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The influence of soil moisture and solar altitude on surface spectral albedo in arid area

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Abstract

Using data collected from a specially designed experiment at the Dunhuang Station (40°10′N, 94°31′E, 1150 m) from September 2017 to September 2018, we have characterized the influences of soil moisture and solar altitude on surface spectral albedo in an arid area. The specific settings of our experiment allowed us to minimize the influences of underlying surface, cloud cover, aerosol and weather conditions, and thus highlight the influence of soil moisture and solar altitude. During the timespan of the experiment, we observed the annual mean surface albedo of global radiation (GR), ultraviolet radiation (UV), visible radiation (VIS) and near-infrared radiation (NIR) to be 0.24, 0.11, 0.24 and 0.25. A significantly negative linear correlation between surface albedo and soil moisture was identified, with the correlation coefficients between GR, UV, VIS, NIR and soil moisture being $-0.68$, $-0.75$, $-0.70$ and $-0.61$. In addition, we identified an exponential relationship between surface albedo and solar altitude. The exponential regression coefficients are $-0.21$, $-0.077$, $-0.53$ and $-0.21$, respectively. From these analyses, we derived a new two-factor parametric formula for depicting the influence of soil moisture and solar altitude on surface spectral albedo. Using observation data, we demonstrate that the formula recapitulates the real-world relationship between soil moisture, solar altitude and surface spectral albedo with little deviation. These findings may help us gain a deeper understanding of improving land surface parameterizations and have potential implications for solar energy research and applications.

1. Introduction

The Earth’s climate system has experienced dramatic changes, especially in Northern Eurasia, where climate changes are substantially larger than the global average (Groisman \textit{et al} 2009). As a consequence of perturbations in the Earth’s energy budget, regional climate changes are caused by numerous factors, one of which is the change of surface albedo. Defined as the proportion of incident solar radiation that is reflected by a surface, surface albedo reflects its ability to regulate the Earth’s energy budget (Liang 2001). Since Charney \textit{et al} (1975) first pointed out that the increase of surface albedo in desert areas could lead to regional drought, the climate impact of surface albedo has gradually gained traction in the field of Earth climate system science and is now recognized as one of the most significant climate variables (Knobelspiesse \textit{et al} 2008).

Surface albedo reflects the reflection ability of the Earth’s surface to solar radiation. It is often related to solar altitude, underlying surface condition, soil humidity, meteorological conditions and other factors (Brest and Samuel 1987, Song, 1998, Tsvetsinskaya \textit{et al} 2002). Changes in surface albedo affect the atmospheric circulation by altering the energy intake of the whole land atmosphere system, causing local and global climate changes. Therefore, surface albedo is

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usually incorporated as an important parameter in atmospheric and land surface models. However, a series of factors including solar altitude, soil moisture, precipitation and vegetation cover all contribute to surface albedo, and hence fluctuations in other factors must be excluded when studying the relationship between surface albedo and single factors (Wang et al. 2005).

Another critical aspect of surface albedo is its spectrum. Previous studies of surface radiation and surface albedo are mostly based on full-band radiation observation. Limited research has been done to further dissect the spectral components of solar radiation and surface albedo. In land surface process models such as the community land model (CLM) and the land surface model (LSM), surface albedo is only divided into two components: visible radiation (VIS) and near-infrared radiation (NIR) with a wavelength of 0.7 μm (Bonan, 1996, Dai et al. 2003, Oleson et al. 2010). Furthermore, the models assume a simple two-fold relationship in the surface albedos of NIR and VIS, which contradicts the findings of Zheng et al. (2012) that the surface albedos of VIS and NIR are 0.23 and 0.26, respectively, in arid areas. Since different bands of radiation typically possess different characteristics, such misalignment between models and reality keeps us from gaining a deeper understanding of the Earth’s energy system, and may also hinder broader applications in Earth energy science. For example, the spectral response of solar cells varies with the material. The response band of single-crystal silicon batteries is 400–1100 nm, whereas that of silicon thin-film batteries is about 400–700 nm (Yang et al. 2013). Having a precise modeling will guide policy-making and application choices.

