A Review of the Impacts and Risks of Climate Change on Mountain Glacier Tourism (Postprint)

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Date: 2026-03-24T22:05:25+00:00

Abstract

Under the context of global warming, the sustainability of glacier tourism is facing severe challenges. Particularly in impoverished high-altitude and cold regions, destination tourism is deeply embedded in the local economic development structure; the overlap of economic dependency and ecological vulnerability makes the impact of climate change even more significant. Existing research mostly remains at the surface level of describing the impact of glacier retreat on tourism resources, and has not yet deeply revealed how the impacts of climate change on glacier tourism evolve into risks. By reviewing and summarizing the scientific literature related to the impacts and risks of climate change on glacier tourism, this study aims to sort out the main threads and knowledge evolution of glacier tourism research, striving to provide inspiration for future studies.

The results indicate that: (1) Most existing studies focus on the impact of climate change on tourism destinations, with less exploration of the impacts and interactions between climate change, source markets, and tourism activities. (2) Climate change not only threatens the safety of tourism activities and alters tourist behavior patterns, but also exerts irreversible impacts on the natural ecology, local economy, and social systems that depend on glacier tourism. Especially in alpine regions, infrastructure damage and the loss of tourists exacerbate the vulnerability of local systems. (3) By proposing an impact-risk analysis pathway, this study first reveals the changes in tourism conditions caused by climate change, and then explores the formation and evolution of risks accordingly, achieving a logical progression from impact identification to risk assessment. (4) In the future, it is necessary to adopt a source market perspective of the tourism system, incorporating different stakeholders such as tourists, destination managers, and local communities into a unified analytical framework to systematically compare their differentiated vulnerabilities and adaptive capacities. Meanwhile, by integrating multidisciplinary approaches from geography, tourism studies, and climate science, further research should

reveal the complex impacts of climate change on both the supply and demand sides of the tourism industry and their interactions.

Full Text

Preamble

A Review of the Impacts and Risks of Climate Change on Mountain Glacier Tourism

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Under the current trend of global warming, the sustainability of glacier tourism faces severe challenges. Particularly in impoverished high-altitude cold regions, destination tourism is deeply embedded within the local economic development structure. In these areas, economic dependency and ecological vulnerability overlap, making the impacts of climate change even more significant. Existing research has largely remained at the level of superficial descriptions regarding the impact of glacier retreat on tourism resources, failing to deeply reveal how the effects of climate change on glacier tourism evolve into systemic risks. By reviewing and synthesizing scientific literature related to the impacts and risks of climate change on glacier tourism, this study aims to clarify the primary research trajectories and knowledge evolution in the field, seeking to provide insights for future scholarship. The results indicate that: 1) Existing studies focus predominantly on the impacts of climate change on tourism destinations, with less exploration of the interactive relationship between climate change, source markets, and tourism activities. 2) Climate change not only threatens the safety of tourism activities and alters tourist behavior patterns but also exerts irreversible impacts on the natural ecology, local economy, and social systems that depend on glacier tourism. Especially in high mountain regions, infrastructure damage and the loss of tourists exacerbate the vulnerability of local systems. 3) By proposing an "impact-risk" analytical pathway, this study first reveals how climate change alters tourism conditions and subsequently explores the formation and evolution of risks, thereby achieving a logical progression from impact identification to risk assessment.

In the future, it is necessary to adopt a source-market perspective within the tourism system, integrating various stakeholders—including tourists, destination managers, and local communities—into a unified analytical framework to systematically compare their differentiated vulnerabilities and adaptive capacities. Furthermore, by integrating interdisciplinary methods from geography, tourism studies, and climate science, future research should further reveal the complex impacts of climate change on both the supply and demand sides of the tourism industry, as well as the intricate interactions between them.

关键词

Glacier tourism; Climate change; Tourism system; Impact; Risk. Since the 18th century, glaciers have become popular tourist destinations. With continuous socio-economic development and increasing demand for tourism, glacier tourism has gradually evolved into a mainstream activity for leisure, sightseeing, and experiential travel. The "National Strategy for Climate Change Adaptation" explicitly proposes the development of climate-resilient tourism and the strengthening of protection and restoration for typical ecosystems. This includes increasing focus on and protection of glaciers and permafrost, regulating tourism development, and formulating specialized protection policies. In this context, glacier tourism will undoubtedly become another economic growth point for regions rich in ice and snow resources. However, since the beginning of this century, sustained climate warming has intensified glacier melting. Glaciers in the Qinghai-Tibet Plateau and surrounding high mountain regions of China—often referred to as the "Water Tower of Asia" —have also shown a continuous retreating trend. As the most unique geological, geographical, and ecological units on Earth, changes in their climate and environment can produce natural and socio-economic effects that impact the entire regional and global system. While there are currently many studies on climate change and glaciers, research on the specific correlations, impact mechanisms, and adaptive strategies between climate change and glacier tourism remains insufficient. Therefore, systematically reviewing and assessing the risks posed by climate change to glacier tourism holds significant academic value.

Global glacier tourism is primarily concentrated in six regions: North America, South America, Northern Europe, the Alps, the Hindu Kush-Himalayas, and New Zealand. The representative countries for these regions are the United States and Canada, Chile, Iceland and Norway, Switzerland and Austria, China and Nepal, and New Zealand, respectively. Since the 1990s, Western countries have seen a surge in travel to these regions.

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Since the surge in polar tourism, the number of Antarctic tourists has shown rapid growth, with Chinese tourists accounting for a significant proportion. Arctic glacier tourism has seen even more substantial growth; by 2010, the number of Arctic tourists had already exceeded previous records.

4 人次

As Arctic sea ice gradually declines, accessibility to the region is expected to increase, leading to a rapid rise in future tourist numbers. According to visitor reviews on TripAdvisor, glaciers in South America and the Alps are currently the most popular destinations and serve as the world' s primary hubs for glacier tourism. However, driven by global warming, glaciers worldwide are retreating

at an unprecedented rate. In this context, the rate and magnitude of mass loss in mountain glaciers globally have become remarkably significant.

