Correlation between the distribution of solar energy resources and the cloud cover in Xinjiang

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Abstract. In order to study the influence of cloud cover on solar energy resources, it provides scientific basis for the development and utilization of solar radiation resources. Based on the Cloud and the Earth’s Radiant Energy System (CERES) and European Centre for Medium-Range Weather Forecasts (ECWMF) data from 2014-2018, the correlation between the temporal and spatial distribution of solar energy resources and the cloud cover in Xinjiang was studied and analyzed. The results show that solar energy resources have generally shown an upward trend in the past five years, with an average annual radiation of 7206.5 MJ/m² and very stable. The overall distribution of solar radiation is mainly dominated by latitude, decreasing from south to north, and the change is relatively uniform. The maximum value of annual total radiation in the southern area of Xinjiang is about 9000 MJ/m², which is 1.5 times of that in the northern area. The maximum daily total radiation is 28.88 MJ/m² in July, which is 3.3 times of that in December. The total radiation in summer can reach up to 2200 MJ/m², which is 2.2 times of that in winter. Summer radiation is high but fluctuating, and winter radiation is small but relatively stable. The autumn is the period with the least amount of total cloud during the year, the cloud cover in the northern area is about 40%, and the winter in the northern area is the highest along the foothills of the Tianshan Mountain, up to 70%. The fitting effect of radiation attenuation and cloud cover in the northern area is higher than that in the southern area, and the maximum correlation coefficient is 0.98 in summer and the minimum is 0.571 in winter. The solar radiation is mainly affected by clouds in summer, while in winter, there are other factors such as aerosols.

1. Introduction

Solar radiation is the source of energy for life on earth [1], and also the basic driving force for all physical processes or phenomena in the atmosphere [2]. The radiation budget of the earth-atmosphere system plays a decisive role in the heat and circulation of the atmosphere and oceans, shaping the main features of the Earth's climate [3,4]. When solar radiation passes through the atmosphere, about 20% is absorbed by the atmosphere, 30% is reflected back to the universe by the ground and the atmosphere, and about 50% reaches the surface of the earth [5]. Nevertheless, the total amount of solar radiation is still very huge. According to the European Photovoltaic Industry Association (EPIA), the amount of
radiation reaching the Earth's surface is equivalent to 130 trillion tons of standard coal [6]. As a kind of clean energy, solar energy is receiving more and more attention. The research on the temporal and spatial characteristics and changing laws of solar energy resources has also become a hot topic of domestic and foreign scholars [7-10].

At present, researches on solar radiation mainly focus on the climatological calculation and analysis of solar energy [11-14]. Zuo Dakang et al. first studied the spatial distribution characteristics of total solar radiation and plotted the total radiation and annual total radiation distribution in China [11]. After Wang Bingzhong first proposed China's solar zoning indicators in 1983[13], many researchers have done a lot of work on the temporal and spatial distribution and zoning of solar energy resources in some provinces and cities based on observation data from meteorological stations [15-17]. Although existing studies have analyzed the spatial distribution characteristics of solar energy resources, the possible influencing factors of solar radiation changes arriving at the ground are relatively complex [18,19]. In addition to the changes of the sun, the solar radiation changes arriving at the ground are also affected by clouds, dust, water vapor, and aerosols. About 50% of the global surface is covered by clouds. The transmission, absorption, reflection and infrared radiation emitted by clouds control the solar radiation incident to the earth's surface, so clouds have a very important impact on the solar resources reaching the ground [20,21].

Xinjiang is located at 33.5°N~48.5°N, in the hinterland of Eurasia, surrounded by mountains, away from the ocean, with dry air, less cloud and rain, good atmospheric transparency, more sunshine, and abundant solar energy resources. Xinjiang's solar energy resources are higher than those of North China and Northeast China at the same latitude, and also higher than those of the lower latitudes of the middle and lower reaches of the Yangtze River and the South China, mainly due to its specific geographical location and climatic conditions. The solar radiation energy reaching the horizontal surface of the earth's surface is greatly affected by the climatic conditions and the characteristics of the underlying surface. The dry climate and a small amount of cloud and rain make Xinjiang have unique advantages in solar energy resources [22,23]. Considering that the difference in cloud characteristics between different regions or different time periods directly affects the amount of solar energy reaching the surface [24], this paper takes Xinjiang region as an example to analyze the correlation between the temporal and spatial distribution of solar energy resources and the cloud cover from the perspective of the region.

