Multi-time Scale Variation Characteristics and Influencing Factors of Total Solar Radiation in Dunhuang (Postprint)

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Abstract

Using Ensemble Empirical Mode Decomposition (EEMD) and the M-K abrupt change test method, and based on meteorological data from Dunhuang City for 1971—2020, including total solar radiation, relative humidity, total cloud cover, and dust storm days, the multi-timescale characteristics of the evolution of total solar radiation in Dunhuang City were analyzed, and the key meteorological factors affecting solar radiation in Dunhuang City were investigated. The results show that: (1) The annual total solar radiation in Dunhuang City showed a significant upward trend from 1971 to 2020, with a linear climatic tendency rate of 49.6 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$. The multi-year average annual radiation was 6354.0 $\mathrm{MJ \cdot m^{-2}}$, placing it in the category of regions with the most abundant solar energy resources. Annual radiation was lowest in the 1970s and highest in the 2010s. Solar radiation in Dunhuang City shows distinct seasonal variation, with radiation amounts in the order of summer > spring > autumn > winter, increasing at rates of 32.5, 13.4, 2.9 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$, and 1.1 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$, respectively. Over the past 50 years, the interannual variations of 2.9 a and 7.1 a and the interdecadal variation of 16.7 a have dominated the total solar radiation in Dunhuang City. (2) Monthly solar radiation variation exhibits a “single-peak” pattern, increasing sharply from March and reaching its peak in May, then gradually decreasing from June and reaching its annual minimum in December. The hourly distribution of total solar radiation also shows a single-peak pattern, with the daily maximum occurring between 12:00 and 13:00. (3) The abrupt change times for annual, spring, and summer solar radiation variations were 1997, 2000, and 1982, respectively. (4) The meteorological elements affecting solar radiation in Dunhuang can be summarized into three factors: atmospheric transparency factor, illumination factor, and humidity factor, with the correlations between each meteorological factor and solar radiation varying by season.

Full Text

Multi-time Scale Variation Characteristics and Influencing Factors of Total Solar Radiation in Dunhuang

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Abstract

Using ensemble empirical mode decomposition (EEMD) and the M-K mutation test, the multi-timescale characteristics of total solar radiation evolution in Dunhuang City were analyzed based on meteorological data including total solar radiation, relative humidity, total cloud cover, and dust days from 1971 to 2020. The key meteorological factors influencing solar radiation in Dunhuang were explored. The results show that: (1) Annual total solar radiation in Dunhuang exhibited a significant upward trend from 1971 to 2020, with a linear climate tendency rate of 49.6 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$. The multi-year average annual radiation was 6354.0 $\mathrm{MJ \cdot m^{-2}}$, placing Dunhuang in the category of regions with the most abundant solar resources. Annual radiation was lowest in the 1970s and highest in the 2010s. Dunhuang experiences distinct seasonal solar radiation patterns, with radiation increasing at rates of 32.5, 13.4, 2.9, and 1.1 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$ for summer, spring, autumn, and winter, respectively. Over the past 50 years, total solar radiation in Dunhuang has been dominated by interannual variations of 2.9 and 7.1 years and interdecadal variations of 16.7 years. (2) Monthly total solar radiation follows a "single-peak" pattern, increasing sharply from March, peaking in May, gradually decreasing from June, and reaching its annual minimum in December. The hourly distribution of total solar radiation is monomodal, with the maximum occurring between 12:00 and 13:00. (3) Abrupt changes in annual, spring, and summer solar radiation occurred in 1997, 2000, and 1982, respectively. (4) Meteorological factors affecting solar radiation in Dunhuang can be attributed to three factors: atmospheric transparency, illumination, and humidity, with correlations between these factors and solar radiation varying by season.

