Journal of Himalayan Earth Sciences Volume 52, No. 2, 2019 pp. 145-160

Snow cover trend analysis using modis snow products: A case of Shayok River Basin in Northern Pakistan

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Submitted: Accepted: Published online:

Abstract

To tackle the challenges of the growing water demands, an improved Water resource management is required. The main contributor of water resources in Pakistan is the Indus river, which Inflow largely depends on glacier and snowmelt from Upper Indus Basin located in the mountainous ranges of Himalaya–Karakoram–Hindukush (HKH). Despite such importance, assessment of cryosphere dynamics cannot be done manually with accuracy, especially in mountainous areas comprising difficult terrain. To obtain precision, other sources of information such as station data and remotely sensed snow-covered area, should be used together to make accurate conclusions about the snow cover and climate variability conditions which will affect downstream population for water-related activities and its management and, for example, hydropower generation, etc. Therefore, this study was done to explore the changes in snow-covered area in Shayok River basin (Sub-catchment of the Indus River) through remote sensing and GIS. Satellite images of MODIS sensor were used to examine the variation in snow. Modis 8-day composite images from 2000-2018 were selected to investigate SCA due to its high accuracy. Furthermore, climate data from one (only available) high altitude climate station located at the same basin was used to study correlation among now cover variations with varying preticipation, minimum and maximum year-round temperatures for the period of 2000-2018. Analysis showed that remote sensing is a useful technique for estimation of snow in difficult and complex topography. Moreover, results also indicate that SCA is highly correlated with the climatic parameters (Temperature and Precipitation data) therefore it is important to get accurate climate data to understand snow extent properly. Our results will be helpful to manage water resources properly in downstream population which indicate one-month shift of snow cover accumulation and depletion. However, to make more accurate and conclusions, we recommend on detail study of each river basin and long-term monitoring of whole UIB.

Keywords: Snowcover data, Meteorological parameters, MODIS, Shayok river basin.

1. Introduction

Econmomy of Pakistan mostly depends on rural-based of agriculture and around 75% of population lives in rural areas, and nearly 44% of population is involved in farming and agriculturally based industries. Consequently making Pakistan one of countries having the largest consumers of water. The rapid growth in population and larger demands of water for domestic and commercial use results in scarcity of water and the rise in pressure on irrigation system (Afzal, 1996; Ali et al., 2009; Kahlown & Majeed, 2002; Qureshi, 2011).

The Karakorum and surrounding high-altitude areas covered with snow are the main source of Indus River which is the longest river with length and drainage area of 2900 km and 966,000 km2 respectively. It originates in the Tibetan plateau, passes through Ladakh, travels through ranges of Hindukush-Karakoram-Himalaya, and then merge into the Arabian Sea by forming the world's largest irrigation system (Mazhar et al., 2016). Indus river system is further divided into western rivers i.e., Indus, Jhelum, and Chenab and eastern i.e. Ravi, Beas, and Sutlej. The main inflow to these rivers is mostly snow and glacier-melt water, which comes from the catchment area upstream named as Upper Indus River Basin (UIB). The UIB holds the ranges of Himalaya-Karakoram

Hindukush (HKH), which stores more snow and ice outside of the polar regions than anywhere else in the world and are also known as the 'The Third Pole' (Phillips & Sloan, 2000). Larger irrigation systems are dependent on runoff from the (UIB) for providing water supply for those river basins that are downstream. In Asian mountains Karakoram contains the largest concentration of snow and ice that is 70 to 80 % annually. An area of about 16300 km2 is covered by Karakoram among which 13000 km2 lie within Pakistan (Hewitt, 2014).

The major concern in (HKH) is the changing climate (Schild, 2008; Singh et al., 2011). Mountains are very sensitive to climate impacts, therefore, a variant behavior of snow covers and glaciers is observed over the time. Due to rise in temperatures, it is observed that glaciers in the Himalaya region are depleting rapidly (IPCC, 2007; Singh & Bengtsson, 2003; Singh & Kumar, 1997; Spies, 2016; Stocker et al., 2013). Spatial precipitation patterns were pretend regional climate model 4.3 in the Upper Indus basin. However in the late 1990s an unusual behavior was found in Karakoram glaciers named as 'Karakoram anomaly' which founds that Karakoram glaciers did not follow the global trend of glacial decline while the heterogenous behavior of advancing and surging these glaciers in against stability (Brahmbhatt et al., 2015; Hasson et al., 2013; Hewitt, 2005).

