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Spatio-Temporal Assessment of Glacier Changes (1990-2025) and Their Relationship with Climate Variability in the Tirich Mir Region, Hindu Kush, Pakistan

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Abstract: Glaciers of the Hindu Kush region in northern Pakistan are important freshwater sources, yet; their response to recent climate variability remains spatially heterogeneous. This study assessed spatio-temporal changes between years 1990 and 2025 in five major glaciers of the Tirich Mir including massif—Dirgoi, Lower Tirich, North Barum, Owir, and South Barum—using multi-temporal Landsat imagery, the Normalized Difference Snow Index (NDSI), ASTER GDEM terrain data, and GIS-based area analysis. Landsat-5 TM, Landsat-7 ETM+, Landsat-8 OLI, and Landsat-9 OLI-2 images were analyzed for years 1990, 2000, 2010, 2020, and 2025, respectively. Climate variability was evaluated using NASA POWER summer-temperature and winter-precipitation data in R/R-Studio through linear regression, the Mann-Kendall test, Sen's slope, and Pearson correlation. Overall study findings show that total glacier extent has decreased from 64.23 km² in 1990 to 52.81 km² in 2025, corresponding to a loss of 11.42 km² (17.8%). The NDSI-derived clean-ice/snow-covered surface has declined from 36.89 km² in 1990 to 5.21 km² in 2010 and subsequently increased to 30.83 km² in 2025. Mapped debris-covered ice has increased from 27.34 km² in 1990 to 54.53 km² in 2010, while declined to 21.98 km² in 2025. Summer temperature showed a significant increasing trend (Sen's slope = 0.070 °C yr^{-1}, p = 0.0071) during period of 2005-2025, whereas winter precipitation showed no significant trend. Correlations between the mapped clean-ice surface and temperature (r = -0.17, p = 0.782) and precipitation (r = 0.40, p = 0.508) were non-significant. Hence, glacier shrinkage in the Tirich Mir region occurred concurrently with significant regional warming, whereas precipitation exhibited no statistically significant trend. Overallglacier variability was found to be influenced by factors such as debris cover, topography, and seasonal snow conditions . Focusing on glaciated terrains, present study approach will be helpful in prospective studies of regional cryosphere assessment.

Keywords: Landsat; NDSI; Mann-Kendall test; Sen's slope

Graphical abstract

Based on Landsat data and GIS technique, the current study evaluated the spatio-temporal variation of glacier surface in Tirich Mir of Hindu Kush mountain range in Pakistan for the period of 1990–2025. The findings revealed that the mapped surface of clean-ice/snow covered area has reduced from 36.89 km² to 30.83 km² with a net loss of 16.43%. Similarly, mapped surface of debris-covered ice area has reduced from 27.34 km² to 21.98 km², which amounted to the net loss of 19.60%. Moreover, the mapped glacier area has reduced from 64.23 km² to 52.81 km² with a net loss of 17.78%, respectively (Fig. below).

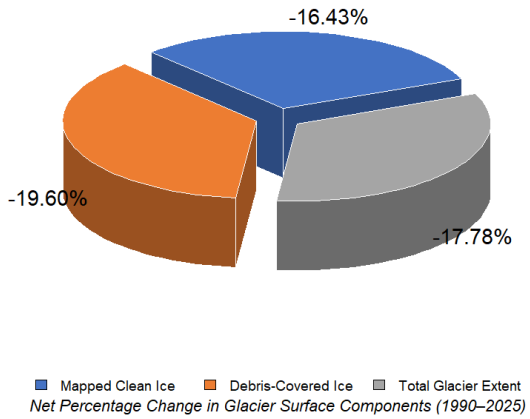


Figure. Change (net percentage based) in glacier surface (1990-2025)

Introduction

Mountain glaciers are critical indicators of climate change because their mass balance responds to variations in air temperature, snowfall, radiation, and surface-energy regimes. Global assessments show widespread glacier loss with subsequent effects on water resources, hydrological regimes, natural hazards, and downstream livelihoods (Intergovernmental Panel on Climate Change, 2021). The Hindu Kush-Karakoram-Himalaya (HKH) region ishigh mountainous terrain of Asia and comprise one of the world's largest zone of high-altitude glacier ice outside the polar regions which provides an important source of water to densely populated downstream areas (Immerzeel et al., 2010; Wester et al., 2019). Particularly, Pakistan is dependent on this region glacier- and snow-fed river systems. Moreover, glaciers in the HKH region also sustain seasonal stream-flow, support irrigation and hydropower generation, and contribute to domestic water supply. However, glaciers in northern Pakistan show non uniform response to climate forcings. Some glaciers in the Karakoram range have shown stable or advancing behaviors, known as the Karakoram Anomaly (Hewitt, 2005). On the other hand, some glaciers in these glaciated ranges have shown retreating, thinning, and degrading behaviors (Bolch et al., 2012). Therefore, local studies are highly significant, as; the response of glaciers differs due to factors like topography, morphology, aspect, debris cover, snow cover, and even the period of satellite imagery acquisition.

The combination of remote sensing (RS) with geographic information system (GIS) is an efficient tool for studying glaciers in areas of high altitude and inaccessible terrains, which involves costly, dangerous, and challenging fieldwork. In this perspective, the Landsat satellites data archive serves well as it comprises a long historical sequence and spectral ranges suitable for showing contrast between snow and glacier ice surface. Additionally, the use of Normalized Difference Snow Index (NDSI) is widespread in detecting snow and highly reflectant surfaces of ice, which are characterized by high reflectance at visible wavelengths, as well as high absorption at shortwave-infrared wavelengths (Hall et al., 1995). Nevertheless, NDSI is insufficient for defining debris-covered glacier ice due to similarity in the spectra of supraglacial debris and adjacent bedrock and moraines (Bhambri et al., 2011; Moazzam et al., 2022; Paul et al., 2004). Although glacier changes have been widely investigated across the Karakoram and Himalayan regions, comparatively limited information is available for individual glacier systems in the Tirich Mir region of the Hindu Kush. The present study focuses on the glaciers around Tirich Mir. It is the highest mountain peak in the Hindu Kush mountain range with an elevation of about 7708 meters above sea level. The melt water of the glaciers located around this mountain peak flows down into the Chitral valley which is used by the downstream communities for irrigation, farming, cattle, and other daily needs.

