Spatiotemporal Variation of Surface Albedo and Its Influencing Factors in the Junggar Basin (Postprint)

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Abstract

Changes in surface albedo affect surface radiation budget and energy balance, thereby influencing regional and global climate. Taking the Junggar Basin as the study area, surface shortwave albedo was retrieved using the MODIS satellite remote sensing data product MOD09A1, and combined with meteorological data and vegetation indices to analyze the spatiotemporal variation characteristics and influencing factors of surface albedo over desert grassland in the Junggar Basin from 2001 to 2018. The results show that: the spatial distribution of surface albedo in the Junggar Basin exhibits significant regional differences, with an annual mean value of 0.303, showing an overall pattern of high in the northeast and low in the southwest; its interannual variation rate shows a decreasing trend, with an average of 1.4$×10^{-4}$ per year, and the decreasing area accounts for approximately 52.8% of the total area; seasonal spatial distribution variations are evident, with similar patterns in spring, summer, and autumn, the highest value in winter (0.551) and the lowest in summer (0.203). The Altai Mountains on the northeastern margin of the Junggar Basin exhibit relatively intense intra-annual variations in surface albedo; the normalized difference vegetation index (NDVI) values during the growing season follow the order: summer > autumn > spring. Overall, surface albedo in the Junggar Basin is negatively correlated with NDVI, negatively correlated with mean temperature in most areas, and positively correlated with precipitation, with the magnitude of correlation following the order: temperature > NDVI > precipitation. There is a significant correlation between MODIS retrieval results and ground-based measurements (R^2=0.8908, P<0.01), with a root mean square error of 0.014. This study provides a theoretical basis for understanding the land surface characteristics of the Junggar Basin and objectively evaluating land surface changes and their positive and negative feedback response mechanisms in arid regions under global climate change.

Full Text

Abstract

Surface albedo influences the balance between surface radiation and energy, thereby affecting regional and global climates. Taking the Junggar Basin as the study area, this research uses MODIS satellite remote sensing data product MOD09A1 to retrieve surface shortwave albedo, combined with meteorological data and vegetation index to analyze the spatio-temporal variation characteristics and influencing factors of surface albedo over desert grassland in the Junggar Basin from 2001 to 2018. The results show that the spatial distribution of surface albedo in the Junggar Basin exhibits obvious regional differences, with an annual mean value of 0.303, showing characteristics of high values in the northeast and low values in the southwest. Its interannual variation rate shows a decreasing trend, with an average annual decrease of 1.4$\times 10^{-4}$, and the decreased area accounts for approximately 52.8{2}$ = 0.8908, P < 0.01), with a root mean square error of 0.014. This study provides a theoretical basis for understanding the land surface characteristics of the Junggar Basin, objectively evaluating land surface changes in arid regions under global climate change, and determining the positive and negative feedback response mechanisms.

Keywords: Junggar Basin; surface albedo; desert grassland; spatio-temporal variation; NDVI

1.1 Study Area Overview

The Junggar Basin is located in the hinterland of Central Asia, in northern Xinjiang, with geographical coordinates of 82.0°–93.5°E and 43.5°–48.5°N. It is surrounded by the Tianshan and Altai Mountain tectonic troughs, with an east-west length of approximately 850 km, a north-south width of about 380 km, and an area of about 2.2$\times 10^{5}$ km^2. The basin is higher in the east and lower in the west, with an elevation of about 850 m in the east and decreasing to 400 m in the southwest. The basin margins are mostly piedmont alluvial-pluvial plains, alluvial plains, and some rocky denudation plains and hills, while the center of the basin is the Gurbantünggüt Desert. The Junggar Basin has a temperate continental desert climate, with an average annual temperature of about 7.85 ℃ and average annual precipitation of about 226.43 mm. The central part of the basin is the Gurbantünggüt Desert, with extensive desert grasslands and sandy lands, extreme aridity, low rainfall, and obvious soil salinization. Due to the influence of westerly winds, the Junggar Basin receives more precipitation in winter and spring, and its vegetation distribution and landscape are relatively rare compared with other desert regions in China. The study area contains various grassland types, including temperate mountain meadows, temperate desertified steppes, temperate steppes, temperate meadow steppes, temperate deserts, alpine meadows, alpine steppes, swamps, and lowland meadows. Desert grassland vegetation is dominated by spring-rain ephemeral plants and ephemeral-like plants, with typical desert vegetation constructed by *Haloxylon persicum* and *Haloxylon ammodendron*. The geographical location and vegetation type distribution of the Junggar Basin are shown in Figure 1.

