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Spatial and temporal patterns as well as major influencing factors of global and diffuse Horizontal Irradiance over China: 1960–2014

Hong Wang[a], Fubao Sun[a,b,c,d,*], Wenbin Liu[a]

[a] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] Research School of Qilian Mountain Ecology, Hexi University, Zhangye City, Gansu Province 734000, China
[c] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
[d] Center for Water Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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ABSTRACT

Global Horizontal Irradiance (GHI) on Earth is a central element of climate systems. With changes in the climate and regional development, the patterns and influencing factors of GHI, in addition to presenting global consistency, are increasingly showing regional particularities. Based on data for GHI, Diffuse Horizontal Irradiance (DHI) and potential impact factors (geographical position, elevation, cloud cover, water vapor, and ground atmospheric transparency related variables) from 1960 to 2014 in China, we analyzed the pattern and major influencing factors of GHI and DHI. The results showed that the major influencing factors of the GHI spatial pattern were the total cloud cover (*TCC*) and relative humidity (*RH*) in China. Dividing all of China into two regions, the major factors were the water vapor pressure (*WVP*) in the northern region and *TCC* in the southern region. And we divided the GHI and DHI data into two periods (1960–1987 and 1988–2014) due to global dimming and brightening observed in China in the late 1980s. The temporal GHI showed that 31 of 58 decreased significantly with an average decreasing rate of 95 MJ 10 yr^{-1} during the periods of 1960–2014 and 49 of 76 stations decreased significantly with an rate of 342 MJ 10 yr^{-1} during 1960–1987, whereas 57 of 88 stations did not change and 24 stations increased significantly with an rate of 201 MJ 10 yr^{-1} during the period of 1988–2014. The temporal DHI showed that 40 of 61sites did not change significantly from 1960 to 1987. The major influencing factors for temporal changes of GHI in nine typical cities from 1960 to 2013 were as follows: air quality-related variables in super cities, sandstorms and wind in desert oasis cities, clouds in cities with good air quality, and a low cloud amount (*LCA*) and annual fog days (*FD*) in Chengdu. Overall, we identified characteristics of GHI and DHI based on global climate change and regional urban development and found that the spatial characteristics of GHI results for China are consistent with global trends, whereas the spatial characteristics of DHI and temporal characteristics of GHI and DHI have changed significantly and exhibit these measurable trends due to strong regional influences of changing cloud amounts, water vapor, and air quality.

1. Introduction

Variations of GHI on the Earth's surface profoundly affect humans, the climate, the hydrological cycle, plant photosynthesis, and solar power (Liu and Jordan, 1960; Monteith, 1972; Pinker et al., 2005; Roderick and Farquhar, 2002). In particular, in the present climate state, warming is unequivocal, and since the 1950s many of the observed changes have been unprecedented over decades to a centuries (IPCC, 2013). As a result, solar radiation management (SRM) and geoengineering of the climate (Davies, 2010) are gaining interest but remain a controversial strategy to cool the earth (Arino et al., 2016; Govindasamy et al., 2003; Irvine et al., 2012; Macmartin et al., 2013; Mercer et al., 2011; Ricke et al., 2012; Ruckstuhl and Norris, 2009; Winickoff et al., 2015). Measurements of GHI have great importance in preparing humans for the challenge of climate change (Che et al., 2005; Ramanathan et al., 2001).

A decline in GHI, known as global dimming, on land surfaces was apparent in many observational records until the 1980s (Wild et al., 2005; Pinker et al., 2005; Liepert, 2002). Subsequent increases, known as global brightening, have been observed (IPCC, 2013; Ohmura, 2009; Stanhill and Cohen, 2001; Wild, 2012). The GHI revealed an estimated 7 W m^{-2} or 4% decline at sites worldwide from 1961 to 1990, with the

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* Corresponding author at: Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.
E-mail address: sunfb@igsnrr.ac.cn (F. Sun).

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strongest declines occurring at the United States site, of 19 $W m^{-2}$ or 10% (Liepert, 2002). An increasing rate of 7.8 $W m^{-2}$ per decade has been noted from 1996 to 2011 in the USA (Augustine and Dutton, 2013). The same decline and then opposite increasing trend was found in China. GHI decreased at a rate of 2–8 $W m^{-2}$ per decade from 1961 to 1990 in China (Che et al., 2005; Norris and Wild, 2007; Qian et al., 2007; Yang et al., 2014). Radiative forcing, caused by the internal variability of clouds and by variations of the concentrations of aerosols and greenhouse gases, including water vapor, has become a major topic. Some results showed that the reversal, from dimming to brightening, was a reconcilable change in terms of cloudiness and atmospheric transmission (Wild et al., 2005). The clear sky optical thickness effect accounted for $-8 W m^{-2}$, and cloud optical thickness effected for $-18 W m^{-2}$ from 1961 to 1990 and were attributed to the strongest declines occurring at the United States site (Liepert, 2002). The increasing aerosol load from the emission of pollutants was responsible for the observed reduced GHI and increased DHI (Qian et al., 2007; Tarasova et al., 1999; Yang et al., 2016). Only one type of dust event reduced the direct solar radiation by 30–40% in the West Coast of Asia (Husar et al., 2001).

