Data Quality Assessment and the Long-Term Trend of Ground Solar Radiation in China

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ABSTRACT

Solar radiation is one of the most important factors affecting climate and the environment. Routine measurements of irradiance are valuable for climate change research because of long time series and areal coverage. In this study, a set of quality assessment (QA) algorithms is used to test the quality of daily solar global, direct, and diffuse radiation measurements taken at 122 observatories in China during 1957–2000. The QA algorithms include a physical threshold test (QA1), a global radiation sunshine duration test (QA2), and a standard deviation test applied to time series of annually averaged solar global radiation (QA3). The results show that the percentages of global, direct, and diffuse solar radiation data that fail to pass QA1 are 3.07%, 0.01%, and 2.52%, respectively; the percentages of global solar radiation data that fail to pass the QA2 and QA3 are 0.77% and 0.49%, respectively. The method implemented by the Global Energy Balance Archive is also applied to check the data quality of solar radiation in China. Of the 84 stations with a time series longer that 20 yr, suspect data at 35 of the sites were found. Based on data that passed the QA tests, trends in ground solar radiation and the effect of the data quality assessment on the trends are analyzed. There is a decrease in ground solar global and direct radiation in China over the years under study. Although the quality assessment process has significant effects on the data from individual stations and/or time periods, it does not affect the long-term trends in the data.

1. Introduction

Solar radiation arriving into the Earth–atmosphere system drives atmospheric circulation and influences climate. Surface solar radiation can be affected by both astronomical and meteorological factors (including clouds, water vapor, gas species, and aerosols, etc.). The study of surface solar radiation, besides its direct climatic significance, can also help to detect changes in atmospheric composition, such as aerosol loading, and to estimate the available solar energy. Recent investigations concerning surface solar radiation revealed significant *global dimming* and *brightening* trends on decadal scales, implying a profound effect on climate change (Stanhill and Cohen 2001; Wild et al. 2005). Routine radiation data are important for climate change research because of their long time series and areal coverage.

Any likely sources of errors or problems related to solar radiation measurements fall into two major categories: 1) equipment error and uncertainty and 2) operation-related problems and errors. Thus data quality assessments (QA) are very important when analyzing long-term variations of solar radiation (Younes et al. 2004; Muneer and Fairooz 2002; Rigolier et al. 2000; Maxwell et al. 1993).

A number of studies have been implemented using ground solar radiation data over China, including solar

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radiation climatological studies (Lu and Gao 1987; Weng 1964), studies of long-term trend and seasonal-variation characteristics of solar radiation (Cha 1996; Li et al. 1998; Zhang et al. 2004), and retrievals of atmospheric composition (Luo et al. 2000). Among these studies, however, either the temporal or spatial coverage is limited, or the data are used without a strict data quality test.

The solar radiation measurement network in China was established in 1957, the International Geophysical Year. The meteorological observatories have used two kinds of solar radiation instruments over time: one similar to that used in the former Soviet Union and the other manufactured in China. Instruments made in China were phased in during the period of 1990–93, replacing the instruments similar to those used in the former Soviet Union. The China Meteorology Administration (CMA 1996) performs some quality checks on the solar radiation data it collects, but the quality of the data can be affected by extraneous things such as the accuracy and modification of instruments, artificial factors during operation, and location change of stations. Thus the reliability of solar radiation data obtained in China, as well as in other areas in the world, is often doubted and has to be tested more strictly before their wider use in scientific studies.

In this paper, a set of QA algorithms is introduced that has been systematically tested on data collected during the years spanning 1957–2000 at 122 stations in China. The long-term temporal and spatial variations of ground solar radiation in China, with and without the QA, have been compared to investigate the effect of the data quality assessments.

2. Data and instruments

The daily solar irradiation and sunshine duration data analyzed here are from the Meteorological Information Center that is part of the CMA. The ground solar daily irradiation dataset includes measurements of global, direct, and diffuse daily irradiation, denoted by G, S, and D, respectively. Note that not all stations have collected a complete set of solar daily irradiation measurements over the past few decades; 78 stations have measurements of G, S, and D, and 44 stations have measurements of only G. Monthly sunshine duration datasets from 194 stations in China are also used in this analysis.

Before 1990, the instruments used to measure solar irradiation in China were modeled on those used in the former Soviet Union. For direct solar irradiation, the Yanishevsky thermoelectric actinometer was used; for global and diffuse irradiation, the Yanishevsky thermoelectric pyranometer was used. After 1990, instruments manufactured in China were used to measure solar irradiation. For direct solar irradiation, the DFY-3 pyrheliometer was used; for global and diffuse irradiation, the DFY-4 pyranometer was used. All of the radiative receivers were calibrated using a multistep method: calibration at least once per month at the stations against the reference instruments; calibration of the reference radiometers against the regional reference instruments; and calibration of the regional reference instruments every 2 yr against the Chinese reference instruments. The pyrheliometers have been regularly calibrated against reference pyrheliometers in Tokyo, Japan, or Pune, India. All reference instruments are now conserved and maintained by the Chinese Academy of Meteorological Sciences. The calibration process is traceable to the World Radiometric Reference. Although there is no published reference regarding the accuracy of radiation measurements before 1990, Tooming (2002) pointed out that the errors in the Yanishevsky actinometers and pyranometers did not exceed 3% and 5%, respectively. The operational criterion for solar irradiation measurements taken in China prior to 1990 was basically benchmarked to that of the former Soviet Union. So it is likely that the errors in solar irradiation measurements do not exceed 3% and 5% for actinometers and pyranometers, respectively. After 1990, the errors of the pyrheliometers and pyranometers do not exceed 2% and 5%, respectively.