Previous regional studies have mainly examined broad glacier trends, whereas; the temporal behavior of clean-ice/snow-covered surfaces, debris-covered ice, and total glacier extent around Tirich Mir remains insufficiently explored. In addition, few studies have jointly examined multi-decadal glacier-surface changes and local temperature and precipitation variability for this glacier system. This lack of spatially detailed and temporally consistent data limits understanding of glacier-surface dynamics and their signifcant implications for the downstream water resources. Hence, this study investigated changes in NDSI-derived clean-ice/snow-covered glacier surfaces, debris-covered ice, and total glacier extent fot the study focus period of the years 1990 to 2025 in the Tirich Mir region. Moreover, it evaluated temperature and precipitation variability, as well as explores whether these climatic variables are associated with spatial (mapped) surface changes. The specific objectives were to: (i) map glacier extent for the years 1990, 2000, 2010, 2020, and 2025; (ii) to estimate spatial (mapped) clean-ice/snow-covered surface area, debris-covered ice area, and total glacier area; (iii) to quantify glacier-area change over the 35-year period; and (iv) to examine relationships between climate variability and mapped glacier changes.

Materials and methods

Study area

The study focuses on five major glaciers: Dirgoi, Lower Tirich, North Barum, Owir, and South Barum in the Tirich Mir region of the Hindu Kush, Chitral District, Pakistan. These glaciers lie between latitude 36°10′ and 36°25′N and longitude 71°45′ and 72°05′E. Elevations in the study region vary from about 1596 m to greater than 7463 m based on the ASTER DEM data, while that of Tirich Mir peak rises to about 7708 m withhigh relief and steep slopes typify the topography. The accumulation zones of glaciers contain surfaces of clean ice and seasonal/perennial snowfields, whereas; glacier tongues are typically covered with debris which forms from rock falls, avalanches, and unstable surrounding slopes. Runoff from these glaciers flow into Chitral river system. These overall aspects signifies the contribution of these glaciers to water sources downstream. The five glaciers selected are located in the area shown in Figure 1.

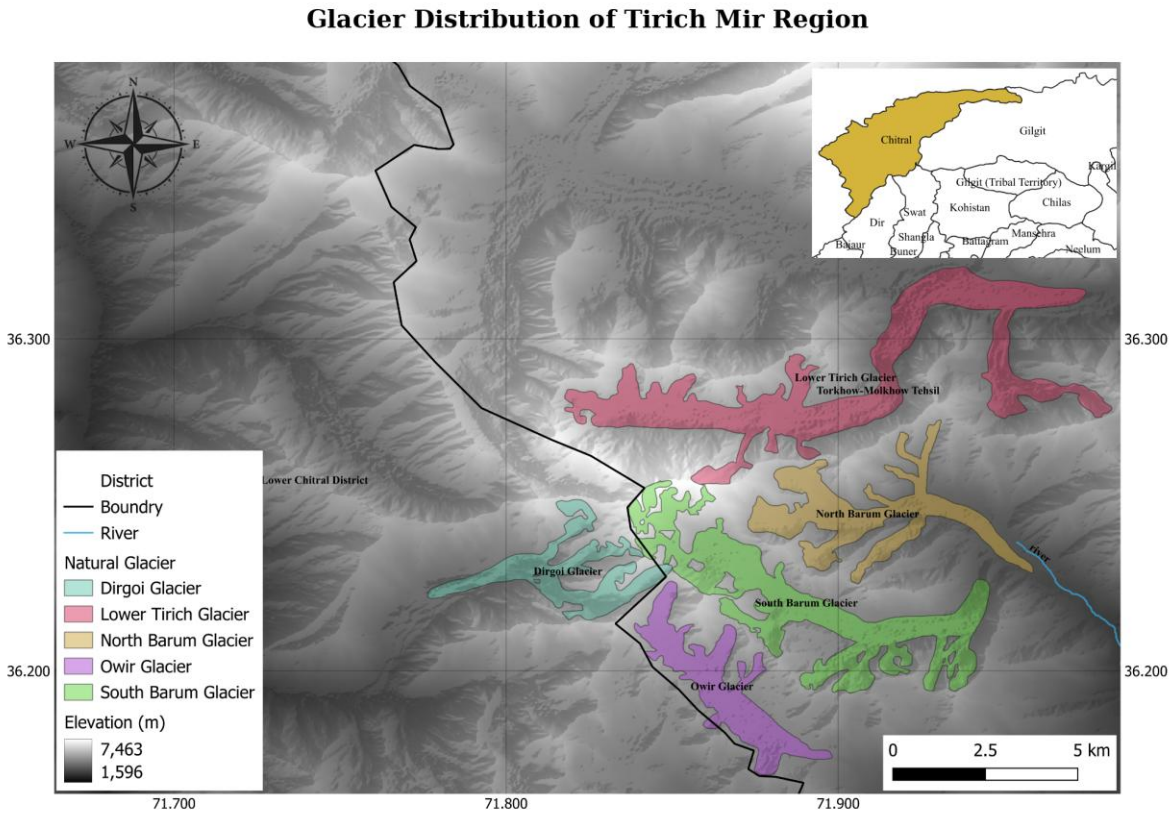


Figure 1. Study area and glacier distribution map of the Tirich Mir region, showing the five selected glacier systems: Dirgoi, Lower Tirich, North Barum, Owir and South Barum

Satellite data and ancillary datasets

Multi-temporal Landsat images corresponding to five years of observations (1990, 2000, 2010, 2020, and 2025) were used for determination of the glaciers outlines (U.S. Geological Survey, n.d.). Landsat imagery was chosen based on long-term availability of data, moderate spatial resolution, and proper spectral bands for surface mapping based on NDSI technique. In order to minimize cloud influence and seasonal snow cover, imagery was collected in the late-summer ablation season. Information on satellite datasets used for glacier mapping is given in Table 1. ASTER GDEM with 30 m spatial resolution was used for derivation of terrain features (slope, elevation) (NASA/METI/AIST/Japan Spacesystems & U.S./Japan ASTER Science Team, 2019). Climate dataset was collected from NASA Prediction of Worldwide Energy Resources (POWER) (NASA POWER Project, n.d.). Moreover,

average temperature for summer months (May–September) and average winter precipitation for November–February were also calculated.