2. Data and methods

Due to the sparse solar radiation observation sites in China and the lack of total solar radiation data, the detection data of Cloud and the Earth's Radiant Energy System (CERES) [25]from 2014 to 2018 (resolution is 1°×1°) and the model forecast data of the European Centre for Medium-Range Weather Forecasts (ECMWF)[26] from 2014 to 2018 (resolution is 0.125°×0.125°) are used to study the temporal and spatial changes of solar resources in Xinjiang and the correlation between them and the cloud cover.

According to the standard QX/T 89-2008 "Solar Resource Assessment Method", the solar energy resources in Xinjiang are evaluated and analyzed. The annual total solar radiation is divided into four grades: the most abundant (A), very rich (B), rich (C), general (D). The classification criteria are shown in Table 1.

| Grade name   | Grading threshold kW h/(m²a) | Grading threshold MJ/(m²a) | Grade symbol |
|--------------|------------------------------|----------------------------|--------------|
| Abundant     | G≥1750                       | G≥6300                     | A            |
| Very rich    | 1400≤G<1750                  | 5040≤G<6300                | B            |
| Rich         | 1050≤G<1400                  | 3780≤G<5040                | C            |
| General      | G<1050                       | G<3780                     | D            |

Note: G represents annual irradiation, a: annually.
3. Temporal and spatial distribution of solar energy resources

The solar energy resources in Xinjiang were evaluated by the data of the last five years (2014-2018). According to the calculation results, the average annual radiation amount was 7206.5 MJ/m², which reached the most abundant level, which is conducive to the development and utilization of solar power generation. The spatial and temporal characteristics of solar energy resources are analyzed below.

3.1. Temporal variation characteristics of solar radiation

Figure 1 and Figure 2 respectively show the annual average, daily average and standard deviation of solar radiation in the Xinjiang region from 2014 to 2018. It can be seen from the figure that the annual total radiation is above 7100 MJ/m², and the solar energy resources are very rich, showing an overall upward trend in the past five years. The total solar radiation increased first and then decreased throughout the year, and the maximum daily radiation amount is 28.88 MJ/m² in July, which is 3.3 times of that in December with 8.75 MJ/m². It can be seen from the daily standard deviation that the daily fluctuations are relatively weak, the large deviations mainly are from June to August with 2.0 MJ/m², and the small deviations are from November to February with 0.72 MJ/m². Summer radiation is high but fluctuating, and winter radiation is small but relatively stable. The overall fluctuations that do not exceed the annual average value indicate that the solar energy resources are very stable in Xinjiang.

3.2. Spatial variation characteristics of solar radiation

Figure 3 and Figure 4 respectively show the annual average distribution and seasonal distribution of solar radiation in Xinjiang from 2014 to 2018. As can be seen from the figures, the overall solar radiation shows a trend of decreasing with the increase of latitude, and the annual total solar radiation in various regions is basically above 6000 MJ/m². The maximum value of annual total radiation in the southern area of Xinjiang is about 9000 MJ/m², which is 1.5 times of that in the northern area with 6000 MJ/m². From the seasonal distribution of solar radiation, the total radiation in summer is the largest, and the maximum can reach 2200 MJ/m² in the central and eastern regions of Xinjiang, which is 2.2 times of that in winter with 1000 MJ/m². The total amount of radiation in spring is larger than that in autumn, and the distribution is mainly affected by latitude, decreasing from south to north, and the change is relatively uniform.

4. Cloud distribution

Figure 5 and Figure 6 respectively show the distribution of total cloud cover and radiation attenuation in Xinjiang. It can be seen from the Figure 5 that the autumn is the period with the least amount of total cloud during the year, the cloud cover in the northern area is about 40%, the eastern and southern are about 30%, and the winter in the northern area is the highest along the foothills of the Tianshan Mountain, up to 70%. The radiation attenuation distribution of the four seasons is consistent with the cloud distribution in the corresponding season. Since solar radiation is the largest in summer, the radiation attenuation caused by the cloud layer can reach 250W/m² or more. Overall, the radiation attenuation in the northern of Xinjiang is higher than that in the southern area, indicating that the cloud is also one of the main causes that the solar radiation in the eastern and southern is higher than that in the northern.
Figure 3. Annual average distribution of solar radiation (Unit: MJ/m²).