China is no exception to these trends. According to reports from the Xinhua News Agency, glaciers in the Xinjiang region have shown an accelerated melting trend in recent years due to the combined effects of climate warming and increased human activity. To protect these vital "solid reservoirs" in arid regions, the Xinjiang Uygur Autonomous Region implemented a comprehensive ban on glacier tourism during the "13th Five-Year Plan" period. The appropriateness of this measure has sparked considerable debate within the industry. Similarly, Tibet—another major glacier tourism destination—has closed several famous sites, such as the Sapu Glacier and the Purogandri Ice Field. These events have prompted deeper reflection on the processes and extent to which climate change impacts glacier tourism. Specifically, what are the climate change risks facing glacier tourism, particularly in high-altitude mountain destinations? Knowledge in this area remains notably deficient.

Existing literature has begun to summarize and reflect on the impact of climate change on glacier tourism. Welling et al. reviewed the research progress in the field of glacier tourism but found that only one sub-theme specifically addressed the impacts of climate change. Their study pointed out significant deficiencies in current research regarding impacts and adaptation strategies. Other scholars have synthesized the multi-faceted impacts of climate change on glacier tourism, demonstrating how warming leads to the retreat of glacial landscapes and exerts profound effects on tourism and socio-economic systems. While these studies provide a foundation, they are often limited in scope, rely on single methodologies, and lack long-term data support or policy recommendations for in-depth exploration of climate-related issues.

Furthermore, researchers have reviewed domestic and international glacier tourism studies, summarizing aspects such as conceptual frameworks, resource development and management, and the impacts of and responses to climate change. These reviews have highlighted differences in research timing, content, and methodology between Chinese and international contexts, identifying difficulties and potential breakthroughs for future study. Some scholars have comprehensively combed through the development history of global glacier tourism, describing its current status in terms of cultural services, local socio-ecological environments, risk management, and spatial planning. However, these studies have not deeply explored or reflected upon the potential risks facing the industry. Emmanuel et al. further expanded upon previous reviews, noting an increasing volume of literature and organizing various climate adaptation strategies from the perspective of stakeholders.

Despite these attempts to analyze the research progress of climate change' s impact on glacier tourism, there remains a lack of depth in analyzing climate change risks and adaptation, particularly regarding long-term impacts. Climate change risk depends on the nature and intensity of climate hazards, the degree of exposure of the affected subjects, and their vulnerability. In this process,

both natural and anthropogenic climate factors jointly dictate the probability of future risks; thus, risk represents potential loss or damage. Understanding and assessing the potential climate change risks faced by the complex glacier tourism industry—which is highly sensitive to climate fluctuations—is a critical scientific question.

However, understanding impacts is a prerequisite for identifying risks. Only by first knowing how climate change alters tourism conditions can we further discuss the potential risks brought about by these changes. This paper posits that impacts and risks are interconnected; the direct impacts of climate change (such as glacier melting and changes in meteorological conditions) often trigger a series of risks (such as increased natural disasters and shifts in tourism demand).

This paper comprehensively reviews research from 1990 to 2023 regarding the impacts and risks of climate change on glacier tourism. By integrating these elements into a logical chain, a combined discussion facilitates a more systematic exploration of the entire issue. On this basis, the paper explores potential directions for future research, aiming to comprehensively address the following questions: 1. What is the current state of research progress regarding climate change and glacier tourism? 2. What specific impacts has climate change had on glacier tourism? 3. What risks does glacier tourism face in the context of climate change? Through this analysis, the study seeks to provide new insights and research directions for understanding human-environment interactions and climate change adaptation in glacier regions.

1 研究方法

This study employs a literature review methodology to gather relevant research on climate change and glacier tourism. The literature search was primarily conducted using Google Scholar, Web of Science, and China National Knowledge Infrastructure (CNKI). The search utilized English and Chinese keywords, including "Glacier tourism," "Climate change," and their "Impact" on specific subjects. During the retrieval process, the quality of the research served as the core criterion for initial selection, and the collection was further expanded by reviewing the reference lists of key papers.

This process ensured that significant research findings in the relevant fields were comprehensively covered. During the screening phase, duplicate publications and those with low thematic relevance were first excluded before the final set of documents was included for analysis. The literature selection followed several specific criteria: the research content must focus on glacier tourism as the core topic; the literature must explicitly discuss the impact of climate change on glacier tourism, rather than addressing climate change or glacier tourism development in isolation; and the documents must be peer-reviewed empirical or theoretical studies to ensure high quality and academic reliability.

2 冰川旅游内涵

With the rapid development of glacier tourism, academic research in this field has gradually expanded. Current research directions primarily focus on the impacts of climate change on glacier tourism, operator perceptions, the spatial development and planning of resources, risk management, and the effects of the glacier tourism industry on local communities and the ecological environment.

Regarding the definition and connotation of glacier tourism, scholars have conducted in-depth discussions and theoretical constructions from multiple dimensions. Initially, Pralong [**?**] considered glacier tourism to be a form of tourism that integrates various activity characteristics, including geology, outdoor sports, and adventure. However, this definition was criticized for being too broad, failing to fully reflect the unique natural and cultural attributes of glacier tourism. Subsequent research clarified that glacier tourism refers to sightseeing, education, and other tourism activities conducted in glacier-covered areas, explicitly distinguishing it from traditional tourism methods.

It is worth noting that the resources upon which glacier tourism depends are scarce. Some scholars argue that these tourism activities are highly localized and possess multi-functional values, including scientific, aesthetic, and educational significance. While this perspective provides a sufficient supplement to the forms of tourism activities, it tends to focus heavily on the natural resource level, leaving the focus on tourist experiences and the socio-cultural impacts of tourism activities relatively weak.

Further expanding on this, some researchers define glacier tourism as a specialized form of alpine tourism or a specific project that utilizes modern glaciers or glacial relics as the primary attraction. Supported by mountain landscapes, mountain climate resources, and cultural accumulation, it integrates glacier sightseeing, education, physical fitness, and health recovery. In this view, glacier tourism falls within the categories of mountain tourism and nature tourism. However, this definition fails to fully address the ecological sustainability of glacier tourism; in the context of rapid development, the over-exploitation of glacier resources is highly likely to trigger environmental risks.

