Impacts of climate change on cryosphere and streamflow in the Upper Indus Basin

Shakil Ahmad Romshoo[1,2,3], Tariq Abdullah[2] and Jasia Bashir[2]

[1]Centre of Excellence for Glacial Studies in the Western Himalaya, Hazratbal Srinagar, Jammu & Kashmir, India 190006 shakilrom@kashmiruniversity.ac.in
[2]Islamic University of Science and Technology, 1-University Avenue Awantipora, Jammu and Kashmir, India
[3]Department of Earth Sciences, University of Kashmir, Hazratbal Srinagar, Jammu and Kashmir, India

Abstract

During the past several decades, global climate change has exerted a profound impact on high mountain environments, notably the cryosphere, which is highly susceptible to atmospheric changes due to its fragility. Climate change is quite evident in the Indus Basin and is adversely impacting various natural resources and the livelihoods of communities inhabiting the catchment areas of its rivers. In the Jhelum basin, a tributary of the Indus, the temperature has increased by 0.8 °C from 1980–2016 and is projected to further rise by 3°C and ~5.2 °C by the end of the century under the RCP4.5 and RCP8.5 emission scenarios respectively. Similarly, in the Chenab and Indus basins, temperatures are projected to rise by 3.5 °C and 4.8 °C and 4.8 °C and 6.5 °C, respectively, under the two scenarios. Concerns persist over the potential shrinkage of glaciers, reduced water storage capacity, and diminished seasonal snow availability. According to IPCC reports, Himalayan glaciers have receded faster since 1850 than anywhere else globally- a trend expected to continue. Over the last decade alone, glaciers in the Upper Indus Basin (UIB) have melted at a rate of -0.35 ±0.33 m a^{-1}, with considerable variability across different mountain ranges. As there is no substitute for glaciers-melt in the long run, continued glacier recession could lead to significant water shortages in the basin, severely affecting livelihoods and economy in the basin. Global climate change projections also suggest significant decreases in river flows originating from the UIB, raising serious concerns. For instance, in the Jhelum basin, snowmelt contribution is projected to decrease by 44% by the end of the 21st century under the RCP 8.5 emission scenario. However, significant knowledge gaps remain regarding the precise impacts of climate change on glaciers and other water resources in the basin. It is worth noting that the Indus waters, originating from the Himalayas, are shared between India and Pakistan under the Indus Water Treaty (IWT). Given the critical importance of these waters, It is imperative for both countries to collaborate in developing effective mechanisms to better understand and address the impacts of changing climate across various sectors in the basin.

Keywords: Upper Indus Basin; Climate Change; Cryosphere; Streamflow

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1. Introduction

In recent decades, global climate change has exerted a substantial impact on the delicate high-mountain environment of Asia, encompassing snow, glaciers, and permafrost, all of which are highly sensitive to atmospheric fluctuations. Instrumental records indicate a systematic increase in the global mean temperature at a rate of 0.07°C per decade over the past century (Jones & Moberg, 2003). Notably, the 1990s, 2000s, and 2010s emerged as the warmest decades, with 2016 ranking as the hottest year since the commencement of global temperature recording in 1856 (Arguez et al., 2020). However, this warming trend has not been uniform across the globe. High northern latitudes, in particular, have experienced more pronounced effects, with reconstructions of mean surface temperature over the past two millennia indicating unprecedented warmth in the late twentieth century (Mann & Jones, 2003), largely attributed to anthropogenic climate forcing (Thorne et al., 2005).

There are indications that the Himalayan region, including the Upper Indus Basin (UIB), exhibits a unique response to global warming (Kumar et al., 1994; Yadav et al., 2004), characterized by an increased Diurnal Temperature Range (DTR) and cooling of mean temperature in certain seasons, possibly influenced by local factors. During spring, summer, and autumn, a significant portion of water in the UIB rivers originates from snow and ice melt (Kaser et al., 2010). Projections suggest that spatial variations in observed and anticipated climate change will be more pronounced in mountainous regions and their downstream areas compared to plains and coastal zones (IPCC, 2007a), given that the rate of warming in the lower troposphere intensifies with altitude (Bradley et al., 2006). Additionally, the diverse climate zones within mountainous areas, resulting from significant altitude variations over short horizontal distances, render them particularly vulnerable to climate shifts (Beniston et al., 1997).

Globally, glaciers have largely retreated since the Little Ice Age (LIA) (WGMS, 2002), with a general trend of recession since 1850 (Mayewski & Jeschke, 1979). While many glaciers in the UIB are indeed shrinking (Abdullah et al., 2020; Rashid et al., 2017; Romshoo et al., 2022; Romshoo et al., 2020; Romshoo et al., 2015), there exists a debate among scientists regarding the retreat of all glaciers in the Himalaya-Karakoram-Hindu Kush region. The trans-Himalayan UIB boasts approximately 20,000 km^2 of perennial snow and ice cover, with the Karakoram–Himalaya harboring extensive glacier coverage due to extreme cold temperatures at high altitudes (Young & Hewitt, 1990; Hewitt, 2011). Nearly 11.5% of the UIB's total area is encompassed by perennial glacial ice, marking the largest glacier coverage outside the polar and Greenland regions (Hewitt, 2007). Forecasts suggest that up to a quarter of global mountain glacier mass could vanish by 2050, with potentially half of the glacier mass lost by 2100 (Wester et al., 2019). Several studies predict that glaciers will largely disappear in certain regions by century's end, while others suggest that glacier cover will persist in reduced form for centuries (Chaturvedi et al., 2014; Kaser et al., 2010; Wester et al., 2019).

The retreat of glaciers has served as a clear indicator of global warming since the LIA (Oerlemans, 2005). Across the world, including the UIB, evidence from glacier moraines provides insights into their maximum extent during the LIA, confirming their recession globally in response to warmer climates (Armstrong, 2010). Immerzeel et al. (2010) observed significant negative trends in winter snow cover in the UIB from 1999 to 2008, impacting the hydrological regime of the basin.