Keywords: solar radiation; variation characteristics; ensemble empirical mode method; mutation test; meteorological elements; Dunhuang

Introduction

Solar radiation is the primary driver of atmospheric motion, the water cycle, and life activities on Earth. It serves as crucial input data for modeling land surface processes such as hydrology, ecology, and agriculture, and represents an important indicator for solar energy utilization. The solar radiation received by the Earth-atmosphere system is a key factor maintaining energy balance in Earth's climate and ecosystems. However, due to influences from atmospheric transparency, cloud cover, altitude, latitude, sunshine duration, and other factors, the amount of solar radiation reaching the surface exhibits regional variability. Solar radiation plays a significant role in agricultural production layout, crop growth, and soil water evaporation and transpiration. The "14th Five-Year Plan for Renewable Energy Development" explicitly states that optimizing regional layout and accelerating the construction of onshore new energy bases in desert, Gobi, and barren land areas, with the Hexi Corridor as a key focus, represents an important measure for achieving the "dual carbon" goals. Dunhuang, Gansu, is one of the regions rich in both solar energy and land resources, renowned as a global golden zone for photovoltaics, and currently hosts the nation's largest million-kilowatt-scale photovoltaic power generation base. Analyzing the spatiotemporal variation of solar radiation in this region holds significant practical importance for agricultural climate research, zoning, and the development and utilization of solar energy resources.

Over the past decades, numerous scholars have conducted extensive research on ground-level solar radiation variation characteristics, revealing that surface solar radiation exhibits phased patterns over time, showing distinct decadal alternations of decreasing and increasing trends. From the 1950s to the early 1980s, surface solar radiation decreased, a phenomenon termed "global dimming," followed by a reversal and increasing trend known as "global brightening." Ma et al. reported that most regions in Northwest China experienced significant declines in total solar radiation. Yang et al., in their study of surface solar radiation in Xinjiang and the applicability of CERES satellite data, noted that daily variation of total radiation follows a single-peak distribution. Qian et al. analyzed variation patterns of total solar radiation and sunshine hours over the past 50 years in the eastern Hexi Corridor, finding that annual average total solar radiation increased with fluctuations. Wu examined solar energy resource variation patterns using data from five radiation stations in the Hexi Corridor. However, few studies have investigated the multi-timescale characteristics of total solar radiation in extremely arid Dunhuang and the influence of periodic oscillations at different timescales on the overall variation characteristics. Based on hourly data from the Dunhuang solar radiation station, this study conducts a detailed analysis of multi-timescale temporal characteristics, examining variation features and trends of surface solar radiation at different timescales in this region, and evaluating the abundance of solar energy resources to provide decision-making support for rational solar energy development and agricultural industry layout.

1. Materials and Methods

1.1 Study Area

Dunhuang City is located at the junction of Gansu, Qinghai, and Xinjiang provinces, at the westernmost end of the Hexi Corridor, between 39°40 –41°40 N and 92°13 –95°30 E, with a total area of 3.12×10^4 km^2. The terrain is high in the north and south, low in the middle, sloping from southwest to northeast, with an average elevation of 1139 m. Situated deep inland and surrounded by Gobi and desert, Dunhuang has an arid climate with low precipitation, high evaporation, long sunshine duration, and abundant solar radiation. Annual sunshine hours range from 2690.9 to 3298.8 h, average annual precipitation is 44.6 mm, and average annual temperature is 10.4°C, classifying it as an extremely arid region with abundant solar energy resources. The relatively flat terrain provides advantages for solar energy development. Local vegetation consists mainly of drought-resistant shrubs and semi-shrubs, with major soil types including irrigation silt soil, meadow soil, aeolian sandy soil, marsh soil, saline soil, and meadow soil.

1.2 Data Sources and Methods

1.2.1 Data Sources Daily data from Dunhuang Meteorological Station for 1971–2020 were used, including total solar radiation, sunshine duration, water vapor pressure, relative humidity, evaporation, air temperature, maximum temperature, minimum temperature, and total cloud cover. All data were obtained from the China Integrated Meteorological Information Service System (CIMISS), with unified data service interfaces provided by the Gansu Meteorological Information and Technology Equipment Support Center. Missing data points were replaced using 5-day moving averages. Data precision and reliability strictly followed the China Meteorological Administration's Specifications for Surface Meteorological Observation regarding basic technical performance of surface meteorological instruments. Seasons were defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Hourly total solar radiation data were recorded in Beijing time.

1.2.2 Calculation Methods **Climate Tendency Rate.** The climate tendency rate method was used to analyze variation trends of solar radiation in Dunhuang. The slope of the linear equation represents the average trend of the time series: $y = at + b$, where t is the time series, b is the regression intercept, and a is the regression slope. A positive a indicates an overall increasing trend in solar radiation over time, while a negative a indicates a decreasing trend. The F-test was used to determine the significance of the climate tendency rate.

