>
<td>72</td>
<td>2.7</td>
<td>1.76</td>
<td>Shi et al. [2008]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1984–1994</td>
<td>42</td>
<td>9.64</td>
<td>6</td>
<td>Wu and Fu [2011]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ANN</td>
<td>1961–2000</td>
<td>71</td>
<td>−2.1</td>
<td>−1.3</td>
<td>Tang et al. [2011]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hybrid</td>
<td>1961–2000</td>
<td>72</td>
<td>−2.1</td>
<td>−1.3</td>
<td>Tang et al. [2011]</td>
<td>Hybrid method with sunshine duration</td>
</tr>
<tr>
<td></td>
<td>Hybrid</td>
<td>1961–2000</td>
<td>459</td>
<td>−2.3</td>
<td>−1.4</td>
<td>Tang et al. [2011]</td>
<td>Hybrid method with sunshine duration</td>
</tr>
<tr>
<td></td>
<td>Hybrid</td>
<td>1961–1989</td>
<td>459</td>
<td>−2.5</td>
<td>−1.5</td>
<td>Tang et al. [2011]</td>
<td>Hybrid method with sunshine duration</td>
</tr>
<tr>
<td></td>
<td>Hybrid</td>
<td>1990–2006</td>
<td>459</td>
<td>0.4</td>
<td>0.2</td>
<td>Tang et al. [2011]</td>
<td>Hybrid method with sunshine duration</td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1961–2009</td>
<td>57</td>
<td>−1.67</td>
<td>−2.8</td>
<td>Ohmura [2006]</td>
<td></td>
</tr>
<tr>
<td>Southeast China</td>
<td>Pyranometer</td>
<td>1961–1989</td>
<td>6</td>
<td>−12</td>
<td>−7.7</td>
<td>Ohmura [2006]</td>
<td></td>
</tr>
<tr>
<td>Northwest China</td>
<td>Pyranometer</td>
<td>1961–2000</td>
<td>7</td>
<td>−5</td>
<td>−2.8</td>
<td>Ohmura [2006]</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Pyranometer</td>
<td>1961–1990</td>
<td>26</td>
<td>−8</td>
<td>−5</td>
<td>Ohmura [2006]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1990–2002</td>
<td>26</td>
<td>8</td>
<td>5</td>
<td>Ohmura [2006]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1971–1989</td>
<td>86</td>
<td>−1.3</td>
<td>−0.8</td>
<td>Norris and Wild [2009]</td>
<td>CCRE</td>
</tr>
<tr>
<td></td>
<td>Pyranometer</td>
<td>1974–2006</td>
<td>53</td>
<td>2.2</td>
<td></td>
<td>Tsutsumi and Murakami [2012]</td>
<td></td>
</tr>
</tbody>
</table>
Wang et al. (2011) divided the whole of China into eight climatic regions, i.e., the Western arid/semi-arid regions, Tibetan Plateau, Eastern arid regions, Southwest China, North China, Central China, South China, and Northeast China. Three or four stations were selected in each region, and 40 stations in total were used for long-term trend analysis. During the period from 1961 until 1990, the shortwave irradiance decreased in most regions, except for during the 1960s–1970s on the Tibetan Plateau. The shortwave irradiance on the Tibetan Plateau began to decrease during the 1970s and intensified in the 1980s, before suddenly recovering since around 1990. However, Shi et al. (2008) pointed out that the shortwave irradiance data for Lhasa on the Tibetan Plateau were considered to be erroneous around the period 1988–1991. Wang et al. (2011) also analyzed data for the four seasons and revealed that the seasonal trends in the shortwave irradiance had large spatial variations.

Pyranometer measurements from 1961 until 2005 at 45 stations were also analyzed by dividing all of China into four regions (Xia 2010). The annual average data showed a decreasing trend until 1990, before beginning to increase in all of the regions. In the northeast and northwest regions, the increasing trends changed again to decreases around 1993, while the increasing trends continued in the southeast and southwest regions. As reported by Tang et al. (2010) and Wang et al. (2012), errors may have occurred at some of the stations when the instruments were replaced. Nevertheless, it is clear that a decreasing trend occurred in northern China and an increasing trend occurred in southern China over the period from 1993 until 2005.