[Figure 1: see original paper]

1.2.1 Remote Sensing Data Sources

The MOD09A1 land surface reflectance product acquired by the Terra satellite was used in this study. The data employs a sinusoidal projection, with a spatial resolution of 500 m and an 8-day composite interval, covering visible, near-infrared, and shortwave infrared bands. The MOD09A1 product selects optimal pixels based on principles of high coverage, low observation angle, and cloud-, shadow-, and aerosol-free conditions, which greatly ensures product availability. Data were obtained from the NASA website (https://ladsweb.modaps.eosdis.nasa.gov).

1.2.2 Meteorological Data and Spatialization

Annual average temperature and precipitation data from meteorological stations in and around the Junggar Basin were selected from the China Meteorological Data Network (https://data.cma.cn). The modified inverse distance weighted (IDW) method, which provides optimal spatial interpolation accuracy for temperature in the Xinjiang region according to Wu et al., was used for spatial interpolation. Considering the influence of altitude at each meteorological station on temperature, the average temperature at any point can be expressed by the formula $T = T_0 - A \times E$, where T_0 is the interpolated result, A is a constant of 0.006 ℃$\cdot m^{-1}$ (indicating a temperature decrease of 0.6 ℃ per 100 m increase in altitude), and E represents elevation. Digital elevation model (DEM) data were obtained from the Geospatial Data Cloud Platform (http://www.gscloud.cn) with a spatial resolution of 30 m$×$30 m, and the meteorological data interpolation results were finally resampled to 500 m.

1.2.3 Vegetation Index Calculation

The normalized difference vegetation index (NDVI) is typically calculated using red and near-infrared band reflectance. Using MOD09A1 data, the band operation formula is as follows: NDVI = (NIR - R)/(NIR + R), where NIR is the near-infrared band and R is the red band. The study period was 2001–2018.

1.3.1 Surface Albedo Calculation and Accuracy Verification

The MODIS Reprojection Tools (MRT) were used for preprocessing, including mosaicking, reprojection, and format conversion of MOD09A1 data. The Liang algorithm was used to calculate narrowband and broadband albedo, obtaining shortwave (0.3–3.0 m) white-sky and black-sky albedo data through batch processing. The formula for converting MODIS narrowband albedo to broadband albedo is:

$$\alpha_{\text{short-MODIS}} = 0.160\alpha_1 + 0.291\alpha_2 + 0.243\alpha_3 + 0.112\alpha_4 + 0.081\alpha_5 - 0.0015$$

where α_1-α_5 are the albedos of the corresponding MOD09A1 bands, and $\alpha_{\text{short-MODIS}}$ is the shortwave broadband albedo.

Real surface albedo is a combination of black-sky and white-sky albedo. This study used a linear weighting method to obtain real shortwave broadband albedo:

$$\alpha = (1 - S) \times \alpha_{\text{bsa}} + S \times \alpha_{\text{wsa}}$$

where α is the real surface albedo, α_{bsa} is the black-sky albedo, α_{wsa} is the white-sky albedo, and S is the sky diffuse ratio factor, which can be obtained from the cosine of the solar zenith angle provided by MODIS.

The real surface albedo dataset was batch-clipped to the Junggar Basin using ArcMap ModelBuilder to obtain long-term shortwave surface albedo data. Monthly average surface albedo was calculated from MOD09A1 product data, followed by seasonal (March–May as spring, June–August as summer, September–November as autumn, December–February as winter) and annual average surface albedo. Finally, the spatial distributions of seasonal and annual average surface albedo in the Junggar Basin were obtained.