Mann-Kendall Test. The Mann-Kendall (M-K) test is a non-parametric method for detecting mutation points in solar radiation time series, with minimal human influence and high quantification. By defining forward sequence

UF and backward sequence UB statistics and conducting sequence analysis, the trend of the original climate sample series can be obtained. Positive UF or UB values indicate increasing radiation, while negative values indicate decreasing radiation. Intersection points of UF and UB curves within the confidence interval represent mutation points. When UF or UB curves exceed the confidence interval, the radiation change is significant.

Ensemble Empirical Mode Decomposition (EEMD). EEMD is an improved version of Empirical Mode Decomposition (EMD) for analyzing nonlinear and non-stationary signals. It automatically decomposes signals into different timescale fluctuations, generating a series of data sequences with different timescales, effectively solving mode mixing problems during signal decomposition. The main steps are: (1) adding Gaussian white noise to the original sequence to provide a relatively high-frequency, uniform extreme value distribution; (2) performing EMD decomposition on the noise-added sequence to obtain Intrinsic Mode Functions (IMFs); and (3) conducting Hilbert-Huang Transform (HHT) on each component with ensemble averaging to cancel the influence of added white noise on the real signal. EEMD can adaptively extract IMFs and better capture long-term trend information. The nonlinear trend obtained from the trend term reflects the true climate change trend. Based on previous research, this study set the noise amplitude k to 0.2 and the ensemble number M to 100.

Factor Analysis. To further clarify the influence of various meteorological factors on solar radiation, factor analysis was conducted using SPSS statistical software. The applicability of selected meteorological elements for factor analysis was first verified through KMO and Bartlett's sphericity tests, with KMO > 0.6 and $p < 0.05$ indicating suitability for factor analysis.

2. Results and Analysis

2.1 Interannual and Interdecadal Variation of Total Solar Radiation

The multi-year average annual total solar radiation in Dunhuang is $6354.0\ \mathrm{MJ} \bullet \mathrm{m}^{-2}$. According to the national standard GB/T 37526-2019 for solar energy resource assessment, annual total solar radiation values $\geq 6300\ \mathrm{MJ} \bullet \mathrm{m}^{-2}$ indicate the most abundant solar resource areas, confirming that Dunhuang belongs to the category of regions with the most abundant solar resources. Statistical analysis reveals that annual average solar radiation in Dunhuang increased with fluctuations, with a linear increase rate of $49.6\ \mathrm{MJ} \bullet \mathrm{m}^{-2} \cdot (10\mathrm{a})^{-1}$, significant at the 95% confidence level (Figure 1). This increase mainly occurred after the late 1970s. The maximum value appeared in 2016 ($6960.6\ \mathrm{MJ} \bullet \mathrm{m}^{-2}$), while the minimum occurred in 1993 ($5304.0\ \mathrm{MJ} \bullet \mathrm{m}^{-2}$). Investigation shows that monthly total solar radiation in 1993 decreased to varying degrees, particularly in May. Analysis of meteorological factors affecting solar radiation revealed anomalous characteristics in Dunhuang during 1993, including dust events, relative humidity, precipitation days, and total cloud cover. Specifically, dust days from January to May 1993 were significantly higher than the historical average, with March having the most dust storm days on record, April recording 10 blowing sand days, and May experiencing 8 floating dust events. Relative humidity from January to May 1993 was notably higher than the historical average, with April ranking first historically. Precipitation days from January to May exceeded the historical average, with May having the most precipitation days in nearly 50 years. Combined with high total cloud cover in spring, these factors collectively contributed to 1993 having the lowest solar radiation in nearly 50 years.

As shown in Figure 1, annual total solar radiation in Dunhuang exhibited an increasing trend from 1971 to 2020. Most years before 2000 had negative anomalies, while after 2001, only 2019 showed a negative anomaly. Thus, 1971–2000 represents a period of significantly low annual solar radiation, with an average of 6203.0 $\mathrm{MJ \cdot m^{-2}}$, 150.8 $\mathrm{MJ \cdot m^{-2}}$ below the multi-year average. In contrast, the 2001–2020 period averaged 6431.7 $\mathrm{MJ \cdot m^{-2}}$, 77.7 $\mathrm{MJ \cdot m^{-2}}$ above the multi-year average.