The surface measurements of the downward shortwave irradiance at 42 stations for 1984–2004 were compared with the GEWEX-SRB dataset (Wu and Fu 2011). It was found that the GEWEX-SRB dataset tended to overestimate the shortwave irradiance over China by an average of 14.6 W m\(^{-2}\). This result is consistent with that of a similar study by Hayasaka et al. (2006), in which the difference between surface measurements and the GEWEX-SRB dataset was quantitatively attributed to absorbing aerosols in the sub-cloud layer. With respect to the long-term trend in shortwave irradiance, Wu and Fu (2011) indicated that positive trends were observed at 30 surface-measurement stations, while negative trends were observed at 12 stations during the period. The GEWEX-SRB data corresponding to surface-measurement stations showed positive trends at seven stations and negative

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**Fig. 2.** Examples of long-term variations in surface shortwave irradiance in China and Japan. Two curves in lower graph show differences from average values.
trends at 35 stations. Wu and Fu (2011) also divided the whole area of China into five regions. Positive trends were observed from the surface measurements for the period 1984–1994 in all of the regions, and the largest trend in 14.5 W m$^{-2}$ decade$^{-1}$ was observed in southwest China. Positive trends were observed in most of the regions for the period 1984–1994, which became negative or leveled off after 1994. The largest negative trend of $-7.42$ W m$^{-2}$ decade$^{-1}$ was observed in northern China. On the other hand, the GEWEX-SRB dataset showed negative trends in all of the regions for the period 1984–2004, which is consistent with the results of Tang et al. (2011), in which GEWEX-SRB data corresponding to 592 meteorological stations were analyzed. A large negative trend of $-8.29$ W m$^{-2}$ decade$^{-1}$ was observed, particularly in northern China, for the period 1994–2004, as well as in the surface measurements. Although they divided the period into 1984–1994 and 1994–2004, it can be seen from Fig. 8 of Wu and Fu (2011) that the changes in the trends from negative to positive appeared to occur around 1990–1992 in northwest and southern China. This pattern is consistent with those identified in other studies, and the trends became negative again several years after 1990.

To summarize the long-term variations in the shortwave irradiance in China, linear decreasing trends were observed in almost all of the areas for the period from the 1960s until the 1980s and then became increasing trends around 1990. On the other hand, Gilgen et al. (2009) indicated that the shortwave irradiance linearly decreased in most of China over the period from the early 1960s until 2000. This finding appears to be inconsistent with the results of the studies discussed above, but the inconsistency was probably caused by the analysis method used by Gilgen et al. (2009). A linear formula and a quadratic formula were used to fit the temporal variation in the shortwave irradiance data, but it was concluded that the quadratic formula was not statistically suitable for analyzing the variations in the shortwave irradiance in China. Therefore, it can be concluded that the downward shortwave irradiance decreased linearly until around 1990, after which it began to increase.

b. Factors affecting shortwave irradiance variations in China

There are 78 stations in China that measure both the global and diffuse shortwave irradiances. Accordingly, the direct irradiance has been estimated from the difference between the global and diffuse irradiance values. It should be noted that the above diffuse irradiance measurements might exhibit some errors due to shadowing rings; thus, the direct irradiance measurements also contain some uncertainties. Datasets from 64 stations were used to confirm that a decrease in surface direct shortwave irradiance occurred during the period 1961–1990, while the diffuse shortwave irradiance did not change over the same period (Shi et al. 2008). Using the same data at 36 stations, Wang and Shi (2010) revealed an increase in the levels of atmospheric aerosols over the period 1957–2007 based on an analysis of the global and diffuse shortwave irradiances under clear sky conditions, although the absorbing optical thickness of aerosols could not be separated from the total absorbing optical thickness, which included gaseous absorption. Both the scattering and absorbing optical thicknesses of the clear sky atmosphere leveled off in the early 1990s after the increases in optical thicknesses observed since 1957. Qian et al. (2007) analyzed the shortwave irradiance data for only days with a clear sky and concluded that an increase in the aerosol loading from anthropogenic emissions of pollutants was responsible for the observed decrease in the shortwave irradiance and the increase in the diffuse radiation during the period with a decreasing trend. They suggested that the single scattering albedo was rather small during the period from the 1950s until the 1980s and then increased due to an increase in SO$_2$ emissions. The effect of aerosols under cloudy sky conditions has not been ignored. It was shown by Hayasaka et al. (2006) that absorbing aerosols in the sub-cloud layer also cause direct radiative forcing at the surface, even under overcast conditions, because the visible radiation is transmitted through the cloud. Moreover, the absorbing aerosols in the cloud layer also affect the shortwave irradiance at the surface.