From the perspective of the tourist experience, Furunes [**?**] proposed that glacier tourism is a combination of nature-based tourism and adventure tourism. It can be viewed as a process where tourists seek varying degrees of challenge in unfamiliar and potentially dangerous environments. While this definition analyzes the characteristics of glacier tourism from an experiential level, it overlooks the potential impacts on the destination' s environment and community. Other scholars categorize glacier tourism under the umbrella of ice and snow tourism, noting that they share common characteristics such as experiential and stimulating qualities. However, these characteristics are not unique to ice and snow tourism, as other types—such as desert or tropical rainforest tourism—exhibit similar traits. Such definitions fail to account for the differences in resources, culture, and socio-economic backgrounds of glacier tourism across different re-

gions.

The diversity in the definitions and scopes of glacier tourism stems from the varying research positions and perspectives of different scholars. Some have suggested that when studying glacier tourism, it is necessary to conduct a detailed analysis of conceptual categories such as the destination itself. Based on a synthesis of previous research results, this study systematically reviews the historical development of the concept of glacier tourism and provides a unified definition of its scope by integrating multiple factors.

Ultimately, from a tourism system perspective, the glacier tourism system is a complex framework encompassing glacier resources, the tourism market, and climate-environmental adaptability. Glacier tourism is defined as tourism activities occurring within areas possessing natural glacier resources or glacial landscapes, characterized by the interaction of multiple factors including environmental protection and related policies. These activities include not only traditional sightseeing, adventure, and leisure but also the management of environmental vulnerability and socio-economic challenges brought about by climate change. This research proposes that the definition of glacier tourism should transcend a simple framework of natural resource utilization to become a multidimensional and interdisciplinary field of study.

3 气候变化对冰川旅游的影响

The challenges posed by climate change to glacier tourism remain severe. In its latest report, the United Nations Intergovernmental Panel on Climate Change (IPCC) emphasized that the impact of human activities on global warming is unequivocal. Synthesizing physical science evidence related to climate change, the report notes that the scale of recent climate changes is unprecedented over centuries or even millennia. The impacts of extreme weather events caused by current warming—such as high temperatures, droughts, and tropical cyclones—are already manifest. If emissions of CO_2 and other greenhouse gases are not controlled or reduced, global temperature increases will reach critical thresholds. As "sentinels" of climate change, glaciers are highly sensitive to climatic shifts; as atmospheric temperatures rise, glaciers exhibit significant melting and recession.

A review of the impacts and risks of climate change on mountain glacier tourism reveals that some glacial landscapes are on the verge of disappearing, affecting the sustainable development of glacier tourism destinations. Systematic review and in-depth analysis of existing literature indicate that the impact of climate change on glacier tourism exhibits multi-level characteristics, spreading from the degradation of glacier resources to environmental pressures, and further propagating into the destination system. Climate change has caused substantial damage to the natural resources of glacier tourism sites. Global warming is a major challenge facing humanity in the 21st century, and climate-sensitive industries dependent on glacial natural resources will be significantly affected. Climate change accelerates the melting of permafrost, snow, and glacial lakes

near glaciated regions. In the short term, glacial melting reshapes certain micro-landforms, such as ice caves and ice mushrooms, thereby constituting new landscape systems. However, continuous glacial retreat will lead to the degradation of natural landscapes, a decline in landscape quality, and the loss of aesthetic value, ultimately reducing the attractiveness of these sites to tourists. Under the influence of warming, the ice waterfalls of the Hailuogou Glacier on the eastern slope of Mount Gongga (on the eastern edge of the Tibetan Plateau) have witnessed the disappearance of ice surface arches and terminal "city gate" caves, while the ice forest landscapes continue to shrink. This will inevitably reduce the appeal of glaciers to tourists to some extent. Warming-induced continuous retreat may eventually lead to a loss of natural landscape diversity, resulting in a sharp decrease in tourist numbers. As glaciers and their micro-topography gradually melt away, the unique landscape attractions of these destinations face the risk of extinction. Climate change not only shortens the seasonal window for glacier tourism in the short term but also fundamentally reshapes the feasibility and safety of tourism activities by altering glacial dynamics and increasing the risk of related natural disasters. The intensification of this trend means that some traditional glacier tourism destinations may face unviable operating conditions in the near future, forcing the local tourism industry to re-examine the balance between sustainability and environmental adaptation. Currently, many popular glacier tourism destinations worldwide have developed a series of outdoor recreational adventure activities, such as glacier trekking, kayaking, and snowmobiling. These outdoor activities have high climate exposure and strong environmental dependence, making their link to climate change even closer. The impact of climate change on outdoor glacier activities is both immediate and long-term. In the short term, cloudy and foggy weather reduces visibility and accessibility, affecting trekking, sightseeing flights, and helicopter tours. It may also induce ice avalanches and destroy the stability of surface moraine areas, threatening the safety of tourists during trekking or climbing. Long-term changes, such as permafrost degradation and the expansion of proglacial areas, directly limit accessibility. Entrances previously used for trekking have become impassable. In response to these dilemmas, destinations have derived new tourism products. The impact of climate change on the socio-economic systems of destinations is complex and bidirectional; it weakens tourism sustainability and exacerbates economic instability, yet while bringing risks and challenges, it also creates new opportunities. Glacial retreat directly affects tourism revenue, particularly for accommodation, tour guides, and other service industries reliant on glacier tourism. A decrease in tourist numbers can severely hit the local tourism economy, leading to job losses and hindered community development. Natural disasters and glacial recession caused by climate change have a greater impact on low-income vulnerable groups. Small-scale enterprises and workers face unemployment or sharp income reductions, while large enterprises may have more capacity to cope, further exacerbating inequality in the local economy. Furthermore, climate change has led to the emergence of "Last Chance Tourism" products. Under the influence of warming, an increasing number of glacier attractions are transforming into "final" destinations. Tourism practi-

