

Mapping Fluctuations of Hispar Glacier, Karakoram, using Normalized Difference Snow Index (NDSI) and Normalized Difference Principal Component Snow Index (NDSPCSI)

Nausheen Mazhar^{1,2 & 3}, Dania Amjad², Kanwal Javid⁴, Rumana Siddiqui²,
Muhammad Ameer Nawaz,⁵ Zaynah Sohail Butt²

¹Department of Geography, Lahore College for Women University, Pakistan

²Department of Geography, University of the Punjab, Lahore, Pakistan

³School of Earth and Environment, University of Leeds, UK

⁴Department of Geography, Government College University, Lahore, Pakistan

⁵State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, China

*Email, nausheen.mazhar@lcwu.edu.pk

Received, 23 November, 2020

Accepted, 03 December, 2020

Abstract, Investigation of the fluctuations in the snow-covered area of the major glaciers of the Karakoram range is essential for proper water resource management in Pakistan, since its glaciers are responding differently to the rising temperatures. The objective of this paper is to map snow covered area of Hispar glacier in Hunza river basin for the years 1990, 2010 and 2018. Two techniques, (NDPCSI) Normalized Difference Principal Component Snow Index and (NDSI) Normalized Difference Snow Index were used. Hispar glacier of the Hunza basin has lost 114 km² of its ice cover area, during the last 28 years, with an alarming annual retreat rate of 1.67 km² of glacier ice from 1990 to 2018. Hunza basin experienced a +1°C rise in both mean minimum and mean maximum temperature during 2007 to 2018. as a result, Karakoram ice reserves have been affected by rising temperature of the region. Due to temperature rise, retreat of snow-covered area of Hispar, Karakoram mountain range shows a shift in the cryospheric hazard zone.

Keywords, GIS, glacial mapping, HKH, NDPCSI, NDSI, water resource management.

Introduction

Upper Indus basin is the core of Pakistan's fresh water backup (Mazhar et al., 2016). About 80 percent fresh water is contributed to Indus river, depending on the snow melt and glacial composition in the upper Indus basin (Hewitt, et al., 2007). The 11.5% of the total area of this basin is covered with glaciers having perennial snow and ice cover reserves of 20,000 km² (Hewitt, 2011).

Himalayan glaciers are retreating at a more rapid scale than any other part of the world (Cruz, et al., 2007). Hasnain (1999) reported considerable glacial retreat of the eastern and central Himalayas. Glacial retreat has been reported throughout HKH region, with more than 80% of the western China experiencing glacial retreat in the last 50 years (Kehrwald et al., 2008). Kehrwald et al., (2008), concluded that Naimona' Nyi glacier in Tibet (Himalayas) has not received any net accumulation of ice since 1950.

The cryospheric reserve in the Karakoram range is home to major glaciers which act as freshwater resource, on which Pakistan's agrarian economy depends heavily. Snow assumes a critical role in impacting worldwide, territorial and local radiation balances alongside heat regimes (Bajracharya et al., 2015). The supply of water downstream is always influenced by the melting of extensive glaciers (Rankl et al., 2014). This influences even the volume and

timing of stream-flow, which provides water for irrigation (Bajracharya et al., 2015).

According to IPCC (2007) South Asia is becoming prone to flood events due to glacial melting. As a result, the maximum areal coverage of seasonally frozen land has declined by almost 7% since 1900, which would impact this region's fresh water supply, hydropower production and quantity of seasonal flows of the rivers. Fowler and Archer (2005) concluded that the 1° C drop of mean summer temperature in UIB is estimated to result in a decrease of almost 20% of the flows of Hunza river, since summer mean temperatures and summer runoff are directly correlated with higher elevation basins of UIB in 2005.

Another significant finding of Fowler and Archer (2006) that the summer temperature of many valley stations of UIB has continued to decrease from 1961 to 2000, while for the same time period, in winter mean minimum and maximum temperatures showed an increasing trend. The reduction of mean summer temperature and positive trend of mean winter precipitation trends are clues of Karakoram glacial expansion (Fowler and Archer, 2005). However, after 2005, the temperature started having a rising trend.

Bocchiola (2011) reported that the Karakoram glaciers had witnessed limited ice thinning and, in some cases, even glacial advancement has been reported for the period 1980-2009. According to Minora et al. (2016) there was general stability during 2011-2010 period,

and a slightly negative trend for the area coverage by glaciers of the region. However, the Karakoram glaciers are mostly advancing, and if retreat is detected in some glaciers, its rate is very slow. This phenomenon is termed as Karakoram anomaly, which is in stark contrast to the rapid retreat of Himalayan glaciers. Qureshi et al. (2017) reported glaciers of Hunza basin to be relatively stable and regarded temperature as a significant factor of climate change that affected the glacial length and coverage in the Hunza basin during 1973-2014 period. Moreover, the appropriate mapping techniques for gauging variations in snow covered area of glaciers in the Hunza basin, and exploring the relation of this variation with temperature fluctuations are lacking. Present study is aimed to map the variations in the snow-covered area of Hispar glacier, using NDSI and NDPCSI, and relating the variations in the snow-covered area with temperature fluctuations of the region.

