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Factors affecting the surface radiation trends over China between 1960 and 2000

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ABSTRACT

In this paper, the surface solar radiation data from 1960 to 2000 gathered from 40 weather stations over China were reexamined, and the relationship of long-term trends of the solar radiation and climate factors were analyzed. The results indicate that the surface solar radiation in most regions of China begins to increase after 1990. Decreases in cirrus and cirrostratus clouds, which account for a larger percentage of the total cloud amount over China, have an important contribution to the increasing trend of the surface solar radiation. Further examination of the surface water vapor changes reveals that the surface solar radiation negatively correlates with the near surface water vapor in most region of China, and this negative correlation is more pronounced in higher latitudes of China where the atmosphere is compared to regions in southern China.

1. Introduction

During the past decades, precipitation, temperature, evaporation, sea level pressure and vegetation cover have changed significantly (Easterling et al., 1997; Henderson-Sellers, 1986; Liu et al., 2004). Among various climate factors, the solar radiation variation is the most dramatic. Previous studies have showed that both the surface solar radiation and atmospheric visibility in China exhibit a decreasing trend from 1961 to 1990 (Li et al., 1998). This decadal surface global radiation variation does not match continued surface temperature increases in most regions of China. Similar results were found in other regions of the world (Stanhill and Moreshet, 1992; Peterson et al., 2002; Lawrimore and Peterson, 2000; Roderick and Farquhar, 2002). Che et al. (2005) analyzed the direct and diffuse solar radiation before 1990 in China and concluded that decreased surface solar radiation is mainly resulted from increased emissions of anthropogenic aerosols, especially in the eastern part of the China. Qian et al. (2006) also pointed out that increasing aerosol loading from emissions of pollutants is responsible for the observed global radiation and diffuse radiation trends under cloud-free conditions. However, Liepert et al. (1994) found that the surface solar radiation data in Germany also has a decreasing trend between 1964 and 1990 and they attributed this decreasing trend to cloud changes over Germany. If cloud changes over China are also responsible for the decreasing surface solar radiation trend, the cloud cover over China should increase, but Kaiser (2000) reported a decreasing trend of cloud cover over China. Some other studies also found that the annual mean total cloud amount over China has a decreasing trend before 1990 (Liang and Xia, 2003; Qian et al., 2007).

A recent observational study by Wild et al. (2005) showed that global radiation in the last several years start increase. Pinker et al. (2005) found from satellite data that the surface solar radiation increased at a rate 0.16 Wm^{-2}/yr since 1990, which is consistent with decreasing cloudiness observed from satellite. They concluded that clouds are the most important modulator of solar radiation reaching the land surface.

Another prevailing opinion for the negative global radiation (GR) trend in China is related to greenhouse gases (GHGs). Qian et al. (2006) reported that the relativity humidity in China decreases since 1992 and they suggested that decreasing water vapor may be responsible for decreasing GR in China. However, this result does not coincide with average countrywide lower troposphere total atmospheric water vapor across China, which is increasing during 1970–1990 (Zhai and Zhou, 1997).

The studies mentioned above add our understanding on the radiation changes over China, but the factors impacting the radiation trends are still under debate. The relationships between long-term surface solar radiation changes and cloud or aerosol changes are still a subject of much debate. In these previous studies which used the observational data of China, the analysis mainly based on the data from large cities (Capital cities of provinces of China) and limited sites of China, which sustain heavy pollution. However, aerosol emissions are much lower in small cities than in big cities.

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An investigation of GR decadal variations in a broader area which covers both large and small cities can help clarify the effects of aerosols and cloud cover on the GR trend in China.

In this paper, we re-examine surface solar radiation data over China in an attempt to provide more understanding of GR changes in China. The GR changes are investigated on different climate regions over China. As previous studies (e.g., Che et al., 2005, 2007; Qian and Giorgi, 2000, Qian et al., 2006) have investigated radiation changes in cloudy and cloud-free conditions. We will focus mainly on the effects of clouds, alto-clouds in particular, on the GR trend over China. We also analyzed potential relationships between changing solar radiation and water vapor trends.

2. Data

This study will first discuss the regional surface radiation trends in the context of the climate regions of China classified by Zhang et al. (1985). The study area is divided into 8 climate regions (Fig. 1), i.e., the Western arid/semi-arid regions (WA), Tibetan plateau (TP), Eastern arid regions (EA), Southwest China (SW), North China (NC), Central China (CC), South China (SC) and Northeast China (NE). In each region, 3 or 4 stations with long-term records were chosen to analyze the surface solar radiation trend and its relationship with other climatological parameters.

