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RESEARCH ARTICLE

Climatic Anomalies and Glacial Dynamics in the Himalayan Region Northern Pakistan: A Spatio-Statistical Approach

Zarka Mukhtar[1], Fazlul Haq*[2], Syed Ali Asad Naqvi[3] and Munazza Afreen[4]
[1]Free University of Bozen Bolzano, Italy, [2,3,4]Department of Geography, Government College University Faisalabad Pakistan

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Correspondent email:
fazli_haq@yahoo.com

Abstract Glaciers are always climate-sensitive and affected by minor changes in temperature and other climatic elements. Past studies on the northern mountain ranges of Pakistan reveal changes in climatic patterns in and around these ranges. In this study, an attempt is made to explore and assess the temporal and spatial fluctuations occurring in the ice cover of the Himalayan Region of Pakistan as a result of changes in climatic pattern. Satellite imageries and meteorological data were used to explore the dynamics of both the ice cover and climatic elements. Remote Sensing and Geographical Information System were used to detect changes in snow cover both spatially and temporally. Various statistical techniques, mainly Mann Kendall Trend Test and Sen's Slope Estimator, were used to analyze the temporal trend of climatic elements. Moreover, correlation and regression analysis were applied to establish the relationship between climate and ice cover. Analysis of the data reveals that the temporal trend in ice cover is not monotonic as there is glacial advancement in certain years while retreating in others. Moreover, it was found out that climatic elements such as temperature and precipitation have recorded changes during the past few decades.

1.Introduction

Cryosphere dynamics in response to climatic anomalies has been a field of interest for scholars and academicians from various fields. The past 5 to 6 decades have witnessed visible changes in the climatic pattern worldwide (Chen *et al.*, 2015; Dale *et al.*, 2001). Continuous variations in the climatic pattern are causing heating up of the atmosphere and ocean, leading to rapid snowmelt and rising sea level. Besides numerous other impacts, climate change has a long-term effect on snow and ice cover throughout the world, including Pakistan's glaciers. Several research studies have been conducted on the association between climatic uncertainties, and glacial dynamics in different parts of the world (Wulf, 2006; Thayyen, 2008; Wang *et al.*, 2014; Dimri *et al.*, 2018; Singh *et al.*, 2018; Liu *et al.*, 2019) The first observation about glacier retreat was made in the 1920s and 1940s and then after the drastic withdrawal of snow was detected between 1988 to 1995 in North America (Grove, 2004). Glaciers are more sensitive than other features to be affected by changes in temperature and precipitation, and the withdrawal of snow or melting of many glaciers globally is the clear sign of global warming (Oerlemans, 2005; Liu *et al.*, 2019). Studies reveal that Jakobshavn Glacier in Greenland retreated at a rate of 17 km/year till 2003 (Radford 2015). The volume of Lewis Glacier has retreated from 7.7 km^3 to 0.3 km^3 from 1978 to 2004, and the ice bodies on Kilimanjaro have shrunk rapidly from 20 km^2 before the 1880s to 2.5 km^2 in 2003 (Zemp *et al.*, 2008) and as stated by Kirby (2015, P.3) "intense ice loss of the last two decades has resulted in a strong imbalance of glaciers in many regions of the world".

A considerable part of ice reserves in the form of glaciers is present in High Asia, providing fresh water resources to widespread areas in the foothills and plains of the Indo-Pak Sub-continental region (Zemp *et al.*, 2009; Mal *et al.*, 2019). Glaciers of High Asia have passed through different stages of advancement and retreat (Tandong *et al.*, 2004; Eriksson *et al.*, 2009; Gurung *et al.*, 2011). The third pole of the world, i.e. the Hindu-Kush-Himalayan Region, feeds up 60 rivers in Pakistan, India and Afghanistan. The ongoing changes and ice cover loss has resulted in receding 40-60 meter of freshwater sources per decade (Rasul *et al.*, 2011; WMO, 2016). The situation is quite alarming as the excessive melting of ice causes flooding in the present scenario and can reduce flow in the river system of Pakistan in the future (Rasul *et al.*, 2020).

To spread awareness and get ready for the crises before they occur and reduce the effects of water-related issues, monitoring, mapping and planning about changes happening with ice mass have become the need of the time. Global Land Ice Measurement from Space (GLIMS) program has started major efforts to notice all the glaciers of earth, but many regions need to be considered (Bishop *et al.*, 2004). The northern mountainous areas of Pakistan are home to several glaciers that feed the country's river system and provide water to the agricultural sector. Most of the studies conducted on the cryosphere of the HKH Region are mainly focused on individual parameters such as a change in mass balance, volume, streamflow and surface area (Kääb *et al.*, 2015; Brun *et al.*, 2017; Marazi and Romshoo 2018; Armstrong *et al.*, 2019; Brun *et al.*, 2019). Moreover, some studies covered small areas such as a single glacier or individual drainage basins, and that these studies covered shorter data spans, making it difficult to understand the overall cryosphere dynamics of the HKH region as certain studies suggested advancement while other reported retreats (Bolch *et al.,* 2017; Forsythe *et al.,* 2017; Bolch, 2019; Farinotti *et al.,* 2020).