Study Area

Hispar glacier (49 km long) is located in the part of the Karakoram mountains lying within the Gilgit–Baltistan region of Pakistan. Hispar glacier meets Biafo glacier (63 km long) at an altitude of 5127.95m, at the Hispar La (Pass), creating the world's largest glacial mass system outside the polar regions (Paul, et al., 2017). Hispar glacier lies in the central Karakoram and drains into the Hunza catchment in Pakistan. It is located at 36° 5' 0" N, 75° 16' 0" E spatial coordinates. Hunza basin is laid in the westerly influenced zone and has experienced a decrease in the mean annual snow cover (Hasson et al., 2014).

This glacier falls under the category of Mustagh type of glacier and the accumulation area ratio (AAR) of this glacier was reported to be 0.29 with a concentration factor of 5.1 (Dyurgerov and Meier, 2000). Hispar has lost 15% debris covered area out of its main glacier area (Hewitt, 2011). The ice tongues at lower elevation are protected by debris (Fig. 1).

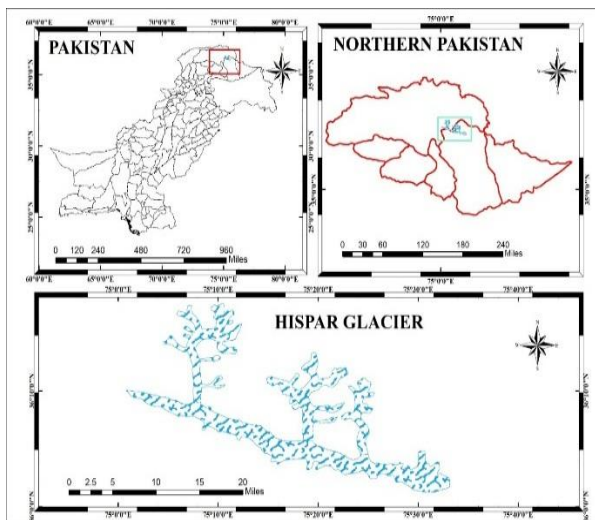


Fig. 1 Study area map.

Materials and Methods

To deduct cryospheric changes or fluctuations in Hunza basin, over the past few decades (1990-2018) remotely sensed multi-temporal images of Hispar glacier were acquired from Landsat TM (1990), ETM+ (2010) and Landsat 8 OLI (2018) for the month of October. Autumn imageries were preferred as in this season there is the least cloud cover over study area (Rashid, et al., 2018). Moreover, the perimeter of all three imageries is same for all the three years (1990, 2010, 2018) that was 245 km².

Two techniques Normalized Difference Principal Component Snow Index (NDPCSI) and Normalized Difference Snow Index (NDSI) were used to generate improved glacial mass mapping. In this study NDSI was used to divide the difference in reflectance which is observed in the Landsat 8 short wave infrared band (1.57-1.65μm) and green band (0.53-0.59μm). NDSI is widely used for mapping the snow extent primarily due to its favorable benefit to deal with the topographical effects (Negie et al., 2010; Kour et al., 2016; Mazhar et al., 2018), since it can conceivably outline the snow even in mountain shadows (Kulkarni et al., 2006). According to Kour et al. (2016) green band 3 (0.53 to 0.6μm) and shortwave-infrared band 6 (1.56 to 1.66μm) are used in Land sat 8, for calculating NDSI in order to find the snow-covered area. A threshold of 0.40 was set for NDSI as its range varies from -1 to +1 (Kour et al., 2016). NDSI is chosen to identify ice or snow in study area. Individual images were geometrically corrected before any calculations were made. NDSI was applied using Equation (1).

$$NDSI = \frac{Green_{0.53} - SWIR_{1.65}}{Green_{0.568} + SWIR_{1.65}} \quad \text{Eq. (1)}$$

The values greater than 0.4 would highlight the presence of snow. As suggested by Kulkarni et al. (2006) and Xiao et al. (2002) to improve NDSI classification accuracy a near-infrared reflectance value (greater than 0.11) was used to mask out water pixels.