Table 1. Satellite imagery used for glacier mapping

Year	Satellite/Sensor	Acquisition Date	Cloud Cover	Green Band		SWIR Band	Spatial Resolution	Main Purpose
1990	Landsat-5 TM	06-09-1990	<10%	Band 2		Band 5	30 m	Glacier Surface Mapping
2000	Landsat-7 ETM+	09-09-2000	<10%	Band 2		Band 5	30 m	Glacier Surface Mapping
2010	Landsat-5 TM	28-08-2010	<10%	Band 2		Band 5	30 m	Glacier Surface Mapping
2020	Landsat-8 OLI	23-08-2020	<10%	Band 3		Band 6	30 m	Glacier Surface Mapping
2025	Landsat-9 OLI-2	14-09-2025	<10%	Band 3		Band 6	30 m	Glacier Surface Mapping

Image preprocessing

Satellite image preprocessing included projection and clipping. Images were projected to WGS84 / UTM Zone 43N to facilitate uniform distance and area calculations and were clipped to the study area boundary. Spatial preprocessing, classification, area calculation, and map preparation were conducted in QGIS and ArcGIS environment. The spectral bands were then used to calculate NDSI, as well as visual interpretation. The overall analytical workflow is presented in Figure 2.

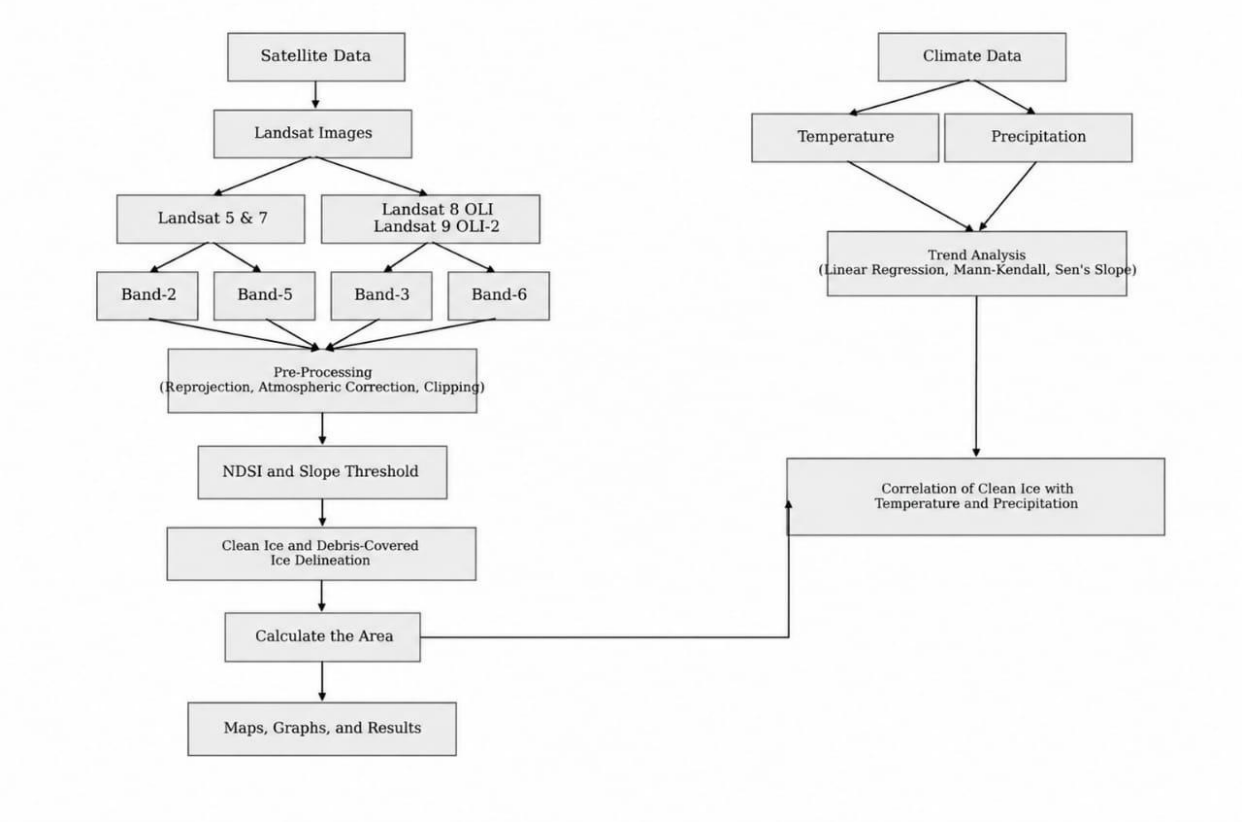


Figure 2. Methodological workflow used for glacier mapping, area calculation and climate trend/correlation analysis

Clean-ice extraction using NDSI

The Normalized Difference Snow Index (NDSI) was used to map spectrally bright glacier surfaces comprising clean glacier ice and snow and was derived from the following equation:

$$\mathrm{NDSI} = \frac{(\mathrm{Green} - \mathrm{SWIR})}{(\mathrm{Green} + \mathrm{SWIR})}$$

For Landsat-5 TM and Landsat-7 ETM+, the green and SWIR bands were Band 2 and Band 5, respectively; for Landsat-8 OLI and Landsat-9 OLI-2, the corresponding bands were Band 3 and Band 6. An NDSI threshold of 0.40 was used to separate clean-ice/snow-covered surfaces from surrounding non-glacier surfaces, consistent with commonly applied snow- and ice-mapping approaches (Hall et al., 1995; Paul et al., 2002). In this study, the term 'mapped clean ice' is used for brevity to refer to this NDSI-derived clean-ice/snow-covered surface class; hence, not to be interpreted as a direct measure of glacier ice mass.

