Analysis of stable snowpack distribution pattern and influencing factors

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Abstract

Under the background of climate warming, the distribution pattern of snowpack in mountainous areas is naturally under the focus of attention, and the changes in the snowpack pattern in mountainous areas have important impacts on hydrological processes such as downstream river runoff, water supply, and so on. In this study, based on the MODIS day-by-day cloud-free snowpack area dataset, we analysed the process of stable snowpack formation and the final pattern of snowpack in spring and winter in two typical topographic regions, the hilly plateau and the alpine valley region, in the eastern part of the Tibetan Plateau, and constructed a model based on the Maximum Entropy Model (MEM) method for predicting the influencing factors of the stable snowpack. A model was constructed based on the maximum entropy model method to predict the factors influencing the stable snowpack, and the dominant factors of the stable snowpack in spring and winter in the watersheds of the two topographic regions were analysed. The main conclusions are as follows: (1) The snow ablation rate on the western Sichuan Plateau is different in winter and spring, and is greater in spring than in winter; there is also a difference in the snow ablation rate in different topographic regions, with a greater difference in the hilly plateau than in the high mountain valleys. (2) The distribution pattern of stable snow in the two major terrain areas of the Western Sichuan Plateau varies in seasons, and the spatial distribution area is relatively small, mostly showing a rising trend with increasing altitude. (3) The influence factors of stable snowpack in different terrain areas in different seasons are different, and elevation is the main factor influencing the distribution pattern of stable snowpack. The results of this paper have some reference value for the study of snow hydrology in the climatic context of the Western Sichuan Plateau.

Analysis of stable snowpack distribution pattern and influencing factors

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Abstract: Under the background of climate warming, the distribution pattern of snowpack in mountainous areas is naturally under the focus of attention, and the changes in the snowpack pattern in mountainous areas have important impacts on hydrological processes such as downstream river runoff, water supply, and so on. In this study, based on the MODIS day-by-day cloud-free snowpack area dataset, we analysed the process of stable snowpack formation and the final pattern of snowpack in spring and winter in two typical topographic regions, the hilly plateau and the alpine valley region, in the eastern part of the Tibetan Plateau, and constructed a model based on the Maximum Entropy Model (MEM) method for predicting the influencing factors of the stable snowpack. A model was constructed based on the maximum entropy model method

to predict the factors influencing the stable snowpack, and the dominant factors of the stable snowpack in spring and winter in the watersheds of the two topographic regions were analysed. The main conclusions are as follows: (1) The snow ablation rate on the western Sichuan Plateau is different in winter and spring, and is greater in spring than in winter; there is also a difference in the snow ablation rate in different topographic regions, with a greater difference in the hilly plateau than in the high mountain valleys. (2) The distribution pattern of stable snow in the two major terrain areas of the Western Sichuan Plateau varies in seasons, and the spatial distribution area is relatively small, mostly showing a rising trend with increasing altitude. (3) The influence factors of stable snowpack in different terrain areas in different seasons are different, and elevation is the main factor influencing the distribution pattern of stable snowpack. The results of this paper have some reference value for the study of snow hydrology in the climatic context of the Western Sichuan Plateau.

Keyword: Snow; Remote sensing; the Western of Sichuan Plateau; the maxent model

1. INTRODUCTION

Mountainous environments are very complex, with various physical and chemical processes interacting with each other on a vertical scale, playing an important role in the environment, and also being an important source of water for downstream areas. Seasonal changes in the cryosphere play an important role in regulating rivers and sediments in mountainous areas and downstream areas, and also have a significant impact on the production and living of downstream residents and other types of social needs(Huss et al. 2017).

Snowpack plays a crucial role in the cryosphere, and its response to climate change has profound implications for the regional and global energy balance as well as the water cycle. The high albedo of snowpack effectively reflects solar radiation, thereby reducing the amount of radiation absorbed by the ground. This, in turn, affects the climate system. Additionally, the melting of snowpack has a substantial impact on the water cycle (Brown et al. 2009,Yasunari et al. 1991,Zuo et al. 2011). Snowmelt is an important freshwater resource, providing 17 per cent of the global population with water for productive use. As the climate changes, the snowpack in many regions undergoes drastic changes. The significant decrease in the number of snow days and the increasing trend towards "snowlessness" in some areas have had a significant impact on the regional water cycle and on the interaction of the various layers. The temperature increase is particularly severe at high altitudes at low latitudes. The snowpack in the northern hemisphere has shown a decreasing trend in recent decades(Wang et al. 2018,Xiao et al. 2020). However, there is heterogeneity in snowpack changes in different regions, for example, in parts of Central Asia there is a significant increasing trend in snowpack, and snowpack anomalies are increasing from year to year (Gong et al. 2007,Tang et al. 2017). Snowpack anomalies can lead to significant changes in spatial distribution patterns, with important implications for regional runoff: when the spatial distribution of snowpack is not uniform, and the rate of snowmelt varies in different regions, this leads to an uneven spatial and temporal distribution of surface runoff and subsurface runoff, which has an impact on the allocation and utilisation of water resources within the basin(de Jong et al. 2009). Warming temperatures lead to changes in snowpack phenology that have a greater impact on river flows in downstream areas. Currently, the first day of snowpack is significantly earlier in most areas, and some of the snowpack is melting earlier, which increases the risk of flooding due to higher flood levels in the spring floods (Peng et al. 2013,Stewart. 2009). At the same time, it may exacerbate summer drought conditions in some areas. The Tibetan Plateau is located in Central Asia, with an average altitude of 4,000 metres above sea level and widespread glaciers and snow, and is known as the Third Pole. It is the source of many large rivers and is known as the "water tower of Asia". In addition, the snow pattern on the Tibetan Plateau has a significant impact on the Asian monsoon(Qian et al. 2011,Zhao et al. 2004). Due to its unique geographical location, has become a hotspot for global snow research (Yang et al. 2015). Studying the distribution pattern of stable snow accumulation in the region contributes to understanding the response of snow to climate change, changes in regional ecological environment, and socio-economic development.

Due to the unique geographical conditions of the Tibetan Plateau, most of the snow exists for a short period of time and melts quickly, often instantaneously (Zhang et al. 2014), The distribution of snowpack exhibits significant heterogeneity due to the substantial variation in environmental factors across different regions

(Liu et al. 2019). To address this issue, numerous scholars have conducted studies on the partitioning of snowpack on the Tibetan Plateau. In the 1980s, Li et al proposed a classification system for the snowpack, categorizing it into stable and unstable snowpack based on the accumulation of snow days over a span of 60 days per year (Li et al. 1983). In the 1990s, based on SSRM remote sensing data, it was found that most of the Tibetan Plateau is an unstable snowpack area, and the distribution of the stable snowpack area is small and scattered in the western Sichuan Plateau (Li. 1995). Considering the significant inter-annual variability of snowpack in the majority of Tibetan Plateau regions, He et al. (Year) proposed a method for classifying snowpack. This method combines the annual cumulative number of snow days with the inter-annual variability of snowpack. The study revealed that stable snowpack areas on the Tibetan Plateau are primarily concentrated in the central and eastern regions (He et al. 2012). In addition, the temporal continuity of the snowpack serves as a significant indicator for classifying its stable characteristics. Zhang et al employed the number of consecutive snow days as a method to classify the snowpack in Eurasia. Their findings demonstrated that this method exhibits superior applicability (Zhang et al. 2014). There is an urgent need to study the distribution pattern of stable snowpack, as it provides a more accurate reflection of the regional snowpack distribution in the context of climate change, where significant changes in snowpack are occurring.

