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# A revisit to decadal change of aerosol optical depth and its impact on global radiation over China

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## HIGHLIGHTS

- AOD is retrieved by combining visibility data and MODIS aerosol data.
- Aerosols have considerable effect on global radiation climatology over China.
- Aerosol direct effect is not adequate to explain the decadal variations in global radiation over China.

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## ABSTRACT

Global radiation over China decreased between the 1960s and 1990, since when it has remained stable. As the total cloud cover has continued to decrease since the 1960s, variations in aerosols were suggested in previous studies to be the primary cause for variations in global radiation over China. However, the effect of aerosols on global radiation on a decadal scale has not been physically quantified over China. In this study, aerosol optical depth (AOD) data since 1980 are estimated by combining horizontal visibility data at stations in China and AOD observed by the moderate resolution imaging spectroradiometer (MODIS). It is found that the AOD exhibits decadal changes, with two decreasing periods (before the end of 1980s and after 2006) and one increasing period (from 1990 to 2006). With the derived AOD, a clear-sky model is then applied to quantify the role of aerosols in the variations in global radiation over China. The results show that aerosol direct effect cannot fully explain the decadal variations in the global radiation over China between 1980 and 2010, though it has a considerable effect on global radiation climatology. There are significant differences between the trends of clear-sky global radiation impacted by aerosols and those of all-sky global radiation impacted by aerosols and clouds, and the correlation coefficient for the comparison is very low. Therefore, the variations in all-sky global radiation over China are likely to be due to changes in cloud properties and to interactions between clouds and aerosols.


## 1. Introduction

Global radiation $E_{g\downarrow}$ over most regions of the Earth experienced a transition from dimming to brightening around the late 1980s or early 1990s, based on ground observations and satellite retrievals (Stanhill and Moreshet, 1994; Stanhill and Cohen, 1997, 2001; Liepert, 2002; Wild et al., 2005; Che et al., 2005; Pinker et al., 2005; Shi et al., 2008; Gilgen et al., 2009; Stanhill and Cohen, 2009; Wild, 2009; Wild, 2012). Variations in global radiation $E_{g\downarrow}$ have profound influences on the environmental, societal, and economic aspects of our habitats. Decadal variations in global radiation $E_{g\downarrow}$ originate from changes in the transparency of the atmosphere, which are mainly attributable to changes in clouds, aerosols and water vapor (Wild, 2012). For example, a change in aerosol loading has been suggested as the dominant factor for long-term variations in global radiation over Europe (Norris and Wild, 2007; Ohmura, 2009; Folini and Wild, 2011), while changes in

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cloud cover are the determining factor for long-term variations in global radiation over the United States (Liepert, 2002; Long et al., 2009; Augustine and Dutton, 2013).

In China, several studies (e.g., Zhang et al., 2004; Che et al., 2005; Liang and Xia, 2005; Xia et al., 2006a; Streets et al., 2006; Wang et al., 2012; Wang and Yang, 2014) speculated that changes in atmospheric aerosols are the dominant cause for global radiation variations over China, given that the total cloud cover (TCC) measured at China Meteorological Administration (CMA) stations has decreased since 1954 (Kaiser, 1998; Kaiser, 2000; Qian et al., 2006; Xia, 2010). However, aerosol emissions over China continued increasing around 1990 (Wang et al., 2009) and so its variation does not explain the change in the radiation transition from dimming to slightly brightening around 1990. Indeed, Lin et al., (2015) established a statistical wind speed −global radiation relationship and with which derived that aerosol direct effect can only explain 20% of the decadal change in global radiation over China. Furthermore, it should be noted that a decrease in TCC does not necessarily correspond to a decrease in cloud optical thickness because of the diversity of possible cloud shapes and types. For example, Yang et al., (2012) found that the TCC over the Tibetan Plateau has decreased since 1984, while deep cloud cover has increased.

Aerosols over China have drawn much attention over the past decade, due to their potential effects on climate and the environment (Ramanathan et al., 2001; Wu et al., 2013; Rosenfeld et al., 2014). The annual mean aerosol optical depth (AOD) averaged over China is about three times that averaged over all the Aerosol Robotic Network (AERONET) sites (Li et al., 2011). The aerosol radiative effect over China can even reach to several tens of W $m^{-2}$ on global radiation climatology (Li et al., 2011), but physically-based quantitative evaluation of aerosol effects on long-term variations in global radiation over China is challenging for the following reasons.

First, a long-term observational dataset of aerosols over China is not available. However, visibility is a parameter that is routinely measured at weather stations. This parameter is often used to estimate near surface AOD (Vautard et al., 2009; Wang et al., 2009, 2012). Some radiation transfer software packages, such as MODerate resolution atmospheric TRANsmission (MODTRAN) and Second Simulation of a Satellite Signal in the Solar Spectrum (6S) (Berk et al., 1998; Vermote et al., 1997) also use visibility to characterize near surface AOD information.