The purpose of this study is to identify the influence of soil moisture and solar altitude on surface spectral albedo. We chose an arid area for the observation and evaluated the correlations between soil moisture, solar altitude and surface albedo. The underlying surface of the arid area is stable, while factors like underlying surface, cloud cover, aerosols and weather conditions are controllable. Therefore, our experiment minimizes the impact of other factors and highlights the influence of soil moisture and solar altitude.

2. Design of the experiment

To investigate the effects of soil moisture and solar altitude on surface spectral albedo, an observational experiment was carried out at the Dunhuang Station. Located in northwest China, this station is far from the sea and extremely arid. The observational site is located at 40°10’N, 94°31’E, at an altitude of 1150 m, at the center of the Gobi, which is not covered by any vegetation. The stable properties of the land surface in the Gobi allowed us to eliminate the inherent changes of surface albedo. The annual mean precipitation of the experiment site is only 39 mm and the potential evaporation reaches 3400 mm (Li et al. 2017a, 2017b). Such stable conditions of aerosol presence, cloud cover and other weather changes also helped minimize unwanted influences in the experiment.

The underlying surface condition of the experiment site and observation instruments are shown in figure 1. The instruments used for the experiment included a precision spectral pyranometer (PSP), a total ultraviolet radiometer (TUVR) and SKE510 visible radiometers from the Eppley Company, USA, with a setting height of 1.5 m. A soil moisture depth of 2 cm
was measured by a QP-SS humidity sensor (Canada), which is specifically designed for sandy soil. The experimental data collector was the DT600 (Australia), which records data every 30 min. The parameters used for the observational instruments are shown in table 1. The methods of Zheng et al. (2015) were adopted for data quality control.

NIR can be expressed as

\[ \text{NIR} = \text{GR} - \text{UV} - \text{VIS} \]  

where GR is global radiation, UV is ultraviolet radiation and VIS is visible radiation (the same is used below).

Surface spectral albedo can be expressed as

\[ \alpha_{\text{GR}} = \frac{\text{GR}}{\text{GR}_s} \]  

\[ \alpha_{\text{UV}} = \frac{\text{UV}}{\text{UV}_s} \]  

\[ \alpha_{\text{VIS}} = \frac{\text{VIS}}{\text{VIS}_s} \]  

\[ \alpha_{\text{NIR}} = \frac{\text{NIR}}{\text{NIR}_s} \]

where \( \alpha \) is surface albedo, and ‘\( - \)’ and ‘\( + \)’ represent absorption and reflectance of solar radiation at the surface, respectively.

When studying the contributions of multiple factors, surface albedo can be expressed as

\[ \alpha = f(w_i, h_o, c_{lo}, a_{er}, \ldots) \]

where \( \alpha \) is the surface albedo, \( f \) is an unknown function and \( w_i, h_o, c_{lo}, a_{er}, \ldots \) represent soil moisture, solar altitude, cloud cover, aerosol and other factors, respectively.

Excluding the impacts of cloud cover, aerosols and other factors, the surface albedo can be expressed as

\[ \alpha = f(w_i, h_o) \]

Assuming that there is no interaction between soil moisture and solar altitude, (7) is transformed into

\[ \alpha = f_1(w_i) + f_2(h_o) \]

where \( f_1 \) and \( f_2 \) are unknown functions.

When the solar altitude is larger than 40°, the variation curve of surface spectral albedo is relatively flat, which indicates that solar altitude has little impact on surface albedo (Idso et al. 1975, Bedidi et al. 1992).

When the solar altitude is larger than 40°, \( f_2(h_o) \approx 0 \), (8) can be expressed as

\[ \alpha_1 = f_1(w_i) + 0 = f_1(w_i) \]  

where \( \alpha_1 \) is the surface albedo, \( f_1 \) is an unknown one-factor function that represents the relationship between soil moisture and surface albedo, and \( w_i \) is soil moisture.

