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Solar radiation trend across China in recent decades: a revisit with quality-controlled data

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Abstract

Solar radiation is one of the most important factors affecting climate and environment, and its long-term variation is of much concern in climate change studies. In the light of the limited number of radiation stations with reliable long-term time series observations, this paper presents a new evaluation of the long-term variation of surface solar radiation over China by combining quality-controlled observed data and two radiation models. One is the ANN-based (Artificial Neutral Network) model and the other is a physical one. The two models produced radiation trends comparable to the observed ones at a few stations possessing reliable and continuous data. Then, the trend estimation is extended by the ANN-based model to all 96 radiation stations and furthermore extended by the physical model to all 716 China Meteorological Administration (CMA) routine stations. The new estimate trend is different from previous ones in two aspects. First, the magnitude of solar radiation over China decreased by about $-0.19\,\mathrm{W\,m^{-2}\,yr^{-1}}$ between 1961 and 2000, which is greatly less in magnitude than trends estimated in previous studies (ranging over -0.41 to $-0.52\,\mathrm{W\,m^{-2}\,yr^{-1}}$). Second, the "From Dimming to Brightening" transition in China during the late 1980s and the early 1990s was addressed in previous studies, but this study indicates the solar radiation reached a stable level since the 1990s and the transition is not noticeable. These differences are attributed to inappropriate data and approaches in previous studies.

1 Introduction

As the ultimate energy source for the lives on our planet, solar radiation incident at the Earth's surface drives most of the water, energy, and carbon cycles of the Earth's system, and it is also a major determinant of the climate conditions of our habitats (Wild et al., 2009). Changes in the amount of solar radiation have received prominent attention due to its potential influences on the environmental, societal, and economic aspects of people's living (Pinker et al., 2005). These changes could be the consequences from either or both natural and anthropogenic factors such as large amount of emission by volcanic eruption, emission of pollutants gases from industrial or commercial activities, and climatic change. Measurement of solar radiation is of primary importance because it provides the most essential information for evaluation of climate changes and global warming due to its high sensitivity to the anthropogenic disturbances (Ramanathan et al., 2001). Long-term variations in the observed records of surface solar radiation have been widely investigated in many countries (Stanhill et al., 1995, 1997, 1998; Abakumova et al., 1996; Liepert et al., 1997, 2002; Wild et al., 2009a,b; Gilgen et al., 1998, 2009). They found that the intensity of solar radiation incident on the earth surface has a decreasing trend (about 6 to 9 $\mathrm{W\,m^{-2}}$ from the 1960s to the 1990s, i.e. about 5%). This weakening trend is believed to have a profound impact on the climate, hydrological cycle, plant photosynthesis, solar power intensity, and daylighting availability. However, Wild et al. (2005) found that the decreasing trend does not persist into the 1990s and they reported that there is a recovery trend since the late 1980s in most regions of the world. This result well agrees with satellite observation on the land surface of the Earth (Pinker et al., 2005). This transition phenomenon is popularly called “From Dimming to Brightening”.

There are also many similar studies which had been done to investigate the long-term variations of surface solar radiation over China. A preliminary study of the solar radiation data collected at three observation stations in the Yangtze River Delta Region was done by Zhang et al. (2004), and a decreasing trend of surface solar radiation was found between 1961 and 2000. Che et al. (2005) analyzed the variations in annual mean solar radiation data collected at 64 radiation stations for the period from 1961 to 2000. Liang and Xia (2005) did a similar study only with the data at 42 first-class stations recognized by the CMA. Both studies indicated that there is a decreasing trend of solar radiation in China before the 1990s but it does not persist thereafter. With the same data of the 42 first class stations, Xia et al. (2006) divided China into four regions (South China, North China, Northeast China, and West China) and they found that there are negative trends over all the four regions between 1961 and 2000 while there are positive trends over all the four regions between 1984 and 2000. Furthermore, Averaging over 43 stations in China, Ye et al. (2009) derived the time series of annual mean solar radiation anomalies from 1961 to 2007 and identified a trend transition (from dimming to brightening) at 1990.

However, the quality control process of the radiation data in the above studies is still primitive or vague. In fact, some recent study results revealed that systematic errors often occur in the radiation measurements. Shi et al. (2008) pointed out that the quality of solar radiation data obtained in China is often doubted. For example, there is an obvious abnormal low solar radiation level presented by the data collected from three Tibetan stations (Naqu, Shiquanhe, and Lhasa) for the period of 1988 to 1992. More abnormal data are found in Tang et al. (2010). The trends reported in previous studies may have been distorted by erroneous observational data. In order to avoid this problem, Shi et al. (2008) introduced a quality control scheme in their study. Upon analyzing the data obtained by 72 radiation stations between 1961 and 2000, they agreed that a transition trend happened in the early 1990s. However, they also pointed out that the transition might be caused by the large scale of retrofit to radiation instruments at CMA stations around the early 1990s. Moreover, using the corresponding climatological values to replace the erroneous and suspected data is a step in their quality control scheme, which might also introduce extra uncertainties into their analysis. Norris and Wild (2009) used cloud cover data to exclude suspicious data at 23 radiation stations over China, and reached that surface solar radiation over China decreased by a statistically significant 1.1 $\mathrm{W\,m^{-2}\,yr^{-1}}$ between 1971 and 1989 and increased by a non-significant 0.4 $\mathrm{W\,m^{-2}\,yr^{-1}}$ between 1990 and 2002. However, they also noticed that their results could not represent the entire country since many areas lacked solar radiation measurements.