Currently, four types of snow data are commonly used on the Tibetan Plateau: station data, remotely sensed data, reanalyzed data, and model data (Gao et al. 2012,Huang et al. 2020,Shi et al. 2011,Zhang et al. 2021). Station data remain highly reliable sources of information for current snowpack studies due to their field measurements and daily observations. However, the uneven distribution of stations on the Tibetan Plateau and the significant spatial heterogeneity of snowpack in certain areas contribute to substantial errors in the interpolation process. While reanalyzed and modeled data help mitigate errors associated with individual data points, they are not ideal for small- and medium-scale snowpack studies due to their high resolution (Bian et al. 2020). Remote sensing data compensates for the uneven distribution of station data sites because it has the ability to monitor a larger area. Furthermore, the Moderate Resolution Imaging Spectroradiometer (MODIS) possesses not only a high resolution of 500 meters, but also performs daily observations with consistent time intervals. This makes the data ideal for investigating the formation of stable snow and its patterns across various topographic conditions on the western Sichuan Plateau.

The Western Sichuan Plateau is situated in the eastern part of the Tibetan Plateau within the Hengduan Mountains. It exhibits a complex topography and is primarily divided into two regions: the Northwest Sichuan Plateau and the Western Sichuan Mountains. The Northwest Sichuan Plateau is characterized by high altitudes and flat terrain, whereas the West Sichuan Mountains have a complex terrain with significant elevation changes and distinct vertical zoning characteristics. The environmental conditions in the Western Sichuan Plateau are unique, leading to inconsistent spatial and temporal continuity of the snowpack and significant year-to-year variability. Consequently, there is an urgent need to investigate the current distribution pattern of stable snowpack and the factors influencing it under different topographic conditions in the western Sichuan Plateau. In this study, we selected the Mamukao River basin in the northwestern part of the western Sichuan Plateau and the Hanliu River basin in the east-central part of the western Sichuan Plateau as representative areas of hilly plateaus and alpine valleys, respectively (see Fig. 1). We conducted an investigation into the distribution pattern of stable snowpack and the influencing factors during a single snowfall event in both spring and winter in these two areas. The aim was to explore the variations in distribution patterns and influencing factors of stable snowpack across different seasons and areas within the western Sichuan Plateau. The findings from this study will serve as a reference for effective resource utilization and ecological conservation in the region, thereby contributing to the overall sustainable development of the area.

2. Data and Methods

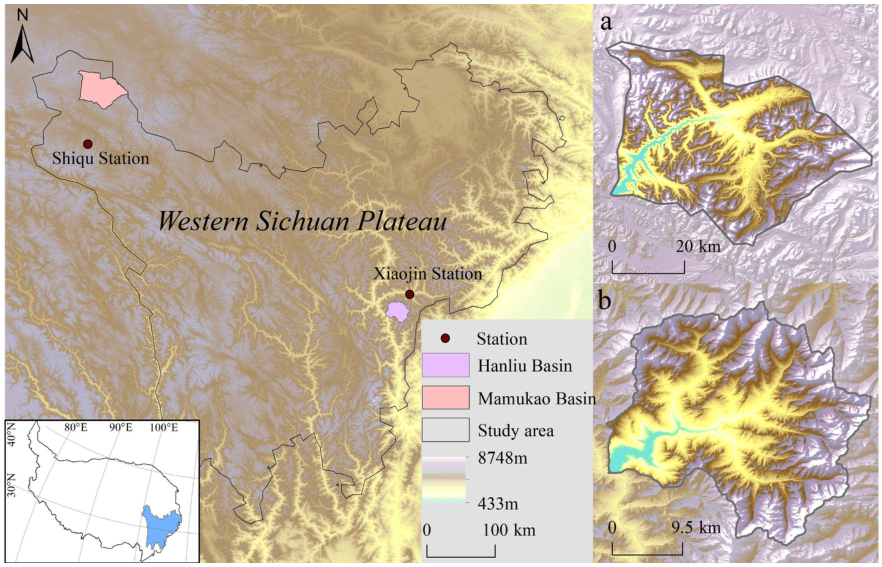


Figure 1 Overview of the study area

2.1Data

2.1.1 Snow data

The snowpack data utilized in this study is derived from the MODIS day-by-day cloud-free snow cover dataset (2000-2022) specifically for the Asian water tower region. This dataset was obtained from the Science Data Bank(https://www.scidb.cn) and is based on the MODIS Global Surface Launch Product MO/YD09GA. The snow cover dataset for the Asian Water Towers region during the period of 2000-2022 was prepared using the de-cloud algorithm. The data is provided in tif format with a resolution of 0.005°.

2.1.2 Meteorological data

The meteorological dataset utilized in this study was obtained from the surface meteorological element-driven dataset for the Chinese region spanning from 2002 to 2017. This dataset was provided by the National Tibetan Plateau Scientific Data Centre Network (https://data.tpdc.ac.cn/). Considering the distinctive natural conditions of the study area, a total of five elements, specifically surface air temperature, wind speed, precipitation, incident short-wave radiation, and long-wave radiation, were ultimately chosen. These elements were available in NETCDF format and had a spatial resolution of 0.1°.

2.1.3 Subsurface data

The subsurface data were acquired from the China Land Cover Ratio dataset, which was provided by the National Tibetan Plateau Science Data Centre (https://data.tpdc.ac.cn/) in tif format. The dataset has a spatial resolution of 1 km. For this study, four types of feature ratios were chosen: grass-irrigation ratio, forest ratio, cropland ratio, and bare ground ratio.

2.1.4 DEM data

The Digital Elevation Model (DEM) data were obtained from the Geospatial Data Cloud (https://www.gscloud.cn/), specifically the SRTMDEM 90m resolution raw elevation data in TIFF format. In this study, we utilized the slope, slope direction, and focus statistics, as well as the raster calculator tools of ArcGIS 10.8 software, to generate the slope, slope direction, and topographic relief data for the study area, respectively.

2.2 Thoery and Method

2.2.1 Pre-processing of snow data

It has been demonstrated that an image element can be classified as snow-covered when its snow cover factor (SCF) exceeds 50% (Tang et al. 2013). In this study, the MODIS day-by-day cloud-free snowpack area data was binarised using ENVI 5.3 software. Pixels with values lower than 50% were assigned a value of 0, representing the non-accumulating snow area, while pixels with values equal to 50% were assigned a value of 1, representing the accumulating snow area. This process divided the snowpack data into binary snowpack data of 0 and 1. Next, snow accumulation processes in spring and winter were selected for analysis based on data from the nearest meteorological stations, namely the Shiqu station and Xiaojin station, in the two basins. These processes were chosen to examine the stable snow formation process and final pattern. Specifically, in the Mamukao River basin, the snow accumulation process from 7 March to 20 March 2019 in spring and from 6 November to 22 November 2019 in winter was selected. In the Hanliu River basin, the snow accumulation process from 11 April to 28 April 2019 in spring and from 6 December to 17 December 2019 in winter was chosen (see Fig 2). Finally, the binarised snow data for the selected time periods in both basins were cropped using ArcGIS 10.8 software.

