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Assessing Climate Variability and Cryosphere Response in Baltistan through ERA5-Land Data

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ABSTRACT

The Karakoram mountain range harbors the greatest concentration of glaciers and permanent snowfields outside the polar regions, making seasonal snowmelt the cornerstone of freshwater availability for the Indus River system. Despite this critical hydrological role, the spatiotemporal dynamics of snow and glacier melt in Baltistan Division remain poorly constrained, largely due to the scarcity of ground-based observations and the complexity of the terrain. This study addresses that gap by examining near-surface air temperature and snowmelt variability across the four districts of Baltistan Division Skardu, Shigar, Khaplu (Ghanche), and Kharmang during the primary melt season (March–June) from 2020 to 2025. ERA5-Land reanalysis data at approximately 9 km resolution, accessed through Google Earth Engine (GEE), were processed into daily day-of-year (DOY) time series to enable systematic interannual comparison. All study years exhibited a coherent seasonal warming trajectory from approximately −20°C in early March to near 0°C or above by late June. Snowmelt onset was observed between DOY 97 and 125, with peak melt intensities occurring between DOY 155 and 180. The year 2022 stood out as the warmest early-season year, associated with anomalously early snowmelt initiation but suppressed peak melt consistent with early depletion of the winter snowpack. In contrast, 2023 exhibited a pronounced cold anomaly between DOY 130 and 150, yet ultimately recorded the highest snowmelt peak of the study period (~0.015 m day^{-1}), reflecting enhanced snow accumulation during the delayed spring. These findings demonstrate significant interannual variability in cryospheric response and carry direct implications for flood risk assessment, water resource planning, and hydropower management in the Upper Indus Basin.

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1. Introduction

The Karakoram Range in the northern highlands of Pakistan is popularly known as the most heavily glaciated mountain system outside the polar regions. Baltistan Division is in the middle of this landscape, and incorporating the districts of Skardu, Shigar, Khaplu (Ghanche), and Kharmang) lies at a strategic location in the hydrology of South Asia. The three main rivers flowing through the area, viz. Indus, Shyok and Shigar, receive over 70 percent of their yearly amounts of water by seasonal snow and glaciers melt. This melt water supports agriculture, hydropower stations and domestic water supply in most parts of Pakistan and thus makes it one of the most strategically important hydrological systems in the developing world.

Against this background, climate change is becoming an increasing challenge to the predictability and seasonality of meltwater supply. Evidence indicates that increasing temperatures are rapidly intensifying the melt of cryospheric ice, shifting the season of the melt, the peak of the melt, and the duration of melt, and increasing the occurrence of extreme hydrological events (Immerzeel, Van Beek, & Bierkens, 2010; Lutz et al., 2014). The 2020-2025 window offers a particularly instructive case of studying these dynamics and covers a range of climatic anomalies. Most notably, the 2022 multi-day catastrophic flood, the worst in the modern history of Pakistan with more than 1,700 casualties and estimated USD 30 billion economic damages, were partly related to the abnormal melting of the snow and glacier lake outburst flood (GLOF) in the upper Indus catchments (World Bank, 2022).

Although the significance of the cryosphere in Baltistan is obvious, there is a lack of characterization of the dynamics of snowmelt at the district level. Continued problems are the lack of in-situ meteorological stations in the high-altitude landscape, extensive cloud cover which invalidates optical satellite retrievals, and the sheer topographic character which makes extrapolation locally challenging. Alternatives to these limitations, generated by the European Centre of Medium-range Weather Forecasts (ECMWF) as part of the Copernicus Climate Change Service, offer a physically consistent, high-resolution (approximately 9 km), and time-continuous alternative to escape most of these limitations: the ERA5-Land reanalysis dataset (Muñoz-Sabater et al., 2021).

The paper capitalizes on the data of ERA5-Land daily temperature and the amount of snowmelt, processed through Google Earth Engine (GEE), cloud-computing to perform an orderly interannual investigation of the cryospheric response in the Baltistan Division between March and June in the timeframe 2020-2025. The investigation is directed by three main objectives: (1) to describe the warming trend of seasonal near-surface temperatures over the study area; (2) to measure the year-to-year differences in the time, peak, and duration of snowmelt; and (3) to investigate the mechanistic relationships between warming of spring surface temperatures and antecedent snowpack, and the resulting melt response with a particular focus on the differences in behavior between 2022 and 2023.

