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A Study of Spatiotemporal Monitoring of Land Cover Dynamics in Mountain Vertical Natural Zones in the Context of Climate Change

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Abstract: In the context of global climate change, monitoring the spatial and temporal land cover dynamics of mountain vertical natural zones is crucial for understanding ecological responses and climate regulation. Through methods such as literature research and case studies, this study reviews the differential response of vertical natural zones of maritime and continental glaciers to global warming, as well as the existing land cover classification systems, remote sensing monitoring and analysis techniques, and ground-based monitoring techniques. The results show that climate change has a significant impact on the vertical natural zones in mountainous areas, with maritime glaciers retreating faster and vegetation zones moving upwards under the influence of oceanic climate, while continental glaciers are less sensitive due to their inland location, but still show a continuous retreat under the long-term warming trend. In addition, different remote sensing and monitoring techniques have their own characteristics and limitations. This study highlights the need for cross-regional comparative studies and technology integration, which can help construct ecosystem response prediction framework applicable to different mountain environments and provide a scientific basis for global ecological governance and sustainable development.

Keywords: Mountain vertical natural zones, climate change, maritime glacier, continental glacier, land cover, remote sensing

1. Introduction

Mountainous natural zones vary dramatically in the vertical direction, and vertical differentiation phenomena such as vegetation zones and glacier boundaries amplify climate signals, making these regions highly sensitive to global warming and key indicators of climate change impacts. Therefore, systematic study of vegetation changes in the spatiotemporal dynamics of land cover in the vertical natural zones of glaciated mountains can provide highly sensitive ecological indicators for global climate change monitoring and facilitate decision-making on regional ecological protection and climate governance. Past research has been fruitful, Zhang et al. [1] studied vertical land cover change in the middle Himalayas, revealing the impact of climate change on land cover in mountainous regions, Rubel et al. [2] demonstrated the relationship between Köppen-Geiger climate classification and Alpine elevation zones by calculating the boundaries of climate zones. Hock and Huss [3,4] point to mutual feedback mechanisms between glaciers and climate, with temperature being the main driver of global glacier mass loss and glaciers being the main driver of recent global mean sea level rise. At

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the same time, land-cover classification and remote sensing technologies have continued to make progress, remote sensing technologies, such as Sentinel-2 and Landsat, being widely used as the core tools for dynamic monitoring of vegetation coverage, which have improved the accuracy of land-cover classification.

Glaciers, as core components of mountain systems, show different ways of responding to differences in their climate context. Existing studies have mainly focused on the dynamics of the vertical band spectrum of a single typical glacier, such as the Himalayas and the Alps. However, the intrinsic properties of glaciers are less well addressed as factors in their differential climate response, and the lack of systematic comparisons in the existing literature that attribute observed changes to differences in glacier types limits our overall understanding of climate-glacier interactions.

The purpose of this paper is to study the monitoring of land cover dynamics of mountain vertical natural zones under the background of climate change, and to compare the different responses of vertical natural zones of maritime and continental glaciers to climate change. The article first reviews the relevant background knowledge, including the eco-climatic significance of glacial vertical natural zones, classification criteria and technical methods; then analyses the climate-driven changes in the two types of glacier vertical natural zones, and then summarizes the classification system and monitoring techniques of mountain vertical natural zones; finally, it puts forward suggestions and outlooks for future research to contribute to global ecological conservation and sustainable development.

2. Background

2.1. Eco-climatic significance of glacial vertical natural zonation

Under specific conditions, the gradient of natural zone variation in the vertical direction can be 1,000 times greater than that in the horizontal direction. The study of mountain altitudinal zonation is an effective approach to reveal the complexity and heterogeneity of mountain environments. Moreover, Changes in vertical zonation serve as both indicators and ‘amplifiers’ of climate change signals [1]. For example, as a large number of studies in dendroecology have shown, growth responses of forest trees at the treeline of mountains or slightly below the alpine treeline are very sensitive indicators for assessing the impacts of rapid climate change [2]. These vertical zonation dynamics are particularly remarkable in glacial regions. Losapio et al. [5] indicate that the interactions between glaciers and climate create a positive feedback loop that accelerates further warming, resulting in additional glacier retreat and heightened threats to highly-adapted biodiversity and ecosystem services that rely on glaciers.