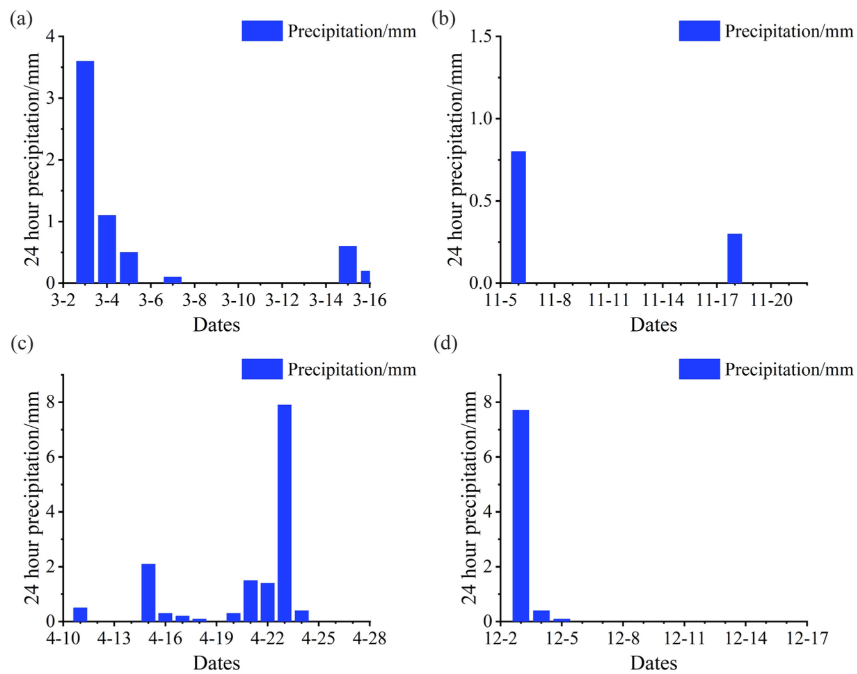


Figure 2 24h precipitation data from meteorological stations (a-b: Shiqu; c-d: Xiaojin)

Note:Since the meteorological stations have a certain distance from the watershed, the station data are used for reference. The actual selection of the timing of the snowfall process is based on remote sensing imagery

2.2.2 Environmental factor selection and pre-processing

Table 1 33 environmental factors and their abbreviations

Environmental factors	**Abbreviations**	**Environmental factors**	**Abbreviations**	**Environmental factors**	**Abbreviations**
Elevation	Alt	Summer precipitation	Supr	Autumn shortwave radiation	Fsrad

Environmental factors	Abbreviations	Environmental factors	Abbreviations	Environmental factors	Abbreviations
Aspect	Apt	Autumn precipitation	Fpr	Winter shortwave radiation	Wsrad
Slope	Slp	Winter precipitation	Wpr	Annual longwave radiation	Alrad
Undulation	Und	Annual average wind speed	Awd	Spring longwave radiation	Slrad
Average annual temperature	At	Spring average wind speed	Swd	Summer longwave radiation	Sulrad
Average spring temperature	St	Average summer wind speed	Suwd	Autumn longwave radiation	Flrad
Average summer temperature	Sut	Average wind speed in autumn	Fwd	Winter longwave radiation	Wlrad
Average temperature in autumn	Ft	Annual winter wind speed	Wwd	Proportion of grass-irrigated area	Gsa
Average winter temperature	Wt	Annual shortwave radiation	Asrad	Proportion of forest area	Foa
Annual precipitation	Apr	Spring shortwave radiation	Ssrad	Proportion of croplandarea	Cra
Spring precipitation	Spr	Summer shortwave radiation	Susrad	Proportion of bare land area	Baa

Temperature and precipitation are the primary factors that impact the distribution of snow, with terrain exerting an indirect influence on both (Namias. 1985,Tong et al. 2009). In areas with high wind conditions, particularly on plateau surfaces and mountain peaks, wind-blown snow is highly likely to accumulate, resulting in the redistribution of snow. Additionally, radiation plays a significant role in the melting process of snow (Fujita et al. 2010,Golding et al. 1986). Additionally, the type of subsurface has a significant impact on surface albedo, radiation reception, and surface roughness, among other factors. It also has an intercepting effect on the snowpack (Jost et al. 2007). In this study, a comprehensive selection of 33 environmental factors was made to analyze the dominant factors influencing the distribution pattern of the stable snowpack in the selected study area (see Table 1). The selection of these factors took into full consideration both the snowpack influencing factors and the unique natural conditions of the study area.

2.2.3 Stable snow

Stable snowpack is characterized by either having more than 60 days of snow per year or experiencing a continuous period of snow lasting more than 30 consecutive days (Liu et al. 2011). Since all the remote sensing images selected for this study have time periods of less than 30 days, the study defines stable snowpack as the areas where snow is consistently present throughout the selected time periods. The extraction of stable snow areas from the remote sensing images was performed using the GIS intersection method.

2.2.4 Maxent model

The maximum entropy model is derived from the maximum entropy principle, which was proposed by Jaynes et al in 1957. According to this principle, when only partial constraints of an unknown distribution are known, the probability distribution that satisfies these constraints while maximizing entropy should be selected. By maximizing entropy, the maximum entropy principle expresses the likelihood of the chosen distribution. Therefore, the maximum entropy model is considered the best model among all possible probability models due to its maximum entropy. In constructing the maximum entropy model, it is crucial to assess the significance of each factor for the input factors of the environment layer (Kumar. 2012). The Jackknife method, also known as the Knife Cut method, was proposed by an expert in 1949 as a resampling technique to reduce estimation bias in the research process. This method is widely used for hypothesis testing and calculating confidence intervals. It allows for the analysis of the impact of variable factors on the predictive accuracy of a model and provides insights into the accuracy of these variables. Additionally, the Knife Cut method serves specific functions, such as correcting bias in statistical sampling and conducting more accurate data testing based on statistical principles (Miller. 1974). In order to mitigate the impact of overfitting caused by variable factors, the knife-cut method is employed to evaluate the contribution and importance of all variables in the model. This involves conducting an independent variable importance analysis for each variable and considering the role of the remaining variables after removing each variable. The contribution rate indicates the extent to which an environmental factor contributes to the model, with higher values indicating a greater degree of contribution. The cumulative contribution rate represents the cumulative value of the contribution rate. The replacement importance measures the reduction in AUC (Area Under the Curve) when a randomly selected environmental factor is replaced in the training sample points. Higher values suggest that the model is more reliant on that particular environmental factor, signifying its equal significance (Préau et al. 2018). ROC stands for Receiver Operating Characteristic and is used to evaluate the performance of a model in an assessment test. The ROC curve is a graph that plots the False Positive Rate (FPR) on the horizontal axis, which represents the probability of correctly predicting counterexamples out of the total counterexamples, and the True Positive Rate (TPR) on the vertical axis, which represents the probability of correctly predicting positive counterexamples out of the total positive counterexamples. The Area Under Curve (AUC) of the ROC curve is a commonly used metric to measure the accuracy of the system being tested. Unlike other evaluation metrics, the AUC value is not affected by the threshold value and is considered more desirable. Simply looking at the curve alone cannot accurately assess the effectiveness of the classifier. Therefore, the AUC value is used to indicate the predictions of the classifier on positive examples and the probability of correctly predicting counterexamples. In theory, the AUC value ranges from 0.5 to 1, with a value closer to 1 indicating a more perfect test. The specific relationship between the AUC value and model accuracy is as follows: AUC value < 0.6 indicates poor model accuracy, AUC value between 0.6 and 0.7 indicates general model accuracy, AUC value between 0.7 and 0.8 indicates more accurate model accuracy, AUC value between 0.8 and 0.9 indicates accurate model accuracy, and AUC value > 0.9 indicates extremely accurate model accuracy. In other words, as the AUC value approaches 1, the model accuracy increases, resulting in more accurate prediction results.

3 Result

3.1 Stable snow formation processes

3.1.1 Mamukao River

In the Mamukao River Basin, there are differences in snowmelt processes between spring and winter. During spring (see Fig 3(a)), the rate of snowpack ablation was slower. Snowfall increased the proportion of snow cover in the watershed to 96.56%, and within 7 days after snowfall, the snowpack changed more slowly, with the area decreasing by only 2.96%. However, the rate of snow ablation accelerated during days 8-11, and the area decreased by 3.24%. It started to level off at day 12, and then the next snowfall occurred at day 14, causing the snowpack area to rebound. This snow ablation process had an ablation rate of -0.707%/day. During winter snowfall (see Fig. 3(b)), the snowfall increased the proportion of snow area in the watershed to 99.18%, and the proportion of snow cover on day 2 was 96.73%, which was less variable. From day 3 onwards, the proportion of snow cover declined sharply, and the snow-covered fraction (SCF) decreased by 75.16% in the period of days 2-10, after which the trend of change became stable. The rate of decline was -5.216%/day in 17 days, which was much larger than the spring snow ablation rate. Therefore, the spring snow ablation rate is less than the winter snow accumulation in the Mamukao River basin.