2. Study Area

Baltistan Division occupies the northeastern corner of Gilgit-Baltistan Province, Pakistan, positioned between the Karakoram range to the north and east and the western Himalayas to the south (Figure 1). The four constituent districts Skardu, Shigar, Khaplu (Ghanche), and Kharmang together cover approximately 26,000 km², encompassing one of the most topographically extreme landscapes on Earth. Elevations range from approximately 2,200 m a.s.l. in the floor of the Skardu valley to beyond 8,600 m a.s.l. at the summits of K2 and adjacent Karakoram peaks. This extraordinary vertical relief, illustrated in the DEM inset of Figure 1, produces sharp gradients in temperature, precipitation phase, and melt timing across relatively short horizontal distances.

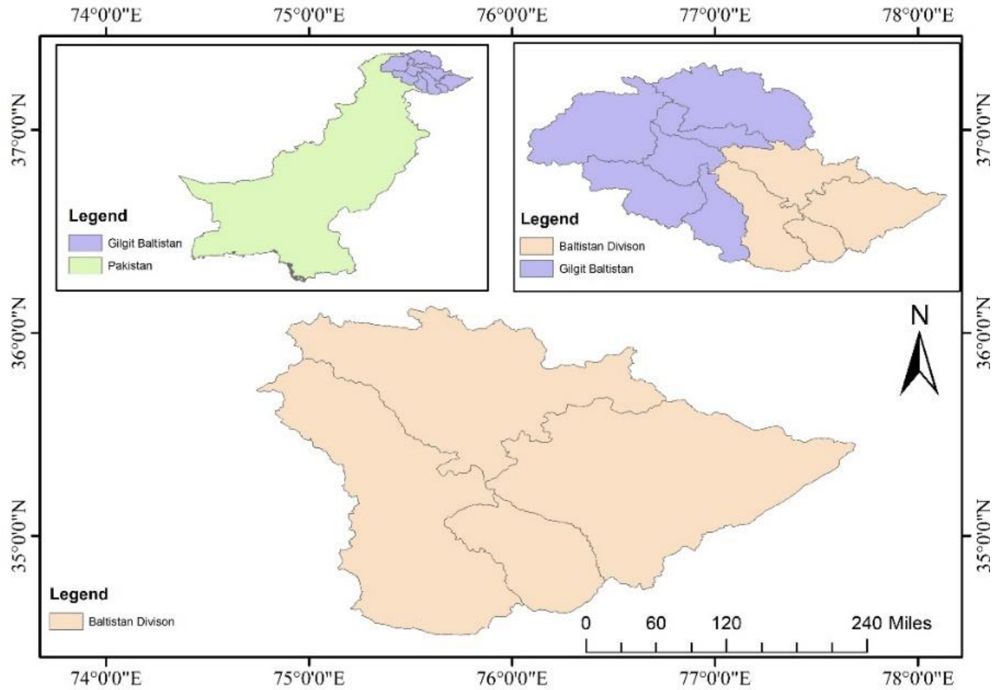

Figure 1: Study Area Map of Baltistan Division, Gilgit-Baltistan, Pakistan

The climate of the region is semi-arid to alpine. It is long and cold in winter and short and warm in summer. The prevailing precipitation is the snowfall, which falls in the period between November and March and the summers (May-August) have slight yet at times heavy precipitation of monsoon influence. The area sustains a portion of the largest glaciers in the world such as the Baltoro, Biafo, and Hispar glaciers that make up an enormous deposit of solid freshwater. These glaciers and the snowfields adjacent to them melt into the Indus River and its major tributaries the Shyok and Shigar which drain into agricultural land and population centers lower.

