Estimation of Surface Solar Radiation and Analysis of Its Influencing Factors in the Tizinafu River Basin (Postprint)

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Abstract

Surface solar radiation constitutes the primary energy source for the Earth' s surface and plays a decisive role in surface energy balance, energy exchange, and eco-hydrological processes. Due to complex terrain in mountainous areas, surface solar radiation exhibits substantial spatiotemporal variations that are difficult to estimate. This study employed a mountainous-area-suitable surface solar radiation model to estimate the spatiotemporal distribution of surface solar radiation in the Tizinafu River Basin of the Kunlun Mountains in northwestern China, analyzed the seasonal spatial distribution patterns of solar radiation in this watershed, and examined the influences of two important factors—terrain and clouds—on the spatial distribution of solar radiation. The results show that: (1) Among topographic factors, the shielding effect of surrounding terrain, namely the sky view factor (SVF), exhibits the most significant relationship with annual total solar radiation, which increases with increasing SVF. (2) Annual total solar radiation first decreases and then increases with elevation. An investigation of SVF variation with elevation reveals a trend largely consistent with that of solar radiation variation with elevation; therefore, relying solely on elevation for correction in surface solar radiation estimation under complex mountainous terrain is clearly inadequate, necessitating comprehensive consideration of topographic effects. (3) The study calculated correlation coefficients between the spatial distributions of seasonal cloud occurrence frequency and solar radiation, demonstrating that solar radiation in summer is significantly more affected by clouds than in other seasons. A quantitative analysis of the contribution rates of topographic factors and clouds to the spatial distribution of surface solar radiation indicates that the shielding effect of surrounding terrain (SVF) exerts the greatest influence, followed by elevation and clouds. Therefore, comprehensively considering the effects of terrain and clouds on solar radiation is essential for solar radiation simulation in mountainous areas. This research

can provide a theoretical basis for surface solar radiation simulation in mountainous regions and methodological support for eco-hydrological process studies in such areas.

Full Text

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Abstract: Surface solar radiation is the primary energy source for the Earth' s surface and plays a decisive role in surface energy balance, energy exchange, and eco-hydrological processes. Mountainous terrain is complex, making surface solar radiation difficult to estimate due to large spatiotemporal variations. This study employs a mountain-suitable surface solar radiation model to estimate the spatiotemporal distribution of surface solar radiation in the Tizinafu River Basin of the Kunlun Mountains in northwestern China. The seasonal spatial distribution patterns of solar radiation are analyzed, and the impacts of two important factors—terrain and cloud—on the spatial distribution of solar radiation are discussed. The results show that: (1) Among terrain factors, surrounding terrain blocking, expressed as sky view factor (SVF), has the most significant relationship with annual total solar radiation, which increases with SVF. (2) Annual total solar radiation first decreases and then increases with elevation. The trend of SVF changes with elevation is consistent with that of solar radiation changes with elevation, indicating that using elevation alone for topographic correction in solar radiation estimation over complex mountainous terrain is insufficient and that topographic effects must be considered comprehensively. (3) The study calculated the spatial correlation coefficients between seasonal cloud occurrence frequency and solar radiation distribution, revealing that summer solar radiation is more significantly affected by clouds than other seasons. Quantitative analysis of the contribution rates of terrain factors and clouds to the spatial distribution of surface solar radiation shows that surrounding terrain blocking has the greatest impact, followed by elevation and cloud. Therefore, considering the combined effects of terrain and cloud on solar radiation is essential in mountainous solar radiation simulation. This study provides a theoretical basis for mountainous surface solar radiation simulation and methodological support for eco-hydrological process research in mountain areas.

Keywords: mountain area; solar radiation; cloud; terrain

1.1 Study Area Overview

The Tizinafu River Basin is a major tributary of the Yarkant River Basin in the Kunlun Mountains, covering an area of 5518 km^2 with an average elevation of 4000 m. Located in the arid desert hinterland of the Eurasian continent, the basin is characterized by a typical warm continental arid climate. The Kunlun and Karakoram mountain ranges to the south and west block monsoon entry, while the northern terrain is relatively open, allowing dry continental air masses and cold Arctic air currents to enter. The southern region of the basin features high mountains where sunshine duration is 5%-30% less than in the northern plain areas due to terrain blocking and weather conditions.

