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Key Points:
- Observed surface albedo over the Tibetan Plateau (TP) has significant weekly scale fluctuations during winter
- Snow cover fraction and snow depth jointly dominate observed rapid changes of surface albedo over the TP
- Excessive snow amount and empirical snow cover fraction schemes lead to spatially divergent bias of surface albedo change

Supporting Information:
Supporting Information may be found in the online version of this article.

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Instant Response of Tibetan Plateau Surface Albedo to Snow Coverage and Depth in Snow Season

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Abstract Tibetan Plateau (TP) snow cover is featured by sub-seasonal changes, affecting weather and climate in surrounding and downstream areas. Previous studies emphasize the effect of background atmospheric circulation on rapid changes of TP snow cover as a whole. However, spatial discrepant changes of snow cover over the TP with complex topography and uneven snowfall remain unaddressed. Our research indicates that snow cover fraction dominates the rapid changes of surface albedo across the TP, and snow depth also significantly influences surface albedo changes through modulating snow albedo in central and eastern TP with shallow snow. However, the excessive snow amount and empirical snow cover fraction schemes introduce spatially divergent biases of surface albedo changes in simulations. Our research highlights the instant response of TP surface albedo to both snow coverage and depth in snow season, and provides a promising perspective for improving TP snow and surface albedo simulations.

Plain Language Summary Tibetan Plateau (TP) snow cover is characterized not only by obvious seasonal changes, but also by rapid sub-seasonal changes, which has a significant impact on the weather and climate of the downstream areas by affecting the surface albedo over the TP. Previous studies have generally concluded that the background atmospheric circulation dominates rapid changes of overall TP snow cover. However, rapid changes of snow cover exhibit spatial discrepancies over the TP with complex topography and uneven snowfall. Our study finds that snow coverage and depth both contribute to rapid changes of surface albedo and energy budget over the TP, which further lead to rapid changes of snow cover. However, current numerical models tend to overestimate the snow and fail to simulate spatial different changes of snow coverage and depth, leading to spatially divergent simulation biases in surface albedo, surface energy balance and local atmospheric circulation over the TP. Therefore, there is an urgent need to improve the snow parameterization in models to enhance the intra-seasonal simulation of snow cover and surface albedo over the TP.

1. Introduction

Extensive seasonal snow covers the Tibetan Plateau (TP), exerting a significant influence on the weather and climate in surrounding and downstream regions (Jia et al., 2021; Qin et al., 2006; Wu & Qian, 2003; You et al., 2020; Zhao & Moore, 2004). Recent investigations have revealed evident intra-seasonal variations in snow cover across the central and eastern TP (Che et al., 2019; Li et al., 2018, 2020; Pu et al., 2007; Song et al., 2019). Previous work further indicates that the intra-seasonal variation in TP snow cover (TPSC) has unneglectable impacts on surface albedo and surface energy budget, thereby shaping circulation systems in East Asia, including the Westerly Jet Stream and East Asia trough (Li et al., 2021).

The intra-seasonal variation of TPSC is governed by local air temperature, precipitation, and water vapor transport, modulated by intra-seasonal oscillations of large-scale circulation, including the tropical low-frequency oscillation Madden-Julian Oscillation and mid-latitude atmospheric circulation (Li et al., 2016; Song et al., 2019). However, recent researches mainly focus on the influence of background atmospheric circulation on the rapid change of TPSC as a whole, leaving the spatial discrepancies in observed rapid changes of snow cover over the TP with complex topography and uneven snowfall unaddressed.

During snow seasons, changes of TPSC can cause rapid changes of surface albedo, which affect the surface energy budget and ultimately acts back on the TPSC itself. Over the TP, the complex topography exerts a significant influence on the distribution of snow cover, resulting in spatially heterogeneous variations in TPSC (Miao et al., 2022). In the mountainous areas of TP, the snow is deep, extensive, and stable. Conversely, in central and eastern TP, the widespread shallow snow has a short duration due to its relatively low albedo (Flanner & Zender, 2005; Liu et al., 2021, 2022; Wang et al., 2020). In addition, the existence of light-absorbing aerosols in snow can also lead to reduced albedo and accelerated snowmelt (Gul et al., 2021; Lee et al., 2017; Li et al., 2022; Roychoudhury et al., 2022). These researches indicate that snow elements that dominate changes of surface albedo may differ in different regions of the TP, and the influence of snow depth (SD) cannot be ignored.

In this study, we employ remote sensing data to map the weekly variation of TP surface albedo. We assess the relative contribution of snow cover fraction and SD to the rapid change of TP surface albedo in observations and regional climate simulations. Furthermore, we discuss the underlying mechanism of rapid changes of TPSC and the correlation between SD, snow cover fraction, and surface albedo.

2. Data and Methods

2.1. Data and Model

To investigate the weekly change of surface albedo over the TP, we analyzed the 8-day surface albedo data of Global Land Surface Satellite products (Liang et al., 2020). A 500 m daily cloudless snow cover fraction data set (Tang et al., 2013) and a 0.05° daily SD data set (Yan et al., 2021) from the National Tibetan Plateau Data Center were used to examine the characteristics of snow cover fraction and SD over the TP (Text S1 in Supporting Information S1).

Furthermore, we conducted the Weather Research and Forecasting (WRF) Model simulations from December 2011 to May 2012 to investigate the influence of snow cover fraction and SD on the rapid change of surface albedo over the TP (see Figure S1 and Table S1 in Supporting Information S1 for details about WRF simulations). We chose SSiB (Simplified Simple Biosphere model; Xue et al., 1991) as the land surface scheme and conducted two sets of comparative experiments NY07TR and EXP based on different snow cover fraction schemes.