The effect of aerosols on the shortwave irradiance trend in China was discussed by Streets et al. (2008) from another point of view, in which the emission of aerosols was estimated to be at a maximum around 1995 using an emission inventory developed with a bottom-up approach. The year with the maximum emission differed from that with the minimum shortwave irradiance, which occurred around 1990 according to pyranometer observations. Streets et al. (2008) also showed that the contribution of black carbon to total aerosol optical thickness was not as large as expected by direct and diffuse radiation measurements. On the other hand, the same approach for estimating the emission of black carbon in China was taken by Ohara et al. (2007), who showed that the emission of black carbon in China leveled off around
Cloud properties as well as anthropogenic aerosol factors have been discussed with regard to the causes of long-term trends in the downward shortwave irradiance in China. From the studies discussed above, it appears that the shortwave irradiance had been decreasing for about three decades before 1990. Cloud cover and sunshine duration observations made from the surface have been analyzed for the period corresponding to the period with decreasing shortwave irradiance (Kaiser 1998; Kaiser and Qian 2002; Qian et al. 2006). During the period from the 1950s until the 1990s, the cloud cover decreased despite decreases in the shortwave irradiance and sunshine duration. Warren et al. (2007) reported that the cloud cover decreased over land surfaces in the period 1971–1996 based on visual observations made from the surface. In China, the annual average cloud cover during daytime decreased by 1.4 % decade\(^{-1}\) and 0.6 % decade\(^{-1}\) in the north and south, respectively. In the summer, high cloud cover decreased by 8 % decade\(^{-1}\) at most, and a major contributor to the negative trend is cirrus clouds. This cloud cover decrease was indirectly supported by decreases in the annual numbers of rainy days recorded at 192 meteorological stations (Liang and Xia 2005). The inconsistency between the sunshine duration and cloud cover trends could be attributable to an increase in aerosol loading, because the direct solar radiation at low elevation angles did not exceed the criterion of 120 W m\(^{-2}\) perpendicular to the surfaces of the instruments’ detectors under heavy aerosol loading conditions; thus, some sunshine duration times were not recorded. A large increase in anthropogenic aerosol loading would overcome the effect of the decrease in cloud cover on shortwave irradiance. Xia (2010) also showed an inconsistency in the long-term shortwave irradiance and cloud cover trends in China, although the inter-annual variations in the shortwave irradiance appeared to correspond to those of the total cloud cover. Zhou (2011) analyzed the relation between the shortwave irradiance and cloud cover, although the area studied was limited to northwest China. The author claimed that the increase in low-cloud cover was consistent with the decrease in the shortwave irradiance in the spring and summer, but the relationship between the low-cloud cover and the shortwave irradiance was not true in the autumn and winter. However, the consistency between the shortwave irradiance and low-cloud cover over the long term was not obvious in Zhou (2011), although a negative correlation was found in the inter-annual variations.

The sensitivity of the shortwave irradiance to cloud cover is related to the cloud optical thickness. The sensitivity is large for large cloud optical thickness, and vice versa. Hayasaka and Shi (2014) analyzed variations in the surface shortwave irradiance and cloud properties in China by applying linear and multiple regression formulae to pyranometer measurements of the shortwave irradiance and the cloud cover and cloud optical thickness data from the ISCCP. The correlation coefficients of the multiple regression analyses were large in the east and south, but small in the northeast. Positive correlations between the shortwave irradiance, cloud cover, and optical thickness were occasionally obtained from the linear regression analyses. It was suggested that the cloud type and aerosols in clear sky conditions accounted for those unrealistic correlation coefficients. The sensitivity of the surface shortwave irradiance to the cloud cover and cloud optical thickness was analyzed. It was shown from the analysis that the sensitivity depends on the average value of cloud cover and cloud optical thickness. The sensitivity to cloud cover reached a maximum for a cloud optical thickness of around 8, while the sensitivity to cloud optical thickness was large for a small optical thickness and decreased with an increase in optical thickness. Cloud cover estimation by satellite observation is related to a lower limit of cloud optical thickness. For example, global cloud cover is 68 % with a lower limit of cloud optical thickness of 0.1 while it is 73 % when including sub-visible cirrus (Stubenrauch et al. 2013). Missing cloud cover appears to be larger from the traditional visual observations at meteorological observatories than that from satellite observations. Therefore, uncertainties in cloud cover should be noted for the analysis of the relation between the surface shortwave irradiance and cloud cover.

