Distributed modeling of surface solar radiation based on aerosol optical depth and sunshine duration in China

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Abstract. Surface solar radiation, as a major component of energy balance, is an important driving condition for nutrient and energy cycle in the Earth system. The spatial distribution of total solar radiation at 10 km×10 km resolution in China was simulated with Aerosol Optical Depth (AOD) data from remote sensing and observing sunshine hours data from ground meteorological stations based on Geographic Information System (GIS). The results showed that the solar radiation was significantly different in the country, and affected by both sunshine hours and AOD. Sunshine hours are higher in the Northwest than that in the Northeast, but solar radiation is lower because of the higher AOD, especially in autumn and winter. It was suggested that the calculation accuracy of solar radiation was limited if just based on sunshine hours, and AOD can be considered as the influencing factor which would help to improve the simulation accuracy of the total solar radiation and realize the solar radiation distributed simulation.

1. Introduction

Solar radiation is the basic source of surface energy and the main driving factor of land surface processes such as plant photosynthesis, transpiration and soil evaporation. It is also an important driving force in the process of climate change. Sunshine goes through the atmosphere, after the absorption, reflection and scattering effect of the cloud, water vapor, atmospheric CO2 and ozone and other gases and aerosol particles, to reach the surface of the earth. Since the 1960s, solar radiation has declined in most parts of the world, including Africa, Asia, Europe and North America. This phenomenon is known as “global dimming” [1]. This “dimming” trend began to slow down after 1980s, and by 1990s the global solar radiation was even beginning to rise, the so-called “global brightening” [2]. In this context, the solar radiation in China has also undergone similar changes. It is confirmed by many researchers that the solar radiation is declining in different parts of China since 1960s [3,4].

Due to the high cost of solar radiation measurement, its site density is much lower than the conventional meteorological elements. It is difficult to accurately calculate the spatial distribution characteristics of solar radiation by relying on the existing radiation site observations. The most commonly used method for estimating solar radiation is the Angstrom-Prescott formula based on the sunshine hours recommended by the World Food and Agriculture Organization (FAO) [5]. Studies have shown that sunshine hours have declined in many countries since the 1960s, and this trend has shifted around 1990 [6], which is consistent with changes in solar radiation trends. In the latest 50 years, sunshine hours in most areas of China also showed a significant reduction trend [7]. Moreover,
domestic and foreign scholars generally suggest that the reductions of solar radiation and sunshine hours are mainly caused by the increase of anthropogenic aerosol content [8]. Wang et al. [9] used air pollution index (API) data released by the Chinese Ministry of Environmental Protection to reveal the quantitative effects of API on temporal and spatial changes in sunshine hours. Zhao et al. [10] further analyzed the contribution of the API to the Angstrom-Prescott formula, and the results showed that air pollution had a significant effect on the solar radiation calculation process based on sunshine hours. However, the long-term monitoring sites for API data are limited, which may cause significant uncertainty on the calculation of solar radiation.

Therefore, this study aims to simulate solar radiation based on Aerosol Optical Depth (AOD) obtained by remote sensing. The quantitative relationship between AOD and API is analyzed in the modelling process. Then Geographic Information System (GIS) is combined to estimate the spatial distribution of solar radiation at 10 km×10 km resolution in China.

2. Materials and methods

2.1. Materials
The meteorological data used in this study are from the Chinese meteorological data sharing service network, including the monthly values of sunshine hours at 119 meteorological stations in mainland China. Sunshine measurements record the time that direct solar beam irradiance exceeds a threshold of 120 W/m². Sunshine duration is an equally reliable proxy for exploring changes in solar radiation. The AOD data are derived from Terra/MODIS L2 aerosol data set issued by NASA (spatial resolution of 10km × 10km). Data quality control is conducted by the suppliers and the missing data is excluded. Moreover, the spatial analysis module of GIS is used for the estimation of solar radiation in this study.

2.2. AOD-based solar radiation model
Angstrom-Prescott formula [5] is the most commonly used method of solar radiation estimation based on sunshine hours, that is:

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

(1)

In the formula, \( R_s \) is the solar radiation reaching the surface (MJ/(m²·d)), \( R_a \) is the solar radiation at the top of the atmosphere (MJ/(m²·d)), \( a \)、\( b \) are the empirical coefficient (dimensionless), \( n \) is the sunshine hours (h), \( N \) is the maximum possible sunshine hours (h). Among them, the calculation methods of \( R_a \) and \( N \) refer to Allen et al. [11].