For ground validation, field measurements were conducted in August 2017. Considering the satellite overpass time, fieldwork was carried out during 10:30–16:00 under good weather conditions with few clouds. A total of 20 sample plots were established. To reduce scale differences between ground point data and low-resolution MODIS data, each sample plot covered 500 m$×500m, withfive50m×$50 m subplots taken from the center and four cardinal directions. A solar radiation recorder was used to monitor total solar radiation and reflected radiation, and albedo was calculated. The mean of measured points represented the actual surface albedo for the corresponding pixel. MODIS albedo images from the sampling period were used, and the latitude and longitude coordinates of plot centers were located via ArcMap for matching and comparison, ensuring measured points fell within single pixels.

[Figure 4: see original paper]

1.3.2 Interannual Variation Trend Calculation

A unary linear regression method was used to fit the interannual variation trend of surface albedo in the Junggar Basin from 2001 to 2018, calculating the trend value b:

$$b = \frac{n \sum_{i=1}^{n} (i \times a_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} a_i}{n \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where n is the total number of years in the study period, and a_i is the annual average surface albedo in year i. A positive b indicates an increasing trend, while a negative b indicates a decreasing trend; the absolute value of b reflects the rate of annual change. The significance of the trend for each pixel was tested using the F-test:

$$F = \frac{U}{Q/(n-2)}$$

where U is the regression sum of squares and Q is the residual sum of squares. Based on a significance level of $P = 0.05$, the shortwave surface albedo change trends were classified into six categories: extremely significant increase ($b > 0$, $P < 0.001$), significant increase ($b > 0$, $0.001 \leq P < 0.05$), insignificant increase ($b > 0$, $P \geq 0.05$), insignificant decrease ($b < 0$, $P \geq 0.05$), significant decrease ($b < 0$, $0.001 \leq P < 0.05$), and extremely significant decrease ($b < 0$, $P < 0.001$).

1.3.3 Anomaly Calculation

To quantitatively analyze the interannual variation rate and anomalous changes of surface albedo in the Junggar Basin, the standard deviation of annual and seasonal surface albedo was calculated to represent the degree of anomaly and deviation from the mean. Areas with high standard deviation values are sensitive zones for anomalous surface albedo changes:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (a_i - \bar{a})^2}$$

where n is the total number of years, a_i is the average albedo in year i, and $\bar{a}$ is the multi-year average albedo. A larger standard deviation indicates more intense interannual variation.

1.3.4 Correlation Analysis

Partial correlation analysis was used to examine the relationship between surface albedo and climatic factors. The correlation coefficient between surface albedo and temperature or precipitation was calculated as:

$$R_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}$$

where R_{xy} is the correlation coefficient between variables x and y, x_i is the surface albedo in year i, y_i is the average temperature or precipitation in year i, and $\bar{x}$ and $\bar{y}$ are the multi-year average surface albedo and temperature/precipitation, respectively.

2.1 Temperature Temporal Variation Characteristics

The spatial distribution differences of temperature and precipitation in the Junggar Basin affect the distribution and growth of desert vegetation, which in turn influences surface albedo values. Based on spatial interpolation results from meteorological station data, the climate change characteristics of the study area in recent years were analyzed. The results show that the annual average temperature in the Junggar Basin from 2001 to 2018 was 7.85 ℃ (standard deviation 1.72 ℃), with considerable regional differences. With changes in altitude, the spatial distribution of annual average temperature showed regional heterogeneity. The western and southeastern margins of the basin exhibited a decreasing trend at a rate of -0.013 $℃ \cdot a^{-1}$, accounting for 55.48% of the total area, while the northern and southern margins showed an increasing trend at 0.014 $℃ \cdot a^{-1}$, accounting for 44.52% of the total area. Overall, the basin showed a weak decreasing trend in annual average temperature.