Snow and ice reserves in the UIB, crucial for sustaining seasonal water availability across South Asia, are poised to undergo substantial impacts from climate change to varying degrees (Immerzeel et al., 2010), with far-reaching consequences not only for mountainous regions but also for populated lowlands reliant on mountain water resources for domestic, agricultural, industrial, and hydropower purposes (Romshoo et al., 2022). Concerns regarding the potential impact of climate change on Indus River flow (Rees & Collins, 2006), aligned with global climate change projections (Cruz et al., 2007), have raised concerns of significant reductions in river flow magnitude (Briscoe & Qamar, 2006), though some reports suggest these threats may be overstated (Armstrong, 2010).

Rivers heavily reliant on glacial meltwater are expected to react differently to temperature increases than those primarily fed by monsoon rainwater (Singh et al., 2008). The Karakoram, Himalaya, and Hindu Kush Mountains constitute major drainage sources for the Indus River, receiving contributions from meltwater, seasonal snowfields, glaciers, and direct rainfall runoff. Future climate change projections anticipate substantial decreases in river flows originating from the Himalayas (Rees & Collins, 2006; Akhtar et al., 2008; Bank, 2005), supported by reports of glacier retreat, ice volume depletion, and consequent streamflow decline in the UIB (Abdullah et al., 2020; Romshoo et al., 2015; Shrestha & Shrestha, 2004).

Meltwater remains a crucial component and primary irrigation source for the entire Indus basin. Studies have shown that a significant proportion of UIB flow originates from high snowfall zones and glacierized basins above 3500 m in elevation (Wake, 1989; Young & Hewitt, 1990), with mountainous regions playing a key role in UIB hydrology (Liniger et al., 1998). Snow and glacial melt constitute primary hydrological processes in the mountainous UIB, where temperature and precipitation shifts are expected to significantly influence melt characteristics (Barnett et al., 2005), albeit with inter-basin variability (Pellicciotti et al., 2010). While snow and glacial melt predominantly contribute to UIB runoff (Miller & Rees, 2011), southern Himalayan slopes receive direct runoff from summer monsoon precipitation (Archer & Fowler, 2004).

In this article, we have presented the climate change scenario over the UIB and discussed how it is impacting glaciers and stream flows in the region and other dependent sectors based on the existing literature.

2. Data Set and Methods

Various data sets including temperature and precipitation from various meteorological stations over UIB have been used by several researchers to quantify the changes in climatic variables over the past several decades (Azam et al., 2018). Trend analysis has been carried out to understand the spatial and temporal variability in temperature and precipitation over UIB. Given the scanty network of meteorological observatories over the UIB, various studies have used the gridded and reanalysis data products to understand climatic variability over the region (Romshoo et al., 2020). For future climate change projections and consequent impacts, individual climate models and an ensemble of models from various Coupled Model Intercomparison Projects (CMIPs) experiments under different emission scenarios have been utilized (Romshoo et al., 2020). Similarly, trend analysis of the discharge data available from various gauging stations in the UIB was carried out to understand streamflow variability in response to changing climate. Besides, the future changes in the stream flows have been modeled widely under different climate change scenarios (Romshoo et al., 2022). To understand the glacier dynamics several data sets including historical maps, satellite images, and aerial photographs have been used in most of the studies. These data sets have been mainly used to quantify changes in glacier terminus and area (Romshoo et al., 2022). Given the challenging topographic, adverse climate conditions, logistic constraints, and security impediments, field-based measurements to quantify glaciological, hydrological, and climatological processes over UIB are scanty. Recently, the geodetic approach has been used for the quantitative assessment of glacier mass balance (Abdullah et al., 2020). Several other studies have used the temperature index and energy balance modeling approaches to estimate glacier mass balance. For future glacier projections, most of the studies have relied on the temperature index models and volume-area scaling approach using the temperature and precipitation projections derived from climate models and under different climate change scenarios (Wester et al., 2019).

3. Climate Change Scenario

Fowler and Archer (2005) demonstrated that while mean annual temperatures in the UIB are increasing following global trends, summer temperatures, crucial for glacial melt have exhibited a decline at numerous valley stations in the Karakoram region from 1961 to 2000. Hussain et al. (2005) illustrated analogous declines in temperature during both the monsoon and pre-monsoon seasons in the high mountain area of the Central Himalayas. Furthermore, from 1961-1999 Archer and Fowler, (2004) reported a significant increase in precipitation in the UIB in both winter and summer. However, Romshoo et al., (2015), reported a substantial rise in temperature during all the seasons but did not find any significant changes in precipitation patterns over the Jhelum basin draining into the Jhelum River a major tributary of the Indus. They observed a shift in precipitation patterns, noting sparse snowfall during the winter and spring months. Consequently, there has been a rise in the proportion of rainfall, attributed to rising temperatures, especially during these seasons.

Several studies have also presented varying conclusions regarding temperature trends in UIB (Fowler & Archer, 2005, Bhutiyani et al., 2020). Fowler and Archer (2005) analyzed the seasonal and annual temperature patterns within the Karakoram and HKH mountains spanning the years 1961 to 2000. Their analysis also involved a comparison with adjacent mountainous areas and the broader Indian subcontinent. The findings demonstrated significant disparities in the behavior of winter versus summer temperatures, as well as variances between maximum and minimum temperature observations. Fowler and Archer, (2006) based on the analysis of mean and minimum summer temperatures reported a consistent trend of cooling in the UIB starting from 1961. Chaudhry and Rasul, (2007) on the other hand reported an increasing trend, though non-significant in the annual mean temperature over UIB in Pakistan. Evidence suggests that the historical climatic patterns in the UIB do not align with global trends in seasonal temperatures (Fowler & Archer, 2006), nor do they match global precipitation trends (Archer and Fowler, 2004), Sheikh et al., (2009) assessed changes in climatic variables across Pakistan and identified significant deviations from global patterns. Additionally, analysis of temperature data dating back to the 19th century in the UIB reveals a significant upward trend in annual temperatures across all three stations analyzed in the Northwestern Himalayan region (Bhutiyani et al., 2010).