However, there is a critical gap in research on the glacial dynamics of the HKH region. No attention is yet being paid to human factors of glacial dynamics, which might have been playing a pivotal role. Therefore, while studying the cryosphere dynamics of the HKH region, an integrated and holistic approach needs to be adopted, motivating this proposed study. Extensive research is required in order to explore the historical trends of ice cover in these ranges and determine the fluctuations in glaciers. The present study attempts to quantify the trend and magnitude of changes in ice cover during the recent few decades and establish the relationship between these changes with changing climatic patterns.

2. Methods

Description of the Study Area

Himalaya is a Sanskrit word meaning 'House of Snow'. Himalaya is the highest mountain range in the world, holding more than 110 elevated peaks having an elevation of more than 7300 meters above sea level (Shiba et al., 2017). The western part of the Himalayas is in Pakistan. Its extension is from west to east from Nanga Parbat (the highest peak of Himalaya) in Kashmir, the heaven of the Earth in Pakistan, to the Namjagbarwa Peak in China. From the northwestern side, it is bordered by the Hindukush Mountain Range. There is the Tibetan Plateau in the north, and Potohar Plateau and the Salt Range bound the southern side in the Punjab, Pakistan. Because of the great altitude and glacial characteristics, it is home to several vital glaciers of the world.

Himalaya is also characterized by several beautiful valleys, lakes and rivers, including the Kaghan Valley, the Lake Saif-ul-Muluk and the Indus River. The Mighty Indus River has formed several deep gorges, including one of the world's deepest gorges in the Kohistan District. This study is carried out in the central part of Gilgit-Baltistan, home of many highest peaks in Pakistan. The study area covers the districts of Skardu, Astore, Hunza Nagar, Gilgit and Diamir, located between 35°08´ N to 37°01´ N latitude and 73°87´ E to 76° 51´ E longitude. The major sub-ranges located in this area are, Batora, Hispar, Rakaposhi-Haramosh, Ghujerab, Masherbrum, Dedosai and Chongra (Fig 1).

Sources and Methods of Data Collection

This study covers the changes in climatic elements from 1980 to 2016 and the temporal changes in glacial cover from 1990 to 2016, divided into five-year intervals. Satellite imagery of high resolution, topographic sheets and digital elevation data were from various websites (a detailed methodological framework has been shown in Figure 2). LANDSAT imageries were downloaded free of cost from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov). A total of six images were downloaded as per the requirement of the study for the years 1990, 1995, 2001, 2005, 2010 and 2016 (Table 1).

Pakistan Meteorological Department Head Office Lahore was consulted for the acquisition of climatic data. Temperature, humidity and precipitation data were collected for a few met-stations in the Hindukush-Himalayan Region, covering a time period of three to four decades. The main met stations for which data were collected including Gilgit, Astore, Chilas, Gupis, Bunji and Skardu from the Gilgit-Baltistan Region, while Dir, Drosh, Chitral and Saidu Sharif