Monthly mean radiation, water vapor data from 1961 to 2000 were also collected from 40 weather stations in China. It is well known that the instrumental record for the early part of this period had some biases such as lack of temperature compensation. According to a World Radiation Revised (WRR) suggestion, radiation values were multiplied 1.022 before 1981. The above datasets have also been calibrated and used by Che et al. (2005). Recently, Shi et al. (2007) reported that the percentage of erroneous and suspicious data is 0.77% with the monthly GR in above data after taking data preprocessing. Cirrus and cirrostratus clouds data are extracted from NOAA ISCCP data set. ISCCP collects and analyzes satellite radiance measurements to infer global distributions of clouds, and their diurnal, seasonal, and interannual variations. Data covers the period from July 1983 to 2009. In this study we use the ISCCP-D2 monthly mean cloud amount data from 1983 to 2000. The ISCCP cloud amount actually represents fractional area coverage of clouds. In the gridded ISCCP products, several cloud types are defined to give more detailed information on the variations of cloud properties. In this investigation, we only use the cirrus and cirrostratus clouds data since alto-clouds are supposed to have a greater impact on the solar radiation reaches the Earth's surface. The Interpolated OLR (outgoing long wave radiation) data, which serves as a proxy for total cloud amount, is provided by National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences (NOAA-CIRES).

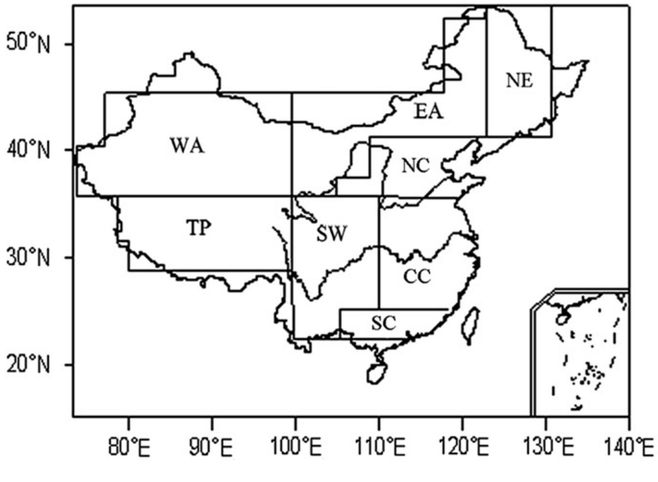

Fig. 1. The Climatic regions used in this study (classified by Zhang et al., 1985). 1. WA (Western arid/semi-arid regions), 2. TP (Tibetan plateau), 3. EA (Eastern arid regions), 4. SW (Southwest China), 5. NC (North China), 6. CC (Central China), 7. SC(South China), 8. NE (Northeast China).

3. The radiation change over China between 1960 and 2000

Fig. 2 shows the trends of the surface solar radiation in different time periods. The surface solar radiation in most regions of China decreased from 1961 to 1980. The lowest values were observed during the period from 1981 to 1990. The surface solar radiation over most regions of China then exhibits an increasing trend from 1991 to 1999 except in the NC where the surface solar radiation continues to decrease (Fig. 2).