Overall, the temperatures in the Himalayas show a significant warming trend, although the rate of change and periods vary depending upon the regions and seasons. The western Himalayas have shown a rise of 0.9 °C between 1901 and 2003 (Dash et al., 2007). Several studies have reported that this observed trend is largely related to the increase in temperature after the 1970s (Dash et al., 2007). Zaz et al., (2019) reported an increase of around 0.8°C in the mean annual temperature over UIB in Jammu and Kashmir from 1980 to 2018. From the existing literature, it can be summarized that the rate of warming in the UIB surpasses the global average of 0.74°C over the last century (Du et al., 2004, IPCC, 2007a, IPCC., 2007b).

Contrary to temperature patterns, much of the literature indicates a lack of spatially consistent trends in precipitation across the region. Moreover, discrepancies in precipitation trends are noticeable across various seasons within the area. Over the north-western Himalayas, Bhutiyani et al., (2010) observed a statistically significant decreasing trend in the average annual rainfall from 1866 to 2006. Similarly, Sontakke et al. (2010) observed a comparable trend across the region from 1960 to 2006, A similar trend was noted over the region from 1960 to 2006 (Sontakke et al., 2010) although statistical significance wasn't explicitly mentioned. The literature reveals intra-regional disparities in winter rainfall trends. Insignificant changes in precipitation over the Jammu, Kashmir, and Ladakh regions of the UIB have been reported by Zaz et al., (2019) from 1980 to 2018.

In the future, the warming induced by climate change is expected to be particularly pronounced in the UIB, even if global warming is limited to 1.5 °C. The increase in the average annual temperature in UIB is anticipated to surpass that of other regions in the Himalayas. Nevertheless, there are considerable uncertainties in future precipitation patterns across the entire Himalayan region, including the UIB, as highlighted in various studies (Hasson et al., 2014, Mishra and Ramgopal, 2015, Choudhary and Dimri, 2018). Previous research on the Himalayas (Wester et al., 2019; Kulkarni et al., 2013; Sanjay et al., 2017) has projected a precipitation change ranging from -9.8% to +29.3% over the northwestern Himalayas.

Romshoo et al., (2020) observed a notable upward trend in temperatures by the end of the 21st century under A1B, RCP4.5, and RCP8.5 scenarios over the UIB. Additionally, the study delved into the future changes in the extent and distribution of the climate zones in the UIB under the A1B, RCP4.5, and RCP8.5 IPCC emission scenarios (Fig. 1). The projected climate classification (Köppen-Geiger) by the year 2100 under various climate change scenarios indicated an expansion of subtropical and temperate zones, with a significant reduction in the cold desert zone across all scenarios. The subtropical climatic zone in the southern UIB (Chenab basin) is expected to encroach into the temperate climatic zone in the Jhelum basin. Similarly, it is projected that the cold desert zone within the UIB will likely be encroached upon by the temperate ending 21st century (Fig. 1).

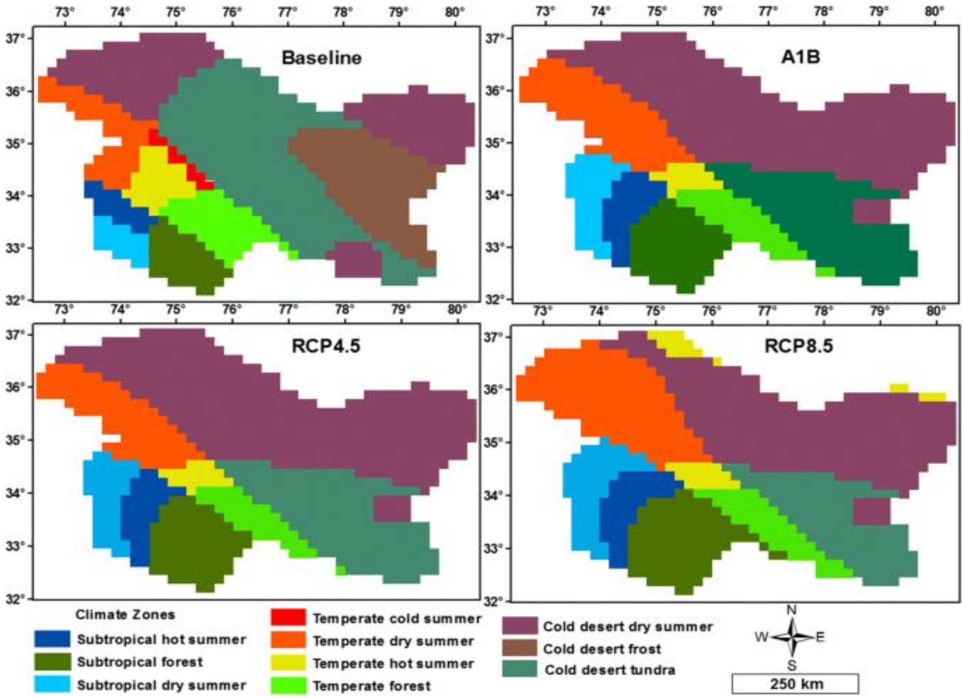

Figure 1. Revised Köppen-Geiger climate classification/zonation for the Jammu and Kashmir region under the baseline (1961–1990), A1B, RCP 4.5, and RCP 8.5 scenarios by the end of the twenty-first century (Source: (Romshoo et al., 2020).

More recently, Bashir and Romshoo, (2023) projected the temperature and precipitation over the UIB using the downscaled CMIP5 climate model outputs and reported a differential rise in temperature across the three river basins of the UIB basin. The study projected a temperature rise of 3 °C and 5.2 °C in the Jhelum basin, 3.5 °C and 4.8 °C in the Chenab basin, and 4.8 °C and 6.5 °C in the Indus basin under RCP4.5 and RCP8.5 scenarios respectively (Fig. 2).