Debris-covered ice mapping

A semi-automated GIS approach was used to delineate debris-covered ice because NDSI alone cannot reliably distinguish debris-covered glacier surfaces from landforms such as moraines or bare soil (Paul et al., 2004). The approach combined ASTER GDEM-derived slope and elevation, vegetation masking based on NDVI, thermal information, visual interpretation, and glacier-outline refinement. Debris-covered ice was identified using the rule: Debris-covered ice = (LST < 285 K) AND (Slope < 24°) AND (NDVI < 0.15) AND (NDSI mask = 0). This rule selected areas likely to represent debris-covered glacier surfaces on the basis of low slope, sparse vegetation, a non-clean-ice spectral signature, and relatively cool surface temperature. LST was treated as a secondary indicator because it can vary with sensor, acquisition date, illumination, and moisture conditions. The resulting debris-covered glacier outlines were visually evaluated against ASTER DEM topography, Landsat false-color composites, pre-existing glacier outlines, and Google Earth imagery. Since the classification was not validated with field observations or high-resolution reference data, the derived debris-cover layer should be interpreted as a mapped surface class, rather than as a validated glacier inventory.

Glacier area and change calculation

Area statistics for the mapped clean-ice class, debris-covered ice, and total glacier extent were calculated in km² for each observation year from the NDSI and debris-cover classifications. Glacier-area change between the reference year (1990) and the most recent year (2025) was calculated as the difference between final and initial area, and percentage change was calculated as:

Percentage change = [(Area2025 - Area1990) / Area1990] x 100

Climate trend and correlation analysis

Statistical analyses, including linear regression, the Mann-Kendall trend test, Sen's slope estimation, and Pearson correlation, were performed in R using R-Studio software. To examine temporal differences in climate trends over the study interval, climate records were divided into two periods, 1990-2004 and 2005-2025. The Mann-Kendall test was used to determine whether temperature or precipitation showed a statistically significant monotonic trend, while Sen's slope was used to estimate the annual rate of change. Trends with $p < 0.05$ were considered statistically significant. Mean summer temperature and winter precipitation were then compared with mapped clean-ice area using Pearson correlation. Glacier-area observations were available for only five selected years. Consequently, the correlation analysis had limited statistical power and was treated as exploratory. The correlation results were therefore interpreted cautiously and were not used to infer causation.

Results

Spatio-temporal glacier area changes

The total mapped glacier area of the five selected Tirich Mir-glaciers has decreased from 64.23 km² in 1990 to 52.81 km² in 2025, with a net loss of 11.42 km² (17.8%). It determines that glaciers lost an average of about 0.33 km² per year during the 35-year period of this study. The decline was not uniform through time, as; total glacier area decreased from 64.23 km² in 1990 to 60.60 km² in 2000 and 59.74 km² in 2010, remained nearly unchanged in 2020 (59.75 km²), while afterward decreased to 52.81 km² in 2025. The mapped clean-ice class showed stronger temporal variability with adecrease from 36.89 km² in 1990 to 29.02 km² in 2000 and reaching its minimum spatial (mapped) extent of 5.21 km² in 2010. In a contrast, debris-covered ice increased from 27.34 km² in 1990 to 31.58 km² in 2000 and peaked at 54.53 km² in 2010. After 2010, spatial based (mapped) clean ice increased to 24.51 km² in 2020 and 30.83 km² in 2025, while debris-covered ice decreased to 35.24 km² and 21.98 km², respectively. These area statistics are reported in Table 2, and their spatial distribution across the five observation years is shown in Figure 3.

Table 2. Mapped clean ice, debris-covered ice and total glacier extent in the Tirich Mir region

Year	Mapped Clean Ice Area (km²)	Debris-Covered Ice Area (km²)	Total Glacier Extent (km²)
1990	36.89	27.34	64.23
2000	29.02	31.58	60.60
2010	5.21	54.53	59.74
2020	24.51	35.24	59.75
2025	30.83	21.98	52.81