First, cloud cover changes effectively modulate GHI on an internal basis; however, its contribution to longer-term GHI trends is ambiguous, and there has been a long history of unexplained anomalous absorption of GHI by clouds (Cess et al., 1995; Norris and Wild, 2007; Sanchezlorenzo et al., 2012; Zerefos et al., 2009). Second, aerosol particles attenuate GHI by scattering and absorbing GHI or act as cloud condensation nuclei (e.g., carbonaceous, dust aerosols) and modify cloud reflectivity and lifetimes (IPCC, 2013; Liepert, 2002). Some results have shown that increasing the aerosol effect by increasing air pollution alone can explain approximately 3 $W m^{-2}$ of the observed decline in the United States (Liepert, 2002). Greenhouse gas warming has led to an increased cloud optical thickness in overcast conditions by increasing the cloud height and liquid water content (Tselioudis and Rossow, 1994). Third, visibility conditions and *RH* were also potential affecting factors of GHI changes (Wang et al., 2009). The decline of low-visibility conditions, e.g., due to fog, mist and haze, and the associated GHI increase may have contributed, on average, to approximately 10–20% of Europe's recent daytime warming and 50% of Eastern Europe's warming over the past 30 years (Vautard et al., 2009). The increased atmospheric moisture has enhanced the thermal radiative emission of the atmosphere to the surface, reducing the net thermal and cooling of the surface (Allan, 2009; Philipona et al., 2009; Wang and Liang, 2009; Willett et al., 2008). Additionally, changes in the DHI or diffuse fraction (DHI/GHI) have been observed during the last decades (Mercado et al., 2009; Sanchez-Lorenzo et al., 2013). The results also showed that variations of diffuse fractions have largely been associated with the 'global dimming' period by enhancing the land carbon sink by approximately one-quarter between 1960 and 1999 (Mercado et al., 2009).

Many complex influencing factors, together with climate change and regional development characteristics, have allowed the variation and influencing factors of GHI and DHI to have largely global consistency and regional particularities. Based on data for GHI and DHI and potential impact factors from 1960 to 2014 in China, we analyzed the spatial and temporal patterns and major influencing factors of GHI and DHI.

2. Data and methods

The data were mainly obtained from the China Meteorological Data Service Center (CMDC) (http://data.cma.cn/). Some missing data were supplemented through references (Chang et al., 2009; Chen and Wang, 2015; Hao et al., 2007; Wu et al., 2010; Yu et al., 2013). There are 83 radiation stations that monitor GHI and DHI at the same time from 1960 to 2014 in China. Fig. 1(a) shows their distribution, except for three stations with incorrect data, and the detailed station information is shown in Table s1 of the supporting information. Considering the global dimming and brightening, we divided the GHI and DHI data into two periods (1960–1987 and 1988–2014) and analyzed their changes and influencing factors for three periods (1960–2014, 1960–1987 and 1988–2014). We selected the stations with a monitoring period not shorter than 45 years for 1960–2014 and 20 years for 1960–1987 and 1988–2014 for analysis. Since 1993, most of the national radiation stations stopped observing DHI in China, and the remaining radiation stations that monitored GHI and DHI at the same times are showed in Fig. 1(b).

When conducting data analyses, it is also important to address the estimated uncertainties of the measured data sets. Before 1993, solar radiation measurements were made by instruments based on thermoelectric detectors made of constantan and maganin with a common black paint applied to the receiver. The estimated measurement uncertainty of this design is about ± 10%. Measurements after 1993 were made with an improved pyranometer design using a thermoelectric detector made from a wire-wound constantan and copper thermopile receiver coated with an optically black paint. The estimated uncertainty of these more recent measurements is ± 5% (http://data.cma.cn/data/cdcdetail/dataCode/RADI_MUL_CHN_DAY.html). And Shi et al. (2008) applied a set of quality assessment algorithms to test the quality of GHI, direct normal irradiance (DNI) and DHI measurements taken at 122 observatories in China during 1957–2000 and found that the data failed to pass assessment was no more than 3.07%.

As GHI passes through the Earth's atmosphere, some of it is absorbed or scattered by clouds, aerosols, water vapor, and air molecules (Qian et al., 2007). Therefore, we identified five types of potential impact factors: geographical position, elevation, cloud cover, water vapor, and ground atmospheric transparency-related variables. Pearson correlation coefficients (PCC) were used to determine the strength of possible relationships between GHI, DHI and these variables. Linear regression equations were used to estimate the temporal linearity trend of GHI and DHI.

We then used Principal Components Analysis (PCA) (Hotelling, 1933; Pearson, 1901) to analyze data of the observed variables, because PCA is advantages in identifying patterns and reducing the dimensions of the dataset with minimal loss of information (Smith, 2002; Abdi and Williams, 2010). It is a way of identifying patterns in data, and expressing the data in such a way as to highlight their similarities and differences. Since patterns in data can be hard to find in data of high dimension, where the luxury of graphical representation is not available, PCA is a powerful tool for analysing data. And it is that once you have found these patterns in the data, and you compress the data, i.e., by reducing the number of dimensions, without much loss of information. It has been widely extended to the study of atmospheric sciences (Zarzo and Martí, 2011; Rcjr and Vojtesak, 1983) and geography (Wang et al., 2011; Christophersen and Hooper, 1992; Astel et al., 2007) to identify major influencing factors from a set of possibly correlated variables.

PCA is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The number of principal components is less than or equal to the smaller of the number of original variables or the number of observations. The first principal component (PC) has the maximum variance. Successive components progressively explain smaller portions of the variance and are all uncorrelated with each other. We selected only PCs with eigenvalues > 1.0 (Brejda et al., 2000). For each PC, we selected the variables with the highest weighted factor loading (within 10% of the highest factor loading) to represent a PC (Mandal et al., 2008; Wang et al., 2011). Traditional statistical analyses were