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A Study on Parameterization of Surface Albedo over Grassland Surface in the Northern Tibetan Plateau

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ABSTRACT

The relationship of surface albedo with the solar altitude angle and soil moisture is analyzed based on two-year (January 2002 to December 2003) observational data from the AWS (Automatic Weather Station) at MS3478 in the northern Tibetan Plateau during the experimental period of CEOP/CAMP-Tibet (Coordinated Enhanced Observing Period Asia-Australia Monsoon Project on the Tibetan Plateau). As a double-variable (solar altitude angle and soil moisture) function, surface albedo varies inconspicuously with any single factor. By using the method of approximately separating the double-variable function into two, one-factor functions (product and addition), the relationship of albedo with these two factors presents much better. The product and additional empirical formulae of albedo are then preliminarily fitted based on long-term experimental data. By comparison with observed values, it is found that the parameterization formulae fitted by using observational data are mostly reliable and their correlation coefficients are both over 0.6. The empirical formulae of albedo though, for the northern Tibetan Plateau, need to be tested by much more representative observational data with the help of numerical models and the retrieval of remote sensing data. It is practical until it is changed into effective parameterization formulae representing a grid scale in models.

Key words: Tibetan Plateau, surface albedo, parameterization, solar altitude angle, soil moisture

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1. Introduction

The interactions of air, land, and sea have attracted more and more attention with the proposition of the Earth Science System leading to mainly global changes and climate anomalies. The earth's surface is a main boundary with a physical significance from which the energy is input to the air (Avissar and Pielke, 1991). Land surface is not only one of the main parts but also the most complex part of the earth's surface. Besides the thermal difference related to the heat and water storage abilities of soil and sea water, there is a great difference between heat and water transfer from the land surface to air due to the heterogeneity of soil, vegetation, and gradients on the land surface. The study of land-air interaction has already become a popular topic with the development of the global climate change study. Dickinson (1995) especially pointed out that land surface processes (LSP) and four-dimensional data assimilation are probably the two most important aspects to improve the models' simulating ability, but as to models' physical mechanism, the former is much more important.

According to Trenberth's (1993) definition, LSP are all processes that occur on the land surface and control the exchange of water, heat, and momentum between the land surface and the atmosphere, such as thermal, hydrographic, and biologic processes. These exchange processes take place at or near the land surface and couple with the atmospheric boundary layer

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to achieve the exchanges of energy and matter between the free atmosphere and the lower atmosphere. Ways to describe and calculate the surface physical parameters objectively and accurately in land surface models is a main reason to develop and perfect these models. It is important to understand LSP and determine LSP parameters through field observational experiments. So far, a few large experiments have been carried out in the world to study land-air interactions, for example, HAPEX-MOBILHY (Andre, 1988), FIFE (Sellers et al., 1988), NOPEX (Lundin and Halldin, 1994a,b), EFEDA (Bolle et al., 1993), etc. There are also numerous LSP experiments carried out in China, such as HEIFE (The core working group of the HEIFE, 1991), TIPEX (Zhou et al., 2000), IMGRASS (Lu, 1997), GAME/Tibet (Hu et al., 1998), and CEOP/CAMP-Tibet, which is the data source for this study. The details of CEOP/CAMP-Tibet will be described later. These experiments or projects have made great contributions to the study of LSP.