3. Methods of data quality assessment and tested results

As mentioned above, the solar daily irradiation data over China have already undergone a basic quality check by the CMA before release. However, the criterion used in the quality check was too simple because it only required that both direct and diffuse irradiation components be lower than the global irradiation for daily data. Several studies have been made concerning the quality assessment of solar radiation data in China. For instance, Ma et al. (1998) performed a basic quality assurance test on daily solar global, direct, and diffuse irradiation data and the extreme-value test for monthly averaged global irradiation data by using theoretical global irradiation at each latitude belt under the condition of a clear sky on the 15th of that month; more stringent tests were not done for the daily radiation data. Gilgen and Ohmura (1999) performed a QA of the Global Energy Balance Archive (GEBA) dataset. Younes et al. (2004) recently reviewed related works and proposed a thorough quality assessment program. In fact, all of the QA approaches boil down to setting a threshold for the irradiation data and/or their statistical characteristics, and if the measurements and their statistical characteristics meet the prescribed criteria then the data are valid. Otherwise, the data are regarded to contain gross errors. Based on the existing QA schemes, a new scheme that includes three procedures has been designed in this study.

a. QA1: Physical threshold test

For short-term time scales of less than 1000 yr, the effect of Earth's orbital changes on the amount of solar irradiance reaching the surface can be ignored. The solar irradiance at the top of the atmosphere (TOA) is determined by latitude, day of year, and the solar constant. The daily solar irradiation G_0 at the TOA over a ground station can be calculated by the following formula (Iqbal 1983):

$$G_0 = \left(\frac{24 \times 3600}{\pi}\right) E_{\mathrm{SC}}(1 + \rho) \cos\varphi \cos\delta \times \left[\left(\frac{\pi}{180}\right)\omega_0 - \tan\omega_0\right],$$

where E_{SC} is the solar constant, φ is the latitude of the station, δ is the solar declination, ω_0 is the sunset (sunrise) hour angle, and ρ is the relative eccentricity correction; ρ, δ, and ω_0 are functions of yearday. The solar constant is set as 1367 W m^{-2} in this study.

Solar radiation at the surface is also affected by atmospheric absorbing gases (mainly oxygen, water vapor, and ozone), clouds, and aerosols. Even within the atmospheric visible widow of 0.4–0.7 μm, there still exists a little absorption (Gueymard 2004). The diffuse effects of gases and aerosol/cloud particles not only decrease the amount of direct solar radiation reaching the surface but also increase the diffuse radiation reaching the surface.

It is necessary to introduce the concept of "daily solar global irradiation (DSGI) under clear-sky conditions" (Gcd) before describing the details of QA1. Gcd represents the DSGI received at the surface when the sky is hemispherically clear. Page's clear-sky model (Muneer 2004) is used to calculate the DSGI in this study. The inputs of the model include the Linke turbidity factor with an atmospheric mass of 2, date, and latitude, longitude, and altitude of the station. To represent the clear-sky conditions, the Linke factor with an atmospheric mass of 2 is set at a minimum value of 1.0.

Based on these physical considerations, we can set the following thresholds for the three components of surface solar irradiation.

TABLE 1. QA1 test thresholds and summary of number of days with ESD.

Variable	Lower limit	Upper limit	Measurement days	Error days	Percent of error days
G	$0.03G_0$	G_c	1 220 107	37 466	3.07
S	0	S_c	813 929	117	0.01
D	D_c	G_c	813 943	20 479	2.52
Tot			2 847 979	58 062	2.04

1) GLOBAL RADIATION G

The upper limit for G is set as Gcd and is denoted as G_c. It is possible that the solar global irradiation at the surface can be larger than that at the TOA for a short time period because of the diffusive effects of clouds that are not in the way of the solar beam. However, daily irradiation cannot exceed that at the TOA.

It is difficult to set a strict lower limit for G. For example, under heavy overcast conditions, direct daily irradiation at the surface could tend to nil. However, the diffuse daily irradiation hardly ever reaches zero completely. No matter what the weather and environment are like, the surface always receives some solar irradiation during the day. It is obvious that a lower limit for G larger than zero is reasonable. The lower limit here is set as 3% of the incoming TOA solar irradiation, as suggested by the research of Geiger et al. (2002).

2) DIFFUSE IRRADIATION D

The upper limit for diffuse daily irradiation is set as Gcd and is denoted as G_c. This threshold is flexible because, under normal weather conditions, the direct daily irradiation is generally larger than the diffuse daily irradiation.

