Variation Characteristics of Surface Albedo in Subtropical Rice Paddies (Postprint)

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Abstract

Studying surface albedo of rice paddies using ground-based measurements can, on the one hand, better characterize the energy partitioning process between land and atmosphere in watersheds where rice paddies are the dominant land use type; on the other hand, it can provide more accurate parameter values for land surface models and validation for remotely sensed surface albedo, thereby offering references for better explaining the mechanisms through which land use/cover changes affect global climate change. This study utilizes surface albedo data for rice paddies measured in 2016 by a four-component radiometer at the Lishui Experimental Base of Jiangsu Academy of Agricultural Sciences to analyze the characteristics of surface albedo in rice paddies. Combined with synchronous meteorological observations of solar shortwave radiation, temperature, humidity, wind speed, and wind direction, correlation analysis was conducted to identify the main meteorological factors influencing surface albedo in rice paddies, providing a reference for further quantifying the parameterized relationships between surface albedo and temperature, humidity, and other variables. The results show that on sunny days, surface albedo of rice paddies exhibits an overall "U-shaped" distribution, being lower at noon and higher in the morning and afternoon. The diurnal variation of surface albedo in rice paddies on sunny days displays asymmetric characteristics, which are primarily caused by dew and wind speed and direction. When the solar elevation angle is small, the scattering effect of dew makes the surface albedo value higher in the morning than in the afternoon; whereas when the solar elevation angle is large, southwesterly winds cause crop leaves to tilt, making the surface albedo value higher in the afternoon than in the morning. Surface albedo values of rice paddies on sunny days are higher than those on rainy or overcast days. On sunny days, surface albedo shows the highest correlation with outgoing shortwave radiation (0.670, $P<0.01$), while on cloudy days, it shows the highest correlation with relative humidity (-0.480, $P<0.05$). Throughout the observation period, surface albedo within the rice paddy growing season showed a trend of first increasing and then decreasing. The highest surface albedo values occurred between the grain filling and maturity stages, while the lowest values occurred between transplanting and tillering stages. During the grain filling stage, surface albedo showed relatively high correlations with both solar shortwave radiation and humidity, and both passed the significance test at P<0.01. The tillering and jointing stages are two growth periods within the rice growing season when surface albedo changes relatively rapidly and is significantly affected by meteorological factors.

Full Text

Characteristics of Surface Albedo in Subtropical Paddy Rice Fields

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Abstract: Surface albedo, as a key input parameter for numerical climate models and surface energy balance equations, affects Earth' s climate systems. Ground-based observations of paddy field surface albedo not only better characterize energy partitioning between land and atmosphere in rice-dominated watersheds but also provide more accurate parameter values for land surface models and validation data for remote sensing retrievals, thereby improving understanding of how land use/cover change influences global climate mechanisms. Using CNR4-measured surface albedo data from 2016 at the Lishui Experiment Station of Jiangsu Academy of Agricultural Sciences, this study analyzed paddy field albedo characteristics and examined correlations with concurrent meteorological observations including solar shortwave radiation, temperature, humidity, wind speed, and wind direction to identify primary meteorological factors influencing paddy field albedo. Results provide a reference for quantifying parameterization relationships between surface albedo and temperature/humidity. The findings show that sunny-day paddy albedo exhibits a U-shaped diurnal pattern, with lower values at noon and higher values in morning and afternoon. This diurnal asymmetry is primarily caused by dew and wind conditions. When solar altitude angles are small, dew scattering increases morning albedo above afternoon values; when solar altitude angles are large, southwesterly winds cause crop leaf tilting that increases afternoon albedo above morning values. Sunny-day albedo values exceed those on cloudy and rainy days. On sunny days, albedo correlates most strongly with outgoing shortwave radiation ($r = 0.670$, $P < 0.01$), while on cloudy days it correlates most strongly with relative humidity ($r = -0.480$, $P < 0.05$). Throughout the observation period, growing-season albedo showed an initial increase followed by decrease, peaking between grain-filling and maturity stages and reaching its minimum between transplanting and tillering stages. During grain-filling, albedo showed significant correlations with both solar shortwave radiation and humidity ($P < 0.01$). Tillering and jointing stages exhibited the fastest albedo changes within the rice growing season and were significantly affected by meteorological factors.