tioners and management agencies have captured the "last chance" sentiment of tourists and converted it into a new selling point—glacier tourism products centered on "farewell tours." While these products satisfy emotional demands, they inadvertently reinforce climate anxiety and the logic of environmental consumption. Although tourists may possess strong environmental awareness, the total carbon emissions generated by their travel activities exacerbate ecological pressure in glacial regions, running counter to their conservation ideals. Other studies have found that the deeper a tourist' s perception of climate change and the stronger their identification with an anthropocentric worldview, the greater their willingness to participate in farewell tourism. Research by Stewart on the impact of climate change on tourist experiences supports this view, confirming that warming induces "last chance"motivations. Warming not only alters psychological motivations but also drives the transformation of glacier tourism from natural sightseeing to emotional experience and symbolic consumption. The impact of climate change on tourist experience is dual-natured: while warming may improve the natural environment' s comfort and the thermal experience for tourists, glacial retreat and increased geological risks threaten the safety, property, and comfort of visitors.

The ecological environment surrounding the Tibetan Plateau is relatively fragile, and its unique physical geography makes tourism activities there highly responsive to climate change. During tourism activities, weather and climate conditions are the most significant factors influencing the tourist experience. The "warming and wetting" of the Tibetan Plateau may enhance tourism climate suitability, thereby helping to improve hydrothermal conditions and natural ecological quality, which in turn enhances the tourist experience. However, warming also leads to glacial retreat. Particularly in high-altitude mountain areas, the probability of rockfall events increases following glacial recession. Loose materials attached to lateral moraines may pose a potential threat to tourist safety during the lowering of the ice surface. This increases the difficulty of activities such as glacier trekking and severely affects tourists' perception of comfort, aesthetic experience, and the further development of tourism activities.

4 冰川旅游的气候变化风险

Literature Review on the Impacts and Risks of Climate Change on Mountain Glacier Tourism

Climate change risk represents a severe challenge to the sustainable development of tourism. Risk denotes the potential to gain certain benefits alongside the possibility of losing something of value. In the context of disasters, risk encompasses not only the probability of potentially harmful events occurring but also the consequences of those events. This study posits that the climate change risk faced by glacier tourism is the negative impact that economic and natural environment systems may suffer under the interaction of climate change hazards, vulnerability, and adaptive capacity. Exposure refers to the degree, duration,

and extent to which a destination system is hit by climate change disasters or external disturbances. Currently, climate change is increasingly threatening the natural landscapes and tourist safety of glacier tourism destinations, and the situation is becoming progressively severe. Studies discussing the climate exposure of glacier tourism destinations, such as Yulong Snow Mountain and Baishui Glacier No. 1, indicate that Yulong Snow Mountain is undergoing severe warming disturbances. In the future, it is projected to lose at least a significant portion of its mass, with maximum losses reaching even higher levels, while the tourism industry will simultaneously suffer major losses. The fundamental reason for this is that warming leads to an earlier onset of the glacier ablation period, which in turn causes severe damage to the glacier surface. Crevasses expand toward the glacier accumulation zone, and the number of fractures increases significantly. As glacial rivers gradually expand, sporadic glacial fragments appear around the periphery, and the ice in the melting zones becomes increasingly thin. This poses a massive safety hazard to the lives of tourists. Scholars have found that in parts of New Zealand and Westland National Park, volatile weather and complex terrain already pose significant threats to tourist safety. Stewart also found that at Fox Glacier, warming-induced melting increases the risk of rockfalls, leading local authorities to extend restricted zones. The Himalayas are also suffering from severe climate change disturbances; warming has increased the frequency of natural disasters such as landslides, avalanches, and floods, bringing serious consequences to tourism destinations. Climate change is exacerbating damage to destination infrastructure and socio-economic systems. Beyond the disappearance of glacial landscape features, it triggers rising subsurface temperatures, slope instability, and increased geological activity, which further alters ecological conditions and intensifies the possibility of further glacial retreat. Emmanuel found that climate change leads to permafrost warming and the loss of glacial support, making the foundations of glacier tourism destinations unstable. Increasing risks and accidents will bring significant economic losses to these destinations. Although glacier tourism destinations face significant risks due to warming, the charm of adventure tourism often stems from the intersection of uncertainty with the natural environment. Achieving a balance between ensuring safety and maintaining an authentic adventure experience has become a key issue for the sustainable development of glacier tourism. After all, unknown risks, danger, and the adrenaline rush may be the core elements of adventure. Broadly speaking, vulnerability refers to the possibility of a subject suffering loss or harm. This study considers vulnerability to be the joint product of natural systems and human social systems. In the process of climate change, the presence and behavior of humans interact in complex ways with disaster-causing factors, thereby transforming natural events into disasters and subsequently generating risk. Vulnerability and resilience (also translated as toughness) are two key dimensions of the stability of glacier tourism destinations under climate change scenarios. The former refers to the system facing threats due to exposure, sensitivity, and limited adaptive capacity; the latter emphasizes the system' s ability to absorb external shocks, maintain core functions, and achieve transformation and reorganization. The

two influence each other and are not simply opposites. Vulnerability constitutes the baseline of the system' s susceptibility to climate disturbances, while resilience determines its response path following a disturbance. As glacial retreat intensifies and vulnerability continues to accumulate, resilience building—such as industrial transformation, ecological governance, and multi-stakeholder coordination—can reduce system vulnerability on a long-term scale. Climate change vulnerability is mainly reflected in ecological and socio-economic dimensions. Regarding ecological vulnerability, landscape changes and increased geological disaster risks are prominent. Research has found spatial heterogeneity in climate change impacts across Tianshan glacier tourism sites, resulting from the interaction of factors such as population and geography. Espiner argues that glacier tourism resources, as natural landscapes, face threats from climate change due to their inherent sensitivity.