Norris and Wild (2009) also conducted an analysis of the effect of cloud cover on the shortwave irradiance. They used Geba radiation data and synoptic observation data for cloud cover obtained at domestic meteorological observatories as well as ISCCP cloud data. It was suggested from this analysis that the decreasing trend in the shortwave irradiance in China from 1971 until 1989 was mainly caused by anthropogenic aerosols and the increasing trend from 1990 until 2002 was attributed to changes in both cloud cover and aerosol loading. These results are consistent with those of Wang and Shi (2010) and Qian et al. (2006) with regard to the importance of the effect of anthropogenic aerosols on the shortwave irradiance under clear sky conditions. The direct effect
of aerosol loading in the sub-cloud layer cannot be ignored if the aerosols have strong absorption properties (Hayasaka et al. 2006). Wang et al. (2011) claimed that the recovery of the shortwave irradiance after the 1990s was due to a change in cirrus and cirrostratus cloud cover. They also reported that the shortwave irradiance trend was inversely correlated with the surface water vapor concentration. However, the effects of water vapor on the long-term trend in the shortwave irradiance are not evident, even though they are related to day-by-day and short-term variations. Moreover, this variation in water vapor is not consistent with the relation between the shortwave irradiance and pan-evaporation shown by Qian et al. (2006).

5.2 Japan

5.2.1 Observed downward shortwave irradiance in Japan

In Japan, shortwave irradiance observations by JMA began in 1931 in Tokyo using a bimetal sensor. Following the IGY, in 1960 the bimetal pyranometers were replaced by Eppley type pyranometers at Sapporo, Sendai, Tateno, Osaka, and Fukuoka. In 1971, Moll–Gorzynski thermopile pyranometers were installed at 67 stations.

In one of the pioneering studies of global dimming and brightening, Stanhill and Moreshet (1992) showed that shortwave irradiance observed by a pyranometer at several stations in Japan had decreased from 1968 until 1985, i.e., −7.6 % at Sapporo, −15.7 % at Tateno, and −12.7 % at Kagoshima. Ohmura (2006) used JMA pyranometer data at 26 locations to analyze the long-term variations in the shortwave irradiance in Japan. A rapid decreasing trend in the annual mean shortwave irradiance was observed from the 1960s until the early 1990s, when it began to increase. After 1993, it reached a large value, with no obvious trend during the following period. Different datasets of pyranometer measurements at 40 JMA stations were used by Ohmura (2009), with similar long-term variations to those reported by Ohmura (2006), with the exception of a large decrease in the shortwave irradiance in the 1960s. Ohmura (2009) reported that the shortwave irradiance decreased by 20 W m$^{-2}$ from 1960 until the early 1990s, with a decrease of about 15 W m$^{-2}$ observed in the 1960s.

Stanhill and Cohen (2008) linearly related the sunshine duration to the surface shortwave irradiance and indicated an increasing trend in the annual average shortwave irradiance for the period 1890–2002. The shortwave irradiance trend after 1961 shown by Stanhill and Cohen (2008) is not consistent with other results based on pyranometer measurements. They indicated an increasing trend in the shortwave irradiance during the 1960s and 1970s and a large increase in the shortwave irradiance after around 1980. This is not consistent with pyranometer observations (Ohmura 2006, 2009). The instrument used for sunshine duration measurements in Japan was changed from the Jordan type to the rotating mirror type around 1986. Stanhill and Cohen (2008) adjusted the bias that was found between these instruments, and it does not appear to affect the long-term variations in sunshine duration. They discussed the causes of the trend in relation to solar activity by considering sun-spot numbers and aerosols emitted from volcanic eruptions, but neither explained the variation in the shortwave irradiance. An increase in the global mean surface air temperature from the 1920s until the 1940s has been attributed to solar activity (IPCC 2013). However, the effect of changes in solar activity is too small to have caused the magnitude of change (several percent) in the shortwave irradiance shown by Stanhill and Cohen (2008). The effect of volcanic eruptions has also been extensively studied, and it is evident that volcanic eruptions can affect the shortwave irradiance for several years. The heavy volcanic aerosol loading that can affect sunshine duration does not last for more than several months. The effect of volcanic aerosol on shortwave irradiance is not large, although it can have a large effect on direct solar radiation. It is not yet known why the shortwave irradiance obtained from the pyranometer measurements is not consistent with that estimated based on the sunshine duration observations.