Zhao et al. [10] established the solar radiation improved model based on the API and sunshine hours, including linear, exponential and logarithmic forms. The logarithmic model was used to calculate solar radiation in this study, as follows:

\[ \frac{R_s}{R_a} = a + b(n/N) + c \log (API/100) + d(n/N) \log (API/100) \]  

(2)

In the formula, the API is the air pollution index (dimensionless), and the other parameters have the same meaning as formula (1). The selection of the four empirical coefficients is shown in Table 3 of Zhao et al. [10]. The API is defined on several major air pollutant concentrations near the ground and their duration. The items for calculating API are inhalable particulate matter (PM₁₀), sulfur dioxide, nitrogen oxides and ozone and so on. Although the Ministry of Environmental Protection added some new items such as PM₂.₅, and revised the API into AQI (Air Quality Index) in 2012, the data involved in this study are derived from API data released daily by the Ministry of Environmental Protection before revision.

In order to establish the quantitative relationship between API and AOD, it is assumed that the API is calculated from PM₁₀. In fact, the primary pollutants in most cities in China are indeed PM₁₀ [12]. Table 1 shows the quantitative conversion relationships between AOD and PM₁₀ in typical cities or regions of China (including Beijing, 7 cities of Hebei, Nanjing, Urumqi, Guangzhou, Lanzhou). The relational expression is derived from the references listed in the table. The rationality and significance
of every formula in Table 1 is validated by authors of corresponding reference. There is no details for the sake of brevity. The cities and regions involved in the table can cover all the geographical orientation of China. Therefore, the spatial distribution of the quantitative relationship of AOD and PM$_{10}$ in China is obtained by spatial interpolation using the equation coefficients in the table.

| Cities or Regions | Relation formula | Source literature |
|------------------|------------------|------------------|
| Beijing          | $Y^a=969.17X^a+53.70$ | Zhang et al. [13] |
| Shijiazhuang     | $Y=619.90X+77.00$ | Cheng et al. [14] |
| Xingtai          | $Y=279.00X+72.70$ | Cheng et al. [14] |
| Baoding          | $Y=503.10X+90.20$ | Cheng et al. [14] |
| Tangshan         | $Y=512.20X+125.90$ | Cheng et al. [14] |
| Qinhuangdao      | $Y=353.50X+141.60$ | Cheng et al. [14] |
| Chengde          | $Y=568.90X+87.30$ | Cheng et al. [14] |
| Zhangjiakou      | $Y=337.40X+78.60$ | Cheng et al. [14] |
| Lanzhou          | $Y=185.62X+95.60$ | Chen et al. [15] |
| Guangzhou        | $Y=50.34X+22.60$ | Wang et al. [16] |
| Urumchi          | $Y=383.97X+53.78$ | Liu et al. [17] |
| Nanjing          | $Y=131.40X+84.01$ | Jiang et al. [18] |

(Note: $^a$ X in the table represents AOD. $^b$ Y represents PM$_{10}$.)

3. Results and discussions

The following analysis takes the calculation results in 2012 as an example. According to the climatology, the average value in March, April and May represents the spring, June, July and August averages represent the summer, September, October and November averages represent the autumn, December, January, February averages represent winter.