There are several other factors which may contaminate the trend analysis. The first one is the representative problem with the number of the CMA radiation stations. Though CMA has 122 radiation stations, long-term solar radiation observation stations are sparsely available in the Mainland of China, comparing to the entire China territory and to the number of all CMA routine weather stations. This situation is particularly true in West China. For example, there are only four routine radiation stations (Lhasa, Shiquanhe, Naqu, and Germu) over the Tibetan Plateau, though its area occupies about one fourth of China. Second, it is always difficult to obtain a quality-consistent long-term dataset for this type of studies, due to the retrofit of obsolete instruments, removal of stations, and poor maintenance of the instruments. Therefore, a strict station selection is of primary importance for better identifying the trend of solar radiation. Third, most of the radiation stations are located in developed urban or suburban areas, and thus, early reported weakening trends may be not able to represent the ones in vast developing and less polluted areas.

Therefore, it is not straightforward to quantify the radiation trend in China with available radiation data, due to their discontinuity, quality-inconsistency, and non-representativeness. In order to get rid of their potential impacts, this study combines quality-controlled data and two radiation models to estimate the trend of surface solar radiation over China. First, a quality control scheme is adopted to select long-term reliable observation data from 122 radiation stations and the selected dataset is applied to derive true radiation trends at the selected stations. Second, the derived radiation trends are used to verify the capability of the two radiation models when used to estimate the radiation trend. One model is the Artificial Neural Network (ANN)-based model, the other one is a hybrid model developed in Yang et al. (2006). The ANN-based model is trained with reliable radiation data that are available in recent years and then it is used to extend the radiation records to a long period for each radiation station. This approach extends the trend estimation from a few selected radiation stations to all radiation stations. Moreover, the hybrid model estimates solar radiation from sunshine duration data and other meteorological measurements and it works at all CMA stations, making it possible to estimate the radiation trend across China.

The rest of this paper is organized as follows. Dataset and two radiation models used in this study are described in Sect. 2. Section 3 evaluates the trends produced by the two radiation models against the observed one. In Sect. 4, the spatial-temporal patterns of solar radiation trend over China are given, and discussions are presented in Sect. 5. Finally, conclusions are given in Sect. 6.

2 Dataset and models

2.1 Observation data

Daily meteorological data at 716 CMA routine weather stations were released at the CMA Meteorological Information Center. The data at each station comprise air temperature, air pressure, relative humidity, sunshine duration and precipitation. Solar radiation was first measured in 1957, and then, its measurement was gradually conducted at a total of 122 stations. However, the measurement at some stations stopped in the past. Since 1994, there are 96 stations remaining to measure solar radiation and a new type of radiometer was used at these stations. Figure 1 shows the geographical distribution of 716 stations. Among them, the 96 radiation stations are marked by star symbols.

Meanwhile, attention needs to be paid to both availability and quality consistency of the radiation data. Among the 96 stations, "complete records" (defined as a set of data that contain at least 20 d records in every month) between 1961 and 2006 are available only from a small number of stations. In the history of CMA radiation measurement, two different types of the radiometers have been used to measure solar radiation before 1994 and afterwards, respectively. One is imitated based on those used in the former Soviet Union, and the other is the so-called DFY-4 manufactured by China. These instruments are calibrated by a set of standard procedures based on a time table (The detailed procedures are described in Yang et al., 2008). The errors of the two pyranometers would not exceed 5% as pointed out by Shi et al. (2008). However, these standard calibration procedures were not strictly conducted at some stations, especially for the periods from the late 1960s to the early 1980s and from the early 1990s to the middle 1990s (CMA 2005). In the light of these calibration problems before 1994, the radiation data for this period need quality control; the data since 1994 are considered be reliable and will be the basis for constructing the following ANN-based model.

The quality of the observed global radiation data are controlled by a scheme described in Tang et al. (2010). As a result, spurious data and inaccurate measurements in the observations are excluded. After the quality control, there remain only six stations with “complete records” for the years from 1979 to 2006. The radiation trends derived from these six stations are employed to form the basis for evaluating the trends produced by the ANN-based model and the hybrid model.

2.2 ANN-based model

The ANN employed in the present study is a commercial computer package (Demuth et al., 2008). It is an information processing system which often applies to recognize patterns, fit a function, and cluster data. Recently, many researchers utilized ANN-based models to estimate surface solar radiation (e.g., Tymvios et al., 2006; Mubiru and Banda, 2008; Jiang, 2009). Their results did show its superior performance over the traditional regression methods applying in radiation estimates. In this study, a feed-forward back-propagation (BP) neural network is adopted. It consists of several layers of neurons that are linked with connections. A neuron is a simplified mathematical model like a biological neuron, and a connection is the unique link between the sending and the receiving neurons for information transport. The first and last layers of neurons are called input and output layers, respectively. Between these layers are one or more hidden layers. Simply speaking, neurons receive inputs and combine them, and then perform operations and output the final results.

In the present ANN-based modeling, the input layer has 6 parameters including daily air temperature range; daily mean temperature; relative humidity; sunshine duration; precipitation; and air pressure. The only one hidden layer has 20 neurons equipped with hyperbolic tangent sigmoid transfer function which can be expressed as:

$$f(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{1}$$

In the last layout, there is only one neuron to produce the output of estimated daily solar radiation and the transfer function of this layer is a logistic sigmoid function which can be expressed in the following:

$$f(x) = \frac{1}{1 + e^{-x}} \tag{2}$$

All of the ANN works are performed by MATLAB neural network toolbox. For more detailed theoretical knowledge of ANN, we can refer to Neural Network Toolbox™ 6 User's Guide (Demuth et al., 2008).

In this study, quality-controlled observation data between 1994 and 2006, which are deemed reliable, are employed to train the ANN-based model at each of the 96 radiation stations. The dataset collected before 1994 are not used for this training, because of its quality issue. The trained model is then applied to trace back the daily solar radiation before 1994 at each radiation station.