Interdecadal characteristics of total solar radiation in Dunhuang are distinct. The 1970s had the lowest radiation (6189.8 $\mathrm{MJ \cdot m^{-2}}$), while the 1980s showed the fastest decline, decreasing by 110.3 $\mathrm{MJ \cdot m^{-2}}$ compared to the 1970s. The 1990s saw a rapid increase to 6523.2 $\mathrm{MJ \cdot m^{-2}}$, the highest in 50 years, representing a 333.4 $\mathrm{MJ \cdot m^{-2}}$ increase from the lowest 1970s value. Linear regression analysis for each decade shows that solar radiation increased significantly in the 2010s at a rate of 68.1 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$, substantially higher than the linear trend rate. The 1970s showed a slight increasing trend, while other decades exhibited decreasing trends, particularly the 1990s.

EEMD decomposition of Dunhuang's annual total solar radiation from 1971 to 2020 yielded IMF1–IMF4 components and a trend term (res), each reflecting inherent oscillations at different characteristic scales in the original series. Table 1 presents the periods and variance contribution rates of different modes after EEMD decomposition. IMF1–IMF4 components all show multi-fluctuation characteristics, with variance contribution rates quantifying the influence of each mode's fluctuation frequency and amplitude on annual solar radiation data. Combined with Figure 2, the dominant components are IMF1 (2.9 yr), IMF2 (7.1 yr), IMF3 (16.7 yr), and the trend term, which together determine Dunhuang's annual total solar radiation. Their variance contribution rates are 27.8%, 23.8%, 22.0%, and 15.9%, respectively, with a cumulative contribution of 88.5%. IMF1, with a 2.9-year period, contributes most significantly, showing relatively large amplitude fluctuations around the 16.7-year period and relatively stable changes at other times. IMF2 has a 7.1-year period with the second-highest variance contribution rate (23.8%), with amplitude in the 1990s significantly greater than other periods. IMF3 shows a 16.7-year period with 22.0% variance contribution, exhibiting large amplitude fluctuations before the early 1990s and in the 2010s. The trend term contributes 15.9% of variance, reflecting the overall increasing trend of Dunhuang's annual total solar radiation over time. As shown in Table 2, the nonlinear increasing rate from the EEMD decomposition trend term is 85.9 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$, significantly higher than the linear trend rate.

Significance testing via energy spectral density can determine whether IMF components obtained from EEMD decomposition are real and effective, validating result reliability. Figure 3 shows the energy spectral density distribution of decomposed components, with the horizontal axis representing average period and the vertical axis showing the natural logarithm of energy spectral density. The figure indicates that IMF1 (2.9 yr), IMF2 (7.1 yr), and IMF3 (16.7 yr) show significant periodic distributions with average periods above 2.9 years, demonstrating strong energy in radiation variation processes. In contrast, IMF4 (33.3 yr) shows insignificant periodic oscillations with weak energy.

2.2 Seasonal Variation of Total Solar Radiation

Dunhuang exhibits distinct seasonal patterns in total solar radiation: summer (2175.1 $\mathrm{MJ \cdot m^{-2}}$) > spring (1911.7 $\mathrm{MJ \cdot m^{-2}}$) > autumn (1356.1 $\mathrm{MJ \cdot m^{-2}}$) > winter (911.1 $\mathrm{MJ \cdot m^{-2}}$). Summer has the highest radiation and winter the lowest, with winter averaging only 41.9% of summer values, primarily because summer has the highest solar elevation angle and longest sunshine duration, resulting in greater astronomical radiation received. To better understand seasonal variation, linear fitting was performed for each season. Over the past 50 years, linear tendency rates for spring, summer, autumn, and winter total solar radiation were 32.5, 13.4, 2.9, and 1.1 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$, respectively, all showing increasing trends similar to annual total radiation characteristics (Figure 4). Trend term components reflect the overall temporal increasing trend of seasonal total solar radiation in Dunhuang, with nonlinear increasing rates of 4.7, 3.2, 2.1, and 1.8 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$ for spring, summer, autumn, and winter, respectively—all higher than linear rates, consistent with annual total solar radiation changes.

