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Trends of the sunshine duration and diffuse radiation percentage on sunny days in urban agglomerations of China during 1960–2005

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A B S T R A C T

The long-term observational data of sunshine duration (SD) and diffuse radiation percentage (defined as diffuse solar radiation/total solar radiation, DRP) on sunny days during 1960–2005 were analyzed in 7 urban agglomerations and the whole of China. The results show that the sunny sunshine duration (SSD) has decreased significantly except at a few stations over northwestern China in the past 46 years. An obvious decrease of the SSD is found in eastern China, with the trend coefficients lower than −0.8. Accompanied by the SSD decline, the sunny diffuse radiation percentage (SDRP) in most stations shows obvious increasing trends during the 46 years. The averaged SDRP over China has increased 2.33% per decade, while the averaged SSD shows a decrease of −0.13 hr/day per decade. The correlation coefficient between SDRP and SSD is −0.88. SSD decreased over urban agglomerations (small to large city clusters) in the past 46 years, especially in large cities and medium cities, due to the strong anthropogenic activities and air pollution represented by aerosol option depth (AOD) and tropospheric column NO_2 ($TroNO_2$). On the regional scale, SSD has an opposite trend from SDRP during 1960 to 2005, and the variation trends of regional mean values of SSD and SDRP in southeastern China are more pronounced than those in northwestern China.

Introduction

China has become one of the most densely populated and rapidly industrialized regions of the world over the last decades. The rapid growth of population and human activities has caused a continuous increase in the emission of aerosols and their precursors (Qian et al., 2007; Shi et al., 2008; Wang et al., 2013). Such a remarkable increase in the emissions of pollutants can result in a significant increase in anthropogenic aerosol loading in the atmosphere, and can further impact the regional climate and hydrological cycle through aerosol radiative forcing (Ruckstuhl et al., 2010). Aerosols can directly attenuate surface solar radiation by scattering and absorbing solar radiation (direct effect), or indirectly attenuate surface solar radiation through their ability to act as cloud condensation nuclei (CCN), thereby increasing cloud

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reflectivity and lifetime (indirect effect), further reducing sunshine duration (Wang et al., 2012). The surface solar radiation in China declined significantly in total and the direct component from 1960 to 2000, but no significant linear trend exists for diffuse radiation (Che et al., 2005). The visibility over China during 1981–2005 showed a significant decreasing trend after 1990, at −2.1 km per decade (Che et al., 2007). Annual sunshine duration and total cloud cover have declined by −1.2% and −1.7% per decade during 1961 to 2005 over China (Xia, 2010). There have also been a number of studies focused on sunshine duration over the long term (Kaiser and Qian, 2002; Sanchez-Lorenzo et al., 2008) and solar radiation (Stanhill and Cohen, 2005; Li et al., 2012; Zhang et al., 2013) due to increasing levels of aerosols. However, the above-mentioned research mostly used sunshine duration data and solar radiation data under all weather conditions, and discussion of long-term trends and relationships between these data exclusively for sunny days is rare in previous studies.

In this article, we mainly focused on the long-term trend and possible relationship between sunshine duration (SD) and diffuse radiation percentage (defined as diffuse solar radiation/total solar radiation, DRP) and their potential origin from anthropogenic aerosols. The daily SD and DRP data on sunny days only were selected. This is different from many previous works that used data under all weather conditions, which will be contaminated by some meteorological factors like cloud, fog and relative humidity. Consequently, we used the latest available data from an expanded weather station network in China and chose the daily SD and DRP data according to limits defined for relative humidity data and total cloud cover data. Only the SD and DRP data meeting the requirement of a sunny sky (daily mean total cloud cover less than 0.2) and lower relative humidity (RH ≤ 70%) can be defined as sunny sunshine duration (SSD). The sunny diffuse radiation percentage (SDRP) was also defined by this standard. This work attempts to investigate the long-term SSD and SDRP variations affected by aerosols.

1. Data and methods

The daily sunshine duration data during 1960–2005 was obtained from 650 meteorological stations in China, and the geographical location of the stations is shown in Fig. 1. A quality control procedure for sunshine duration was applied based on the work of Wu et al. (2012). In brief, the basic rules are introduced as follows: exclude the data when the total cloud cover is higher than 20% and the relative humidity is higher than 70%. SDRP data from only 47 stations were used after excluding stations with too much missing data. In addition, MODIS aerosol option depth (AOD) data (with the resolution of 1° × 1° longitude and latitude) and OMI tropospheric column NO_2 ($TroNO_2$) data (0.25° × 0.25°) were used, which are derived from the websites http://modis.gsfc.nasa.gov/ and http://ozoneaq.gsfc.nasa.gov/. We also used total energy consumption, vehicles for civil use and GDP in the recent 46 years in this analysis. Annual data for these categories are from the National Bureau of Statistics of China (http://www.stats.gov.cn/).

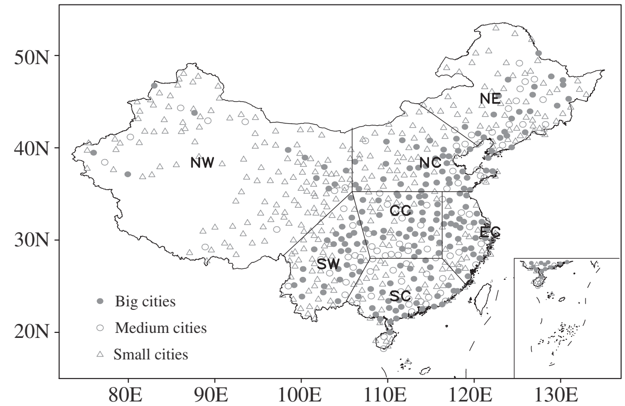

Fig. 1 – Locations of 650 weather stations over China within 7 regions of urban agglomerations, NE for Northeast China (GS(2015)991).

To reveal the differences of SSD in the urban agglomerations, the 650 stations in China were classified into large cities, medium cities and small cities as in Wu et al. (2012). Based on the population size of the cities in 2005, large city, medium city and small city are defined as population more than 1,000,000, between 500,000 and 1,000,000, and less than 500,000, respectively, and the corresponding numbers of stations are 192, 94 and 364. In addition, many small cities, especially in eastern China, are close to large and medium cities (within the distance of 100 to 200 km), so the transport of pollution over this short distance is likely, which might make it possible that the air pollution produced in large and medium cities will cause lower SSD in a neighboring small city. That is why the analysis of the features of SSD in different regions is indispensable, and we divided the total area of China into 7 regions, which include Northeast China (NE), North China (NC, containing Beijing-Tianjin-Hebei city cluster), Northwest China (NW), Central China (CC), East China (EC, Yangtze River Delta city cluster), Southwest China (SW) and South China (SC, Pearl River Delta city cluster). The distribution of the regions is shown in Fig. 1.

The trend coefficient r_{xt} (details by Wu et al., 2012) was calculated as follows. r_{xt} is defined as a correlation coefficient between elements of the nth (year) time sequence and natural numbers as 1, 2, 3…, n:

$$r_{xt} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(i-\bar{t})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(i-\bar{t})^2}}$$

where, n is the time by years, x_i stands for the magnitude of an element in the ith year, $\bar{x}$ represents the average sample variable, and $\bar{t} = (n+1)/2$. If r_{xt} is positive (negative), the variable has an increasing (declining) trend during the n years. In addition, the statistical methods of regression analysis, trend fitting and correlation analysis were also used in this study.