2.3 Hybrid model

The hybrid model applied to the present study is a physical model which was developed by Yang et al. (2001) and then further improved by Yang et al. (2005, 2006). Inputs of the model are daily mean air temperature, relative humidity, air pressure, sunshine duration, the Ångström turbidity, and the thickness of ozone layer. The Ångström turbidity is produced by the Global Aerosol Data Set 2.2a (GADS) model (Koepke et al., 1997; Hess et al., 1998). The thickness of ozone layer is obtained from Total Ozone Mapping Spectrometer (TOMS) zonal means provided by NASA/GSFC Ozone Processing Team (see http://toms.gsfc.nasa.gov/ozone/ozone_v8.html). For brevity, details of this model are not given in the present paper but refer to Yang et al. (2006).

The hybrid model was recognized by many researchers (Gueymard, 2003a,b; Paulescu and Schlett, 2004; Madkour et al., 2006) as one of the best broadband models. It has been also applied to provide solar radiation input data for hydrological modeling in Tang et al. (2007, 2008). In the present study, this hybrid model is applied to expand the radiation dataset to the 716 CMA stations and then estimate the radiation trend in China.

3 Validation of radiation trends in the models

In order to use the estimated solar radiation to re-evaluate the long-term trends, we need to validate the trends of the estimated against the observed ones. After the quality control, only six stations' data taken from 1979 to 2006 have "complete records" and consistent quality. In order to enhance the representation of the validation dataset, other four stations, which have "complete records" except for a few months (no more than 3 months from 1979 to 2006), are also selected. The monthly-mean values of these months are replaced by the ANN estimated ones. Details of these replacements are listed in Table 1. The ten selected radiation stations are: Beijing, Geermu, Guangzhou, Gushi, Jinghong, Nanjing, Tulufan, Urumchi, Yinchuan, and Zhengzhou. Radiation data collected at these stations provide the validation basis.

In this study, linear and second-order regression fitting methods are used to determine the trends of the observed values and the estimated ones. The confidence levels of the derived trends are determined according to the Student's t-test with the following expression:

$$t = r[(n-2)/(1-r^2)]^{1/2} \tag{3}$$

where r is the correlation coefficient between the observed time series and the fitted time series, and n is the total number of years.

Figure 2 shows the comparison of the annual mean solar irradiance time series during 1979–2006 among the observed, the estimated by the ANN-based model, and the estimated by the hybrid model at the ten validation stations selected above. It can be found that the estimated values by the ANN-based model are very close to the observed ones. The hybrid model also produces similar inter-annual variability though it slightly overestimated the values. The trends derived from the ANN-based model and the hybrid model are compared with the observed ones in Fig. 3. It is shown that the model-derived trends are comparable to the observed ones, and their correlation coefficients are above 0.85 ($p<0.01$). These high correlation values demonstrate that the two models can be used to estimate the radiation trend.

In order to obtain the radiation trends at more stations, the two models are then applied to all radiation stations. During the period from 1979 to 2006, only 84 radiation stations have "complete records" of meteorological parameters that are required to apply the two models. Figure 4 compares the trends estimated by the ANN-based model with the ones by the hybrid model at the 84 stations during 1979–2006. We can find that the trends derived by the two independent models match each other very well and their correlation coefficient is up to 0.96 ($p<0.01$). Therefore, the hybrid model is believed capable of reproducing the trend of surface solar radiation.

4 Trend of surface solar radiation over China

Based on the above reasoning, the hybrid model is used to extend the trends to all CMA stations. Although there are 716 CMA stations, only 592 stations can provide "complete records" for the years from 1979 to 2006, and 382 stations provide "complete records" for the years from 1961 to 2006. In this section, discussed are the results at the 592 and 382 stations.

Figure 5 shows the spatial distributions of the trend in surface solar radiation at the 592 stations for the years from 1979 to 2006. From these results, negative trends are seen at 381 stations and are statistically significant at 161 of them. The trends at the other 211 stations are positive and are statistically significant at 52 of them. During this period, "dimming" mainly occurred in the Tibetan Plateau and North China Plain.

“Brightening” mainly occurred in the northwest part of Xinjiang Uygur Autonomous Region, northeast part of Inner Mongolia, western part of Guangdong Province, Gansu Province, and Shaanxi Province.

Figure 6a shows the variations of the solar radiation averaged over all CMA stations in the entire China, with the least-order fitted linear curve and second-order curve. The linear trend (in solid line) of the surface solar radiation is negative at 0.11 $\mathrm{W\,m^{-2}\,yr^{-1}}$ and it is significant at a 95% level of confidence. It is worth noting that the transition from dimming to brightening from the late 1980s to the early 1990s did not apparently happen in our result, though it was reported in previous studies (Che et al., 2005; Liang et al., 2005; Shi et al., 2008; Ye et al., 2009). In fact, the decreasing trend just slowed down and reached a steadily low level after the 1990s. This difference can be due to the data quality inconsistence in the measured data. As shown in Tang et al. (2010), there was an abruptly increase at some stations around 1993–1994, when CMA upgraded its radiometers. The “jump” of the measured radiation, however, is not found in the radiation values derived from the ANN-based model and the hybrid model.

In order to extend our view to a longer time scale, time series between 1961 and 2006 are also analyzed after averaged over the 382 CMA stations. As shown in Fig. 6b, the annual mean solar radiation from 1961 to 2006 has a decreasing trend of about $-0.18\,\mathrm{W\,m^{-2}\,yr^{-1}}$, with a significance of 95% level of confidence. The linear trend between 1961 and 1989 is negative and it is about $-0.20\,\mathrm{W\,m^{-2}\,yr^{-1}}$ with significance at a 95% level of confidence. However, the linear trend between 1990 and 2006 is negligible, suggesting the radiation recovery did not occur from the late 1980s to the early 1990s in China.