The average annual precipitation in the Junggar Basin was approximately 226.43 mm (standard deviation 350.75 mm). The results indicate that the annual precipitation change rate from 2001 to 2018 showed an overall increasing trend at 1.45 $mm \cdot a^{-1}$, covering 86.3% of the total area. Areas with decreasing precipitation accounted for about 13.7% of the study area, with an average decreasing rate of -0.45 $mm \cdot a^{-1}$, mainly concentrated in the western corner and central southern margin of the basin (Figure 2). In general, the Junggar Basin exhibited a weak decreasing trend in annual average temperature and an increasing trend in precipitation.

[Figure 2: see original paper]

2.2 NDVI Spatial Distribution Characteristics

Climate change and human activities in recent years have affected vegetation, causing changes in vegetation growth in the study area. Analysis of remote sensing images from the Junggar Basin revealed that the average NDVI over the past 18 years was 0.29. Areas with good vegetation cover accounted for 11.1% of the total study area, mainly distributed in the northern margin of the Junggar Basin and agricultural land at the foot of the Tianshan Mountains. Areas with poor vegetation cover accounted for 29.9% of the total area. The highest seasonal average NDVI value occurred in summer (0.35), while the lowest was in spring (0.23). As vegetation recovered, coverage increased, reaching its maximum in summer. High-value areas were mainly distributed in the southern margin of the Junggar Basin, the Altai Mountains, and the Tianshan Mountains. Influenced by moisture conditions, vegetation growth showed considerable variation. The vast majority of the study area is dominated by desert grassland, with relatively low overall NDVI values.

[Figure 3: see original paper]

2.3 Surface Albedo Variation Characteristics

2.3.1 Surface Albedo Distribution Characteristics

Analysis of the average surface albedo data for the Junggar Basin shows that the basin exhibits obvious spatial regional differences in albedo, with an overall pattern of high values in the northeast and low values in the southwest, closely related to altitude. The multi-year average surface albedo is 0.303. High-value areas are sporadically distributed in the Altai Mountains and central basin, with a maximum value of 0.551, which is related to the region' s long, cold winters with extended snow cover, short summers, and low vegetation coverage and soil moisture. The northwestern margin of the Junggar Basin is a low-value area for surface albedo, which is inseparable from the relatively humid local climate and predominance of grasslands and forests. Surface albedo in most areas of the basin is concentrated between 0.25 and 0.35, accounting for about 58.35% of the total area.

The spatial distribution of the standard deviation of annual average surface albedo in the Junggar Basin (Figure 5) shows that the largest standard deviations are found in the Hefeng Salt Field in Tacheng region, with a maximum value of 0.045. This area has abundant salt mineral resources that can easily cause variations in surface albedo. In most areas of the basin, interannual variation of surface albedo is relatively sensitive, with a standard deviation of 0.012, mainly influenced by precipitation and desert grassland vegetation changes. The southern margin of the basin has uniform surface cover types and the smallest interannual standard deviation of surface albedo. The northeastern margin of the Junggar Basin and the Altai Mountains are areas with intense intra-annual variation in surface albedo.

[Figure 5: see original paper]

2.3.2 Surface Albedo Seasonal Variation

Analysis of the spatial distribution characteristics of multi-year average surface albedo in different seasons shows that the spatial distributions in spring, summer, and autumn are similar. Areas with annual average surface albedo between 0.25 and 0.35 are mainly distributed across most of the Junggar Basin, accounting for over 59% of the total area. The largest area in this range occurs in spring, accounting for 61.4% of the total area, followed by autumn at 59.4%. Areas with albedo between 0.15 and 0.25 are mainly distributed in the southwestern and southeastern margins of the basin, with the largest area in this range occurring in summer (44.2%). Due to snow cover, winter has the highest annual average surface albedo, reaching up to 0.85 in the Altai Mountains.

Overall, seasonal effects cause obvious spatial distribution changes in the four seasons across the Junggar Basin. Winter has the highest mean surface albedo (0.551), followed by spring (0.328) and autumn (0.285), while summer has the lowest mean (0.203). The spatial distributions in spring, summer, and autumn are similar to the multi-year average distribution. Winter surface albedo is mainly concentrated between 0.35 and 0.55.