1.2 Data Sources

The ASSRM model requires atmospheric data (aerosol optical depth, water vapor, ozone optical depth, surface pressure), cloud-related parameters (cloud optical thickness, cloud particle effective radius, cloud height), and ground parameters (surface albedo). This study uses MODIS atmospheric and cloud property datasets as model inputs, with missing values interpolated using corresponding data. The model validation data comes from observations at three automatic weather stations (Momuke, Kudi, and Xihexin) installed in the Tizinafu River Basin, which measure temperature, precipitation, wind speed, and solar radiation at 10-minute intervals from 2016 to 2018. The stations are located at different altitudes with varying surrounding terrain blocking conditions, providing a good reference for evaluating model applicability.

Table 1 Input datasets for ASSRM model

Dataset	Spatial Resolution	Time Resolution
Aerosol optical depth	10 km	Daily
Water vapor	0.5°$×0.625°|1hour||Ozoneopticaldepth|0.5°×0.625°|1hour||Surfacepressure|0.5°×$0.625°	1 hour
Cloud optical thickness, cloud water path, cloud particle effective radius, cloud top height	1 km	1 hour
Surface albedo	500 m	8 days
Digital Elevation Model (DEM)	30 m	Static

1.3.1 Solar Radiation Model

This study employs the ASSRM model to simulate surface solar radiation (direct and diffuse) in the study area. The model' s distinguishing feature is its consideration of mountainous terrain and cloud effects on both direct and diffuse radiation. The model uses Skyshed (calculated via Solar Analyst) to characterize terrain blocking at each location and simulates the non-uniform distribution of clear-sky diffuse radiation in the hemispherical sky using a Sky weight map. When calculating diffuse radiation, the model superimposes the Sky weight map and Sky cloud map to simulate the effects of terrain and clouds on radiation. For direct radiation, the model superimposes Skyshed and Sky cloud map in the solar direction to calculate terrain and cloud impacts. The model uses a corrected sine interpolation function to upscale instantaneous values from two satellite transit times (Terra and Aqua) to daily solar radiation.

Model validation shows good performance, with correlation coefficients between simulated and observed instantaneous solar radiation exceeding 0.8 at all stations and overall relative bias of -0.2%. The relative absolute bias is 25.79% at Xihexin, 17.02% at Kudi, and 1.43% at Momuke. At the daily scale, the model shows overall overestimation but better performance than at the instantaneous scale, with correlation coefficients exceeding 0.9 at all stations. Compared with published models, ASSRM demonstrates higher overall accuracy, making it suitable for solar radiation estimation in complex mountainous terrain.

Figure 1 Overview of the Tizinafu River Basin and the distribution of meteorological stations

Figure 2 Anisotropic diffuse radiation modules of ASSRM model

1.3.2 Geodetector

Geodetector is a statistical method for detecting spatial stratified heterogeneity and its influencing factors. The method assumes statistical association between dependent and independent variables when their spatial distribution trends are consistent. The measure for determining the explanatory power of independent variables on dependent variables is expressed as:

$$P_{D,H} = 1 - \frac{\sum_{I=1}^{m} n_{D,I}\sigma^2_{H_{D,I}}}{n\sigma^2_H}$$

where $P_{D,H}$ is the influence index of factor D on solar radiation spatial distribution; σ^2_H is the variance of solar radiation in the study area; n is the sample size; m is the number of variable categories; $n_{D,I}$ is the sample size of factor D in category I; and $\sigma^2_{H_{D,I}}$ is the variance of solar radiation in category I. $P_{D,H} \in [0,1]$, where $P_{D,H} = 0$ indicates the factor does not affect solar radiation spatial distribution, and larger values indicate greater explanatory power.

2.1 Spatiotemporal Distribution of Surface Solar Radiation in the Tizinafu River Basin

To investigate the spatiotemporal distribution patterns of surface solar radiation, this study simulated daily solar radiation distribution in the Tizinafu River Basin from 2016 to 2018 and calculated seasonal and annual total solar radiation distributions. Spring and summer solar radiation are significantly higher than in autumn and winter. Spatially, solar radiation in the downstream plain areas with relatively flat terrain shows homogeneous distribution across all seasons. In contrast, the midstream and upstream mountainous areas exhibit strong spatial heterogeneity due to complex terrain. Both annual and seasonal total solar radiation show low-value zones in the central basin, likely because this area has complex terrain with substantial blocking and higher cloud occurrence probability, which significantly reduces surface solar radiation. In the downstream area, although elevation is lower, reduced terrain blocking increases incident solar radiation. In the upstream area, increased elevation reduces atmospheric path length, also increasing incident solar radiation.