5 Trend discussions

5.1 Comparisons with previous studies

Several previously reported trends of surface solar radiation across China between 1961 and 2000 are compared with our result in Table 2. The number of radiation stations used in each study is also indicated in this table. The values reported by other studies are ranged from -0.41 to $-0.52\,\mathrm{W\,m^{-2}\,yr^{-1}}$, which are significantly greater in magnitude than the one in this study ($-0.19\,\mathrm{W\,m^{-2}\,yr^{-1}}$). This large discrepancy is mainly attributed to some shortage and uncertainties in the previous studies, as explained below.

First, the large scale of new instruments retrofit to the CMA radiation stations around the early 1990s and irregular calibration operations might have introduced inconsistency in data quality, but the observed radiation data without data quality control were used for the trend analysis in some previous studies. Some studies may have introduced a quality control scheme in their investigation, but uncertainties still presented, as substitution of erroneous data by climatological values were applied to produce their final results. Second, data provided by a station is not always at the same location in some cases because this station moved from one place to another one. For example: Yantai was moved to Fushan in 1992; Chongqing moved to Shapingba in 1988; Changsha relocated in the same city in 1988; and Longhua (Shanghai) relocated within Shanghai in 1991. Unfortunately, these stations were used for trend analysis in some previous studies. All these uncertainties or problems may have distorted the radiation trend, but they are largely avoided in the present study and therefore a more accuracy value of about $-0.19\,\mathrm{W\,m^{-2}\,yr^{-1}}$ is obtained.

One may suppose that the smaller trend in this study is due to the representativeness of the stations used. Previous studies only used the sparsely distributed radiation stations while this study used all available routine meteorological stations. Theoretically speaking, the latter will be more representative of the whole China. To quantify the effect of the representativeness of the radiation stations on the trend over China, we re-calculated the trend at the 71 radiation stations between 1961 and 2000 by the ANN-based model and the one at 72 radiation stations by the hybrid model. The averaged trends derived by the two models are both $-0.21\,\mathrm{W\,m^{-2}\,yr^{-1}}$. In other words, only a small part of the trend difference between this study and previous studies can be accounted for by the limited representativeness of the radiation stations. To further show this issue, we compare the sunshine trends between the average over 84 radiation stations and the 592 routine stations during 1979–2006. Figure 7 shows that the sunshine trend averaged over the 84 radiation stations is very close to the one averaged over the 582 radiation stations. Again, this indicates that the trend represented at the radiation stations can represent the trend in the entire China approximately.

In other words, the significantly more negative trends in previous studies are not mainly attributed to the representativeness of the radiation stations but the quality inconsistence of the original radiation data.

5.2 Comparisons with satellite-based estimate

The globally-available Global Energy and Water Cycle Experiments – Surface Radiation Budget (GEWEX-SRB; Cox et al., 2006) product provides the possibility to estimate the radiation trend worldwide. Figure 8 compares the annual mean solar radiation time series from 1984 to 2006 averaged over the 592 stations between the satellites estimates and the present estimates from the hybrid model. Both estimates exhibit that surface solar radiation over China experiences a decreasing process, but the satellite-derived trend is much larger in magnitude than the one derived by the hybrid model. This could indicate that the trend derived from the GEWEX-SRB product over the entire China is also overestimated. To further verify this, Fig. 9 shows the trend comparison between the satellite estimate and the observation at the ten validation stations selected in Sect. 3. The trends derived from the GEWEX-SRB product are negative at all the 10 validation stations, and most of them are inconsistent with the observed ones. Their correlation coefficient is only 0.12. Therefore, the ability of satellites to explore variations of surface solar radiation needs to be improved, at least over China.

5.3 Trend over the Tibetan Plateau

Figure 10 presents variation of surface solar radiation during 1979–2006 over the Tibetan Plateau by averaging the hybrid estimation at 75 stations. A decreasing trend about $-0.26\,\mathrm{W\,m^{-2}\,yr^{-1}}$ is found over this region, which is much higher in magnitude than the one of the whole China ($-0.11\,\mathrm{W\,m^{-2}\,yr^{-1}}$). As indicated by Wang et al. (2009), aerosols loads increased on average over all continental regions between 1979 and 2006, which is especially obvious in South and East Asia (including India and China). This seems to a possible reason for the decline of surface solar radiation across China in recent decades. However, this does not help explain the decrease of solar radiation in the Tibetan Plateau, where human activities are still limited as far as the aerosol loads are concerned. This indicates that the decreasing of surface radiation in China could not be merely simply explained by the increasing aerosols emissions and may happen in a large-scale background for the whole climatic change.

6 Conclusions

In this study, we revisited the solar radiation trend over China by radiation observations and two radiation models. One is the ANN-based model, which can estimate surface solar radiation at all radiation stations, and the other is a physical one, which can estimate surface solar radiation at all 716 CMA stations from sunshine duration data and other routine meteorological data. These two models prove to be able to estimate the radiation trend after evaluations against observed radiation trends at ten stations with reliable long-term radiation records. The two models also show comparable estimates of the radiation trends at the radiation stations, and particularly, the hybrid model provides a means to estimate the radiation trend at all CMA routine stations.

