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Impact of Climate Change on Glacier Melting and Water Security in the Karakoram and Himalayan Region of Pakistan

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ABSTRACT

The Karakoram and Himalayan area of Pakistan is a vital part of the Earth's cryosphere; it is the principal reservoir of freshwater for millions of people living downstream. This broad review highlights the complex climate-glacier-water nexus of this vulnerable area, and its critical role in Pakistan's water security. The world has observed extensive mass loss of glaciers due to global warming, but the region is heterogeneous across space with strong evidence of stability, referred to as the Karakoram Anomaly; glaciers maintain stability or even gain mass while regional warming progresses. Recent research shows that, despite the anomalous behavior, warming trends are linked with increased temperatures, altered precipitation patterns, and increased deposition of light-absorbing particles, leading to increased melt rates of glaciers in most areas, particularly in the Himalayan ranges. These modifications are more relevant to the Indus River System, as more than 50% of its annual flow comes from melted snow or glaciers. The water insecurity due to reduced flows represents a significant threat to agriculture, hydropower, and social-economic stability for millions living in Pakistan and South Asia. This analysis calls for urgent integrated research approaches and policy frameworks, along with enhanced cooperation across borders, to build climate resilience for all parts of the region.

INTRODUCTION

The frozen reservoirs of the world's high mountain regions, commonly known as the cryosphere, are recognized as one of the most sensitive and visually striking indicators of global climate change (1). The Karakoram and Himalayan region of Pakistan, in particular, is important hydrologically, as it holds the largest mass of glaciers outside the polar regions of the Earth. This expansive area of ice, often referred to as the "Third Pole" is not a singular entity, but rather a complex evolving outcome of both human and environmental interactions that primarily governs the hydrological cycle across South Asia (2).

Ultimately, the river systems that originate from these ice-covered mountains provide the water resources that support life, agriculture, and economic activity for many hundreds of millions of people (3). The Indus River System is the critical water resource inside Pakistan a mostly agrarian country with water security being closely connected to the meltwater provided by glaciers. Glacial and snowmelt contributions to the flow of the Indus and its tributaries are an outsized contribution as this information accounts for a substantial amount of annual flow of the river system, especially prior to monsoon rains occurring during the dry months of the pre-monsoon season (4). These long-standing dependencies reveal a more precarious situation where not only is the country's water, food, and energy rights at risk from environmental change, but also experiences the consequences of it in the high-altitude cryosphere.

The observed global trend of glacier retreat is a clear yet amplified response to climate change from anthropogenic greenhouse gas emissions (5). However, in contrast to other international trends in glaciers, the behavior of glaciers in the Karakoram and Himalaya region to this global climatic forcing exhibits the degree of regional variability (6). The scientific community is particularly fascinated by a localized phenomenon occurring in the central Karakoram region, which, despite observed retreat in the eastern Himalayas and, indeed, all of the other glacial landscapes around the world, glaciers in the central Karakoram have shown stability and even slight mass gain (7).

This counterintuitive cold-climate behavior has been articulated as the "Karakoram Anomaly" which has added a complication to predicting water supply future in the region. The anomaly suggests important localized climatic drivers (like other influences) including the interacting effects of the South Asian Summer Monsoon, which contributes vital summer precipitation, and the mid-latitude Westerly Disturbances providing ample winter snow (8). As the precise mechanisms behind the anomaly are not well understood, further understanding of them may be essential as the longer-term climate change impacts on water supply may not be observed fully while this anomaly is masking the observation (9).

The basis for a thorough review focused explicitly on the Pakistani aspect of the larger Karakoram and Himalayan context is valid and increasingly pressing. This region lies at the heart of a possible climate emergency, wherein the complicated interplay of warming temperatures, changing precipitation patterns, and complex glacier processes will be the ultimate determinant of water futures for an entire nation (10). The initial impacts of climate change, associated with higher melt rates, may actually lead to a temporary increase in river flows, leading to a hydrological phenomenon frequently described as "peak water" (11). However, this apparent abundance will be temporary and perhaps misleading, followed by a significant and potentially devastating time of reduced water supplies as glaciers continue to lose mass (12).

The aim of this review is to summarize the most up-to-date scientific evidence about observed and projected environmental change across this important region. The review will consider the mechanistic drivers of glacier melt, assess spatially and temporally explicit glacier change with modern remote sensing technologies, and assess cascading impacts on hydrological regimes and water security downstream. Furthermore, it will consider the current adaptation and policy environments of Pakistan and outline some of the major gaps that will continue to hinder the viable building of climate resilience (13). By synthesizing findings from recent research in climatology, glaciology, hydrology, and policy studies, this article aims to present a comprehensive and current understanding of one of the major environmental challenges of our time (14).