[Figure 6: see original paper]

[Figure 7: see original paper]

2.3.3 Surface Albedo Interannual Variation Characteristics

A unary linear regression method was used to fit the interannual variation trend of average surface albedo for each pixel in the Junggar Basin from 2001 to 2018 (Figure 8). The results show obvious spatial differences in the interannual variation of annual average surface albedo, with an overall decreasing trend of 1.4$×10^{-4}$ per year. Most areas showed a decreasing trend, accounting for 52.8% of the total area, with a decreasing rate of 1.09$×10^{-3}$ per year. The change rate of annual surface albedo was mainly concentrated in the range of insignificant increase and insignificant decrease, with proportions of the two being similar.

Areas with extremely significant increase, significant increase, and insignificant increase in interannual variation rate accounted for 0.18%, 2.92%, and 6.55% of the total area, respectively. Areas with extremely significant decrease, significant decrease, and insignificant decrease accounted for 0.62%, 44.0%, and 45.73% of the total area, respectively. Regions with rapid albedo decrease were mainly distributed in the central and eastern parts of the basin, while areas with rapid increase were mainly in the northwestern margin, accounting for about 9.28% of the total area.

[Figure 8: see original paper]

2.4 Analysis of Surface Albedo Influencing Factors

The spatial distribution differences of temperature and precipitation affect the distribution and growth of desert vegetation in the Junggar Basin, which in turn influences surface albedo. Based on the analysis of meteorological factor distribution differences and NDVI, the interactions between temperature, precipitation, vegetation growth, and surface albedo distribution and changes were further analyzed. Analysis of annual and monthly average surface albedo, temperature, and precipitation from 2001 to 2018 at the same resolution (Figure 9) shows that the northwestern margin of the Junggar Basin has scarce annual precipitation (200–350 mm). However, due to the presence of China' s second largest plain grassland (Kurusutai Grassland) with high vegetation coverage, the annual average surface albedo in this region is generally low. The central basin is the Gurbantünggüt Desert, with a dry climate, scarce precipitation, low vegetation cover, and generally high surface albedo.

The correlation between annual average temperature and surface albedo in the Junggar Basin ranges from -0.8 to 0.6, with 98.6% of the area showing negative correlation and very few areas showing positive correlation, scattered in the central and eastern corners of the basin (Figure 10). The correlation between annual precipitation and surface albedo ranges from -0.6 to 0.8, with negatively correlated areas concentrated in the eastern corner and central region of the basin (86.3% of the total area), and positively correlated areas concentrated in the northern basin (13.7% of the total area). Overall, the area proportion of negative correlation between surface albedo and temperature is 98.6%, stronger than positive correlation; the area proportion of negative correlation with precipitation is 86.3%, also stronger than positive correlation. Moreover, the correlation between surface albedo and temperature is stronger than that with precipitation.

Analysis of monthly average surface albedo and its variation from 2001 to 2018 shows that monthly surface albedo variation is closely related to seasonal changes (Figure 9). Across the entire Junggar Basin, albedo shows a good negative correlation with NDVI variation. In spring, as vegetation revives, NDVI gradually increases while surface albedo decreases. In summer, NDVI reaches its maximum while surface albedo remains relatively stable. In autumn, as vegetation withers, NDVI gradually decreases and surface albedo begins to slowly increase. In winter, with increasing snow cover, NDVI decreases to its minimum while surface albedo rises to its maximum. Thus, the annual variation of surface albedo in the Junggar Basin is closely related to seasonal changes.

The correlation between surface albedo and NDVI in the Junggar Basin ranges from -0.8 to 0.6, with 85.7% of the area showing negative correlation and 14.3% showing positive correlation in the western basin. Surface albedo and NDVI are basically negatively correlated (Figure 11). Due to the influence of plastic film mulching, surface albedo over farmland is higher than that over bare land in some periods, which may also cause positive correlation between surface albedo and NDVI in some areas.

[Figure 9: see original paper]

[Figure 10: see original paper]

[Figure 11: see original paper]

3 Discussion

The application of surface albedo products in global land surface energy balance research has attracted considerable scientific attention, particularly regarding accuracy assessment. For example, Chen et al. analyzed the accuracy of full inversion and quantitative inversion results using MCD43B2 albedo products over the Tibetan Plateau, finding that the full inversion results had high accuracy that meets the absolute precision requirements of climate and land surface process models. Yu et al. compared MOD43B3 surface albedo with ground observations, finding a root mean square error of 0.014, which also meets the accuracy requirements for surface albedo.