The new estimate confirms that there was a decline of surface solar radiation in the entire China since the 1960s, as indicated in previous studies. However, the magnitudes of the decreasing rate are different. This study suggests the trend is

$-0.19\,\mathrm{W\,m^{-2}\,yr^{-1}}$ during 1961–2000, whereas previous studies gave much larger values in magnitude, ranging from -0.41 to $-0.52\,\mathrm{W\,m^{-2}\,yr^{-1}}$. Meanwhile, it is found that the trend over China was also overestimated by the GEWEX-SRB satellite observation. Another striking result that differs from previous studies is that the radiation reached a stable level since 1990, and the phenomenon of the transition from dimming to brightening around the year 1990 in China was not observed, at least not significant, although it was reported in several previous studies. Previous conclusions possibly resulted from radiation data with poor quality, since erroneous and suspected data often exist. In contrast, the new trend excluded this deficiency with the aid of the models.

Increasing emissions of aerosols might contribute to the decline of surface solar radiation over the entire China in recent decades. However, the aerosol loads made by human activities are still negligible in the Tibetan Plateau, but the decreasing rate of solar radiation over the Plateau was much larger in magnitude than that of the whole China. This phenomenon cannot be fully explained by the increasing emissions of aerosols, and further investigations are needed to understand the radiation variations over China.

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Table 1. Replacement of the radiation data collecting from four additional radiation stations (see the text).

Station number	Year	Problem month	Number of effective daily data available in problem month	Monthly-mean of observation data (W m^{-2})	Monthly-mean of ANN estimations (W m^{-2})
53614	1987	9	12	191.4	205.3
56959	1995	8	11	175.2	158.4
58208	1990	7	18	249.8	223.2
59287	1983	2	16	64.9	53.1
	1983	3	19	84.6	71.7
	1990	12	14	106.5	127.4

Table 2. Comparison solar radiation trends across China during 1961–2000 between previous reports and present study. "Present study" denotes trend derived by the hybrid model at 382 CMA stations.

Authors	Collected observation data (Number of Stations)	Trend ($\mathrm{W\,m^{-2}\,yr^{-1}}$)
Che et al. (2005)	64	−0.45
Liang et al. (2005)	42	−0.52
Shi et al. (2008)	72	−0.41
Present study	382	−0.19

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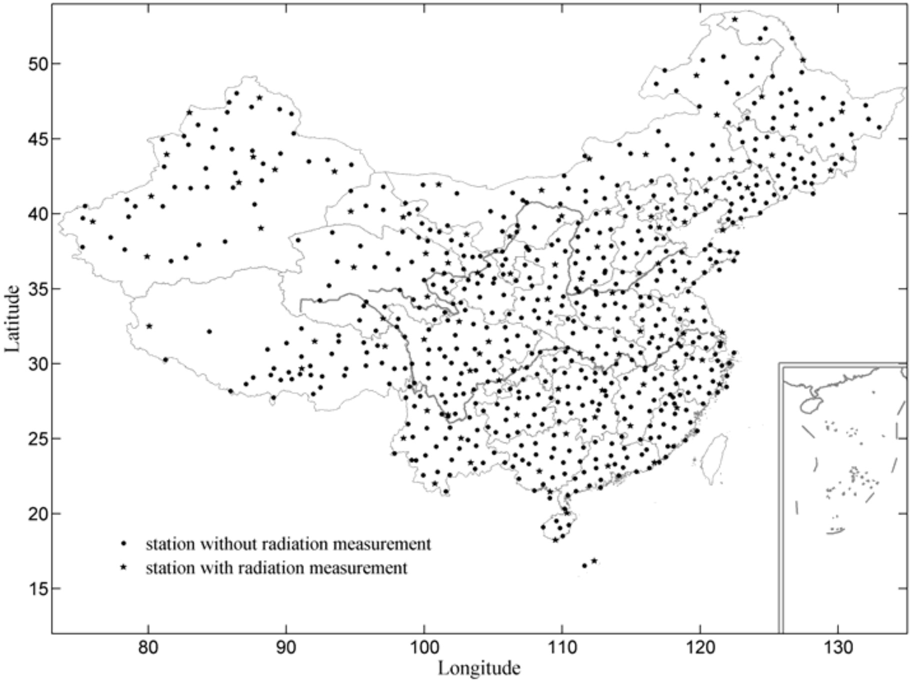

Fig. 1. The spatial distribution of 716 CMA stations, among which there are 96 radiation stations denoted by star symbols.

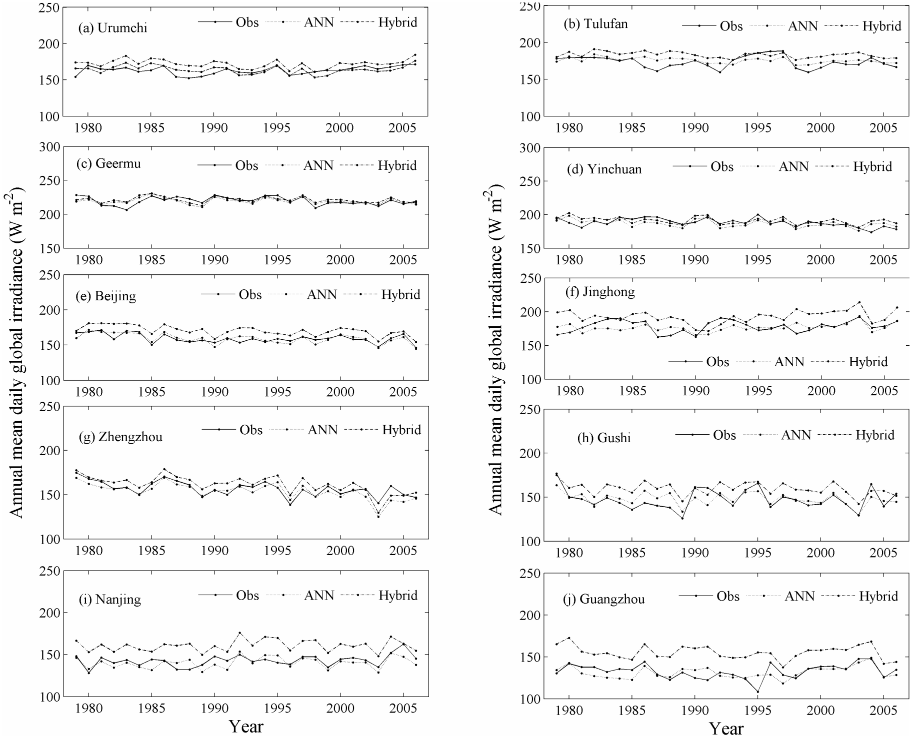

Fig. 2. Comparison of the annual mean daily solar irradiance time series during 1979–2006 among the observed, the estimated by the ANN-based model, and the estimated by the hybrid model at ten radiation stations.