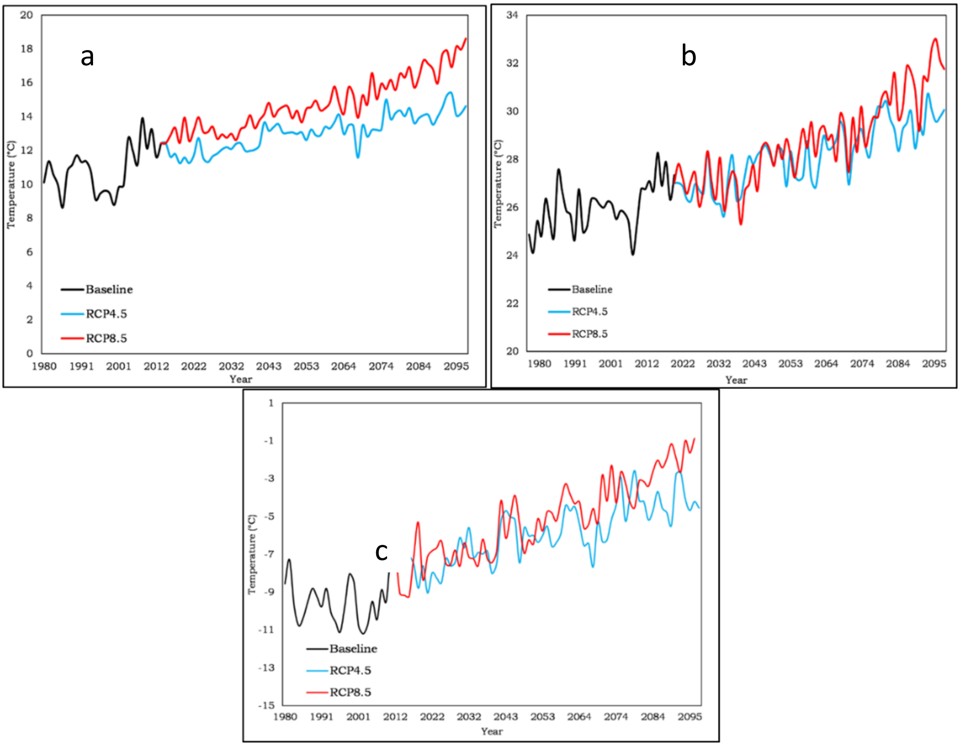

Figure 2. Projected temperature increase in the a) Jhelum b) Chenab c) Indus basins ending 21st century under RCP4.5 and RCP8.5 (Source: Bashir and Romshoo, 2023).

The study further projected only a slight change in precipitation in the UIB with a marginal increase of 0.8% and 3.4% in the Jhelum basin by the end of 21st century under RCP4.5 and RCP8.5 respectively (Fig.3). On the contrary, it is forecasted that precipitation in the Chenab will rise by ~8% and 8.2% in the latter part of the twenty-first century under RCP4.5 and RCP8.5 emission scenarios, respectively. In the Ladakh region (Upper Indus Basin), an increase of 6% and ~8% in precipitation is expected during the early twenty-first century, followed by ~2.6% and 8.7% more precipitation by the late twenty-first century under RCP4.5 and RCP8.5 emission scenarios, respectively.

4. Climate change impacts on glaciers

Goudie et al. (1984) opined that the historical records of glacier fluctuations in the Himalayas and the Karakoram indicate that, in the late 19th and early 20th centuries, the glaciers were generally advancing, followed by predominant retreat observed from 1910 to 1960. The Karakoram glaciers have declined by 5% or more since the early 20th century, mainly between the 1920s and 1960s. However, the recession slowed in the 1970s (Mayewski and Jeschke, 1979), and some glaciers even underwent modest advances (Brun et al., 2017). Fowler and Archer, (2006) reported a thickening and expansion of Karakoram glaciers due to the increased winter precipitation and decreasing summer temperatures. From the later part of the 1990s, some findings about the glaciers stabilizing and, in the high Karakoram, even glacier advances have been reported (Hewitt, 2005, Immerzeel et al., 2009). This is contrary to most of the glaciers in the world reported to have been shrinking for the last several decades, including the neighbouring Greater Himalayas (Berthier et al., 2007, Romshoo et al., 2020). This contrast in glacier evolution shows a climate change pattern in Karakoram that differs from that in the other regions of the UIB (Fowler and Archer, 2005).

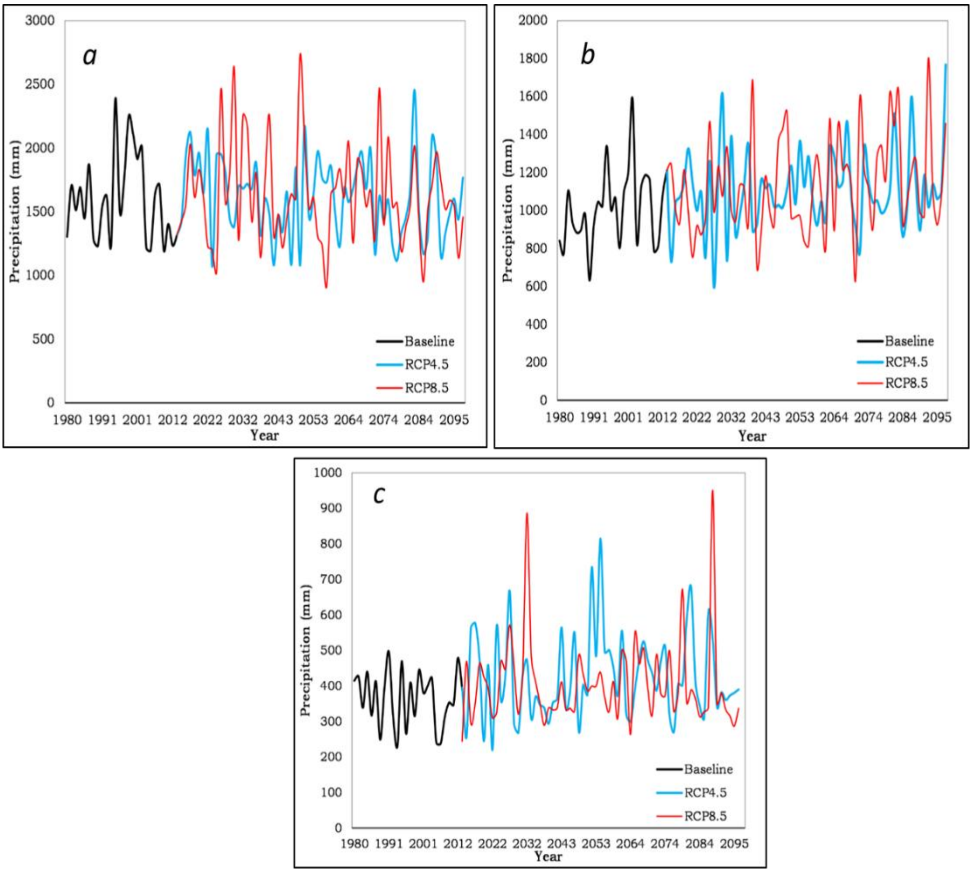

Figure 3. Projected changes in precipitation in the a) Jhelum b) Chenab c) Indus basins ending the 21st century under RCP4.5 and RCP8.5 (Source: Bashir and Romshoo, 2023).