All districts have a unique physical geography which influences the hydrological contribution. The administrative and logistical center in Baltistan is Skardu district, which is the center of the broad intermontane valley of Skardu at an elevation of very approximately 2,228 m a.s.l. The Baltoro Glacier is the longest non-polar valley glacier in the world located in Shigar district. The Khaplu (Ghanche) district is home to the Siachen Glacier system, a water tower under threat along the India-Pakistan border and Kharmang district borders the Indus corridor with the India-controlled Ladakh standing on the controversial border. The strong range of variation of elevation, aspect, glacier cover, and snow cover patterns in these four districts, which makes Baltistan Division a highly appropriate natural laboratory to study cryospheric dynamics that are spatially integrated.

3. Data and Methodology

3.1. Data Sources

The main data used in this study was the ERA5-L and hourly reanalysis of the product, which was created and is managed by ECMWF as a part of the Copernicus Climate Change Service (Muñoz-Sabater et al., 2021). ERA5-Land is a high-resolution reanalysis of the land surface derived from re-running the ECMWF land surface model with ERA5 atmospheric fields at about 9 km spatial resolution. It encompasses 1950-near real time and it contains a complete set of hydrological and thermodynamic variables of the land surface in daily time. Central to this analysis were two variables (1) 2-meter air temperature (t2m) which is atmospheric thermal forcing near the surface and which directly controls the amount of energy available to melt the snow, and (2) snowmelt (smlt) which is the daily depth of liquid water equivalent of snow melted, in meters per day. The access and processing of the data was done through the Google Earth Engine cloud geospatial computing service (Gorelick et al., 2017) with the dataset identifier of ECMWF/ERA5LAND/DAILYAGGR.

3.2. Study Area Delineation

As a vector asset, administrative boundary shapefiles of the districts of Skardu, Shigar, Khaplu (Ghanche), and Kharmang were imported into GEE. The four polygons marking the four districts were then geometrically summed to form one unified region of interest (ROI). All further spatial averaging procedures of temperature as well as of snowmelt - were computed over this composite ROI such that outputs are generated that indicate synthesized conditions over the entire area of Baltistan Division.

3.3. Temperatures Data Processing

The daily images of ERA5-Land of air temperature of 2 meters were filtered to the window of the melt season (March 1- June 30) (Day of Year 60-180) of each year between 2020 and 2025. The original dataset contained raw temperature, which was in Kelvins, so to be converted to degrees Celsius, the values were subtracted by 273.15. Each image also had an acquisition date, a day-of-year (DOY) index calculated and made an image property to enable the same temporal alignment and be able to compare the images across years in the six-year study period.

3.4. Snowmelt Data Processing

Data of ERA5-Land daily snowmelt was cut out at the same time (March-June, 2020-2025) on the same image collection. Snowmelt values in ERA5-Land are the liquid water equivalent depth of snow melt calculated by the HTESSEL land surface model in meters of water equivalent per day (m day-1). The same process applied to the temperature data was used to assign DOY indices to each snowmelt image, which allowed paired time analysis of the two variables.

3.5. Time Series Generation and Visualization

Mean daily temperature and snowmelt values for the unified ROI were extracted using GEE's mean spatial reducer applied at 11,132 m scale — chosen to match the native grid spacing of ERA5-Land. Two DOY-indexed time series charts were produced: the first showing mean 2-meter air temperature (°C) as a function of DOY for each of the six study years, and the second displaying mean daily snowmelt (m day^{-1}) over the same temporal domain. Supplementary bar charts were generated in Microsoft Excel to facilitate visual comparison of cumulative seasonal patterns and inter-year variability across all study years.

4. Results

4.1. Seasonal Temperature Trajectory (2020–2025)

Figure 2 demonstrates the DOY-indexed time series of spatially averaged near-surface air temperature across all six years of the study during the period of March June melt season in Baltistan Division. There is a strong, climatologically consistent warming pattern each year. In early March, Temperatures are between −18°C to −21°C and at the end of June between −1°C and +5°C with respect to total seasonal warming 18–25°C taking around 120 days. This pattern is in line with the fact that the incoming radiation of the sun at high elevations and latitudes is increasing progressively at the boreal spring-summer transition.