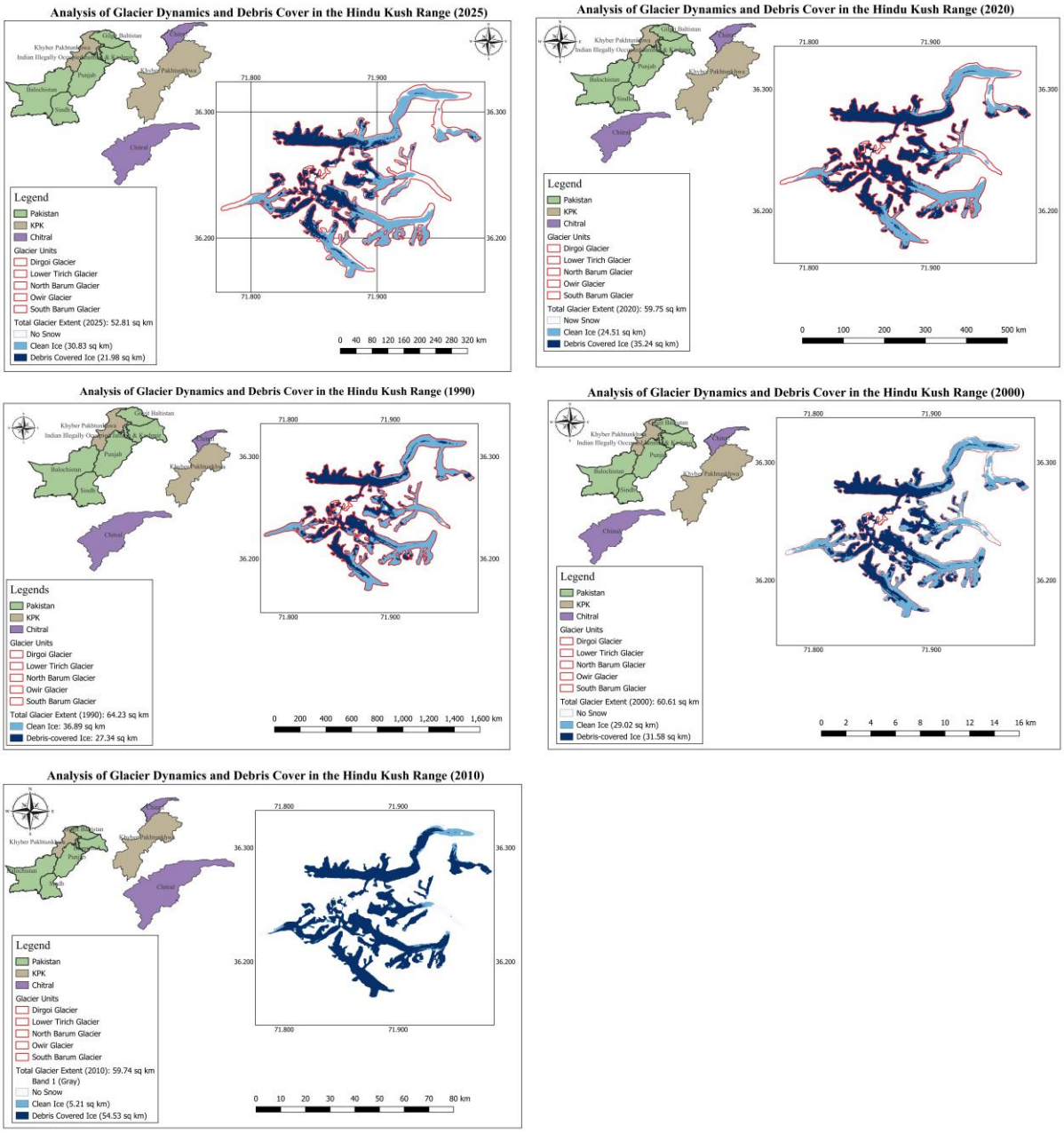


Figure 3. Spatio-temporal distribution of clean ice and debris-covered ice in the Tirich Mir glacier system: (a) 1990, (b) 2000, (c) 2010, (d) 2020 and (e) 2025. Light blue represents clean ice, dark blue represents debris-covered ice and red outlines represent glacier boundaries

Area change by observation period

Period-wise changes show that the largest losses in total glacier area occurred during 1990-2000 and 2020-2025, whereas; total mapped (spatial) extent has changed very little in last ten years i.e., between 2010 and 2020. The mapped clean-ice class has declined substantially from 1990 to 2010 and then increased during 2010-2025, while debris-covered ice followed the opposite pattern. The unusually low mapped clean-ice area and high debris-covered area in 2010 probably reflect strong late-summer ablation and debris exposure, as well as influence of seasonal conditions, image acquisition timing (season), topographic shadow, and the sensitivity of the debris-classification procedure at medium spatial resolution. Accordingly, the 2010 result is interpreted as an anomalous spatial (mapped) surface condition rather than evidence of sudden glacier mass loss. Importantly, the significant shift from

mapped clean ice to debris-covered ice in 2010 was without a similar decrease in glacier extent, indicating a shift in the mapped surface condition of the glacier rather than equivalent proportionate loss of glaciated area. Overall changes occurrence in the area over the period are summarized in Table 3, and the temporal variations in spatial (mapped) clean ice and debris-covered ice are shown in Figure 4.

Table 3. Period-wise glacier area changes

Period	Mapped Clean Ice Change (km²)	Debris-Covered Ice Change (km²)	Total Extent Change (km²)
1990-2000	-7.87	+4.24	-3.63
2000-2010	-23.81	+22.95	-0.86
2010-2020	+19.30	-19.29	+0.01
2020-2025	+6.32	-13.26	-6.94
1990-2025	-6.06	-5.36	-11.42

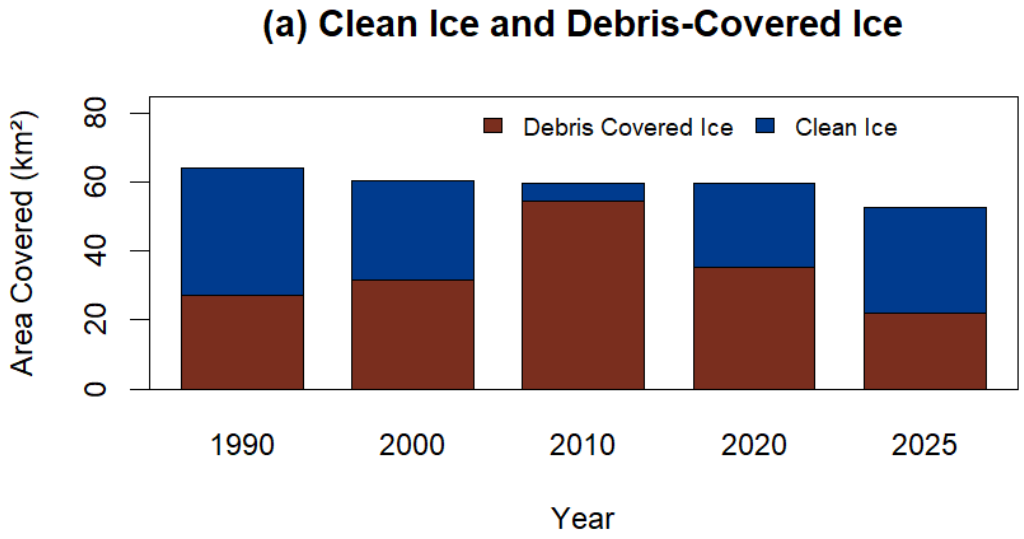


Figure 4. Temporal variation in clean ice and debris-covered ice area from 1990 to 2025

Climate trend analysis

Climate trend analysis was performed using R showed warming for both periods, with only the 2005-2025 temperature trend being statistically significant. The increase in mean summer temperature over 1990-2004 was 0.059 °C yr^{-1} with a Sen's slope significance level of 0.0748. During 2005-2025, mean summer temperature increased significantly at 0.070 °C yr^{-1} ($p = 0.0071$). Winter precipitation showed no significant trend in either period as; Sen's slopes were 1.685 mm yr^{-1} for 1990-2004 ($p = 0.7287$) and 1.065 mm yr^{-1} for 2005-2025 ($p = 0.8798$). The results showed significant year to year fluctuations in precipitation without a clear long-term trend. The Mann-Kendall and Sen's slope results are summarized in Table 4 and the linear trends are illustrated in Figure 5.