2.2. Surface Albedo Calculation in Land Surface Models

In current climate models and land surface models, surface albedo is primarily derived through the area-weighted average of individual component albedos. Taking the equation of surface albedo in the land surface model SSiB3 (Simplified Simple Biosphere model version 3; Sun & Xue, 2001) as an example (Equations 1 and 2), the surface albedo (α_{surface}) is calculated by the weighted average of the albedo of vegetated and non-vegetated areas (Equation 1). *vcover* is the vegetation cover fraction, and α_{canopy} is the canopy albedo. The albedo for the non-vegetated area corresponds to the ground albedo (α_{ground}), which is obtained by combining the albedo of snow-covered and snow-free areas (Equation 2). Therefore, snow greatly influences α_{surface} through α_{canopy} and α_{ground}. However, during snow season, the vegetation (mainly grassland and meadow) over the TP is sparse and short, and there are spatial differences between snow and vegetation (Figure S2 in Supporting Information S1), resulting in a limited contribution of vegetation to α_{surface}.

$$\alpha_{\text{surface}} = vcover \cdot \alpha_{\text{canopy}} + (1 - vcover) \cdot \alpha_{\text{ground}} \tag{1}$$

$$\alpha_{\text{ground}} = SCF \cdot SA + (1 - SCF) \cdot \alpha_{\text{soil}} \tag{2}$$

$$\alpha_{\text{ground}} = \alpha_{\text{soil}} + SCF \bullet (SA - \alpha_{\text{soil}}) \tag{3}$$

Equation 3 is a variant of Equation 2, which indicates that α_{ground} is governed by soil albedo (α_{soil}), snow cover fraction (SCF) and snow albedo (SA). Considering the complexity of α_{soil} changes, especially with frozen soils prevailing over the TP during snow season, we exclude them from our study. Consequently, we mainly focus on the effect of snow on α_{ground}.

2.3. Shallow Snow Albedo

Changes of snow albedo play a crucial role in the snow melting process and snow area changes (Budyko, 1969; Qu & Hall, 2007; Xue et al., 2003; Yang et al., 2001). A previous study highlighted that the albedo of shallow snow is far less than 0.8 (thick snow albedo value) (Giddings & LaChapelle, 1961). However, many current land surface models still adopt fixed values for snow albedo (Chen et al., 1996; Dai et al., 2003; Dickinson et al., 1993; Sellers et al., 1996), leading to significant biases in simulating surface energy balance.

To address this issue, the Snow and Ice Aerosol Radiation (SNICAR) model; Flanner et al., 2021; Flanner & Zender, 2005, 2006) was developed to accurately simulate snow radiative properties based on snow grain size and aerosols in snow. Based on the SNICAR model, a previous study developed a novel shallow snow albedo scheme, effectively reducing the simulation biases of snow cover over the TP (Wang et al., 2020). Similarly, another study introduced a SD factor to the default snow albedo scheme to account for the unique radiative properties of shallow snow over the TP (Liu et al., 2021, 2022). In this paper, we will refer to the above two studies to calculate the shallow snow albedo over the TP in observations and simulations.

2.4. Rapid Change of Surface Albedo

To characterize the rapid changes of snow and α_{surface}, we use the absolute change of elements (x) between adjacent time steps (t and t-1) as the indicator (Equation 4).

$$|\Delta x_t| = |x_t - x_{t-1}| \tag{4}$$

During snow season, the α_{surface} (or α_{ground}) change over the TP is dominated by snow without considering vegetation and soil changes. In Equation 3, SA-α_{soil} is the increase in albedo compared to soil albedo due to the presence of snow. Previous studies have shown that this increase in albedo is proportional to SD until the SD reaches a certain value, for example, 4 cm (Wang et al., 2020). Therefore, we introduce a new variable, the change of SD below 4 cm (SD_4) to represent the changes of SA-α_{soil}. In order to quantify the contribution of different snow elements, we simply assume SD_4 and SA-α_{soil} to be linearly correlated. The α_{soil} is set to 0.19 when there is no snow, and the snow albedo is set to 0.79 when the SD is greater than 4 cm (Liu et al., 2021, 2022), therefore the relationship between SA-α_{soil} and SD_4 can be presented as:

$$SA - \alpha_{\text{soil}} = \frac{0.79 - 0.19}{4} \cdot SD_4 = 0.15 \cdot SD_4 \tag{5}$$

According to above assumptions, the rapid changes of ground albedo can be split into two terms as Equation 6, term SCF ($0.15 \cdot \Delta SCF_t \cdot \frac{(SD_4)_{t-1} + (SD_4)_t}{2}$, the SCF-dominated ground albedo change) and term SD_4 ($0.15 \cdot \Delta (SD_4)_t \cdot \frac{SCF_{t-1} + SCF_t}{2}$, the SD_4-dominated ground albedo change). We will compare the relative contributions of SCF and SD_4 to ground albedo based on these two terms.

$$\begin{aligned} \Delta\left(\alpha_{\text{ground}}\right)_t &= 0.15 \cdot \Delta (SCF \cdot SD_4)_t \\ &= 0.15 \cdot SCF_{t-1} \cdot \Delta (SD_4)_t + 0.15 \cdot \Delta SCF_t \cdot (SD_4)_{t-1} + 0.15 \cdot \Delta SCF_t \cdot \Delta (SD_4)_t \\ &= 0.15 \cdot \Delta SCF_t \cdot \frac{(SD_4)_{t-1} + (SD_4)_t}{2} + 0.15 \cdot \Delta (SD_4)_t \cdot \frac{SCF_{t-1} + SCF_t}{2} \end{aligned} \tag{6}$$

3. Results

3.1. Rapid Changes of TP Winter Surface Albedo

Surface albedo is a key variable in surface energy balance and budget, and it is also sensitive to changes of snow cover. We first investigate the rapid change of surface albedo over the TP. Figure 1c shows the regional mean 8-day rapid variations of TP surface albedo from 2011 to 2015. We observe that TP surface albedo undergoes rapid changes during snow season (September to the following May). In autumn/spring, monotonic increases/decreases of TP surface albedo are correlated with snow accumulation/melting processes (Figure S3 in Supporting Information S1). However, the TP surface albedo exhibits distinct fluctuations in winter, with a maximum 8-day increase of 0.070 and a maximum 8-day decrease of 0.064 recorded in January 2012. To examine the spatial heterogeneity of these rapid changes of TP surface albedo, we divide the TP region into three sub-regions based on the topography and snow distribution (Figure 1d). The magnitude of winter surface albedo variation is slightly greater in the Qiangtang Plateau (QT) and eastern TP (ETP) than in the southeastern TP (SETP).