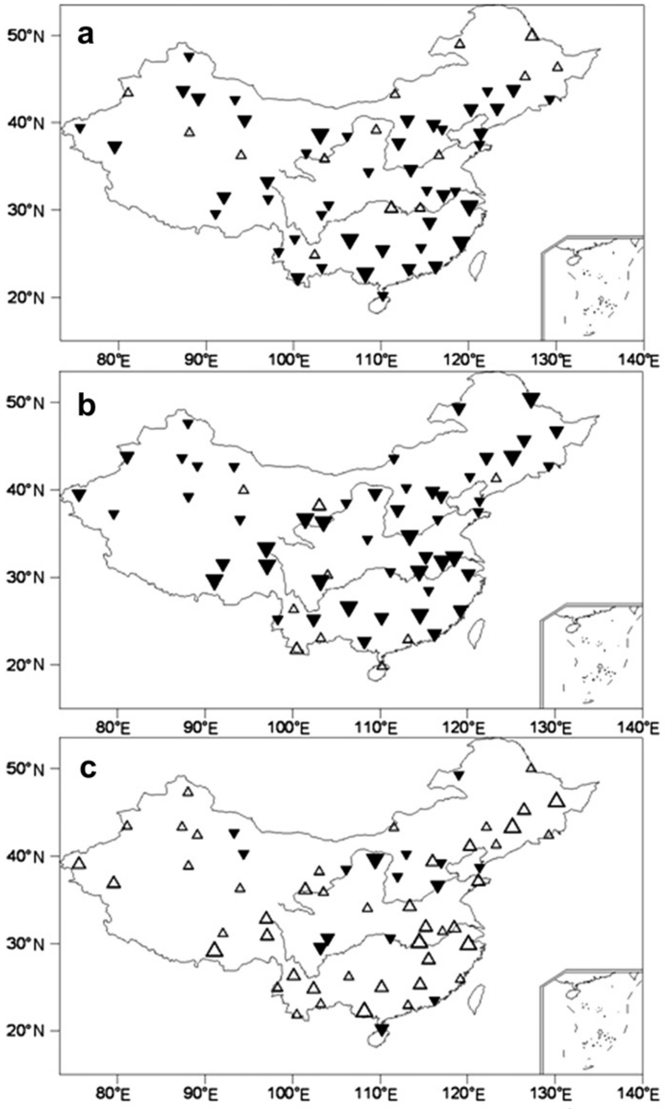

Fig. 2. The trends of the surface solar radiation in different time period: (a) 1970s–1960s; (b) 1980s–1970s and (c) 1990s–1980s (up-triangle denotes increasing trend, and down-triangle denotes decreasing trend, and the size of triangles is proportional to magnitudes of the trends.).

Table 1
Decade change rates (%) of the surface solar radiation in 8 climate regions.

Years	WA	TP	EA	SW	NC	CC	SC	NE
1970–1960	−3.62	1.84	−3.43	−6.57	−4.34	−6.71	−7.34	−1.41
1980–1970	−2.56	−14.75	−5.29	−9.91	−6.93	−11.63	−6.02	−6.40
1990–1980	−0.37	10.37	7.03	10.16	−1.64	6.35	20.07	8.16

Decadal change rates of surface solar radiation in the 8 climate regions are listed in Table 1. We can see that surface solar radiation changes have evident spatial variation. The surface solar radiation over CC and TP changed most significantly and decreased by 11% and 12%, respectively, during 1970–1980. It is also obvious that surface solar radiation increases during the period 1980–1990 except in NC. The radiation changes in WA are less significant. After 1990, the largest change occurred in SC with a 20% increase.

Fig. 3 shows the seasonal GR trends. Note that GR trends are overall consistent in different seasons. However, the trends in spring and fall are not always smaller than that in winter. Also note that the seasonal trends of the surface solar radiation have significant spatial variation.

Figs. 2 and 3 indicates that the surface solar radiation changes in most regions of China have a similar variation. The surface solar radiation decreased in 1970–1990 and started increasing after 1990. The long-term surface solar radiation changes can be classified into two types: persistent/continuous decrease (in WA, NE and NC) and parabolic change (in the other regions). The parabolic