Figure 3 Spatial distributions of seasonal and annual total solar radiation in the study area

2.2 Terrain Effects on Solar Radiation Spatial Distribution

Mountainous solar radiation exhibits high spatiotemporal heterogeneity primarily due to terrain effects. This study examines the relationship between terrain and solar radiation spatial distribution based on model simulation results. Terrain factors include self-blocking and surrounding terrain blocking. Self-blocking is analyzed from elevation, slope, and aspect perspectives.

Elevation affects the path length of solar radiation reaching the surface. Under clear skies, atmospheric path length decreases with increasing elevation, resulting in higher solar radiation at higher altitudes. However, with cloud cover, the relationship becomes more complex. The study area' s elevation ranges from 1488–6306 m. Divided into 500 m intervals, the area proportion is highest in the 3500–4000 m range (16.04%) and smallest in the 5500–6306 m range (2.00%). Annual total solar radiation first decreases then increases with elevation, with the turning point occurring in the 3000–3500 m interval. In the <3000 m interval (downstream plain), despite longer atmospheric paths, flat terrain with minimal blocking results in relatively high solar radiation. In the 3000–3500 m interval, complex terrain increases blocking, reducing surface solar radiation. Above 3500 m, although terrain blocking persists, reduced atmospheric path length and decreased blocking at higher elevations increase solar radiation.

Slope and aspect represent terrain self-blocking. Slope ranges from 0–80.4°, with the 20°–30° range covering the largest area. Solar radiation decreases with increasing slope, while intra-interval standard deviation increases with slope, indicating greater spatial variability on steeper slopes. Aspect analysis shows south-facing slopes receive more radiation than north-facing slopes, with southeast slopes receiving more than southwest slopes. Standard deviation also shows greater variability in north-facing areas.

To investigate surrounding terrain blocking effects, this study calculated SVF (sky view factor) at 30 m resolution using Viewshed analysis. SVF represents the proportion of visible sky in a hemispherical view. The relationship between SVF and solar radiation shows that solar radiation increases significantly with SVF, while standard deviation decreases with increasing SVF. Larger SVF values indicate more open terrain with less surrounding blocking and more uniform terrain, resulting in higher solar radiation with smaller spatial differences. The correlation coefficient between annual total solar radiation and SVF spatial distributions is -0.48 ($p<0.05$), indicating significant influence of surrounding terrain blocking on solar radiation distribution. Seasonal analysis shows spring has the greatest impact, winter the smallest.

Figure 4 Annual total solar radiation changes with elevation, slope, aspect and sky view factor

Figure 5 Relationship between SVF and solar radiation, and SVF changes with elevation

2.3 Cloud Effects on Solar Radiation Spatial Distribution

Cloud is the primary factor affecting solar radiation attenuation. Mountainous areas have higher cloud occurrence frequency than flat areas, especially at high altitudes. This study first calculated seasonal cloud occurrence days and their correlation with surface solar radiation. Winter shows the highest cloud frequency, primarily in complex high-mountain terrain, with spatial distribution consistent with terrain patterns. High cloud frequency in winter may explain larger model simulation errors. Spring and summer also show relatively high cloud frequencies, with spring cloud distribution matching terrain patterns and summer clouds concentrated in mid-altitude complex terrain areas. Autumn has the lowest cloud frequency, characteristic of "clear autumn weather."

Correlation analysis between seasonal cloud occurrence frequency and solar radiation shows summer solar radiation spatial distribution is most affected by clouds ($R^2 = 0.18$, $p<0.05$), while other seasons show smaller effects (spring: $R^2 = 0.08$, autumn: $R^2 = 0.07$, winter: $R^2 = 0.05$). To further investigate cloud effects, this study compared the Kumar model (which considers terrain blocking but not cloud attenuation) with the ASSRM model (which considers both). The Kumar model overestimates daily solar radiation by approximately 19.48 $MJ \cdot m^{-2}$ on average, with maximum differences reaching 2398 $MJ \cdot m^{-2}$ annually. Seasonal differences are smallest in autumn (consistent with lowest cloud frequency) and largest in summer (due to high cloud frequency and high overall radiation levels). Spatial correlation coefficients between model differences and cloud occurrence frequency are: spring ($R^2 = -0.10$), summer ($R^2 =$

-0.26), autumn (R^2 = -0.05), and winter (R^2 = -0.40), confirming that summer clouds most significantly affect solar radiation spatial distribution.