According to climatic conditions and physical properties, glaciers can be divided into maritime and continental glaciers. Maritime glaciers are formed in oceanic climate zones and are characterised by high precipitation, large snowpack and strong temperature sensitivity, while continental glaciers are found in inland areas and exhibit low precipitation, a high snow line and a slower response to climate warming. The climatic differences between the two types of glaciers directly affect the vegetation pattern, with maritime glacier areas influenced by humid air currents and has a variety of vertical vegetation zones, while continental glacier areas are dominated by arid-adapted vegetation such as alpine deserts, with a limited distribution of forested zones [6]. This difference highlights the need to explore the dynamics of vegetation cover in these two types of regions in the context of climate change.

2.2. Criteria and technical methodologies of land cover classification

The precise land cover classification in the vertical natural zonation of glaciers is crucial for studying the interaction between climate and ecosystems. Current classification systems, such as the UN-FAO

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Land Cover Classification System developed by the United Nations Food and Agriculture Organization, aim to provide a consistent framework for the classification and mapping of land cover, overcome the rigidity of prior land cover classifications, and the International Council for Science (ICSU) initiated and organized the International Geosphere-Biosphere Programme (IGBP), which defined the classification of ecosystem surface.

Remote sensing technology is the core method for monitoring glacier land cover. Multispectral data (such as Landsat 8/9 and Sentinel-2) distinguish natural band types such as ice and snow, bare rock, and vegetation through threshold analysis of indices like NDVI and NDSI. For instance, Ernst et al. [7] quantified the area abundance of plant species using the ground values of NDVI, collected ground hyperspectral data with visible and near-infrared imaging spectrometers, and mapped plant communities. Chen et al. [8] resampled NPP data to analyze the vegetation changes in regional vertical natural zones.

However, Paul et al. [9] indicate that the accuracy of mixed pixels in transition zones is relatively low. Meanwhile, the multi-endmember spectral mixture analysis algorithms had the highest accuracy in bare land, grassland, and the Himalayan region [10].

2.3. Classification and characteristics of maritime glaciers and continental glaciers

Glaciers can be classified into maritime and continental glaciers based on climatic conditions and physical properties. Maritime glaciers are usually located in areas close to the ocean and are influenced by the oceanic climate, with high precipitation and snowpack in winter and temperature sensitivity in summer, thus responding significantly to climate change. Continental glaciers, on the other hand, develop in continental climatic zones with lower precipitation, higher snow lines and slower response to climate change.Holmlund and Schneider noted that, in the context of global warming, continental glaciers typically retreat 10 to 15 years later than maritime glaciers.

3. Climate change impacts on mountain vertical natural zones and monitoring of land cover dynamics

3.1. Climate-driven changes in mountain vertical natural zones

It is widely recognized that the most prominent feature of mountain landscapes is that with increasing altitude, there is a clear vertical differentiation in climate, vegetation, soil, and the entire natural geographic complex of the mountain area. This differentiation results in a variety of interconnected climatic zones, as well as vegetation and soil zones, particularly those exhibiting a certain order and structure, with vegetation serving as the primary symbol [11]. Mountains' natural environment is primarily governed by their climate, which affects their biological, physical, and chemical activities. Global change is posing previously unheard-of difficulties for the distinctions and interconnections among the vertical zones of mountain forests [12]. Climate-driven studies of vertical natural zones in mountains have focused on changes in the forest line, plant succession, and biodiversity.

3.1.1. Maritime glacier

Maritime glaciers are found in areas that are significantly influenced by moist ocean currents, and their proximity to the ocean results in high humidity and precipitation, high snowfall accumulation, and a low snow line. Such as the Alps, the Pacific Coastal Mountains of North America, and the eastern Himalayas. The formation and melting of these glaciers are mainly controlled by both precipitation and temperature. However, the vegetation cover of such glaciers is also more susceptible to global warming.

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In the case of the eastern Himalayas in China, are influenced by the warm and humid currents of the Indian Ocean and are home to the Kachin Glacier, the longest marine glacier in China. A unique and complete vertical natural belt spectrum of humid types has developed here, characteristic of the northern edge of the tropics. The study **(**Mountain Research Initiative EDW Working Group,2015**)** noted that higher altitudes are warming faster than lower altitudes, and the Himalayas are one of the fastest-warming regions in the world. Niti and Kumar [13] indicate that greening (as detected by rising atmospheric carbon dioxide concentrations and nitrogen deposition) dominates at most low and middle elevations (regions below 4200m). With increasing temperatures, the glacier area decreases significantly, the upper limit of the forest belt shifts upward, and the alpine meadow belt expands to higher altitudes.