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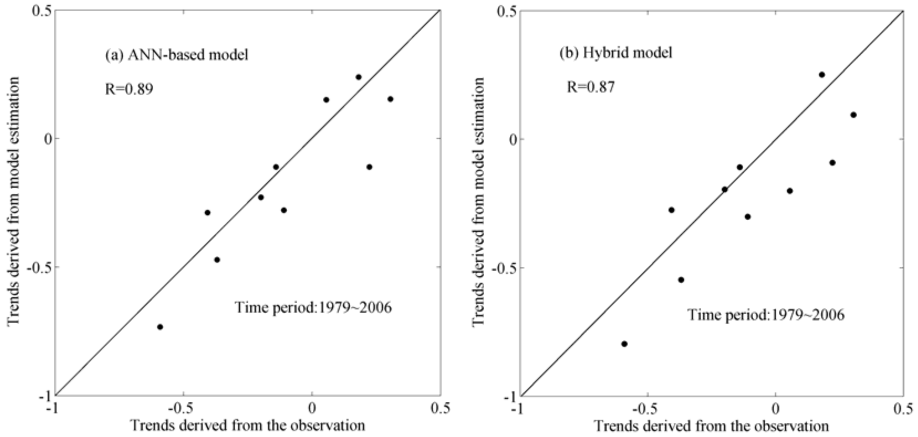

Fig. 3. Solar radiation trends comparison between the observation and the ANN-based model estimation and the hybrid model estimation at ten validation stations during 1979–2006. The unit of the trend is $\mathrm{W\,m^{-2}\,yr^{-1}}$.

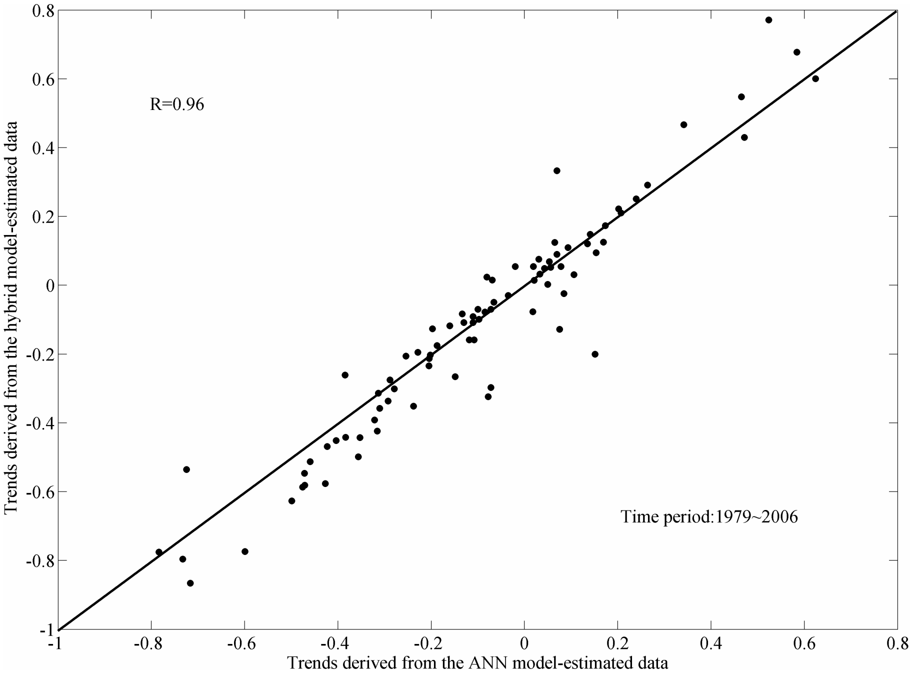

Fig. 4. Solar radiation trends comparison between the ANN-based model estimation and the hybrid model estimation at 84 radiation stations during 1979–2006.

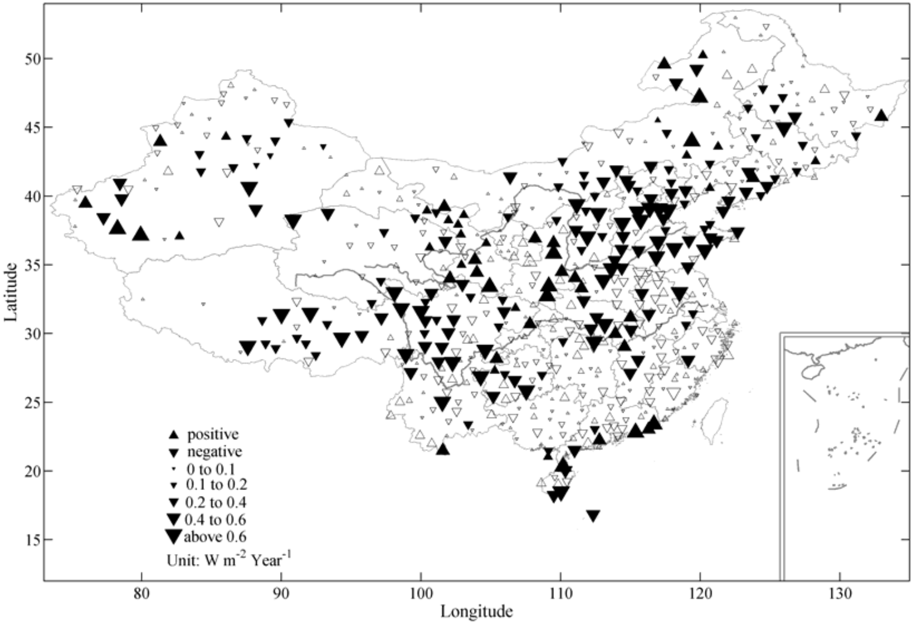

Fig. 5. Spatial distribution of the trends of annual mean solar radiation estimated by the hybrid model from 1979 to 2006 at 592 stations.