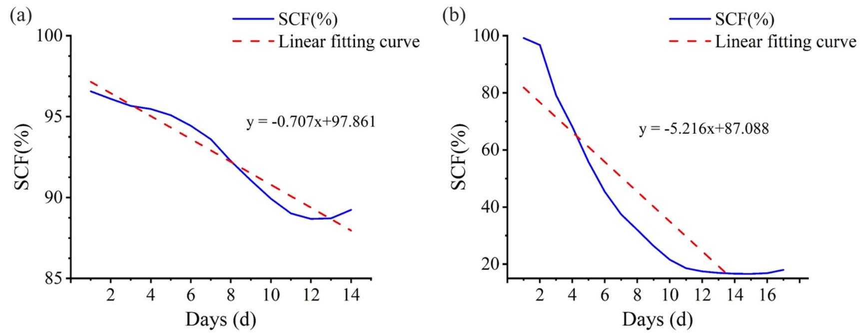


Figure 3 Rate of snowmelt in the Mamukao River Basin during spring and winter precipitation(a: Spring; b: Winter)

The snowpack in the Mamukao River Basin exhibited varying rates of change across the four altitudinal zones. This is supported by the observation that as the altitude increased, the rate of snowmelt decreased. Furthermore, the rate of snow decline in the spring remained lower than that in the winter. In altitudes below 4400 m (Fig 4(a, b)), the snow ablation rates were the fastest, measuring at -3.935%/d in spring and -4.037%/d in winter. It is important to note that the fitted curves were averaged out due to the absence of snow cover on day 6 in winter, resulting in larger slopes of the fitted curves than in reality. For elevations between 4400-4600 m (Fig 4(c, d)), the rate of decline was -0.852%/d in spring and -5.66%/d in winter. During spring, the proportion of snow cover stabilized at 85%, whereas in winter, it approached 0. In the interval of 4600-4800 m (Fig 4(e, f)), the rate of decrease in the proportion of spring snow cover was only -0.278%/d, whereas in winter, it was -5.051%/d. For altitudes above 4800 m (Fig 4(g, h)), the change in snow cover remained stable, with a rate of decrease of -0.139%/d in spring. However, in winter, the rate of decrease was relatively faster at -2.752%/d.

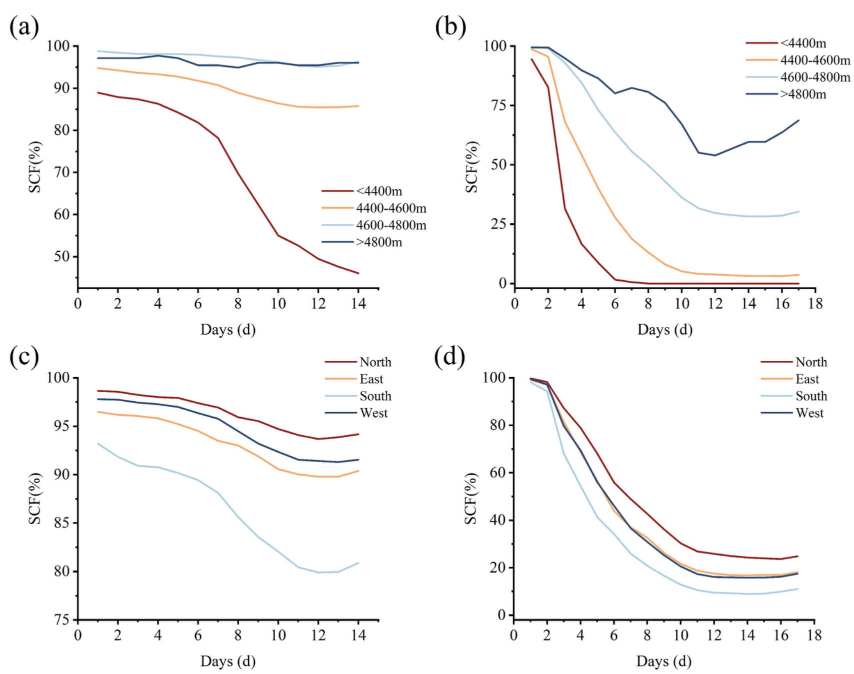


Figure 4 Changes in snowpack at different elevation slopes of the Mamukao River during spring and winter. (a, b. Spring and winter altitude; c, d Spring and winter slope direction)

The ablation rates of different slope directions in the Mamukao River Basin exhibited variation (Fig 4(c, d)). During spring, the ablation rates followed the following order: south slope > west slope > east slope > north slope, with the south slope experiencing the highest rate of ablation and the north slope the lowest. Conversely, in winter, the ablation rates followed this order: west slope > east slope > south slope > north slope, with the west slope exhibiting the highest rate of ablation and the north slope the lowest. The north slope consistently demonstrated the lowest ablation rate in both winter and spring, likely due to the relatively flat topography of the Mamukao River and its location on the shaded side during these seasons, resulting in reduced solar radiation and consequently lower rates of ablation compared to the other three slopes. In winter, the south slope displayed the fastest ablation rate, attributable to the low precipitation during this season and the increased solar radiation received. In spring, the east and south slopes, being windward slopes, experienced precipitation that slowed down the ablation rate, whereas the west slope, located on the leeward side with lower precipitation, exhibited the highest ablation rate. Additionally, the northward movement of the sun during spring resulted in reduced radiation received by the south slope, further contributing to the west slope's relatively greater ablation rate.

3.1.2 Hanliu River

In the Hanliu River Basin, there are differences in the snowmelt process between spring and winter. In spring (see Fig 5(a)), the rate of snow ablation is slower. Initially, snowfall increased the proportion of snow cover in the watershed to 18.67%, which then gradually decreased. From day 13 onwards, the rate of snowpack decline became faster, resulting in a total decrease of 6.75% in the proportion of snow cover by day 16. During the winter season (see Fig 6(b)), snowfall initially increased the proportion of snow-covered area in the watershed to 38.47%. However, it rapidly declined and stabilized after day 5, with a decrease of 23.31% in the proportion of snow cover during this period. The overall rate of decline was calculated to be -1.5% per day. Consequently, the rate of ablation of the spring snowpack in the Han River Basin was lower than that of the winter snowpack.

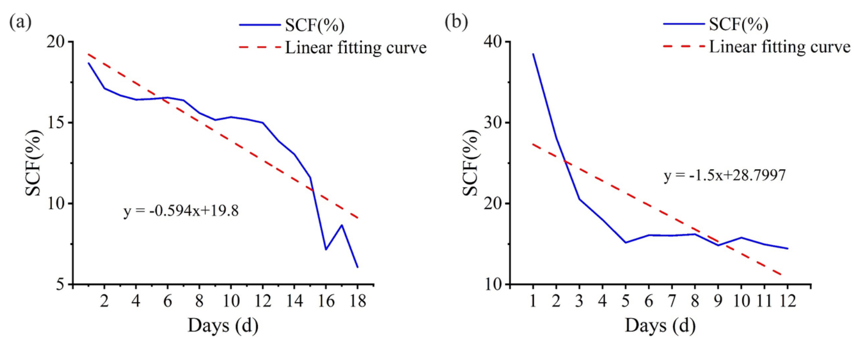


Figure 5 Rate of snow melting in the Hanliu River Basin during spring and winter snowfalls(a: Spring; b: Winter)

In the Hanliu River Basin, there are differences in the snowmelt process between spring and winter. In spring (Fig. 5(a)), the rate of snow ablation is slower. The proportion of snow cover in the watershed was initially 18.67% due to snowfall, and then gradually decreased. From day 13, the rate of snowpack decline became faster. By day 16, the proportion of snow cover had decreased by a total of 6.75%. During the winter season (Fig. 6(b)), snowfall initially brought the proportion of snow-covered area in the watershed to 38.47%. However, it rapidly declined and stabilized after day 5, with the proportion of snow cover decreasing by 23.31% during this time period. The overall rate of decline was -1.5% per day. Therefore, the rate of ablation of the spring snowpack in the Han River Basin was lower than that of the winter snowpack.