Many land surface parameters in LSP models, such as the surface albedo, soil heat conductivity, and the roughness length are expressed by using parameterizations. Henderson's Research (Henderson-Sellers et al., 1993) shows that imperfect parameterization schemes in atmospheric LSP models can cause a remarkably inaccurate estimation of surface fluxes. The mass and energy exchange between land and air is affected by the land surface properties, which follow the laws of conservation of mass and energy. Therefore, it is important to describe physical parameters of the land surface in a parameterization scheme and present the land surface processes to the most extent. The surface albedo is one of the most important parameters to reflect the land surface characteristics. Charney et al. (1977) thought that the increase of surface albedo could bring the decrease of the radiant flux traveling from the ground surface and therefore reduce the convective cloud and precipitation. Liu and Ma (1996) also pointed out that the surface albedo of the Tibetan Plateau was one of the important factors to influence short-term climate change in China. They also found that a higher surface albedo could weaken the summer monsoons of East Asia and the Tibetan Plateau. Sensitivity tests show that SSiB (Simplified Simple Biosphere model) is sensitive to some surface parameters like albedo. It should be noted that these parameters must be observed correctly and defined exactly, while continuing to work to improve the veracity of some parameters in the models (Zhu et al., 2006). Albedo parameterization schemes in most LSP models have already, to some extent, taken account of snow cover, the solar altitude angle, soil moisture et al. For the albedo scheme of the Biosphere-Atmosphere Transfer Scheme (BATS), soil is divided into 12 types of particle size and 8 classes of color; albedo varies with each soil texture and color (Dickinson et al., 1993). The impact of the solar altitude angle on albedo is roughly considered in the Simple Biosphere Model (SiB). In this model, it selects some empirical values of soil moisture based on soil color (Sellers et al., 1986). The Noah Land-Surface Model (LSM) provides monthly values of the surface albedo fraction (snow-free) and adds snow cover effects to the albedo (Bonan, 1996). The surface albedo is described by a direct or diffuse beam, for visible and near-infrared wavebands in the Community Land Model (CLM); the soil color determines a dry or saturated soil albedo. The overall direct beam and the diffuse ground albedo are weighted (Oleson et al., 2004). The land surface, however, is much more complex because these schemes are mostly applicable in finite regions, therefore making it necessary to further study the albedo scheme regarding the solar altitude angle and soil moisture (Yan et al., 1987).

The land-air interactions over the Tibetan Plateau are special compared with other regions. The area of the Tibetan Plateau is up to 2 million km^2 with an average elevation of 4–4.5 km. Its main body reaches up to the middle troposphere thus forming a special boundary layer there. The thermal and dynamic effects of the Tibetan Plateau gradually influence the free atmosphere through the ground layer and boundary layer (Ma et al., 2000, 2002). It is difficult to determine and describe the land surface physical parameters due to the lack of long observational data series and the complexity of the land surface properties on the Tibetan Plateau. Some authors have calculated the surface albedo on the Tibetan Plateau in some special weather conditions (e.g., clear sky) (Qian et al., 2003) or monthly/seasonal average values (Zhou et al., 2000; Ma, 2004; Li and Hu, 2006), but it is not enough to use them in LSP models. In this paper a parameterization formula of the surface albedo is set up using field data observed at a high-cold grassland in the northern Tibetan Plateau. It may provide some understanding of the surface albedo for parameterization schemes in LSP models at a grid scale.

2. Field observation site and data

"CEOP/CAMP-Tibet" [Coordinated Enhanced Observing Period (CEOP) Asia-Australia Monsoon Project (CAMP) in the Tibetan Plateau] is an international project cooperated with Chinese, Japanese and Korean scientists following "GAME/Tibet". Its scientific objectives aim at quantitatively understanding land-air interactions, further studying the meteorological-hydrographic cycle, developing LSP models, and establishing and verifying the method of using satellite data to calculate land surface parameters on the Tibetan Plateau. To reach the objectives, CEOP/CAMP-Tibet set up 9 observational sites in a mesoscale area of 150 km×200 km (30.5°–33°N, 91°–92.5°E) and in other regions along the Qinghai-Tibetan road. For further details of the experiment, refer to the description contained in Ma (2004). The data obtained at the MS3478 station from 2002 to 2003 are selected to study the parameterization of albedo for two reasons: (1) There are upward and downward solar shortwave radiation data as well as soil moisture data; (2) The length of the data series is longer than two years. These reasons, therefore, make it easy to set up and verify the fitting formula.

The MS3478 station is located at 31.93°N, 91.72°E with an altitude of 4620 m above sea level. The terrain near there is flat and wide-open. There are some hills about 5 km to the east, 30 km to the west, and 10 km to the south and north with relative heights of 100–200 m. The land surface is covered by short-grass about 15 cm high. The observational items include wind speed (10 m, 5 m, 1.0 m), wind direction (10 m), air temperature and relative humidity (8.2 m, 1.0 m), air pressure, precipitation, shortwave/longwave radiation (upward and downward), ground surface temperature, soil temperature (0 cm, −4 cm, −10 cm, −20 cm, −40 cm), soil moisture (−4 cm, −20 cm), soil heat flux (−10 cm, −20 cm), and snow depth.

The data in 2002 is used for fitting the formula and the data in 2003 is used for verifying the results in this paper.