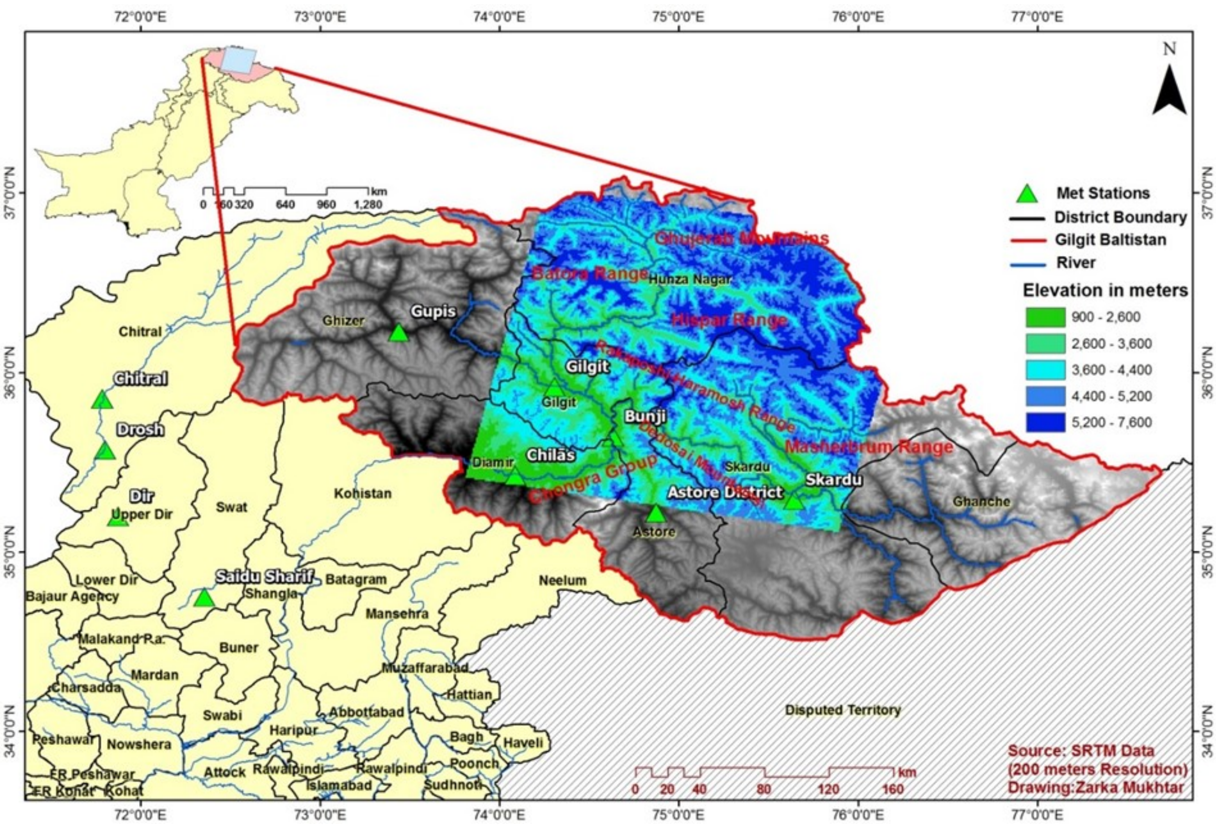

Figure 1. Study Area: Location, Drainage and Physiography

Table 1. Characteristics of the Remote Sensing Images used in the study

Acquisition date	Spacecraft identifier	Sensor	WRS Path	WRS Row	Resolution (m)
7-Sep-1990	Landsat-5 TM	*TM/SAM	149	35	30
10-Sep-1995	Landsat-5 TM	**ETM+/BUMPER, ***SAM	149	35	30
17-Sep-2001	Landsat-7 ETM	ETM+/BUMPER,SAM	149	35	30
14-Sep-2005	Landsat-7 ETM	ETM+/BUMPER,SAM	149	35	30
12-Sep-2010	Landsat-7 ETM	ETM+/BUMPER,SAM	149	35	30
26-Sep-2016	Landsat-7 ETM	ETM+/BUMPER,SAM	149	35	30

*TM (thematic mapper), **ETM (enhanced thematic mapper plus), ***SAM (scan angle monitor)

stations were selected from the northern Khyber Pakhtunkhwa Province located in the proximity of the ice cover areas.

Analysis and Presentation of the Data

Analysis of Ice Cover Dynamics

For the baseline data point, i.e., before 1990, high-resolution satellite images are not available and; therefore, topographic maps/sheets were used to explore the distribution of glaciers in that time. For this purpose, the maps were scanned and rectified in ArcMap (ArcGIS) package. The rectified raster maps were digitized and processed for the preparation of maps showing glacial distribution. On the other hand, satellite images are available for the rest of the data points, i.e., 1990, 1995, 2001, 2005, 2010 and 2016. These images were classified through ERDAS Imagine 2014 and ArcMap Software using Normalized Differential Snow Index (NDSI) analysis. The classified images were imported in ArcMap to calculate the areas under ice cover and prepare change detection maps.

Analysis of Climatic Data

Microsoft Excel and Statistical Package for Social Sciences (SPSS) were used to handle and analyze the climatic data. To check the time trend line of climatic data, spatio-statistical tests, mainly Mann Kendal Trend Model (MKTM) and Sen's Slope Estimator (SSE), were applied using MS Excel. Moreover, to display variations in climatic elements in space and time, the Inverse Distance Weighted (IDW) method was used in ArcMap. Hence, both spatial and statistical techniques were applied to analyze and display changes in climatic elements.

Analysis of Glacier-Climate Interrelationship

To analyze the relationship between the dependent variable (ice cover) and independent variables (temperature and precipitation); Linear Regression and Bivariate Correlation analyses were used. Scatter plots were constructed in SPSS to determine the strength and direction of the relationship between climatic elements and ice cover. Moreover, Bivariate Correlation analysis (Pearson Product Movement Correlation Coefficient) was also used to quantify the relationship between the dependent and independent variables. Linear Regression Model was used to compare the role of independent variables in determining the fluctuations of dependent variables.

3.Results and Discussions

Spatio-Statistical Trend of Mean Annual Temperature

Mean temperature amongst the five years intervals ranges from 9⁰C to 21⁰C. The spatial distribution of mean annual temperature reveals that Saidu Sharif and Chilas experience the highest temperature while Astore, Gupis and Skardu are the coolest stations. The monotonic increase in temperature of Saidu Sharif is broken during the 2005-2010 interval, and a slight decrease can be observed (Fig 2). On the other hand, the pattern shows a gradual increase in the mean annual temperature of the Himalayan Ice Cover area areas, i.e. Gupis and Astore stations. Here it can be observed that these areas have been shifted from the 9 – 11 ⁰C category to the 11 - 13⁰ C category during the study period. Such spatial and temporal variations in climatic elements have also been observed by other researchers from this region and the surrounding areas (Atta-ur-Rahman and Dawood 2017; Dawood *et al.*, 2020).

The Mann Kendall Trend results reveal that the null hypothesis (H_o) is rejected in the case of Astore, Gilgit, Chilas, Bunji and Dir as there is a time trend in the data. Kendal's Tau values of 0.008, 0.001, 0.003, 0.007, and 0.004 are lower than the alpha level (α=0.05), hence confirming the time trend in the data for these stations. The same met stations are having a higher variance value of 186.00, 249.00, 182.00, 176.00 and 194.00, showing a strong association of time with temperature values revealing a rising trend (Greater the value stronger the trend and lower the value weaker the trend). The results of the remaining five met stations Gupis, Chitral, Drosh, Skardu and Saidu Sharif, show no time trend, and hence the null hypothesis is accepted. Kendal's Tau value is less significant in met stations data of Skardu, Gupis, Chitral, Drosh and Saidu Sharif with the values of -0.075, -0.094, 0.102, 0.038 and 0.154, respectively (Table 2).