Currently, most surface albedo products have spatial resolutions at the kilometer scale, and many studies have focused on using MCD43 products to retrieve surface albedo. Although good accuracy has been achieved, the increasing demand for refined regional and local applications has placed higher requirements on remote sensing data resolution. This study used MOD09A1 product data, improving the spatial resolution to 500 m. Through comparative analysis of ground measured data and retrieved surface albedo products, the root mean square error was 0.014, which meets the accuracy requirements for surface albedo while improving spatial resolution and producing more detailed image textures. Moreover, MOD09A1 data products have fewer fill values and relatively higher effective retrieval rates.

Research on retrieving surface albedo using MOD09A1 products is relatively scarce, particularly regarding the spatio-temporal distribution and variation characteristics of surface albedo in the Junggar Basin. This study used Liang' s retrieval method to effectively characterize the seasonal and interannual variation features of surface albedo in the Junggar Basin and analyzed its relationships with climate change and NDVI. Since current research on surface albedo is mostly based on station data to analyze daily, seasonal, and annual variation characteristics, with less in-depth analysis of large-area, surface-based variation features, this study focused on pixel-by-pixel analysis of surface albedo across the large region of the Junggar Basin, emphasizing the relationships between albedo and climate change and vegetation index NDVI over typical desert grasslands, thereby providing basic validation for remote sensing retrieval of surface albedo.

Due to the scarcity and uneven distribution of meteorological stations in the study area, the accuracy of spatial interpolation using meteorological data is reduced, which correspondingly lowers the accuracy of the meteorological data grids matching the albedo pixel size, potentially introducing errors in the correlation analysis of surface albedo. This study explored the relationships between surface albedo and influencing factors in the Junggar Basin, but further research is needed to deeply reveal how potential factors affect surface albedo changes in desert grasslands and to quantify the contribution rate of each factor. Future studies should combine land ecosystem models and other relevant research methods to quantitatively analyze the impact and magnitude of each factor on surface albedo, deepening understanding of land surface characteristic responses to climate change in arid and semi-arid regions.

4 Conclusions

Using MOD09A1 remote sensing data to retrieve surface shortwave albedo from 2001 to 2018 in the Junggar Basin, combined with meteorological data and vegetation index, this study analyzed the spatio-temporal variation characteristics of surface albedo and its correlation with vegetation and climate factors. The main conclusions are:

1) The spatial distribution of surface shortwave albedo in the Junggar Basin shows obvious regional differences. The multi-year average surface albedo during the study period is 0.303, with most areas concentrated between 0.25 and 0.35, accounting for about 58.35% of the total area. The overall pattern shows high values in the northeast and low values in the southwest. The interannual variation rate shows a decreasing trend of 1.4$×10^{-4}$ per year, with the decreased area accounting for about 52.8% of the total area. Seasonal spatial distribution varies significantly, with similar patterns in spring, summer, and autumn, highest in winter (0.551) and lowest in summer (0.203). The surface albedo in the Altai Mountains on the northeastern margin changes dramatically within the year. NDVI values in the growing season are 0.23 in spring, 0.31 in autumn, and highest in summer (0.35).

2) The overall surface albedo in the Junggar Basin is negatively correlated with NDVI and average temperature, and positively correlated with precipitation in most areas, with correlation strength following the order: temperature > NDVI > precipitation. There is a significant correlation between retrieved results and ground measured values ($R^2 = 0.8908$, $P < 0.01$), with a root mean square error of 0.014. This study provides a theoretical basis for understanding land surface characteristics of the Junggar Basin, objectively evaluating land surface changes in arid regions under global climate change, and determining positive and negative feedback response mechanisms.

References

[The references section appears to be incomplete and fragmented in the original text. The full reference list would need to be properly formatted based on the complete original manuscript.]

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