In contrast, there are few studies those contradict this result (Spies, 2016). Since the area consists of mostly difficult terrain and remote for researchers the discussion will remain inconclusive. However, most of the researchers agreed that the impact of any change of climate on this area, which contains large glaciers and snow area will have drastic impacts on water, further impacting on livelihood of large population living in downstream (Akhtar et al., 2008). The level of impact may vary in different river basins. Any variation in snow cover or glacier's mass have direct effects on agriculture and water-based activities like hydropower plants. Therefore, in this context, there is a need of continuous assessment of any changes in the snow cover area in the Karakorum is of very significant. However, the measurement of snow cover extent of few basins of Karakorum that include our study area have not been focused by researchers except few (Bhambri et al., 2012; Bhutiyani, 1999; Gilany & Iqbal, 2016) whereas some have presented their work on whole Upper Indus Basin (Bilal et al., 2019). These glaciers certainly play main role to the sustainability of glaciers and mountain ecosystem in the region in the long run.

To understand changes in glaciers and snow extent, monitoring of seasonal snow cover trend is important. Manual mapping of snow is potentially dangerous and very expensive because of the difficult mountainous terrain. To estimate snow cover area accurately, remote sensing techniques are used. Remote sensing provides useful information for finding spatial-temporal patterns of snow cover across large areas and inaccessible terrain (Christopher et al., 1998). For assessment of snow cover area (SCA), the Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover products are used extensively. The MODIS instrument was launched by NASA in 1998 (Christopher et al., 1998). It is a multispectral radiometer, which is proven to be applied for a large variety of applications (atmosphere, oceans, land surface, and cryosphere) globally. MODIS data is proven to be useful for a large variety of applications (land, ocean, and snow). MODIS works on two satellites Terra denoted as MOD10, since 24 February 2000 with a morning Equator crossing, and Aqua denoted as MYD10 since 24 June 2002 with an afternoon Equator crossing.

In this study, we analyze temporal (weekly, monthly, seasonal, and annual) variation of snow cover in the Shayok basin of Karakorum region and compared trends with local weather station data. This research is expected to unveil some significant trends in the long-term based on the information over the 19 years about snow cover trends in Shayok basin of Karakorum. We used MODIS snow cover products from 2000 to 2018, covering the Shayok basin in the Karakorum range in Pakistan and around bordering India and China. In-situ climate data (Temperature and participation) from one high altitude station

(3075 m) from the same basin are used to validate the results.

The main objectives of the research are to investigate:

1. To calculate annual, monthly, and seasonally snow cover dynamics in Shayok basin situated in the Karakorum Range for two decades (the period between 2000 to 2018).

2. To measure that how much climate variability effects the behavior of snow cover extent of Shayok basin and investigating decadal trend analysis.

3. To correlate of snow cover extracted from MODIS data with the meteorological data (max temperature, min temperature, and precipitation) in the study area.

2. Study area

The present evaluation of snow cover extent is done in the Shayok river basin (sub-basin of UIB) situated in the eastern part of Karakoram (Fig. 1). The region lies between latitude and longitude of 35° 12' 60.00" N and 75° 52' 59.99" E respectively, surrounded by Indian Jammu and Kashmir in the south and basin of Indus river in the west. The total area of catchment of Shayok basin is 11654 km2. The elevation of the catchment ranges from 2000 m to 7000 m. The mean precipitation recorded annually in the catchment is approximately 300 mm at Hushey (3075 m) climate station, according to the 19 years data available from 2000 and 2018. The area covered by glaciers is 3013.2 km2 in Shayok basin. There is only one climate station at Hushey at 3075 m.