Tsutsumi and Murakami (2012) analyzed the surface shortwave irradiance measured with a pyranometer and the cloud cover at 53 JMA stations for the period 1974–2006. They found that the surface shortwave irradiance and cloud cover increased by 2.2 % decade$^{-1}$ and 1.5 % decade$^{-1}$, respectively, over this period. Although this result appears to be inconsistent with that of Ohmura (2006), this difference is attributable to the different analysis periods. In Japan, the decreasing shortwave irradiance trend became an increasing trend around 1990, as it did in other regions of the world. The decreasing trend before 1990 was so small that the trend for the period 1974–2006 became positive.

To summarize for Japan, a decreasing trend in surface shortwave irradiance was clear in the 1960s but was absent or very small for the next two decades and became a positive trend around the early 1990s. This pattern differs from those observed in China,
where clear decreasing trends were observed from the 1960s until the 1990s, as shown in Fig. 2.

b. Factors affecting variation in shortwave irradiance in Japan

Norris and Wild (2009) analyzed the inter-annual variations in the surface shortwave irradiance and their relations to cloud cover in Japan. A strong decline in the shortwave irradiance in Japan was indicated by the GEBA data for the period before the mid-1960s. The shortwave irradiance increased slightly during the 1970s, decreased slightly during the 1980s, and then increased strongly after the early 1990s. The inter-annual variations in the shortwave irradiance have been shown to be consistent between pyranometer observations and the ISCCP-FD data for 1983–2005, although the increasing trend indicated by pyranometer observations is not found in the ISCCP-FD data. The data indicate that changes in cloud cover have influenced the decrease in the shortwave irradiance over the period 1971–1989 in Japan, whereas aerosols did not have any effects during this period. The increase in the shortwave irradiance in 1990–2002 was ascribed to changes in both aerosol loading and cloud cover. Therefore, the attribution of the decreasing trend in Japan differs from that in China based on the same analysis.

Tsutsumi and Murakami (2012) compared the surface shortwave irradiance trend and the variations in the total cloud cover obtained by visual observations. The results showed that both trends were positive for the period 1974–2006. This finding was inconsistent with the general relation between the shortwave irradiance and total cloud cover. They speculated that this inconsistency might be attributable to a change in the frequency of cloud appearance against the solar zenith angle or a change in cloud optical thickness due to the aerosol indirect effect. The cloud type might also affect the results since they used only total cloud amount. Moreover, they indicated that the transparency of a clear sky atmosphere inferred from pyrheliometer observations did not affect the trend in the shortwave irradiance over the period analyzed.

Kudo et al. (2012) analyzed the direct and diffuse radiation under clear sky conditions at 14 stations in Japan to retrieve aerosol optical thickness and the single scattering albedo. They found that the aerosol optical thickness decreased by 0.02 from the late 1970s until the 2000s, while the single-scattering albedo increased by 0.21 during the same period. It was shown that transmission in a clear sky atmosphere increased by 5%, of which 1% was attributed to a decrease in the aerosol optical thickness and 4% was due to an increase in the single-scattering albedo. The diffuse radiation increased according to the increase in the single-scattering albedo of aerosol. They also estimated that the shortwave irradiance trend due to cloud cover resulted from the difference between the surface solar irradiances measured under cloudy sky conditions and clear sky conditions. The results of Tsutsumi and Murakami (2012) and Kudo et al. (2012) may be understood as follows. The increasing shortwave irradiance trend after the late 1970s was attributable to a change in the clear sky atmosphere. Because the single-scattering albedo of aerosol became large, the shortwave irradiance under clear sky conditions, which consists of direct and diffuse radiation, increased. The increase in the shortwave irradiance under clear sky conditions overcame the decrease in the shortwave irradiance under cloudy sky conditions, with an increase in the total cloud cover. It is interesting that this result is the opposite to that found in China, i.e., a decrease in the shortwave irradiance with a decrease in cloud cover.