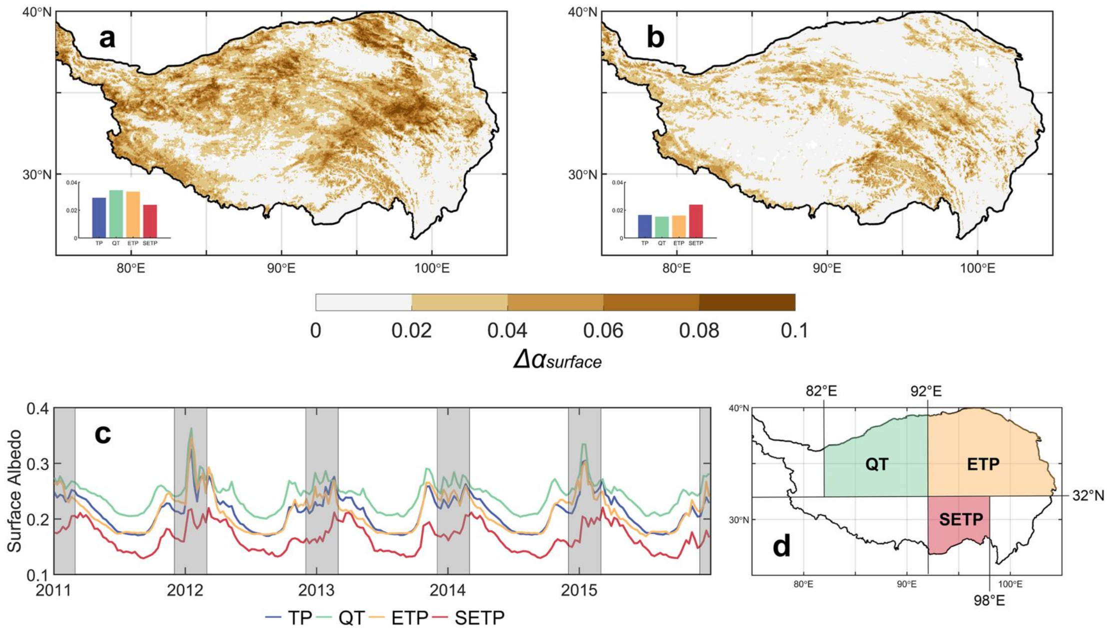

Figure 1. Weekly changes of surface albedo over the Tibetan Plateau (TP). (a) Multiyear (2011–2015) winter mean absolute 8-day change of surface albedo over the TP. (b) Same as (a) but in spring. The regional mean values of (a and b) are in the lower left corner of the figures. (c) Regional mean 8-day change of surface albedo over the TP (2011–2015). The shade indicates the boreal winter. (d) Division of the three sub-regions (Qiangtang Plateau, eastern TP, southeastern TP).

To quantify the rapid change of TP surface albedo, we employ the mean absolute change as a measurement index (see Section 2.4). Figures 1a and 1b show the spatial pattern of the mean absolute 8-day change of surface albedo ($|\Delta\alpha_{\mathrm{Surface}}|$) over the TP during winter and spring, respectively. Obviously, the $|\Delta\alpha_{\mathrm{Surface}}|$ in winter (0.029 for regional mean) is larger than that in spring (0.017 for regional mean). In spring, rapid changes of surface albedo occur mainly in the southeastern and western TP, where large areas of thick snow are also distributed (Figures S4b and S4c in Supporting Information S1). Accelerated snowmelt may contribute to the rapid decrease in surface albedo. However, the distribution of surface albedo change in winter exhibits a distinctive spatial pattern compared to its seasonal mean (Figure S4a in Supporting Information S1). Large $|\Delta\alpha_{\mathrm{Surface}}|$ occurs in the QT (0.034), ETP (0.033) and SETP (0.024). Besides, in most areas of southwestern TP (Himalayas), $|\Delta\alpha_{\mathrm{Surface}}|$ is greater than 0.02, or even beyond 0.04. As a whole, the winter surface albedo is characterized by rapid weekly fluctuations across the TP.

3.2. Influence of Snow Depth on Rapid Changes of Surface Albedo

Extensive seasonal snow covers the TP during winter (Figure S4 in Supporting Information S1), which is highly likely to affect fluctuations in surface albedo. Here we use a commonly employed algorithm for surface albedo in land surface models to illustrate the relationship between variations in surface albedo and snow cover (see Sections 2.2 and 2.4).

We first show the 8-day changes of winter SCF. Figure 2a demonstrates a notable and rapid variation in SCF during winter, with a regional mean change of 5.50%. Moreover, the spatial distribution of SCF exhibits a similarity to that of surface albedo, as indicated by a spatial correlation coefficient of 0.71. However, we note that the winter mean SD in the QT (1.09 cm) is much lower than the TP average (2.52 cm), which indicates the presence of extensive areas with unstable shallow snow in the QT. The snow albedo increases with SD, and the widely distributed shallow snow over the TP exhibits lower albedo than thick snow. Therefore, the observed rapid changes of surface albedo cannot be fully explained by SCF alone, especially in the areas with shallow snow.

During winter, over half of the SD across the TP are below 4 cm, and SD remains below 4 cm for the majority of time in the QT region (Figure 2e). Observations indicate that the probability of occurrence of shallow snow over the TP is 0.275 in winter, which is 0.693 during the days with snow (Figure S5 in Supporting Information S1).