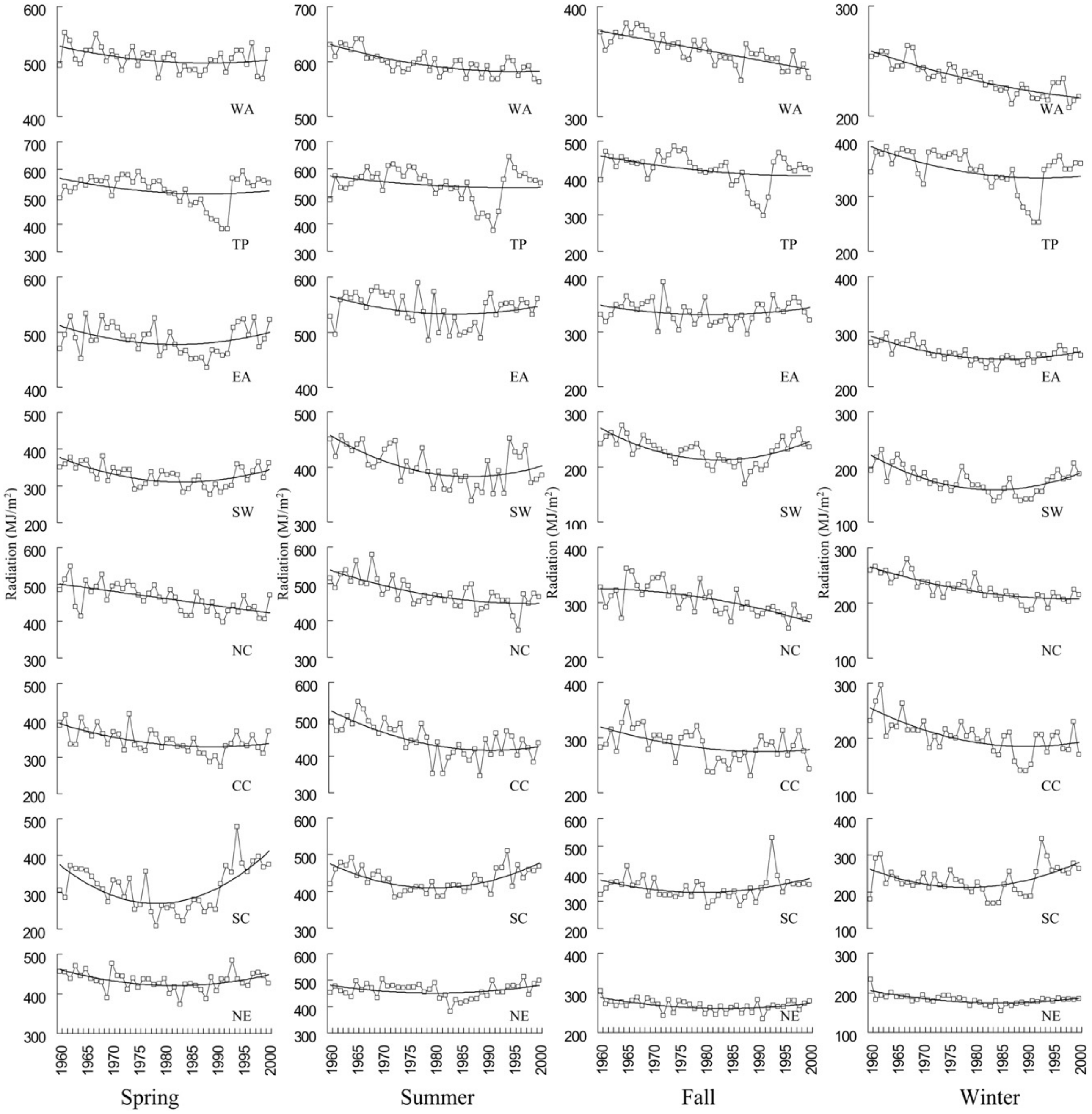

Fig. 3. The long-term trends of the GR solar radiation of four seasons in different climate regions of China (the radiation unit is MJ/m^2).

change is characterized by decreasing surface solar radiation through the 1970s, followed by an increasing in the 1980s.

4. Effect of alto-clouds on GR trend

Previous studies have showed that cloud cover is a major modulator of solar radiation reaching the surface. Some observational studies reported that global total cloud decreases in the 1980s (Ding et al., 2004, Liu et al., 2003), although the decreases in total cloud in most regions of China start later than 1980s. In order to further investigate the effect of clouds on the surface GR, Fig. 4 shows long-term changes in surface solar radiation, atmospheric optical depth (AOD), total cloud and OLR averaged over China. Note that the trends of the global radiation and the cloud cover are opposite to each other, suggesting that a decease/increase in clouds corresponds to an increase/decrease in the GR. The observed cloud cover measured by satellite also shows a negative trend in China from 1984 to 2000 (Kaiser, 1993, 1998, 2000; Kaiser and Vose, 1997), which is in accordance with the positive surface solar radiation trend. These results indicate that cloud is a crucial factor impacting on the GR.

From Fig. 4 we can see that both the OLR (a proxy for total cloud amount) (Liebmann and Smith, 1996; Takahashi et al., 2009) and cloud cover observed from the surface decrease after 1990, but an increase can be noted around 1995, and then decreases again. As we know, the surface absorbs short wave radiation and emits long wave radiation and warms the atmosphere. Fig. 4 indicates that both the OLR and GR have the same trends, i.e., the temperature trend is closely correlated with the OLR trend. The AOD has been increasing before 1990 (Luo et al., 2001), suggesting that negative surface solar radiation trends before 1990 can be attributed at least partly to increases in aerosol loading over China (Fig. 4b). But the trend in the GR reverses after 1986, while there is no sufficient evidence that aerosols are decreasing in these regions in the recent years. Therefore, the change in aerosol loading is not a sole factor that impacts on the GR trend.