The lower limit for the diffuse daily irradiation is set as the daily surface diffuse irradiation under clear-sky conditions D_c. Diffuse irradiation usually increases with the atmospheric turbidity and cloud amount; therefore, the daily diffuse irradiation should be larger than that calculated under clear-sky conditions.

3) DIRECT IRRADIATION S

The lower limit for the direct daily irradiation is set to zero and the upper limit is set as the daily surface direct daily irradiation under clear-sky conditions, denoted as S_c.

4) RESULTS

Table 1 summarizes the thresholds used here and the results of QA1 for the three components of daily solar

TABLE 2. Monthly distribution of number of days failing QA1 threshold tests.

	Error days (upper-limit error days/lower-limit error days)											
Variables	1	2	3	4	5	6	7	8	9	10	11	12
G	885/3542	566/3636	424/3549	255/2466	263/2208	176/2253	167/1781	168/1613	239/2511	380/3087	564/2945	816/2937
D	0/2489	0/2521	0/2191	0/1487	0/1221	0/1185	0/884	0/865	0/1503	0/1985	0/2014	0/2134
S	26/0	8/0	8/0	12/0	2/0	0/0	2/0	1/0	9/0	16/0	19/0	14/0

irradiation. A term called the percentage of erroneous and suspected data (PESD) is introduced here and is defined as the ratio of the number of data points that have not passed the quality assessment tests to the total number of data points tested. It can be seen from Table 1 that the PESD for the global and diffuse daily irradiation is relatively large and that the PESD for the direct daily irradiation is smaller.

Table 2 is the monthly distribution of erroneous and suspected data (ESD). For global daily irradiation, the greatest occurrence of ESD is during the winter months and for all months most of the data classified as ESD fell below the lower limit. The ESD due to the lower limit is highest in summer and is lowest in winter. For diffuse daily irradiation, data points fail the lower-limit test. For direct daily irradiation, they tend to fail the upper-limit test. For these two components of daily irradiation, most of the ESD is found during the winter months. The geographical distribution of the occurrence of ESD for global and diffuse daily irradiation is given in Fig. 1. It can be seen from the figure that most of the stations with the greatest number of ESD are located in the Yangtze River area and throughout southern China in general. Also the distributions of the ESD for global and diffuse daily irradiation are consistent because the ESDs for global daily irradiation result from failure of the lower-limit test, as do the ESDs for diffuse daily irradiation.

b. *QA2: Sunshine duration test of global daily irradiation*

Surface global radiation results from the extinction of extraterrestrial radiation by Earth's atmosphere, and it depends on the atmospheric transmittance and sky condition, especially when there are clouds. It is well known that the surface global radiation is smaller when the cloud amount is large and vice versa. A method was conceived in the early 1900s to calculate global radiation by using cloud amount (Kimball 1919). GEBA also used cloud amount to test radiation data. Another factor with a closer relationship to the surface global radiation is the sunshine duration. Global solar radiation can be calculated using sunshine duration data (SDD; Weng 1964; Zuo et al. 1963).

Testing the quality of surface global irradiation can be done by using cloud amount and cloud optical properties information and SDD. However, there are advantages to using SDD rather than cloud cover for quality assessment (Muneer and Gul 2000; Bennett 1969), and therefore the SDD is used here for QA2.

The monthly percentage of sunshine duration (MPSD) for each station is calculated using the monthly SDD. The MPSD is the ratio of monthly observed sunshine duration S to the monthly available sunshine duration L, which can be calculated as follows:

$$L = m\frac{24}{\pi}\arccos(-\tan\varphi\tan\delta),$$

where φ is the latitude of the station, δ is the solar declination on the 15th day of that month, and m *is* the number of days in the month.

To compare the sunshine duration percentage P with surface global daily irradiation G, we need to calculate a "clearness index" K_t from the irradiation data. Monthly averaged K_t is given by $K_t = G/G_0$, where G_0 is the same as that in QA1.

Of the 122 stations, only 67 have both global daily irradiation and sunshine duration measurements; therefore, QA2 is applied to the data from these stations. The following describes the four steps used in the analysis:

1) calculate monthly clearness indices by using global daily irradiation data that passed the QA1 test,
2) perform a linear regression between K_t and P by using the least squares method,
3) calculate the differences d between the observed monthly clearness indices and fitted monthly clearness indices and obtain the standard deviation S_d of these differences, and
4) for each station, if $|d| \leq 3S_d$ then the global daily irradiation data pass the QA2 test—otherwise, the data are rejected.

As a result of the QA2 test, the PESD differs from site to site, and its range varies from 0% to 2.35%. The geographic distribution of the ESD is relatively uniform; among the 27 196 monthly data tested, 210 (or 0.77% of the data) did not pass the QA2 test.