Data with soil moisture less than 1.5% were selected to approximate dry soil conditions. For dry soil, \( w_i = 0 \). Consequently, (8) is transformed into

\[ \alpha_2 = f_1(0) + f_2(h_o) = f_1(h_o) \]

where \( \alpha_2 \) is the surface albedo, \( f_2 \) is an unknown one-factor function that represents the relationship between solar altitude and surface albedo when the soil is dry, and \( h_o \) is the solar altitude.

3. Results

3.1. The characteristics of surface spectral albedo

The diurnal variation curve of surface spectral albedo is roughly U-shaped (figure 2), suggesting that surface albedo is likely inversely proportional to solar altitude. We also observed a small diurnal variation for the surface albedo of UV, which reflects the stable aerosol condition at the experiment site, since UV is greatly affected by it. The observed ratios of incident UV, VIS and NIR to GR are approximately 0.04, 0.42 and 0.54, respectively. The observed ratios of reflected UV, VIS and NIR to GR are approximately 0.02, 0.41 and 0.57, respectively. It is obvious that NIR accounts for the largest proportion of GR, followed by VIS and UV. In CLM3.0, one of the land surface parameterizations in models, the surface albedo of NIR is considered to be twice that of VIS. Although the model was updated in later versions like CLM4.0 and CLM4.5, the two-fold relationship between the surface albedos of NIR and VIS remains unchanged in the case of saturated soil, whereas the surface albedo of dry soil is calculated based on that of saturated soil (Oleson et al. 2004, 2010, 2013). The surface albedos of NIR and VIS are 0.25 and 0.24 in our experiment, which clearly

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Table 1. Specific parameters of observational instruments.

| Feature       | GR          | UV          | VIS         |
|---------------|-------------|-------------|-------------|
| Sensor type   | PSP         | TUVR        | SKE51       |
| Manufacture   | Epoley, USA | Epoley, USA | Epoley, USA |
| Sensitivity   | 9 μV Wm⁻²   | 150 μV Wm⁻² | 1 mV/100 Wm⁻² |
| Spectral range| 280–2800 nm | 285–395 nm  | 400–700 nm  |
| Long-term stability | ±2%     | ±2%         | ±2%         |
| Response time | 1 s         | 5 ms        | 10 ns       |
| Linearity error| ±0.5%      | ±2%         | <0.2%       |
| Cosine error  | ±1% (0° < Z < 70°) | ≤±3.5% (0° < Z < 70°) | 3% |
| Temperature response | ±1%/°C (−20 °C–40 °C) | ±0.3%/°C (−40 °C–40 °C) | ±0.1%/°C (−35 °C–70 °C) |
argues against the hypothesis in CLM. Therefore, the quantitative setting in land surface parameterizations needs to be refined.

Although surface albedo is an inherent property of the underlying surface, it varies slightly with the seasons. Surface spectral albedo outliers are generally high in winter as shown in figure 3. There were two snowfall events in February 2018 (9th and 19th, respectively), and snow cover considerably affects surface albedo since the albedo of snow is much higher than other land cover types (Li et al 2017a, 2017b). The observed mean surface albedo of GR, UV, VIS and NIR reached 0.25, 0.12, 0.26 and 0.26, respectively, in winter. The surface albedo is indeed higher in winter than in other seasons. The monthly average surface albedo of GR, VIS and NIR reached a maximum of 0.26, 0.27 and 0.26 in January, whereas the largest monthly average surface albedo of UV was 0.13 in February 2018. The surface albedo is usually the largest in winter, and the smallest in summer, followed by spring and autumn. In the spring it is slightly larger than in autumn.

Table 2 shows the mean surface albedo of each waveband at different soil moisture. The soil moisture is measured every 5% band. It can be seen that the surface albedo of each waveband decreases along with the increase in soil moisture. The standard deviations of GR, UV, VIS and NIR are 0.03, 0.02, 0.01 and 0.06.