Keywords: Rice paddy field; Surface albedo; Growing season; Asymmetrical; Meteorological factors

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Surface albedo controls the net radiation energy reaching Earth's surface [1] and reflects energy partitioning between land and atmosphere. As a critical variable in Earth' s climate system, it significantly influences water and heat exchange between surface and atmosphere [2-4]. For a given incoming solar shortwave radiation, higher surface albedo indicates more reflected solar radiation and less energy absorbed by the surface, while lower albedo indicates less reflected radiation and more absorbed energy, producing a warming effect [5]. Surface albedo affects biophysical and chemical processes including surface temperature, evapotranspiration, photosynthesis, and respiration, thereby directly and indirectly influencing global and regional climate [5].

High-resolution surface albedo parameters play important roles in monitoring sudden natural processes such as precipitation and crop disasters, regional-scale human activities like crop planting and harvesting [6-8], radiation energy balance in natural ecosystems [9], and urban heat islands [10]. As an essential input parameter in many land surface climate models and energy balance equations, surface albedo is a key variable affecting Earth' s climate system [11].

Surface albedo magnitude is influenced by multiple factors. It decreases with increasing solar altitude angle and soil moisture [12]. Using NOAA satellite data, Chen et al. [13] retrieved surface albedo over northwestern China and found that under combined effects of vegetation coverage and soil moisture, surface albedo showed distinct zonal distribution patterns. Yang et al. [10] used MODIS bidirectional albedo product MOD43B3 to analyze spatiotemporal distribution and variation characteristics of surface albedo in Beijing, finding lowest values in mountainous areas, followed by urban areas, with higher values in plain areas and the Yongding River basin. Cai et al. [14] used NCEP reanalysis data to show that July had the lowest annual surface albedo, with higher values in spring and autumn and the highest in January. Remote sensing provides an effective method for obtaining large-area surface albedo, but since remote sensing data reflect comprehensive surface information related to resolution, retrieved albedo requires validation with ground measurements. Furthermore, in current land surface process models, surface albedo is a diagnostic variable derived from other parameters, creating substantial temporal and spatial uncertainties [2]. Therefore, considering underlying surface heterogeneity, conducting observational experiments on various underlying surfaces is critically important.

Zhang et al. [15] studied albedo variation characteristics during spring wheat development stages in arid regions, finding that sunny-day surface albedo showed a U-shaped diurnal distribution with asymmetry primarily caused by morning dew on wheat leaves. Yu et al. [16] analyzed surface albedo variations in wheat and rice fields in Shouxian, Anhui, finding similar trends between wheat and rice fields throughout their growth periods. Although previous studies have examined farmland surface albedo, research on farmland albedo under different climate conditions, particularly in subtropical paddy fields, remains limited. This study observed paddy field surface albedo during the warm-humid year of 2016 and analyzed its variation characteristics.

Focusing on paddy fields in the Qinhuai River basin of subtropical regions, this study used four-component net radiometers at the Lishui Experiment Station of Jiangsu Academy of Agricultural Sciences to analyze paddy field albedo characteristics under different weather conditions and throughout the growing season, combined with meteorological data including temperature, humidity, wind speed, and wind direction to identify influencing factors. The results aim to provide relevant parameters for land surface models and ground validation for remote sensing retrievals of surface albedo.

1.1 Study Area Overview

The observation site is located at the Lishui Experiment Station of Jiangsu Academy of Agricultural Sciences in Baima Town, Lishui County (119.2°E, 31.6°N, elevation 38 m). The 0.8 km^2 station is surrounded by paddy fields with water supplied from the Baima Lake Reservoir. The basic landform type is hilly with white pulp soil. The station lies within the Qinhuai River basin in a subtropical monsoon climate with abundant rainfall (annual precipitation 1,048 mm), distinct seasons, and mean annual temperature of 15.4 °C. Analysis of long-term meteorological data (1985-2016) from Lishui Station shows that May and June 2016 had lower average temperatures than the historical average, while other months were warmer. The rice growing season in 2016 had slightly above-average temperatures. Except for August, relative humidity and precipitation during the 2016 rice growing season exceeded historical averages. Overall, 2016 was a warm-humid year for the rice growing season (Table 1). The observed rice variety was 'Nanjing 9108' , transplanted on June 17, 2016, entering tillering on June 27, jointing on July 15, heading on August 12, grain-filling on August 15, maturity on October 10, and harvested on October 25.