Table 4. Mann-Kendall trend test and Sen's slope results for climatic variables

Parameter	Period	p-value	Trend Significance	Sen's Slope
Temperature	1990-2004	0.0748	Not significant	0.059 °C yr^{-1}
Temperature	2005-2025	0.0071	Significant	0.070 °C yr^{-1}
Precipitation	1990-2004	0.7287	Not significant	1.685 mm yr^{-1}

Parameter	Period	p-value	Trend Significance	Sen's Slope
Precipitation	2005-2025	0.8798	Not significant	1.065 mm yr^{-1}

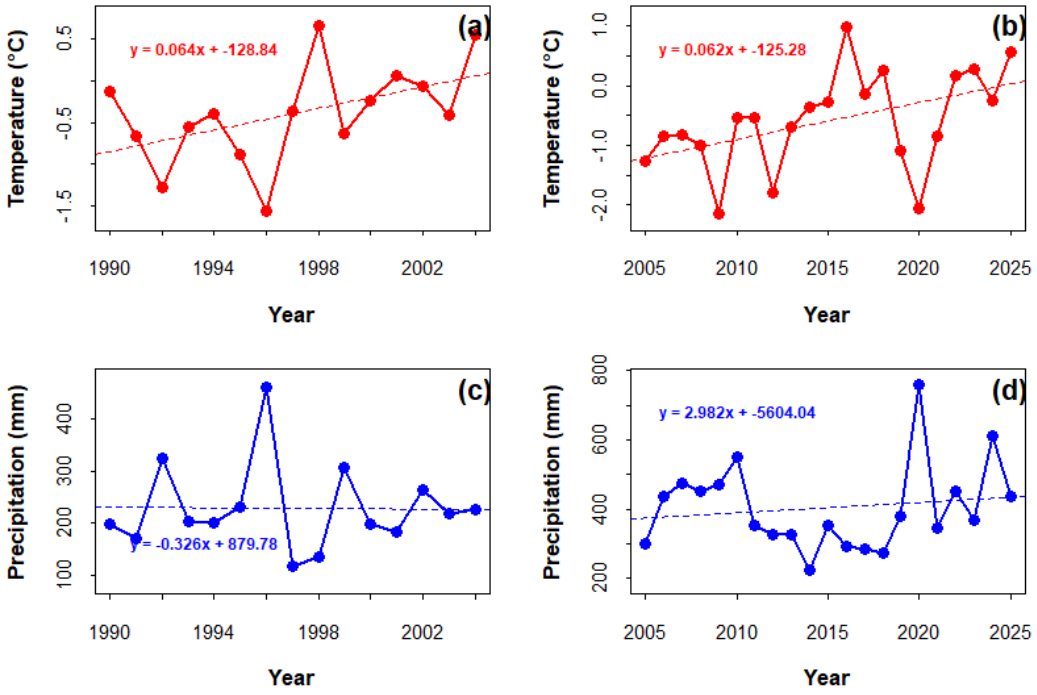


Figure 5. R-based linear trend analysis of mean summer temperature and winter precipitation for 1990-2004 and 2005-2025

Relationship between clean ice and climatic variables

Pearson correlation showed a weak, non-significant negative relationship between mapped (spatial) clean-ice area and mean summer temperature ($r = -0.17$, $p = 0.782$) and a moderate, non-significant positive relationship between mapped clean-ice area and winter precipitation ($r = 0.40$, $p = 0.508$). These relationships should not be interpreted as evidence of direct climatic control, as, only five glacier observation years were available. Topography, debris thickness, seasonal snow cover, image-acquisition timing (season or period of acquisition), and delayed glacier response to climate forcing may also influence the mapped surface classes. Correlation statistics are provided in Table 5, and the exploratory relationships are visualized in Figure 6.

Table 5. Pearson correlation between mapped clean ice and climatic variables

Variable 1	Variable 2	Pearson Correlation (r)	p-value	Relationship
Mapped Clean Ice	Temperature	-0.17	0.782	Weak negative, not significant
Mapped Clean Ice	Precipitation	0.40	0.508	Moderate positive, not significant

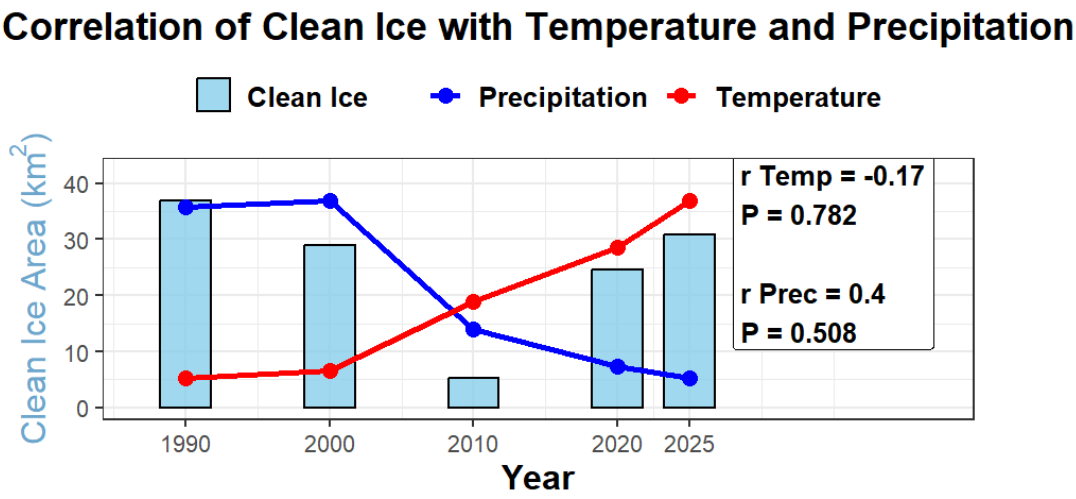


Figure 6. R-based exploratory correlation of clean ice with temperature and precipitation for the selected observation years.