3. Parameterization of surface albedo

Surface albedo is generally influenced by soil color, surface roughness length, soil moisture, solar altitude angle (Zhang et al., 2003), snow cover, and the presence of frozen soil (Sun and Jin, 1997), etc. Variation of soil color greatly changes the surface albedo. Black/white soil can absorb/reflect all the solar radiation in the visible spectrum and it corresponds to the smallest/largest albedo respectively. The color of real soil is usually grey but its albedo changes with its level of grey. However, the local soil color usually maintains the same grey level over time, so the variability of soil color is not considered as a factor in determination of the local surface albedo in this study.

Roughness length influences the albedo through forming a shaded area of solar radiation. Generally the bigger the roughness length is, the smaller the albedo. Furthermore, the influence of roughness length on the albedo varies with the sun angle. However, it is difficult to calculate the roughness length and its temporal variation accurately (Li et al., 2002b) because the value of roughness length and its diurnal and monthly variation are too small on the grassland of the Tibetan Plateau (Li et al., 2002a). Therefore the roughness length is also not considered in this study.

According to a previous study (Li and Hu, 2006), the value of the surface albedo at the MS3478 station is about 0.18 in summer and autumn and 0.22–0.23 in spring and winter, with an annual average around 0.20. The seasonal amplitude is approximately 0.04–0.05. It indicates that the albedo is higher in winter and spring than in other seasons due to the existence of snow cover and frozen soil. However, snow cover and frozen soil are inhomogeneous compared with the grassland surface. If these two factors are taken into account in one parameterization formula, the contribution of one factor relating to surface albedo would be confused by others.

The reflectivity of water is very small, and the water surrounding soil particles increases the absorbing path of sunlight, so the larger the soil moisture is, the smaller the albedo. Meanwhile, the soil moisture and the solar altitude angle not only have obvious diurnal variations but also remarkably influence the climate. Therefore, it is necessary to parameterize the surface albedo by using the solar altitude angle and the soil moisture to satisfy the physical requirements in LSP models.

Figure 1 shows the relationship of the surface albedo with its influencing factors of the solar altitude angle and the soil moisture at 4 cm depth. It is obvious that the relationship between the albedo and every single factor is not good. The correlation coefficients are only 0.293 and 0.393 respectively. The standard deviations of fitting curves reach 0.033 and 0.03 respectively. It is important to note, though, that this does not mean that the solar altitude angle and the soil moisture do not influence albedo, actually the albedo is impacted by these two factors simultaneously.

Generally, surface albedo can be expressed as

$$a = f(h_\theta, w_\mathrm{s}) , \tag{1}$$

f is an unknown function in the equation above, h_θ is the solar altitude angle, w_s is the soil moisture. Assume that h_θ and w_s are independent, then the formula (1) can be written as a product function:

$$a = f_1(h_\theta) \times f_2(w_\mathrm{s}) , \tag{2}$$

where both f_1 and f_2 are unknown functions.

3.1 *Fitting and verification of surface albedo and solar altitude angle*

The data processing is as follows:

(1) Select the data where the soil moisture at 4 cm

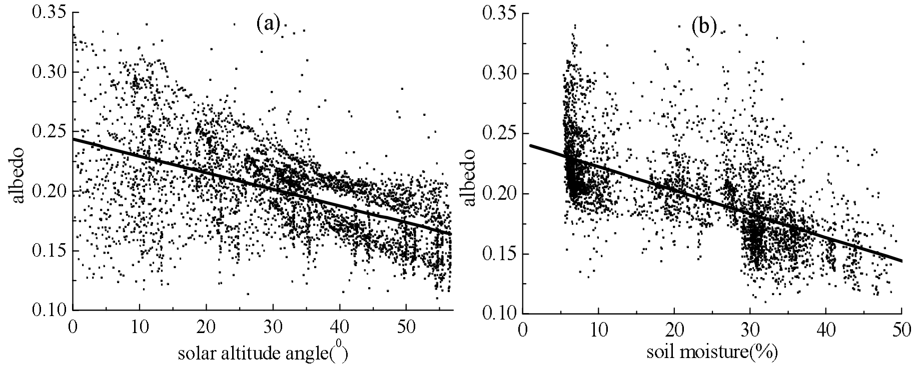

Fig. 1. Variation of surface albedo on the northern Tibetan Plateau with (a) solar altitude angle (degrees) and (b) soil moisture in the depth of 4 cm (% saturation).