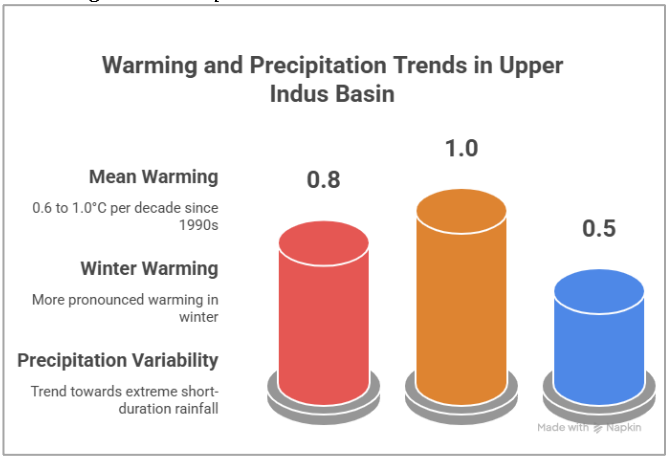
Climate Change Trends and Regional Atmospheric Dynamics

The climate dynamic affecting the Karakoram and Himalayan region is a constructed field comprised of global climate forcing components and local topographic influences, which creates heterogeneous warming signals and different precipitation regimes that directly determine glacier behavior and evolution.

Instrumental records and climate reanalysis data have consistently documented substantial warming trends across the Upper Indus Basin. Multiple studies support a mean warming trend of between 0.6 and 1.0°C per decade, since the 1990s, in line with rates often exceeding the global average (10). This warming pattern is characterized by seasonal variability, namely, pronounced winter warming a trend that will have important ramifications for seasonal snow accumulation. Precipitation patterns have also become more variable, suggesting a trend toward more extreme short-duration rainfall events, despite total annual precipitation exhibiting spatial variability that presents as both increases and decreases (15).

Figure 1

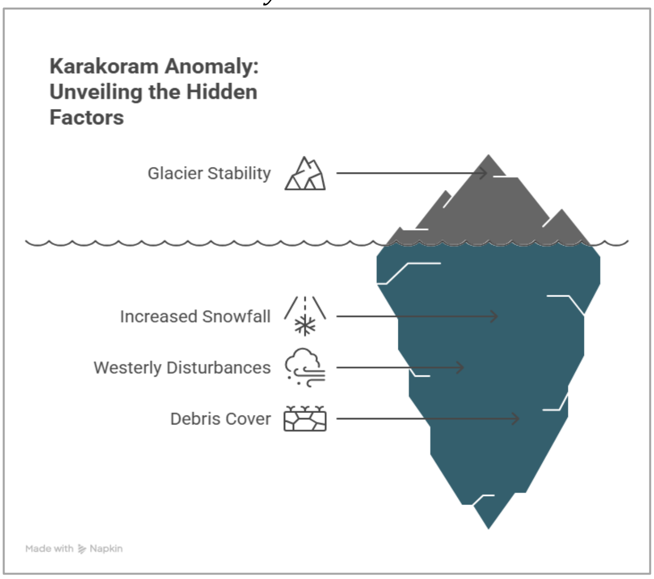
Warming and Precipitation Trends



The "Karakoram Anomaly" continues to situate an important part of the cryospheric response of the region, referring to the stability or slight mass gain of glaciers in the central Karakoram, which stands in stark contrast to the widespread mass loss reported in other areas. Studies in recent years continue to clarify the explanations for the observed conditions. The primary explanation focuses on the potential increased winter snowfall as a result of more frequent and intense mid-latitude Westerly Disturbances, which produce thick, insulating snow layers that significantly limit summer melt rate (16). The extensive debris cover on Karakoram glaciers further complicates the mass balance dynamics; thicker debris cover provides an insulative cover of the ice from solar radiation, while thinner debris can promote enhanced melting (17).

Figure 2

The Karakoram Anomaly



The basic climatological contrast of monsoon-driven eastern Himalayas versus the westerly-driven Karakoram is one of the primary controls on glacier mass balance. The South Asian Summer Monsoon introduces moisture into the eastern Himalayas, leading to summer accumulation, but also leads to melting due to temperature and precipitation. Alternatively, western Karakoram and Himalayan glaciers receive the majority of their precipitation from mid-latitude Westerly Disturbances that produce significant winter snow that provides a snowpack (18). Climate modeling has consistently predicted intensification for both of these systems; however, there is considerable uncertainty on the overall impacts on glacier mass balance (19).