The rapid retreat of Himalayan glaciers stands out globally, predominantly driven by global warming from human activities (IPCC, 2007b). Specifically, in the Hindu Kush Himalaya (HKH) region, glaciers are shrinking at a notable pace of

10 to 60 meters annually, leading to the disappearance of many smaller glaciers of less than 0.2 sq. km (Bajracharya et al., 2007). This trend is not isolated to the HKH region, as glaciers across High Mountain Asia are also experiencing a recession, with some retreating faster than the global average (Oerlemans, 2001).

Climatologists point out that alpine glaciers, like those in the Upper Indus Basin (UIB) of the Himalayas, serve as critical indicators of climate change due to their high sensitivity and the ongoing retreat of these glaciers, driven by increased atmospheric temperatures and changes in snowfall patterns at higher elevations, is projected to persist (Nesje & Dahl, 2016). These environmental changes in the UIB have resulted in glacier retreats and reduced streamflows, further emphasizing the significant impact of climate change on these vital natural resources (Romshoo et al., 2015).

Recent studies have highlighted an increasing trend in the retreat rates of many Himalayan glaciers, with a particular focus on the changes occurring at the glacier snouts (Bajracharya et al., 2007, 2008). Historical data tracing glacier fluctuations in the Upper Indus Basin (UIB) extend over the last 170 years, offering valuable insights into glacier dynamics since the mid-nineteenth century. Notably, comprehensive records exist for several key glaciers, including Kolohoi, Hispar, Siachen, Raikot, Biofo, Minapin, Aktash, Panmah, Central Rimo, and Baltoro, revealing significant retreat patterns over time (Bhambri et al., 2013; Hewitt, 2011; Rashid et al., 2017).

The retreat of Himalayan glaciers since the mid-19th century is a well-documented phenomenon, although the rates of retreat and the extent of area shrinkage vary significantly from one glacier to another and across different regions. Research conducted across the Himalaya-Karakoram region, aimed at quantifying changes in glacier length/snout, area, and mass balance, has revealed diverse outcomes. These studies indicate varying rates of area shrinkage, snout retreat, and changes in mass balance, underlining the complex nature of glacier dynamics in this region. The summarized findings are provided in Table 1, which details the snout, area, and mass balance changes across the Himalayan glaciers, with references indicating the number of studies contributing to each data point.

As indicated by Table 1 the glacier changes over the Karakoram –Himalaya region are quite differential. The glaciers in the Karakoram have witnessed the least recession whereas the glaciers in the eastern Himalayas are losing mass at higher rates compared to the western (UIB) and central Himalayas.

Table 1. Glacier snout, area and mass balance changes over the Himalayan region. The number in brackets indicates the number of studies contributing to the average of the parameters.

	Region			
	Eastern Himalaya (30)**	Central Himalaya (68)	Western Himalaya (46)	Karakoram (13)
Snout retreat m/yr	-14.26 (30)	-17.67 (68)	-17.03 (46)	-1.56 (13)
Area Change %/ yr	-0.63 (8)	-0.37 (38)	-0.40 (21)	-0.015 (04)
***MB m w e /yr**	-0.78 (2)	-0.63 (11)	-0.39 (11)	NA

** Only based on field studies ** estimation based on number of studies*

The differential glacier dynamics is even quite evident over relatively smaller geographical regions, for example, in a recent study, Romshoo and Marazi, (2022) demonstrated the differential response of glaciers across different mountain ranges in the UIB by analyzing various glacier parameters including length, area, surface elevation and equilibrium and glacier volume (Fig. 4).

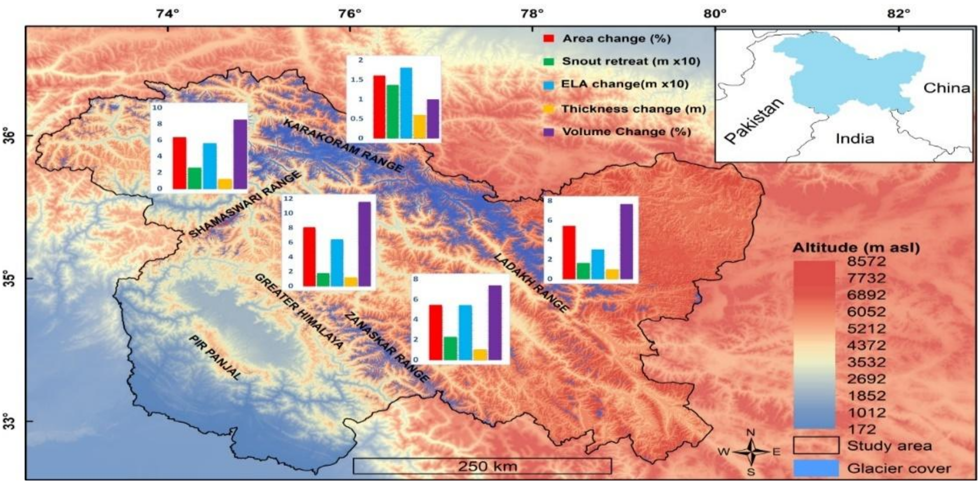

Figure 4. Changes observed in different glacier parameters in the five mountain ranges of the UIB: Karakoram (KKR), Ladakh (LR), Zanaskar (ZR), Shamaswari (SR) and Greater Himalaya (GHR). The column charts indicate changes in the glacier area, thickness change, volume loss, snout retreat and upward shifting of ELA (Source: Romshoo et al., 2022).