6. Discussion and summary

6.1 Global dimming and brightening in East Asia

Since the study by Ohmura and Lang (1989) regarding the decreasing trend in the shortwave irradiance in Europe, many studies have been undertaken to investigate the long-term variations in the shortwave irradiance around the world. Stanhill and Moreshet (1992) summarized the long-term trends in the shortwave irradiance in a wide range of regions, and Stanhill and Cohen (2001) reviewed the trends again on the global scale. As a result of these reviews, decreasing trends were identified in many parts of the world, including the Arctic and Antarctic. Stanhill and Cohen (2001) showed that zonal mean values of the shortwave irradiance decreased at all latitudes, but particularly in the mid-latitudes of the Northern Hemisphere from 1958 until 1992, although the numbers of observation sites differed at different latitudes. The concept of global dimming was still not fully accepted two decades ago, because the decreasing trends were quite large and the observation sites were limited to land areas. Since then, many studies have been conducted, and the long-term trends in the shortwave irradiance are now recognized as important topics within the climate research community (Wild 2009). The number of observation sites might change, and the instruments might be replaced by new ones for the past several decades.
Those uncertainty factors might affect the evaluation of the surface shortwave irradiance. Nevertheless, it is worthwhile to study the long-term trends because they are quite important in climate change studies. In a review by Wild (2012), it was shown that the trends in the shortwave irradiance in Japan are in line with those in the United States and Europe over the same period, i.e., decreasing trends in the surface shortwave irradiance were found for the period from the 1950s until the 1980s, and the trends became increases in the period from the 1980s until 2000 and after 2000. On the other hand, the increasing trends changed to decreases in China around 2000. The decreasing trend has continued in India for the past several decades, although the number of observation sites is limited.

Although the details of the inter-annual variations in the shortwave irradiance before 2000 differ between China and Japan, the causes of the variations appear to be similar in these two countries. The most important factors are the direct effects of absorbing aerosols. In the East Asian region, the number of CCN seems to be saturated, so a change in the aerosol concentration would not significantly affect cloud condensation. On the other hand, absorbing aerosols affect the surface shortwave irradiance since they also exist below the cloud layer (Hayasaka et al. 2006), because the scattered visible radiation passes through the cloud layer and the underlying absorbing aerosols reduce the amount of radiation that reaches the surface. Accordingly, decadal variation in absorbing aerosols plays a key role in the shortwave irradiance trends in China and Japan. The importance of absorbing aerosols was also reported by Liepert and Tegen (2002) in a shortwave irradiance trend comparison between the eastern and western United States. For the period 1995–2007, brightening trends were observed at five ARM sites and six SURFRAD sites in the United States (Long et al. 2009). The brightening trends were attributed to a decrease in cloud cover and an increase in scattered radiation under clear sky conditions. Wild (2012) reported the importance of sulfate aerosols but noted that the direct effect of sulfate aerosols on the surface shortwave irradiance is reduced by increased scattered radiation. If sulfate aerosols are added to overcast cloud conditions in which the clouds have moderate and large optical thicknesses, the effect is small because the added sulfate aerosols appear to increase the clouds’ optical thicknesses slightly.

The long-term variations in the shortwave irradiance have now been identified worldwide, even in pristine areas such as the Antarctic and ocean areas far from land, although aspects of the temporal variations and their magnitudes differ among the observation sites or regions. Dutton et al. (1991) reported a 15% decrease in the shortwave irradiance at the South Pole from 1976 until 1987. It has also been reported that decreasing trends of −0.28 W m⁻² yr⁻¹ on average were observed during the period 1957–1994 at 12 Antarctic stations (Stanhill and Cohen 1997). It was suggested that slight variations in cloud cover were not responsible for the decreasing trends, although only five stations reported cloud cover observations. However, in the Antarctic, the effects of cloud cover on the shortwave irradiance are enhanced by the multiple reflections between the snow surface and cloud base (Yamanouchi 1983).