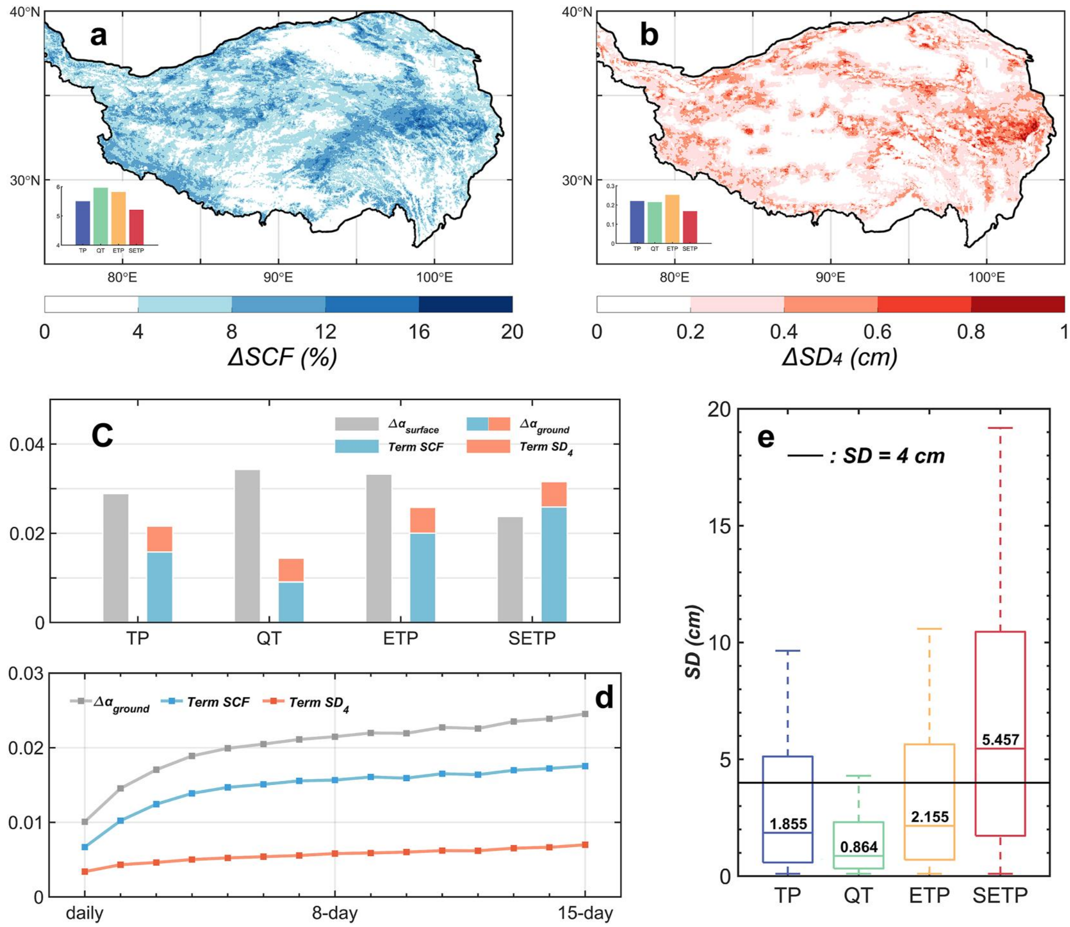

Figure 2. Weekly changes of winter snow cover over the Tibetan Plateau (TP). (a) Multiyear (2011–2015) winter mean absolute 8-day change of snow cover fraction (SCF) over the TP. (b) Same as (a) but for snow depth with a 4 cm limitation (SD_4). The regional mean values are in the lower left corner of (a and b). (c) Rapid variation of regional mean winter $\alpha_{surface}$, α_{ground}, Term SCF and Term SD_4 over the TP. (d) Changes of rapid variation of α_{ground}, Term SCF and Term SD_4 with temporal resolution. (e) Distribution of snow depth in different regions. The upper and lower bottoms of the boxes are the upper quartile and lower quartile, respectively, and the middle line and number are the median. The maximum whisker length is specified as 1.5 times the interquartile difference.

Here we introduce a new variable SD_4 as a simplified indicator of SA variations (Section 2.4). SD_4 exhibits notable and rapid fluctuations (0.22 cm) with distinct spatial patterns compared to SCF (Figure 2b). Specifically, the large values of ΔSD_4 are concentrated in the eastern and northwestern TP, while SCF contributes more to rapid changes of surface albedo in the southeastern TP.

We further compare the contributions of SCF and SD_4 to ground albedo changes. Figure 2c reveals that the calculated ground albedo changes (0.022 for the whole TP) are closed to that of observed surface albedo (0.029 for the whole TP), except for the QT region, which may result from the improper representation of "snow albedo-SD_4" relationship or the ignorance of soil albedo changes. Term SCF contributes more to the rapid changes of ground albedo (0.016), especially in the SETP. Meanwhile, Term SD_4 exhibits a comparable magnitude with little spatial heterogeneity (0.006), albeit smaller than Term SCF. Moreover, Term SD_4 maintains a remarkable effect on the rapid change of ground albedo on a daily to biweekly scale, with the most pronounced influence observed at daily scale (Figure 2d).

Hence, the observations strongly suggest that snow cover fraction governs the rapid change of TP surface albedo during winter, and the contribution of snow depth is also remarkable, especially in the central and eastern TP with large areas of shallow snow.