Take the typical temperate maritime glacier, the Swiss Alps, for example. According to the study [14] climate change will result in the upward migration of elevational vegetation zones. During the past 210 years, the timber line has fluctuated in elevation by around 100 meters. The tree line has moved upward by around 157 meters during the 19th and 20th centuries. Compared to the Eastern Alps, this upward turn in the Western Alps is 35 meters higher. The snow line and the borders of the other altitudinal bands have been estimated to show similar tendencies.

In terms of changes in biodiversity, Sun and Cheng [15] showed that on a large scale, species richness increased by 10% and 9% in the upper alpine and sub-snow-covered areas, respectively, and by 3% and 1% in the lower alpine and timberline areas, respectively. The small-scale and large-scale changes were quite different, with species richness decreasing at lower altitudes and the opposite trend at higher altitudes.

3.1.2. Continental glacier

Continental glaciers are mainly distributed in arid and semi-arid regions far from the oceans and are less sensitive to climate change, such as the Tian Shan and Kunlun Mountains in Central Asia and the interior of the Rocky Mountains in North America. However, they are still experiencing increased glacier ablation under the influence of long-term warming trends, but the rate of glacier ablation is usually slower than that of maritime glaciers because of the relative stability of their glacier accumulation, which relies mainly on small amounts of solid precipitation.

According to the study by Zheng [16] on the mountains of the Tibetan Plateau, the continental belt spectrum system is primarily dominated by desert and grassland sub-bands, with montane forest belts occurring only in localized areas. For example, the upper boundary of the alpine desert on the main ridge of the Central Kunlun Mountains is directly connected to the subglacial snow belt. Additionally, the upper limit of forests tends to rise from semi-arid to arid types, while the upper alpine scrub-meadow belt gradually differentiates into alpine-meadow belts and alpine-meadow and cushion-vegetation belts. Furthermore, the distribution of subglacial belts is significantly elevated towards the interior of the plateau.

Taking the Tianshan Mountains as an example, the study [17] shows that the 'warming' trend of temperature change in the Tianshan mountain system is obvious, and the upper limit of the mountain grassland belt fluctuates relatively little, and the lower limit of the distribution declined by about 150-200 m from 2001 to 2018; the upper and lower limits of the distribution of the forest belt fluctuate less in elevation; and the lower limit of the distribution of the ice belt as a whole shows a state of retreat to higher elevations. The lower limit of the distribution of the ice and snow belt as a whole shows a state of retreat to higher altitudes.

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3.2. Land cover classification methods for mountain vertical natural zones

Land-use and land-cover change (LUCC) plays an essential part in global environmental change, and it has a substantial impact on biodiversity, climate change, ecosystem services, biogeochemical cycles, and Earth-atmosphere interactions. Therefore, to achieve sustainable development and make better use and management of valuable land resources, it is essential to comprehend their dynamic processes and effects [18]. Global mountains cover one quarter of the Earth's land surface, with complex topography, climate variability, and significant differences between maritime glaciers and continental glaciers, and are most susceptible to environmental change and global warming, making the classification and detection of land cover types a unique challenge and opportunity.

3.2.1. Classification system

Internationally, the Land Cover Classification System (LCCS) of the Food and Agriculture Organisation of the United Nations (FAO) is the widely used basic framework. It provides a uniform standard for global land cover classification, and the classification system can be used as a reference base applicable to all regions, thus serving as a benchmark for cross-regional comparisons in studies of mountain vertical natural zones [19].

The fact that the land cover classification of vertical natural zones in mountains can develop different characteristic systems is rooted in the significant differences in mountain ecosystems around the world. On the one hand, natural environmental factors such as topography, climate conditions, and hydrological characteristics vary greatly from one region to another; on the other hand, different modes and intensities of human activities also affect the classification of mountain land cover. Therefore, in order to meet the diversified needs of scientific research purposes and applications, and to ensure that ecological protection is carried out according to local conditions, different regions will construct different land cover classification systems according to their own characteristics.