In addition to this background pattern, strong interannual variability is observed both in the strength and timing of warming. The year 2022 is an unusually warm early season year: between DOY 80 and DOY 120, there was an average of 3–5°C above the mean of the six-year' worth of temperature measurements a departure that has substantial effects in terms of when and how much snow would melt. To offset this even more, an unusual cold spell occurred between about DOY 128 and DOY 152, when the temperatures dropped to −14°C to −15°C values more characteristic of mid-March than of late April. This aberration is a large scale thermal reversal that is built into an otherwise progressive season of melting. The highest end-of-season temperature was registered in 2024, reaching around +5°C by DOY 180. In each year of study, the critical 0degC isotherm the critical point past which spatially averaged melt was thermodynamically possible was always exceeded at DOY 155-170.

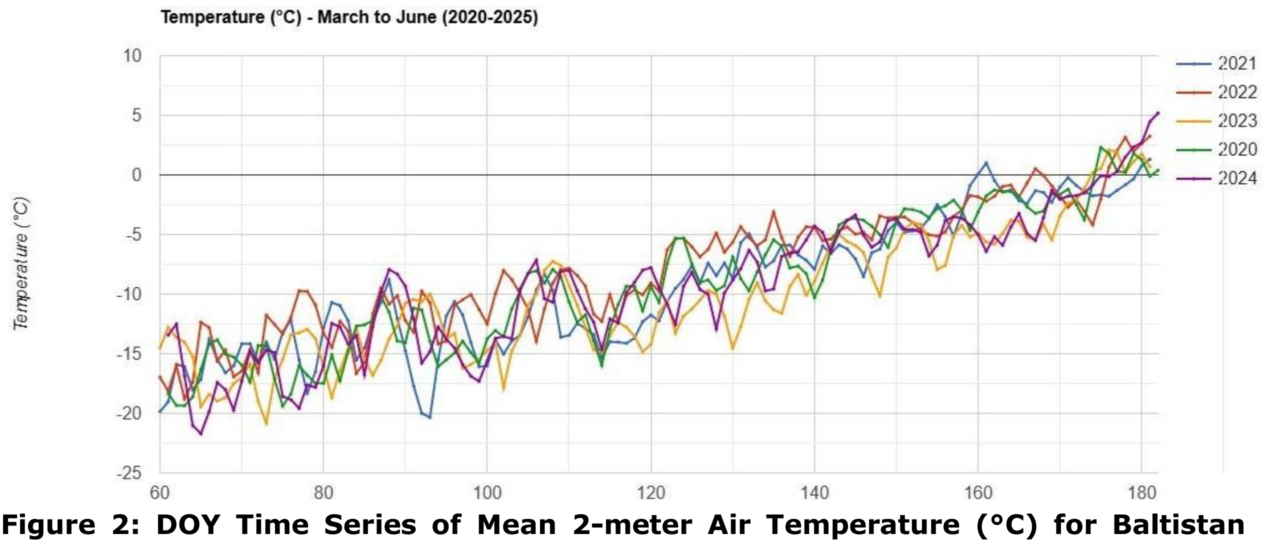

Figure 2: DOY Time Series of Mean 2-meter Air Temperature (°C) for Baltistan Division (2020–2025) during March–June (DOY 60–180) Using ERA5-Land Data via Google Earth Engine