Discussion

Glacier retreat in the Tirich Mir region

The overall findings reveal that total mapped glacier extent has decreased clearly over the 35-year study period, from 64.23 km² in 1990 to 52.81 km² in 2025. This represents a net reduction of 11.42 km² (17.8%). The result is consistent with previously reported retreat and degradation of many glaciers in the HKH region (Bolch et al., 2012; Yao et al., 2012). However, since the present study maps the surface extent rather than glacier mass balance, the observed area loss may be interpreted as a change in mapped glacier extent rather than a direct measurement of ice-volume loss.

The temporal pattern was not linear as the mapped (spatial) clean-ice class declined markedly to 2010, when debris-covered ice reached its maximum spatial (mapped) extent. Total glacier area remained nearly stable from 2010 to 2020, while the relative proportions of mapped clean ice and debris-covered ice changed substantially. These patterns demonstrate that glacier-surface classification can vary with topography, shadow, seasonal snow at the time of image acquisition, debris cover, as well as mapping (spatial) uncertainty, hence; should not be interpreted as a simple linear trajectory of glacier mass change.

Clean ice, debris cover and the 2010 surface-condition anomaly

The most striking spatial surface condition occurred in 2010, when the clean-ice class reached its minimum and debris-covered ice its maximum. The decline from 36.89 km² of the spatial (mapped) clean ice in 1990 to the 5.21 km² in 2010 probably reflect increased exposure of supraglacial debris, reduced seasonal snow, exposed-ice visibility, or else; sensitivity of the applied thresholds to the conditions present in the 2010 scene (imagery). At the same time, mapped (spatial) debris-covered ice reached 54.53 km².

Hence, the 2010 result may not be interpreted as evidence of rapid melt. It more likely reflects a combination of glacier surface conditions and the challenge of separating debris-covered ice from surrounding terrain without ground validation. Thin debris can enhance melt by lowering surface albedo, whereas thick debris can insulate the underlying ice, thus; producing non-linear responses. Debris-covered glaciers in the Tirich Mir region are complex, and both mapped boundaries, as well as surface classes are sensitive to the limitations of medium-resolution imagery (Bhambri et al., 2011; Paul et al., 2004).

Climate variability and glacier response

The significant warming trend during the study period of 2005-2025 indicates increasing summer temperatures in the Tirich Mir region. Warmer conditions can enhance the melt of seasonal snow and exposed glacier ice, hence; can influence the timing and visibility of debris-covered surfaces. In contrast, winter precipitation showed no significant trend, indicating substantial variability in accumulation from year to year. Although these climatic patterns are physically consistent with processes that can affect glacier surfaces, the present analysis does not establish direct attribution of the spatial based (mapped) glacier changes to temperature or precipitation alone.

Statistically, neither Pearson correlation was found as significant. The weak negative correlation with temperature and the moderate positive correlation with winter precipitation are therefore best treated as exploratory patterns rather than evidence of a causal relationship. The very small sample of five glacier observation years limits statistical based values, while debris cover, topographic setting, seasonal snow, image-acquisition timing, and delayed glacier response can further obscure simple climate-area relationships.

Comparison with previous glacier studies

The total mapped (spatial based) extent of the five selected Tirich Mir glaciers has decreased by 17.8% between 1990 and 2025, while the mapped clean-ice/snow-covered surface has decreased by 16.4%, from 36.89 to 30.83 km². These changes describe different aspects of glacier conditions as: total extent represents the combined mapped clean-ice and debris-covered classes, whereas the clean-ice/snow-covered class is also sensitive to seasonal snow and surface exposure.

For the wider Chitral region, Ahmad et al. (2025) reported a 30.8% reduction in mapped clean-ice glacier area between three decades period of 1992 and 2022, from about 2650 to 1834 km². Both studies therefore indicate a net reduction in mapped clean-ice area, although the percentage reduction was smaller for the selected Tirich Mir glaciers. This comparison should be interpreted cautiously due to the studies focused approach differences in spatial coverage, observation periods, satellite imagery, and classification methods. The regional estimate should not be directly compared with the 17.8% reduction in total glacier extent as reported here, which includes mapped debris-covered ice.

The pronounced redistribution between clean ice and debris-covered ice in 2010 further highlights the importance of distinguishing changes in glacier-surface classes from changes in total glacier extent. The sharp decrease in mapped clean ice was accompanied by an increase in the debris-covered class, with relatively little change in their combined area. Previous remote-sensing studies have shown that seasonal snow conditions, terrain shadow, debris exposure, image-acquisition timing, and the spectral similarity between debris-covered ice and surrounding terrain can influence glacier classification (Bhambri et al., 2011; Hall et al., 1995; Paul et al., 2002; Paul et al., 2004). These factors may explain part of the anomalous pattern of year 2010, although their individual contributions were not quantified in the present study. The agreement with the regional glacier-recession pattern reported for the wider Chitral region (Ahmad et al., 2025) provides useful context for the present findings. However, it may not be interpreted as independent validation of the mapped glacier boundaries, or else, as a evidence of direct climatic causation.

Implications for water resources and climate adaptation

The observed reduction in total glacier extent may have significant implications for the timing and long-term availability of meltwater in the downstream Chitral basin, where agriculture and domestic water use depend partly on glacier and snow-fed runoff. Continued warming may also alter seasonal runoff and the occurrence of glacier-related hazards, however; runoff and flood processes were not directly analyzed in this study. Moreover, glacier-related hazards are well recognized across the Himalaya (Richardson & Reynolds, 2000). Hence, continuous monitoring, improved ground observations, efficient irrigation, and water-conservation measures could support local adaptation and water-resource planning.

Overall, some limitations maybe considered from this study. The 30 m Landsat resolution and the spectral similarity between debris-covered ice and surrounding terrain may reduce mapping accuracy, particularly in steep and shadowed areas. Moreover, the use of only five observation years limits the statistical power of the climate-correlation analysis, while seasonal snow, acquisition timing, cloud and shadow effects, and threshold sensitivity may influence the mapped (spatial) classes. Related prospective studies using higher-resolution imagery, UAV observations, and field validation could improve mapping accuracy and reliability.