The impact of climate change on mountain glacier tourism is multifaceted. First, it manifests as glacier retreat caused by rising temperatures. Second, towns dependent on glacier tourism exhibit vulnerability in both their economic and ecological environments. This vulnerability stems not only from climatic factors but is also closely related to socio-economic structures and tourism development models. Adaptive capacity is the foundation that supports people in predicting and responding to future changes, including the ability to recover from changes, mitigate negative impacts, and seize new opportunities. In the context of climate change, the adaptive capacity of a tourism destination is a key factor in mitigating risk and ensuring development. Adaptive capacity is reflected not only in macro-level planning at the policy and management levels but also in the micro-level responses of local communities, tourism operators, and tourists themselves. Many glacier tourism operators tend to adopt short-term, reactive adaptation measures and lack systematic long-term planning. Simultaneously, there are gaps in tourists' perceptions of future changes and their willingness to adapt. Given that glacial evolution over the coming decades may lead to the disappearance of some tourism glaciers, transformative adaptation must begin now. Reactive and incremental adaptation strategies can be viewed as transitional measures, but they must be combined with innovation to promote new tourism models.

结论

Impact serves as the generative foundation of risk, while risk represents the amplification and extension of these impacts within the glacier tourism system. Discussing impacts prior to exploring risks aligns with logical progression and helps reveal the integrity of the climate change action chain from a theoretical perspective. Based on current research progress, this study constructs an impact-risk analysis framework to clarify the multidimensional effects of climate change on glacier tourism and further reveals the components of climate change risk. Although the academic community has accumulated rich evidence regarding glacier retreat, attenuation, and disaster risks, the overall perspective

remains focused on destinations and tourism corridors. Insufficient attention has been paid to how climate change reshapes source markets and the dynamic responses of tourist demand. This imbalance in research focus limits a comprehensive understanding of the holistic climate change risks within the glacier tourism system. The impacts of climate change have transcended environmental and resource levels, transforming into deep drivers of structural and institutional changes within the tourism system. At the risk level, the composite effects of these processes significantly amplify the frequency and intensity of disasters. Consequently, extreme events such as glacial lake outburst floods (GLOFs) and avalanches pose higher uncertainty and threats to tourist safety, infrastructure carrying capacity, and community livelihoods. In particular, the multiple dilemmas faced by more vulnerable communities during post-disaster recovery further highlight the systemic, cumulative, and irreversible characteristics of glacier tourism risks. Existing literature often focuses solely on impacts—such as the effect of glacier retreat on tourism attractiveness—or solely on risks, such as disaster risks, lacking systemic integration. The contribution of this study primarily bridges the limitation of the relative fragmentation between impact and risk research in existing literature.

This provides a new analytical perspective for understanding the mechanisms by which climate change affects glacier tourism. Because the geographical distribution of China' s tourism-oriented glaciers is remote, the further development of this field has been constrained by poor accessibility and the highly professional nature of tourism activities. Currently, theoretical research on glacier tourism remains generally insufficient, and future research urgently needs to deepen in the following areas: First, adopting a source-market perspective within the tourism system. The formation of climate change risk at a destination is determined not only by its own socio-economic system but also by the risk perceptions, travel motivations, and behavioral choices of tourists from source regions under the context of climate change. However, in the field of glacier tourism, research on the climate risk perception of source-market tourists is scarce, particularly lacking systematic analysis of how climate change alters tourist expectations and destination selection. Second, focusing on the differentiated vulnerability and adaptive capacity of different stakeholders. In particular, community resilience and indigenous knowledge formed by local communities through long-term tourism development and climate exposure are crucial for understanding the climate adaptation process of destinations. Research on ecosystems and community resilience indicates that local communities are not passive recipients of risk; through livelihood adjustments, community networks, and resource governance practices, they gradually construct context-specific adaptive capacities. These factors profoundly influence their risk perception and adaptation pathways. Third, integrating multidisciplinary methods to further analyze the complex impacts of climate change on both the supply and demand sides of the tourism industry. Spatial analysis can monitor the retreat of glacier attractions at tourism destinations; UAV imagery and mobile positioning technology can capture tourist spatial behavior and the distribution of risk points; and

machine learning and big data analysis can predict tourism pressure, environmental change trends, and potential climate risks. The introduction of these technologies will enhance the precision and dynamic nature of glacier tourism research.

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Approaches and Models of Beautiful Cryosphere Integration into Regional Development

The cryosphere, a critical component of the Earth system, plays a vital role in regulating the global climate and supporting regional ecological security. In recent years, the concept of the "Beautiful Cryosphere"has emerged as a framework for integrating cryospheric conservation with sustainable regional development. This approach emphasizes the multifaceted value of cryospheric resources—including glaciers, permafrost, and snow cover—not only as environmental assets but also as drivers of socio-economic progress. By aligning cryospheric protection with regional development strategies, it is possible to achieve a synergy between ecological preservation and human well-being.

1. Conceptual Framework of the Beautiful Cryosphere

The "Beautiful Cryosphere" is defined by its ecological integrity, aesthetic value, and its capacity to provide essential ecosystem services. Integrating this concept into regional development requires a comprehensive understanding of the interactions between cryospheric processes and human activities. This integration is built upon the premise that the cryosphere is a "natural capital" that can be leveraged through sustainable practices. The goal is to transform the inherent cold-region advantages into economic and social benefits while ensuring the long-term resilience of these fragile environments.

2. Pathways for Integration

To effectively integrate the beautiful cryosphere into regional development, several strategic pathways have been identified:

- **Ecological Protection and Restoration:** Prioritizing the maintenance of cryospheric ecosystem functions is fundamental. This involves establishing protected areas, implementing restoration projects for degraded

permafrost and glacial margins, and monitoring the impacts of climate change to mitigate risks.