Table 2 lists the correlations between GR and cloud cover over different climate regions of China. We can see that there is a large negative correlation between total cloud cover and GR in EA, CC, but in other regions, correlations between GR and total cloud cover are relatively small. Table 2 also indicates that there are significant negative correlations between alto-cloud cover and the GR, particularly in TP, EA, SW, NE (over 99% significance level). Cirrostratus clouds are strongly correlated with surface solar radiation in NE, WA. This is because cirrus and cirrostratus are mainly ice particles, which can significantly weaken the GR through reflection and scatting of the solar radiation. In CC, although the correlation between GR and both cirrostratus and cirrus clouds are less significant, the effect of total cloud on the GR change is evident. This result is in contrast to the results of Qian et al. (2007). One possible reason for this discrepancy is that the cloud cover in China used by Qian et al. (2007) is observed in midday (Kaiser, 2000), while the cloud cover in our study is from ISCCP. Kaiser (2000) also pointed out that it is much more difficult to accurately estimate cloud amount at night, especially when thin cirrus clouds are present.

Fig. 5 shows long-term trends in cirrus, cirrostratus and cirrus + cirrostratus, as well as the correlations between the surface solar radiation and the clouds all over China. We can see that cirrus and cirrus + cirrostratus clouds exhibit a negative trend from 1984 to 2000, while cirrostratus amount shows a positive trend after 1990. Recall that the GR trend is positive after 1990 implying that the contribution of cirrostratus in the GR change is greater than that of cirrus. As cirrostratus clouds are generally mixed with ice particles and water droplets while cirrus clouds are all ice particles, it is understandable that cirrostratus clouds can have a more significant impact on the GR change than cirrus clouds.

Fig. 6 further shows the percentage distribution of cirrus and cirrostratus in total clouds at different climate regions. The percentage cirrus and cirrostratus amounts within each climate regions are the averages of the ISCCP gridded data for time period from 1984 to 2000 over all grid points within a corresponding climate region. We can see that cirrus and cirrostratus clouds account for a larger percentage of total cloud amounts over China. Though cirrus fractions over SW, CC, SC and NE are all less than 30% of total cloud cover and cirrostratus is less than 30% in all regions, but the sum of cirrostratus and cirrus amount is greater than 30% except in CC. This further confirms that alto-clouds are the most important modulator of the solar radiation over China.

Previous studies have showed that aerosols also have a large impact on the surface solar radiation trend (Chuang and Penner, 1996; Russak, 1990; Qian et al., 2006; Che et al., 2005). Some studies pointed out that volcanic eruptions could cause significant increases in atmospheric aerosol loading, hence weakening the solar radiation reaching the surface (Lukac, 1994; Cadle et al., 1976). We have also mentioned above that aerosols may be responsible for the positive GR trend before 1990. It is worth noting that the famous Pinatubo volcano eruption happened in 1991, surface solar radiation minima occurred before 1991 in most regions of China

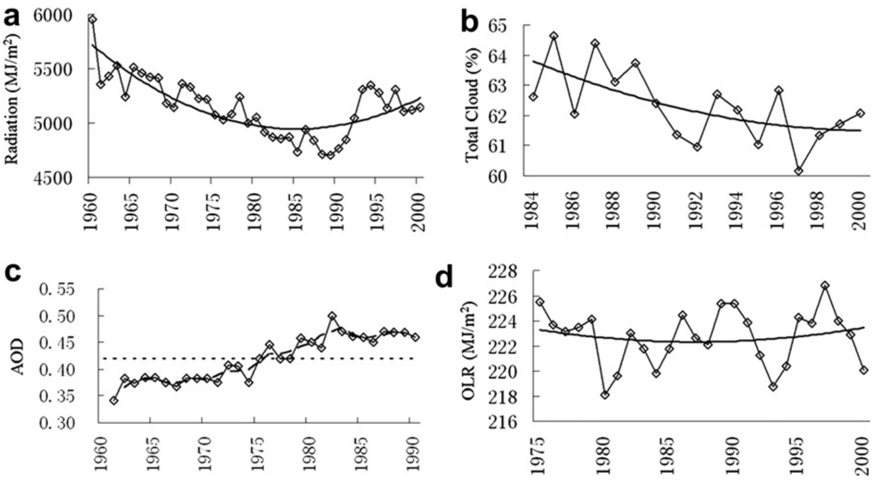

Fig. 4. The long-term variations of (a) the surface solar radiation (MJ/m^2), (b) atmosphere optical depth (AOD) (Luo et al., 2000), (c) total cloud (%), and (d) outgoing long wave radiation (OLR: W/m^2) averaged over China.