Elevation-dependent warming (EDW) is a widely recognized phenomenon across High Mountain Asia, where elevations receive greater warming than global or lower elevation averages. This increased warming occurs through a number of mechanisms including snow-albedo feedback, increases of water vapor in the atmosphere, and changes in energy flux associated with the atmosphere (20). The implications for glacial systems are significant and complicated. With a rising freezing level, more precipitation that falls will be rain instead of snow, even into the higher altitude region, which reduces accumulation and exposes glacier ice sooner in the melt season (21).

Mechanistic Drivers of Glacier Melting

Loss of mass from glaciers is a direct result of the energy imbalance at the ice/ atmosphere interface. Multiple processes, often working in concert, contribute to the observed rapid ice melt in the region.

Anthropogenic global warming provides the fundamental energy forcing for glacier melt primarily through emissions of greenhouse gases. Gradually increasing concentrations of long-lived greenhouse gases, such as CO_2 and CH_4, accentuate the greenhouse effect in the atmosphere, causing increases in near-surface air temperature and sensible heat transfer to the ice surface, while simultaneously elevating glacier equilibrium line altitudes (ELAs). As a result, larger areas of glaciers are placed in a melting (ablation) zone for longer periods of time (22). The overall trend of warming represents the overarching driver of widespread glacier retreat around the world.

The accumulation of light-absorbing particulates such as black carbon (from fossil fuel combustion, agricultural burning, and industrial manufacturing) and mineral dust (from deserts and agricultural landscapes) effectively decreases the albedo of snow and ice, absorbs additional solar radiation, and increases melt rates. Recent quantitative estimates indicate that black carbon and mineral dust potentially contribute to a significant amount of regional glacier melt (23). In certain Himalayan glaciers, light-absorbing particulates can create radiative forcing comparable to greenhouse gas warming, especially during the pre-monsoon season when glaciers are particularly vulnerable (24).

Cryoconite is a black granular material made up of mineral dust, soot and complex microbial communities, including cyanobacteria and algae that form unique depressions on the surface of ice. These cryoconite holes have a very low albedo and deepen rapidly, contributing to positive melt feedback. Also, the microbes within cryoconite contribute darkening; cyanobacteria are producers of dark UV-absorbing pigments and their metabolic processes and filamentous structures facilitate the clustering of mineral particles, which stabilize cryoconite granules (25). The biological darkening mechanism is a new front of research and it has been identified as a key mechanism of reduced surface albedo, especially in ablation zones.

The surface albedo feedback serves as a potent amplifier of initial melt. As snowlines recede and the seasonal snow cover is diminished, dark ice or firm that has persisted longer with a relatively low albedo is exposed. These surfaces also absorb more incoming solar radiation, which results in additional melting and warming, resulting in additional exposure of dark ice surfaces (26). The positive feedback loop is particularly powerful in helping initiate and prolong melt seasons.

Water that melts and drains from the surface to the glacier beds through crevasses and moulins lubricates the ice-bedrock interface. An increase in basal water pressure will reduce frictional resistance, resulting in enhanced basal sliding and increased velocity of ice flow. This mechanism actively transfers ice from higher-elevation accumulation zones to lower elevation, warmer ablation zones at an accelerated rate, leading to increased mass loss rates (27). While their areally dominant processes are more consequential, localized anomalous geothermal heat fluxes associated with tectonic activity may also contribute to basal melting of ice, therefore thinning ice from below and surely influencing the dynamics of glaciers (28).

Figure 3

Mechanistic Drivers of Glacier Melting

Hydrological Implications and Water Security

The evolving cryosphere has extensive implications for water resources, influencing various sectors and millions of residents across the Indus Basin.

Glacier melt is the primary contributor to hydrology in the Upper Indus Basin, estimated to provide over 50% of total flow, and this proportion can exceed 80% in the spring and early summer just prior to the onset of the monsoon season, when water is critical for irrigation (29). In addition, snowmelt contributes to runoff, and the combined total from both glacial and snowmelt sources in the Upper Indus Basin can exceed 70% of total flow (30).

Climate change continues to influence the hydrological regime. We are currently still in the period of increased meltwater and streamflow due to greater available water, with the shifts to greater flow occurring earlier in the season, followed by declines in improved flow as glacial ice mass continues to decrease in volume. More advanced hydrological change will see reduced flows during the dry season when traditionally water supplies were supplied by glaciers as they diminished, creating deep shortages for irrigation and domestic supply (31). Hydrological models indicate that condition and modeling peak water at mid-century and beyond for many sub-basins throughout the Indus Basin, and after that point flows will be decreasing (32).