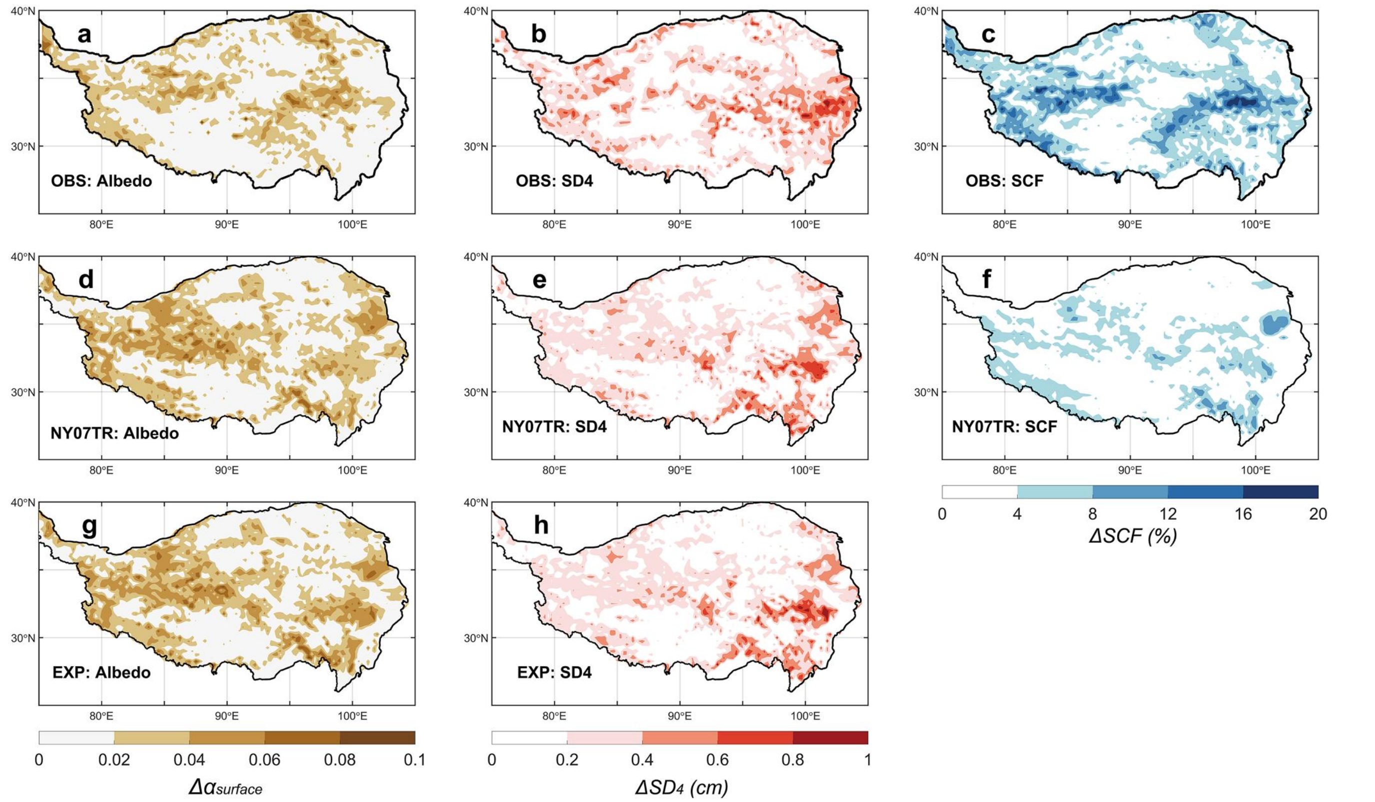

Figure 3. Weather Research and Forecasting-simulated 8-day changes of winter surface albedo, SD_4 and snow cover fraction (SCF) over the Tibetan Plateau in the winter of 2011–2012 (a–c) The observed rapid change of surface albedo, SD_4 and SCF, respectively (d–f) Same as (a–c) but for the NY07TR experiment (g–h) Same as (a–b) but for the EXP experiment.

3.3. Simulated Rapid Changes of Surface Albedo

To further assess the impact of snow on the variation in TP surface albedo in simulations, we conduct two additional WRF experiments in the winter of 2011–2012. Overall, the control experiment NY07TR accurately captures the observed 8-day changes of winter SD_4 over the TP, although there is an underestimation in the central TP (Figure 3d–3f). Notably, the simulated SCF 8-day change (2.55%) is largely underestimated compared to the observation (4.41%). In comparison with the mean (Figure S6 in Supporting Information S1), the underestimation of SCF changes may result from the excessive simulated snow cover (SD_4 reaches 4 cm, SCF reaches 100%) in the central and eastern TP. The smaller SCF changes lead to underestimated surface albedo changes in the eastern TP where covers the stable snow. However, in the central TP, the excessive snow amount amplifies the albedo changes in shallow snow areas. Eventually, the excessive simulated snow brings an opposite bias in surface albedo change in the central and eastern TP.

Furthermore, the ratio of term SCF to term SD_4 is 2.6 compared to 3.0 of observation, which suggests that the underestimated SCF leads to a larger contribution of SD_4 to ground albedo changes. To better represent the effect of SD_4 on rapid changes of surface albedo, we set SCF to a constant value of 1 (or 100%) to remove its variability (EXP experiment). Surprisingly, the increased SCF only causes a slight increase of mean and change of simulated surface albedo and SD_4 in the eastern TP compared to the NY07TR experiment (Figure 3h and Figure S6 in Supporting Information S1), which may result from consistent spatial distribution of SCF and SD_4 changes. The spatial correlation coefficient for the changes of SCF and SD_4 is 0.62, while it is 0.92 for their means. However, the SCF and SD_4 in observations are spatially differentially distributed with a spatial correlation coefficient of 0.30 for the changes and 0.67 for the means.

In summary, compared to observations, excessive simulated snow results in underestimated snow variations, especially SCF, and consequently a spatially divergent bias in surface albedo change and an increased

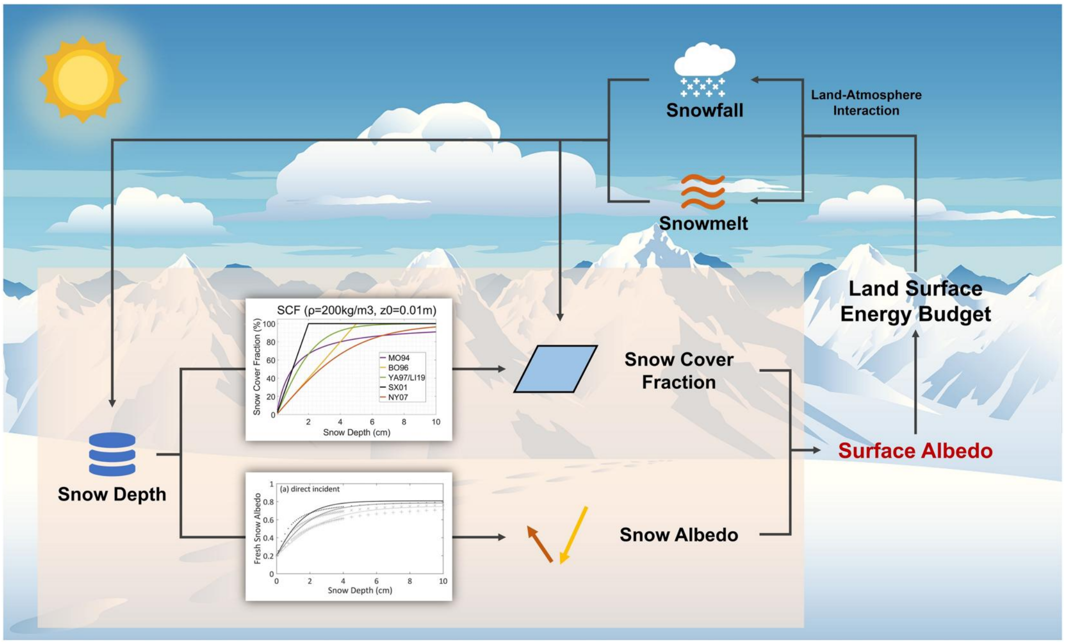

Figure 4. Schematic diagram of the correlation between snow depth, snow cover fraction, and snow albedo. The light orange area is the focus of our attention, where the two sub-graphs present the "snow cover fraction-snow depth" (upper sub-graph) and "snow albedo-snow depth" (lower sub-graph) relationships in models from previous studies.

contribution of SD_4 to ground albedo changes. Besides, the SD_4 and SCF show a highly consistent spatial distribution, which may also cause uncertainties in simulating surface albedo changes.