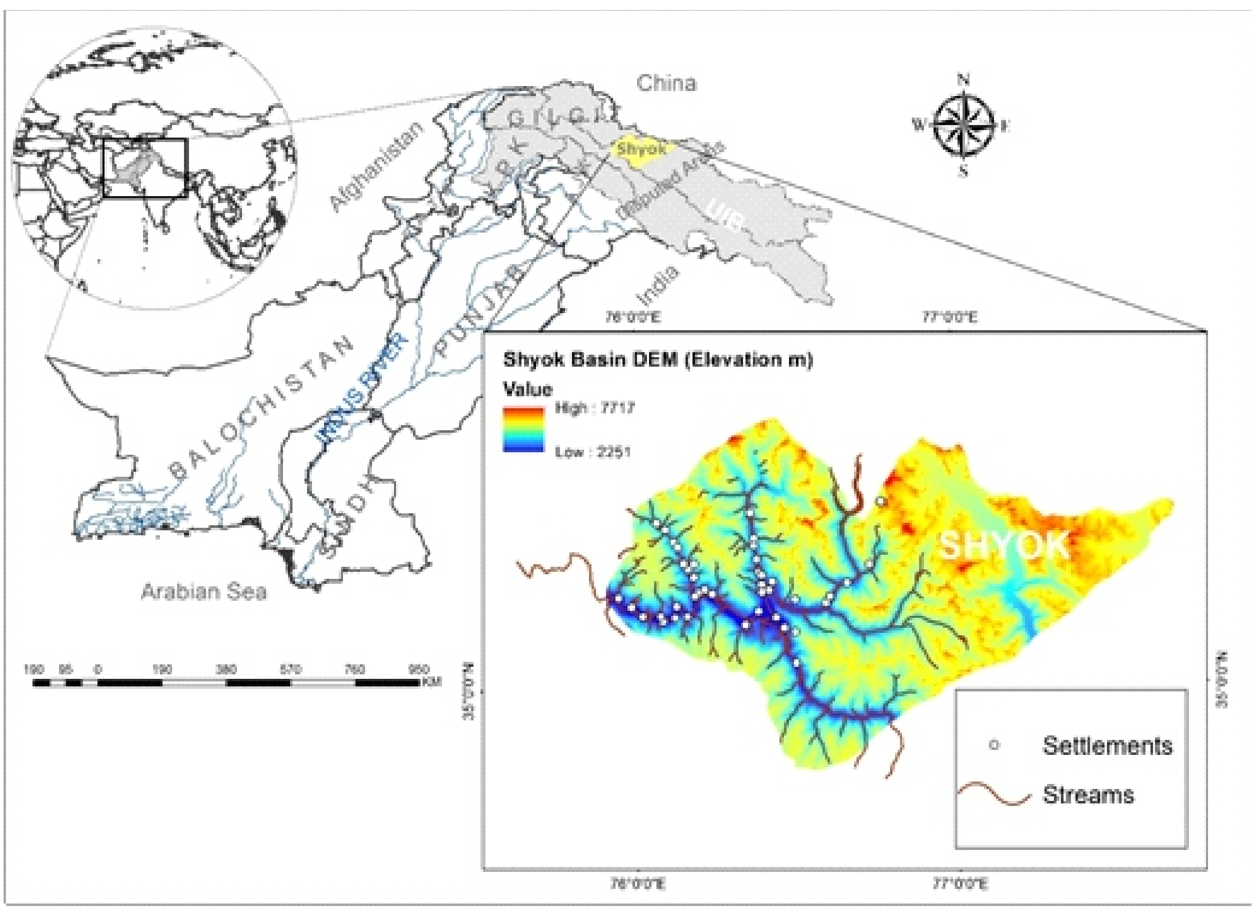

Fig. 1. Map of study area.

3. Materials and methods

3.1. Dataset

Several types of data collected, processed, and analyzed using different tools and techniques. These various types of data include MODIS snow data, vector data for boundary of study area and Meteorological Data. The MODIS snow products (Terra & Aqua) were available through National Snow and Ice Data Center (NSIDC), Boundary of study area was available from Pakistan topographic Sheets and Meteorological Data for daily precipitation, maximum and minimum temperature was provided by Water and Power Development Authority (WAPDA), Government of Pakistan. Details about datasets used as given below in Table 1.

Several studies have reported high accuracy between 93 to 97% of MODIS data with ground stations observation data for snow cover areas (Hall & Riggs, 2007; Jain et al., 2008; Klein & Barnett, 2003). They further noted that MODIS data have limitation to map snow with depth of less than 4 cm (Hall & Riggs, 2007). For the present study, MODIS/Terra Snow Cover 8-Day L3 Global 500 m spatial resolutions and MODIS/Aqua Snow Cover 8-Day L3 Global 500 m resolution, version 6, snow products from their available date to present date were downloaded and analyzed to calculate the snow cover difference in the study area. There are 36 horizontal (H) and 18 vertical (V) tiles covering the entire globe, starting with tile h00v00 and ending at h35v17. The H24V05 tile that covers the complete study area was used, around 1700 Images of snow data were downloaded in HDF-EOS (Hierarchical Data Format – Earth Observing System) and processed in ArcGIS software.

8-Day Snow products was acquired by compositing data set tiles for eight days and each day has assigned a bit value. If snow is observed on that day, the bit value is set to (1) else it is set to (0) for cloud, land, or missing data. Furthermore, the cell data was converted it into binary form e.g. if a cell contains the value 135 then 8-bit representation of the number in binary would be 10000111. If we read the bits from right to left it is observed that snow is observed in the cell on day 1, 2, 3, and 8 of the compositing periods, while no snow was observed on day 4, 5, 6, and 7.

8-Day Snow Cover product is used since daily snowfall is thin and short-lived and, daily snow cover map gives lower accuracy in Mountains terrain and forests as compared to croplands and agricultural areas where accuracy is up to 99% (Gascoin et al., 2015; Wang et al., 2009).