Moreover, to classify snow and glacier base on pixels, NDPCSI method is used (Sibandze et al., 2014; Kulkarni et al., 2006). It is the best method to identify the threshold between snow and glacier. To highlight the presence of snow, NDPCSI was then computed because it produced higher classification accuracy, since it combined the principal component imager created by using PCA with commonly used NDSI (Sibandze et al., 2014). These are the best indices to generate improved snow cover mapping. To detect snow, every single principal component was individually analyzed. As shown in the equation 2, NDPCSI was calculated to highlight snow covered area using principal component 1 and 2, illustrated in the equation 2.

$$NDPCSI = \frac{PC_{brightest} - PC_{darkest}}{PC_{brightest} + PC_{darkest}} \quad \text{Eq. (2)}$$

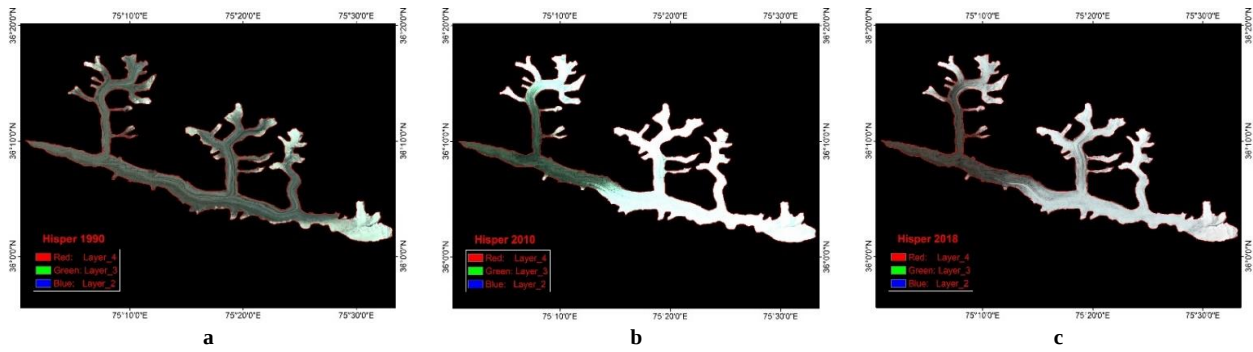


Fig. 2 Satellite image view of Hispar glacier for a) 1990, b) 2010 and c) 2018.

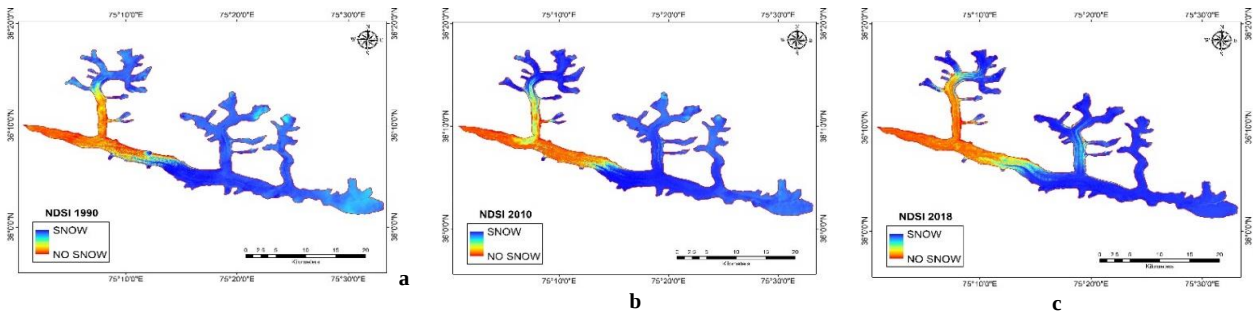


Fig. 3 Snow cover area of Hispar glacier using NDSI, a) 1990, b) 2010 and c) 2018.

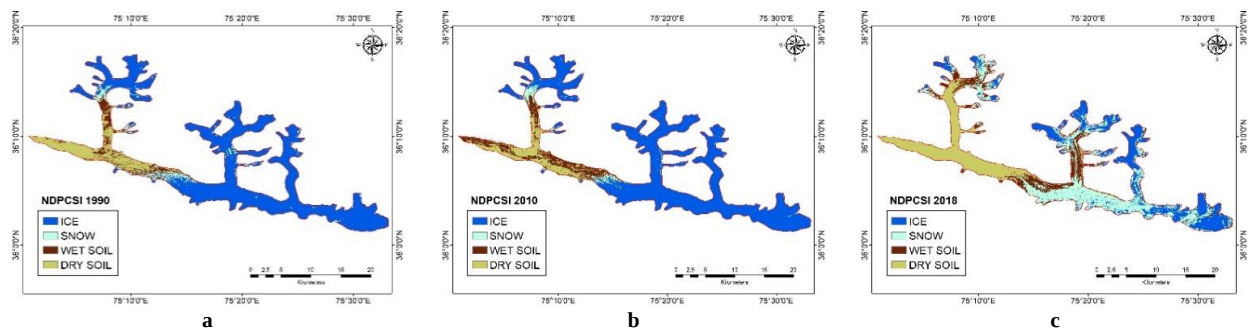


Fig. 4 Snow cover area of Hispar glacier using NDPCSI, a) 1990, b) 2010 and c) 2018.