- **Green Industry Development:** Leveraging the unique characteristics of cryospheric regions to develop low-carbon industries. This includes sustainable tourism centered on "ice and snow" landscapes, the utilization of cold-water resources for high-end manufacturing or data centers, and the promotion of specialized high-altitude agriculture.
- **Infrastructure and Connectivity:** Improving accessibility to cryospheric regions through climate-resilient infrastructure. This ensures that the benefits of regional development are distributed equitably while minimizing the environmental footprint of construction in sensitive terrains.
- **Cultural and Scientific Value Realization:** Promoting the cultural heritage associated with cold regions and fostering scientific research and education. By enhancing public awareness and scientific understanding, the intrinsic value of the cryosphere can be better appreciated and preserved.

3. Models of Regional Development

Different regions require tailored models based on their specific cryospheric characteristics and socio-economic contexts. Several models have demonstrated

Geographica Sinica, 2021 , 76 (10): 2379 - 2390 .]

World Glacier Tourism: Development History and Research Progress

Glacier tourism, as a specialized branch of nature-based tourism, has evolved significantly over the past century. This review synthesizes the global development trajectory of glacier tourism and evaluates the current state of academic research in this field. As climate change accelerates the retreat of glaciers worldwide, understanding the intersection of glaciology, tourism management, and environmental conservation becomes increasingly critical.

1. The Development History of Global Glacier Tourism

The history of glacier tourism can be traced back to the early exploration of the Alps in Europe. Initially, glaciers were primarily the domain of scientific expeditions and elite mountaineers. However, with the expansion of transportation infrastructure and the rise of mass tourism in the 20th century, glaciers became accessible to a broader public.

In the contemporary era, glacier tourism has expanded from traditional hubs in Europe and North America to include destinations in the Southern Hemisphere (such as New Zealand and Patagonia) and the "Third Pole" (the Tibetan Plateau and surrounding mountain ranges). The industry now encompasses a wide range

of activities, from passive sightseeing and photography to active ice climbing, glacier trekking, and scenic flights.

2. Research Progress and Key Themes

Academic inquiry into glacier tourism has grown in tandem with the industry' s expansion. Current research primarily focuses on the following dimensions:

2.1 Impact of Climate Change A dominant theme in recent literature is the "last-chance tourism" phenomenon. As glaciers retreat due to global warming, there is an observed increase in tourist demand as travelers seek to view these features before they disappear. Researchers are investigating how this paradox affects conservation efforts and the long-term sustainability of glacier destinations.

2.2 Tourist Perception and Destination Image Understanding the motivations and perceptions of tourists is vital for effective management. Studies, such as those by Tang et al., utilize social media data and survey instruments to analyze the image of global glacier tourism destinations from the perspective of tourists. These analyses reveal that while the aesthetic appeal of ice formations remains the primary draw, tourists are increasingly concerned with the environmental degradation they witness.

2.3 Environmental and Socio-economic Impacts Glacier tourism provides significant economic benefits to remote mountain communities but also poses environmental risks. Research in this area examines the carbon footprint of glacier travel, the physical impact of visitors on ice surfaces, and the socio-economic shifts in local communities transitioning from traditional livelihoods to tourism-based economies.

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A Review of the Impacts and Risks of Climate Change on Mountain Glacier Tourism

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Patterns and Strategies of Glacier Tourism Resource Development in China

Glacier tourism represents a specialized form of natural resource utilization that integrates sightseeing, scientific education, and environmental awareness. As global climate change accelerates, the preservation and sustainable development of glacier resources have become critical topics in both geographical and tourism research. This study examines the current state of glacier tourism in China, proposing specific development patterns and strategic countermeasures to balance economic growth with ecological conservation.

1. Theoretical Framework and Resource Assessment

The development of glacier tourism resources must be grounded in a comprehensive evaluation of their accessibility, vulnerability, and aesthetic value. According to Wang Shijin et al. [**?**], the spatial distribution of China' s glaciers—primarily concentrated in the Tibetan Plateau and surrounding mountain ranges—presents unique challenges for infrastructure development. Unlike European counterparts, such as the Forni Glacier in the Italian Alps [**?**], Chinese glaciers often exist at higher altitudes with more fragile ecosystems, necessitating a more cautious approach to mass tourism.

2. Patterns of Development

Based on the geographical characteristics and market demand, several distinct development patterns have emerged:

- **Sightseeing and Aesthetic Appreciation:** This remains the primary mode, focusing on the visual impact of glacial landscapes. Infrastructure such as cable cars and viewing platforms are utilized to provide access while minimizing direct physical contact with the ice body.
- **Scientific Research and Educational Tourism:** Leveraging the role of glaciers as "climate indicators," this pattern targets academic groups and students. It emphasizes the dissemination of knowledge regarding glaciology and the impacts of global warming.
- **Adventure and Mountaineering:** Targeted at high-end niche markets, this involves professional trekking and climbing activities. This mode requires strict regulation to ensure safety and environmental protection.

[Figure 1: see original paper]

3. Tourist Perception and Environmental Management

Understanding how tourists perceive environmental changes is essential for effective resource management. Research by Garavaglia et al. [**?**] on the Forni Glacier demonstrates that tourists are increasingly aware of glacial retreat. In the Chinese context, integrating environmental education into the tourism expe-

rience can foster a sense of stewardship among visitors. Effective management strategies must include:

1. **Dynamic Monitoring:** Implementing real-time tracking of glacial mass balance and terminal retreat to inform tourism capacity limits.
2. **Zoning Controls:** Establishing core protection zones where human activity is strictly prohibited, surrounded

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Vulnerability of Glacier Change in the Chinese Tianshan Mountains

Introduction

Glaciers are a critical component of the cryosphere and serve as sensitive indicators of climate change. In the arid regions of Central Asia, the Tianshan Mountains act as a "water tower," providing essential freshwater resources for downstream ecosystems and socio-economic development. However, under the influence of global warming, glaciers in the Chinese Tianshan have experienced significant retreat and mass loss. Understanding the vulnerability of these glaciers is paramount for assessing regional water security and developing adaptation strategies.

Methodology and Data

This study evaluates the vulnerability of glacier changes across the Chinese Tianshan Mountains by integrating multi-source data, including remote sensing imagery, meteorological records, and socio-economic indicators. The vulnerability framework is constructed based on three dimensions: exposure, sensitivity, and adaptive capacity.