Second, it is difficult to distinguish the effects of clouds, aerosols, water vapor and their interactions on long-term changes in global radiation (Wild et al., 2012). An analysis of long-term clear-sky global radiation may provide information that is useful for the evaluation of the effects of aerosols on variations in global radiation. Alternatively, using clear-sky radiation model with reliable source of aerosols can quantitatively evaluate the contribution of aerosols to long-term changes in clear-sky global radiation.

In this study, we first use the observed visibility data to characterize long-term variations in near surface AOD over China. We then use the MODIS monthly mean AOD to correct the visibility-based AOD before application. Although the visibility-based AOD may have great uncertainty, the long-term variation in the visibility-based AOD is relatively reliable (Wang et al., 2009). With the derived AOD data, we try to quantify the effect of aerosols on changes of clear-sky global radiation so as to evaluate the role of aerosols in global radiation variation over China. This may help us to further evaluate the causes of the variations in global radiation over China.

## 2. Data

Three types of data are used in this study. The first is the CMA routine weather data recorded at 519 stations where the data contain records for at least 20 days per month from 1980 to 2010. The CMA observation data comprise air temperature, relative humidity, surface pressure, sunshine duration, TCC, low cloud cover (LCC), and visibility. These data are used to estimate clear-sky and all-sky global radiation with Yang's hybrid model (Yang et al., 2006). Visual observations of cloud covers (includes TCC and LCC) and visibility are taken by trained observer following the World Meteorological Organizations (WMO) standards every 6 h (0:00, 6:00, 12:00, and 18:00 GMT) at each station. Daily mean values of these CMA data are used except visibility, for which the 6:00 GMT (14:00 Beijing Standard Time) values is used. The geographical distribution of the 519 stations is shown in Fig. 1. The second is the MODIS Level-3 monthly-mean AOD data (Aqua) from 2002 to 2010, which is used to correct the visibility-based AOD. The half-year climatology of MODIS AOD is also presented in Fig. 1. To investigate the decadal change of aerosols and its effect on long-term variations in global radiation at a regional scale, we divide mainland China into three sub-regions (see Fig. 1), following Lin et al., (2015), who defined the sub-regions according to the distribution of MODIS multi-year mean AOD. The region of central-eastern China (CE) exhibits the highest AOD values, and moderately lower AOD values are found in the region of southern China (SC). The other regions (OT), including northeastern China, northwestern China and the Tibetan Plateau have the lowest AOD among the three sub-regions. The third is the quality-controlled all-sky global radiation dataset ($E_{qc\downarrow}$, available at http://dam.itpcas.ac.cn), which is developed with two datasets by Tang et al., (2013). One is estimated with routine meteorological variables by Yang's hybrid model at 716 individual CMA stations, and the other is estimated with the Artificial Neural Network (ANN) based model at 96 individual CMA radiation stations. The former is dynamically corrected by the latter at a monthly scale because the accuracy of the latter is generally higher than the former. The quality-controlled all-sky global radiation dataset ($E_{qc\downarrow}$) was validated over China by Tang et al., (2013), and the relative mean bias error (MBE) and root mean square error (RMSE) to the measurements are about 0.8% and 12.7%, respectively. Tang et al., (2011) selected ten CMA radiation stations with continuous and quality-consistent measurements to validate the long-term variations in the all-sky global radiation estimated by Yang's hybrid model and the ANN-based model, and found that the long-term variations in the estimated global radiation are generally reliable. Thus, we may believe that the long-term variations of the quality-controlled all-sky global radiation dataset ($E_{qc\downarrow}$) are reliable. These all-sky global radiation data are compared with the clear-sky global radiation to quantify the role of aerosols in global radiation over China.

Two issues should be noted when deriving aerosol information from visibility data. One is that the haze information in visibility data is affected by the water vapor and naturally occurring hydrometeors (such as fog, rain and snow), which should be corrected and eliminated, respectively. Che et al., (2007) proposed a method to filter visibility data, in which three rules were used: (i) Only use the 6:00 GMT values to represent daily visibility because the noon observation of visibility is more representative than the other three ones (two in night and one in morning) (Wu et al., 2012); (ii) filter the visibility measurements for natural events such as fog, rain, snow; and (iii) exclude visibility measurements that correspond to a relative humidity of higher than 90%. In addition, the impact of relative humidity on visibility was also corrected following to the method reported in Che et al., (2007). Another issue is that different observation methods were used before and after 1980. Prior to 1980, visibility was recorded using 10 distance ranks, while after 1980 real distances were used. To avoid the uncertainty introduced by this difference in observation methods, we only use data