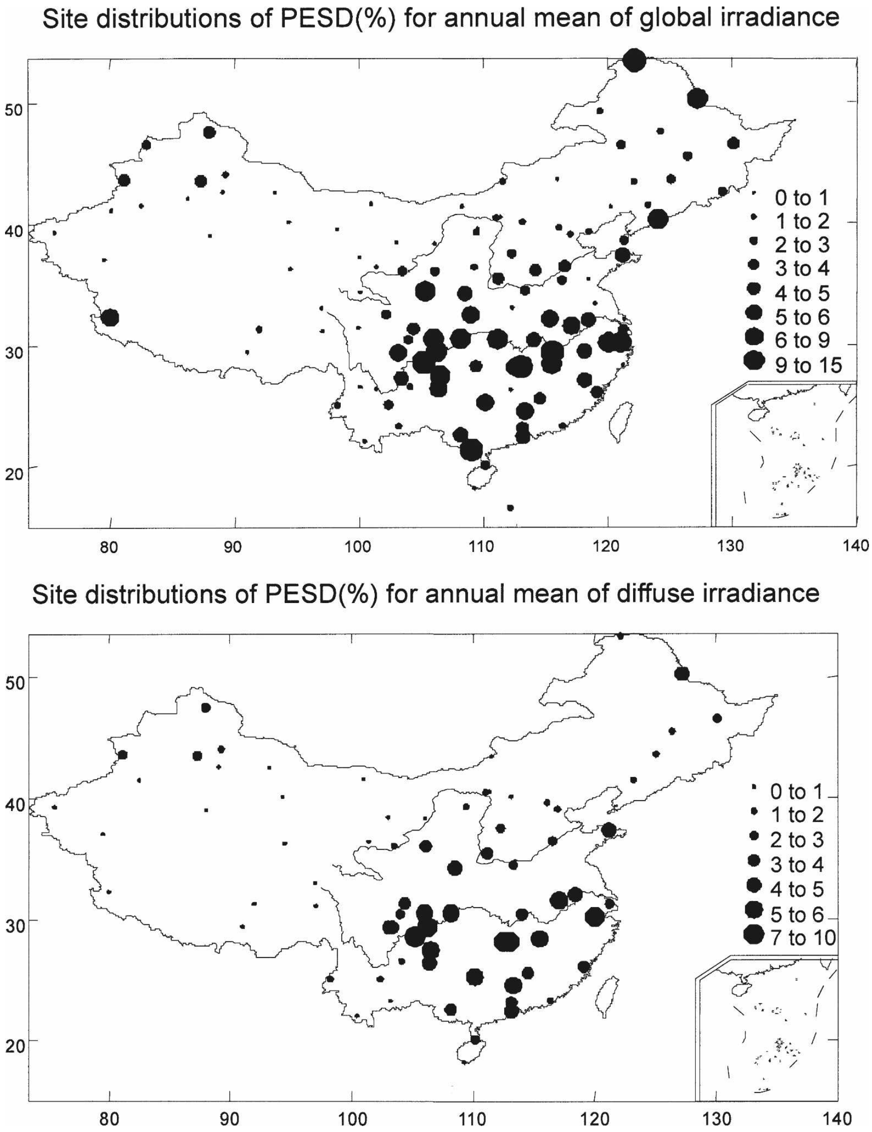

FIG. 1. Distribution of PESD (circles of different sizes as marked in key; %) for (top) global solar radiation and (bottom) diffuse solar radiation measurements in China.

c. *QA3: Standard deviation test for annually averaged global irradiance time series*

The two quality tests discussed so far either constrain the data based on physical considerations (QA1) or compare them with another related variable (QA2). The third quality test, QA3, is different in that the constraint imposed on the data is from the data themselves.

QA3 is a kind of climatological statistical method. If the samples are few, the statistic significance will be lost. In this study, we selected 84 stations at which measurements have been taken for more than 15 yr and for which all of the data have been tested by the QA1, with some further tested by the QA2.

For the time series of the yearly means of irradiance $Y(t)$, the average m_Y and the standard deviation S_Y can be calculated by

$$m_Y = \frac{1}{N}\sum_t Y(t) \quad \text{and}$$

$$S_Y^2 = \frac{1}{N-1}\sum_t [Y(t) - m_Y]^2,$$

where N is the observation period in units of years. Because of the annual climatic variation caused by natural and/or anthropogenic factors, the surface solar irradiance will change and a nonzero S_Y will result. At

TABLE 3. Regional mean global solar irradiance (W m^{-2}) $m(m_Y, Z)$ and standard deviation $m(S_Y, Z)$ and standard deviation of S_Y, $s(S_Y, Z)$.

Region	$m(m_Y, Z)$	$m(S_Y, Z)$	$s(S_Y, Z)$
50°–60°N	119	6.4	1.14
40°–50°N	154	9.38	4.45
30°–40°N	196	12.27	3.94
20°–30°N	213	10.00	2.75

the same time, however, other factors, such as the aging and incorrect operation of the instruments, can also affect the measurement of surface solar irradiance and cause a nonzero S_Y. The aim of the QA3 is to reject ESD while keeping enough data to glean information concerning climate change. It is therefore vital to select a proper S_Y. If S_Y is set too small, useful information concerning climate change is lost. On the other hand, if S_Y is unreasonably large, too much ESD will be left in the dataset.