These analyses were processed in ERDAS IMAGINE. Geometrically corrected temporal remotely sensed data sets were further improved by classification algorithms and reclassified by using the reclassify tool in ArcGIS 10.5. The resultant snow cover map of Hispar is shown in Figure 2. To deduct Hispar glacial mass fluctuations, four classes were created i.e., ice, wet soil, dry soil, and snow. Pixels that have threshold range from 0.4 to +1 were classified as ice. Similarly, those pixels which have equal to and greater than 0.4 were called snow cover. Threshold values for wet soil class is greater than 0 and less than 0.4 and from 0 to -1 pixels were classified as dry soil. When reclassified the attribute table for each layer was generated which was used to calculate the total amount of snow cover area in square kilometers (Table 1).

Inverse Distance Weighted (IDW) interpolation was used for presenting the 5 yearly mean maximum and mean minimum temperature variations, of the Northern Areas of Pakistan, for the period 1989-2018. The results

of IDW interpolation technique performed in Arc GIS version 10.5 took into consideration the mean minimum and mean maximum temperature data for 30 years (1989-2018) of five meteorological stations working in the Gilgit Baltistan region namely Astore, Bunji, Chilas Gilgit and Skardu. In the present study, average of five years has been used for analyzing the climatic variation and it is more favorable to take the average of 5 years for 30-years' time span. The increase in temperature can be seen from blue (minimum) to red (maximum) (Figs. 7, 8). The mean maximum and minimum monthly temperature data of Hunza meteorological station, where Hispar glacier occurs was available for past ten years only, and thus its variations were graphically presented.

Results and Discussion

Glacial retreat in the form of ice-free area is clearly visibly in the satellite image view, for Hispar glacier (Fig. 2). The comparative multi temporal images of

satellite image view of Hispar glacier shows that it remains the glacier suffering from major ice cover loss from 1990 to 2018 (Fig. 3). Ice covered area is retreating continuously, since Hispar lost 114 km² of its ice cover in the last 28 years.

Table 1. Comparison in snow covered areas of Hispar glacier for the years 1990, 2010 and 2018.

Metrological stations	1990		2010		2018	
	Temp °C	Rainf -all mm	Temp °C	Rainf -all mm	Temp °C	Rainf -all mm
Astore	10.09	57.21	10.51	31.72	18.81	33.22
Bunji	17.96	11.58	15.08	13.35	30.93	10.85
Gilgit	24.95	7.42	24.13	7.58	24.60	7.83
Skardu	13.39	24.35	11.45	41.28	21.73	8.09
Hisper	16.59	25.14	15.29	23.48	24.01	15.00

Table 2. Comparison in mean annual temperature and rainfall from different metrological stations for the years 1990, 2010 and 2018.

Class	1990	2010	2018
	Sum_Area sq.km	Sum_Area sq.km	Sum_Area sq.km
Ice	184	185	70
Snow	13	9	81
Wet Soil	15	24	34
Dry Soil	33	27	60

Source, PMD

Figure 4 and Table 1 represent the Hispar glacial mass fluctuation with classes i.e., ice, snow, wet soil and dry soil. Comparative study of these images (Fig. 4) also shows that Hispar glacier lost 114km² area of ice cover during 28 years (1990-2018).

On the other hand, snow cover area has increased dramatically from 13 km² (1990) to 81 km² (2018) but this snow is not converted into ice due to incessantly increasing temperature in the study area and (Table 2, Figs. 5 to 8). Resultantly, wet soil area has increased by 19 km². The area of dry soil also increased due to rising temperature. Hispar glacier suffered a retreat of ice-covered area, indicating an annual retreat of about 1.67 km² of snow, and retreat of 0.139 km² per month, respectively.

The results of this study are in line with another recent study that calculated the recent surge of Hispar glacier, during 2013-2017, in the central and eastern portion of the glacier (Rashid et al., 2018). The Hispar glacier's upper part in the eastern and central Hispar underwent surge, while the velocity of the glacier was reported to be minimum in the western Hispar, where the present study also reports no snow area and hence maximum dry soil coverage.

Climatic Variations in Study Area

Variations in temperature and precipitation have impacts on glacial behavior. Warmer temperatures cause glaciers to melt faster than they can accumulate new snow. Figures 4 to 6 and precipitation data show the greater variability of mean annual temperatures and mean annual rainfall in Hunza basin over the period of 1990 to 2018. These data have been collected from

Gilgit meteorological station, which lies in Hunza basin where Hispar glacier is located. The comparison between the mean annual rising temperature (Table 2) and snow cover area of Hispar glacier (Figs. 3,4) strengthens the present study's conclusion that western Karakoram glacier Hispar is facing faster retreat due to higher temperature variabilities.