3.2.2. Monitoring techniques

Methods of research in the field of mountain vertical vegetation zones, with the development of space technology, analysis methods based on remote sensing technology have gradually become the mainstream tools [20]. High-resolution remote sensing satellites, such as the Landset series satellites and Sentinel-2 satellites, are effective in identifying the type of vegetation, snow, and ice cover, etc., in the vertical natural zones of mountainous regions by acquiring the spectral characteristics of different features. The normalised vegetation index (NDVI) is commonly used to monitor changes in vegetation cover, while the normalised snow index (NDSI) is suitable for extracting glacier and snow information.

In recent years, remote sensing collaborative inversion has become a frontier research field. With the help of geographically assisted knowledge base and multi-source remote sensing data, this technology quantitatively describes the characteristic parameters of spatio-temporal changes of the ground surface and comprehensively inverts the ground surface parameters, which can establish the information model of spatio-temporal multi-variable elements as well as the theoretical and methodological system of parameter inversion based on the assistance of systematic a priori knowledge. At the same time, it exerts the advantages of the combination of multi-sensor spatial information and spectral features, and has high application value in vegetation remote sensing mapping [21]. Yao et al. combined topographic constraints with multi-source and multi-temporal high-resolution remote sensing data, ground survey data and vegetation type map data to effectively extract vegetation types at all levels. Zhang et al. extracted characteristic parameters from Radarsat-2 full polarization SAR data and Sentinel-2 optical data to cooperatively invert soil moisture in the surface layer of winter wheat cover using multi-source remote sensing data.

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The current research findings indicate that the DEM-NDVI scatter plot is the optimal method for quantitatively delineating vegetation vertical zones [22]. DEM-NDVI scatter plots characterise alpine vegetation NDVI with elevation more completely than sample point DEM-NDVI distribution plots [23]. However, Studies find it challenging to differentiate between deciduous and evergreen forests using NDVI alone in forest ecosystems with abundant summer vegetation because they have similar NDVI values [24]. Therefore, it is challenging to estimate the boundaries between different vertical zones based on scatter diagrams.

Zhao et al. [25] analysed the structure of the NDVI-DEM scatter plot, qualitatively assessed the vegetation types corresponding to each area of the scatter plot, and quantitatively delineated the vertical zones of the vegetation in the Tibai Mountains by using the binomial curve and half-peak width calculation method. Chang et al. [26] used Landset TM remote sensing images to obtain DEM-NDVI scatter plots to analyse the characteristics of NDVI changes with elevation, and then used the existing data and the interpretation results of WorldView-2 high-resolution remote sensing images to analyse the corresponding vegetation types of each section, and to quantitatively depict the characteristics of the vertical zonation of vegetation in the Wolongguan valley in Wolong Giant Panda Nature Reserve.

These two techniques complement each other in the study of vertical natural zones in mountains. Remote sensing collaborative inversion helps researchers to understand the overall environmental conditions of the natural zones by providing multi-dimensional comprehensive data, while NDVI-DEM scatter map focuses on the quantitative delineation of the vertical vegetation zones and clarifies the specific boundaries, and the two of them provide a strong support for the study of vertical natural zones in mountains from different perspectives.

3.3. Ground-based monitoring

Ground-based monitoring techniques are equally important in validating remotely sensed data and capturing ecological changes in the vertical natural zones of mountains. Unlike satellite observations, ground-based techniques can provide high-resolution data on plant communities, microclimate, and substrate characteristics. The main ground-based monitoring methods include sample plot-based surveys, drone technology, and microclimate instrumentation. Sample plot surveys quantify vegetation composition and soil properties at specific elevations by identifying sample points and sampling profiles. For example, Wang et al. [27] set up sample plots according to elevation based on the differences in natural vegetation and soil types in the vertical zone of Mount Lushan, and analysed and processed the collected samples for the determination of soil physicochemical properties. UAV technology, on the other hand, fills the gap between satellite and ground data. As noted by Xie et al. [28], with the development of UAV low-altitude photogrammetry and remote sensing technology, UAV-LiDAR has become a more flexible LiDAR technique capable of acquiring a wide range of vegetation canopy information. And they applied the UAV-LiDAR equipment and vertical structure extraction and analysis techniques to the study of vertical structures in broadleaf evergreen forests. Microclimate instruments help researchers reveal the relationship between land cover change and climate drivers. Wei et al. used a soil time-domain reflectometer to determine the soil moisture content of microplots, a digital electrocouple probe thermometer to determine the soil temperature of the microplots, and a digital temperature and humidity meter to determine the relative humidity of the air above the microplots. To obtain the microclimate dynamics of the pit and mound complex within the forest gap of Pinus koraiensis-dominated broadleaved mixed forest.