3.1. Temporal and spatial characteristics distribution of solar radiation in China

Figure 1 shows the distributed simulation results of the seasonal solar radiation in China with 10 km $\times$ 10 km resolution. It can be seen from the figure that the solar radiation is significantly different in spatial distribution. Solar radiation gradually increased from south to north, except for some regions in the northwest and southwest. This is inconsistent with the spatial distribution of solar radiation initial data (astronomical radiation) [19], indicating that solar radiation through the atmosphere to the ground, will be affected by absorption, scattering and reflections by various trace gases, aerosol particles, moisture in the atmosphere, as well as terrain factors (altitude, slope, aspect and surrounding terrain). In the all four seasons, the influence of terrain and water vapor absorption on solar radiation is obvious. Solar radiation is generally characterized by greater in the plateau than that in the plain, greater in the inland than that in the coastal, and greater in the dry area than that in the humid area. The Qinghai-Tibet Plateau, Hexi Corridor and Inner Mongolia region show stable high-value of solar radiation because of the dry climate, high altitude and less cloudiness. While Sichuan Basin has become a stable low center for solar radiation due to a large amount of cloud cover and the water vapor content, and then this pattern extends to the entire Yangtze River Basin and its southern area. The solar radiation of part of Xinjiang is relatively small due to dry climate, more wind and sand, and the poor atmospheric transparency. These regional distributions are consistent with the results of Wang [20], which indicates that the calculated method of solar radiation in this study shows good accuracy, and it is rational to use the sunshine hours and AOD as the independent variables of the calculation.
Figure 1. Spatial distribution of solar radiation (MJ/ (m^2·d)) simulated by AOD and sunshine duration for each season in China.

Overall, the solar radiation in summer is the highest in China, with the average value of 16.31 MJ/ (m^2·d), and the range of 9.94~21.97 MJ/ (m^2·d). Solar radiation is the lowest in winter, and the average value is 7.39 MJ/ (m^2·d), with the range of 4.05~11.12 MJ/ (m^2·d). Solar radiation in spring is slightly higher than that in autumn, with the average of 14.99 MJ/ (m^2·d) and the variation range of 8.48~20.7 MJ/ (m^2·d).

The radiation in the northeastern region, North China, parts of southwest and northwest China in the four seasons is higher, and the radiation in the Central China, the South China region, the East China region and the northwest region is lower.

In particular, the solar radiation in spring shows obviously increasing trend from south to north, and is the highest in the northeastern region, with the average value of 17.85 MJ/ (m^2·d), but is the lowest in South China, with the average of 10.38 MJ/ (m^2·d). The solar radiation is a little lower in North China than that in the northeast region, with the small local difference and the range of 13.78~18.99 MJ/ (m^2·d).

The difference of solar radiation in summer is obviously higher than that in other seasons. The solar radiation is the highest in the northeastern region and the lowest in the South China, with the average value of 18.74 MJ/ (m^2·d) and 13.49 MJ/ (m^2·d) respectively. The zonal distribution in the southwest region is more obvious, and the solar radiation from south to north is gradually increased, ranging from 9.94~18.41 MJ/ (m^2·d).

The amount of solar radiation in autumn is high in the central region, and gradually decreasing to the northwest and southeast region. The solar radiation in the North China is the highest, with the average value of 11.73 MJ/ (m^2·d), and is the lowest in the Central China, with the average value of 9.04 MJ/ (m^2·d). The difference of amount of solar radiation in the northwest shows greatly, with the minimum value of 7.31 MJ/ (m^2·d), and the highest value of 13.67 MJ/ (m^2·d).

The distributed pattern of radiation in winter is similar to that in autumn. The solar radiation is the highest in North China, with the average value of 8.54 MJ/ (m^2·d), and is the lowest in South China, with the average value of 5.04 MJ/ (m^2·d). The zonal difference in Central and East China is more obvious, and the solar radiation increases gradually from south to north, with the ranges of 4.33~7.47 MJ/ (m^2·d), 4.26~8.82 MJ / (m^2·d) respectively.
3.2. Influencing factors of temporal and spatial variation of solar radiation

In order to compare the influence factors of solar radiation on different space-time scales, the seasonal spatial distribution of sunshine hours and AOD are given in figure 2 and figure 3 respectively.

![Figure 2. Spatial distribution of sunshine hours (h) for each season in China.](image)

![Figure 3. Spatial distribution of AOD for each season in China.](image)

It can be seen from figure 2 that the spatial distribution of sunshine hours is influenced by the latitude and terrain, except for some local areas. Sunshine hours is gradually increasing from southeast to northwest, which is consistent with the results of Chen [21] and Qian et al. [22]. Compared with figure 1, it can be found that the spatial pattern of sunshine hours and solar radiation is approximately similar, which confirms that the sunshine hours is the best choice of proxy for solar radiation [23–25].