Stanhill and Moreshet (1994) analyzed shortwave irradiance data at seven pristine sites: Resolute A, Canada (74°43’N, 94°59’W); Valentia, Ireland (51°56’N, 10°15’W); Hohenpeissenberg, Germany (47°48’N, 11°01’E); Chichijima, Japan (27°04’N, 142°11’E); Minanotorishima, Japan (24°18’N, 153°58’E); Keetmanshoop, S. Africa (26°53’S, 18°12’W); and Mirny, Antarctica (66°33’N, 93°01’E), all of which are not affected by air pollution. They found decreasing trends from the late 1950s until the early 1990s at all of the sites, although the trend was not conspicuous at Keetmanshoop. The average linear decreasing trends at all of the statistically significant sites (excluding Keetmanshoop) were −0.56 W m⁻² yr⁻¹ and −0.37% yr⁻¹. It was concluded that reductions in the shortwave irradiance occurred in these regions, but that these reductions were not attributable to clouds or anthropogenic aerosols. The decreasing trends obtained in pristine areas, including the Antarctic, are comparable to those observed in China, Japan, and other polluted regions. Regions in which the shortwave irradiance is decreasing are found around the world. Some regions are affected by air pollution, whereas other regions are isolated from the influence of air pollution. Accordingly, it is inferred that the factors affecting the long-term trends in the shortwave irradiance differ between regions.

6.2 Natural and anthropogenic factors affecting shortwave irradiance

Changes in cloud cover are closely related to the surface shortwave irradiance, except for clouds with small optical thicknesses. Eastman and Warren (2013) investigated the global cloud cover trends based on visual observations made at the surface. The total cloud cover averaged over the oceans increased from the latter half of the 1950s until the middle of the
1990s and then began to decrease. These observations are consistent with the decreasing trend in the shortwave irradiance on a global scale. On the other hand, after the decrease in cloud cover in the early 1980s, the trend leveled off until 2009. The average cloud cover trends were not negative in China and South America for the period from 1971 until 2009. Changes in cloud properties are caused not only by anthropogenic factors, but also by natural factors. Eastman and Warren (2013) also reported the importance of the Indian summer monsoon in determining summer cloud cover on a global scale, and stated that it may affect the inter-annual variations in cloud cover and, consequently, the shortwave irradiance. They also indicated that the centers of the cloud cover maxima in the mid-latitude regions of both hemispheres have tended to shift poleward. The relation to El Niño was also analyzed as a potential cause of the inter-annual variations in cloud cover. The results showed that the maximum cloud cover zones have tended to shift equatorward. Although the relations between these large-scale cloud distribution changes and regional cloud cover are uncertain, the shortwave irradiance may be affected in some areas.

Cloud cover is the most important factor affecting the surface shortwave irradiance when compared with clear sky conditions. However, the relative contributions of atmospheric factors to the shortwave irradiance change according to their combination. Kawamoto and Hayasaka (2008) evaluated the sensitivity of the surface shortwave irradiance to clouds, aerosols, and water vapor in East Asia and showed that the shortwave irradiance was affected more by changes in cloud optical thickness in the west of China, where the average cloud optical thickness is relatively small, particularly in the summer, than in other areas with large cloud optical thicknesses. On the other hand, changes in cloud cover affected the shortwave irradiance in southwest China during the summer. The sensitivity to aerosol optical thickness was found to be large in the east of China during the summer.

When we discuss the long-term trend in the shortwave irradiance, natural aerosols, such as volcanic dust, must be considered. The secular variations in the surface shortwave radiation and volcanic aerosol have been discussed in investigations of climate change. Budyko (1969) showed that, based on pyrheliometer measurements, the surface air temperature in the Northern Hemisphere over an 80 year period since the late 19th century was correlated with the amount of direct solar radiation. He suggested that volcanic eruptions have affected the surface shortwave irradiance and, consequently, surface air temperatures. The effects of volcanic aerosols on the direct shortwave radiation at the surface have also been studied using long-term pyrheliometer measurements at 14 JMA observatories, at which the longest data record covers the period 1933–1992, and the effects of the eruptions of Mt. Agung in 1963, Mt. El Chichon in 1982, and Mt. Pinatubo in 1991 on the shortwave radiation were clearly detected (Yamauchi 1995). In an earlier study, the secular variations in the atmospheric turbidity in Japan from around 1950 onward were estimated and related to air pollution, although the influence of stratospheric aerosols due to volcanic eruptions was not discussed (Yamamoto et al. 1971). An effect of the eruption of Mt. Pinatubo on the surface shortwave irradiance was also obtained by ship-borne pyrheliometer measurements in the western Pacific (Hayasaka et al. 1994). The abovementioned influences of volcanic eruptions were found under clear sky, particularly pristine conditions, while their influences were not obvious under all sky conditions with heavy air pollution. It is considered that volcanic eruptions larger than those of Mt. El Chichon and Mt. Pinatubo frequently occurred in the past millennium (IPCC 2007). The effect of each volcanic eruption on the surface shortwave irradiance continues for only three or four years (Shiobara et al. 1991; Hayasaka et al. 1994). However, those large volcanic eruptions may affect the climate via long-term memory in the ocean heat content according to the frequency and scale of eruption (IPCC 2013).