4. Summary and Discussion

This study reveals the rapid change of TP surface albedo during winter using satellite observations, which presents in most areas of the TP. We emphasize the joint influence of snow cover fraction and snow depth on the rapid change of TP surface albedo. However, the excessive snow amount and consistent spatial variations of snow cover fraction and snow depth in simulations introduce spatially divergent biases in surface albedo changes and amplify the contribution of snow depth to ground albedo.

Both snow cover fraction and snow albedo play crucial roles in driving changes of surface albedo and energy budget, which subsequently influences snowfall and snowmelt through land-atmosphere interactions (Figure 4). Over the TP, the rapid changes of snow may result from the combination of infrequent snowfall events and accelerated snowmelt. First, the intra-seasonal variations of atmospheric circulation modulate the water vapor transport from South and Central Asia, which in turn affects the snowfall over the TP (Song et al., 2019). Second, the widespread shallow snow over the TP has a low albedo, and it will be further reduced by the aerosol and dust in snow and snow aging (Roychoudhury et al., 2022; Sarangi et al., 2020; Zhang et al., 2018). The low snow albedo brings accelerated snowmelt through "snow-albedo" positive feedback, and this is the main pathway that snow depth affects surface albedo changes. Third, the complex topography and strong wind over the TP can lead to non-uniform snowfall distribution, snow blowing and south-slope preferential snowmelt, thereby non-uniform sub-grid distribution of snow cover and possible rapid changes of snow cover fraction (Miao et al., 2022; Mott et al., 2018; Xie et al., 2019). In summary, snow depth (or snow albedo) and snow cover fraction jointly dominate the rapid changes of TP snow through "snow-albedo" feedback, which is the underlying mechanism of rapid changes in snow over the TP.

Furthermore, the WRF simulation results in this work show that the simulated surface albedo, snow cover fraction (SCF), and snow depth (SD) display consistent spatial variations over the TP (Figure 3), which does not match the observed spatially heterogeneous distributions of SCF and SD. We attribute this discrepancy to a model error induced by presenting the correlation between snow depth, snow cover fraction, and snow albedo. Current climate models mainly rely on parameterization schemes to estimate SCF. Actually, most current SCF schemes are empirical schemes based on SD or snow water equivalent (Douville et al., 1995; Helbig et al., 2015; Li et al., 2019; Niu & Yang, 2007; Roesch et al., 2001; Wu & Wu, 2004; Yang et al., 1997). The upper sub-graph in Figure 4 shows five representative SCF schemes used in our previous research (Miao et al., 2022). SCF increases with SD but remains unchanged when SD is large, which is not consistent with observations. This suggests that employing empirical relationships based on SD fails to accurately capture SCF variations, which can lead to significant biases in climate simulations. Notably, SA also exhibits a similar relationship with SD (the lower sub-graph in Figure 4 quoted from Wang et al. (2020)). Consequently, SCF and SA are both derived from SD in models, resulting in snow-related surface albedo variability is largely dependent on SD. However, this approach cannot capture the rapid changes of surface albedo observed in areas with thick snow (Figure 1a). This deficiency in simulations will be passed to climate simulations through intra-seasonal processes.

In conclusion, SCF and SD jointly influence the rapid changes of surface albedo over the TP, but the model fails to capture the magnitude and spatial distribution of changes in snow and surface albedo. The simulation biases of rapid snow accumulation/melting processes over the TP can lead to the biases in seasonal snow simulations. Therefore, better parameterization of snow processes, for example, more accurate SCF scheme, is crucial for effectively improving the weather forecasting, intra-seasonal forecasting, and climate prediction capabilities of current models over the TP. Further combining the underlying mechanism of rapid changes in TPSC in this work, we can target improvements in surface albedo simulations, which is a promising approach to reduce the uncertainty of regional climate simulations, especially "cold bias" of surface air temperature simulations during snow seasons over the TP.

Data Availability Statement

The daily cloudless Moderate Resolution Imaging Spectroradiometer (MODIS) snow area ratio data set of the TP is downloaded at https://data.tpdc.ac.cn/en/data/94a8858b-3ace-488d-9233-75c021a964f0/. The 0.05° snow depth data set for Tibetan Plateau is available at https://data.tpdc.ac.cn/en/data/0515ce19-5a69-4f86-822b-330aa11e2a28/. And the Global Land Surface Satellite (GLASS) albedo products are available at http://www.glass.umd.edu/Albedo/MODIS/0.05D/.

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References

Budyko, M. I. (1969). The effect of solar radiation variations on the climate of the Earth. *Tellus*, *21*(5), 611–619. https://doi.org/10.3402/tellusa.v21i5.10109

Che, T., Xiaohua, H., Liyun, D. A. I., Hongyi, L., Xiaodong, H. U. A. N. G., & Lin, X. I. A. O. (2019). Snow cover variation and its impacts over the Qinghai-Tibet plateau. *Bulletin of Chinese Academy of Sciences*, *34*(11), 1247–1253. https://doi.org/10.16418/j.issn.1000-3045.2019.11.007

Chen, F., Mitchell, K., Schaake, J., Xue, Y., Pan, H.-L., Koren, V., et al. (1996). Modeling of land surface evaporation by four schemes and comparison with FIFE observations. *Journal of Geophysical Research*, *101*(D3), 7251–7268. https://doi.org/10.1029/95JD02165

Dai, Y., Zeng, X., Dickinson, R. E., Baker, I., Bonan, G. B., Bosilovich, M. G., et al. (2003). The common land model. *Bulletin of the American Meteorological Society*, *84*(8), 1013–1024. https://doi.org/10.1175/BAMS-84-8-1013

Dickinson, R., Henderson-Sellers, A., & Kennedy, P. J. (1993). Biosphere atmosphere transfer scheme (BATS) version le as coupled to the NCAR community climate model. *NCAR Technical Note*, *72*. https://doi.org/10.5065/D67W6959