The data and knowledge about glacier terminus and area fluctuations within the Upper Indus Basin (UIB) have seen considerable improvement; however, field observations concerning mass balance remain limited. Notably, glaciological mass balance serves as an immediate and direct indicator of climate change, making such observations crucial for studying climate change, particularly in remote areas like the UIB where the relationship between climate and glaciers is not fully understood. Despite the development of more direct and comprehensive methods for year-to-year glacier system condition assessments through mass balance measurements, the complexity and time requirements of these methods have resulted in only a limited number of studies within the UIB (Romshoo et al., 2023).

In the Karakoram, glaciological measurements have predominantly been confined to the ablation area of the Baltoro glacier (Mayer et al., 2006). Since the initial mass-balance observation on the Gara glacier in 1974/75, the Himalayas have mostly experienced negative annual mass balances, with the longest continuous series being only 12 years for the Chhota Shigri glacier, indicating a mass balance of -0.56 ± 0.40 m.w.e per year over 2002-2014.

To address this knowledge gap and enhance our understanding of glacier-climate interactions, the University of Kashmir, Kashmir Srinagar has initiated the monitoring of approximately seven benchmark glaciers in the UIB over the last several years. This monitoring includes mass balance, snout, area, and velocity changes, with Hoksar and Kolahoi glaciers in the Jhelum basin among those studied. Observations from 2013 to 2018 show the Hoksar glacier's mass balance was consistently negative, averaging -0.95 ± 0.39 m.w.e annually (Romshoo et al., 2022). Similarly, the Kolahoi glacier exhibited an average in situ mass balance of -0.83 ± 0.34 m.w.e annually from 2014-2019, with notable year-to-year variations (Romshoo et al., 2023). Furthermore, the study has reconstructed the Kolahoi glacier's mass balance since the 1980s, highlighting the significant influence of summer temperatures and winter precipitation on its mass balance, both annually and over decades (Fig. 5).

Owing to the accessibility and logistic limitations in glaciological mass balance measurements, the geodetic mass balance has emerged as a viable alternative method for evaluating changes in glacier mass balance on a regional scale. Abdullah et al. (2020) recently conducted research covering the UIB, including the Jammu, Kashmir, and Ladakh regions, to analyze glacier mass changes using TanDEM-X and SRTM DEMs from 2000 to 2012. The findings indicated an average thinning of -0.35±0.33 m a^{-1} from 2000 to 2012 across the UIB (Table 2).

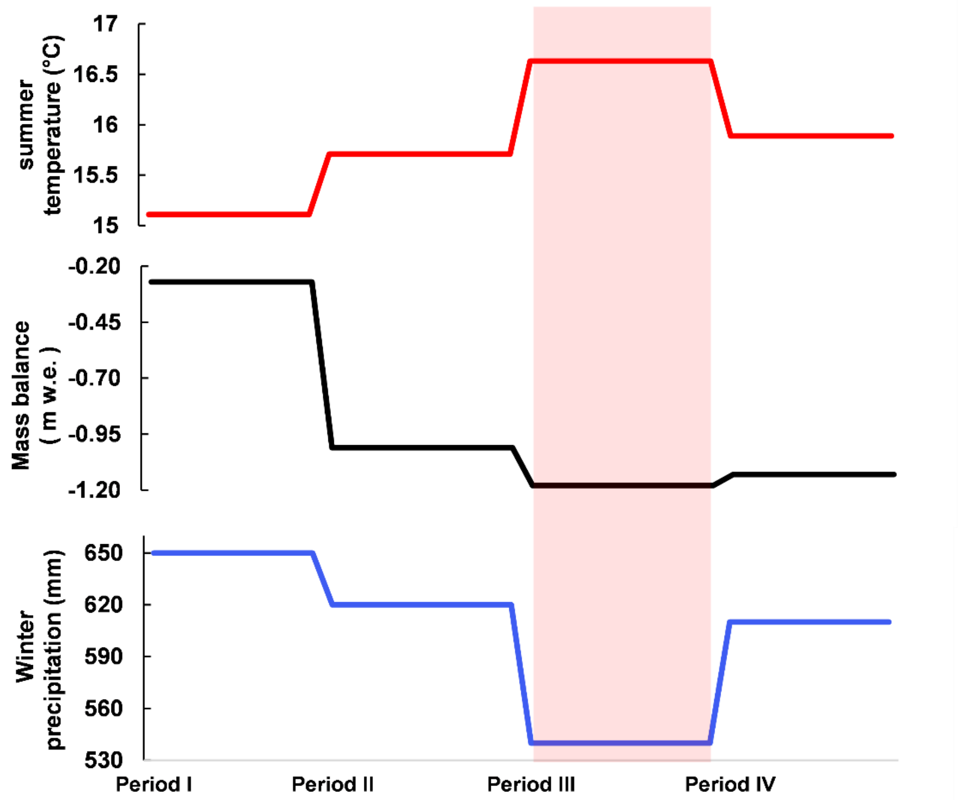

Figure 5. Mean annual mass balance of the Kolahoi glacier during four distinct periods from 1980 to 2019 (black thick line). The red thick line represents the mean summer temperatures, and the blue line represents the mean winter precipitation from 1980 to 2019 (Source: Romshoo et al., 2023).

The thinning was more pronounced in the Pir Panjal mountain range where glaciers have thinned -1.69±0.60 m yr^{-1}, whereas, marginal glacier thinning of -0.11±0.32 m a^{-1} was observed in the Karakoram. The observed changes in glacier thickness suggest a pronounced impact of topographic factors. Greater reductions in thickness were noted in glaciers at lower altitudes (-1.40±0.53 m yr^{-1}) and with gentler slopes (-1.52±0.40 m yr^{-1}). Glaciers situated on southern slopes exhibited significantly higher rates of thinning (-0.55±0.37 m yr^{-1}). Moreover, thickness loss was more pronounced in debris-covered glaciers (-0.50±0.38 m yr^{-1}) compared to clean glaciers (-0.32±0.33 m yr^{-1} (Fig. 6). Between 2000 and 2012, a total glacier mass loss of -70.32±66.69 Gt was observed. The heterogeneity in the glacier mass loss over the Karakoram-Himalaya region encompassing the UIB has been reported in several other studies (Bhutiyani, 1999, Naz et al., 2008, Kääb et al., 2012, Gardner et al., 2013, Vijay and Braun, 2018).

