Impact of global dimming/brightening on estimating Angström-Prescott parameters based on geographically weighted regression in China

Zhiguo Wang 1, Junzhu Du 2, Na Zhao 2,*

1 Hubei Provincial Communications Planning and Design Institute Co., LTD., Wuhan, Hubei Province, China
2 School of Hydropower and Information Engineering, Huazhong University of Science and Technology, Wuhan, Hubei Province, China
* Corresponding author. E-mail addresses: na.zhao.2011@hust.edu.cn (N. Zhao)

Abstract. Variations of solar radiation is related to energy planning and architectural designing. It is important to estimate solar radiation from other climate factors because of the limited measurement solar radiation data. In this study, temporospatial changes of solar radiation and sunshine hour are analysed for global dimming/brightening periods based on meteorological data in China. Results show that the trends of solar radiation and sunshine hour are both decreasing dramatically for 1961–1990 (the global dimming period) but levelling off for 1991–2010 (the global brightening period), which indicates that sunshine hour can be used the reliable indicator of solar radiation. Spatially, the change trends of solar radiation are consistent with sunshine hour in 36 stations during the period of 1961–1990, but they are consistent in just 27 stations during the period of 1991–2010. To assess the impact of changing solar radiation on Angström-Prescott parameters (a and b) in the equation of solar radiation estimation from sunshine hour, geographically weighted regression is developed to calculate a and b. There is not dramatic difference in the spatial patterns of a and b for the period of 1961-2010 and 1961-1990. However, there is significantly inconsistent changes in a and b during the global brightening period compared with the global dimming period, which suggests that global dimming/ brightening has important impact on estimating solar radiation from sunshine hour, with dramatic variability among different regions.

1. Introduction
Global dimming/brightening, which showed temporal change of surface solar radiation (SR) in the last decades, was discussed in a large number of studies [1-3]. In details, global dimming means a widespread decline of SR between the 1960s and 1980s [4] and global brightening means a tendency toward an opposite trend after the 1980s [5]. There seemed to be a lot of implications of these decadal changes, both in China and other countries [3, 6-7].

SR estimation may be the most important problems because of the limited stations with reliable long-term records for radiation measurement [2, 8]. Sunshine hour (SH) was probably the most appropriate to estimate SR among the proxy factors (SH, cloud cover or daily temperature range), [9-11]. In fact, SH could be used to calculate SR through Angström-Prescott formula [12-13], which was applied in many countries of the world [14-15]. Some of these studies developed modified forms of Angström-Prescott equation [14], or introduced other parameters (such as location, altitude, climate
factors and air pollution index) to Angström-Prescott equation [16-17]. However, the temporal-spatial variation of parameters in Angström-Prescott formula under the background of global dimming/brightening was few considered. Especially, the spatial pattern of Angström-Prescott parameters was always developed according to liner regression of temporal series of SR and SH in each station. That meant the interaction among neighboring stations was ignored.

Geographically weighted regression (GWR) was a new developed regression method which had special emphasis on spatial non-stationarity [18]. Unlike conventional regression, such as global ordinary least squares (OLS) regression, which produced a single regression equation to measure relationships between the independent and dependent variables, GWR could provide weighting of locally associated information and allow parameters in regression model to vary in space [19]. Many recent publications had demonstrated the analytical utility of GWR in climatology [20], environmental and ecological areas [21-22]. These studies showed that GWR could efficiently reveal spatial variations in relationships among explanatory and dependent variables that were otherwise ignored in traditional analysis.

Therefore, the objective of this study was to analyze the temporal and spatial changes in SR and SH in China from 1961 to 2010 and then assess the impact of global dimming/brightening on estimating Angström-Prescott parameters based on GWR.

2. Materials and methods

2.1. Data
Meteorological data (annual average daily solar radiation and sunshine hour in 46 stations for the period of 1961 to 2010) were from the Meteorological Information Center of China Meteorological Administration (CMA) and available at the website of CMA Data Sharing Service System (http://cdc.cma.gov.cn/). All the data were validated by CMA using quality control procedures.