Meteorological data of daily mean temperatures (Minimum and Maximum) and daily total precipitation over 19 years (2000–2018) for Weather Station Hushey provided by WAPDA, Government of Pakistan within the Shayok basin was used to investigate correlation between station data and Snow data. Moreover, monthly and Yearly correlations of snow-covered area versus station data (Average minimum temperature, average maximum temperature, and total precipitation) were also investigated.

3.2. Method

We downloaded the "Snow Cover Daily Tile" field from MOD10A1 and MYD10A1 containing the snow/no snow and cloud masks. Our study area crosses the MODIS sinusoid grid tiles H24V05. The grid was downloaded and re-projected over a region of study area covering the Shayok basin using the ArcGIS 10 reprojection tool (extent given in Fig. 1). The different classes in the MODIS product were reclassify in three classes: no-snow, snow, no-data (clouds and missing data).

Further following steps were taken in sequence: if their no-data was found in MOD10A1 for each pixel then the value was replaced from MYD10A1. Otherwise, MOD10A1 value was kept. The priority for pixel value was given to MOD10A1. In next step, snow cover area was calculated, and that leads to development of daily, monthly, and annual graphs of snow cover area. In parallel to computation of snow cover area, climate station data was processed to extract daily, monthly and annual graphs to observe correlation with snow cover area data. Figure 2 shows flowchart of our Methodology.

Table 1. Data sources and description.

Data Type	Source	Resolution/Scale	Description	Revisit Time	Recording Time period
Snow data	NSIDC https://nsidc.org/	500 × 500 (m)	MODIS/Terra Snow Cover 8-Day MODIS/Aqua Snow Cover 8-Day	1-2 days	(2000-2018)
Climatic data	WAPDA	Millimeters (mm), Celsius	Precipitation, Temperature	Daily	(2000-2018)