Spring solar radiation shows the greatest fluctuation, followed by summer, while autumn and winter are relatively stable. The increase in solar radiation mainly comes from contributions in spring and summer. Analysis of interdecadal anomaly changes in seasonal total solar radiation (Table 3) reveals varying interdecadal trends across seasons. Spring solar radiation patterns match annual characteristics, with the 2010s showing the highest values (101.5 $\mathrm{MJ \cdot m^{-2}}$ above the multi-year average) and the 1970s and 1990s showing negative anomalies. The 1980s had the lowest spring radiation (87.3 $\mathrm{MJ \cdot m^{-2}}$ below average). Summer, autumn, and winter patterns differ from spring, with the 2010s showing highest values, followed by the 2000s, and the 1970s, 1980s, and 1990s all showing negative anomalies. The 1970s had the lowest radiation for summer and autumn, while winter had relatively low values in the 1980s. In summary, spring solar radiation peaked in the 2010s and reached its minimum in the 1980s, while summer, autumn, and winter radiation peaked in the 2010s, with minima varying slightly across the 1970s (spring, summer, autumn) and 1980s (winter).

EEMD decomposition of seasonal total solar radiation isolates different temporal variation signals. In spring, solar radiation shows interannual variations of 3.1 and 7.7 years and interdecadal variation of 25.0 years, with IMF1, IMF2, IMF3, and the trend term contributing significantly to variance and correlating significantly with the original series. Summer radiation exhibits interannual variations of 2.9 and 7.1 years and interdecadal variation of 16.7 years, with IMF1, IMF2, IMF3, and the trend term cumulatively contributing 85.9% of variance. Autumn radiation shows interannual variations of 3.4 and 9.1 years and interdecadal variation of 16.7 years, with IMF1, IMF2, IMF3, IMF4, and the trend term contributing 92.3% of variance. Winter radiation displays interannual variations of 2.8 and 5.3 years and interdecadal variation of 12.5 years, with IMF1, IMF2, IMF3, and the trend term contributing 87.0% of variance. All components show significant correlations with the original series.

2.3 Monthly Variation of Total Solar Radiation

Analysis of monthly average radiation from 1971 to 2020 (Figure 5) shows that monthly total solar radiation follows a "single-peak" pattern, increasing sharply from March, reaching a peak in May ($756.68\ \mathrm{MJ \cdot m^{-2}}$), gradually decreasing from June, and reaching its annual minimum in December ($261.51\ \mathrm{MJ \cdot m^{-2}}$). The minimum value is only 34.6% of the maximum. Measured total radiation from May to July exceeds $700\ \mathrm{MJ \cdot m^{-2}}$, with May accounting for 11.9% of annual total radiation, representing the period with the most abundant solar energy resources. Monthly climate tendency rates show increasing trends from January to May and July to December, with March to May passing significance tests and May showing the largest increase ($13.42\ \mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$). June shows a decreasing trend (not significant), with November having the largest decrease. Table 5 demonstrates that increasing rates far exceed decreasing rates for most months.

2.4 Hourly Variation of Total Solar Radiation Under Different Weather Conditions

Figure 6 shows hourly distributions of total solar radiation under different typical weather conditions. To eliminate differences from sunrise and sunset times, typical cases from the same month and day in different years were selected (June 15 in this study), including sunny (2018), blowing sand (1984), cloudy (1993), and precipitation (2019) conditions. Under sunny conditions, daily total solar radiation shows a single-peak pattern, with maximum values occurring between 12:00–13:00 and an average of $2.43\ \mathrm{MJ \cdot m^{-2}}$, reflecting the relationship between solar radiation intensity and solar elevation angle. Solar radiation intensity is strongest when the solar elevation angle is highest at midday (12:00–13:00). Under blowing sand, cloudy, and precipitation conditions, solar radiation reaching the surface is substantially weakened, with peaks only about half of sunny conditions and peak occurrence times varying with cloud cover, precipitation, and dust timing, generally appearing around 10:00–13:00, demonstrating differences in total solar radiation under various weather conditions.

