Evaluating the performance of parameterization schemes in simulating warm-season snowfall proportions over the Tibetan Plateau

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Abstract: Simulating warm-season snowfall proportions over the Tibetan Plateau presents a unique challenge due to the complex interactions between temperature, altitude, and monsoonal influences. This study evaluates the performance of three parameterization schemes in simulating snowfall during the warm season (April to September), using Global Land Data Assimilation System (GLDAS) data as the observational reference. The GLDAS data indicate significant spatial variability, with the highest snowfall proportions occurring in the western and northern regions, while the southeastern regions experience predominantly rainfall. The Jordan and BATS schemes consistently overestimated snowfall proportions, particularly in the central and southern regions of the Plateau. The FRZ scheme performed better overall, with lower biases, especially in marginal temperature zones, but still showed moderate overestimation in southern areas. This study highlights the need for topographic influences to enhance the accuracy of phase-aware precipitation simulations during the warm season.

Keywords: Tibetan Plateau; Warm-Season Snowfall; Parameterization Schemes

1. Introduction

The Tibetan Plateau exerts a profound influence on the regional and global climate system, particularly through its interactions with the monsoon and atmospheric circulation patterns. As one of the highest and most expansive plateaus on Earth, its role in the hydrological cycle is critical, with significant implications for downstream water resources in Asia. While snowfall typically dominates the cold season in the Tibetan Plateau, snowfall events during the warm season (April to September) also play a vital role in shaping the region's water availability. Understanding and accurately simulating warm-season snowfall is essential for predicting snow accumulation, which affects river flow, glacier mass balance, and water storage in the region.

Warm-season snowfall is influenced by complex interactions between elevation, temperature, and atmospheric moisture, with snowfall more likely at higher elevations where temperatures remain lower, even during the warmer months.[1-2] However, simulating this phenomenon in climate models remains a challenge, particularly given the Plateau's highly variable topography and climatic conditions.[3] Accurate simulation of snowfall during the warm season is crucial for water resource management, as it affects the timing and quantity of snowmelt feeding into rivers that sustain large populations downstream.

Despite the importance of warm-season snowfall in the Tibetan Plateau, simulating this process accurately has proven difficult for many climate models. Warm-season snowfall is heavily influenced by marginal temperature conditions, where the boundary between rain and snow is especially sensitive to small changes in temperature.[4-6] Many parameterization schemes used in regional and global climate models oversimplify this phase transition, leading to significant biases in snowfall simulation, particularly in regions with complex terrain like the Tibetan Plateau.

The goal of this study is to evaluate the performance of three parameterization schemes—Jordan, BATS, and FRZ—in simulating the proportion of snowfall during the warm season over the Tibetan Plateau. Each scheme employs different approaches to determine the phase of precipitation (snow versus rain) based on surface temperature and other atmospheric variables. By comparing the simulated snowfall proportions with observational data from the Global Land Data Assimilation System (GLDAS), this study aims to assess the strengths and limitations of each scheme in capturing warm-season snowfall.

2. Data and methodology

The primary data source for this study is the Global Land Data Assimilation System (GLDAS), which provides high-resolution observational data for a variety of land surface variables, including precipitation. Hourly snowfall and rainfall data for the warm season (April to September) are extracted from the GLDAS dataset. This dataset provides the observational baseline for comparing model simulations of snowfall proportions across the Tibetan Plateau.

This study evaluates three commonly used parameterization schemes—Jordan, BATS, and FRZ—in their ability to simulate the proportion of snowfall during the warm season. These schemes use different approaches to determine whether precipitation falls as rain or snow, based primarily on surface temperature.

The Jordan scheme calculates the fraction of precipitation falling as snow based on a temperature-dependent phase transition. This scheme allows for a smooth transition between rain and snow, accounting for intermediate temperatures. The Biosphere-Atmosphere Transfer Scheme (BATS) uses a simpler, binary approach to classify precipitation as rain or snow. This scheme makes a sharp distinction between rain and snow based on temperature, without accounting for any intermediate phases. As such, it may be less flexible in capturing marginal temperature conditions. The FRZ scheme is the simplest of the three, applying a strict freezing point threshold to classify precipitation as either rain or snow. If the surface temperature is at or below freezing, all precipitation is classified as snow. This rigid approach may result in significant biases, particularly in regions where temperatures fluctuate around the freezing point, leading to potential misclassification of rain as snow or vice versa.