To check the magnitude of the trend detected in MKTM, Sen Slope Estimator (SSE) analysis was applied as also used by Atta-ur-Rahman and Dawood (2017). The slope magnitude amongst most of the meteorological stations has

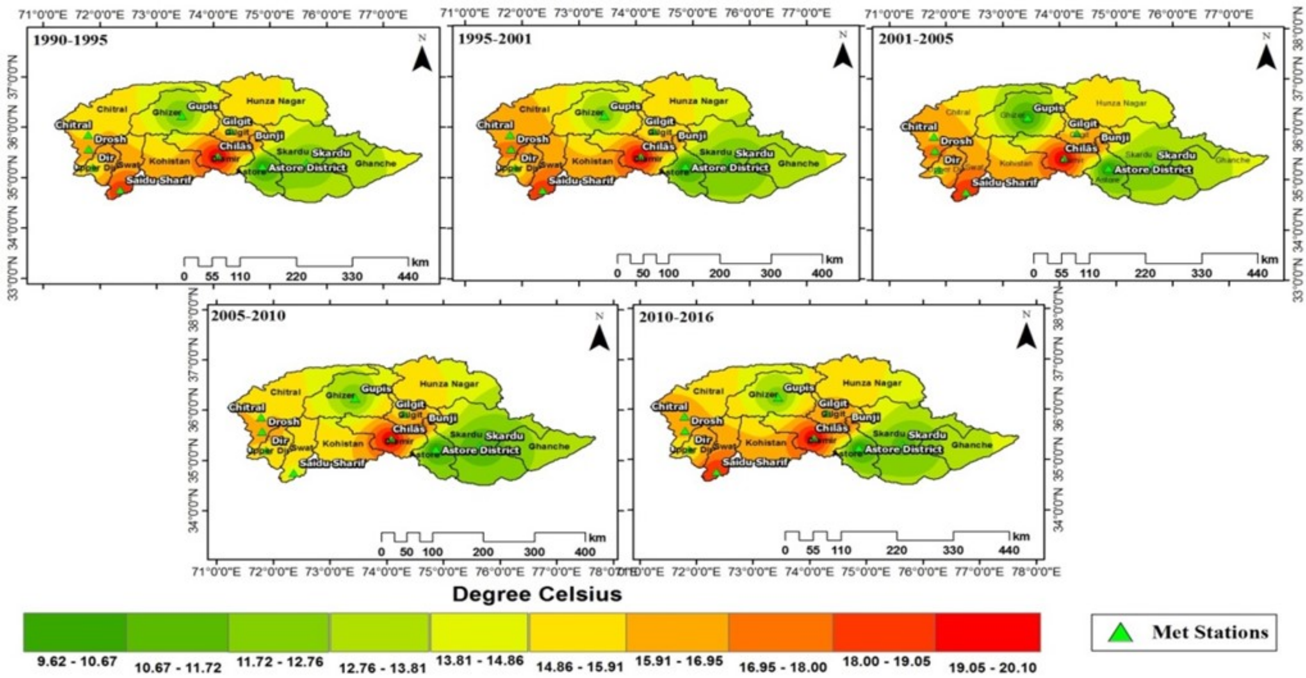

Figure 2. Spatio-Temporal Trend of Mean Annual Temperature in the Study Area

Table 2. Mann Kendal Trend Model Results for Mean Annual Temperature

Name of met station	Mean	Kendal's Tau	S	P value (tow tailed test)	Model Interpretation
Astore	9.909	0.279	186.00	0.008	Reject Ho (*MSTD)
Gilgit	15.833	0.374	249.00	0.001	Reject Ho (MSTD)
Skardu	11.877	−0.075	-50.00	0.739	Accept Ho (*NSTD*)
Chilas	20.305	0.243	182.00	0.003	Reject Ho (MSTD)
Gupis	12.342	-0.094	-79.00	0.061	Accept Ho (** *NSTD*)
Bunji	17.375	0.264	176.00	0.007	Reject Ho (MSTD)
Chitral	16.114	0.102	64.00	0.195	Accept Ho (*NSTD*)
Dir	15.392	0.308	194.00	0.004	Reject Ho (MSTD)
Drosh	16.612	0.038	24.00	0.377	Accept Ho (*NSTD*)
Saidu Sharif	19.054	0.154	97.00	0.095	Accept Ho (*NSTD*)

been recorded positive. However, the magnitude reflects a slight positive change and no strong trend was found. Skardu is the only station representing negative slope magnitude, which means that this station is having decreasing trend with the -0.006 SSE (AM temp). Chitral and Drosh also have negative magnitude but only in mean minimum temperature, and the rest of the stations are the direct indication of positive magnitude in data as they have positive signs (Table 3).