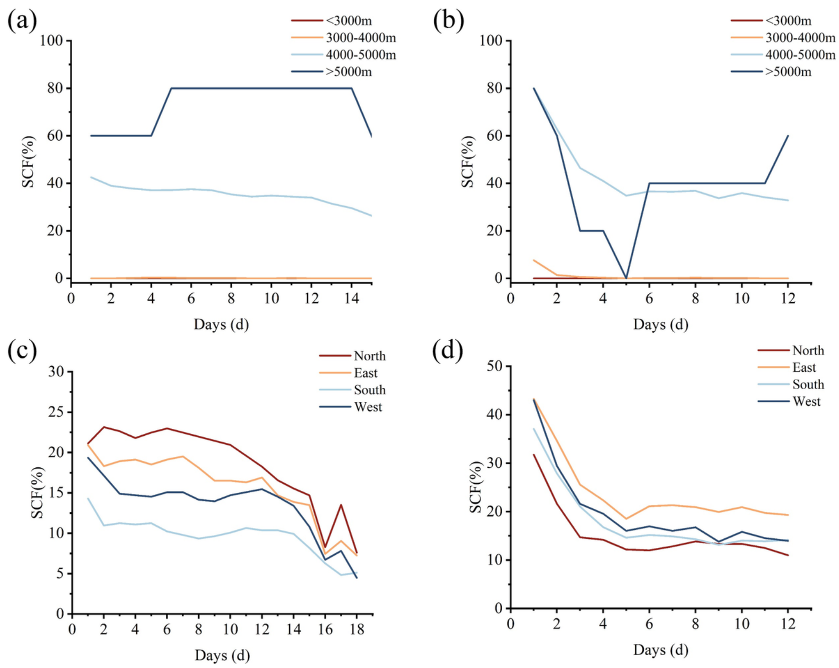


Figure 6 Changes in snowpack at different elevation slopes of the Hanliu River during spring and winter. (a, b. Spring and winter altitude; c, d Spring and winter slope direction)

The ablation rates of different slope directions in the Hanliu River Basin varied across seasons (see Fig 6 (c, d)). During spring, the descending order of ablation rates for the four slope directions was as follows: north slope > east slope > west slope > south slope, with the north slope having the highest rate and the south slope having the lowest rate. In winter, the order was: west slope > south slope > east slope > north slope, with the west slope exhibiting the highest ablation rate and the east slope showing the lowest ablation rate. The notable disparity in ablation rates between the two seasons can be attributed to the distinct influencing factors that govern ablation in spring and winter. During spring, the snowpack is primarily affected by precipitation, and the north slope, located on the leeward side, receives little precipitation, resulting in rapid snow ablation. Conversely, the south slope, situated on the windward side, experiences greater precipitation, leading to abundant snow accumulation and a slower ablation rate. In winter, the snowpack is significantly influenced by radiation. The western and southern slopes, being exposed to direct sunlight, have a higher capacity to absorb solar radiation, resulting in faster melting. On the other hand, the northern slopes, situated in shaded areas, are less affected by solar radiation, leading to a slower melting rate.

3.2 Stabilising snow distribution patterns

3.2.1 Mamukao River

In the spring (Fig 7(a)), the distribution of stable snowpack in the Mamukao River is extensive, covering 85.51% of the total area of the zone. However, stable snow cover is limited to the central and northern parts of the district, primarily due to their lower altitude valley locations. As altitude increases across different altitude zones, the percentage of area covered by stable snow gradually rises. At altitudes below 4400m, the distribution of stable snow areas is minimal, accounting for only 32.63% of the total area. Conversely, in the elevation range of 4400-4600m, the extent of stable snow accumulation is larger, covering 83.08% of the region's total area. The maximum coverage of stable snow accumulation is observed in the 4600-4800m elevation range, representing 92.66% of the area. Altitudes above 4800m account for 92.05% of the region.

In winter (Fig 7(b)), the Mamukao River is only partially covered by stable snow, accounting for a relatively small proportion of 10.6%. This coverage is significantly smaller compared to the area covered by stable snow in spring. The distribution of the stable snowpack is sporadic, primarily found in the eastern and western regions, while it is almost non-existent in the central and northern parts. The proportion of the area covered by stable snow gradually increases with higher altitudes. Below an altitude of 4400m, there is no distribution of stable snow, resulting in a snow cover proportion of 0. Between 4400m and 4600m, the area covered by stable snow is minimal, constituting only 1.61% of the total area. In the altitude range of 4600-4800m, the proportion of stable snow coverage increases to 17.96%. Finally, at altitudes exceeding 4800m, the proportion of stable snow cover reaches 47.16%, significantly surpassing other altitude areas.

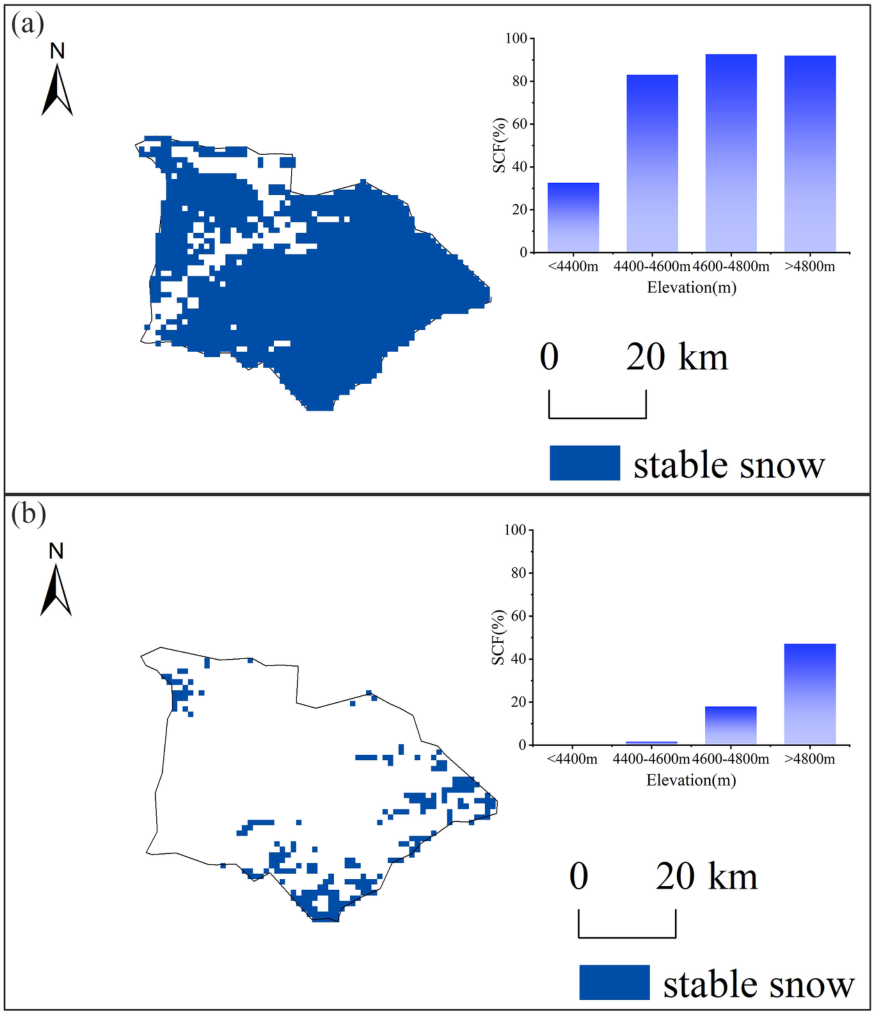


Figure 7 Patterns of stable snowpack distribution on the Mamukao River in spring and winter(a: Spring; b: Winter)