2.2. Estimation of solar radiation from sunshine hour
Angström-Prescott formula is

\[ \frac{R_s}{R_a} = a + b \cdot \left( \frac{n}{N} \right) \]  

(1)

In which Rs is global solar irradiance (MJ m\(^{-2}\) d\(^{-1}\)) and Ra is extraterrestrial solar irradiance (MJ m\(^{-2}\) d\(^{-1}\)); n is sunshine hours (h) and N is maximum possible sunshine hours (h); a and b are empirically determined regression constants. Ra and N are calculated according to Yang and Tsukamoto [23].

2.3. Method of trend analysis
Annual solar radiation and sunshine hour were evaluated with the nonparametric Mann–Kendall trend test [24-25] which was commonly used in testing the randomness of climatic time-series [26-27].

3. Results and discussions

3.1. Long-term changes in solar radiation and sunshine hours
The variations of annual solar radiation and sunshine hour from 1961 to 2010 for the average of 46 stations are shown in figure 1. Obviously, trend of SH was consistent with that of SR. They were both dramatically declining from 1960s to 1980s and levelling off since 1990s.
Figure 1. Time series of average annual solar radiation and sunshine hour from 1961 to 2010.

Statistically, trends of SR and SH change are tested by the Mann Kendall method. Results showed that solar radiation decreased significantly \( (Z = -6.24, P < 0.001) \) at a rate of \(-25.64 \text{ MJ m}^{-2} \text{ per year}\) from 1961 to 1990, and slightly decreased \( (Z = -0.75, P > 0.1) \) at a rate of \(-2.82 \text{ MJ m}^{-2} \text{ per year}\) from 1991 to 2010. For the whole time series (1961 – 2010), negative trend in annual average SR was significant \( (Z = -4.32, P < 0.001) \) at a rate of \(-8.64 \text{ MJ m}^{-2} \text{ per year}\). Therefore, global radiation change in this study does not fit well the pattern of “from dimming to brightening” in the global scale [5]. However, this observation is consistent with results of the early studies in China [3]. It is worth noting that marginal brightening in the early 1990s cannot compensate for dramatic dimming in the whole period of 1961-2010 (figure 1).

Similarly, significantly negative tendency in SH was observed \( (Z = -4.60, P < 0.001) \) from 1961 to 1990 at a rate of \(-7.26 \text{ h per year}\). Slight decline \( (Z = -1.14, P > 0.1) \) was observed from 1991 to 2010 at a rate of \(-1.42 \text{ h per year}\), while the trend was insignificant. Negative trend in SH was significant \( (Z = -6.57, P < 0.001) \) at a rate of \(-4.57 \text{ h per year}\) for the whole period. This observation is also consistent with results of the early studies in China [3], but inconsistent with results of the global scale [5].

In addition, figure 1 suggests that the decline trend of SR is more dramatic than that of SH, especially in the period of 1961 – 1990.

3.2. Spatial trends in solar radiation and sunshine hours

To compare the different variations of SR and SH among 46 individual stations for the different periods, trends in annual SR and SH for each station during the three periods (1961–2010, 1961–1990, 1991–2010) are shown in figure 2.

In the whole period of 1961–2010, negative trends in SR were observed at 41 stations, and 27 of them were statistically significant (figure 2a). For the same period, SH showed decreasing trends at 37 stations and 28 of them were statistically significant (figure 2b). It is worth noting that 36 stations show consistently decreasing trend in SR and SH, but just 2 stations show consistently increasing trend. This indicates that SH can be representative of SR in most of stations during 1961–2010. However, for other stations, it may need further studies in less time range.