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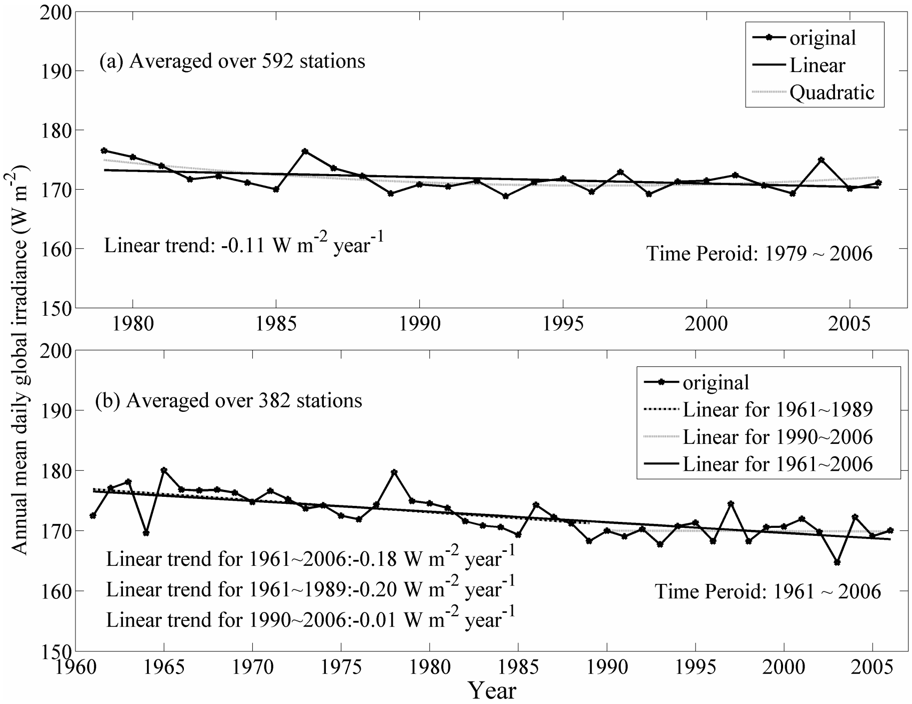

Fig. 6. The hybrid model-derived time series of the annual mean daily solar irradiance: **(a)** averaged over 592 stations during 1979–2006, and **(b)** averaged over 382 stations during 1961–2006.

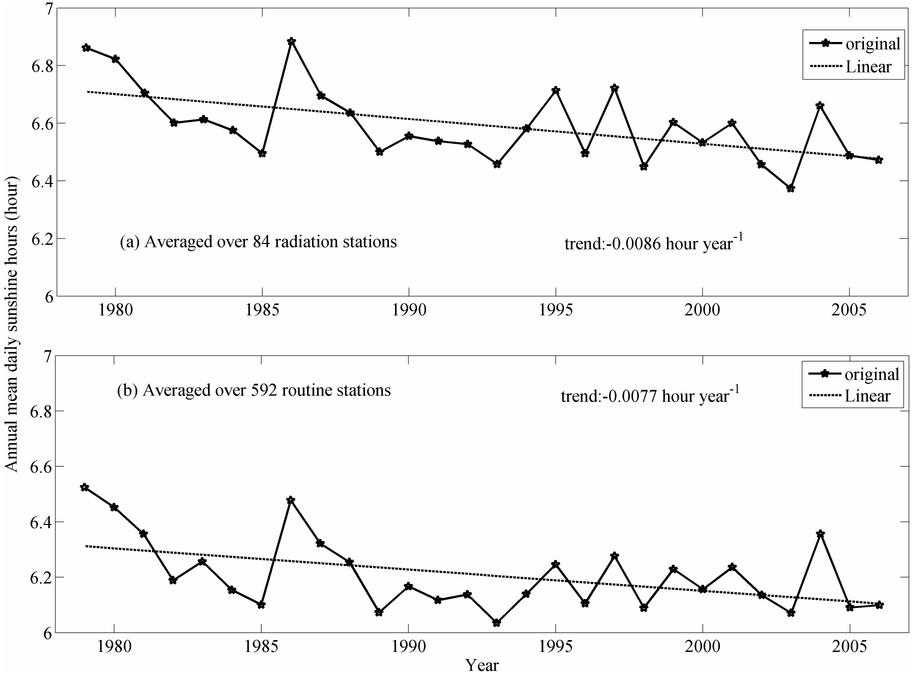

Fig. 7. Time series of annual mean daily sunshine hours during 1979–2006: **(a)** averaged over 84 radiation stations, and **(b)** averaged over 592 routine stations.