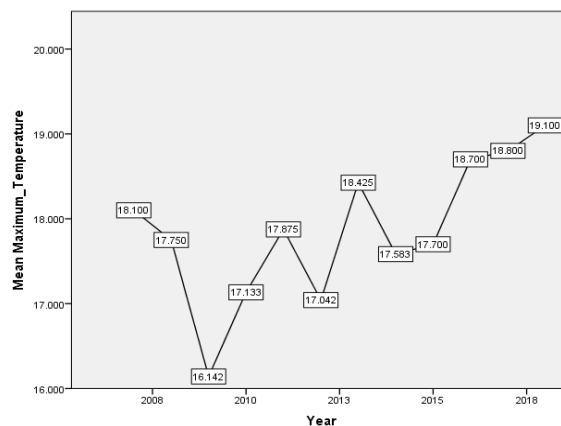


Fig. 5 Mean Maximum Temperature 2007-2018.

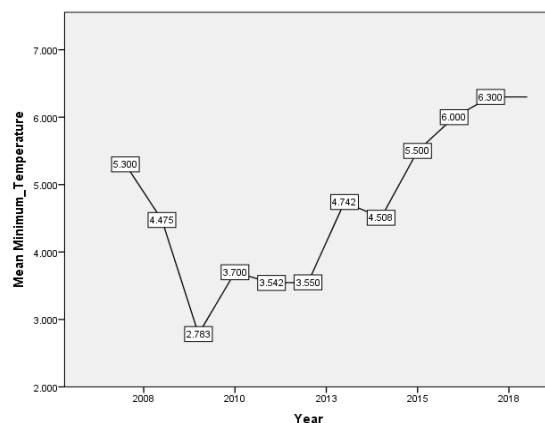


Fig. 6 Mean minimum temperature 2007-2018.

The mean maximum temperature of Hunza valley which is near the Hispar glacier has increased in the past 10 years. During these 10 years period, a rise of 1°C in the mean maximum temperature of Hunza valley was recorded, which increased from 18.1 °C to 19.1 °C (Fig. 5).

This 1°C rise in mean minimum temperature in 10 years is significant. The mean minimum temperature also increased from 5.30 °C to 6.30 °C and there was a fluctuation in the temperature throughout the time period.

Warmer temperatures cause glaciers to melt faster than they can accumulate new snow. The comparison between rising trends of mean minimum and maximum temperatures and decrease in snow covered area of Hispar glacier support the present study conclusion that western Karakoram glacier Hispar is facing faster retreat due to higher temperature variability (Table 1). The mean minimum temperature of Hunza valley which

is nearest the Hispar glacier has also increased in the past 10 years.

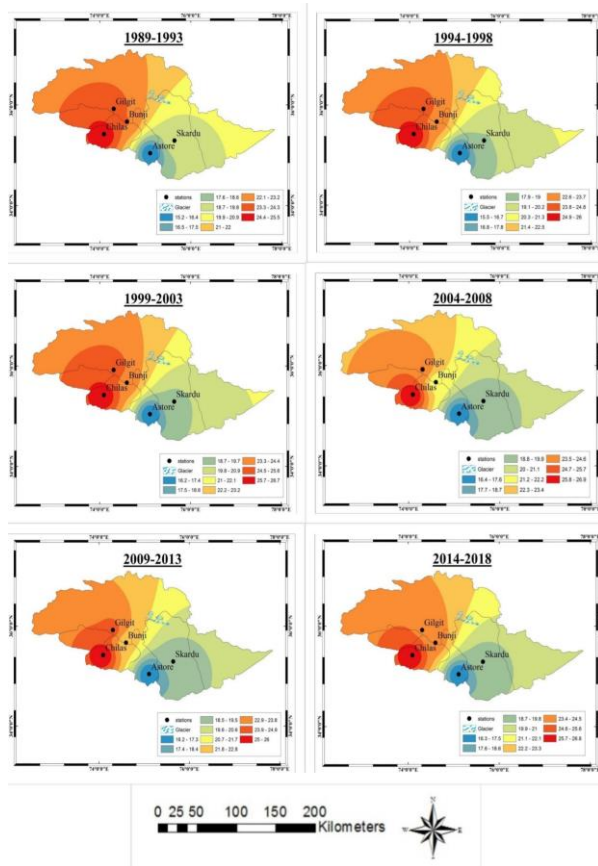


Fig. 7 Mean maximum temperature 1989-2018.

Figure 7 presents the 5 yearly mean maximum temperature for the Northern areas of Pakistan. For the period 1989-1993, the mean maximum value of temperature for Astore was 15.21 °C, which rose to 16.29 °C by 2014-2018, i.e., a rise of +1.09°C. While, Bunji, Chilas, and Gilgit also experienced a rise of +0.82°C, +1.35°C and +0.68°C in their mean maximum temperatures, respectively during the last 29 years. Skardu, however, witnessed a minor decline of -0.09°C in the mean maximum temperature value, during the same period. Secondly over the period study the Hispar glacier has undergone variations in mean maximum temperature, for example, in 2004-2008 the entire glacier was experiencing 21-2°C to 22.2°C, but by 2014-2018, the temperature of western part of the glacier had increased from 23.4°C to 24.5°C.

