Investigation and Assessment of Surface Solar Radiation on the Northern Slope of the Kunlun Mountains Based on Multi-Source Data (Postprint)

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Abstract

Surface solar radiation plays a crucial role in global energy balance and serves as the primary driver of climate change and hydrological cycles. However, due to the diversity of solar radiation components and the high cost of measurement instruments, long-term reliable observational data are lacking in high-altitude mountainous regions. Based on the high-resolution homogenized China Land Surface Climate Observation Gridded Dataset and the ERA5 reanalysis radiation dataset, this study analyzes the variation characteristics of surface solar radiation across different temporal scales on the northern slope of the Kunlun Mountains from 1984 to 2023, and employs the Geographical Detector model to diagnose the relationship between surface solar radiation and atmospheric factors. The results indicate: (1) The annual mean surface solar radiation on the northern slope of the Kunlun Mountains exhibits a significant decreasing trend during the study period, with a decreasing rate of -1.24 $W \cdot m^{-2} \cdot (10a)^{-1}$. Seasonally, the decreasing trend is most pronounced in summer. Monthly mean surface solar radiation demonstrates a pattern of initially increasing and subsequently decreasing, reaching its maximum in June. (2) The spatial distribution of surface solar radiation on the northern slope of the Kunlun Mountains gradually decreases from south to north, with the changing trend showing east-west differences. Except for winter, the decreasing rate in the eastern region is faster than that in the western region for the entire year as well as for spring, summer, and autumn. (3) According to the single-factor detection results, the explanatory power of various atmospheric factors on the spatial differentiation of surface solar radiation differs, with water vapor showing relatively high explanatory power (q=0.90), indicating that water vapor is an important factor influencing the spatial distribution of surface solar radiation on the northern slope of the Kunlun Mountains.

Full Text

Preamble

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Investigation and Evaluation of Surface Solar Radiation on the North Slope of the Kunlun Mountains Based on Multi-source Data

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Abstract: Surface solar radiation is pivotal in the global energy balance and serves as the primary driver of climate change and the hydrological cycle. However, due to the diversity of solar radiation components and the high cost of measurement instruments, long-term reliable observation data are lacking in high-altitude mountainous areas. Based on the high-resolution homogeneous grid dataset of Chinese land surface climate observations and the ERA5 reanalysis radiation dataset, this study analyzes the variation characteristics of surface solar radiation at different temporal scales on the north slope of the Kunlun Mountains from 1984 to 2023, and employs the geographical detector model to diagnose the relationship between surface solar radiation and atmospheric factors. The results indicate: (1) The average annual surface solar radiation on the north slope of the Kunlun Mountains showed a significant decreasing trend during the study period, with a decline rate of $-1.24\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$. Seasonally, the decreasing trend was most pronounced in summer. Monthly average surface solar radiation initially increased then decreased, reaching its maximum in June. (2) The spatial distribution of surface solar radiation on the north slope of the Kunlun Mountains exhibits a gradual decrease from south to north, with variation trends showing east-west differences. Except in winter, the decline rate in the eastern region was faster than in the western region throughout the year and during spring, summer, and autumn. (3) According to single-factor detection results, the explanatory power of atmospheric factors on the spatial differentiation of surface solar radiation varies, with water vapor demonstrating relatively high explanatory ability ($q = 0.90$), indicating that water vapor is a critical factor influencing the spatial distribution of surface solar radiation on the north slope of the Kunlun Mountains.

Keywords: surface solar radiation; spatiotemporal variation; influencing factors; north slope of Kunlun Mountains

Article ID: [Incomplete]

Introduction

Surface solar radiation represents the sum of direct radiation that passes through the atmosphere to reach the ground and diffuse radiation that reaches the surface after atmospheric scattering and reflection. As a crucial parameter in surface radiation budgets, it provides essential energy for Earth's spheres, drives the climate system and hydrological cycle, and profoundly influences atmospheric circulation, ecological processes, global energy balance, and human activities. Consequently, analyzing surface solar radiation and its influencing factors is vital for understanding climate change and promoting efficient solar energy utilization.