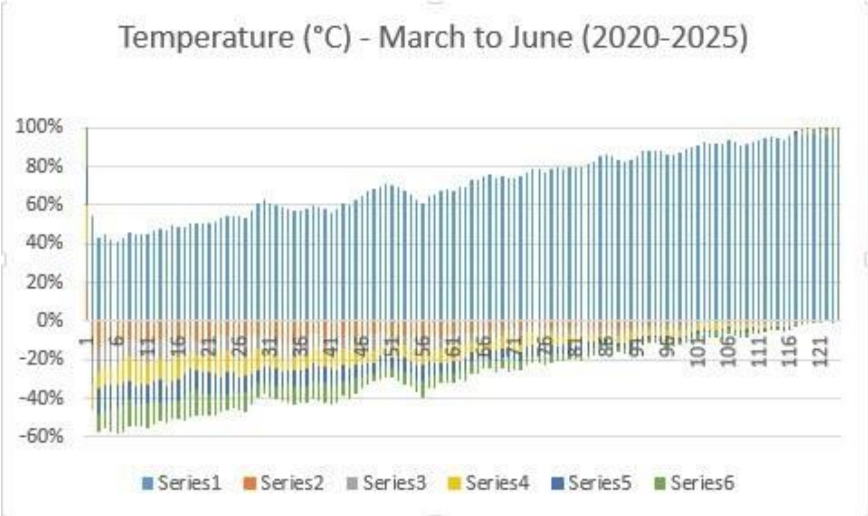

Figure 3: Supplementary Bar Chart Showing Temperature (°C) Distribution by Day Index Across 2020–2025, Highlighting Cumulative Warm-day Patterns Relative to the Multi-year Baseline (Series 1–6 = 2020–2025).

4.2. Snowmelt Dynamics and Interannual Variability (2020–2025)

In Figure 4, the 2020-2025 time series of the mean daily snowmelt in Baltistan Division are shown as a DOY time series. In line with the above thermal conditions, the snowmelt rates are negligibly low in all years up to around DOY 97-125, which demonstrates that the temperatures of the region are thermally inactive during the month of March. The transition from frozen to melt-active states varies significantly over the years and is directly linked to the temperature anomalies that have been detected in Section 4.1.

The first melt onset occurred in 2022 and started at approximately DOY 97-100 as a direct reaction to the abnormally warm early-season temperature. Nevertheless, even with this early onset, 2022 had the lowest peak melt of the study period, at about 0.004 m day-1 about a quarter the size of the multi-year average peak. This counterintuitive finding can be best attributed to the premature withdrawal of the winter snowpack: does warm early spring actually immediately precipitate sublimation and melt, depleting a lot of the stored snow before the climatological apex melt window? The highest melt onset-to-peak trajectory that was recorded in 2021 was greatly increasing to a value of about 0.013 m day-1 towards DOY 157-160, the largest early-season peak in all the years of the study.

The most striking example is 2023 that even though the onset was delayed due to the late-spring cold anomaly, eventually, this season ended with the largest single season snowmelt of the entire analysis period, around 0.014-0.015 m day-1 around DOY 172-176. This process is the snow accumulation-melt feedback process, where the long cold spring kept the existing snowpack intact and increased in size compared to its usual seasonal size to the point that when the temperature finally hiked up, the melt was both intense and quick. The year 2020 and 2024 had an intermediate behavior with the highest melt values being in the range of 0.010- 0.012 m day-1.