Table 2
Correlations between the surface solar radiation and clouds in 8 climate regions based on the data the period from1961 to 2000.

	WA	TP	EA	SW	NC	CC	SC	NE
Cirrus	−0.16	−0.48[a]	−0.60[b]	−0.68[b]	0.28	−0.10	−0.16	−0.68[b]
Cirrostratus	−0.62[b]	−0.17	−0.23	−0.37	−0.38	0.04	−0.09	−0.53[a]
Cirrus & Cirrostratus	−0.35	−0.53[a]	−0.67[b]	−0.79[b]	0.14	−0.08	−0.10	−0.71[b]
Total cloud	−0.21	−0.18	−0.67[b]	−0.38	−0.24	−0.55[a]	−0.14	−0.27

[a] $\alpha = 0.05$.
[b] $\alpha = 0.01$.

(except TP and SW). Therefore, changes in clouds after 1990 is more likely responsible for the positive surface solar radiation trend.

5. The connections between the radiation trend and near surface water vapor

The analysis in Section 4 reveals that the clouds, particularly alto-clouds are mainly responsible for the surface solar radiation trends in China. However, Qian et al. (2006) suggested that decreasing water vapor may be also responsible for decreasing GR in China. Thomas (2000) reported that sunshine strongly associated with evapotranspiration changes in south of 35°N of China. In this section, we further examine whether the water vapor changes also have a contribution to the surface solar radiation trends in China.

Fig. 7 shows long-term trends in near surface water vapor pressure and GR anomaly. Note that the water vapor pressure exhibits an overall increasing trend in all climate regions from 1961 to 2000. Zhai and Zhou (1997) also showed that the average countrywide atmospheric water vapor has increased since 1978, particularly in the lower troposphere over NC, SW and SC (note in their definition SC includes CC and SC of this paper). The water vapor trends in Fig. 7 have large spatial variations. The increasing trends of the near surface water vapor in SW, CC, NE is obviously less significant than those in other regions.

Due to the absorption of solar radiation by the atmospheric water vapor, increases in water vapor will cause decreases in