Table 2. Glacier thickness changes observed over the Upper Indus Basin (Source: Abdullah et al., 2020).

Mountain	Number	Fraction of dH/dT coverage	dH/dT	Mass balance	Mass change
Range	N	%	$m\ a^{-1}$	$m\ w.e.\ a^{-1}$	$Gt\ a^{-1}$
KKR	5579	78.52	-0.11 ±0.32	-0.09±0.27	-1.32±3.8
LR	3717	92.93	-0.46 ±0.26	-0.39±0.24	-0.96±0.59
ZR	1720	92.93	-1.17 ±0.41	-0.99±0.43	-2.34±0.84
SR	878	94.40	-1.28 ±0.46	-1.08±0.48	-0.69±0.26
GHR	243	94.10	-1.12 ±0.40	-0.95±0.42	-0.88±0.04
PPR	106	59.55	-1.69 ±0.60	-1.43±0.63	-0.38±0.01
JK&L	12243	82.12	-0.35 ±0.33	-0.29±0.29	-5.86±5.55

The existing literature suggests that mass loss would accelerate in the future under changing climate, for example, Chaturvedi et al., (2014) reported that within the Karakoram-Himalaya region, approximately 10.3% and 10.6% of the glaciated area is projected to potentially vanish by the 2030s. This figure increases to 10.6% and 13.2% by the 2050s, and substantially to 10.6% and 27% by the 2080s, based on the RCP2.6 and RCP8.5 scenarios, respectively. For the Karakoram region glacier volume loss between -18.6 and -30.3% and -19.1 and -35.9% is expected under RCP4.5 and RCP8.5 respectively (Kraaijenbrink et al., 2017). Similarly, 33% glacier area loss is projected in the Baltoro sub-basin of the UIB under RCP8.5 by ending 2100. Also, 20-28% loss in glacier area is reported over the UIB under RCP4.5 and RCP8.5 respectively by 2050s (Immerzeel et al., 2013). (Ren et al., 2007) utilized three Global Circulation Models to examine the warming effects under a high-emission scenario spanning 30 years from 2001 to 2030 across the Greater Himalayan region. Their findings suggest a spatially averaged reduction in glacier thickness of around 2 m specifically for areas situated below an elevation of 4000 m asl.

5. Climate Change Impacts the Streamflow

In total, approximately 40% of the meltwater in the Indus Basin is derived from snow and glaciers, according to research by Immerzeel et al. (2010). However, glacier or snow-melt components shall vary with time and space and there are therefore varying reports of the glacier- and snow-melt contributions to the stream flow in Himalayan rivers. Fowler and Archer, (2005) reported a 20% decline in summer runoff within the Hunza and Shyok river systems, primarily linked to a documented 1°C decrease in average summer temperatures since 1961. These two catchments, Shyok and Hunza, collectively account for over a quarter of the inflow to the Tarbela Dam. This dam serves as the primary control structure for the Indus Basin Irrigation System, one of the globe's most expansive integrated irrigation networks (Fowler & Archer, 2005). Romshoo et al., (2015) demonstrated a considerable decrease in streamflow from the primary tributaries of the Jhelum in the UIB, despite a diminishing demand for irrigation associated with the declining paddy cultivation in the region. This decline in streamflow is linked to diminished glacial mass, limited snowfall, and escalating water demands driven by the growing population in the basin (Romshoo et al., 2015)

Analysis of the monthly streamflow data in the Upper Indus Basin (UIB) indicates predominantly rising trends in winter flows and declining trends in summer flows from 1980 to 2004. Conversely, analysis of hydrological data in the Indus River did not detect any significant alterations in flow patterns. This observation applies to both inflows into Tarbela (1961 - 2004) and Kalabagh (1922–2002), as well as the Jhelum River's flow measured at Mangla (1922 – 2004) (Ali et al., 2009). The study did reveal an upward trend in Chenab river flows at Marala (1922–2004). However, a notable decrease was observed in the flow of the Kabul River at Nowshera from 1961 to 2004. Akhtar et al. (2008) explored three hypothetical scenarios of glacial depletion–complete disappearance, 50% reduction, and no change—from 2071 to 2100 in the UIB. Their findings suggest that rising temperatures and precipitation towards the end of the 21st century could lead to increased discharge under scenarios of total or partial glacier loss, while obviously, less water would be available in the river system with no glacier loss.

Several studies have reported the alterations in streamflow within the UIB attributable to the accelerated decline of snow and glacier reserves, a response to escalating temperatures. Ali et al. (2017), Immerzeel et al. (2009), and Romshoo & Marazi (2022) have each investigated this phenomenon, employing models to assess the contributions of snow, glaciers, rainfall, and baseflow to streamflow using historical climate data. Their collective findings underscore the heightened vulnerability of the UIB to climate change.

Similarly, Lutz et al. (2016) noted a marked reduction in snow and glacier melt contributions to streamflow in the UIB, correlating with rising temperatures anticipated in the 21st century. Studies indicate that basins predominantly reliant on snow and glacier melt, with precipitation projections showing minimal change yet confronting escalating temperatures, are poised to experience earlier spring runoff peaks and diminished summer flows (Barnett et al., 2005).

Recently, Romshoo and Marazi (2022) demonstrated a significant decline in both snow precipitation and snowmelt contributions to streamflow by the end of the 21st century across various climate change scenarios in the Jhelum basin. Their study further anticipates a notable shift in peak runoff toward early spring amidst changing climatic conditions (see Fig. 6).