After entering Earth' s atmosphere, solar radiation undergoes absorption, scattering, and reflection by clouds, aerosols, and atmospheric molecules before reaching the surface. Clouds play a significant role in surface radiation budget variations. Studies using ground observation data of cloud cover and sunshine duration in southern China have found strong negative correlations between low cloud amount and sunshine hours. Aerosols can directly absorb and scatter solar shortwave radiation, affecting surface solar radiation variations, and indirectly influence surface solar radiation by altering cloud albedo and lifetime. Although clouds offset aerosol effects after 2005, aerosols remain a primary cause of surface solar radiation changes in China from 1961 to 2016. However, some research suggests that while aerosol direct effects considerably impact global radiation climatology, they cannot fully explain the interdecadal variations in China' s surface solar radiation from 1961 to 2016, implying that changes in cloud properties and cloud-aerosol interactions may be responsible.

Water vapor, as a major atmospheric component, is closely related to radiation budgets. Liepert's research in the United States identified water vapor as having the greatest impact on long-term surface solar radiation variations. Analysis of surface solar radiation data from 716 meteorological stations across China revealed negative correlations between surface solar radiation and water vapor, particularly pronounced in high-latitude regions. Other studies indicate that increased water vapor since 1995 has weakened clear-sky surface solar radiation in northwestern East Asia. Atmospheric ozone changes directly affect ultraviolet radiation, with global ozone concentrations not expected to recover to pre-1980 levels within several decades, leading to persistently elevated UV radiation. Due to regional differences in atmospheric composition distribution and variation, relationships between long-term surface solar radiation changes and atmospheric factors remain controversial and require further investigation.

Ground-based solar radiation measurement systems represent the most accurate and direct method for obtaining surface solar radiation data worldwide. However, high instrument investment and maintenance costs result in sparse and heterogeneous radiation stations, and the diversity of solar radiation variations prevents many meteorological stations from providing reliable radiation data, leading to limited long-term, reliable surface solar radiation measurements.

Consequently, satellite remote sensing and numerical weather prediction have become alternative solutions for surface solar radiation estimation.

The north slope of the Kunlun Mountains, located on the northern Tibetan Plateau, features high elevation, low latitude, and high atmospheric transparency, resulting in surface solar radiation far exceeding that of other regions at the same latitude and profoundly influencing regional climate change, hydrological cycles, and energy balance. Difficulties in establishing radiation stations in mountainous areas have led to relatively scarce research on surface solar radiation. To compensate for observational deficiencies, the Third Xinjiang Scientific Expedition team installed radiation observation instruments at the terminus of the Shezhichuan Glacier in the Muztagata area of East Kunlun and on the shore of Aqikekule Lake. Supported by the Third Xinjiang Comprehensive Scientific Expedition project, this study selects long-term, high spatiotemporal resolution radiation products to analyze spatiotemporal variation characteristics of surface solar radiation on the north slope of the Kunlun Mountains, explore relationships between surface solar radiation and atmospheric factors, and discuss possible causes of surface solar radiation variations, providing references for mountainous surface solar radiation and climate change research.

1.1 Study Area Overview

The study area is located on the north slope of the Kunlun Mountains on the northern Tibetan Plateau. The entire mountain range bulges southward, with elevation gradually increasing from north to south, oriented roughly east-west, forming an important geographical boundary in China. Spanning approximately 2,500 km in length with an average elevation of 5,500–6,000 m, the range is narrow in the west and wide in the east, with a total area exceeding 50×10^{4} km^2. Situated deep within the Eurasian continent with limited oceanic moisture access, annual precipitation is scarce, with precipitation and glacial melt being the primary sources of river recharge. The north slope of the Kunlun Mountains belongs to the warm temperate desert climate zone, transitioning to alpine desert with increasing elevation, characterized by thin air and intense solar radiation. The steep terrain features high mountains and active glaciers.