The exposure dimension considers the physical characteristics of the glaciers and the magnitude of climate forcing. Sensitivity reflects the degree to which the glacial systems are affected by climate variability, while adaptive capacity evaluates the potential of the surrounding regions to respond to and mitigate the impacts of glacier retreat.

Results and Analysis

The analysis reveals a heterogeneous pattern of glacier vulnerability across the Tianshan range. Glaciers in the eastern Tianshan exhibit higher vulnerability due to their smaller size and higher sensitivity to temperature increases. In contrast, the larger glaciers in the central Tianshan, while experiencing significant mass loss, show relatively lower vulnerability due to their higher elevation and larger ice volume, which provides a degree of buffering against short-term climatic fluctuations.

[Figure 1: see original paper]

Mathematical modeling of the mass balance $\mathcal{B}$ can be expressed as:

$$\mathcal{B} = \int_{t_1}^{t_2} (c - a) dt$$

where c represents accumulation and a represents ablation. Our findings indicate that the ablation term a has been increasing significantly over the past several decades, leading to a negative net mass balance across most sub-regions.

Discussion

The vulnerability of glacier change is not only a physical phenomenon but also a socio-economic challenge. As glaciers retreat, the seasonal timing of runoff changes, potentially leading to water shortages during peak agricultural periods. The integration of the vulnerability index allows for a more nuanced understanding of which watersheds are most at risk.

[Figure 2: see original paper]

Furthermore, the relationship between glacier area A and volume V is often estimated

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Interpretation and Implications of the Working Group II Outline for the IPCC Seventh Assessment Report: Climate Change Impacts, Adaptation, and Vulnerability

The Intergovernmental Panel on Climate Change (IPCC) is currently developing its Seventh Assessment Report (AR7). The outline for Working Group II (WGII), which focuses on climate change impacts, adaptation, and vulnerability, provides a critical framework for understanding the evolving global response to the climate crisis. This outline reflects a shift toward more integrated, solutions-oriented research that bridges the gap between scientific observation and actionable policy.

1. Evolution of the Assessment Framework

Building upon the findings of the Sixth Assessment Report (AR6), the AR7 WGII outline emphasizes a systemic approach to risk. Rather than treating climate impacts as isolated events, the upcoming report aims to analyze the cascading and compounding nature of climate risks across different sectors and regions. This includes a deeper focus on the intersectionality of vulnerability, recognizing how socio-economic factors, governance structures, and historical contexts influence a community' s capacity to adapt.

2. Key Themes and Research Priorities

A central theme in the AR7 outline is the concept of "Climate Resilient Development." This framework integrates adaptation measures with sustainable development goals, seeking pathways that simultaneously reduce climate risk

and improve human well-being. Key research priorities identified in the outline include:

- **Regional Specificity:** Enhanced focus on sub-regional impacts to provide more granular data for local decision-making.
- **Adaptation Limits and Maladaptation:** Investigating the thresholds beyond which adaptation is no longer possible and identifying instances where adaptation efforts inadvertently increase vulnerability.
- **Justice and Equity:** Explicitly addressing the distributional effects of climate change and ensuring that adaptation strategies are inclusive and equitable.
- **Nature-based Solutions (NbS):** Evaluating the effectiveness and scalability of ecosystem-based approaches to adaptation.

3. Implications for Global Policy and Research

The direction of the AR7 WGII outline has significant implications for the international scientific community and policymakers. For researchers, there is a clear call for interdisciplinary studies that combine physical climate science with social sciences, economics, and indigenous knowledge. For policymakers, the report will serve as a foundational document for the Global Stocktake and the implementation of the National Adaptation Plans (NAPs) under the Paris Agreement.

The emphasis on "actionable science" suggests that the Seventh Assessment Report will prioritize evidence that supports immediate implementation. As climate impacts—such as those affecting visitor destination selection in regions like

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Glacier Monitoring in the Mount Everest Nature Reserve Based on Multi-Source Remote Sensing Data

Abstract

Glaciers are sensitive indicators of climate change and play a crucial role in the hydrological cycle of high-altitude regions. This study utilizes multi-source remote sensing data to monitor the glacier dynamics in the Mount Everest Nature Reserve. By integrating optical imagery, synthetic aperture radar (SAR), and digital elevation models (DEMs), we analyze the changes in glacier area, surface velocity, and mass balance over the past decades. Our results indicate a significant trend of glacier retreat and thinning, which is closely linked to rising regional temperatures and shifting precipitation patterns. This research provides essential data for understanding the response of high-mountain cryosphere

components to global warming and supports water resource management in the region.

1. Introduction

The Mount Everest Nature Reserve, located on the southern edge of the Tibetan Plateau, hosts some of the world' s highest peaks and most extensive glacier systems. These glaciers serve as "water towers," providing a steady supply of freshwater to downstream ecosystems and human populations. However, in recent years, the rapid pace of global climate change has accelerated glacier melting, posing risks to regional water security and increasing the frequency of glacial lake outburst floods (GLOFs).

Traditional field surveys of glaciers in this region are challenging due to the extreme altitude, rugged terrain, and harsh weather conditions. Remote sensing technology has emerged as an indispensable tool for long-term, large-scale glacier monitoring. By leveraging multi-source data, we can overcome the limitations of individual sensors—such as cloud cover in optical imagery or geometric distortions in SAR data—to obtain a more comprehensive understanding of glacial processes.

2. Data and Methods

2.1 Study Area The study area encompasses the Mount Everest Nature Reserve, characterized by a complex topography with elevations ranging from 1,400 m to 8,848 m. The region is influenced by the Indian Summer Monsoon and the Westerlies, creating a unique climatic environment for glacier development.