Figure 6 Spatial distribution of seasonal cloud occurrence days

Figure 7 Spatial distributions of differences between Kumar model and ASSRM model in different seasons

2.4 Quantitative Analysis of Terrain and Cloud Effects on Solar Radiation Spatial Distribution

To quantitatively analyze the relative contributions of terrain factors and clouds, this study applied Geodetector to assess each factor' s impact on solar radiation spatial distribution. Annual total solar radiation serves as the dependent variable, while elevation, slope, aspect, SVF, and cloud occurrence frequency are independent variables (all categorized into 10 classes). Factor detector results show the influence ranking: SVF > elevation > cloud frequency > slope > aspect. SVF and elevation rank as the top two contributors, indicating terrain significantly affects solar radiation spatial distribution, particularly surrounding terrain blocking. Cloud frequency ranks third, demonstrating that clouds not only attenuate solar radiation but also substantially influence its spatial distribution. These results confirm that considering SVF and cloud radiative effects is necessary to improve simulation accuracy in complex mountainous terrain.

Figure 8 Contribution of different factors to spatial distribution of surface solar radiation

Figure 9 Comparison of spatial distributions of annual total solar radiation and SVF

3 Discussion

Mountainous surface solar radiation exhibits high spatiotemporal heterogeneity, with terrain and cloud being the two main influencing factors. Previous studies have analyzed relationships between terrain factors (elevation, slope, aspect) and solar radiation. Huang et al. found solar radiation increases with slope in western Sichuan, consistent with this study. Their research also showed solar radiation does not monotonically increase with elevation, aligning with our findings, though trends differ due to different study areas and their focus on clear-sky conditions versus our all-weather analysis. This study additionally examined surrounding terrain blocking effects, finding a very significant relationship.

Essery and Marks identified surrounding terrain blocking as the primary terrain element affecting direct radiation, consistent with our results. However, they did not quantify relative contributions of different terrain factors. Using Geodetector, this study quantified these contributions, finding surrounding terrain blocking has the greatest impact on solar radiation spatial distribution—

valuable for improving clear-sky mountain radiation models.

Previous research primarily focused on clear-sky solar radiation, with few studies addressing cloud effects on mountain solar radiation spatial distribution. Mountains have high cloud occurrence frequency. This study used remote sensing cloud data, compared cloud-inclusive versus clear-sky radiation models, analyzed cloud-radiation spatial relationships, and quantified relative contributions of terrain factors and clouds. These results provide reference for factor selection in empirical all-weather mountain surface solar radiation models.

Conclusions

This study estimated spatiotemporal distribution of surface solar radiation in the Tizinafu River Basin of the Kunlun Mountains using a mountain-suitable model and investigated terrain and cloud effects. Main conclusions are:

1) Spring and summer solar radiation are higher than autumn and winter. Spatially, solar radiation is relatively homogeneous in downstream flat areas across all seasons, while upstream mountainous areas show strong heterogeneity due to complex terrain.
2) Among terrain factors, surrounding terrain blocking (SVF) shows the most significant relationship with solar radiation, which increases with SVF. Annual total solar radiation first decreases then increases with elevation, with the turning point in the 3000–3500 m elevation band. The consistent trend between SVF and elevation changes demonstrates that elevation-only correction is insufficient in complex terrain.
3) Summer solar radiation spatial distribution is more affected by clouds than other seasons. Geodetector analysis shows SVF has the greatest impact on solar radiation spatial distribution, followed by elevation and cloud.

These findings indicate that future empirical models for mountainous solar radiation estimation should prioritize SVF, elevation, and cloud factors. Comprehensive consideration of terrain and cloud effects is necessary to improve simulation accuracy and support mountain eco-hydrological process research.

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Note: Figure translations are in progress. See original paper for figures.