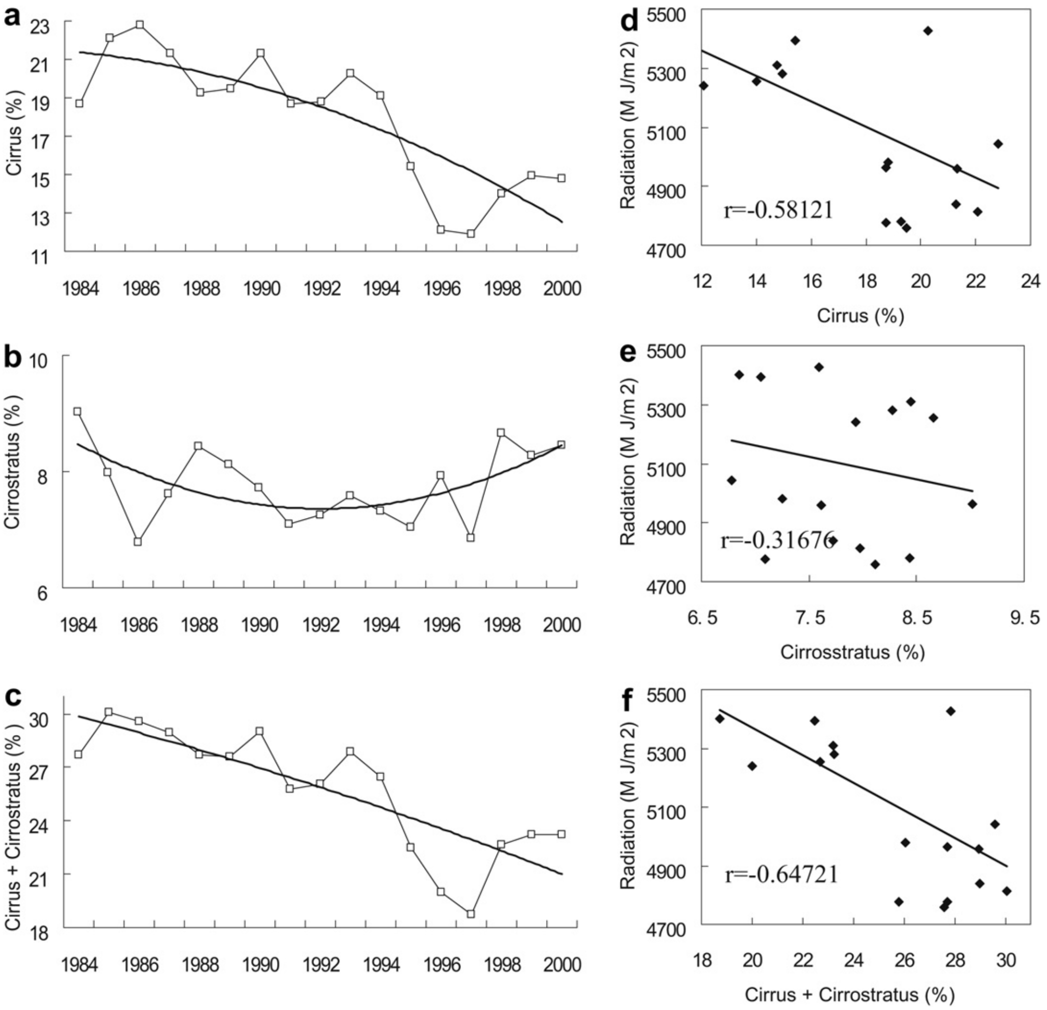

Fig. 5. Long-term trends of (a) cirrus, (b) cirrostratus and (c) cirrus + cirrostratus (%), also shown are the correlation plots between the surface solar radiation and (d) cirrus, (e) cirrostratus and (f) cirrus + cirrostratus (horizontal axis is cloud cover rate (%), and vertical axis is radiation (MJ/m^2). r represents correlation coefficients.

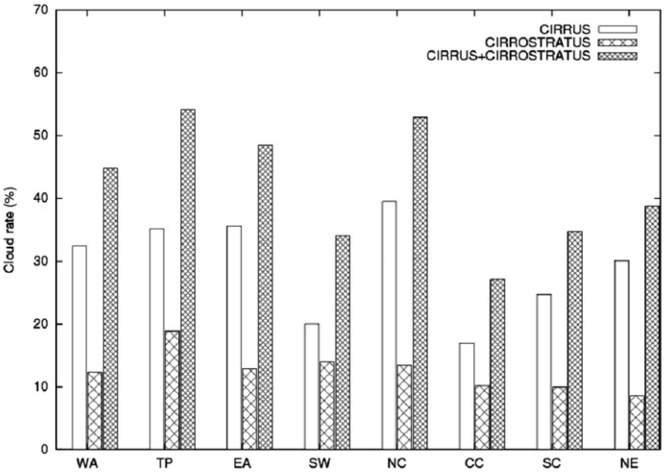

Fig. 6. The percentage distribution of cirrus and cirrostratus in total cloud at different climate regions. The percentage cirrus and cirrostratus amounts within each climate regions are the averages of the ISCCP gridded data for time period from 1984 to 2000 over all grid points within a corresponding climate region.

Table 3
Correlation coefficients between the GR and near surface water vapor pressure, for the period from1961 to 2000.

	WA	TP	EA	SW	NC	CC	SC	NE
e vs GR	−0.583[a]	−0.198	−0.196	0.251	−0.582[a]	−0.183	−0.008	−0.519[a]

[a] $\alpha = 0.01$.

surface solar radiation, i.e., the surface solar radiation should negatively correlated with the atmospheric water vapor. Fig. 7 indicates that surface solar radiation trends and the atmospheric water vapor trends in WA, NC, CC and NE regions have reversed signs, but in SC and SW, especially in SC where the atmospheric water vapor is more abundant, the near surface water vapor trends have the same sign as the surface radiation trends. The results here suggest that the atmospheric water vapor changes indeed have an anti correlation with the surface radiation changes, particularly in relatively dry regions of China.