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4. Suggestions and prospects

In the context of climate change, spatiotemporal monitoring of land cover dynamics in mountain vertical natural zones, especially the contrast responses study of maritime and continental glaciers, is of great significance. Based on the above research content of this paper, the following suggestions and prospects are proposed.

4.1. Strengthening the integration of multi-scale monitoring techniques

SIn the monitoring of land cover dynamics in mountain vertical natural zones, remote sensing technology, analysis technology, and ground-based monitoring technology complement each other, and it is crucial to combine them correctly. In future research, it is possible to explore how to integrate multi-scale and multi-source data more effectively in order to improve the accuracy and efficiency of monitoring.

With the development of artificial intelligence and big data technologies, the use of machine learning algorithms and large-scale processing techniques can be explored in the future to optimise land cover classification and monitoring methods, and to improve the efficiency of the study and the prediction of change trends.

4.2. Long time series analysis in a wider range of regions

The current study focuses on typical mountainous regions, such as the Alps, the Himalayas, and the Rocky Mountains, etc. In the future, it is necessary to expand the scope of the study, especially in some less-studied regions, such as some mountain ranges in Africa and South America, to understand the universality of land cover changes in the global mountainous vertical natural zones is as important as the specificity. This will not only deepen human scientific knowledge of natural geographic processes, but also provide a key basis for ecological environmental protection and resource management at the regional and global scales. At the same time, there is a need to strengthen the analysis of land-cover dynamics over long time series, and the use of historical data over long time spans can more accurately predict the long-term evolution of land cover in the vertical natural zones of mountains.

4.3. Strengthening research on interaction mechanisms

Changes in the Earth's natural environment are always interlinked, especially in the current context of global warming, and a comprehensive and in-depth understanding of the interaction mechanisms will provide a scientific basis for the optimisation of global ecological governance as a whole. Currently, there is a lack of research on the different responses of maritime and continental glaciers to climate change, and there is a need to further quantify the long-term trends of these differences. It is recommended that more cross-regional and cross-scale comparative studies be carried out in the future to explain the profound impacts of climate change on the dynamics of different types of glaciers. Furthermore, there are interaction mechanisms between different land cover types in the mountain vertical nature zone, and understanding these interaction mechanisms can help to develop more rational management measures for ecological conservation.

5. Conclusion and prospect

This paper focuses on the spatiotemporal monitoring of land cover dynamics in the vertical natural zones of mountains under the background of climate change, and through a comparative study of maritime and continental glaciers, it specifically explains their different responses under the background of global warming. Meanwhile, by reviewing a large number of related studies, research

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methods such as remote sensing with its analysis techniques, ground monitoring tools and classification systems are summarised.

It was found that climate change has a significant impact on the vertical natural zones of mountains, and there is a significant difference in climate response between maritime glaciers and continental glaciers. Maritime glaciers are more sensitive to climate change due to the influence of the oceanic climate, which is manifested by the faster rate of glacier retreat and the obvious migration of the forest belt; while continental glaciers are located inland, so their response is relatively lagging behind, and their sensitivity degree is low, but they still show a retreat trend under the long-term warming trend. The continental glaciers are less sensitive because they are landlocked, but still show a retreating trend under the long-term warming trend. In addition, different remote sensing analysis techniques and monitoring techniques have their own characteristics and limitations; DEM-NDVI scatter plot can comprehensively describe the relationship between NDVI and elevation of alpine vegetation, and quantitatively delineate the vertical vegetation zones, but it has limitations in the processing of mixed pixels. Ground monitoring technology effectively complements the limitation of the resolution of remote sensing analysis technology, helping the study to obtain higher precision and deeper analysis.

Looking ahead, follow-up studies should carry out more comparative studies across regions and scales, strengthen the integration of multi-scale monitoring techniques, further explore the understanding of interaction mechanisms, and seek international cooperation and integration with new technologies. This study is of great significance to global ecological conservation and sustainable development, and will help researchers to better understand mountain ecosystems in order to cope with the far-reaching impacts of climate change on them.

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