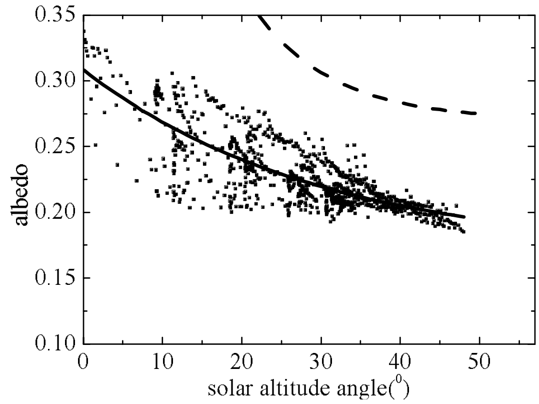

Fig. 2. Surface albedo as a function of solar altitude angle based on 990 samples of dry soil in 2002: the solid line shows the fitted curve of Eq. (4) and the dash line shows the Paltridge curve of Eq. (5).

depth is lower than approximately 8% (At the MS3478 station, the soil moisture is all greater than 5%). The soil should be approximately dry in order to decrease the impact of soil moisture on the surface albedo when fitting it with the solar altitude angle.

(2) Select data from 1000 to 1900 LST. A high measuring error of solar radiation at sunrise and sunset will make a wrong estimation of the albedo.

(3) Eliminate the data where the albedo increases rapidly. In this situation, it usually occurs when there is snow cover on the land surface.

The above data processes improve the relationship between the surface albedo and the solar altitude angle. The number of samples is 990 after the data is processed.

For dry soil, $w_{\rm s} = 0$. Eq. (2) can be expressed as

$$a_1 = f_2(0) \times f_1(h_\theta) = f_3(h_\theta)\,, \tag{3}$$

f_3 is also an unknown function. It reflects the variation of albedo with the solar altitude angle when the soil is dry. In Eq. (3), $f_2(0)$ is a constant coefficient of function $f_1(h_\theta)$, so Eq. (3) is actually a one-factor function.

Figure 2 shows the relationship of albedo with the solar altitude angle in the condition of dry soil. The albedo obviously decreases with the increase of the solar altitude angle. The correlation coefficient increases to 0.63 and the standard deviation decreases to 0.017. The fitted equation is as below:

$$a_1 = f_3(h_\theta) = 0.1684 + 0.1401e^{-0.0335\times h_\theta}\,. \tag{4}$$

An authoritative relational expression of albedo varying with the solar altitude angle was deduced by Paltridge et al. (1981). It was written as:

$$a = 0.27 + 0.73 \times e^{-0.1\times h_\theta}\,. \tag{5}$$

The dashed line in Fig. 2 is from Eq. (5) of Paltridge et al. (1981). It is much different from the solid line, depicting Eq. (4). The coefficients of Paltridge's formula were obtained when the roughness length and the soil moisture were not fixed. If using Paltridge's formula directly on the land surface of the northern Tibetan Plateau, there is a big deviation in the albedo. The coefficients should therefore be determined from situ observational data allowing the formula to approach the real situation much better.

In 2003, 1004 samples satisfying the request of dry soil were used to verify the Eq. (4). Figure 3 is the comparison of a calculated from the fitted exponential empirical formula (4) to the observed values $a_{\rm o}$. The correlation coefficient is 0.664 and the standard deviation is 0.012. It is obvious that the error caused by the empirical formula fitted from observational data is less than that caused by the Paltridge formula.

3.2 *Fitting of surface albedo and soil moisture*

In fact, the empirical formula (4) cannot be directly used to calculate the local surface albedo in LSP mod-

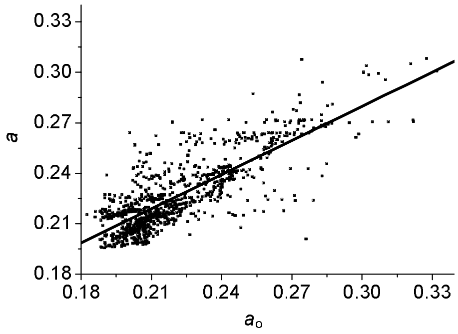

Fig. 3. Comparison of surface albedo a calculated from Eq. (4) and observed values a_o under dry soil conditions (1004 samples in 2003 used for verification).