Pakistan's agricultural sector, more than 90% of which is irrigated through the Indus Basin irrigation system (the largest in the world), will be directly threatened by the timing and volume of flow changes in its rivers. Such changes will compromise the productivity of essential wheat and rice cropping systems and pose serious risks to national food security and the livelihood of millions of farmers (33). Climate change impacts may lower wheat and rice yields by 10 - 20% by the year 2050 as a result of high-emission scenarios. Hydropower is also an important element of the energy strategy for Pakistan. Decreasing and more unpredictable flows, and increasing sedimentation stemming from accelerated glacial erosion and slope instability, can impact the efficiency, operational life, and economics of existing and planned hydropower projects (34). The sediment load in the Indus has risen almost 15% since 2000 due to accelerated erosion in deglaciated areas (35). Major urban centers and numerous rural communities directly use the Indus and its tributaries for drinking water. Reduced dry-season flows will exacerbate water scarcity situations, which may escalate allocation issues and costs of water supply. As surface flows become more unreliable, reliance on groundwater has risen, exacerbating depletion issues in aquifers throughout the Indus Basin (36).

Glaciers that are melting often create unstable lakes that are dammed by moraine, and when these lakes fail, they can set off disastrous Glacier Lake Outburst Floods (GLOFs). In Gilgit-Baltistan alone, hundreds of these lakes exist, and dozens of them have been classed as 'dangerous', with potential negative impacts for downstream infrastructure, communities and people (37). At least five catastrophic GLOF events have been documented in the region since 2000, leading to several significant floods and some loss of life (38).

Monitoring, Technology, and Data Innovation

The Himalayan and Karakoram region's complexity and remoteness require advanced monitoring methods. Recent advances in technology have greatly changed our ability to detect and quantify cryospheric changes at multiple scales.

UAVs or drones outfitted with high-resolution cameras, thermal sensors, and LiDAR have facilitated centimeter-scale mapping of glacier surfaces and have provided unprecedented detail of supraglacial morphology, melt patterns, and surface evolution (39). UAVs are also particularly well-suited for sampling hazardous locations of the glacier, as well as validating satellite-derived products. Furthermore, UAVs integrated with satellite imagery provide multi-scale tracking on everything from singular crevasses to entire glacier systems.

Machine learning has also begun to revolutionize cryospheric research with automated mapping of glaciers, change detection, and identifying features, including the growing class of deep learning models capable of accurately identifying and mapping glacier boundaries from satellite imagery, classifying surface types, and identifying glacial lakes all with minimal human involvement (40). Advancements in these methods have decreased processing times while improving accuracy, which in turn has allowed analysis of decades of satellite data throughout the entire region. Emerging AI systems are being implemented for predictions of glacier mass balance, surge precursors, and to aid in optimal planning of multi-sensor networks (41).

Comprehensive glacier observatories that utilize combinations of automated weather stations, time-lapse cameras, GPS networks, and hydrological sensors are enabling continuous, high-frequency data collection that is critical to understanding glaciers and processes (42). These comprehensive and elaborate systems capture the analysis of important interactions that are taking place between the atmosphere, cryosphere, and hydrosphere, facilitating in-depth studies on energy balances and model calibration studies. Recent efforts have expanded monitoring programs to high elevation areas (>5000 m) to fill important data gaps in glaciers' accumulation zones (43).

Strengthening connectivity with local communities, researchers, and tourists for data collection has considerably built the observational capacity throughout the region. Community-based monitoring programs train community members to document changes in glaciers, stream levels, and other hazardous events utilizing established and standardized methods. Smartphones have created the capacity for tourists and climbers to upload geotagged photos and observations that can build temporal records on the state of the glacier (44).

Modeling and Future Projections

While our modeling capabilities have improved our understanding of potential future cryospheric changes, considerable uncertainty persists in the complex Karakoram and Himalayan region.

Dynamical downscaling using high-resolution Regional Climate Models (RCMs) has significantly enhanced the representation of complex topography and local climate processes. Recent inter-comparison exercises showed that RCMs were much better at reproducing the spatial heterogeneity of temperature and precipitation than GCMs (45). However, there remain challenges simulating the so-called Karakoram Anomaly, with difficulties replicating the observed stability-explanation. The use of RCMs in combination with glacier and hydrological models enables more realistic projections of future water availability (46).