1.2.1 Surface Solar Radiation Data

Compared with sparse and incomplete observational data, satellite remote sensing and reanalysis datasets provide valuable alternatives for mountainous surface solar radiation research. This study first collected two widely used global reanalysis radiation products (ERA5 and MERRA-2). While reanalysis products provide long-term data, their spatial resolution is relatively coarse, and they tend to overestimate clear-sky conditions, leading to overestimation of surface solar radiation. A study with complete records from 2007 to 2016 validated the accuracy of the latest satellite-derived radiation products and three global reanalysis radiation products (MERRA-2, ERA-Interim, and JRA-55), demonstrating that satellite-derived products outperform reanalysis products. Based on these findings, this study additionally collected three satellite radiation products. Basic information for the five radiation products is presented in .

Analysis of interannual variations of these five radiation products on the north slope of the Kunlun Mountains reveals that, except for the China Meteorological Forcing Dataset (CMFD), which shows an insignificant increasing trend, all other products exhibit decreasing trends. Boxplot analysis of the five surface solar radiation products ([Figure 3: see original paper]) indicates that CMFD contains outliers. Both reanalysis products (ERA5 and MERRA-2) show significantly higher surface solar radiation values than satellite products, with MERRA-2 having the highest average. The global high-resolution surface solar radiation dataset (SSR-tang) shows large fluctuation ranges within the study area. Based on these analyses, this study selected the homogeneous grid dataset of Chinese land surface climate observations (SSR-wang) and the ERA5 reanalysis radiation dataset. Both datasets show decreasing trends on the north slope of the Kunlun Mountains, with correlation coefficients of 0.65 temporally and 0.71 spatially. The ERA5 dataset is an improved reanalysis dataset based on the ECMWF system, considering aerosol-radiation interactions and bidirectional feedback with atmospheric processes, providing data from 1979 to present. To analyze both long-term sequences and recent variations, the two datasets were bias-corrected and unified to a spatial resolution of 0.25°$×$0.25°, extending the surface solar radiation data to 2023.

1.2.2 Atmospheric Factor Data

Atmospheric factor data were selected from the ERA5 reanalysis dataset, including monthly values of total cloud cover, low cloud cover, atmospheric column water vapor content, and ozone concentration from 1984 to 2023. Since ERA5 does not include aerosol data, monthly aerosol optical depth (AOD) data were collected from the MERRA-2 product to analyze impacts of different atmospheric factors on surface solar radiation on the north slope of the Kunlun Mountains.

The user wants me to translate a specific section from Chinese to English. This is the "### 1.3 Research Methods" section of an academic paper.

Let me analyze the requirements: 1. Translate the Chinese text into fluent, readable English for an academic audience 2. Preserve ALL math exactly as given - the equation is already in LaTeX format, so I must keep it unchanged 3. Preserve ALL citations - there are none in this section 4. Preserve ALL figure/table markers - there are none in this section 5. Maintain academic tone, precision, and technical accuracy 6. Produce flowing, readable prose - prioritize natural English over literal translation 7. Merge fragmented text into complete, well-formed sentences and paragraphs 8. Skip garbage text - there doesn' t appear to be any in this section 9. Organize by logical sections - this is already a single section 10. Each paragraph should express a complete thought (typically

3-8 sentences) 11. Use clear topic sentences and logical transitions 12. Return as clean Markdown with the same structure 13. Romanize author names using pinyin - "Wang Jinfeng et al." is already in pinyin 14. DO NOT leave any Chinese characters - I need to check for any hidden Chinese characters 15. The user specifically mentions Chinese characters found: 加, 叠 - these appear in the phrase "叠加 q values" which I need to translate properly

Let me translate the text carefully:

Original Chinese text (as provided in English, but with some Chinese terms): "This study primarily employs climate tendency rate, spatial interpolation, and geographic detector methods to explore spatiotemporal variations and influencing factors of surface solar radiation, with particular emphasis on the geographic detector model. Developed by Wang Jinfeng et al., the geographic detector is a statistical method for investigating spatial differentiation and driving factors of geographic elements, widely applied in meteorological research. The method requires categorical independent variables and determines interaction effects between factors by comparing single-factor and two-factor 叠加 q values. This study primarily uses factor detection to measure the explanatory power of individual influencing factors on the spatial differentiation of the dependent variable, calculated as:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where q represents the detection value for each influencing factor, ranging from $[0, 1]$. Larger q values indicate greater explanatory power of the factor on the spatial differentiation of surface solar radiation. L represents the stratification of dependent or independent variables; N_h and N are the unit numbers in layer h and the entire study area, respectively; and σ_h^2 and σ^2 are the variances of layer h and the entire study area, respectively."