Overall, sunshine hours in spring and summer are higher, with the average of 224.34 h and 220.82 h respectively, and the variation range of 58.17~352.32 h and 82.41~361.39 h respectively. Sunshine hours is the lowest in winter, with the average value is 154.97 h, and the range of 17.94~285.67 h.
In autumn, the average value of sunshine hours is 191.83 h, and the range is 45.27–283.53 h. The sunshine hours in the northeastern region, North China, parts of southwest and northwest China for the all four seasons are higher, while the sunshine hours in the Central China, South China, East China are lower. In particular, sunshine hours in spring appears to be gradually increasing from southeast to northwest, with the highest values of the average 268.33 h in the northwest and the lowest of the average 110.51 h in southern China. The amount of sunshine hours in North China is a little lower than that in the northwest region, with the small local difference and the range of 158.55–302.1 h. The distribution characteristics of sunshine hours in summer is obviously regional difference. Sunshine hours gradually increase from the south to the north, with the highest value in the northwest region (the average of 270.45 h), and the lowest in southern China (the average value of 170.93 h). The local distribution in the southwest is the most obvious, where the amount of sunshine hours from south to north is increasing gradually, with the range of 82.41–288.12 h. Sunshine hours in autumn is higher in the southwest and northwest regions, with the highest value in the northwest region and the average of 225.79 h. The lowest sunshine hours shows in Central China, with the average value of 125.95 h. The average sunshine hours in North China is 194.32 h and the variation range is 148.23–260.63 h. The sunshine hours in winter reflects the most significant features of the local area, with the highest value in the northeast region and the average of 175.25 h, and the lowest value in South China and the average value of 42.35 h, which is consistent with the distribution trend of solar radiation. The zonal distribution of the sunshine hours in Central and East China is obvious, and the amount of sunshine hours from south to north is gradually increased, with the range of 23.21–125.27 h and 69.52–178.98 h respectively.

Comparing figures 1 and 2, the distribution of sunshine hours is approximately consistent with that of solar radiation. However, in some parts of the northwest, such as Xinjiang, there is higher sunshine hours but lower solar radiation. Sunshine hours in Xinjiang of spring has the average values of 286.35 h and the range of 274.37–352.32 h. The minimum and average values are both higher than that in the northwest region for the same season. While, solar radiation in Xinjiang of spring has the average values of 13.90 MJ/(m²·d) and the range of 11.96–16.67 MJ/(m²·d). The maximum and average values are both lower than that in the northwest region. This suggests that just using sunshine hours as an independent variable for simulating solar radiation is not rational enough, although sunshine hours is the best choice as a proxy indicator of solar radiation. Therefore, it is necessary to consider other factors, especially the aerosol which has the significant effect on sunshine hours and solar radiation.

Figure 3 shows the distribution of AOD for the four seasons, which presents two low regions and two high regions. One of the low-value regions is located in the northeast (Heilongjiang) and parts of North China (Inner Mongolia), and another low-value region is in the high altitude area of southwest China. While the two high-value areas are located in most parts of eastern China (especially in the North China Plain, Sichuan Basin, the Yangtze River Delta, the Pearl River Delta and other regions) where the population density are the highest in China, and the northwest part of the region (southern Xinjiang Basin). The spatial pattern of AOD is consistent with the boundary of Hu Huanyong lines proposed by Zheng et al.[26].

In general, AOD is the highest in spring, with the average of 0.44, and the range of 0.02–2.16. AOD is the lowest in autumn, with the average value of 0.27, and the range of 0.01–2.84. AOD in the Central China, South China, many parts of the East China and parts of the northwest China of the four seasons is higher, while AOD in the northeastern region, North China, many parts of southwest is lower. Specifically, the spatial difference of AOD in spring is significant, with the highest content of AOD in Central China (the average value of 0.61), and the lowest in the southwest and northeast China (the average value of 0.31). The average content of AOD in the northwest region is 0.51 and the variation range is 0.05–1.82, among which the content of AOD in Xinjiang is higher, with the average value of 0.64, and the range of 0.11–1.82. The trend of AOD distribution in summer is roughly similar with that of AOD in spring, with the highest AOD content in East China (the average of 0.61) and the lowest in northeast China (the average of 0.28). The AOD content in northern China is higher, with the mean value of 0.61, and the larger local difference with the variation range of 0.08–2.27. AOD in
autumn is the highest in Central China and East China (the average of 0.42), and the lowest in the southwest and northeast regions (the average of 0.19). The average AOD content in the North China region is 0.23, with the variation range of 0.01~2.33, in which AOD in the Inner Mongolia region has the average of 0.21 and the range of 0.01~1.39. The maximum and average value of AOD are lower than that in the North China, and the lowest AOD value of North China locates in Inner Mongolia. AOD in winter is the highest in Central China, with the average of 0.56, and the lowest in northeast and North China, with the average of 0.2.