The above analysis again demonstrates that surface albedo is greatly affected by multiple factors like soil moisture, solar altitude, cloud cover, aerosols and so on, as shown in formula (6). In order to find out the relationship between soil moisture, solar altitude and surface spectral albedo, a special experiment is needed.

In the absence of cloud cover, aerosols and other weather conditions, during the timespan of the experiment, we observed annual mean surface albedos of 0.24, 0.11, 0.24 and 0.25 for GR, UV, VIS and NIR. The standard deviation of these values was 0.01, 0.04, 0.03 and 0.02, respectively. The results of the characteristics of surface albedo in this paper are consistent with those of predecessors (0.25 ± 0.02) (Li 2009).

3.2. The relationship between surface spectral albedo and soil moisture

The relationship between surface spectral albedo and soil moisture shown in figure 4 suggests that surface albedo is negatively correlated with soil moisture. The experimental area is an extremely arid area, and the soil moisture is relatively small for a long time without significant change. To better demonstrate the relationship between soil moisture and surface spectral albedo, we chose to study cloudless days after rainfall. The correlation coefficients of surface albedos of GR, UV, VIS and NIR and soil moisture were −0.68, −0.75, −0.70 and −0.61 in the experimental period. We performed linear regression analysis, and the linear regression coefficients of the surface albedos of GR, UV, VIS and NIR and soil moisture were −0.0020, −0.00083, −0.0013 and −0.0024, respectively. Shorter wavelengths correspond to a stronger relationship between the surface albedo and soil moisture. This conclusion is in line with the artificial irrigation experiments conducted in 2017 (Li et al 2019). Among them, the surface albedos of GR, VIS and NIR have little difference with the regression coefficient of soil moisture, while the surface albedo of UV has a
relatively small regression coefficient with soil moisture.

According to the linear relationship between surface albedo and soil moisture proposed by Idso et al (1975) and Dickinson et al (2006), we express the relationships between surface spectral albedo and soil moisture at a depth of 2 cm in arid areas as:

\[
\alpha_{1(\text{GR})} = -0.0020w_s + 0.24 \quad (R^2 = 0.99) \quad (11)
\]

\[
\alpha_{1(\text{UV})} = -0.00083w_s + 0.11 \quad (R^2 = 0.99) \quad (12)
\]

\[
\alpha_{1(\text{VIS})} = -0.0013w_s + 0.22 \quad (R^2 = 0.97) \quad (13)
\]

\[
\alpha_{1(\text{NIR})} = -0.0024w_s + 0.25 \quad (R^2 = 0.97) \quad (14)
\]

where \( \alpha_i \) is the surface albedo and \( w_s \) is the soil moisture at a depth of 2 cm.

As our conclusion, surface albedo decreases with the increase of soil moisture. The form of the relationship obtained in this paper is the same as that obtained by Idso et al (1975) and Zhang et al (2003), both of which are linear functions. However, the coefficients vary in scale, which may be caused by the different types of underlying surface in the experimental setting.

3.3. The relationship between surface spectral albedo and solar altitude

From the observation data, we derived an exponential relationship between surface albedo and solar altitude (figure 5). The exponential regression coefficients between the surface albedo of GR, UV, VIS and NIR
and solar altitude are $-0.21$, $-0.077$, $-0.53$ and $-0.21$, respectively. The relationships between the surface spectral albedo and solar altitude are:

$$a_{2(\text{GR})} = 0.11 \times \exp(-0.21h_\theta) + 0.24 \quad (R^2 = 0.96)$$

$$a_{2(\text{UV})} = -0.012 \times \exp(-0.077h_\theta) + 0.11 \quad (R^2 = 0.67)$$

$$a_{2(\text{VIS})} = 0.014 \times \exp(-0.53h_\theta) + 0.22 \quad (R^2 = 0.89)$$