3.2.2 Hanliu River

The distribution pattern of the stable snowpack area in the Hanliu River is illustrated in Figure 8. During spring, the stable snowpack area is relatively small, comprising only 1.39 percent of the total district area. It is primarily concentrated in the higher elevation regions surrounding the watershed, while no distribution is observed within the watershed itself. Vertically, the proportion of area covered by stable snowpack gradually increases with elevation. Stable snow cover is absent below 4000 meters above sea level. In the elevation range of 4000-5000 meters, some stable snow is present, accounting for 3.08 percent of the snow-covered area.

However, the majority of stable snow during spring is found in areas with altitudes exceeding 5000 meters.

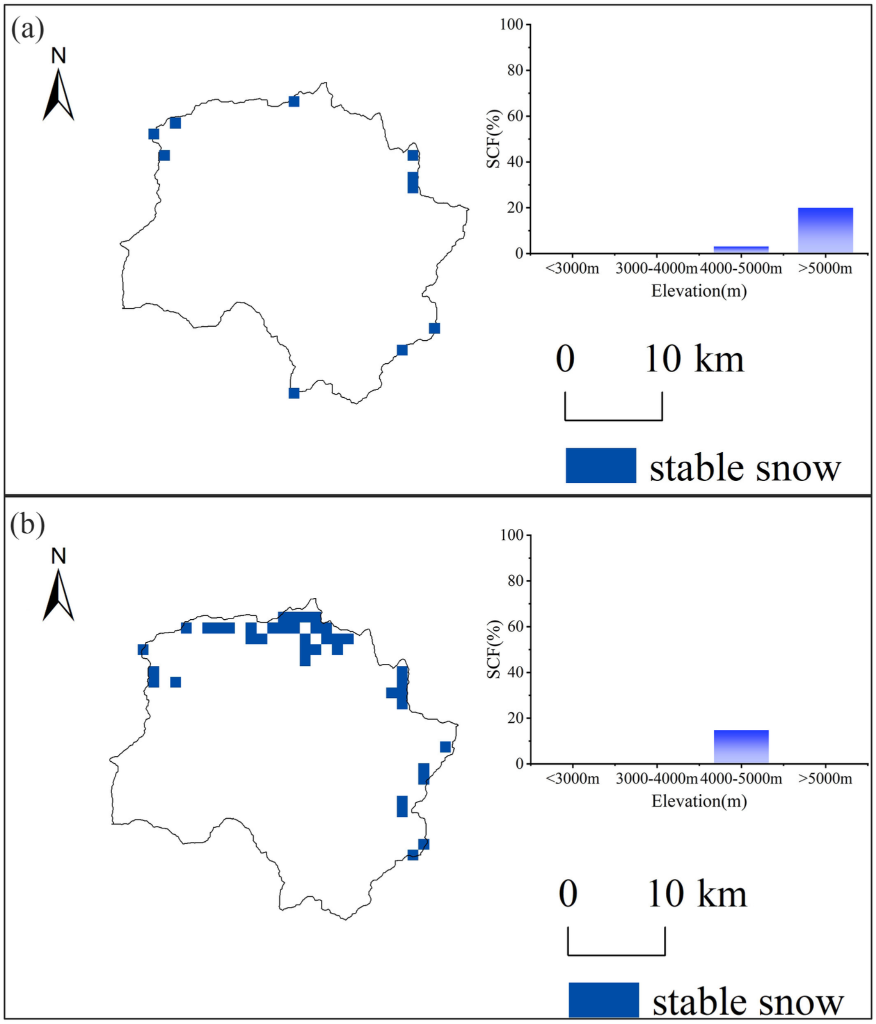


Figure 8 Patterns of stable snowpack distribution on the Hanliu River in spring and winter(a: Spring; b: Winter)

3.3 Impact factor analysis

3.3.1 MAXENT model accuracy check

The accuracy of the MAXENT model was evaluated using the ROC curve and the area under its curve (AUC). In this study, with the exception of the spring stable snowpack in the Mamukao River (Fig 9(a)), the AUC values of the stable snowpack driving factor model were greater than 0.8 for all seasons and areas. This indicates that the model accurately simulates the driving factors. However, the spring stable snowpack model for the Mamukao River showed a poor simulation accuracy, with an AUC value of 0.571. Therefore, the results of this model are only for reference. Apart from the spring stable snowpack in the Mamukao River, the maximum entropy model utilized in this study demonstrates strong applicability in assessing the driving factors of different stable snowpacks.

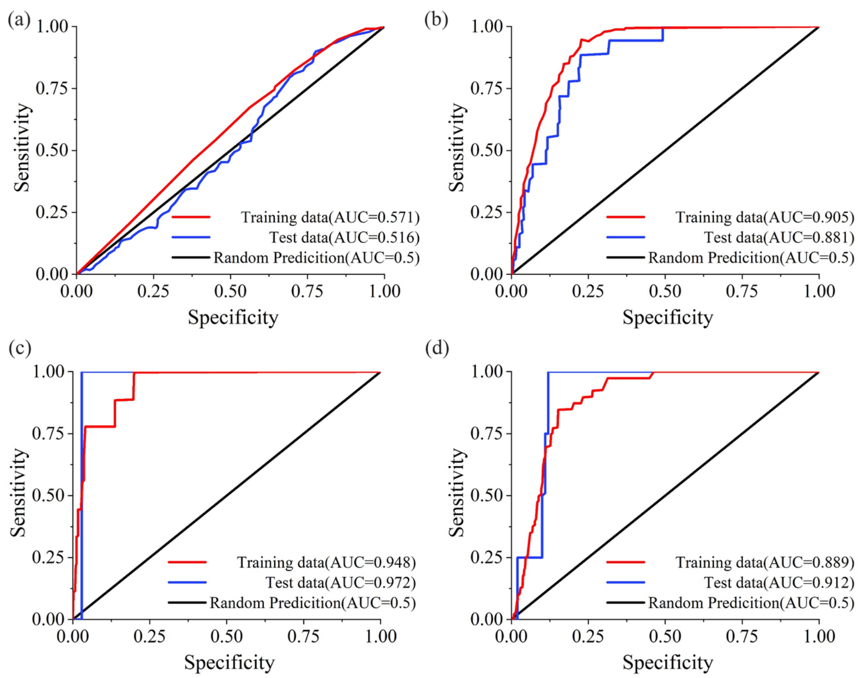
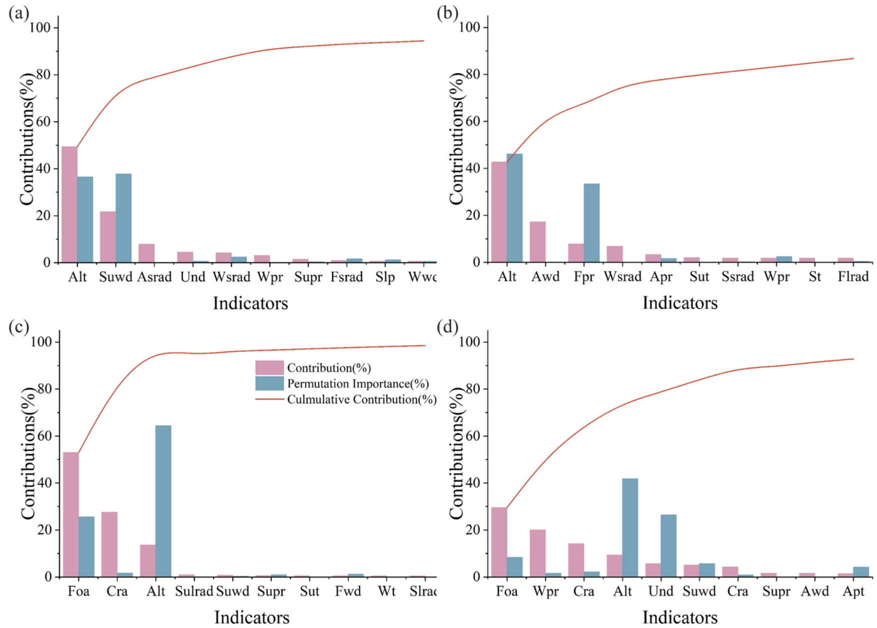