Douville, H., Royer, J. F., & Mahfouf, J. F. (1995). A new snow parameterization for the Meteo-France climate model. Part II: Validation in a 3-D GCM experiment. *Climate Dynamics*, *12*(1), 37–52. https://doi.org/10.1007/BF00208761

Flanner, M. G., Arnheim, J. B., Cook, J. M., Dang, C., He, C., Huang, X., et al. (2021). SNICAR-ADv3: A community tool for modeling spectral snow albedo. *Geoscientific Model Development*, *14*(12), 7673–7704. https://doi.org/10.5194/gmd-14-7673-2021

Flanner, M. G., & Zender, C. S. (2005). Snowpack radiative heating: Influence on Tibetan Plateau climate. *Geophysical Research Letter*, *32*(6), L06501. https://doi.org/10.1029/2004GL022076

Flanner, M. G., & Zender, C. S. (2006). Linking snowpack microphysics and albedo evolution. *Journal of Geophysical Research*, *111*(D12), D12208. https://doi.org/10.1029/2005JD006834

Giddings, J. C., & La Chapelle, E. (1961). Diffusion theory applied to radiant energy distribution and albedo of snow. *Journal of Geophysical Research*, *66*(1), 181–189. https://doi.org/10.1029/JZ066i001p00181

Gul, C., Mahapatra, P. S., Kang, S., Singh, P. K., Wu, X., He, C., et al. (2021). Black carbon concentration in the central Himalayas: Impact on glacier melt and potential source contribution. *Environmental Pollution*, *275*, 116544. https://doi.org/10.1016/j.envpol.2021.116544

Helbig, N., van Herwijnen, A., Magnusson, J., & Jonas, T. (2015). Fractional snow-covered area parameterization over complex topography. *Hydrology and Earth System Sciences*, *19*(3), 1339–1351. https://doi.org/10.5194/hess-19-1339-2015

Jia, X., Zhang, C., Wu, R., & Qian, Q. (2021). Influence of Tibetan Plateau autumn snow cover on interannual variations in spring precipitation over southern China. *Climate Dynamics*, *56*(3–4), 767–782. https://doi.org/10.1007/s00382-020-05497-8

Lee, W. L., Liou, K. N., He, C., Liang, H. C., Wang, T. C., Li, Q., et al. (2017). Impact of absorbing aerosol deposition on snow albedo reduction over the southern Tibetan plateau based on satellite observations. *Theoretical and Applied Climatology*, *129*(3–4), 1373–1382. https://doi.org/10.1007/s00704-016-1860-4

Li, C., Yan, F., Zhang, C., Kang, S., Rai, M., Zhang, H., et al. (2022). Coupling of decreased snow accumulation and increased light-absorbing particles accelerates glacier retreat in the Tibetan Plateau. *Science of the Total Environment*, *809*, 151095. https://doi.org/10.1016/j.scitotenv.2021.151095

Li, W., Guo, W., Qiu, B., Xue, Y., Hsu, P. C., & Wei, J. (2018). Influence of Tibetan Plateau snow cover on East Asian atmospheric circulation at medium-range time scales. *Nature Communications*, *9*(1), 4243. https://doi.org/10.1038/s41467-018-06762-5

Li, W., Guo, W., Xue, Y., Fu, C., & Qiu, B. (2016). Sensitivity of a regional climate model to land surface parameterization schemes for East Asian summer monsoon simulation. *Climate Dynamics*, *47*(7), 2293–2308. https://doi.org/10.1007/s00382-015-2964-8

Li, W., Qiu, B., Guo, W., & Hsu, P. C. (2021). Rapid response of the East Asian trough to Tibetan Plateau snow cover. *International Journal of Climatology*, *41*(1), 251–261. https://doi.org/10.1002/joc.6618

Li, W., Qiu, B., Guo, W., Zhu, Z., & Hsu, P. C. (2020). Intraseasonal variability of Tibetan Plateau snow cover. *International Journal of Climatology*, *40*(7), 3451–3466. https://doi.org/10.1002/joc.6407

Li, W., Zhang, Y., Shi, X., Zhou, W., Huang, A., Mu, M., et al. (2019). Development of land surface model BCC_AVIM2. 0 and its preliminary performance in LS3MIP/CMIP6. *Journal of Meteorological Research*, *33*(5), 57–75. https://doi.org/10.1007/s13351-019-9016-y

Liang, S., Cheng, J., Jia, K., Jiang, B., Zhou, J., Xiao, Z., et al. (2020). The global land surface satellite (GLASS) product suite. *Bulletin of the American Meteorological Society*, *102*(2), 1–37. https://doi.org/10.1175/BAMS-D-18-0341.1

Liu, L., Ma, Y., Menenti, M., Su, R., Yao, N., & Ma, W. (2021). Improved parameterization of snow albedo in Noah coupled with weather research and forecasting: Applicability to snow estimates for the Tibetan Plateau. *Hydrology and Earth System Sciences*, *25*(9), 4967–4981. https://doi.org/10.5194/hess-25-4967-2021

Liu, L., Menenti, M., Ma, Y., & Ma, W. (2022). Improved parameterization of snow albedo in WRF + Noah: Methodology based on a severe snow event on the Tibetan Plateau. *Advances in Atmospheric Sciences*, *39*(7), 1079–1102. https://doi.org/10.1007/s00376-022-1232-1

Miao, X., Guo, W., Qiu, B., Lu, S., Zhang, Y., Xue, Y., & Sun, S. (2022). Accounting for topographic effects on snow cover fraction and surface albedo simulations over the Tibetan Plateau in winter. *Journal of Advances in Modeling Earth Systems*, *14*(8), e2022MS003035. https://doi.org/10.1029/2022MS003035

Mott, R., Vionnet, V., & Grünewald, T. (2018). The seasonal snow cover dynamics: Review on wind-driven coupling processes. *Frontiers in Earth Science*, *6*(197). https://doi.org/10.3389/feart.2018.00197

Niu, G., & Yang, Z. (2007). An observation-based formulation of snow cover fraction and its evaluation over large North American river basins. *Journal of Geophysical Research*, *112*(D21), D21101. https://doi.org/10.1029/2007JD008674

Pu, Z., Xu, L., & Salomonson, V. V. (2007). Modis/terra observed seasonal variations of snow cover over the Tibetan plateau. *Geophysical Research Letters*, *34*(6), 137–161. https://doi.org/10.1029/2007GL029262