$$a_{2(\text{NIR})} = 0.18 \times \exp(-0.21h_\theta) + 0.25 \quad (R^2 = 0.98)$$

where $a_{2}$ is surface albedo and $h_\theta$ is solar altitude. Theoretically, the change of surface albedo has a negative exponential relationship with the solar altitude. However, in our experiment, the surface albedo of UV displays a weak positive correlation with the solar altitude. As shown in figure 2, the surface albedo of UV is not sensitive to the solar altitude, which conforms with formula (16). To sum up, the surface albedo of UV at Dunhuang hardly varies with solar altitude. This proves once again that the diurnal variation of the surface albedo of UV is not significant, as stated in 3.1. The surface albedo of UV is almost a fixed value at Dunhuang, which indicates that the absorption and reflection values of UV are also basically unchanged. The absorption and reflection of UV are affected by aerosols and vegetation (Dickerson et al 1997, Kakani et al 2003), and the insignificant change in the surface albedo of UV is consistent with the fact that there is no vegetation cover and almost no air pollution at Dunhuang Station.

We also explored the relationship with solar altitude by season. The contribution of solar altitude also varies over time. Past studies (Liu et al 2008, Guan et al 2009, Roxy et al 2010) have shown that when the solar altitude is larger than $40^\circ$, the surface spectral albedo tends to be stable. It should be noted that this finding is based on the analysis of data of a shorter period of time, not a long period of time, and the underlying surface was not the Gobi. In our research, from the data for the whole year, the decrease in surface spectral albedo with solar altitude was stabilized at $<40^\circ$. In different seasons, the change of surface spectral albedo tends to be stable at different solar altitudes. In summer and autumn, when the solar altitude is larger than $40^\circ$, the surface spectral albedo changes very little and tends to be constant. But in spring and winter, the change of surface spectral albedo tends to be stable when the solar altitude is smaller than $40^\circ$. The reasons for the seasonal difference need further study.

3.4. The new parametric formula for surface spectral albedo

According to the analysis above, a series of two-factor parametric formulas of soil moisture, solar altitude and surface spectral albedo can be expressed as follows:

$$a_{\text{GR}} = -0.0020w_s + 0.11 \times \exp(-0.21h_\theta) + 0.24 \quad (19)$$

$$a_{\text{UV}} = -0.00083w_s - 0.012 \times \exp(-0.077h_\theta) + 0.11 \quad (20)$$

$$a_{\text{VIS}} = -0.0013w_s + 0.014 \times \exp(-0.53h_\theta) + 0.22 \quad (21)$$

$$a_{\text{NIR}} = -0.0024w_s + 0.18 \times \exp(-0.21h_\theta) + 0.25 \quad (22)$$

where $\alpha$ is surface albedo, $w_s$ is soil moisture, and $h_\theta$ is solar altitude.

A previous study (Henderson Sellers and Wilson 1983) has shown that for the albedo database in the climate model, the absolute deviation from the real value should be controlled within the range of $\pm 0.05$. According to Sellers et al (1995), the accuracy of
surface albedo in climate models should be limited to ±0.02. As a necessary validation, we verified our formula by fitting the observation data to our formula. The blue line represents the observed data, and the red line represents simulated data (figure 6). Although the simulation results are a little larger than the observed ones, there is no significant deviation between the simulation and observation values. The 95.65%, 73.91%, 82.61% and 78.27% values of the simulated surface albedos of GR, UV, VIS and NIR met the ±0.02 deviation. This range of deviation is in line with the findings of Sellers et al (1995), so the new parametric formula above has certain scientific significance.

We further explored the diurnal variation characteristics of surface spectral albedo simulated by the new two-factor parametric formula. The difference between the simulated value and the observed value is slightly larger at sunrise or sunset. This could be due to the influence of real-time meteorological and environmental factors. Under such circumstances, the new parametric formula will not be able to accurately simulate the characteristics of surface spectral albedo. Therefore, further studies can be done in the future to enhance the model and incorporate more complex situations.