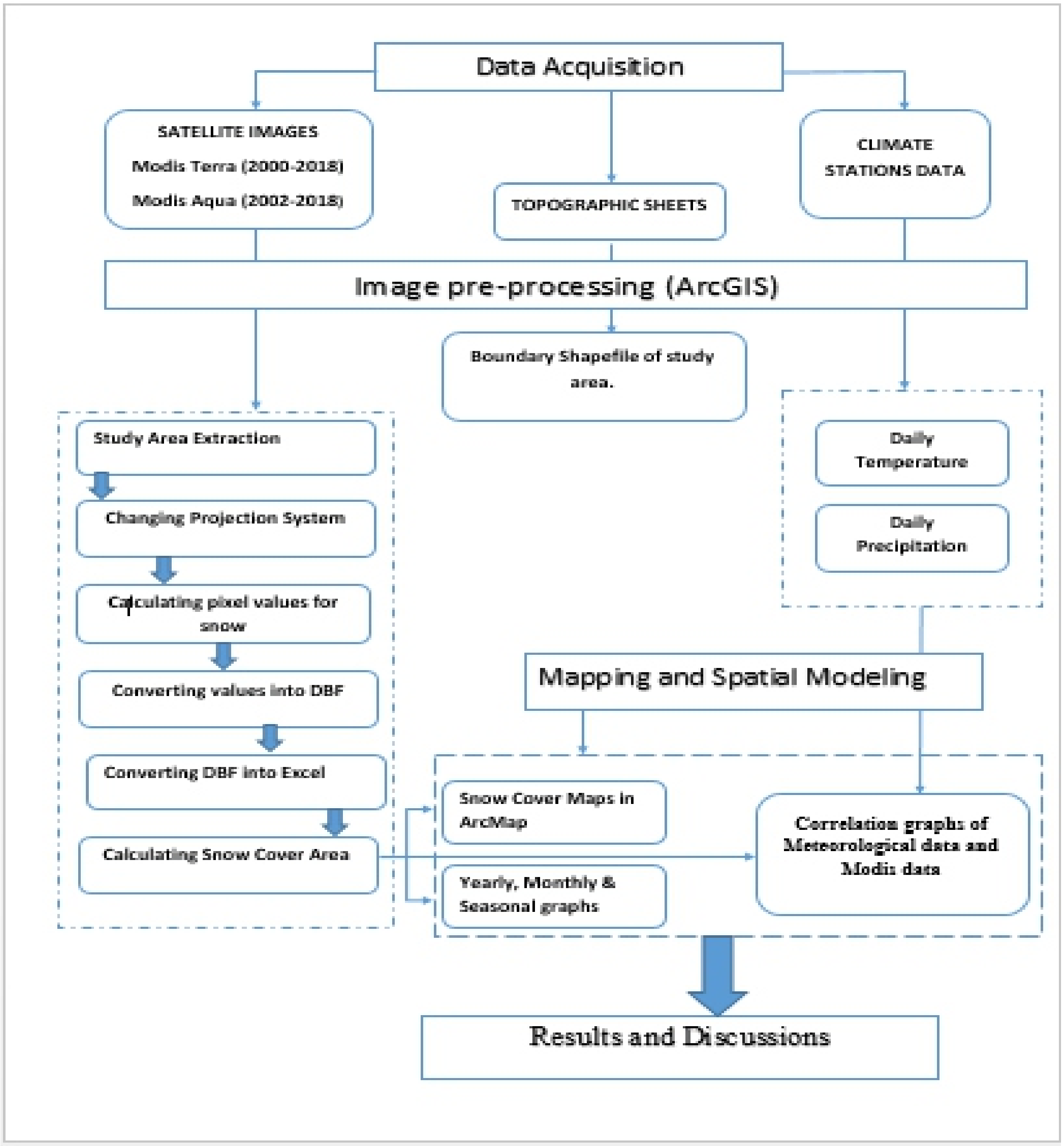

Fig. 2. Methodology/ schematic diagram flowchart.

4. Results

4.1. Snow cover variation in shayok river basin

The current study presents Snow cover area for Shayok River Basin, which was estimated using MODIS 8-day composite images of 500 m spatial resolution throughout 19-years from March 2000 to October, 2018. These Images were treated through GIS tools and techniques in ArcGIS software to get SCA percentage for each 8-day Image. Pixel values of each image depict the percentage of snow cover. Weekly, monthly and annual analysis of snow cover area is as follows:

4.2. Weekly snow cover trend analysis

The snow-covered area was computed from processing MODIS/Terra images. As 8-day composite image is used, therefore one entire year contains 46 images, and total number of images used to compute the area for the overall period of 19-years contains around 870 Images. The overall change in snow cover area for each year in the entire data period for Shayok River basin is presented in Figure 3. Snow cover in the area shows maximum values in spring season (March to May) and minimum values in summers (July to September). For winters mostly, maximum value for snow were found except for some points which shows minimum values.

For the entire period, the year which show maximum snow-covered area was 2015 and the year, which shows minimum snow-covered area was 2007. Weeks which have the minimum snow cover area were 10-17 January, 3-10 February, and 4-11 December, in the years 2008, 2005, and 2003, respectively. Similarly, weeks which have observed the maximum snow-covered area were 28 Dec-1 January, 11-18 February, 1-7 April, in the years 2002, 2000, and 2017 respectively.

4.3. Seasonal variations of snow over the Shayok River Basin

In addition to overall assessment of SCA, seasonal pattern of SCA is also analyzed. Pakistan is a country which enjoys all four seasons of spring, summer, autumn and winter which occurs in March-May, June-August, Sep-Nov and Dec-Feb respectively. Figure 4 shows the seasonal evolution of snow cover from (2000 to 2018). The peak value for snow cover is usually found during springs and winters and low for Summers and Autumns, but in last few years it shows that Summers have higher values for snow cover in contrary to Winters.

4.4. Monthly variations of snow over the Shayok River Basin

Monthly trend analysis is also done to get clear information of months in which snow is accumulated and start depleting in the basin. The Figure 5 shows the average SCA in kilometers over the last two decades (2000-2010) and (2011-2018) separately. Monthly average SCA data of the last 18 years indicates that the snowmelt period starts from May and lasts till August, and Snow accumulation starts in September and reaches the maximum level of 83% in April. The mean maximum SCA is observed in April, and mean minimum SCA is observed in August for both decades. The maximum SCA was 8303 km2 in (2000-2010) and 8575 km2 in (2011-2018), respectively. The minimum SCA was 5636 km2 in (2000-2010) and 5477 km2 in (2011-2018). For both decades the cycle of snow accumulation starts from September and lasts till April and melting starts from May and last till August, but the first decade from 2000-2010 shows melting in the month of November-February.

4.5. Combined terra and aqua snow cover products

Daily data availability and accuracy of Modis Snow products are convenient for hydrological application, but on the other hand MODIS sensor has a drawback of cloud obstruction. It is difficult to exactly extract results from cloudy areas. Therefore, combining both Terra and Aqua snow cover products minimizes not only cloud cover, but it also assist to identify maximum snow cover (Wang et al., 2009).

The step of combining both Terra and Aqua products is the most effective and accurate method to remove cloud cover (Gafurov & Bárdossy, 2009) . As clouds are in a continuous movement, a pixel recorded as cloudy by Terra in morning can be recorded as clear by Aqua in the afternoon and vice versa (Xie, 2009). If one satellite records a pixel as cloud covered and other as cloud-free, then the pixel is considered as a clear pixel; thus, pixels which are detected as snow by Terra and land by Aqua will be composited as snow.