During the period 1961 to 1990, SR decreased at all 46 stations (significantly at 31 stations mainly located in the east and non-significantly in 15 stations of the west region) (figure 2c), which confirmed the influence of global dimming on China. Meanwhile, SH decreased at 41 stations and increased at other 5 stations (figure 2d). More consistent results between SR and SH in this duration could verify the more reliable representative of SH to SR.
Moreover, from 1991 to 2010, SR decreased for 23 stations (3 stations significantly and 20 stations non-significantly) and increased for other 23 stations (5 station significantly and 18 stations non-significantly) (figure 2e). This reconfirmed that there was still a debate on China’s brightening in the academic sphere [3]. At the same time, SH decreased for 26 stations (11 stations significantly and 15 stations non-significantly) and increased for other 20 stations (6 station significantly and 14 stations non-significantly) (figure 2f). It is necessary to note that SR trends were consistent with SH trend at 36
stations (both were decreasing) during the period of 1961 to 1990, while they were consistent for just 27 stations (both decreased for 15 and increased for 12 stations) for the period of 1991 to 2010. This suggests that the changes in SH may be the effective indicator to SR in the period 1961 to 1990, but it could not well represent the changes in SR for the period of 1991 to 2010. Thus, evaluation of the impact of global dimming and brightening for the different periods (1961–1990 and 1991–2010) on estimation SR from SH is needed.

3.3. Impact of global dimming/brightening on Ångström-Prescott parameters

Generally, Ångström-Prescott parameters a and b will keep relatively stable with time and space if SR and SH show the similar trend. In this study, the inconsistency of trends in SR and SH at many stations from 1991 to 2010 indicates that Ångström-Prescott parameters may change in different periods and regions.

To depict the spatial variation of Ångström-Prescott parameters in different time scale, GWR was used to develop the relationship between clearness index and percentage of sunshine in Equation (1). Then temporal and spatial a and b (figure 3) can suggest the impact of global dimming and brightening.

There was not dramatic difference in the spatial patterns of a and b for the period of 1961-2010 and 1961-1990 (figure 3a and figure 3c; figure 3b and figure 3d). Parameter a was slightly higher for 1961-2010 than 1961-1990. The parameter a for 1961-2010 had a median of 0.15 with a range from 0 to 0.22, while the parameter a for 1961-1990 had a median of 0.12 with a range from 0.03 to 0.18. However, parameter b was slightly lower for 1961-2010 than 1961-1990. The parameter b for 1961-2010 had a median of 0.63 with a range from 0.53 to 0.86, while the parameter b for 1961-1990 had a median of 0.67 with a range from 0.57 to 0.80. Spatially, high values of a were noted for north-western region and low values of a were noted for north-eastern region both for the period of 1961-2010 and 1961-1990 (see figure 3a and figure 3c). On the contrary, high values of b were noted for north-eastern region and low values of b were noted for north-western region both for the period of 1961-2010 and 1961-1990 (see figure 3b and figure 3d).

To assess the influence of changing SR on Ångström-Prescott parameters, spatial patterns of a and b in global dimming period (from 1961 to 1990) and brightening period (from 1991 to 2010) were shown in figure 3 (c, d, e, f). There was obvious variation in a and b for the period of 1991–2010 compared with 1961–1990. Parameter a was obviously higher for 1991-2010 than 1961-1990. The parameter a for 1991-2010 had a median of 0.20 with a range from 0 to 0.30. However, parameter b was obviously lower for 1991-2010 than 1961-1990. The parameter b for 1991-2010 had a median of 0.53 with a range from 0.27 to 0.95. Spatially, high values of a were noted for western region, east of north-eastern region and the middle and lower reaches of the Yangtze river basin, and low values of a were noted in the north of the North China for the period of 1991-2010 (see figure 3e). On the contrary, high values of b were noted for the west of Tibet and Xinjiang region and the middle and lower reaches of the Yangtze river basin (see figure 3f). Therefore, there was significantly inconsistent changes in a and b during the global brightening period compared with the global dimming period, which suggested that global dimming/ brightening had important impact on estimating solar radiation from sunshine hour, with dramatic variability among different regions.
Figure 3. Spatial patterns of Angström-Prescott parameters (a and b) in China for different periods (1961-2010, 1961-1990 and 1991-2010).

Acknowledgments
This research was mainly funded by National Key Research and Development Program (2016YFC0401004 and 2016YFC0401005) and the Fundamental Research Funds for the Central Universities, HUST: 2016JCTD115. We acknowledged National Meteorological Information Centre of China for providing the meteorological data.

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