4. Conclusions and discussion

In order to explore the relationship between soil moisture, solar altitude and surface spectral albedo, a continuous experiment was conducted for one year, and a total of 17 520 samples across a whole year during 2017–2018 were obtained. The experiment not only helped delineate the influence factors of surface albedo in arid areas, but also supported the improvement of land surface parameterizations of climate models. The main conclusions are as follows:

(1) The observed annual mean surface albedo of GR, UV, VIS and NIR is about 0.25, 0.11, 0.24 and 0.25, respectively, in arid areas. The standard deviation of these values is 0.01, 0.04, 0.03 and 0.02, respectively. The diurnal variation curve of surface spectral albedo is roughly u-shaped except for UV. Our results differ from the land surface parameterization in climate models. There is still
room for improvement of the model, especially in arid areas.

(2) Surface spectral albedo is affected greatly by soil moisture. A significant negative linear correlation between surface albedo and soil moisture was identified, with the correlation coefficients between GR, UV, VIS, NIR and soil moisture being $-0.68$, $-0.75$, $-0.70$ and $-0.61$. Shorter wavelengths correspond to stronger correlations between the surface albedo and soil moisture. This indicates that surface albedo of shorter wavelength in solar radiation is more sensitive to soil moisture. There is an exponential relationship between surface albedo and solar altitude. The exponential regression coefficients of the surface albedos of GR, UV, VIS and NIR and solar altitude are $-0.21$, $-0.077$, $-0.53$ and $-0.21$, respectively. The surface albedo of UV in arid areas is hardly affected by solar altitude.

(3) According to our observations and analysis, a new two-factor parametric formula of soil moisture and solar altitude to surface spectral albedo is obtained. Our simulation using the formula aligns well with the observation data, although further improvement is still needed because the experiment could not completely exclude the influence of meteorological and environmental factors.

Arid areas account for about 30% of the Earth’s land, with the Gobi underlying surface being one of the major underlying surfaces in arid areas. The radiation data observed at the Dunhuang Station are representative of the region and can represent a large arid area in Northwest China (Li 2009). There is a special response process to solar radiation in arid areas. Due to the scarcity of precipitation and extremely low soil moisture, the diurnal variation of surface albedo in this region is less dependent on the diurnal variation of soil moisture, but is closely related to the variation of solar altitude.

In recent years, studies by Paltridge and Platt (1981), Briegleb et al (1986), Schaf et al (2002), Wang et al (2005), Roxy et al (2010), and Li et al (2019) have explored the relationship between surface albedo, solar altitude and soil moisture. The main conclusion is that surface albedo has a typical exponential relationship with solar altitude, and a linear relationship with soil moisture. The conclusions obtained in this paper are consistent with their conclusions, but the coefficients are different due to the different climatic zones and underlying surfaces. The innovation of this paper is that we focus on the study of surface albedo of different wavelengths. There are few studies on surface spectral albedo and almost no studies on the impact factors of surface spectral albedo. In different research fields, it is necessary not only to know the global radiation, but also to further understand solar spectral radiation characteristics. Therefore, the study of solar spectral radiation can provide a theoretical basis for different research fields. Furthermore, our study establishes a baseline for the development of land surface parameterizations of models, and helps proper application of solar spectral radiation.

Nevertheless, this study also has some limitations. For example, cloud cover, precipitation and snow cover are present during the experiment, despite the exclusion of relevant data, and their effect on surface spectral albedo cannot be completely eliminated, which may affect the analysis results. It is of great significance to further study the contribution of such factors to solar spectral albedo. The underlying surface of
our experiment was the Gobi. Although Dunhuang Station can represent a large arid area in Northwest China, we need to think about the difference between other soil textures in arid areas and Dunhuang. The influence of the different soil textures (sandy soil, clay and loam) on the surface spectral albedo is also of great significance to study. In the future, we will also try to improve the land surface parameterization in climate models.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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