In the current study, both Terra and Aqua snow cover products are combined, and the maximum value is picked among them for mapping SCA in ArcGIS, this process minimizes cloudy pixels and maximize snow-covered pixels. Figure 6 (a) shows annual maximum SCA over 19-years where maximum snow-covered area of 92% is observed for the year of 2017. Figure 6 (b) show minimum annual SCA over the same period where minimum SCA of 7% is observed for the year of 2005. Figure (c) shows monthly maximum SCA where maximum snow-covered area of 93% is observed in April. Figure (d) show monthly minimum SCA where minimum SCA of 21% is observed in February.

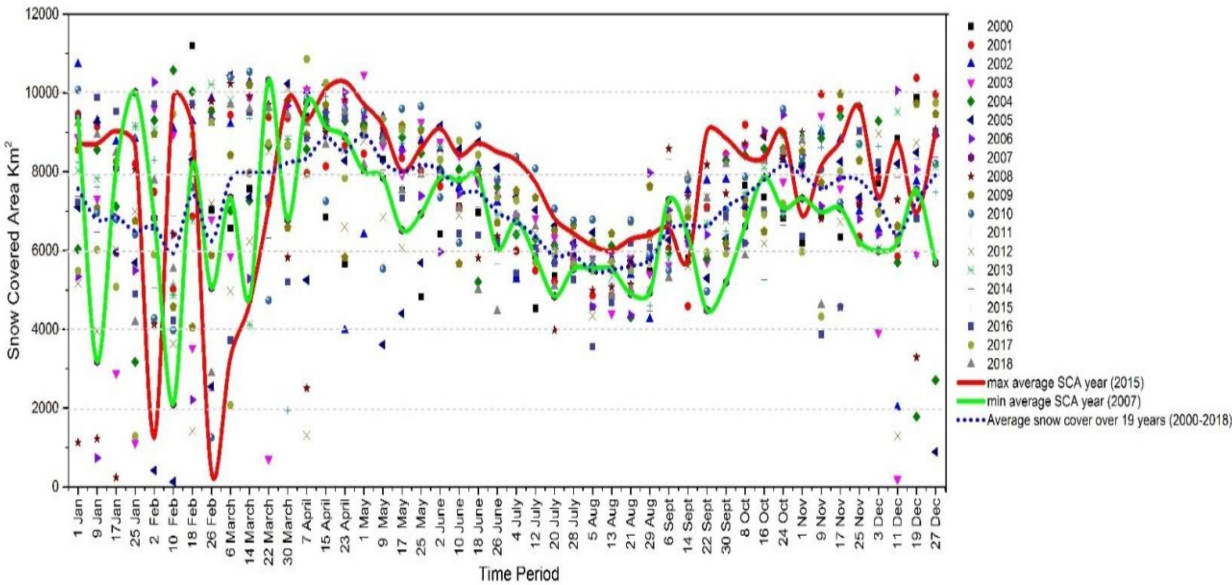

Fig. 3. Weekly trend of SCA over the 19 years.

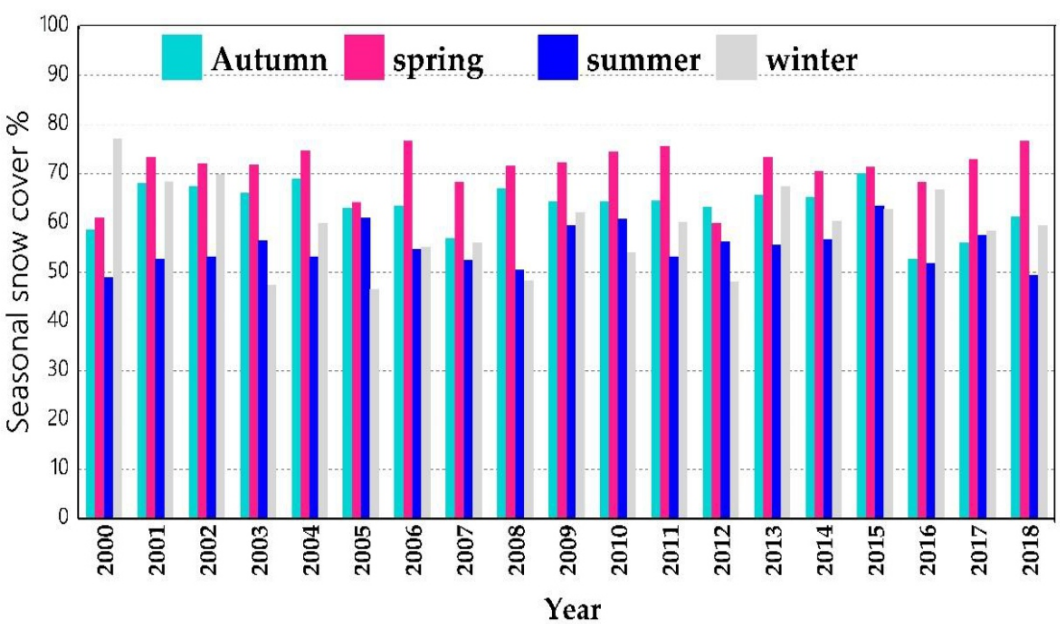

Fig. 4. Graph showing seasonal snow cover (2000-2018).