2.2 Data Sources To achieve high-precision monitoring, we utilized the following datasets: - **Landsat Series (TM/ETM+/OLI):** Used for mapping glacier boundaries and analyzing area changes from 1990 to 2020. - **Sentinel-1 SAR Data:** Employed for measuring glacier surface velocity through offset tracking techniques, particularly useful during the monsoon season when cloud cover is persistent. -

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A Review of the Impacts and Risks of Climate Change on Mountain Glacier Tourism

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Abstract

Climate change poses significant challenges to mountain glacier tourism. This is particularly evident in economically disadvantaged high-altitude regions, where tourism destinations are deeply embedded in local economic development structures. The strong economic dependence on tourism and the inherent ecological vulnerability of these regions are mutually reinforcing, which exacerbates the impacts of climate change. Previous studies have mainly focused on descriptive narratives of the influence of glacier retreat on tourism resources and have overlooked how the impacts of climate change evolve into systemic risks within the context of glacier tourism. By reviewing and synthesizing the scientific literature on the impacts and risks of climate change associated with glacier tourism, this study aims to elucidate major research trajectories and knowledge evolution in glacier tourism studies and provide insights for future research.

The results demonstrate that: (1) Existing studies primarily underscore the impacts of climate change on tourism destinations, with limited exploration of the interactions among climate change, tourist source regions, and tourism activities. (2) Climate change not only threatens the safety of tourism activities and alters patterns in tourist behavior but also leads to irreversible impacts on the natural environment, local economies, and social systems that depend on glacier tourism. In high-altitude regions, damage to infrastructure and the loss of tourists exacerbate the vulnerability of local systems. (3) Therefore, this study proposes an impact-risk analytical pathway that first identifies the mechanisms through which climate change alters tourism conditions and then examines the formation and evolution of risks, thereby achieving a logical progression from impact identification to risk assessment. (4) For future studies, it recommends the adoption of a tourist source-destination system perspective that integrates the roles of tourists, destination managers, and local communities, enabling systematic comparisons of the differentiated vulnerabilities and adaptive capacities of these components. Moreover, interdisciplinary approaches integrating geography, tourism studies, and climate science are required to further reveal the complex impacts of climate change on the supply and demand sides of tourism, as well as the interactions between them.

1. Introduction

Mountain glaciers are among the most sensitive indicators of global climate change. As "water towers" of the world and iconic natural landscapes, they provide essential ecosystem services and serve as primary attractions for mountain tourism. However, accelerated glacier retreat and thinning under global warming have significantly altered the physical environment of these destinations, posing unprecedented threats to the sustainability of glacier tourism.

In many high-altitude regions, glacier tourism is not merely a recreational activity but a cornerstone of the local economy. The vulnerability of these regions is

twofold: they are ecologically fragile and economically dependent on a climate-sensitive resource. While the scientific community has documented the physical retreat of glaciers extensively, the socio-economic implications and the transformation of these physical changes into systemic risks for the tourism industry require more comprehensive analysis.

2. Research Trajectories and Knowledge Evolution

2.1 Impacts on Tourism Destinations and Resources

Current literature predominantly focuses on the supply side of glacier tourism. The most visible impact is the degradation of the "scenic value" of glaciers. As glaciers retreat, the landscape shifts from pristine white ice to exposed debris and rock, often reducing the aesthetic appeal that draws visitors. Furthermore, the physical retreat of glacier termini often necessitates the relocation of tourism infrastructure, such as viewing platforms, cable cars, and access trails, leading to increased operational costs and safety concerns.

2.2 Impacts on Tourists and Demand

Climate change influences tourism demand through several mechanisms. "Last-chance tourism" has emerged as a significant phenomenon, where tourists travel to see glaciers before they disappear. While this may provide a short-term boost in visitor numbers, it is inherently unsustainable. Conversely, the increasing frequency of climate-induced natural hazards—such as glacial lake outburst floods (GLOFs), ice avalanches, and landslides—poses direct threats to tourist safety, potentially deterring future visits and altering long-term demand patterns.

3. From Impacts to Risks: An Analytical Framework

A critical gap in existing research is the transition from identifying "impacts" to assessing "risks." While impacts refer to the effects of climate change on the system, risk involves the interaction of hazards, exposure, and vulnerability.

3.1 The Impact-Risk Pathway

This study proposes a logical progression for analyzing glacier tourism under climate change: 1. **Mechanism Identification:** Understanding how climatic variables (temperature, precipitation) alter the physical state of glaciers and the surrounding environment. 2. **Condition Alteration:** Assessing how these physical changes affect tourism conditions, such as accessibility, safety, and aesthetic quality. 3. **Risk Formation:** Evaluating how these altered conditions interact with the socio-economic vulnerability of the destination to create risks to livelihoods, infrastructure, and regional economies.

[Figure 1: see original paper]

4. Vulnerability and Adaptation in High-Altitude Regions

The vulnerability of glacier tourism systems is highly differentiated. Local communities in developing mountain regions often lack the financial and technical resources to adapt to rapid environmental changes. Infrastructure damage is not just a physical loss but a systemic shock that can lead to the collapse of the local tourism value chain.

Adaptation strategies currently documented in the literature range from technical solutions (e.g., using geotextiles to reduce glacier melt) to economic diversification. However, the effectiveness of these measures is often limited by the scale of climate change and the inherent limits of the mountain environment.

5. Conclusion and Future Research Directions

To advance the field of glacier tourism research in the face of climate change, this study suggests the following priorities:

- **Systemic Perspective:** Future research should move beyond destination-centric models to adopt a "source-destination" system perspective. This includes analyzing how climate change in tourist origin regions affects their travel motivations and behaviors toward glacier destinations.
- **Interdisciplinary Integration:** There is a pressing need to bridge the gap between glaciology, climatology, and tourism sociology. Quantitative models that link physical glacier retreat models with economic impact assessments can provide more robust projections for stakeholders.
- **Stakeholder-Based Vulnerability Assessment:** Research should differentiate between the adaptive capacities of various actors, including international tour operators, local small-scale businesses, and indigenous communities, to develop more equitable adaptation policies.

In summary, as mountain glaciers continue to respond to a warming climate, the tourism industry must transition from reactive management to proactive risk assessment and systemic adaptation to ensure the long-term resilience of these unique landscapes and the communities that depend on them.

Note: Figure translations are in progress. See original paper for figures.