Wait, the user says "Chinese characters found: 加, 叠" but in the text provided, I see "叠加" which means "superposition" or "overlay" or "combined". The phrase is "two-factor 叠加 q values". This should be translated as "two-factor superposition q values" or "combined two-factor q values" or "two-factor interaction q values" . In the context of the geographic detector method, this likely refers to the interaction detection part where two factors are combined.

Let me re-read the text more carefully. The user provided the text in English already, but with some Chinese terms embedded. The instruction says "Chinese characters found: 加, 叠" and "These appear to be: technical terms and specifications" . So I need to identify where these characters appear and translate them appropriately.

Looking at the text: "two-factor 叠加 q values" - here "叠加" is the Chinese term. It means "superposition" , "overlay" , or "combination" . In the context of geographic detector methods, when you combine two factors, you create a superposition layer. So "two-factor 叠加 q values" should be translated as "two-factor superposition q values" or "q values of two-factor superposition" .

Also, I need to check for "加" (addition). I don' t see it explicitly in the text provided, but it might be part of a compound word or I might have missed it. Let me scan again: "climate tendency rate, spatial interpolation, and geographic detector methods" - no Chinese characters there. "Wang Jinfeng et al." - no Chinese characters. "叠加" - yes, found it. "factor detection" - no Chinese characters. The equation is fine. The variables are fine.

So the main Chinese term to translate is "叠加" . The user says "DO NOT leave any Chinese characters - not even one" . So I must replace "叠加" with its English equivalent.

Now, let me craft a proper translation:

The text is already mostly in English, but I need to: 1. Replace "叠加" with an appropriate English term 2. Ensure the flow is natural and academic 3. Check for any other potential issues

The phrase "two-factor 叠加 q values" - in geographic detector methodology, there are different types of detection: factor detection, interaction detection, etc.## 2.1 Temporal Variation of Surface Solar Radiation on the North Slope of Kunlun Mountains

Annual and seasonal scale surface solar radiation variations and trends from 1984 to 2023 are shown in [Figure 4: see original paper]. The multi-year average surface solar radiation is 206.76 $\mathrm{W \cdot m^{-2}}$, exhibiting a significant decreasing trend at a rate of $-1.24\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$ ($P < 0.05$). The highest annual average surface solar radiation occurred in 1994 (238.36 $\mathrm{W \cdot m^{-2}}$), while the lowest occurred in 2016 (155.82 $\mathrm{W \cdot m^{-2}}$). Seasonal differences are evident, with spring average surface solar radiation at 243.83 $\mathrm{W \cdot m^{-2}}$ showing a significant increasing trend of 1.39 $\mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$ ($P < 0.05$). Summer average surface solar radiation is 275.95 $\mathrm{W \cdot m^{-2}}$, showing a significant decreasing trend of $-4.12\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$ ($P < 0.05$). Autumn average surface solar radiation is 182.64 $\mathrm{W \cdot m^{-2}}$, with a significant decreasing trend of $-1.40\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$ ($P < 0.05$). Winter average surface solar radiation is 124.62 $\mathrm{W \cdot m^{-2}}$, showing an insignificant decreasing trend of $-0.83\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$ ($P > 0.05$).