Figure 4. Seasonal distribution of solar radiation (Unit: MJ/m²).

Figure 5. Seasonal distribution of cloud cover in Xinjiang (Unit: Percentage).
5. Correlation analysis

Due to the high altitude of Xinjiang, the difference in altitude between north and south has a great impact on the formation of clouds. Therefore, the whole region is divided into four regions according to the topography of A-B-C-D to analyze the effect of the cloud on the radiation attenuation. Figure 7 and Figure 8 respectively show the topographic distribution and the relationship between radiation attenuation and cloud cover. It can be seen from the figure that the northern region (A) is a basin with lower topography, the southern region (D) and the central region (B) with higher topography and there is also a desert zone (C) between the D and B. By linearly fitting the radiation attenuation and cloud cover in different seasons of the four regions, the radiation attenuation and the cloud cover are linearly correlated, but the correlation between different regions and seasons is significant.

From the radiation attenuation and cloud fitting parameters in Table 2, it can be seen that the region B has the best fitting effect, and the correlation coefficient is up to 0.98 in summer. The fitting effect of region D is weak, especially in winter, only 0.571. The average correlation coefficient of the northern region is 0.935 higher than that of the southern region with 0.62, so the fitting effect in the north region is better. From the perspective of the seasonal fitting, summer has the best fitting effect, and the correlation between spring and autumn is very close, and the correlation in winter is relatively small, indicating that summer radiation is mainly affected by clouds, while other factors such as aerosols are also affected in winter. From the above fitting coefficient, it can be seen that the average correlation coefficient of the northern region is 0.935 and the standard deviation is just 0.07, the correlation between the radiation attenuation and the cloud cover in the north of Xinjiang is very good. The cloud cover can be used to correct and forecast the total radiation, which will help to improve the prediction accuracy of solar power generation.
Figure 8. The relationship between radiation attenuation and cloud cover in Xinjiang (Unit: W/m²).

Table 2. The radiation attenuation and cloud fitting parameters.

| Seasons | Parameters            | Region-A       | Region-B       | Region-C       | Region-D       | Average       |
|---------|-----------------------|----------------|----------------|----------------|----------------|---------------|
| Spring  | Correlation coefficient | 0.957          | 0.977          | 0.948          | 0.636          | 0.879         |
|         | Standard deviation     | 0.043          | 0.026          | 0.022          | 0.049          | 0.035         |
| Summer  | Correlation coefficient | 0.952          | 0.980          | 0.863          | 0.616          | 0.852         |
|         | Standard deviation     | 0.027          | 0.017          | 0.027          | 0.058          | 0.032         |
| Autumn  | Correlation coefficient | 0.969          | 0.953          | 0.898          | 0.658          | 0.870         |
|         | Standard deviation     | 0.054          | 0.051          | 0.05           | 0.098          | 0.063         |
| Winter  | Correlation coefficient | 0.862          | 0.855          | 0.799          | 0.571          | 0.771         |
|         | Standard deviation     | 0.155          | 0.157          | 0.056          | 0.119          | 0.122         |
| Average | Correlation coefficient | 0.935          | 0.941          | 0.877          | 0.620          | /             |
|         | Standard deviation     | 0.070          | 0.063          | 0.039          | 0.081          | /             |

6. Conclusions

Based on the CERES and ECWMF data from 2014 to 2018, the correlation between the temporal and spatial distribution of solar energy resources and the cloud cover in Xinjiang was studied and analyzed. The results show that:

(1) In the past five years, solar energy resources have generally shown an upward trend with an average annual radiation of 7206.5 MJ/m² and very stable. The maximum daily radiation amount is 28.88 MJ/m² in July, which is 3.3 times of that in December with 8.75 MJ/m². Summer radiation is high but fluctuating, and winter radiation is small but relatively stable.