Qin, D., Liu, S., & Li, P. (2006). Snow cover distribution, variability, and response to climate change in western China. *Journal of Climate*, *19*(9), 1820–1833. https://doi.org/10.1175/JCLI3694.1

Qu, X., & Hall, A. (2007). What controls the strength of snow-albedo feedback? *Journal of Climate*, *20*(15), 3971–3981. https://doi.org/10.1175/JCLI4186.1

Roesch, A., Wild, M., & Ohmura, A. (2001). Snow cover fraction in a general circulation model. In *Remote sensing and climate modeling: Synergies and limitations* (pp. 203–232). https://doi.org/10.1007/0-306-48149-9_9

Roychoudhury, C., He, C., Kumar, R., McKinnon, J. M., & Arellano, A. F., Jr. (2022). On the relevance of aerosols to snow cover variability over High Mountain Asia. *Geophysical Research Letters*, *49*(18), e2022GL099317. https://doi.org/10.1029/2022GL099317

Sarangi, C., Qian, Y., Rittger, K., Ruby Leung, L., Chand, D., Bormann, K. J., & Painter, T. H. (2020). Dust dominates high-altitude snow darkening and melt over high-mountain Asia. *Nature Climate Change*, *10*(11), 1045–1051. https://doi.org/10.1038/s41558-020-00909-3

Sellers, P. J., Randall, D. A., Collatz, G. J., Berry, J. A., Field, C. B., Dazlich, D. A., et al. (1996). A revised land surface parameterization (SiB2) for atmospheric GCMS. Part I: Model formulation. *Journal of Climate*, *9*(4), 676–705. https://doi.org/10.1175/1520-0442(1996)009<0676:ARLSPF>2.0.CO;2

Song, L., Wu, R., & An, L. (2019). Different sources of 10- to 30-day intraseasonal variations of autumn snow over western and eastern Tibetan Plateau. *Geophysical Research Letters*, *46*(15), 9118–9125. https://doi.org/10.1029/2019GL083852

Sun, S., & Xue, Y. (2001). Implementing a new snow scheme in simplified simple biosphere model. *Advances in Atmospheric Sciences*, *18*(3), 335–354. https://doi.org/10.1007/BF02919314

Tang, Z., Wang, J., Li, H., & Yan, L. (2013). Spatiotemporal changes of snow cover over the Tibetan Plateau based on cloud-removed moderate resolution imaging spectroradiometer fractional snow cover product from 2001 to 2011. *Journal of Applied Remote Sensing*, *7*(1), 2431. https://doi.org/10.1117/1.JRS.7.073582

Wang, W., Yang, K., Zhao, L., Zheng, Z., Moore, J. C., Mamtimin, A., et al. (2020). Characterizing surface albedo of shallow fresh snow and its importance for snow ablation on the interior of the Tibetan Plateau. *Journal of Hydrometeorology*, *21*(4), 815–827. https://doi.org/10.1175/JHM-D-19-0193.1

Wu, T., & Qian, Z. (2003). The relation between the Tibetan winter snow and the Asian summer monsoon and rainfall: An observational investigation. *Journal of Climate*, *16*(12), 2038–2051. https://doi.org/10.1175/1520-0442(2003)016<2038:TRBTTW>2.0.CO;2

Wu, T., & Wu, G. (2004). An empirical formula to compute snow cover fraction in GCMs. *Advances in Atmospheric Sciences*, *21*(4), 529–535. https://doi.org/10.1007/BF02915720

Xie, Z., Hu, Z., Ma, Y., Sun, G., Gu, L., Liu, S., et al. (2019). Modeling blowing snow over the Tibetan Plateau with the community land model: Method and preliminary evaluation. *Journal of Geophysical Research: Atmospheres*, *124*(16), 9332–9355. https://doi.org/10.1029/2019JD030684

Xue, Y., Sellers, P. J., Kinter, J. L., & Shukla, J. (1991). A simplified biosphere model for global climate studies. *Journal of Climate*, *4*(3), 345–364. https://doi.org/10.1175/1520-0442(1991)004<0345:ASBMFG>2.0.CO;2

Xue, Y., Sun, S., Kahan, D. S., & Jiao, Y. (2003). Impact of parameterizations in snow physics and interface processes on the simulation of snow cover and runoff at several cold region sites. *Journal of Geophysical Research*, *108*(D22). https://doi.org/10.1029/2002JD003174

Yan, D., Ma, N., & Zhang, Y. (2021). Development of a fine-resolution snow depth product based on the snow cover probability in the Tibetan Plateau: Validations and spatial-temporal analyses. *Journal of Hydrology*, *604*, 127027. https://doi.org/10.1016/j.jhydrol.2021.127027

Yang, F., Kumar, A., Wang, W., Juang, H. H., & Kanamitsu, M. (2001). Snow–albedo feedback and seasonal climate variability over North America. *Journal of Climate*, *14*(22), 4245–4248. https://doi.org/10.1175/1520-0442(2001)014<4245:SAFASC>2.0.CO;2

Yang, Z. L., Dickinson, R. E., Robock, A., & Vinnikov, K. Y. (1997). Validation of the snow submodel of the Biosphere-Atmosphere Transfer Scheme with Russian snow cover and meteorological observational data. *Journal of Climate*, *10*(2), 353–373. https://doi.org/10.1175/1520-0442(1997)010<0353:VOTSSO>2.0.CO;2

You, Q., Wu, T., Shen, L., Pepin, N., Aghakouchak, A., Jiang, Z., et al. (2020). Review of snow cover variation over the Tibetan plateau and its influence on the broad climate system. *Earth-Science Reviews*, *201*, 103043. https://doi.org/10.1016/j.earscirev.2019.103043

Zhang, Y., Kang, S., Sprenger, M., Cong, Z., Gao, T., Li, C., et al. (2018). Black carbon and mineral dust in snow cover on the Tibetan Plateau. *The Cryosphere*, *12*(2), 413–431. https://doi.org/10.5194/tc-12-413-2018

Zhao, H., & Moore, G. W. K. (2004). On the relationship between Tibetan snow cover, the Tibetan Plateau monsoon and the Indian summer monsoon. *Geophysical Research Letters*, *31*(14), 101–111. https://doi.org/10.1029/2004GL020040