1.2 Observation Instruments and Data Preprocessing

Surface albedo and meteorological data were obtained from a four-component net radiometer (CNR4), rain gauge (TE525MM), infrared temperature sensor (109-L50), and conventional wind speed/direction sensors installed at the station. The CNR4 measured upward and downward shortwave radiation (spectral range 0.31-2.80 µm) and upward and downward longwave radiation (spectral range 4.20-42.00 µm). The four-component net radiometer and infrared temperature sensor were installed 2 m above ground in the paddy field center, wind sensors at 3 m, and the rain gauge at 70 cm. During analysis, missing values were excluded and half-hourly albedo data from 8:00-17:00 were selected to calculate daily mean daytime albedo for analyzing seasonal and growth-stage variations. Typical sunny-day albedo data from April-November were selected for diurnal variation analysis, combined with temperature, humidity, wind speed, and direction data to analyze asymmetry phenomena. Albedo data under sunny, cloudy, and rainy conditions were analyzed for different weather patterns. Graphical analysis examined albedo variation characteristics under typical sunny and different weather conditions and throughout the growing season. SPSS canonical correlation analysis examined relationships between paddy albedo and shortwave radiation, temperature, and relative humidity. MATLAB processed historical meteorological data.

2.1.1 Paddy Field Surface Albedo on Typical Sunny Days During Different Rice Development Stages

Typical sunny days were selected from pre-transplanting to post-harvest stages to analyze daytime albedo variation (Figure 1 [Figure 1: see original paper]). Selected dates were April 29 (pre-transplant), May 16 (pre-transplant), June 17 (transplanting), July 22 (jointing), August 15 (grain-filling), September 2 (grain-filling), October 9 (maturity), and November 2 (post-harvest).

Diurnal albedo showed a U-shaped distribution with smaller values at noon and larger values in morning and afternoon, consistent with Zhang et al. [15]. Minimum albedo occurred around noon, while maxima appeared in both morning and afternoon. The highest daily albedo value was 0.23 on August 15 and September 2 mornings, while the lowest was 0.07 around noon on June 17. The upward parabolic pattern on sunny days was primarily influenced by solar altitude angle, with albedo decreasing as solar altitude increases. Thus, noon albedo was lower while morning and afternoon values were higher.

As rice grew, diurnal albedo variation became more pronounced. During pre-transplanting stages, albedo variation was small with minimal differences between maximum and minimum values. After transplanting, diurnal albedo fluctuated more dramatically with significantly increased differences between extremes. The U-shaped pattern with lower noon values and higher morning/afternoon values showed opposite trends to solar altitude angle, indicating that growing-season albedo variation was jointly influenced by solar altitude and meteorological conditions.

2.1.2 Asymmetry Characteristics and Causes of Sunny-Day Albedo

Sunny-day paddy field albedo exhibits diurnal asymmetry [15], quantified as the percentage difference between morning and afternoon albedo relative to their mean. Typical sunny days on April 29, May 16, June 17, July 22, August 15, September 2, October 9, and November 2 were selected to analyze asymmetry characteristics (Figure 2 [Figure 2: see original paper]), with April 29, May

16, June 17, July 22, August 15, and September 2 used to analyze asymmetry causes (Figures 3 [Figure 3: see original paper], 4, 5).

Potential causes of half-hourly mean albedo asymmetry include: (1) wind speed and direction effects on vegetation leaves [17-19], and (2) dew scattering on vegetation increasing albedo [20-22]. Figure 2 shows that when solar altitude angle was less than 60°, morning albedo generally exceeded afternoon values; when greater than 60°, afternoon albedo exceeded morning values. Analysis of typical sunny-day meteorological data calculated mean dew point temperatures at each time point. Comparison of dew point and actual air temperatures (Figure 3a) shows nighttime temperatures were close to dew point, favoring dew formation, while daytime differences were larger, inhibiting dew formation. Morning dew scattering increased albedo, causing morning values to exceed afternoon values.

Analysis of typical sunny-day mean incoming and outgoing shortwave radiation (Figure 3b) shows morning incoming radiation was significantly higher than afternoon, while outgoing radiation was similar, indicating that albedo during this period was primarily affected by underlying surface conditions. Wind speed data (Figure 4 [Figure 4: see original paper]) show smaller morning and afternoon winds but larger midday winds, suggesting that asymmetry when solar altitude was high (around noon) may be wind-influenced. The wind rose map (Figure 5 [Figure 5: see original paper]) indicates that about 85% of wind speeds exceeded $2\ \mathrm{m\cdot s^{-1}}$ with dominant southwesterly winds. Wind direction changed leaf inclination angles, and since albedo decreases with increasing solar altitude, morning leaf angles relative to the sun increased (reducing albedo) while afternoon angles decreased (increasing albedo), creating the afternoon-greater-than-morning asymmetry.