Table 3 lists the correlation coefficients between the surface GR and the near surface water vapor. We can see that the GR has a significant negative correlation (at 90% confidence level) with the near surface water vapor. Comparing Table 2 with Table 3, we can find that regions with significant correlations between near surface water vapor and GR are also marked with significant correlations between alto-clouds and GR, such as in WA, NE except in NC. It is apparent from above analysis that both alto-clouds and the atmospheric water vapor can affect the long-term surface radiation trends. The relative importance of the alto-clouds and the lower tropospheric water vapor in modulating the long-term surface radiation trend is worth further investigation.

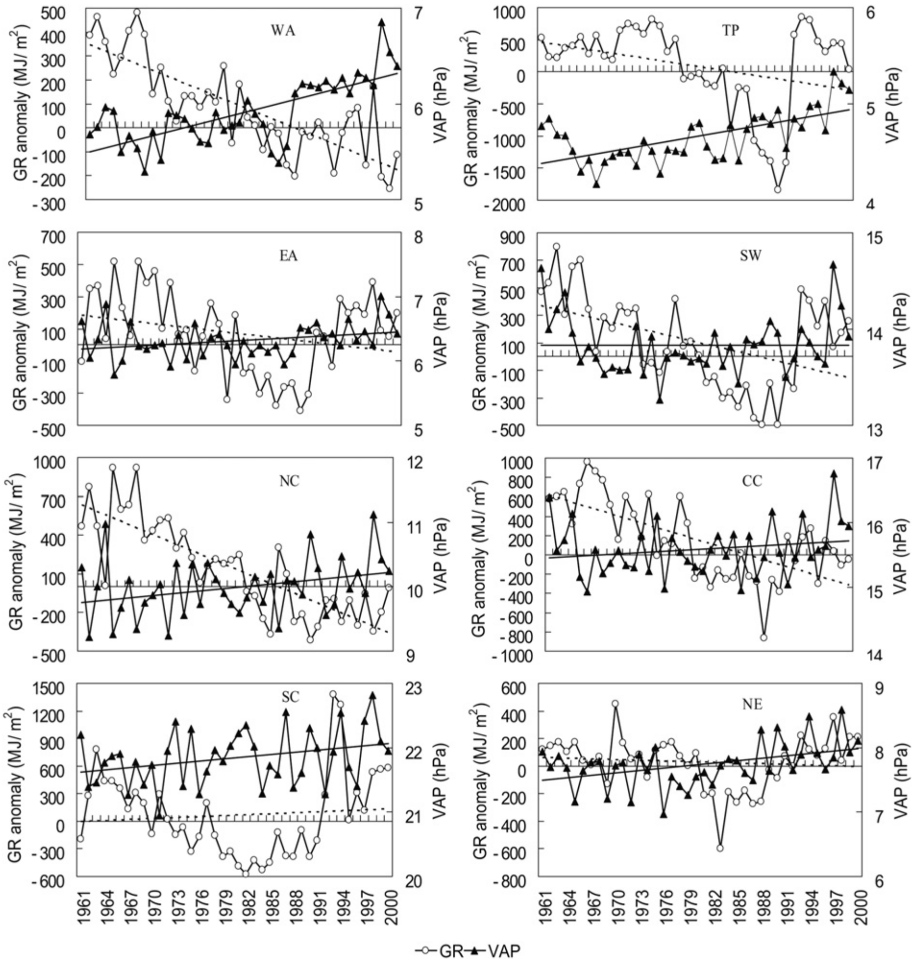

Fig. 7. Long-term trends in the surface solar radiation and water vapor pressure in different climate regions of China. Triangle and square lines indicate radiation and water vapor, respectively. The thin dash and solid lines indicate the trend of radiation and water vapor, respectively.

6. Summary and conclusion

In this study the long-term trends in the surface solar radiation in China are investigated using various observational data. Our analysis indicates that cirrus and cirrostratus account for a larger percentage of total cloud amounts over China and these alto-clouds have a large impact on the surface solar radiation trends in China.

An interesting result found in this study is that there is a strong correlation between the GR and alto-clouds in WA, EA, NE, where the near surface water vapor also increases since the late 1990's. The analysis suggests that the surface solar radiation negatively correlates with the near surface water vapor in most region of China. However, this negative correlation is more pronounced in regions at higher latitudes, for instance in WA, NE where the atmosphere is relatively dry compared to that in regions on southern China.

It should be pointed out that the solar radiation reaching the surface can be affected by various factors. To provide a complete and plausible explanation why radiation, cloud cover are changing in different manners, it requires more observational data combined with the numerical modeling to understand the relative importance of various climate factors in affecting the surface solar radiation trends.

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