2.5 Mutation Analysis of Total Solar Radiation

The M-K test for Dunhuang solar radiation from 1971 to 2020 (Figure 7) shows an overall increasing trend. From 1971 to 1993, annual solar radiation tended to decrease, but not significantly. From 1994 to 2020, the UF curve rose continuously, indicating significant radiation changes, with the UF-UB intersection occurring in 1997, marking a mutation point. For spring radiation, the UF curve exceeded the $\alpha = 0.05$ significance level critical line from 1994 to 2010, with the UF-UB intersection in 2000, identifying 2000 as a mutation point. Summer solar radiation mutation tests show three periods exceeding the confidence interval, with significant increasing trends and the UF-UB intersection in 1982, marking 1982 as a mutation point. Autumn and winter solar radiation shows no significant changes, with curves mostly within confidence intervals. However, after 1997, autumn and winter radiation showed clear decreasing-increasing trends, making 1997 a turning point for seasonal changes. Autumn UF curves rose significantly from 1994–1997, declined rapidly from 1998–2005, and showed small fluctuations with relatively stable changes from 2006–2020. Winter solar radiation differs notably, showing a “two rises and two falls” pattern: significant increase from 1971–1975, fluctuating decrease from 1976–1997, increase from 1998–2005, and fluctuating decrease from 2006–2020.

3. Discussion

As a renewable energy source, solar energy development and utilization have attracted widespread attention. Driven by carbon reduction goals, low-carbon applications have become the focus across many industries. Since surface solar radiation amount and variation trends show regional differences, this study examined Dunhuang’s solar radiation, analyzing its spatiotemporal variation characteristics and influencing factors. Research indicates that meteorological factors affecting surface solar radiation mainly include clouds, atmospheric water vapor, and transparency conditions. For Dunhuang, relative humidity, total cloud cover, precipitation, and dust days are the primary factors influencing radiation variation. However, these factors differ across regions: Chen et al. noted that cloud cover is the main factor affecting total radiation variation on the plateau; Chen et al. suggested that the phased characteristics of total radiation in Qinghai Province relate to cloud-rain conditions and global volcanic eruption events; Hao et al. indicated that wind speed also affects solar radiation, though its impact magnitude varies. Whether wind speed’s effect on radiation in Dunhuang represents positive or negative feedback requires further detailed investigation.

4. Conclusions

Based on Dunhuang's total solar radiation series from 1971 to 2020, using EEMD method, this study revealed multi-timescale characteristics of total solar radiation evolution, analyzed the influence of periodic oscillations at different timescales on overall radiation characteristics, and explored key meteorological factors affecting solar radiation in Dunhuang. The results indicate:

1) The linear climate tendency rate of annual total solar radiation in Dunhuang from 1971 to 2020 was 49.6 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$, showing a significant increasing trend. The multi-year average annual radiation was 6354.0 $\mathrm{MJ \cdot m^{-2}}$, classifying it as a region with the most abundant solar resources. Annual radiation was lowest in the 1970s and highest in the 2010s. Interdecadal characteristics are clear: the 1970s had the lowest radiation, the 2010s the highest. The 1970s showed a slight increasing trend, the 2010s a significant increasing trend, while other decades showed decreasing trends, especially the 1990s.

2) Dunhuang experiences distinct seasonal solar radiation patterns: summer > spring > autumn > winter, increasing at rates of 32.5, 13.4, 2.9, and 1.1 $\mathrm{MJ \cdot m^{-2} \cdot (10a)^{-1}}$, respectively. Over the past 50 years, total solar radiation has been dominated by interannual variations of 2.9 and 7.1 years and interdecadal variation of 16.7 years. Nonlinear increasing rates from EEMD trend terms for annual and seasonal solar radiation all exceed linear rates.

3) Monthly total solar radiation shows a "single-peak" pattern, increasing sharply from March, peaking in May, gradually decreasing from June, and reaching its annual minimum in December. May radiation accounts for 11.9% of annual total radiation, representing the period with the most abundant solar energy resources. Monthly climate tendency rates vary considerably: January–May and July–December show increasing trends, with May showing the largest increase; June shows a decreasing trend, with November having the largest decrease. Hourly distribution of total solar radiation is monomodal, with daily maxima occurring between 12:00–13:00.

4) Abrupt changes in annual, spring, and summer total solar radiation occurred in 1997, 2000, and 1982, respectively. Autumn and winter solar radiation showed no significant changes or mutations.

5) Total solar radiation variation in Dunhuang is closely related to relative humidity, total cloud cover, precipitation, and dust days, all showing negative correlations. Correlations between meteorological factors and solar radiation vary by season. Factor analysis reveals that these meteorological elements can be summarized into three factors: atmospheric transparency, illumination, and humidity.

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