Astore meteorological station lying in UIB, underwent an increase of 2.3°C in its mean minimum temperature during 1989-2018, as the average value of minimum temperature for Astore was 2.45 °C during 1989-1993. However, by 2014-2018, the temperature had increased to 4.57°C. Similar rise in temperature has been reported in areas around Kakul and Astore by Mazhar et al. (2015). Bunji also had a rise of 1.81°C in mean minimum temperature value during the last 29 years. Chilas experienced a minor decrease of 0.11°C in its mean minimum temperature value, during 1989-2018.

Similarly, Skardu also went through a minor rise of 0.19°C in mean minimum temperature value. Gilgit had a significant rise of 1.04°C in its mean minimum temperature during the same 1989-2018 period.

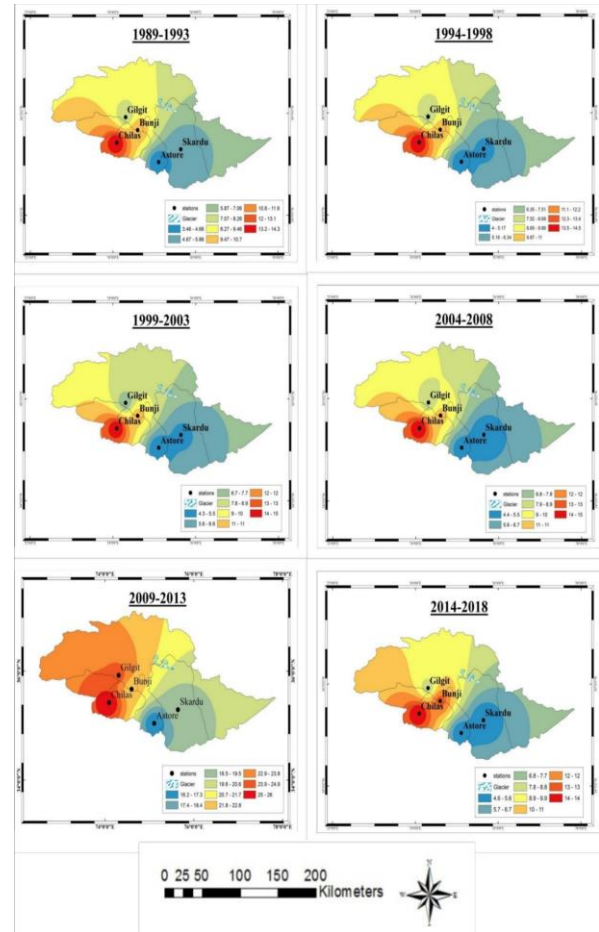


Fig. 8 Mean minimum temperature 1989-2018.

Similar trend (Hispar glacier) can be observed in Urumqi river basin, Tianshan mountain, China, which shortened by 12% between 1962-2003. The pace of the retreat of Hispar glacier is losing its ice-covered area at the rate of 1.67 km² per annum. According to Latief et al. (2016), the zone of Kolahoi glacier, in the north-western Himalayan region, contracted from 12.21 km² in 1962 to 11.61 km² in 2010. As a result, 0.6 km² (600,000 m²) of the total area has been reduced, while its snout is retreating with a rate of 11.97 m/year.

There was a similar reduction in the clean ice area of Haft Khan glacier in Takht-e-Soleiman region, Iran, since 2010 (Karimi, et al., 2015). As the Hispar glacier is shrinking and experiencing changes and retreat some researchers have likewise anticipated the thinning and shrinking of some glaciers of Hindu Kush Himalayan region (Fujita and Nuimura, 2011; Kargel et al., 2011; Kaser et al., 2006; Scherler et al., 2011; Zemp et al., 2009). During 1989-2018, the mean maximum temperature of northern areas has increased Latief et al. (2016). The normal air temperature has also increased in the Liddar valley north western Himalayas, Pakistan during the time period of 1962-2010. The general

pattern over this study period demonstrated a general increase. Some parts of Himalayas are warming at a higher rate contrasted with the worldwide normal warming (Bajracharya, 2015). While examining the temperature fluctuations in Himalayas, Bhutiyani et al. (2007) reported a rise of 1.6° C of the temperature during 1901 to 2002. While, Dar et al. (2014) and Romshoo et al. (2015) have likewise anticipated an increase in temperature in Kashmir valley by 6.26 °C (± 1.84 °C) in 2098, using Predicting Regional Climates for Impact Studies (PRECIS) model.

According to Ashraf and Rehman (2019), rise in temperature directly affects the surface of glaciers, causing quick increase in its melting process. Qureshi et al. (2017) also reported a steady increase in the maximum and minimum temperatures at Bunji and Chilas meteorological stations near the Hispar glacier. Pakistan experienced 0.76 °C increase in temperature during the last 40 years and the rise in temperature was considerably higher (1.5 °C) during a similar period in mountainous regions that support large number of glaciers (Chaudhry et al., 2009). Amjad et al. (2019) also concluded that Mansehra, located near Northern areas, also experienced maximum temperature increase from 25.82°C in 1988 to 26.739°C in the year 2017.