(2) The overall distribution of solar radiation is mainly dominated by latitude, decreasing from south to north, and the change is relatively uniform. The maximum value of annual total radiation in the southern area of Xinjiang is about 9000 MJ/m², which is 1.5 times of that in the northern area with 6000 MJ/m². From the seasonal distribution of solar radiation, the total radiation in summer is the largest, and the maximum can reach 2200 MJ/m² in the central and eastern regions of Xinjiang, which is 2.2 times of that in winter with 1000 MJ/m².

(3) Autumn is the least period of total cloud cover in Xinjiang during the year, the cloud cover in the northern area is about 40%, and the winter in the northern area is the highest along the foothills of the Tianshan Mountain, up to 70%. The radiation attenuation distribution of the four seasons is
consistent with the cloud distribution in the corresponding season and the radiation attenuation in the northern area of Xinjiang is higher than that in the southern area. Since solar radiation is the largest in summer, the radiation attenuation caused by the cloud layer can reach 250 W/m² or more.

(4) The fitting effect of radiation attenuation and cloud cover in northern is higher than that in the southern area, and the maximum correlation coefficient is 0.98 in summer and the minimum is 0.571 in winter. The solar radiation is mainly affected by clouds in summer, while in winter, there are other factors such as aerosols.

Acknowledgements
This research was financially supported by the State Grid Corporation of Science and Technology Project [Research and application of multi-spatial scale variation of photovoltaic output characteristics considering complex factors such as cloud and floating dust: NY71-19-013].

References
[1] Liu C M, Liu X M, Zheng H X et al. 2009 Acta Geographica Sinica 64(11) 1283-1291
[2] Wen X H, Shang K Z, Wang S G et al. 2008 Journal of Desert Research 28(3) 554-561
[3] Ning Sun, John Yearsley, Nathalie Voisin et al. Lettenmaier 2014 Hydrol. Process. doi: 10.1002/hyp.10363
[4] Abdi, R. Endreny, T. 2019 Water 11 1060
[5] Li F, Chen Z H, Duan S X et al.2014 Solar Energy 03
[6] Wilhelm I, Teske S 2011 EPIA Solar generation 6
[7] Wu Q Z, Wang Z F, Cui Y J 2010 Journal of Applied Meteorological Science 21(3) 343-351
[8] Zhao D, Luo Y, Gao G et al. 2010 Resources Science 32(4) 701-711
[9] Du Y D, Mao H Q, Liu A J et al. 2003 Resources Science 25(6) 6-70
[10] Wang X F, Zhu Y, Fan L Z et al. 2009 Advances in Climate Change Research 5(1) 29-34
[11] Zuo D K, Wang B X, Chen J S 1963 Acta Meteorologica Sinica 33 (1) 78-96
[12] Wang B Z, Zou H S, Yin Z Q 1984 Solar Energy 4 19
[13] Wang B Z 1983 Acta Energiae Solaris Sinica 4(3) 221-228
[14] He H L, Yu G R, Niu D 2003 Resources Science 25(1) 78-85
[15] Liu K Q, Chen Z H, Xia Z H 2007 Journal of Huazhong Agricultural University 22(6) 888-893
[16] Liu J, He Q, Liu R et al. 2008 Arid Meteorology 26(4) 61-66
[17] Yu H S, Lin N, Yu Y 2008 Journal of Meteorology and Environment 24(2) 18-22
[18] Petro Topyliko, Igor Penyak, Bogdan Lybinsky 2018 IEEE CSIT 195-198
[19] Shilpa Manandhary, Soumyabrata Devyz, Yee Hui Lee et al. 2018 IEEE URSI 93-94
[20] Wu P F, Chen W M, Wang J K et al. 2003 Journal of Nanjing Institute of Meteorology 26(5) 613-621
[21] Shilpa Manandhar, Soumyabrata Dev, Yee Hui Lee et al. 2017 Progress In Electromagnetics Research Symposium 2166-2168
[22] Jin J X, Zhou Y 2009 Beijing: China Statistics Press 242-244
[23] Li J F 1991 Beijing China Meteorological Press 8-346
[24] Shen Y B, Zhao Z C, Shi G Y 2008 Advances in Earth Science 23(9) 915-923
[25] Kato S , Loeb N G 2003 Journal of Climate 16(15) 2646-2650
[26] Zhong S X, Chen Z T 2020 J Trop Meteor 26(1) 27-34