The range of S_Y proposed by GEBA is used in this study. GEBA divides the whole globe into 18 regions latitudinally, with an interval of 10° for each band, and then the regional averages and standard deviation of S_Y [$m(S_Y, Z)$ and $s(S_Y, Z)$, respectively] are calculated, where Z is the latitude region number. The maximum value for S_Y is $m(S_Y, Z) + 2s(S_Y, Z)$, according to GEBA. As mentioned above, 84 stations in China are selected for the QA3 test, and they are distributed from 20° to 60°N. The regional averages of $m(S_Y, Z)$ and $s(S_Y, Z)$ are shown in Table 3.

The test results show that 6 of the 84 stations had some data that failed the QA3. For three of these stations (Zhongshan, Heihe, and Tongliao), no other data are available to test the quality of solar radiation data, and so they are kept in the dataset. Among 3068 yearly-mean data, 15 did not pass the QA3, which is about 0.49% of the total. The other three stations that failed the QA3 (Geer, Naqu, and Lhasa) are located in Tibet, which recorded exceptionally low values of global solar radiation during the period of 1988–92.

In fact, this is a very interesting phenomenon. Whether these data are badly reported or there is some climatic factor influencing data from the Tibetan locations, further investigation is needed. Toward this end, surface solar global irradiance data retrieved by satellite during 1984–94 were collected. Because sunshine duration data are available only for Lhasa, this site is selected for making comparisons among the routine observations, satellite retrievals of global irradiance, and the sunshine duration data. The results are shown in Fig. 2, where the Global Energy and Water Cycle Experiment–Surface Radiation Budget (GEWEX–SRB) dataset was used for the satellite retrievals. The GEWEX–SRB dataset was produced by the National Aeronautics and Space Administration Langley Research Center, which generated surface shortwave irradiances on a 1° × 1° grid every 3 h (Stackhouse et al. 2004). From Fig. 2, one can see that the satellite retrievals and the sunshine duration data agree very well and that there are no outstandingly low values appearing during the period between 1988 and 1992. Therefore, the observed global irradiance data at the three stations in Tibet are likely ESD although the cause for this is unknown. Instrument malfunction can be ruled out, given the unlikelihood that the instruments at the three sites would simultaneously malfunction.

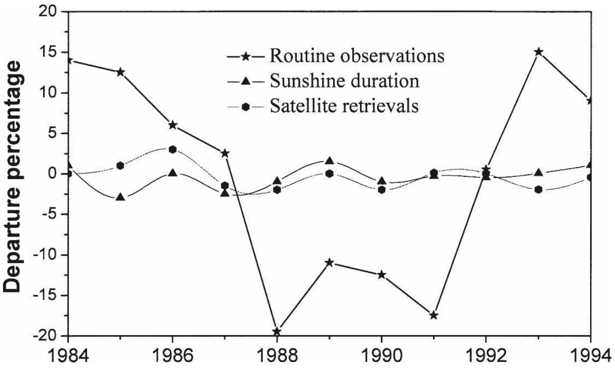

FIG. 2. Departures (%) of sunshine duration, global solar radiations from satellite retrieval, and routine observation in Lhasa from 1984 to 1994.

In summary, three QA algorithms for testing routine solar irradiance data in China and the major results have been introduced. There are other methods that can be applied, such as the use of satellite retrievals for all stations. Satellites can accurately derive the top layer of clouds and its associated cloud cover; however, they are useless for midlevel and bottom-level clouds. Moreover, satellite data are available for the past 20 yr only. Note that the major aim of the QA is neither to judge whether individual data are correct nor to discover the specific reasons for why the data may be ESD. The goal is to reject those data that are physically unreasonable so that scientific results based on the data are more reliable.

We also used the GEBA method (Ohmura and Gilgen 1991) to do data quality assessment of the Chinese solar irradiance data. Six tests were involved, and they check whether 1) the annual mean of global irradiance is greater than the annual mean at the TOA, 2) the monthly mean of global irradiance is greater than the TOA monthly mean for more than 1% of the data, 3) the sum of the annual direct and diffuse components of the global solar irradiance has more than a 25 W m^{-2}

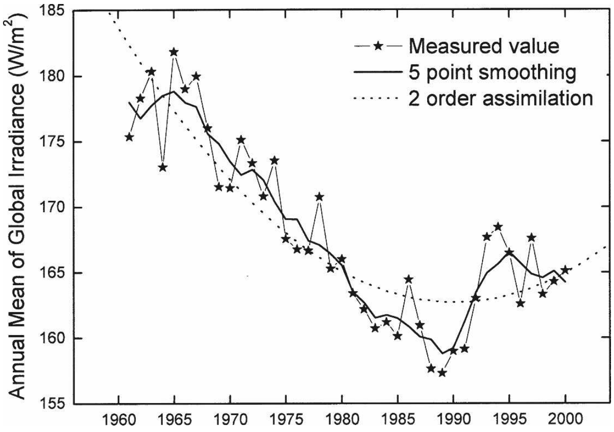

FIG. 3. Time series of annually averaged global solar radiation at all stations.