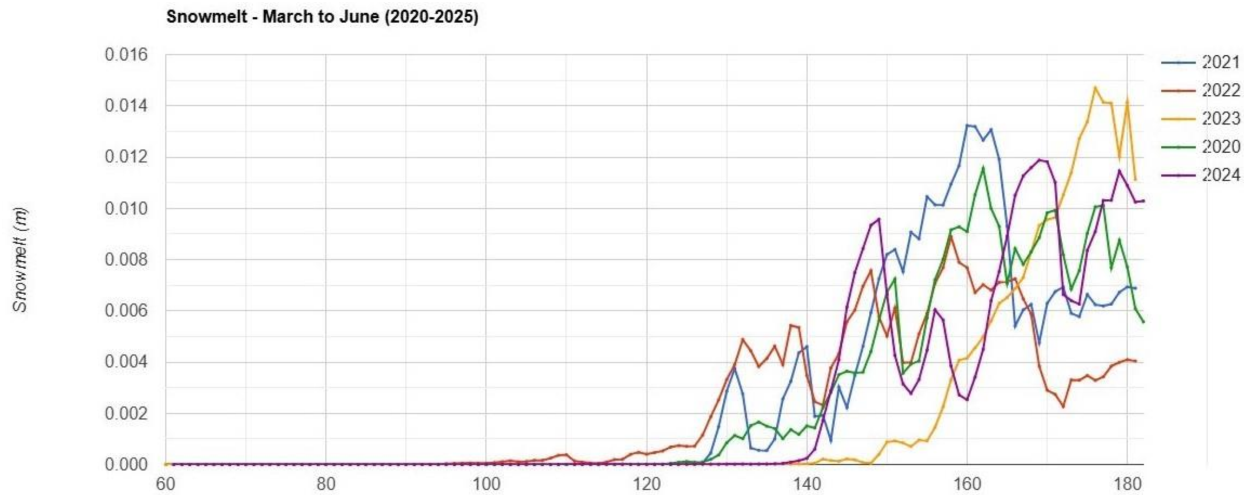

Figure 4: Day-of-year (DOY) Time Series of Spatially Averaged Daily Snowmelt (m day^{-1}) for Baltistan Division During March–June (DOY 60–180) for Each Year from 2020 to 2025, Derived from ERA5-Land Reanalysis Data via Google Earth Engine

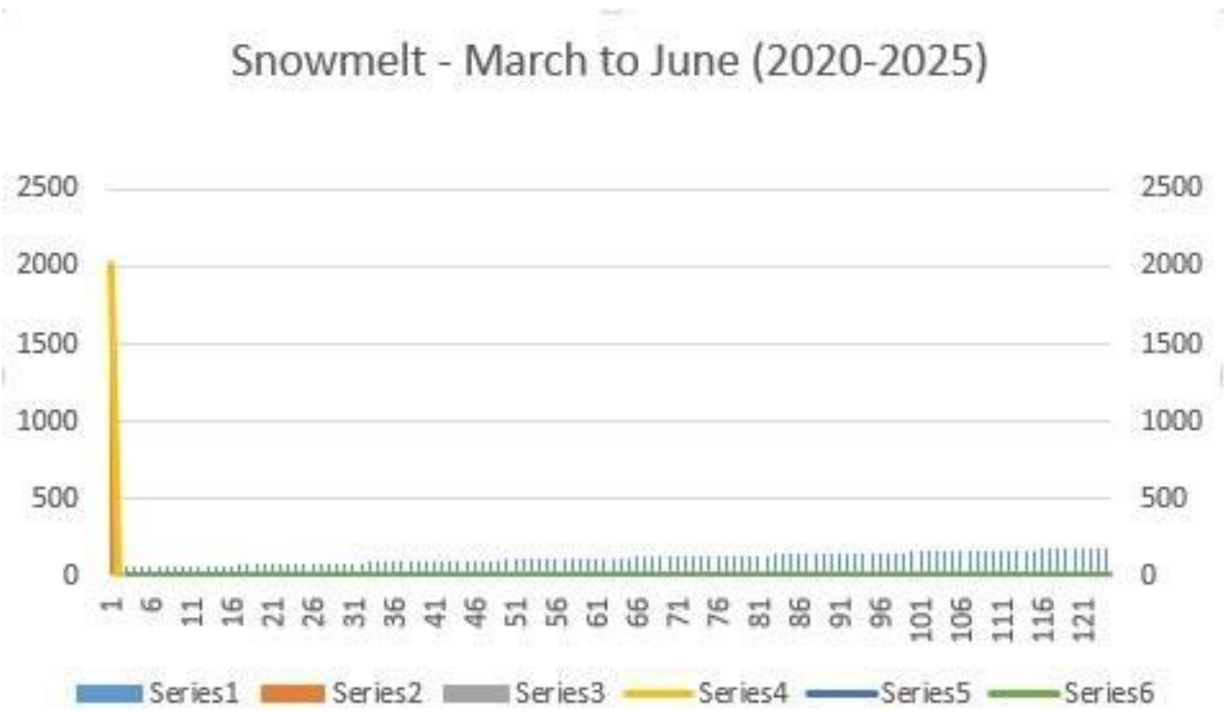

Figure 5: Supplementary Bar Chart Showing Snowmelt (m day^{-1}) Distribution by Day Index Across all Study Years (2020–2025), Highlighting the Episodic and Highly Variable Character of Daily Melt Events. Series 1–6 Correspond to Years 2020–2025 Respectively

4.3. Summary Statistics

Table 1 consolidates the key temperature and snowmelt statistics for each study year. The data collectively underscore the divergent cryospheric responses that can emerge from contrasting spring temperature regimes and highlight the inadequacy of using temperature alone without information on antecedent snowpack state as a predictor of peak melt magnitude.