Figure 9 Accuracy of maximum entropy model simulations of stable snowpack patterns(a: mamukao river spring; b: mamukao river winter; c:hanliu river spring; d: hanliu river winter)

3.3.2 Impact factor analysis

In Figure 10, the cumulative contribution of the top 10 environmental factors in different seasons or regions is examined in relation to stable snowpack. The results show that these top 10 factors account for more than 85% of the overall contribution, suggesting their significant influence on the distribution pattern of stable snowpack. Consequently, this study focuses solely on analyzing the top 10 environmental factors based on the magnitude of their contribution rate. In the Mamukao River Basin (Fig 10(a,b)), there are variations in the dominant factors that stabilize snowpack patterns during spring and winter. The three most significant contributing factors in spring were Altitude (49.38%), Snow Water Equivalent (Suwd) (21.72%), and Incoming Shortwave Radiation (Asrad) (7.87%). Among these factors, Suwd (37.75%) and Altitude (36.56%) had the highest replacement importance, indicating their greater influence compared to other factors. The combined analysis of contribution rates and replacement importance suggests that the distribution pattern of stable snowpack in the Mamukao River during spring is primarily influenced by Altitude, Suwd, and Asrad. In winter, the top three contributing factors were Altitude (42.66%), Accumulated Snow Depth (Awd) (17.2%), and Frozen Precipitation (Fpr) (7.81%). Altitude (46.12%) and Fpr (33.45%) had the highest replacement importance, indicating their significant influence on the distribution pattern of stable snowpack in the Mamukao River during winter. Therefore, the three main factors influencing the distribution pattern of stable snowpack in winter in the Mamukao River are Altitude, Fpr, and Awd.

In the Hanliu River basin (Fig 10(c,d)), the distribution pattern of stable snowpack is influenced by different factors in spring and winter. In spring, the three most significant contributing factors are Foa (53.04%), Cra (27.58%), and Alt (13.63%), with Foa being the most influential. The two factors with the highest replacement importance are Alt (64.43%) and Foa (25.62%). Therefore, the dominant factors in stabilizing the snowpack in the Hanliu River during spring are Foa, Cra, and Alt. In winter, the three factors with the highest contributions are Foa (29.58%), Wpr (20%), and Cra (14.14%), while the two factors with the highest replacement importance are Alt (41.87%) and Und (26.43%). Taking into account both the contribution rate and replacement importance, the factors that have a greater influence on the spatial distribution pattern of stable snowpack in winter are Foa, Wpr, Cra, Alt, and Und.



Comparing the dominant factors contributing to stable snowpack in the two basins and across the two seasons, elevation emerges as a common factor influencing all types of stable snowpack. This suggests that the distribution pattern of stable snowpack is primarily driven by elevation. However, the dominant factors vary considerably between different regions and seasons within the same region.

Figure 10 Contributions and importance of the top 10 contributing environmental factors to the pattern of stable snowpack distribution in two major watersheds in winter and spring(a: mamukao river spring; b: mamukao river winter; c:hanliu river spring; d: hanliu river winter)

4 Discussion

4.1 Impact of stable snow on hydrological processes

In this study, we investigated the process of stable snow formation and its distribution pattern in two major watersheds of the eastern Tibetan Plateau-Kawasaki Plateau by means of the daily MODIS snowpack dataset, showing that the distribution pattern of stable snow was different between the Mamukau River Basin in the hilly plateau region and the Hanliu River Basin in the alpine valley region; in the Mamukau River Basin, the area of stable snow cover was larger in the spring, and the area of stable snow cover was smaller in the winter. The long retention time of the spring snowpack, its ablation rate is much smaller than that in winter, and the large area of stable snowpack provides an adequate water supply for the downstream rivers, similar to the role of glaciers in recharging water resources in summer. It shows that the spring snowmelt can effectively regulate the downstream river runoff, and the water volume is more uniform; while the winter snow melt is fast, the downstream river may rise significantly in a short period of time, but the water volume fluctuates greatly, and the winter snowfall is small, which may lead to some of the rivers in winter with small water volume or "cut-off"(López-Moreno et al. 2020); in the alpine valley area of the Hanliu River Basin, the stable snowpack is mainly distributed in the high altitude area, which is the main source of water supply. In the Hanliu River basin in the alpine valley area, the stable snowpack is mainly distributed in the high altitude areas. Due to the large vertical difference, there are differences in the water and heat conditions in different areas, and the melting of snow shows a situation of "low first and then high", with the snow at low altitude melting faster and the snow at middle and high altitudes melting later, which can play a role in regulating river runoff to a certain extent. In winter, due to less precipitation and faster ablation, this regulation may be less effective than in spring, and in the later stages there may be a significant reduction in the volume of water in the downstream rivers(Harpold et al. 2017).

Stable snowpack, as a stable material, is important for biochemical cycling at regional and hemispheric scales. In the snowy season, the stable snowpack can cache a large amount of snow, which makes the snow and ice gradually melt and infiltrate into the soil, providing a stable runoff supply for the snow melting season. Compared with the unstable snowpack, the snowmelt runoff in the stable snowpack area in the spring and summer snow melting seasons is more stable, which can effectively prevent the spring and summer ice and snow flood disasters, and is of great significance for the residents' production and life and the water supply of the city, and other water resources management. In addition, stabilizing snowpack plays an important role in temperature regulation. Due to its high albedo, snow can effectively reflect solar radiation and reduce the ability of the ground to receive solar radiation. In this study, the snowpack on the Western Sichuan Plateau was studied and analyzed, and although the focus of this study was mainly on the Western Sichuan Plateau, it is representative and exemplary as part of the Tibetan Plateau. At the same time, snowpack, as one of the important elements on a global scale, has a significant impact on climate change and water allocation(Sturm et al. 2005). In-depth study of the formation process and pattern of stable snowpack on the western Sichuan Plateau can provide reference value for the study of stable snowpack in other highland mountain areas and contribute to the understanding of global stable snowpack. In addition, the study of the formation process and stabilization pattern of the stable snowpack in the Western Sichuan Plateau can provide insights into ecological environmental protection, water resource management and disaster prevention on a global scale, which is of great significance in promoting scientific research and practice in this field.