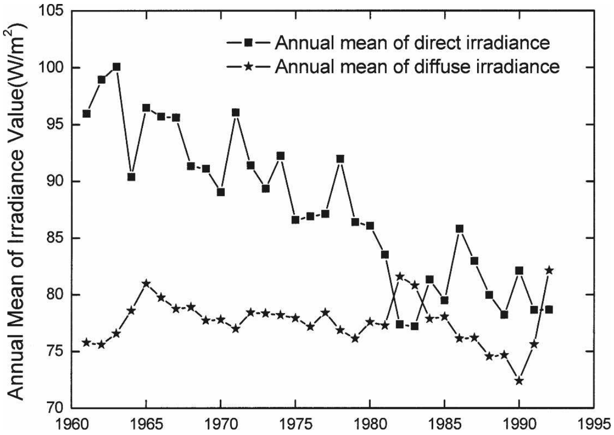

FIG. 4. Long-term variations of direct and diffuse solar radiation.

difference from the annual global mean, 4) the standard deviation of the annual means is larger than 15%, 5) more than 4 months of data show standard deviations greater than 30%, and 6) there exist any sudden jumps (exceeding 80 W m^{-2}) in the time series of the annual means. Data from 84 stations were tested; the 38 remaining stations were removed from consideration because they have data collections shorter than 20 yr. The number of stations that met some or all of the above conditions is 0, 11, 18, 5, 13, and 15 for tests 1–6, respectively. In total, data from 35 stations met at least one of the above criteria for failure.

4. Long-term trends in ground annual mean of global irradiance in China during the past 40 yr

The global irradiance data analyzed here have passed through the QA tests; that is, data from all 122 stations underwent the QA1 test, data from 67 stations underwent the QA2 test, and data from 84 stations underwent the QA3 test. The direct and diffuse irradiance data were filtered through the QA1 test.

a. *Global irradiance*

A total of 72 stations with records spanning over more than 30 yr were used in the long-term trend study. A climatological value was substituted during times for which there were no data available or the data failed the QA tests. Figure 3 shows the annually averaged global irradiance from the 72 stations during 1961–2000. The mean global irradiance is 165.86 W m^{-2}, with an overall average in the decrease of the trend of 2.54% (10 $yr)^{-1}$. From 1961 to 1989, there is a decreasing trend of about 4.61% (10 $yr)^{-1}$; after 1989, the trend changes direction and increases to about 1.76% (10 $yr)^{-1}$. For both periods, a confidence level of 99% is passed. Wild et al. (2005) and Pinker et al. (2005) have found that the solar radiation at Earth's surface seems to increase in 1990s. The change in direction of the global trend at about 1990 in China seems to be consistent with their research results. However, besides the change in solar signal, the wholesale refitting to new instrumentation during the early 1990s is also a potential factor to consider. The two factors are too complicated to identify how much each attributes to the uncertainty. Resolving this problem would require future obtaining independent observations of the atmospheric visibility as well as information concerning the interaction between aerosol particles and clouds.

b. *Direct and diffuse solar irradiances*

As mentioned in section 2, solar irradiance data among the 122 stations in China are not uniform in terms of temporal availability and number of observed components. To study long-term trends in direct and diffuse solar irradiance, 64 stations with data records longer than 25 yr were selected. As in the case of global solar irradiance, climatological values are used when there are no data available or when the data failed the QA tests.

The variations of annually averaged direct and diffuse solar irradiance over the 64 stations from 1961 to 1992 are shown in Fig. 4. The mean direct solar irradiance is 87.50 W m^{-2} during this period and shows a decreasing trend of 7.75% (10 $yr)^{-1}$ with a confidence level of 99%. The mean diffuse solar irradiance is 77.66 W m^{-2} during the same period and shows a weaker decreasing trend of 0.65% (10 $yr)^{-1}$ with a confidence level not exceeding 95%.

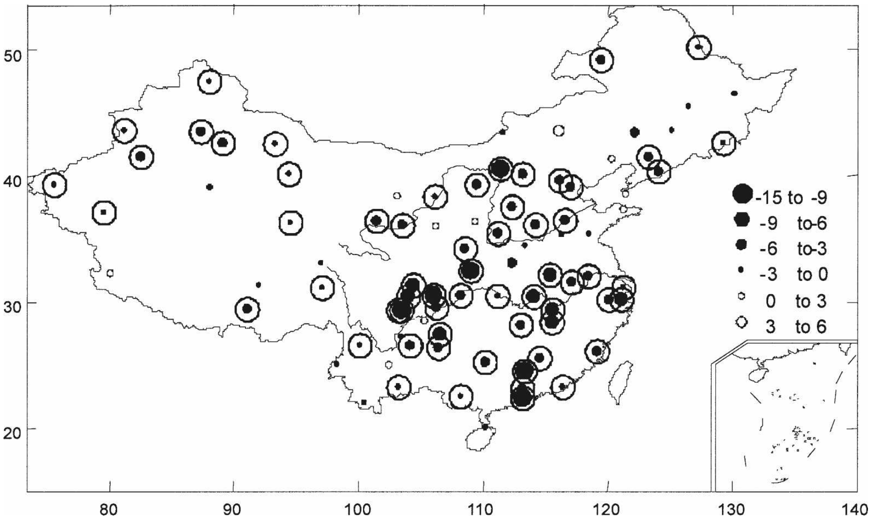

FIG. 5. Distribution of long-term [% (10 yr)$^{-1}$] variations in annual mean global solar radiation in China. Station trend indicators with circles around them are significant at the 95% confidence level.