Spatio-Statistical Trend of Annual Precipitation

The spatial distribution of precipitation reveals that the western parts of the study area receive higher precipitation than the eastern parts. Saidu Sharif, Dir and Chitral are the stations with heavy precipitation records ranging from 1255mm to 1380mm. Astore and Skardu represent moderate precipitation, and the rest of the stations receive the lowest amount of precipitation in the study area ranging from 145 to 270 mm (Fig. 3). Most of the precipitation in Pakistan is received from two main rainfall systems. Therefore, there is vast regional variation in the amount of rainfall received in different places. In the winter months, western depressions from the Mediterranean region cause rainfall in the western and northwestern parts of the country, while the northeastern parts receive most of the rainfall in the summer months from the monsoon system Bengal. Moreover, local abnormalities can also be observed in the amount of precipitation received by the low and moderate precipitation zones. As Kendal's Trend Test reveals, Gilgit, Chilas and Gupis stations represent a significant time trend, and there is a gradual decrease in precipitation with time. Gilgit with Kendal's Tau value of 0.200, Chilas with 0.321 and Gupis with 0.345 indicate a strong association in time series. The probability value of Gilgit, Chilas and Gupis is less than 0.05 as 0.044, 0.042, and 0.034, and variance is 126.00, 242.00 and 253.00, respectively, which are greater than the other met stations (Table 4).

Several data points reveal a negative trend in precipitation. Sen Slope Estimator for Astore, Skardu, Chilas, Chitral and Dir with negative value as -1.317, -0.76, -0.125, -10.443 and -8.196 represent a decreasing trend (Table. 5). On the other hand, the remaining five stations show a positive trend or positive slope magnitude. Saidu Sharif shows the highest magnitude of a slope with an SSE value of 3.264, and there is a slightly less increasing trend in Gilgit, Gupis, Bunji, and Drosh with an SSE value of 0.188, 1.243, and 0.353 and 1.241 in comparison with Saidu Sharif. Hence, it can be found out that Astore, Skardu, Chilas, Chitral and Dir show a decreasing trend in precipitation during the study period, while Gilgit, Gupis, Bunji, Drosh and Saidu Sharif have recorded an increasing trend in rainfall.

Spatio-Temporal Dynamics of Glacial Cover

The results of the NDSI analysis of the images show both retreat and advancement in various time intervals (Fig 4). The overall cryosphere dynamics of the HKH region has been a highly debated issue. Somewhere some studies reported growth in the surface area of snow cover, while other studies have found retreating trends (Bolch *et al.,* 2017; Forsythe *et al.,* 2017; Bolch, 2019; Farinotti *et al.,* 2020). In this study, a comparison has been shown for different time intervals over the study period. The paired images on the left (Fig. 4) show the snow cover variations for the selected years, while the coloured image on the right shows the calculated difference in each pair. The Green colour represents an increase in the respective pair of images while the Red colour shows retreat.

Table 3. Sen's Slope Estimation Magnitude for Mean Annual Temperature

Name of Met Station	Time Period	SSEM (AM max temp)	SSEM (AM min temp)	SSEM (AM temp)
Astore	1980-2016	0.033	0.021	0.026
Gilgit	1980-2016	0.029	0.013	0.020
Skardu	1980-2016	0.011	−0.02	-0.006
Chilas	1980-2015	0.027	0.008	0.012
Gupis	1980-2015	0.031	0.023	0.024
Bunji	1980-2015	0.024	0.014	0.02
Chitral	1980-2016	0.04	-0.009	0.011
Dir	1980-2016	0.029	0.018	0.03
Drosh	1980-2016	0.02	-0.012	0.009
Saidu Sharif	1980-2016	0.028	0.009	0.013