Table 1
Summary of Key Near-surface Temperature and Snowmelt Parameters for Baltistan Division (2020–2025), Derived from ERA5-Land Reanalysis Data Accessed via Google Earth Engine

Year	Min Temp °C(Mar)	Max Temp °C(Jun)	Melt Onset (DOY)	Peak Melt(m/day)	Peak DOY
2020	~−20	~0 to +1	~120	~0.012	~165
2021	~−19	~0	~120	~0.013	~158
2022	~−13	~+3	~97	~0.004	~175
2023	~−21	~+1	~148	~0.015	~174
2024	~−21	~+5	~143	~0.012	~167

5. Discussion

5.1. Temperature Forcing and the Limits of Temperature-Index Melt Models

The findings show that near-surface air temperature is the primary thermodynamic driver of the snowmelt onset and intensity in Baltistan Division as per the other literature on high-mountain Asian cryospheric systems (Archer & Fowler, 2004; Bookhagen & Burbank, 2010; Tahir et al., 2011). The uniform threshold-like nature between all years of study when measurable melt is absent until the spatially averaged temperature starts to reach the melting point and the physical foundations of models of temperature-index melt supports the validity of their possible applicability to operational forecasting in this area.

Nevertheless, the different responses of 2022 and 2023 demonstrate that there is an essential caveat there is no single parameter of spring temperature that determines the extent of peak melt, but the condition of the antecedent winter snowpack is a crucial modulator of peak melt. The case warm early season, suppressed peak melt of 2022 illustrates that early season warmth can be effective in decoupling the start of a melt with the amount of the melt by prematurely melting the snowpack by sublimation and early season runoff. This has immediate consequences for hydrological forecasting: hydrological models based on spring temperature as a proxy of summer melt volume will automatically over forecast such years where the beginning of the season is warm. The case of 2023 has the opposite scenario a rare cold event saved and increased the amount of snow, resulting in a massive and late melt-off after the temperatures came back to normal. Combined, these examples can be used to present a strong case, in support of the incorporation of snowpack condition variables, including snow water equivalent (SWE) of passive microwave or SAR-based retrievals, into operational melt forecasting models of Upper Indus Basin.

5.2. Hydrological Hazard Implications for the Upper Indus Basin

The recorded interannual variability has significant implications to the water resource security and the management of the disaster risks in the entire Pakistan. In the Sindh and Punjab downstream agriculture is nourished by an intricate system of canals and irrigation channels which rely heavily/vitally on the timing and quantity of river discharge due to snowmelt. The hydropower produced in large reservoirs like Tarbela and Mangla also require foreseeable seasonal inflows. Both agricultural planning and flood risk assessment are subject to numerous uncertainties introduced by departures of the historical melt regime regardless of whether they are earlier (as in 2022) or delayed and high-magnitude occurrences (as in 2023).

The results of this paper can help put the 2022 Pakistan floods into important contextual perspective. The early and unusual warm weather noticed in more than 17 application of Baltistan Division in 2022 are climatologically in line with the circumstances that facilitated the early and extensive glacier and snow melting, which added to the high levels of river discharge that reinforced the impacts of the unusual monsoon weeks. GLOFs witnessed in the Karakoram in the same year increased the hydrological risk even more (World Bank, 2022). The possibility of the 2022 early-season warming signal in this study to be replicated with the ERA5-Land offers confirmation that the dataset can be useful in the near term as a climate-driven hydrological hazard monitoring tool in this area.

5.3. Spatial Heterogeneity and Elevation-Band Effects

One of the major constraints of the spatially averaged method used here is the fact that the cryospheric processes taking place within an immensely wide range of elevations between 2,200 m and more than 8,600 m a.s.l. are condensed into a single regional mean. Higher than 4500 m a.s.l. which constitutes a significant portion of the total area of the Baltistan Division, in most years, temperatures near the surface are below freezing during the period of the study (March-June). Therefore, the signal of the melting point attracted by the spatial mean is unproportionally affected by the middle-elevation areas (around 2500-4500 m a.s.l.), between which the snow-melt transformation is assumed. The elevated accumulation areas in the yearly fall of snow accumulation, sustaining the prime valley glaciers, play a minor role in the DOY-scale melt signal, but have vast effects on the ultimate glacier mass equilibrium and the inter-year discharge variability. The analysis must be explicitly disaggregated by elevation band in future studies to overcome the altitudinal organization of the melt dynamics and their varying degrees of contribution to the streamflow.