Advanced glacier models that also incorporate ice dynamics, processes relevant to mass balance and subglacial hydrology provide a more reliable basis for projecting future glacier change. These models incorporate glacier-specific characteristics, including hypsometry, debris cover, and flow dynamics to provide estimates of future mass loss (47). More recently, the need to consider some of the physical processes such as ice avalanching, debris evolution, as well as black carbon deposition become apparent when forecasting longer-term projections. Modeling suggests that, even under moderate warming scenarios, many glaciers in the Himalayas are expected to lose considerable mass by 2100 (48).

The progress in the development of integrated hydrological models that represent cryospheric processes has improved projections of future water availability. These models consider or include water discharge contributions from glacier melt, snow melt, and precipitation sources and include changing seasonality and ice storage dynamics (49). Projections indicate that water will be more available in the early years (often termed as "peak water") before it sharply declines with decreasing glacier storage. While timing of peak water may differ by basin, modeling indicates that catchments at higher elevations tend to peak later than catchments at lower elevations (50).

Machine learning methods are being used more frequently in combination with physical models to improve projections and estimate uncertainties. The approaches are hybrid, using physical understanding to inform machine learning predictions while drawing on data driven approaches to improve estimates of model parameters used in simulations (51). Machine learning applications include downscaling climate model outputs, correcting model bias (i.e. the tendency to under or overestimate), and predicting extreme events. For example, machine learning has been applied to develop early warning systems for glacial lake outburst floods and landslide hazards (52).

Adaptation, Policy Framework and Future Perspectives

Achieving successful interventions will necessitate coordinated action in policy development across multiple levels and sectors, combined with strategic foresight during planning for the future.

Pakistan has implemented several actions, including the National Climate Change Policy, enhanced Nationally Determined Contribution, and the second phase of the GLOF project, which prioritises policies focused on community-based adaptation and early warning systems. Challenges to implementation include limited financial and institutional capacity (53). The Pakistan Meteorological Department is enhancing monitoring at high altitudes, and the Water and Power Development Authority has conducted glacier monitoring surveys to use in hydropower and water resource planning. Developing robust early warning systems for GLOFs and flash floods, by combining satellite monitoring, ground sensors and community-based communication networks, are considered some of the more cost-effective approaches to adaptation (54).

Several early warning systems have been successfully developed in vulnerable valleys. To ensure long-term adaptation, there is a need to design irrigation canals, hydropower dams, and other water supply systems to accommodate increased sediment loads to settlements and variable flow regimes (55). Mountain communities possess a repertoire of indigenous knowledge, such as traditional water harvesting and diversification of crops, that may complement scientific approaches to adaptation. Additionally, the Indus Waters Treaty, with respect to water resources management for Pakistan and India, must be modernized to account for changing climatic conditions. Collaboration at the regional level with SAARC and ICIMOD is important for data sharing and collaborative action (56).

Moving forward, primary areas of focus will be to develop a full National Glacier Monitoring Network for timelier and more continual follow-up on change across all climate types. Using artificial intelligence and machine learning in glacial modeling and water resource planning can allow for better predictability and decision-making. Investments in capacity building at the local level and community-led climate resilience programming can enhance adaptive capacity within communities (57).

Making an explicit connection between cryosphere research and the Sustainable Development Goals, especially Goal 6 (Clean Water), 13 (Climate Action), and 15 (Life on Land) can enhance policy coherence and resource mobilization. Importantly, strengthening climate education, improving scientific communication, and enhancing scientific diplomacy are paramount for educating the public and enhancing regional cooperation to address this transboundary crisis (58).

CONCLUSION

The effects of climate change on the glaciers of the Karakoram and Himalayan region is undeniable and represents a serious threat to Pakistan's water security. Even though the Karakoram Anomaly offers some short-term buffering for the region, it does not counteract the longer-term trend of decreasing glacier mass nor the subsequent consequences for the Indus River system. The consequences for agriculture, energy, and socio-economic stability are serious and indicate a need for immediate strategic response.

Pakistan's national resilience can only be assured through sustainable water management underpinned by sound science, robust infrastructure, and inclusive adaptation. The foundation for successful adaptation planning is provided to some extent by new monitoring technologies and improvements in modeling capacity. But considerable gaps remain in the understanding of the details of regional climate processes, glacial behavior and socio-economic vulnerabilities.

The window of opportunity for action is closing, requiring international partnerships for proactivity and immediate policy change in order to have any chance of success. The challenges are significant, but there are also opportunities for innovation, collaboration, and sustainable development. Pakistan can navigate the challenges climate change raises and plan for a sustainable future for generations to come by decoupling the climate-glacier-water security nexus in integrated ways that combine appropriate science, policy and community involvement.

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