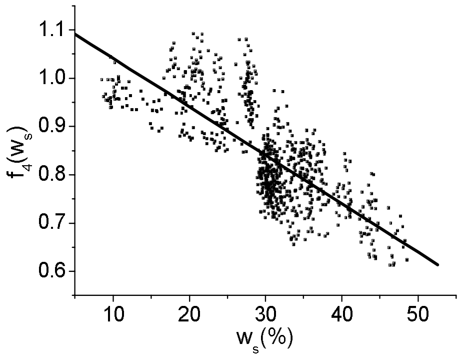

Fig. 4. Function $f_4(w_s)$ in Eqs. (7) and (8) as a function of soil moisture.

els before the influence of the soil moisture has been considered. Let Eq. (2) divided by Eq. (3):

$$\frac{a}{a_1}=\frac{f_1(h_\theta)\times f_2(w_s)}{f_2(0)\times f_1(h_\theta)}=\frac{f_2(w_s)}{f_2(0)}\ . \tag{6}$$

Also as:

$$\frac{a}{f_3(h_\theta)}=\frac{f_2(w_s)}{f_2(0)}=f_4(w_s)\ , \tag{7}$$

f_4 is an unknown function, but it is a one-factor function of soil moisture. f_3 is a known empirical function. a can be substituted by observed albedo. The relationship between the albedo and the soil moisture can be fitted.

The processing is as follows:

(1) Select data where the soil temperature at 4 cm depth is greater than 0°C to ensure the measurement accuracy of the soil moisture at this depth.

(2) Select data where the solar radiation is greater than 500 W m^{-2} in order to reduce the impact of clouds.

(3) Select data at noon (from 1200 to 1600 LST) to decrease the impact of the solar altitude angle.

(4) Eliminate the data where the albedo increases rapidly to avoid the influence of snow.

The number of samples is 806 after data processing. The fitting formula (the solid line in Fig. 4) is

$$f_4(w_s)=1.1417-0.01w_s\ . \tag{8}$$

The correlation coefficient for the fitted curve is 0.5696 and the standard deviation is 0.0686.

Inserting Eq. (8) into Eq. (7), the surface albedo can be described as

$$a=f_3(h_\theta)\times f_4(w_s)$$
$$=(0.1684+0.1401e^{-0.0335\times h_\theta})\times(1.1417-0.01w_s)\ . \tag{9}$$

Equation (9) is actually an empirical formula of albedo where the influence of the solar altitude angle and the soil moisture is multiplied together, making it a product relationship.

In addition, if the relationship of albedo with the solar altitude angle and the soil moisture is simply a superposition form, Eq. (1) can be reformed as:

$$a=f_5(h_\theta)+f_6(w_s)\ , \tag{10}$$

where both f_5 and f_6 are unknown functions. f_6 can be approximately assumed as a two order polynomial function:

$$f_6(w_s)=b_0+b_1\times w_s+b_2\times w_s^2\ , \tag{11}$$

where b_0, b_1, and b_2 are undetermined coefficients. Inserting Eq. (11) into Eq. (10):

$$a=f_5(h_\theta)+b_0+b_1\times w_s+b_2\times w_s^2\ . \tag{12}$$

If the soil is dry ($w_s=0$), Eq. (12) can be described as

$$a_2=f_5(h_\theta)+b_0=f_7(h_\theta)\ , \tag{13}$$

where $f_7(h_\theta)$ is an unknown function that expresses the variation of albedo as the solar altitude angle changes.

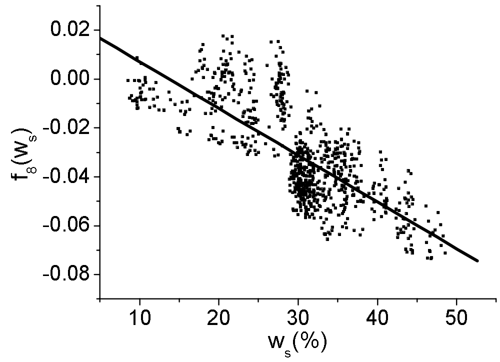

Fig. 5. Function $f_8(w_s)$ in Eqs. (15) and (16) as a function of soil moisture.