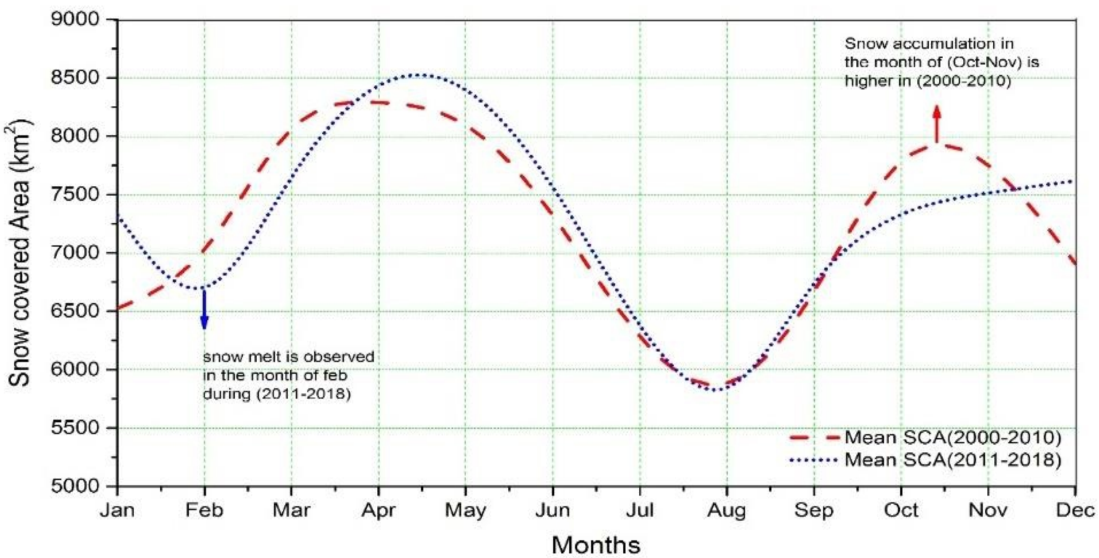

Fig. 5. Comparative monthly trend in two decades.