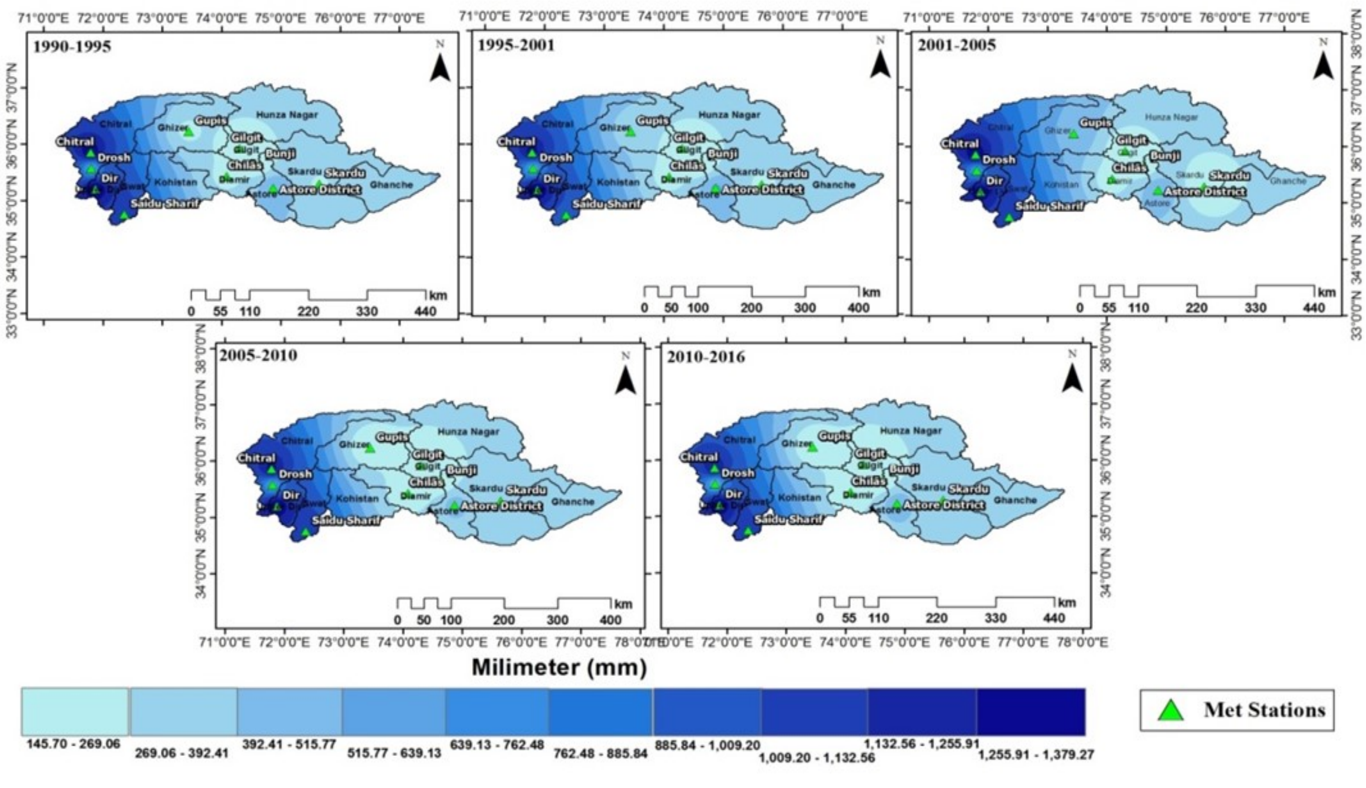

Figure 3. Spatio-Temporal Variations in Annual Precipitation in the Study Area

Table 4. Mann Kendal Trend Model Results for Annual Precipitation

[redacted]					
Astore	487.575	−0.048	-30.00	0.654	Accept Ho *(NSTD)*
Gilgit	141.608	0.200	126.00	0.044	Reject Ho *(MSTD)*
Skardu	458.981	−0.032	-20.00	0.602	Accept Ho *(NSTD)*
Chilas	201.925	0.321	242.00	0.042	Reject Ho *(MSTD)*
Gupis	210.327	0.345	253.00	0.034	Reject Ho *(MSTD)*
Bunji	166.342	0.201	132.00	0.142	Accept Ho *(NSTD)*
Chitral	13981.331	-0.324	-204.00	0.997	Accept Ho *(NSTD)*
Dir	1434.739	-0.222	-140.00	0.971	Accept Ho *(NSTD)*
Drosh	577.272	0.008	5.00	0.478	Accept Ho *(NSTD)*
Saidu Sharif	1047.456	0.073	46.00	0.270	Accept Ho *(NSTD)*

(MSTD) more significant trend detected, (NSTD) no significant trend detected

Table 5. Sen's Slope Estimation Magnitude for Precipitation

Name of met station	Time Period	SSEM (AM precipitation)
Astore	1980-2016	-1.317
Gilgit	1980-2016	1.214
Skardu	1980-2016	-0.76
Chilas	1980-2015	-0.125
Gupis	1980-2015	1.243
Bunji	1980-2015	0.353
Chitral	1980-2016	-10.443
Dir	1980-2016	-8.196
Drosh	1980-2016	0.188
Saidu Sharif	1980-2016	3.264

It can be observed that the variations are very visible and sharp in the first three intervals, i.e. a sharp increase from 1990 to 1995, followed by a drastic decrease during 1995 to 2001 while increased again during 2001 to 2005. Calculations of the quantitative results show a 15% increase in the first pair, i.e. 1990 to 1995, followed by a 15% decrease from 1995 to 2001 (Table 6).

An abrupt decrease can be observed again during the years 2005 to 2010. However, the last time interval, i.e. 2010 to 2016, shows mixed trends in snow cover as advancement can be observed in some areas while retreat can be seen in others. Several studies conducted at different times have reported the retreat in Himalayan glaciers at different times (Raina, 2009; Lutz et *al.*, 2014; Thakuri *et al.*, 2014; Khan *et al.*, 2017; Azam *et al.*, 2018). According to Maurer et al. (2019: P.1), "We observe consistent ice loss along the entire 2000-km transect for both intervals and find a doubling of the average loss rate during 2000–2016 [−0.43 ± 0.14 m w.e. year−1 (meters of water equivalent per year)] compared to 1975–2000 (−0.22 ± 0.13 m w.e. year−1)".