2.2 Surface Albedo Under Different Weather Conditions

October 9 (sunny), October 11 (cloudy), and October 7 (rainy) represent three weather conditions. Results (Figure 6 [Figure 6: see original paper]) show paddy albedo generally followed sunny > cloudy > rainy. Sunny and cloudy day albedo asymmetry was evident, with higher morning values, while rainy-day albedo was more symmetric, likely due to more morning dew on sunny and cloudy days. Sunny days received greater solar shortwave radiation with lower soil moisture, producing higher albedo. Influenced by solar altitude angle, diurnal albedo variation was more pronounced on sunny days. Cloudy days had less incoming shortwave radiation and higher soil moisture, resulting in lower albedo with minimal diurnal variation. Rainy conditions had the least incoming shortwave radiation and highest soil moisture, further reducing albedo with small diurnal variation amplitude.

2.3 Paddy Field Surface Albedo During Different Rice Development Stages

From transplanting on June 17 to harvest on October 25, paddy albedo showed an overall trend of initial increase followed by decrease (Figure 7 [Figure 7: see original paper]), consistent with Raja et al. [23] and Zhang et al. [24]. The highest albedo occurred during grain-filling, while the lowest values appeared during transplanting and maturity stages. Albedo increased slowly and fluctuated after entering tillering on June 27. Rapid increase occurred during the vigorous growth period after jointing began on July 15. Albedo remained relatively high during heading (August 12) and grain-filling (starting August 15) stages, then decreased. After maturity began on October 10, albedo dropped rapidly as crops senesced, decreasing further after harvest.

Precipitation was concentrated between late June-early July (tillering) and early September-early October (grain-filling) (Figure 8 [Figure 8: see original paper]), coinciding with greater albedo fluctuations. Other periods with less precipitation showed less albedo variability, suggesting increased precipitation may be a common cause of larger albedo fluctuations during tillering and grain-filling stages.

2.3.1 Relationships Between Paddy Albedo and Temperature, Humidity, and Shortwave Radiation Under Different Weather Conditions

Correlation analysis (Table 1) shows sunny-day albedo had relatively high correlations with 2 m temperature, humidity, and shortwave radiation, particularly significantly correlated with outgoing shortwave radiation ($r = 0.670$, $P < 0.01$). Cloudy-day albedo correlated most strongly with relative humidity. Rainy-day albedo showed low correlations with all three factors.

2.3.2 Relationships Between Paddy Albedo and Temperature, Humidity, and Shortwave Radiation During Different Growth Periods

1) Albedo and Temperature/Shortwave Radiation Variation

During early rice growth, paddy albedo and temperature showed opposite trends (Figure 9 [Figure 9: see original paper]). From April 20 to early July, decreasing albedo increased solar radiation absorption, raising surface temperature. In late September, increasing albedo reduced radiation absorption, lowering temperature. During other stages with vigorous vegetation growth, the albedo-temperature relationship was less apparent.

Incoming and outgoing shortwave radiation showed consistent temporal variation trends, while albedo variation lagged slightly behind (Figure 10 [Figure 10: see original paper]). Before land preparation, albedo variation was most consistent with incoming shortwave radiation as underlying surface conditions remained relatively constant. After transplanting began, underlying surface changes had greater impact on outgoing radiation, making albedo lag more obvious relative to incoming radiation, particularly during vigorous growth periods when crop development significantly influenced albedo beyond solar altitude and weather effects.

2) Correlations Between Albedo and Temperature, Humidity, and Shortwave Radiation During Different Growth Periods

Correlation analysis shows that throughout the observation period, albedo was positively correlated with temperature and shortwave radiation but negatively correlated with 2 m relative humidity. During the rice growing season, albedo showed relatively high correlations with humidity and shortwave radiation. Different growth stages showed varying correlation strengths, with grain-filling stage albedo showing significant correlations with solar shortwave radiation and relative humidity (both $P < 0.01$). Non-growing season albedo (before transplanting and after harvest) showed higher correlation with 2 m temperature but lower correlations with humidity and shortwave radiation (Table 2).