c. Characteristics of the geographical distribution of global, direct, and diffuse irradiance in China

To study the geographical distribution of the variations in surface solar global irradiance in China over the past 40 yr, 89 stations with data records of more than 10 yr were analyzed for the period of 1957–2000. Figure 5 shows the geographical distribution of the mean solar global irradiance variation. The global irradiance shows a decreasing trend over most of China during the past 40 yr, especially in southern China, the Sichuan basin, and the Guizhou area, as well as the middle and lower reaches of the Yangtze River. The decreasing rates are smaller in the northeastern and western parts of China with magnitudes of no more than 4% (10 yr)$^{-1}$.

As compared with global and direct irradiance, the decreasing trend in diffuse irradiance is not obvious, with 27 stations showing clear increasing trends. The average decrease in diffuse irradiance at the 68 stations is 3.11% during the past 40 yr. Figure 6 shows the geographical distribution of the variation of annually averaged diffuse irradiance. With the exception of several stations in Tibet, stations with increasing and decreasing trends are interspersed.

Because global irradiance consists of direct and diffuse irradiance components, and the latter component does not show a significant decreasing trend, it could be concluded that the decrease of global irradiance is mainly caused by the decrease of direct irradiance, as shown in Fig. 7. In comparison with Fig. 5, it can be found that the geographical distribution of the variation in annually averaged direct irradiance is very similar to that of global irradiance. Throughout most of China, the surface direct solar irradiance has been decreasing over the past 40 yr, and, in general, the decrease in central and eastern China is larger than that in western and northeastern China. The most notable decrease appears in three regions: the Sichuan and Guizhou areas and the middle and lower reaches of the Yangtze River. The decreasing magnitudes of direct irradiance do not exceed 6% in northeastern and western China, except at the Geer, Naqu, and Lhasa stations in Tibet, where the data are questionable, as discussed in the QA3 section.

5. The effect of the data quality assessment on the variation of surface solar irradiation in China during the past 40 yr

To investigate the effect of the data quality assessment on the variation of surface solar irradiation in China, we selected 72 stations with data that passed the QA1, QA2, and QA3 tests.

The long-term mean global irradiation using data that did not go through the QA process is 2.3% lower than that calculated with data that underwent the QA process. This is likely due to the inclusion of data that fall below the lower limits defined for QA1. However, the QA procedures have no significant effect on the long-term trends of surface solar irradiation in China, because the ESD occupied a smaller percentage of the total data, though the decreasing trend with QA is more clear than that without QA and the difference between them is about 0.45% (10 yr)$^{-1}$.

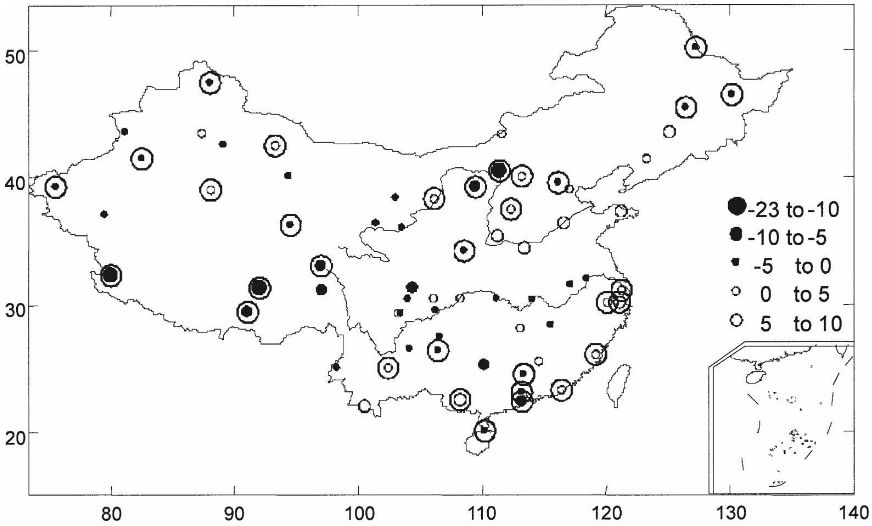

FIG. 6. As in Fig. 5, but for diffuse solar radiation.

6. Conclusions and discussion

The quality of daily solar irradiation data from 122 routine meteorological stations in China from 1957 to 2000 was tested using three QA algorithms, and then their long-term trends were investigated. The six major findings are as follows:

1) The percentages of ESD are 3.07%, 0.01%, and 2.52% for daily surface solar global, direct, and diffuse irradiation, respectively.
2) Monthly mean of global irradiance data from 67 stations for which both global irradiance and sunshine duration observations are available and for which the global irradiance passed the QA1 test underwent the QA2 test, and the percentage of ESD is 0.77%.
3) The QA3 test was performed on data from 84 stations with data records longer than 15 yr, and it was found that a total of 6 stations have ESD. Three of these stations are located in Tibet, and their global irradiance data records from 1988 to 1992 appear to be questionable. Among the 3068 data measurements put through the QA3 test, 15 were identified as ESD, which is about 0.49% of the total.
4) The general features of the distribution of surface global and direct irradiance during the past 40 yr in China are similar. There are clear decreasing trends during 1961 to 1989, followed by an increasing trend