The annual distribution of surface solar radiation on the north slope of the Kunlun Mountains ([Figure 5: see original paper]) shows significant monthly variations, with maximum surface solar radiation reaching 291.07 $\mathrm{W \cdot m^{-2}}$ in June and minimum values of 93.14 $\mathrm{W \cdot m^{-2}}$ in December. Monthly surface solar radiation increases initially, peaking in June, then decreases with seasonal changes. The difference between maximum and minimum monthly surface solar radiation is 183.98 $\mathrm{W \cdot m^{-2}}$.

To further examine the decreasing trend, variation rates of annual and seasonal surface solar radiation were analyzed ([Figure 6: see original paper]). The variation rate range is broad, between -21.66 and 6.51 $\mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$, with more pronounced decreasing trends in the lower-elevation eastern region. Seasonally, spring shows a clear increasing trend with east-west differences, with the most significant increase in the western part of the study area reaching a maximum rate of 20.49 $W \cdot m^{-2} \cdot (10a)^{-1}$. All other seasons show decreasing trends, with summer having a relatively larger area of radiation reduction, with trends ranging from -17.19 to 14.42 $W \cdot m^{-2} \cdot (10a)^{-1}$. Winter shows decreasing trends throughout the southwestern region, reaching -30.88 $W \cdot m^{-2} \cdot (10a)^{-1}$. Annual and seasonal trend distributions show clear east-west differences: except in winter, the eastern region experienced faster decline rates than the western region throughout the year and during spring, summer, and autumn.

2.2 Spatial Variation of Surface Solar Radiation on the North Slope of Kunlun Mountains

The spatial distributions of annual and seasonal surface solar radiation on the north slope of the Kunlun Mountains show zonal patterns, with consistent spatial distributions across annual and seasonal scales, gradually increasing from north to south. Annual average surface solar radiation ranges from 155.70 to 242.53 $W \cdot m^{-2}$ spatially, with high-value areas concentrated in the southwestern part of the study area. These regions have lower latitudes receiving more solar radiation and higher elevations where atmospheric factors have weaker attenuation effects. In summer, surface solar radiation throughout the study area shows high values between 238.36 and 320.80 $W \cdot m^{-2}$. Winter shows low values below 200 $W \cdot m^{-2}$, with maximum values reaching 155.82 $W \cdot m^{-2}$. Areas with surface solar radiation greater than 200 $W \cdot m^{-2}$ account for 73.43% of the study area.

2.3.1 Atmospheric Factor Changes on the North Slope of Kunlun Mountains

Trends in total cloud cover, low cloud cover, aerosol optical depth (AOD), water vapor, and ozone at annual scale on the north slope of the Kunlun Mountains from 1984 to 2023 are shown in [Figure 7: see original paper]. Total cloud cover ranges from 0.40 to 0.48, showing an insignificant decreasing trend at annual scale, with the maximum decreasing rate of $-0.0178 \cdot (10a)^{-1}$ occurring in spring. Low cloud cover ranges from 0.06 to 0.09, with small trends at both annual and seasonal scales, showing a maximum rate of $0.0082 \cdot (10a)^{-1}$ in summer. AOD peaked in 2002, possibly related to dust storms in the Qaidam Basin that year. Except for weak decreasing trends in autumn, other seasons show weak increasing trends. Water vapor ranges from 5.66 to 7.46 $kg \cdot m^{-2}$, showing a significant increasing trend at annual scale with a rate of 0.2779 $kg \cdot m^{-2} \cdot (10a)^{-1}$ ($P < 0.05$), with increasing rates in all seasons except winter, particularly rapid in summer at 0.7234 $kg \cdot m^{-2} \cdot (10a)^{-1}$ ($P < 0.05$). Ozone shows a significant decreasing trend throughout the study period at -2.2210 $DU \cdot (10a)^{-1}$ ($P < 0.05$), with the most pronounced decreasing trend in summer.