Statistical Relationship between Climate and Ice Cover

The vulnerability of hydrological and cryosphere resources to climate change has been a widely discussed issue as there is an obvious interrelationship between both the parameters (Fowler *et al.*, 2006; Akhtar *et al.*, 2008; Qin *et al.*, 2009; Wiltshire, 2014). In this study, an attempt is made to analyze this relationship using statistical approaches in order to quantify the effect of climatic anomalies on ice cover dynamics in the HKH region. The overall correlation results for the Pearson Product Moment Correlation Coefficient are given in Table 7. At the same time, a qualitative assessment of the relationship between the dependent variable (snow cover) and the independent variables (temperature, precipitation,

Table 6. Comparison of Snow Cover Area (Km^2) for different Year Gaps

Changes in glaciers	Snow Cover Area (Km^2)	% Increase or Decrease	Annual Mean Temperature (^{o}C)	Annual Precipitation (mm)	Temperature Increased / Decreased	Precipitation Increased / Decreased
1990	1016.80	________	16.65	848.48	_______	_______
1995	1596.64	16.67 % Increased	15.55	786.41	Decreased	Increased
2001	1224.07	10.71 % Decreased	14.14	533.07	Increased	Decreased
2005	2089.36	24.87 % Increased	15.78	805.88	Decreased	Increased
2010	1338.33	21.59 % Decreased	16.37	901.66	Increased	Increased
2016	1638.67	12.98 % Increased	16.34	888.97	Stable	Decreased

Source: Calculated in ArcMap using NDSI Attributes

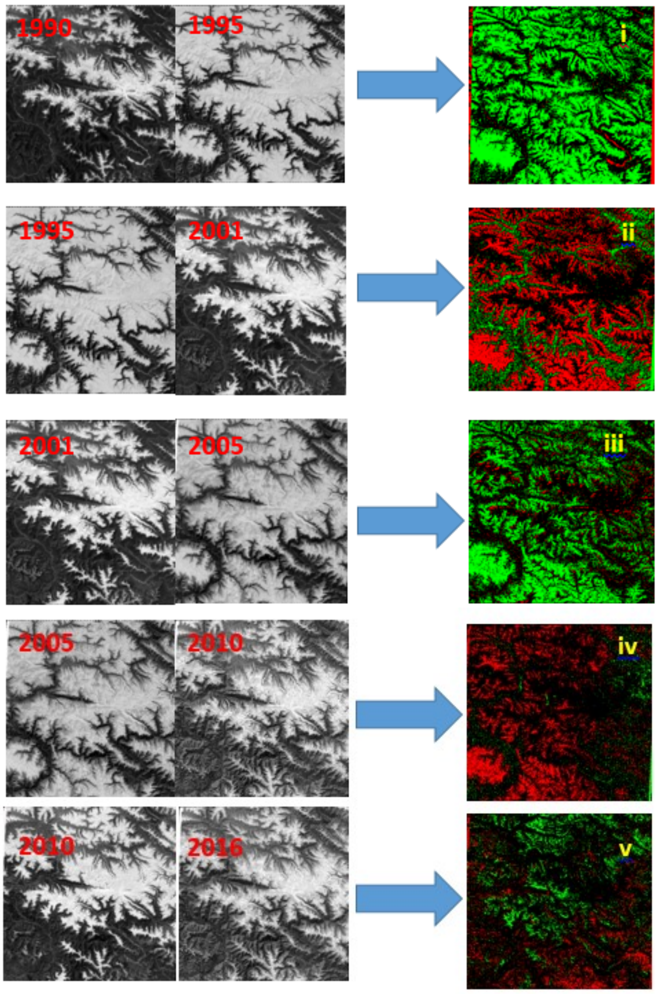

Figure 4. Dynamics of the Snow Cover from 1990 to 2016

and time) can also be made from Table 6. It is evident that there is an inverse relationship between temperature and snow cover (Table 6 and 7). The same conclusions were also drawn by another study (Collins, 2008), which found out that the initial response of ice cover to increasing temperature is the increasing trend in snowmelt and the resultant increase in surface runoff.

Gardelle et al. (2013) are also of the same agreement that the overall glacier mass balance has recorded a decline. While looking at the correlation coefficients for all the three independent variables, temperature with the value of -0.753 has a strong negative relationship with the snow cover. The negative trend line also confirms the strong negative correlation between temperature and precipitation on the scatter chart drawn for the two variables (Fig. 5).

The graphical representation of snow cover area, time, and temperature reveals the relationship in more detail (Fig 6). It can be observed very clearly that the snow cover area has recorded an increase in the years with low mean annual temperature and vice versa. A study conducted in Western China (Liu et al. 2019) also reveals a strong negative correlation between temperature and glacial cover. Similar findings have also been reported by Dimri et al. (2018) on the mass balance status of Indian Himalayan glaciers. "The continuous negative mass balance and rising temperature in the region clearly indicate the impact of warming in reducing the storage of snow and ice in the region with the future implication of shortage of freshwater availability in the snow-glacier fed river system" (Singh *et al.*, 2018: P.1). On the other hand, the present research didn't find a strong and consistent association between precipitation and snow cover area, contrary to the findings of Liu et al. (2019), who established a strong negative correlation between the two. Nevertheless, in 1995 and 2005, a strong positive correlation can be observed between precipitation and snow cover area; however, the