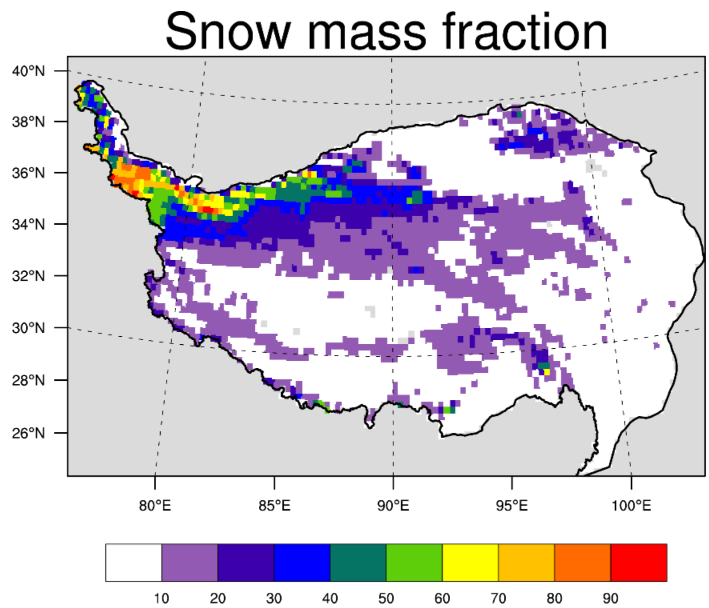

Figure 1 Snowfall mass fraction during the warm season (April to September) across the Tibetan Plateau, based on GLDAS data.

3. Results

Figure 1 represents the proportion of total precipitation occurring as snowfall and shows considerable variability across the Plateau, driven by factors such as altitude, temperature, and regional climate influences. The western and northern regions of the Tibetan Plateau, particularly in areas around 34°N to 38°N and 80°E to 90°E, show the highest snow mass fractions during the warm season, with values ranging from 70% to 90%. These regions are characterized by high elevations and colder temperatures, which favor snowfall even during the warmer months. The snow mass fraction is especially high in areas along the Kunlun and Karakoram ranges, where the influence of altitude ensures that temperatures remain sufficiently cold for snowfall.

As shown in Figure 2, the Jordan scheme consistently overestimated snowfall proportions across most of the Tibetan Plateau, particularly in the central and southern regions (south of 34°N). In these areas, the model's biases range from +1% to +3%, indicating that the Jordan scheme is too aggressive in classifying precipitation as snowfall, especially in regions where GLDAS data shows a significant proportion of rainfall. The overestimation is particularly strong in the southern Plateau (below 30°N), where warm temperatures should favor rain over snow.

The BATS scheme exhibits a similar overestimation pattern to the Jordan scheme, though the magnitude of the biases is slightly smaller. The central and southern parts of the Plateau show overestimations of snowfall proportion by +0.5% to +2%, particularly in regions where warm-season rainfall should dominate. This indicates that the BATS scheme also tends to classify too much precipitation as snow in these regions, although the biases are less extreme compared to the Jordan scheme.

The FRZ scheme performs relatively well in the central and eastern regions (around 30°N to 34°N), where marginal temperature conditions during the warm season make phase transitions between rain and snow more challenging to simulate. The biases in these regions are generally smaller than those observed in the Jordan and BATS schemes, indicating that the FRZ scheme handles marginal temperature zones more effectively.

4. Conclusion

This study evaluated the performance of three parameterization schemes—Jordan, BATS, and FRZ—in simulating warm-season snowfall proportions over the Tibetan Plateau. The accuracy of these schemes was assessed by comparing the simulated results with observational data from the Global Land Data Assimilation System (GLDAS). The GLDAS data revealed significant spatial variability in snowfall proportions during the warm season across the Tibetan Plateau. Each of the three parameterization schemes exhibited notable biases when simulating warm-season snowfall proportions.

Among the three schemes, the FRZ scheme demonstrated the best performance, with lower RMSE and MAE values, particularly in central regions where temperature transitions between rain and snow were more frequent. However, all three schemes showed weaknesses in simulating snowfall in regions with highly variable temperature conditions, highlighting the need for more sophisticated approaches to handle phase transitions during the warm season.

The results of this study highlight several key challenges in simulating phase-aware precipitation during the warm season over the Tibetan Plateau, as well as opportunities for improving model performance in this complex region. One of the primary challenges for all three parameterization schemes is accurately simulating snowfall in marginal temperature zones, where temperatures during the warm season hover near the freezing point. These zones are critical because small temperature variations can lead to significant shifts between rainfall and snowfall. The Jordan and BATS schemes, in particular, struggled with this issue, consistently overestimating snowfall by misclassifying rainfall events. While the FRZ scheme handled these regions better, it still exhibited biases in southern regions where rainfall should dominate.

The complex topography of the Tibetan Plateau poses additional challenges for accurately simulating snowfall during the warm season. Higher-altitude regions tend to maintain colder temperatures, even during warmer months, leading to more snowfall. However, many parameterization schemes fail to fully account for the sharp temperature gradients caused by elevation changes. This was evident in the overestimation of snowfall in lower-elevation regions, particularly in the central and southeastern Plateau, where the models failed to capture the transition from snowfall to rainfall as temperatures increased.

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