5.4. Limitations and Directions for Future Research

This research is prone to a number of limitations that must be taken into consideration when analyzing the findings. First, ERA5-Land has a nominal spatial resolution of about 9 km, which is large in reference to the terrain details of the Baltistan Division, where the elevation difference exceeding 6,000 m is localized on a range of few tens of kilometers. The reanalysis grid is required to smooth topographic features that have a strong effect on local temperature lapse rates, precipitation patterns and melt dynamics. Second, the model of the land surface embedded in ERA5-Land (HTESSEL) was not directly calibrated based on the unique glacier-snow system of the Karakoram, and its overall description of ablation mechanisms can create systematic biases in comparison with the on-site measurements. The study should be validated with data on field-measured snow depth, snow water equivalent or discharge data to support the study findings quite significantly. Third, a 6-year record, though adequate to describe interannual variation in a given time period, is not adequate in identifying statistically significant long-term patterns or separating the anthropogenic signal of climate change decadal variability. This analysis would be further reinforced by extending the analysis to the complete ERA5-Land record (1950-present) to allow attribution of trends.

6. Conclusion

The present research provides a high-resolution, systematic evaluation of near-surface air temperature and snowmelt processes at Baltistan Division, Pakistan, throughout the key melt period (March-June) of 2025 on ERA5-Land reanalyses data processed in the Google Earth Engine cloud computing environment. The area of study that is a four district zone of extraordinary topographically intricate over an elevation gradient of approximately 2,200 m to more than 8,600 m a.s.l. is one of the most hydrologically sensitive glaciated landscapes on Earth.

A consistent seasonal warming pattern was observed over a 6 year study period with an average progression of about 20°C in early March to almost 0°C or more in late June. Both temperature and snowmelt showed considerable interannual variability, which was superimposed on this pattern of background variability. In 2022, there were unusually warm early-season temperatures (DOY 80-120), which resulted in the earliest melt of the study period (approximately DOY 97) but the weakest peak melt intensity (approximately 0.004 m day-1), which is also in line with prematurely melting snowpack. The cold anomaly of 2023 in late April to early May (DOY 128-152) led to a delayed onset of melt (around DOY 148) but resulted in the maximum melt of the experiment (around 0.015 m day-1), due to the increase in accumulated snow that was possible during that extended cold spring. The highest peak of the early season melt (~0.013 m day-1 at DOY 158) was observed in 2021, whereas 2020 and 2024 responded more moderately.

All of these results show that the melt magnitude in Baltistan Division is not solely a function of spring temperature, but rather a non-linear response of a dynamic between thermal forcing and antecedent snowpack state to operational flood forecasting and water resource planning in the Upper Indus Basin. The climatological consistency of the warm early-season temperatures of 2022 with conditions that caused the disastrous Pakistan floods of that year shows the possibility of near-real-time hazard assessment by ERA5-Land-based monitoring. The study should be expanded to the entire ERA5-Land record in the future, with elevation-band disaggregation and results compared to in-situ snow depth and discharge measurements to resolve the issue of altitudinal complexity of cryospheric processes in the Baltistan Division.

Authors Contribution

Jawahir Hussain: Conceptualization, methodology, data processing, analysis, interpretation, and lead authorship
Radha Kumari Yadav: Literature review and background research
Zerish Fatima: Literature review and supporting research
Ali Hasnain Tahir: Data visualization and figure preparation
Ayesha Gull: Data visualization support and graphical outputs
Mussab Fiaz: Data extraction and preprocessing (Google Earth Engine)
Muhammad Sameer: Data extraction and preprocessing support
Saira Batool: Proofreading and formatting
Areeba Jadoon: Research support, writing support (original draft and revisions), and manuscript editing
Avinash Singh: Manuscript review and quality checking

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t. the research, authorship and/or publication of this article.

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