4.1 Comparison of Surface Albedo Between Paddy Fields and Other Farmland

Previous studies [25-27] show large differences in surface albedo among underlying surfaces, with snow-covered surfaces having the highest values (approaching 0.9), followed by sparsely vegetated deserts, Gobi, degraded grasslands, and bare land. Densely vegetated areas like farmland and forest have lower albedo, with forests being the lowest. Among farmland types, albedo varies with crop type [28]. Arid region wheat fields have higher albedo than semi-humid regions, possibly due to higher soil moisture in semi-humid areas. Comparing wheat field albedo during growth periods [15-16] with our paddy field observations shows similar patterns of initial increase then decrease. Yu et al. [16] found wheat field albedo was 0.02 higher than paddy fields in early growth, similar during mid-growth, but paddy fields exceeded wheat by about 0.04 after booting stage and at full maturity. Our rice growing season albedo showed similar trends to Yu et al. [16], with higher values during heading and grain-filling stages and lower values from transplanting to tillering and maturity stages. However, our albedo values were lower within the same growth stages, likely due to the Lishui station's location in the Qinhuai River basin with abundant surrounding reservoirs and higher soil moisture.

4.2 Factors Affecting Surface Albedo

Liu et al. [25] found that maize farmland albedo was negatively correlated with solar altitude angle and soil moisture but positively correlated with vegetation index. Zheng et al. [29] found bare land albedo decreased with increasing solar altitude and soil moisture. Zhang et al. [30] showed that increased soil moisture significantly decreased albedo, with this relationship affected by vegetation growth cycles. Usowicz et al. [31] found that albedo decreased significantly with increasing biochar application, and that post-rainfall albedo decreased in fallow land but increased in grassland. Li et al. [32] found negative correlations between surface albedo and NDVI in Xilinhot, Inner Mongolia. Bsaibes et al. [33] found that the relationship between LAI and albedo was affected by land cover type, with larger albedo differences at small LAI values that stabilized as LAI increased. Thus, surface albedo is jointly affected by multiple factors including underlying surface color, vegetation coverage, soil temperature, soil moisture, solar altitude angle, and atmospheric transmissivity.

Our results show that under typical sunny conditions, paddy albedo relates to solar altitude angle, with lowest values at noon and higher values in morning and afternoon, decreasing as solar altitude increases. Sunny-day diurnal variation is also affected by daily temperature range and wind. When solar altitude is less than 60°, temperature differences cause more dew on vegetation surfaces in the morning, making morning albedo higher than afternoon at the same solar altitude. When solar altitude exceeds 60°, wind causes leaf tilting, making afternoon albedo higher than morning at the same solar altitude. Albedo also relates to weather conditions, with higher atmospheric transmissivity on sunny days producing higher albedo, while cloudy and rainy days with lower transmissivity have lower albedo. Albedo further relates to rice growth status, increasing during early growth, stabilizing near maturity, then decreasing at maturity and further declining after harvest. Future research should focus on effects of soil moisture and vegetation coverage on albedo.

Conclusions

1) Sunny-day paddy albedo shows a U-shaped distribution with lower values at noon and higher values in morning and afternoon. Diurnal variation becomes more pronounced as rice grows. The asymmetry is mainly caused by dew and wind direction. At small solar altitude angles, dew scattering makes morning albedo higher than afternoon; at large solar altitude angles, southwesterly winds cause leaf tilting that makes afternoon albedo higher than morning.

2) Albedo differs under different weather conditions, with sunny-day values exceeding cloudy and rainy days. Sunny-day albedo shows greater variation trends than cloudy and rainy days. Asymmetry is evident on sunny and cloudy days. Albedo correlates most strongly with outgoing shortwave radiation on sunny days ($r = 0.67$, $P < 0.01$) and with relative humidity on cloudy days ($r = -0.48$, $P < 0.05$).

3) Growing-season albedo shows an initial increase followed by decrease, influenced by precipitation. The highest values occur between grain-filling and maturity stages, with lowest values between transplanting and tillering. Albedo correlates relatively strongly with humidity and shortwave radiation during the growing season, but correlation strengths with temperature, humidity, and shortwave radiation vary among growth stages. Grain-filling stage albedo shows significant correlations with solar short-

wave radiation and humidity (both $P < 0.01$).

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