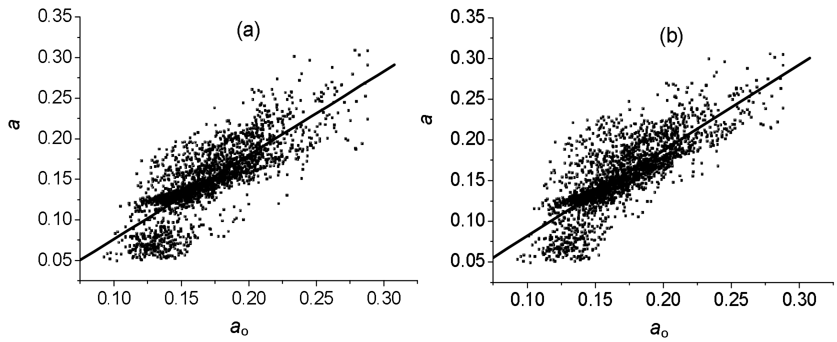

Fig. 6. Verification of (a) the product relationship Eq. (9) and (b) the addition relationship Eq. (17).

Select data in 2002 where the soil moisture in the depth of 4 cm is less than 8% to fit Eq. (13). The fitted curve is the same as Fig. 2. So:

$$f_7(h_\theta) = f_3(h_\theta)\ . \tag{14}$$

Inserting Eqs. (14) and (13) into Eq. (11), then

$$a - f_7(h_\theta) = b_1 \times w_\mathrm{s} + b_2 \times w_\mathrm{s}^2 = f_8(w_\mathrm{s})\ , \tag{15}$$

where $f_8(w_\mathrm{s})$ is an unknown function. Using 806 requested samples at the same time can fit the function $f_8(w_\mathrm{s})$. The relational expression of the fitted curve (shown in Fig. 5) is

$$f_8(w_\mathrm{s}) = 0.0263 - 0.0019w_\mathrm{s}\ . \tag{16}$$

The correlation coefficient is 0.5571 and standard deviation is 0.0134.

Inserting Eq. (16) into Eq. (15), the albedo can then be described as

$$a = 0.1947 - 0.0019w_\mathrm{s} + 0.1401e^{-0.0335\times h_\theta}\ . \tag{17}$$

Equation (17) is another empirical formula of the albedo. The influences of two, one-factor functions, the solar altitude angle and the soil moisture are added together, making it an addition relationship.

4. Verification of multiple-factorial parameterization formulae of surface albedo

2413 samples from January to December 2003 were used to verify the two fitted formulae (9) and (17). Figures 6a and 6b correspond to Eqs. (9) and (17), respectively. The correlation coefficients/standard deviations are 0.6377/0.0252 and 0.6286/0.0262 respectively. Both of them are fit to parameterize the surface albedo in the Tibetan Plateau. The product relationship though fits a little better compared to the addition relationship. It is possible that there is some interaction between the two influencing factors on albedo selected in this study. Perhaps the addition formula does not express it well.

5. Conclusions

Two-year observational data from 2002 to 2003 measured at the MS3478 station in the northern Tibetan Plateau is used to study and parameterize the local surface albedo. There are enough data samples to ensure the reliability of the research results and ability of the parameterization in all climate conditions. This study is a little different compared with similar studies (Bian et al., 2001; Zhao and Chen, 2000).

As a double-variable (solar altitude angle and soil moisture) function, the surface albedo varies inconspicuously with either factor. By using the method of approximately separating the double-variable function into two, one-factor functions (product and addition), the relationships of albedo with the solar altitude angle and the soil moisture are presented much better. The product and addition empirical formulae of albedo are also fitted. These two expressions are virtually equivalent, although there are quite different shapes between them.

The empirical formulae of albedo need further verification and improvement at other locations throughout the Tibetan Plateau. They also need to be tested in LSP models and with the retrieval of satellite data. It is only time before they are introduced into parameterization schemes at a grid scale in numerical models.

Although two empirical formulae are formed through this study, they are different from former expressions in form and degree. It indicates that a parameterization scheme suitable at other places cannot represent the land surface parameters on the northern Tibetan Plateau well; on the other hand, it is difficult to determine the surface physical parameters accurately.

For the parameterization formula in this paper only the impacts of the solar altitude angle and the soil moisture are considered on albedo. It is not a perfect scheme, however. More factors (such as roughness length, snow cover and frozen soil etc.) should be involved in further studies on the parameterization of the surface albedo over grassland surface in the northern Tibetan Plateau.

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