Compared with figure 1, it can be found that AOD has significant negative correlation with solar radiation in spatial distribution pattern, especially in autumn and winter. AOD is lower in the southwest of Qinghai-Tibet Plateau and the northern part of North China, where solar radiation is significantly higher than the surrounding area. While AOD is higher in Central China, the North China Plain and the Sichuan Basin, where solar radiation is significantly lower than the surrounding area. This suggests that the calculation accuracy can be improved obviously by adding AOD as the influencing factor into the solar radiation distributed simulation. The effect of aerosols on solar radiation has been confirmed by many researchers [27]. With the progress of the mechanism of aerosol radiative forcing, it is believed that more and more researchers will be aware that aerosol plays an important role in the solar radiation simulation process.

Combining the results of figure 1, figure 2 and figure 3, the spatial distribution of solar radiation is obviously affected by the combination of sunshine hours and AOD. In the northwest region, for example, the sunshine hours is higher than that in northeast for the all four seasons. However, because of the higher AOD, the solar radiation of the northwest region in four seasons are lower than that in northeast region, especially in autumn and winter, when the level of solar radiation in some areas of northwestern decreases to the similar to southeast part (Central China, East China, South China). In addition, the spatial pattern of sunshine hours and AOD in winter is consistent, indicating that with the low sun height angle and serious pollution in winter, the sunshine hours is significantly impacted by the aerosol. Since the sunshine hours indicates that the solar direct irradiance reaches or exceeds the sum of 120 W/m², the difference in the influence of AOD on solar radiation and sunshine hours in different seasons may be related to the type of aerosol.

4. Conclusions

Based on the quantitative relationship between AOD and API, this paper constructs a distributed calculation model of solar radiation based on AOD. GIS is combined to estimate the spatial distribution of solar radiation in China with 10km × 10km resolution. The main conclusions are as follows.

1) The spatial distribution of solar radiation shows obviously zonal character, except for the northwest and southwest parts. Solar radiation increases gradually from the south to the north. The average solar radiation is the highest in summer, with the average of 16.31 MJ/(m²·d), the lowest in winter, with the average value of 7.39 MJ/(m²·d). Solar radiation is slightly higher in spring than that in autumn, with the average value of 14.99 MJ/(m²·d).

2) The overall distribution trend of sunshine hours and solar radiation is roughly similar, but in parts of northwest China, such as Xinjiang, there is high sunshine hours but low solar radiation. The sunshine hours in spring and summer are the highest, with the average of 224.34 h and 220.82 h respectively, while the sunshine hours in winter is the lowest, with the average of 154.97 h. Sunshine hours in autumn has the average of 191.83 h. Sunshine hours is the best choice for solar radiation indicators, but the simulation accuracy of solar radiation only considering sunshine hours is a little poor.

3) The AOD has significant negative correlation with solar radiation in spatial distribution pattern, especially in autumn and winter. AOD is lower in the southwest of Qinghai-Tibet Plateau and the northern part of North China, where the solar radiation is significantly higher than the surrounding area. While AOD is higher in Central China, North China Plain and Sichuan Basin, where solar radiation is significantly lower than the surrounding area. It is shown that the calculation accuracy can
be improved obviously by adding AOD as the influencing factor into the solar radiation distributed simulation.

(4) The spatial distribution of solar radiation is obviously affected by the combination of sunshine hours and AOD. In the northwest region, for example, the sunshine hours is higher than that in northeast for the all four seasons, but because of the higher AOD, the solar radiation of the northwest region is lower than that in northeast region, especially in autumn and winter, when solar radiation decreases to southeast part (Central China, East China, South China) level.

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