Conclusion

Hispar glacier of the Hunza basin lying in western Karakoram has lost 114 km² of its ice cover area, with an alarming annual retreat rate of 1.67 km² of ice, in a period of 28 years (1990-2018). It is concluded that warmer temperature is one of the main reasons of the glacial retreat, as temperature rises causes the glaciers to melt faster than they can accumulate new snow. Moreover, the greater temperature variability causes greater snowmelt and thus, faster glacial retreat in Hunza basin has been recorded. The climate change is also leaving its impacts on the Karakoram ice reserves.

References

- Amjad, D., Kausar, S., Aslam, R.W., Sarwar, F. (2019). Land cover change analysis and impacts of deforestation on the climate of District Mansehra, Pakistan. *Journal of Biodiversity and Environmental Sciences*, **14** (6), 103-113.
- Ashraf, A., Rehman, H. (2019). Upstream and downstream response of water resource regimes to climate change in the Indus River basin. *Arabian Journal of Geosciences*, **12** (16), 516.
- Bajracharya, S.R., Maharjan, S.B., Shrestha, F., Guo, W., Liu, S., Immerzeel, W., Shrestha, B. (2015). The glaciers of the Hindu Kush Himalayas, current status and observed changes from the 1980s to 2010. *International Journal of Water Resources Development*, **31** (2), 161-173.
- Bhutiyani, M.R., Kale, V.S., Pawar, N.J. (2007). Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change*, **85** (1-2), 159-77.
- Bocchiola, D., G. Diolaiuti, Et Al. (2011). "Prediction of Future Hydrological Regimes In Poorly Gauged High Altitude Basins: The Case Study Of The Upper Indus, Pakistan." *Hydrology & Earth System Sciences Discussions* 8(2).
- Chaudhry, Q. Z., A. Mahmood, G. Rasul and M. Afzaal. (2009). *Climate Indicators of Pakistan*. PMD Technical Report.
- Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C., Huu, Ninh. (2007). N. Asia, in *Climate Change, Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change edited by M. L. Parry et al., 469–506, Cambridge Univ. Press, Cambridge, U.K.
- Dar, R. A., Rashid, I., Romshoo, S. A., Marazi, A. (2014). Sustainability of winter tourism in a changing climate over Kashmir Himalaya. *Environmental monitoring and assessment*, **186** (4), 2549-62.
- Dyurgerov, M.B., Meier, M.F. (2000). Twentieth century climate change, evidence from small glaciers. *Proceedings of the National Academy of Sciences*, **97** (4), 1406-11.
- Fowler, H. J., Archer, D. R. (2005). Hydro-climatological variability in the Upper Indus Basin and implications for water resources. *Regional Hydrological Impacts of Climatic Change—Impact Assessment and Decision Making*, **295**, 131-8.
- Fowler, H.J., Archer, D. R. (2006). Conflicting signal of climatic change in the Upper Indus Basin. *Journal of Climate*, **19** (17), 4276-4293.
- Fujita, K., Nuimura, T. (2011). Spatially heterogeneous wastage of Himalayan glaciers. *Proceedings of the National Academy of Sciences*, **108**(34), 14011-4.
- Hasnain, S.I., Thayyen, R.J. (1999). Controls on the major-ion chemistry of the Dokriani glacier meltwaters, Ganga basin, Garhwal Himalaya, India. *Journal of Glaciology*, **45**(149), 87-92.
- Hasson, S., Lucarini, V., Khan, M. R., Petitta, M., Bolch, T., Gioli, G. (2014). Early 21st century snow cover state over the western river basins of the Indus River system. *Hydrology and Earth System Sciences*, **18** (10), 4077-100.
- Hewitt, K. (2007). Tributary glacier surges, an exceptional concentration at Panmah Glacier,