4.2 The problem of ROC accuracy of the maximum entropy model for the Mamukao River

In this study, the AUC value of the maximum entropy model ROC curve for spring in the Mamukao River was only 0.571, significantly smaller than the AUC values obtained from the other three types of models. Chen et al demonstrated a correlation between the sample size of the species (feature) distribution and the AUC value, indicating that a larger sample size corresponds to a higher AUC value and better accuracy of the predictive model (Chen et al. 2012). However, if the sample size for the presence of the species (feature) is excessively large, such as in the case of presence-only samples, the ROC curve cannot be applied due to the absence of negative examples for measuring specificity at the present moment (Anderson et al. 2003,Phillips et al. 2006). The Mamukao River exhibits a significant presence of stable snow during the spring season (see Figure x). Out of the total 1682 raster samples, only 276 were found to be non-accumulating, while the remaining 85.6% represented accumulating raster samples. However, the lack of specificity in our data may have contributed to a lower accuracy in the prediction model for the spring maximum entropy of the Mamukao River.

4.3 Differences in seasonal snowmelt of the Western Sichuan Plateau

The Mamukao River exhibits a broad distribution of stable snow during spring (see Figure x). The region encompasses 1682 raster sample numbers, of which only 276 represent non-accumulating raster samples. The remaining raster samples, which account for 85.6% of the total, indicate snow accumulation. The lack of specificity in these measurements may result in diminished accuracy of the prediction model. Consequently, the spring maximum entropy prediction model employed in this study yielded low accuracy for the Mamukao River (Jiang et al. 2020,Shuying et al. 2015). However, it has also been shown that radiation, windblown snow, and precipitation all contribute to the snowpack to some degree, and the influencing factors may vary between seasons (Alonso-González et al. 2020,Ding et al. 2023). In the Tian Shan region of Xinjiang, the snowpack extent is significantly influenced by temperature in spring and summer, while precipitation plays a predominant role in winter. In the western Sichuan Plateau, despite lower temperatures during winter compared to spring, snow retention is better, but winter precipitation is limited, and there are more clear days with strong solar radiation. As a result, the snowpack melts faster due to radiation. Additionally, the winter season in the western Sichuan Plateau experiences strong winds, which can cause snow transport and redistribution to lower elevations or sublimation in the atmosphere. On the other hand, in spring, although temperatures are higher, the abundant precipitation and fewer clear days result in reduced ability of the snowpack to absorb solar radiation. Furthermore, lower-altitude areas experience higher temperatures, leading to faster snowmelt. However, these areas have less snow distribution, mainly due to precipitation, whereas higher-elevation mountainous areas receive more snowfall, resulting in a widespread snow distribution. Consequently, snow variations in these areas are relatively stable, leading to a slower snowmelt rate in spring compared to winter.

4.4 Dominant factors stabilising snowpack distribution

At large scales, temperature and precipitation are the primary factors that influence the distribution of snowpack. However, at regional scales, additional factors, such as topography, play a significant role in contributing to the heterogeneity of snowpack distribution (Jiang et al. 2020,Li et al. 2023,Saydi et al. 2020). In this study, elevation played a significant role as the influencing factor for the stable snowpack during both winter and spring in both basins. The areas with high elevation predominantly exhibited the presence of a stable snowpack. This finding aligns with Chu et al.'s study on the spatial distribution of snow cover on the Tibetan Plateau, which indicated a positive correlation between elevation and snow cover extent. Specifically, their study demonstrated that higher elevations experienced greater snow cover (Chu et al. 2017). Additionally, the findings of this study indicate that the distribution of a stable snowpack is influenced not only by elevation but also by factors such as wind speed, radiation, and the proportion of subsurface area. In the Mamukao River Basin, wind speed emerges as the primary determinant in the distribution of a stable snowpack during winter and spring. The prevalence of high wind speeds in this region increases the likelihood of "wind-blown snow" phenomenon, which, in turn, leads to sublimation, ablation, or redistribution of the snowpack. Consequently, this process significantly impacts the overall distribution pattern of the stable snowpack (Fujita et al. 2010). Radiation has implications for the distribution pattern of stable snow in the region. Specifically, the Tibetan Plateau experiences the highest solar radiation levels in China (Qi et al. 2014),The Mamukao River Basin is located in the inland area of the Western Sichuan Plateau. It experiences low precipitation and frequent sunny days, which leads to rapid snowmelt due to high radiation. In the Hanliu River Basin, the stability of snow distribution patterns is mainly influenced by land cover types and precipitation. The Hanliu River is situated in the alpine canyon area of the Hengduan Mountains. The vertical zoning in this area plays a significant role in determining the type of subsurface, which, to some extent, reflects the water and heat conditions of the region. Additionally, the rate of snow melting varies depending on different subsurface conditions (Zhang et al. 2014); The Mamukao River Basin is primarily characterized by grassland ecosystems, and the specific type of land has a minimal impact on the distribution pattern of stable snow. Consequently, the influence of the Mamukao River Basin on the subsurface is relatively limited, while it exerts a greater influence on the Hanliu River Basin. (Note: Please double-check the APA style guide for specific formatting requirements related to citations and references.)

4.5 Remote sensing image uncertainty

This study utilizes the MODIS day-by-day cloud-free snow cover dataset to mitigate the impact of cloud cover to some extent. However, the spatial resolution of the MODIS data is 500m, which may not be sufficient to detect small-scale areas of snow accumulation in the two watersheds examined in this study. Furthermore, the dataset employs the NDSI normalized snow index with a threshold of 0.4 to extract the snowpack, which has demonstrated reliable accuracy in North America (Hall et al. 1 995,Hao et al. 2008a). However, numerous studies have demonstrated that employing an NDSI threshold of 0.4 in China leads to a substantial underestimation of ground snowpack (Hao et al. 2008b,Zhang et al. 2019). Meanwhile, the western Sichuan Plateau is situated in the eastern part of the Tibetan Plateau, characterized by extensive forest coverage. Zhao et al. (year) demonstrated that the accuracy of NDSI in extracting the snowpack in forested areas was inadequate (Zhao et al. 2016). Combined with the aforementioned reasons, the utilization of MODIS day-by-day cloud-free snowpack area data in this study may result in an underestimation of the snowpack area. Consequently, this underestimation may lead to inaccuracies in the classification of snowpack types in certain regions. Therefore, future research conducted in the area should prioritize addressing the concerns of data accuracy and its applicability

5 Conclusions

In this study, we compared the formation process and distribution pattern of stable snowpack during winter and spring in two typical areas of the western Sichuan Plateau: the Mamukao River Basin and the Hanliu River Basin. We utilized the MODIS day-by-day cloud-free snow cover dataset for our analysis. Additionally, we comprehensively analyzed 33 environmental factors to identify the dominant factors influencing the distribution of stable snowpack in the two basins during winter and spring. The following conclusions were drawn:

(1) The snow ablation rate is higher in winter compared to spring on the western Sichuan Plateau, with the Mamukao River Basin experiencing a greater ablation rate than the alpine valley area. In spring, the snow ablation rate generally decreases with increasing altitude in both the Mamukao River Basin and the Hanliu River Basin. Conversely, in the Hanliu River Basin during winter, higher altitudes correspond to a faster snow ablation rate. Furthermore, the ablation rate in the Mamukao River Basin exhibits little variation across different slope directions during winter and spring, whereas the Hanliu River Basin shows significant variation in ablation rate across different slope directions during these seasons.

(2) During seasons other than winter in the Hanliu River Basin, the stable snowpack is predominantly found in high-altitude areas. Moreover, the area covered by stable snowpack increases with higher altitudes. However, in the Hanliu River Basin during winter, the stable snow cover is primarily distributed in areas with altitudes ranging from 4000-5000m.

(3) Elevation is a dominant factor influencing both the Mamukao and Hanliu River basins during winter and spring, although the impact of other factors varies across different seasons and regions. Specifically, the Mamukao River Basin is more significantly affected by wind speed, radiation, and precipitation, whereas the type of subsurface plays a major role in influencing the Hanliu River Basin.

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