6.3 Summary

Recent studies of the long-term trends and inter-annual variations in the surface shortwave irradiance in China and Japan were reviewed in this paper. Since quality control of the data is important for long-term analysis, we first assessed pyranometer calibration and operation and then reviewed the surface shortwave irradiance. Pyranometer observations have indicated decreases followed by increases in the shortwave irradiance in China and Japan for the period from the 1960s until the 2000s. On the other hand, obvious long-term trends were not found in the surface shortwave irradiance datasets based on satellite observations, although such data were only available after 1983. Sunshine duration is often used as a proxy for the surface shortwave irradiance. However, sunshine duration data may not be sufficient, and their use may lead to errors in the analysis of shortwave irradiance trends when the aerosol loading is quite large. The results presented in this review may be
summarized as follows.

(1) The trends and inter-annual variations in the surface shortwave irradiance differ between China and Japan. In China, the surface shortwave irradiance decreased from 1961 until around 1990 and then began to increase. In Japan, on the other hand, the decreasing trend stopped in the 1960s, and the inter-annual variations were small during the 1970s and 1980s, with an increase beginning around 1990.

(2) The differences between the shortwave irradiance trends in China and Japan are mainly ascribed to an increase in the level of absorbing aerosols in China since the 1960s and a decrease in absorbing aerosols in Japan since the late 1970s. Absorbing aerosols decrease both direct and diffuse radiation, while non-absorbing aerosols decrease direct radiation but increase diffuse radiation. Accordingly, the influence of aerosol loading on the surface shortwave irradiance depends on the aerosol radiative properties. Although these aerosol influences are generally found under clear sky conditions, absorbing aerosol could have a direct effect even under cloudy sky conditions.

(3) The trends in the surface shortwave irradiance in China and Japan are in line with the so-called global dimming and brightening processes, although the phases of the minimum periods differ slightly between regions. It has been suggested that the mechanisms of global dimming and brightening also differ between regions. Increased levels of anthropogenic aerosols influence the shortwave irradiance trends through the direct radiative effect of aerosols in polluted areas, while the indirect radiative effect, i.e., changes in cloud cover due to CCN increases, might be dominant in pristine areas. Cloud cover is inversely correlated with the surface shortwave irradiance in ocean areas, but it is not clear whether anthropogenic aerosols cause changes in cloud cover.

(4) It is quite difficult to distinguish between the natural and anthropogenic causes of shortwave irradiance variations. According to studies of long-term variations in clouds, the natural factors that affect cloud properties in East Asia appear to be small compared to the anthropogenic factors. The factor that has the greatest effect on the shortwave irradiance is cloud cover, but the same changes in cloud properties will not affect the shortwave irradiance to the same extent universally since the average cloud properties differ between regions. Therefore, when evaluating the effects that clouds will have on the shortwave irradiance, it is important to determine the relative contributions of changes in cloud properties such as cloud cover and cloud optical thickness.

(5) Other factors, such as variations in water vapor and natural aerosols, appear to play small roles compared to the effects of clouds and anthropogenic aerosols. Although three large volcanic eruptions have occurred since 1960, they had no obvious effects on the long-term variations in the surface shortwave irradiance.

Acknowledgments

The author would like to thank Prof. G.-Y. Shi, of the Institute of Atmospheric Physics, Chinese Academy of Science; Dr. S. Katagiri and Mr. K. Yamada of the Center for Atmospheric and Oceanic Studies, Tohoku University; and Mr. N. Ohkawara of the Japan Meteorological Agency for their helpful discussions and for preparing figures. The author also appreciates valuable comments by two anonymous reviewers. This paper was much improved through the discussions with them.

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