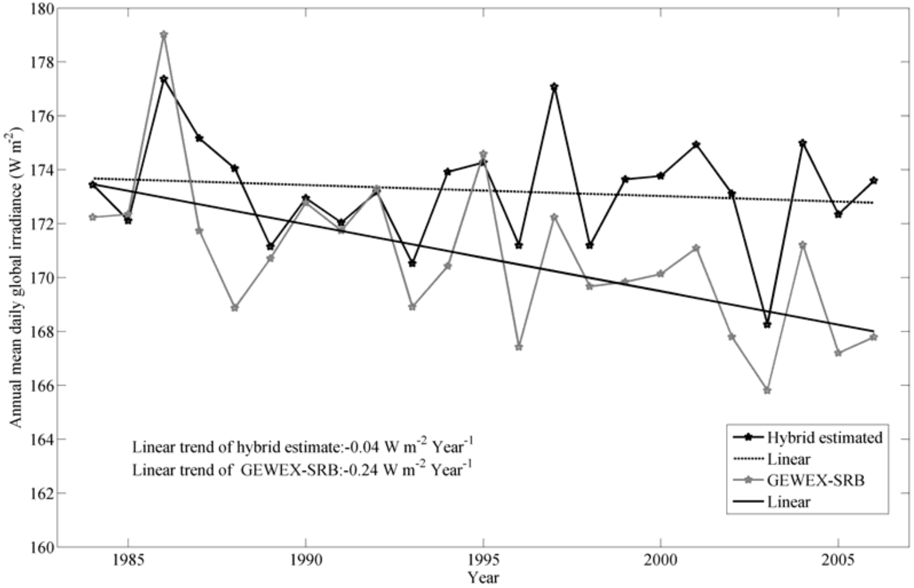

Fig. 8. Comparison of annual mean daily solar irradiance during 1984–2006 between the satellite estimates (GEWEX-SRB) and the hybrid model estimates averaged over 592 routine stations.

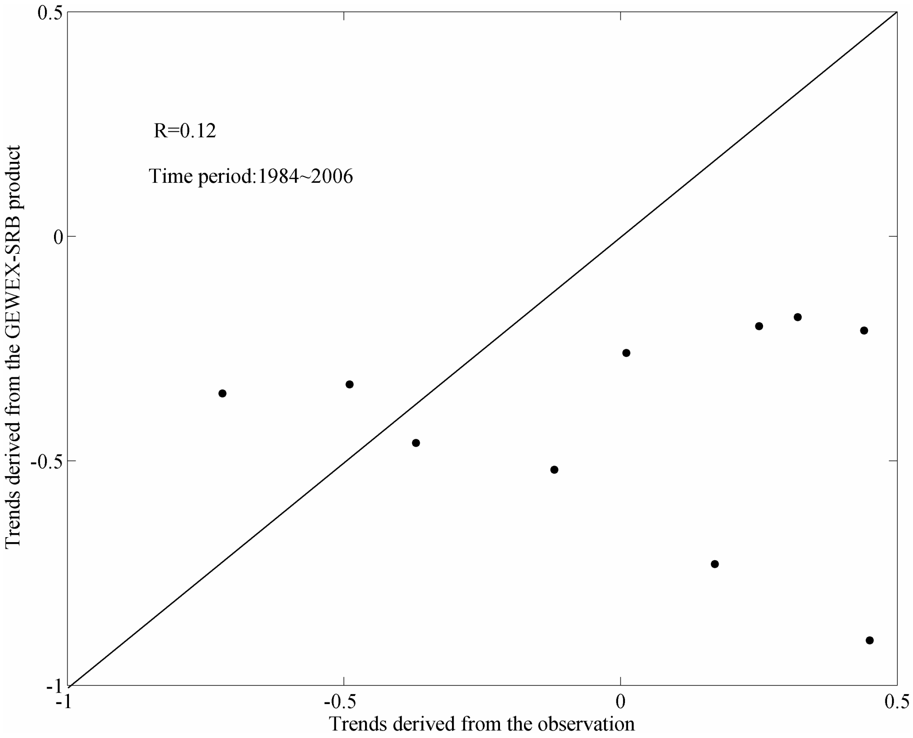

Fig. 9. Comparison of radiation trend during 1984–2006 between the observation and the GEWEX-SRB product at ten validation stations. The unit of the trend is $\mathrm{W\,m^{-2}\,yr^{-1}}$.

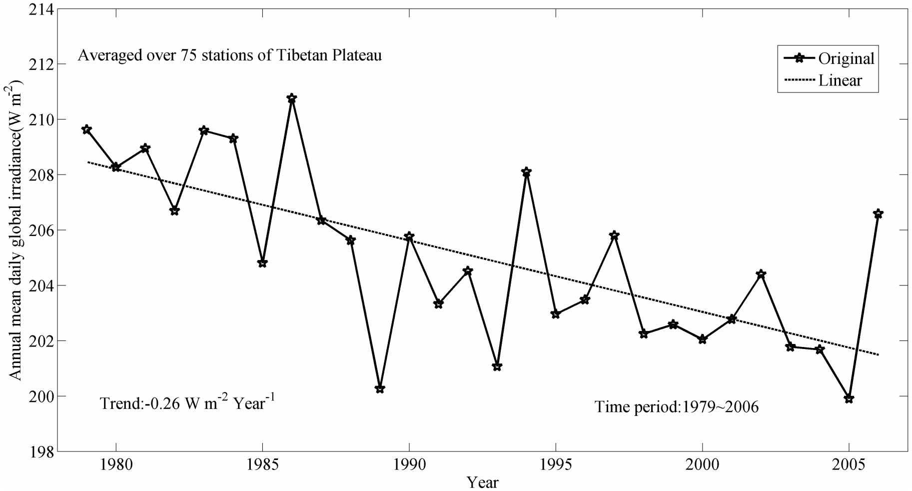

Fig. 10. Time series of annual mean daily global irradiance averaged over 75 stations in Tibetan Plateau during 1979–2006.