Conclusions

This study assessed glacier-surface changes and climate variability in the Tirich Mir region of the Hindu Kush, Pakistan, with a focus study period of years 1990 to 2025. Landsat imagery, NDSI- and threshold-based classification, ASTER GDEM terrain information, NASA POWER climate data, and GIS processing in QGIS and ArcGIS software were used to quantify spatial (mapped) clean-ice/snow-covered surfaces, debris-covered ice, and total glacier extent. Findings revealed a significant decrease in total mapped (spatial) glacier area from 64.23 km² in 1990 to 52.81 km² in 2025, corresponding to a net loss of 11.42 km² (17.8%). The mapped clean-ice class decreased from 36.89 km² in 1990 to 5.21 km² in 2010, while debris-covered ice increased to 54.53 km² in 2010. The area of mapped (spatial basis) clean-ice class increased whereas the area of debris-covered ice decreased after the year 2010. This pattern may not be interpreted as abrupt glacier mass loss followed by recovery due to strong influence of seasonal snow, shadow and debris exposure and threshold sensitivity in the 2010 classification. Furthermore, the mean summer temperature exhibited a significantly positive trend (Sen's slope = 0.070 °C yr^{-1}; p = 0.0071) throughout the study period i.e., 2005 to 2025, while the winter precipitation did not show a statistically significant trend. There was also no significant Pearson correlation between mapped clean-ice area and temperature or precipitation. Resultantly, the glacier changes that were observed in the region occurred at the same time as parallel to regional warming, hence this present analysis does not demonstrate direct climatic causation. The glacier-surface conditions in Tirich Mir are also affected by related regional factors including debris cover, topography, seasonal snow, and the image-acquisition conditions. Conclusively, the study provides a baseline for continued glacier monitoring in the Tirich Mir region. Prospectively, real-time observations, higher-resolution imagery, field validation, and direct mass-balance or geodetic measurements will help to distinguish true glacier change from short-term surface-condition variability, as well as strengthening of the future assessments of water-resource and climate-adaptation implications.

Supplementary materials

No supplementary materials are provided with this article. Derived maps, area calculations and R-scripts are available from the corresponding author upon request.

Declarations

Author contributions

The authors have read and agreed to the published version of the manuscript: Conceptualization, S.U. and S.A.A.; Methodology, S.U. and S.A.A.; Software, S.U.; Validation, S.A.A. and S.A.K.; Formal Analysis, S.U.; Investigation, S.U.; Resources, S.A.A.; Data Curation, S.U.; Writing-Original Draft Preparation, S.U. Tariq Sardar; Writing-Review and Editing, S.A.A. Tariq Sardar and S.A.K.; Visualization, S.U.; Supervision, S.A.A. and S.A.K.

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Institutional review board statement

Not applicable. This study did not involve humans or animals.

Informed consent statement

Not applicable.

Data availability statement

The Landsat satellite images and ASTER GDEM data used in this study are freely available from the U.S. Geological Survey and NASA, respectively. Climate data were obtained from the NASA Prediction Of Worldwide Energy Resources (POWER) project (https://power.larc.nasa.gov/). Derived glacier maps, area statistics, and R scripts are available from the corresponding author upon reasonable request.

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Conflicts of interest

The authors declare no conflict of interest.

Ethical responsibilities of authors

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

References

Ahmad, Z., Altaf, F., Kamp, U., Rahman, F., & Malik, S. M. (2025). Glacier recession and climate change in Chitral, Eastern Hindu Kush Mountains of Pakistan, between 1992 and 2022. Geosciences, 15(5), 167. https://doi.org/10.3390/geosciences15050167

Bhambri, R., Bolch, T., Chaujar, R. K., & Kulshreshtha, S. C. (2011). Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. Journal of Glaciology, 57(203), 543–556. https://doi.org/10.3189/002214311796905604

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., & Stoffel, M. (2012). The state and fate of Himalayan glaciers. Science, 336(6079), 310–314. https://doi.org/10.1126/science.1215828

Hall, D. K., Riggs, G. A., & Salomonson, V. V. (1995). Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data. Remote Sensing of Environment, 54(2), 127–140. https://doi.org/10.1016/0034-4257(95)00137-P

Hewitt, K. (2005). The Karakoram anomaly? Glacier expansion and the “elevation effect,” Karakoram Himalaya. Mountain Research and Development, 25(4), 332–340. https://doi.org/10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2

Immerzeel, W. W., van Beek, L. P. H., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. Science, 328(5984), 1382–1385. https://doi.org/10.1126/science.1183188

Intergovernmental Panel on Climate Change. (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (V. Masson-Delmotte et al., Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

Moazzam, M. F. U., Bae, J., & Lee, B. G. (2022). Impact of climate change on spatio-temporal distribution of glaciers in Western Karakoram Region since 1990: A case study of Central Karakoram National Park. Water, 14(19), 2968. https://doi.org/10.3390/w14192968

NASA POWER Project. (n.d.). Prediction of Worldwide Energy Resources (POWER). NASA Langley Research Center. https://power.larc.nasa.gov/

NASA/METI/AIST/Japan Spacesystems & U.S./Japan ASTER Science Team. (2019). ASTER Global Digital Elevation Model V003 [Data set]. NASA Land Processes Distributed Active Archive Center. https://doi.org/10.5067/ASTER/ASTGTM.003

Paul, F., Huggel, C., & Kääb, A. (2004). Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers. Remote Sensing of Environment, 89(4), 510–518. https://doi.org/10.1016/j.rse.2003.11.007

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., & Haeberli, W. (2002). The new remote-sensing-derived Swiss glacier inventory: I. Methods. Annals of Glaciology, 34, 355–361. https://doi.org/10.3189/172756402781817941

Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. Quaternary International, 65–66, 31–47. https://doi.org/10.1016/S1040-6182(99)00035-X

U.S. Geological Survey. (n.d.). Landsat Collection 2 Level-2 science products. https://www.usgs.gov/landsat-missions/landsat-collection-2-level-2-science-products

Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (Eds.). (2019). The Hindu Kush Himalaya assessment: Mountains, climate change, sustainability and people. Springer. https://doi.org/10.1007/978-3-319-92288-1

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B., & Joswiak, D. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nature Climate Change, 2, 663–667. https://doi.org/10.1038/nclimate1580