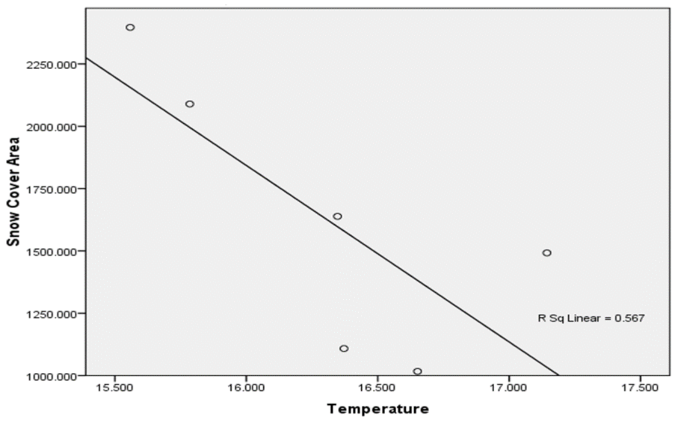

Figure 5. Relationship between Mean Annual Temperature and Snow Cover Are

Table 7. Correlation between SCA and climatic elements

		Year	Temperature	Precipitation	Snow Cover Area
Year	Pearson Correlation	1	-.008	.291	-.020
	Sig. (2-tailed)		.987	.576	.970
	N	6	6	6	6
Temperature	Pearson Correlation	-.008	1	-.485	-.753
	Sig. (2-tailed)	.987		.329	.084
	N	6	6	6	6
Precipitation	Pearson Correlation	.291	-.485	1	-.145
	Sig. (2-tailed)	.576	.329		.784
	N	6	6	6	6
Snow Cover Area	Pearson Correlation	-.020	-.753	-.145]	1
	Sig. (2-tailed)	.970	.084	.784	
	N	6	6	6	6

Correlation is significant at the 0.01 level (2-tailed).

same trend cannot be seen for the rest of the data points (fig 7). This inconsistent relationship can be understood from the fact that years with relatively higher mean annual temperature receive most of the precipitation in the form of rainfall rather than snowfall. Moreover, several underlying factors, both surface processes and tectonic forces, also play a role in glacial cover dynamics.

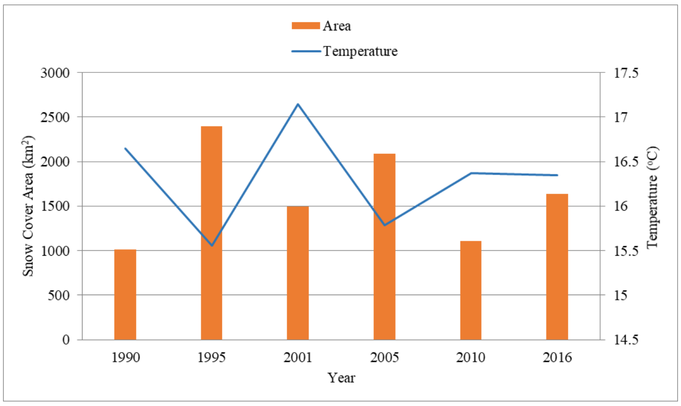

Figure 6. Graphical Representation of the Relationship between Temperature and Snow Cover Area

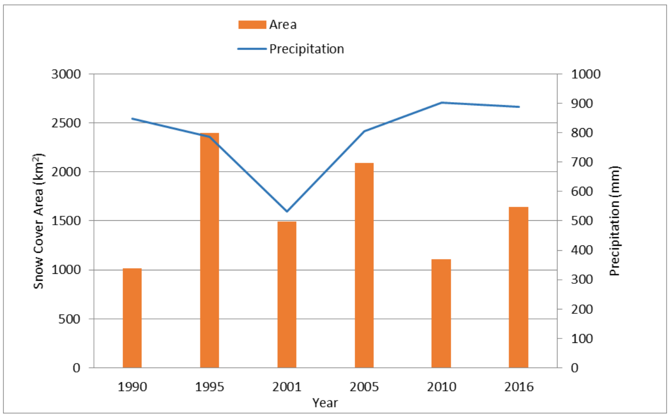

Figure 7. Graphical Representation of the Relationship between Snow Cover Area and Precipitation

Conclusion

The glaciers of the Hindukush-Karakoram-Himalayan Region (HKH) of Pakistan are showing mixed trends of retreat and advancements. Although there have been extensive debates on the fluctuations of glaciers globally as well as in the mountainous areas of Pakistan, this micro-level research reveals a satisfactory situation during the recent decades. Nevertheless, glacier retreat can be seen both in space and time, but this retreat is not monotonic in nature and the melting phases are followed by advancement in intervals. The advancement of glaciers in the early 2010s was also reported by other studies (Kamp *et al.*, 2011; Bocchiola and Diolaiuti 2013) in the study area's upper ranges; Hispar Rakaposhi-Haramosh range and Batora range. Chongra, Dedosai and Masherbrum are showing increasing signs but quite less than other ranges in the upper region of the study area (Bolch *et al.*, 2012).

The glacier retreat and glacier advancement phenomena are quite complex, and numerous underlying factors can play a role. However, as per the scope of this study, the statistical relationship between climatic elements, time and glacial cover reveals the situation quite clearly. The absence of any trend in glacier retreat and advancement shows that there is no relationship between the years passing and the snow cover. Moreover, among the climatic elements, the strongest relationship was found with temperature. The years with increasing temperature have recorded a retreat in glaciers, while advancements can be seen in the colder years. Hence, in conclusion, the null hypothesis for the independent variable temperature is rejected as there is a strong negative correlation between temperature and snow cover area. On the other hand, the null hypotheses for both the time trend and precipitation are accepted as neither any monotonic time trend was found in glaciers nor any noticeable impact of precipitation on glaciers in the study area.

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