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Is there a transition of solar radiation from dimming to brightening over India?

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A B S T R A C T

Recent observational studies show that solar radiation incident on ground has not been stable over the last several decades but underwent significant multi-decadal variations. From the 1950s, solar radiation has had a general decreasing trend, named dimming. Since the late 1980s, a trend reversal and partial recovery has been observed at many observations sites across the globe; it is the so-called brightening. The present study examined temporal and spatial trends in surface solar radiation (global and diffuse) and sunshine duration in India using a 40-year data set (1971–2010) of the twelve stations of solar radiation network of the India Meteorological Department. The research work examines the global solar radiation trends in all-sky and cloud-free sky conditions. The long-term variability in the diffuse components of solar radiation, bright sunshine duration, and cloud cover has also been studied over India.

India is one of the few regions that showed a continuous and steady decline in global solar radiation from the 1970s to 2000. The declining trend of all-sky global irradiance over India as a whole was 0.6 Wm^{-2} $year^{-1}$ during 1971–2000 and 0.2 Wm^{-2} year $-$ ^{1} during 2001–2010. A third-order polynomial fit to the data indicated a reversal in all-sky global irradiance around 2001 at some sites. Reversal or stabilization of global irradiance is also seen in seasonal mean values at some of the stations. The reversal in clear-sky global irradiance was clearly evident from 2001. Similar trend is also observed in bright sunshine duration. This confirms the well-known phenomenon of global dimming and global brightening over India. The analysis of global irradiance data highlights the fact that in general the dimming/brightening is station dependent because of regional sources and meteorology which contribute to the variation in solar irradiance.

1. Introduction

Solar radiation incident at the Earth's surface plays a fundamental role in the surface energy balance. Changes in the amount of solar radiation affect the temperature field, fluxes of sensible and latent heat, atmospheric and oceanic general circulation, and the hydrological cycle. India is endowed with abundant solar energy due to its geographic position in the tropical belt of the earth. Widespread reduction of surface solar radiation from the 1960s to the 1980s has been reported by many researchers (Ohmura and Lang, 1989; Russak, 1990; Stanhill, 1995; Abakumova et al., 1996; Gilgen and Wild, 1998; Liepert, 2002; Liepert and Tegen, 2002; Stanhill and Cohen, 2001; Wild et al., 2005). This decline in surface solar radiation is known as global dimming (Stanhill and Cohen, 2001). A trend reversal or partial recovery in global radiation was observed after 1980s at many of the observation sites (Wild et al., 2005; Philipona et al., 2009). Using satellite data, Pinker et al. (2005) found a significant global linear increasing trend of 0.16 Wm^{-2} year $-$ ^{1} from 1983 to 2001. Fitting a second-order polynomial to the same data indicated a small decreasing trend from 1983 to 1992, with a reversal around 1992. The solar dimming reversed to an increasing trend of 6 $Wm^{-2}decade^{-1}$ in the continental United States between 1995 and 2007 (Long et al., 2009). Norris and Wild (2007) examined global solar radiation data from 75 European sites and found a declining trend with 3.1 $Wm^{-2}decade^{-1}$ in the period of 1971–1986 and then increasing trend of 1.4 $Wm^{-2}decade^{-1}$ from 1987 to 2002. Cutforth and Judiesch (2007) observed a steady decline in solar radiation from the late 1950s to the early 1990s and a steady brightening thereafter over Canadian Prairie. Ruckstuhl et al. (2008) observed the increasing trend in Europe from the 1980s onward at sites in Switzerland, Germany, and Greece. The term “brightening” was thus coined to emphasize that the decline in global solar radiation no longer continued at many sites after the late 1980s (Wild et al., 2005). Wild et al. (2009) observed a continuation of brightening at sites in Europe, United States, and parts of Asia, a leveling off at sites in Japan and Antarctica, and indications for a renewed dimming in China. Updates on latest trends in solar radiation since 2000 provide a

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less coherent picture as compared to the preceding dimming (Wild, 2012).

Many factors are responsible for global dimming and brightening. Variation in surface solar radiation caused by changes in the solar output can be neglected in the interpretation of the observed variations as its contribution is at least an order of magnitude smaller than the changes detected from observations (Frohlich and Lean, 1998; Willson and Mordvinov, 2003). The change in atmospheric aerosol load, cloud cover, and cloud properties are the main factors determining solar dimming/brightening (Abakumova et al., 1996; Stanhill and Cohen, 2001; Pinker et al., 2005; Qian et al., 2006; Romanou et al., 2007; Wild, 2009, 2012; Kumari and Goswami, 2010; Soni et al., 2012). Liepert (2002) showed that the decrease of the global radiation from 1961 to 1990 can be explained by increase in cloud optical thickness and direct effect of aerosols inducing 18 Wm^{-2} and 8 Wm^{-2} solar radiation reductions respectively. He observed that the cloud-free sky solar radiation exhibits a strong decline due to the increasing clear-sky optical thickness and the declining frequency of clear sky. Pinker et al. (2005) attributed the possible causes of global dimming to changing cloud cover, increasing manmade aerosols and the lowering of atmospheric transparency following explosive volcanic eruption. The decline in surface solar radiation over large part of the China can be attributed to increased anthropogenic aerosols as significant decreases in cloud cover was observed during the last half of the twentieth century (Kaiser, 2000; Xu, 2001; Kaiser and Qian, 2002; Che et al., 2005; Liang and Xia, 2005; Xia et al., 2006). This is supported by the fact that observed decadal changes in anthropogenic aerosol emissions are in line with the trends in global solar radiation (Wild, 2009; Folini and Wild, 2011). These evidences have also been supported by changes in solar radiation under clear-sky conditions (Wild et al., 2005; Norris and Wild, 2007, 2009; Ruckstuhl et al., 2008; Folini and Wild, 2011; Soni et al., 2012). Change in aerosol optical depth has been suggested to play a role in the radiation change over China (Kaiser and Qian, 2002), India (Ramanathan and Ramana, 2005; Soni et al., 2012), Europe (Norris and Wild, 2007), and other regions (Wild, 2012). Satheesh and Moorthy (2005) observed that wind speed significantly contributes to radiative forcing by influencing natural aerosol concentration. Alpert et al. (2005) determined that the solar radiation fluxes show a decline of 0.41 Wm^{-2} year $-$ ^{1} for highly populated sites compared to only 0.16 Wm^{-2} year $-$ ^{1} for sparsely populated sites from 1964 to 1989. Their finding highlights that solar dimming may be of local or regional nature.