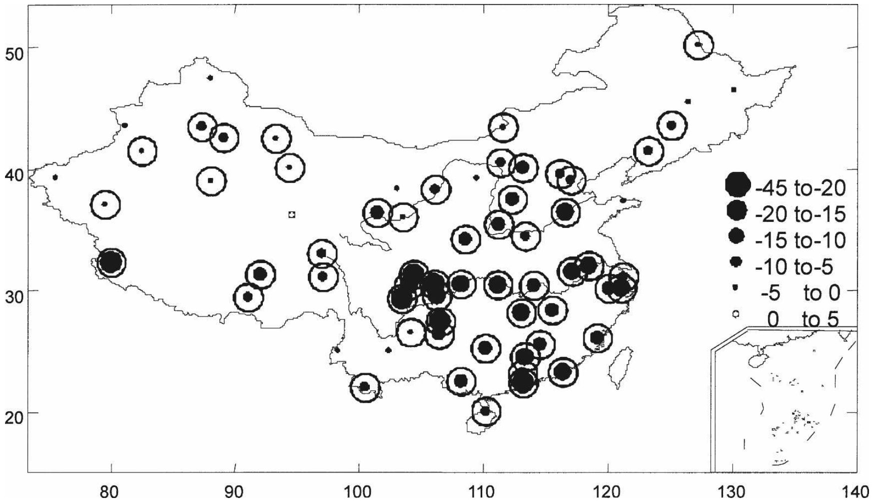

FIG. 7. As in Fig. 5, but for direct solar radiation.

starting from 1990. The average decrease of global irradiance is 2.54% (10 yr)$^{-1}$, which becomes more obvious during 1961–89, during which it reaches up to about 4.61% (10 yr)$^{-1}$, and the increase after 1990 is about 1.76% (10 yr)$^{-1}$. For the seasonal change in global irradiance, the decrease is largest in winter with 4.82% (10 yr)$^{-1}$ with the magnitudes of the decrease for autumn, summer, and spring being 2.63%, 2.15%, and 1.39% (10 yr)$^{-1}$, respectively. In addition, the most obvious decreases occur in southern China, the Sichuan basin, and the Guizhou area, as well as in the middle and lower reaches of the Yangtze River areas. The decreases are smaller in the northeastern and western parts of China, with magnitudes of no more than 4% (10 yr)$^{-1}$.

5) Surface diffuse solar irradiance in China shows no obvious trend over the past 40 yr. The average decrease at 68 stations is 0.95% (10 yr)$^{-1}$, and the total decrease over the past 40 yr is 3.11%. There are 27 stations with increasing trends, which are mainly located in the coastal area and middle and lower reaches of the Yangzte River.
6) Although there are obvious decreasing trends of global and direct solar irradiance over China during the past 40 yr, it is very difficult to make sure of the uncertainty of the trends. The refitting of the instrument in the early 1990s cannot be ignored with regard to the trend of global irradiation in China to increase. More evidence is needed to study this question in depth.

Wild et al. (2005) recently showed that Earth's surface has turned from dimming to brightening during the past 10 yr and pointed out that this reverse is consistent with variations in cloud amount and atmospheric transmittance since 1990. Therefore, it is very meaningful to do such an analysis by using quality-assured surface solar irradiation data from China. There are several issues that must be investigated further. It is well known that, among the many affecting the amount of solar radiation reaching the surface, the most important factors are clouds and aerosols. From an analysis of International Satellite Cloud Climatology Project satellite data over China, we found that the average cloud amount decreased by approximately 3.6% during the period from 1984 to 2000. Ding (2004) also found a similar result. Kaiser (1998) used ground-based cloud observations to show that the cloud amount over China from 1951 to 1984 decreased by 1%–3% (10 yr)$^{-1}$. Explaining the overall decrease of 2.54% (10 yr)$^{-1}$ in global solar irradiance in China requires a substantial increase in the cloud, which is contrary to observations. The decrease in surface solar irradiance can be attributed to an increase in cloud optical depth. However, to explain the reverse of the trend in solar irradiance around 1990, the variations of cloud amount and/or cloud optical depth should also reverse at the same time.

At present, a prevailing view is that the variation of surface solar irradiance can be attributed to aerosol particles (e.g., Che et al. 2005; Liang and Xia 2005; Stanhill and Cohen 2001; Wild et al. 2005). This seems to be reasonable. Studies have shown that there is a good relationship between increases in fossil fuel consumption and decreases of surface solar global irradiance. Sulfates, black carbon, and other aerosol particles are emitted into the atmosphere during the combustion of fossil fuels. In China, as mentioned above, the decreases of global and direct solar irradiance are most obvious in winter, which is the peak season for fossil fuel consumption. The aerosol particles not only decrease surface solar global and direct irradiance but also increase solar diffuse irradiance. These characteristics are consistent with actual observational data. However, this assumption still requires more proof.

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