2.3.2 Attribution Analysis of Surface Solar Radiation Changes on the North Slope of Kunlun Mountains

To further analyze atmospheric factor impacts, this study employs geographic detectors to quantitatively assess each factor' s contribution to surface solar radiation variation from a spatial differentiation perspective. Using surface solar radiation as the dependent variable and total cloud cover, low cloud cover, AOD, water vapor, and ozone as independent variables in single-factor detection, results ([Figure 8: see original paper]) show that water vapor has the highest explanatory power at annual scale (q = 0.90), representing the primary factor influencing spatial differentiation of surface solar radiation. Ozone and low cloud cover are secondary factors with q values of 0.38 and 0.28, respectively. While total cloud cover and AOD influence surface solar radiation variation, their single-factor explanatory powers are relatively low at 0.12 and 0.10, respectively. Seasonally, water vapor contributes most to surface solar radiation variation, with q values of 0.88 (spring), 0.90 (summer), 0.89 (autumn), and 0.83 (winter).

3 Discussion

Previous research identified the transition from "dimming" to "brightening" around 1990 across China, with inconsistent changes between northern and southern China after 1990—northern regions experienced renewed "dimming" while southern regions showed weak "brightening." The Tibetan Plateau, as a unique geographical unit, experienced a shift from brightening to dimming around the late 1990s. Analysis of all-sky and clear-sky surface solar radiation in eastern and central Tibetan Plateau from 1961 to 2013 revealed a decreasing trend in annual clear-sky surface solar radiation at $-1.00\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$. The north slope of the Kunlun Mountains, an important geographical component of the Tibetan Plateau, shows a decreasing trend consistent with plateau-wide patterns, though with some regional differences. The most pronounced decreasing trend occurs in summer at $-4.12\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$, possibly due to substantial water vapor transport and dust aerosol influences during summer.

Studies suggest that deep convective clouds and atmospheric water vapor, rather than aerosols, are the primary factors causing the decline in total radiation over the Tibetan Plateau from 1961 to 2013. Other research indicates that 87.0% of clear-sky surface solar radiation variation over the Tibetan Plateau can be explained by aerosols and water vapor, with water vapor having a greater impact than aerosols. This study's geographic detector analysis similarly concludes that water vapor contributes most significantly. The Tibetan Plateau experiences a low-value center of atmospheric ozone in summer, and this study finds a significant ozone decreasing trend of $-2.2210\ \mathrm{DU \cdot (10a)^{-1}}$. While previous research has focused on the entire Tibetan Plateau, studies of its subordinate geographical units are scarce. Given the spatial heterogeneity of surface solar radiation and its important influence on regional climate change, this study utilizes satellite remote sensing and reanalysis radiation products to analyze spatiotemporal variations of surface solar radiation on the north slope of the Kunlun Mountains from 1984 to 2023, examines atmospheric factor trends, and quantifies the contribution degree of each atmospheric factor, providing references for factor selection in mountainous surface solar radiation estimation models.

4 Conclusions

This study reveals spatiotemporal variation characteristics of surface solar radiation on the north slope of the Kunlun Mountains over the past 40 years using high spatiotemporal resolution satellite remote sensing and reanalysis radiation products, and analyzes atmospheric factor impacts through the geographic detector method. The main conclusions are: (1) Surface solar radiation on the north slope of the Kunlun Mountains showed a significant decreasing trend from 1984 to 2023 at $-1.24\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$ ($P < 0.05$). Except for spring, which showed an increasing trend, all other seasons exhibited decreasing trends, with summer showing the most significant decline at $-4.12\ \mathrm{W \cdot m^{-2} \cdot (10a)^{-1}}$ ($P < 0.05$). Monthly surface solar radiation peaked in June and reached its minimum in December. (2) Spatially, annual and seasonal surface solar radiation gradually decreased from south to north, with high values concentrated in the southwestern high-elevation, low-latitude regions. Variation rates showed distinct east-west differences, with the eastern region declining faster than the western region throughout the year and during spring, summer, and autumn, except in winter. (3) Atmospheric factors exhibited different impacts on surface solar radiation. Single-factor detection revealed water vapor as the dominant factor affecting spatial differentiation of surface solar radiation at both annual and seasonal scales, with increased water vapor enhancing atmospheric absorption of solar radiation and reducing transmitted radiation. These findings provide scientific references for mountainous surface solar radiation estimation and climate change research.

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