Diffuse radiation that forms significant part of global radiation is the part of shortwave solar radiation scattered by gas molecules, aerosols, water vapour, and clouds in the atmosphere. Changes in cloud optical thickness, cloud cover, and atmospheric aerosol loading alter the diffuse radiation reaching the surface. The observed trends in diffuse radiation are not as consistent as those in global radiation during the dimming period (Power, 2003; Long et al., 2009). In contrast to global radiation, there have been relatively few studies evaluating long-term variability in the diffuse radiation due to the scarcity of data. The increasing (decreasing) of the diffuse radiation during the dimming (brightening) period have also been observed during the last few decades over Europe (e.g., Russak, 1990; Stanhill, 1998; Liepert and Tegen, 2002; Power, 2003; Abakumova et al., 2008; Mercado et al., 2009; Sanchez-Lorenzo et al., 2013), United States (Liepert and Tegen, 2002), China (e.g., Liang and Xia, 2005; Zhang et al., 2004), South Africa (Power and Mills, 2005), or India (Soni et al., 2012). Che et al. (2005) analyzed the variability of diffuse radiation based on observational data at 64 stations and found no significant trend in annually averaged diffuse radiation from 1961 to 1990, but a significant declining trend after 1980. Decreases in diffuse radiation have been reported for Germany (Liepert, 1997) and Ireland (Stanhill, 1998). Liang and Xia (2005) observed that the spatial patterns of trends in diffuse radiation are more complex and inhomogeneous in China where 24 sites have shown much less pronounced decreasing trends from 1961 to 2000. Kvalevag and Myhre (2007) found that anthropogenic activity during the industrial era accounts for a decrease in direct solar radiation at the surface of up to 30 Wm^{-2} (30%–40%) and an increase in diffuse solar radiation of up to 20 Wm^{-2}. Long et al. (2009) estimated the brightening trend in all-sky shortwave radiation at about 6 Wm^{-2} per decade in the continental United States with 5 Wm^{-2} per decade coming from diffuse shortwave component for the period 1996–2007. They also observed that changes in clouds and cloudiness have a greater influence on brightening than any decrease in aerosol amounts alone.

Global solar radiation trends analyzed over India earlier from 1981 to 2006 by Kumari et al. (2007) and 1971–2005 by Soni et al. (2012) reported decreasing trend over India. Kambezidis et al. (2014) found declining trend in shortwave radiation derived from satellites over south Asia for the period of 1979–2004. Wild et al. (2009) reported a tendency towards the stabilization of surface solar radiation since the late 1990s over some stations in India. To examine whether the trend continued or not, we report on temporal and spatial trends in surface solar radiation in India using extended time series from 1971 to 2010 of the twelve stations in India. We examined the solar radiation trends in all-sky conditions as well as cloud-free skies so that the effect of cloud cover can be examined. The studies on long-term changes in diffuse solar radiation over India are very scarce. Thus, the trends reported in this quantity help to enhance our understanding.

2. Data and methodology

2.1. Study sites

India is situated approximately between 8°N and 37°N latitude with a unique climatic regime ranging from tropical in the south to temperate and alpine in the Himalayan north. The northern parts of the country have a continental climate with severe summer conditions that alternates with cold winters. In contrast are the coastal regions of the country, where the rains are frequent. Winter season (December, January, and February) in India is characterized by clear skies, fine weather, light northerly winds, low humidity and temperatures, and large daytime variations of temperature. March, April, and May constitutes the summer (pre-monsoon) season in India. Hot and dry winds accompanied with dusty winds blow frequently over the plains of northwest India. Maximum temperatures rise rapidly by the end of May and early June resulting in harsh summers in the north and northwest regions of the country. June, July, August, and September form the southwest monsoon season. Post-monsoon season starts from October and continues till December. Post-monsoon or northeast monsoon is transition season associated with the establishment of the northeasterly wind regime over the Indian subcontinent.

Table 1 gives geographical coordinates of the measurement sites depicted in Fig. 1. Ahmedabad is located in a semi-arid region and is influenced by the Thar Desert in North and Arabian Sea in southwest and is an industrialized region. Jodhpur is located in the eastern periphery of the Thar Desert and has more natural dust load, higher concentration of it occurring during the pre-monsoon season. Jodhpur experiences hot and dry climate with severe summer, relatively clear skies, and short monsoon season are the main reasons for availability of higher solar irradiance. Nagpur is in the central parts of the country and south of the Satpura ranges. Pune is about 100 km inland on west coast of India, on the leeward side of Western Ghats, and has seen a large growth of industrial and consequent urban developmental activities over the years. Delhi is one of the highly polluted major cities of Asia and is also influenced by heavy injection of dust load brought by winds from the deserts in the west. Kolkata, Chennai, Mumbai, Panjim, Visakhapatnam, and Trivandrum are coastal stations where the diurnal variations of temperature are small and relative humidity is high throughout the year. Kolkata, a heavily populated with large industrial installations, is situated in the Gangetic delta and nearer to the east