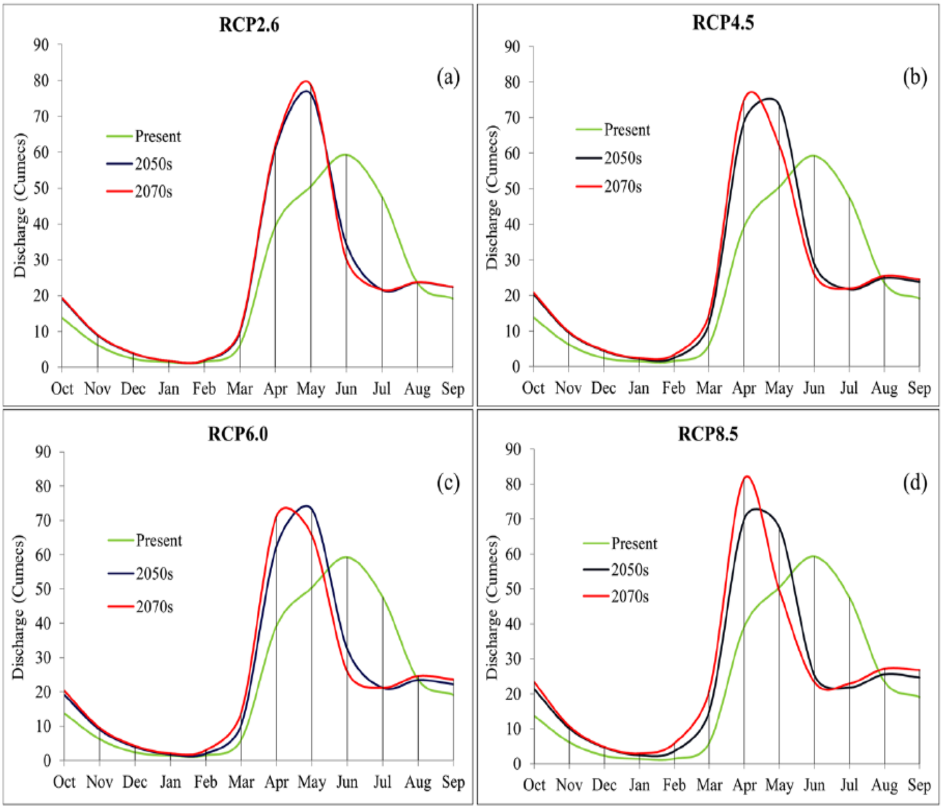

Figure 6. The projected shift in streamflow peak of Lidder River in the Jhelum bains, UIB by mid- and late twenty-first century periods under; a) RCP2.6, b) RCP4.5, c) RCP6.0 and d) RCP8.5 (Source: Romshoo and Marazi, 2022).

It is noteworthy that paddy cultivation, a vital sector of the economy and the primary source of sustenance for those inhabiting the Jhelum basin, relies on flood irrigation from June to October. The commencement of paddy transplantation in June aligns with the peak streamflow in the Jhelum River tributaries. However, projected shifts in streamflow towards spring could result in irrigation shortages during the crucial period of peak paddy crop water demand, negatively impacting crop productivity. This scenario carries significant implications for food security and the livelihoods of downstream communities (Romshoo & Marazi, 2022).

Moreover, in the UIB, Immerzeel et al. (2009) noted that the disappearance of glaciers, accompanied by a projected temperature increase of 4.8°C in winter and 4.5°C in summer by 2100, alongside precipitation increases of 19.7% and 15.7%, respectively, could lead to a reduction in summer maximum flow by around 30%. Additionally, there would be a decrease in the proportion of total precipitation falling as snow from 60% to 48%. While liquid precipitation and earlier snowmelt patterns may benefit downstream agriculture in the Indus basin by providing more water for local irrigation and replenishing reservoirs at the beginning of the growing season in April-May, they also pose challenges to water management strategies.

6. Conclusions

In light of the analyses presented in this paper, the indicators of climate change are quite clear and loud in the Indus Basin. Its impacts are already being felt across various sectors in the UIB, particularly affecting the cryosphere, hydrology, river flows, and the livelihoods of communities residing in the catchment areas of Himalayan-origin rivers.

The cumulative glacier mass loss of -70.32±66.69 Gt was observed from 2000 to 2012 in the UIB, which, if continued, would significantly affect the sustainability of water resources in the basin. There is heterogeneity in the glacier mass loss over the UIB region with some basins showing significantly higher mass losses. The glacier recession over the entire Himalayan region is of serious concern to scientists, policymakers and the general public as global warming may reduce the glaciers and their capacity to store water, as well as the amount of seasonal snow available for melting. The receding glaciers shall further increase the frequency of glacier hazards in both the short- and the long term. While a consistent reduction in glacier extent is evident across the UIB, insufficient data exists regarding the cryosphere, climatology, hydrometeorology, and other associated earth system processes. This lack of data hinders our ability to confidently determine the fate of the Himalayan cryosphere. Access to repositories of paleoclimate data, such as tree rings, pollen, ice cores, paleosols, and historical satellite images at high altitudes, would aid researchers in comprehending cryosphere dynamics in the UIB and addressing existing uncertainties. The water sourced from glaciers is irreplaceable, and its absence could lead to unprecedented water shortages in the region (Narain, 2009). The disappearance of all Himalayan glaciers would have a significantly greater impact on water resources originating from the western Himalayas (UIB) compared to the eastern Himalayas. This impact would manifest as a reduction in the annual mean flow by approximately 33% in the west, and only about 4 – 18%

in the east, relative to 1990 levels. This discrepancy is primarily due to differences in glacial extent and climatic conditions between the arid western and monsoonal eastern regions (Rees and Collins, 2006).

The changes in the streamflow in response to the changes in the magnitude and pattern of climatic variables and shrinking glaciers have the potential to increase the risk of associated hazards like flash floods and Glacier Lake Outburst Floods (GLOFs) (Richardson and Reynolds, 2000). Besides, the retreating glaciers under changing climate have the potential to damage hydropower infrastructure on the glacier-fed streams, for example by increasing the streamflow manifold during a GLOF. Loss of productive agricultural land, accelerated land degradation, the contamination of surface and groundwater resources and a decrease in groundwater recharge is another critical challenge posed by the fluctuations in the streamflow and water availability in response to climate change. These impacts shall put pressure on the water demands of the stakeholders and accelerate the tension between riparian countries (Laghari et al., 2012) and it is, therefore, necessary that the basin countries collaborate on developing a mechanism for cooperation to understand the impacts of changing climate on various sectors.

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