- Karakoram Himalaya. *Journal of Glaciology*, **53**(181), 181-8.
- Hewitt, K., Gosse, J., Clague, J.J. (2011). Rock avalanches and the pace of late Quaternary development of river valleys in the Karakoram Himalaya. *Bulletin*, **123** (9-10), 1836-50.
- IPCC. (2007). Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
- Kargel, J.S., Cogley, J.G., Leonard, G.J., Haritashya, U., Byers, A. (2011). Himalayan glaciers, the big picture is a montage. *Proceedings of the National Academy of Sciences*, **108**(36), 14709-10.
- Karimi, N., Eftekhari, M., Farajzadeh, M., Namdari, S., Moridnejad, A., Karimi, D. (2015). Use of multitemporal satellite images to find some evidence for glacier changes in the Haft-Khan glacier, Iran. *Arabian Journal of Geosciences*, **8**(8), 5879-96.
- Kaser, G., Cogley, J.G., Dyurgerov, M.B., Meier, M.F., Ohmura, A. (2006). Mass balance of glaciers and ice caps, consensus estimates for 1961–2004. *Geophysical Research Letters*, **33** (19).
- Kehrwald, N.M., Thompson, L.G., Tandong, Y., Mosley-Thompson, E., Schotterer, U., Alfimov, V., Beer, J., Eikenberg, J., Davis, M.E. (2008). Mass loss on Himalayan glacier endangers water resources. *Geophysical Research Letters*, **35**(22).
- Kour, R., Patel, N., Krishna, A.P. (2016). Development of a new thermal snow index and its relationship with snow cover indices and snow cover characteristic indices. *Arabian Journal of Geosciences*, **9** (1), 71.
- Kulkarni, A.V., Singh, S.K., Mathur, P., Mishr, V.D. (2006). Algorithm to monitor snow cover using AWiFS data of Resourcesat-1 for the Himalayan region. *International Journal of Remote Sensing*, **27** (12), 2449-57.
- Latief, S.U., Rashid, S.M., Singh, R. (2016). Impact analysis of climate change on Kolahoi Glacier in Liddar Valley, north-western Himalayas. *Arabian Journal of Geosciences*, **9**(18), 705.
- Mazhar, N., Mirza, A.I., Butt, Z.S., Butt, I.A. (2015). An Analysis of Spatio-Temporal Temperature Variability in Upper Indus Basin, Pakistan. *Pakistan Journal of Science*, **67** (3), 259.
- Mazhar, N., Mirza, A.I., Butt, Z.S., Butt, I.A. (2016). Monitoring decadal precipitation variability in upper Indus basin, Pakistan. *Pakistan Journal of Science*, **68**(3), 352.
- Mazhar, N., Mirza, A.I., Zia, S., Butt, Z.S., Shahid, M.G., Mirza, A.I. (2018). An Analysis of Glacial Retreat and Resultant Vegetation Expansion in the Karakoram, A case study of Passu Glacier in Hunza valley. *Biologia Pakistan*, **65**(1), 135-145.
- Minora, U., Bocchiola, D., D’Agata, C., Maragno, D., Mayer, C., Lambrecht, A., Vuillermoz, E., Senese, A., Compostella, C., Smiraglia, C., Diolaiuti, G.A. (2016). Glacier area stability in the Central Karakoram National Park (Pakistan) in 2001–2010, the “Karakoram Anomaly” in the spotlight. *Progress in Physical Geography*, **40**(5), 629-60.
- Negie, H.S., Singh, S.K., Kulkarni, A.V., Semwal, B.S. (2010). Field-based spectral reflectance measurements of seasonal snow cover in the Indian Himalaya. *International Journal of Remote Sensing*, **9**, 2393-417.
- Paul, F., Strozzi, T., Schellenberger, T., Kääb, A. (2017). The 2015 surge of Hispar Glacier in the Karakoram. *Remote Sensing*, **9** (9), 888.
- Qureshi, M.A., Yi, C., Xu, X., Li, Y. (2017). Glacier status during the period 1973–2014 in the Hunza Basin, Western Karakoram. *Quaternary International*, **444**,125-36.
- Rankl, M., Kienholz, C., Braun, M. (2014). Glacier changes in the Karakoram region mapped by multitemission satellite imagery. *The Cryosphere*, **8**(3), 977-89.
- Rashid, I., Abdullah, T., Glasser, N.F., Naz, H., Romshoo, S.A. (2018). Surge of Hispar Glacier, Pakistan, between 2013 and 2017 detected from remote sensing observations. *Geomorphology*, **303**, 410-6.
- Romshoo, S.A., Dar, R.A., Rashid, I., Marazi, A., Ali, N., Zaz, S.N. (2015). Implications of shrinking cryosphere under changing climate on the streamflows in the Lidder catchment in the Upper Indus Basin, India. *Arctic, antarctic, and alpine research*, **47** (4), 627-44.
- Scherler, D., Bookhagen, B., Strecker, M.R. (2011). Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature geoscience*, **4**(3), 156-9.
- Sibandze, P., Mhangara, P., Odindi, J., Kganyago, M. (2014). A comparison of Normalised Difference Snow Index (NDSI) and Normalised Difference Principal Component Snow Index (NDPCSI) techniques in distinguishing snow from related land cover types. *South African Journal of Geomatics*, **3** (2), 197-209.
- Xiao, X., Moore Iii, B., Qin, X., Shen, Z., & Boles, S. (2002). Large-scale observations of alpine snow and ice cover in Asia: Using multi-temporal

VEGETATION sensor data. *International Journal of Remote Sensing*, **23**(11), 2213-2228.

Zemp, M., Hoelzle, M., Haeberli, W. (2009). Six decades of glacier mass-balance observations, a review of the worldwide monitoring network. *Annals of Glaciology*, **50** (50),101-11.