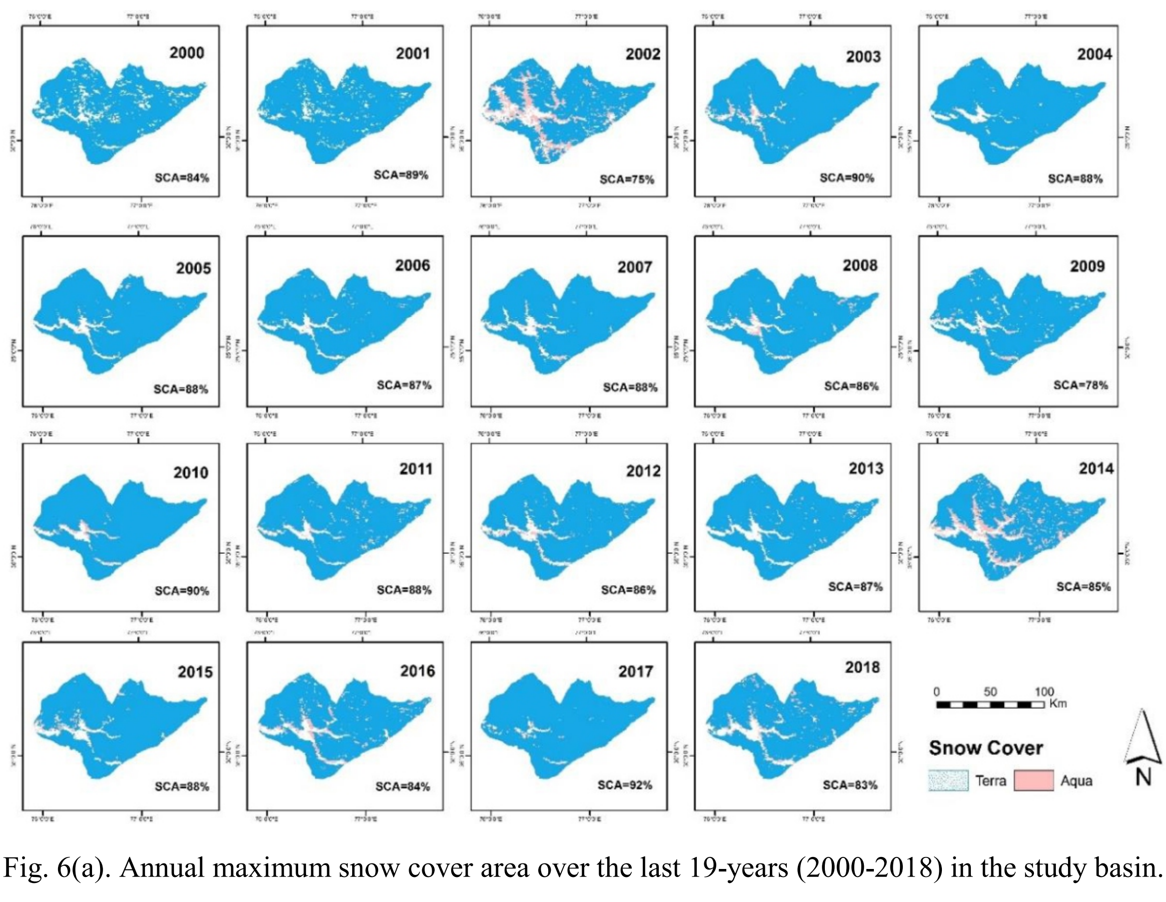

Fig. 6(a). Annual maximum snow cover area over the last 19-years (2000-2018) in the study basin.

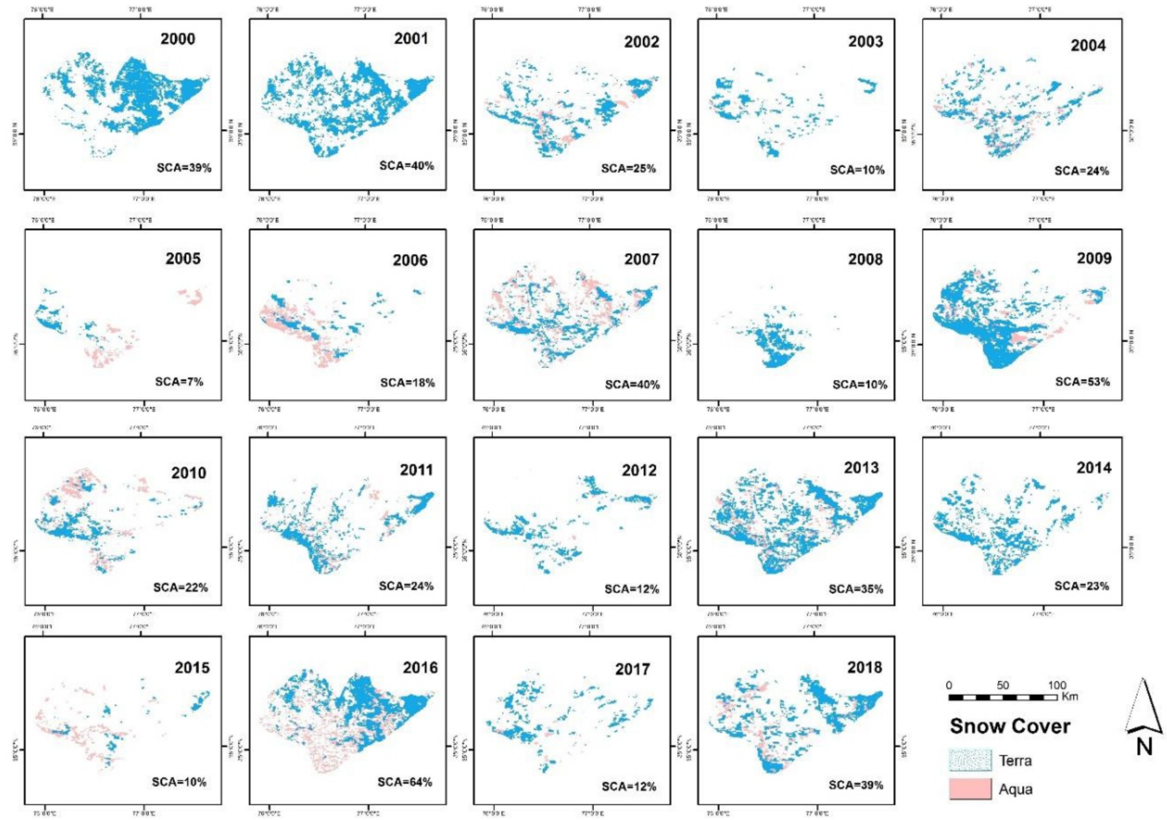

Fig. 6(b). Annual minimum snow cover area over the last 19-years (2000-2018) in the study basin.

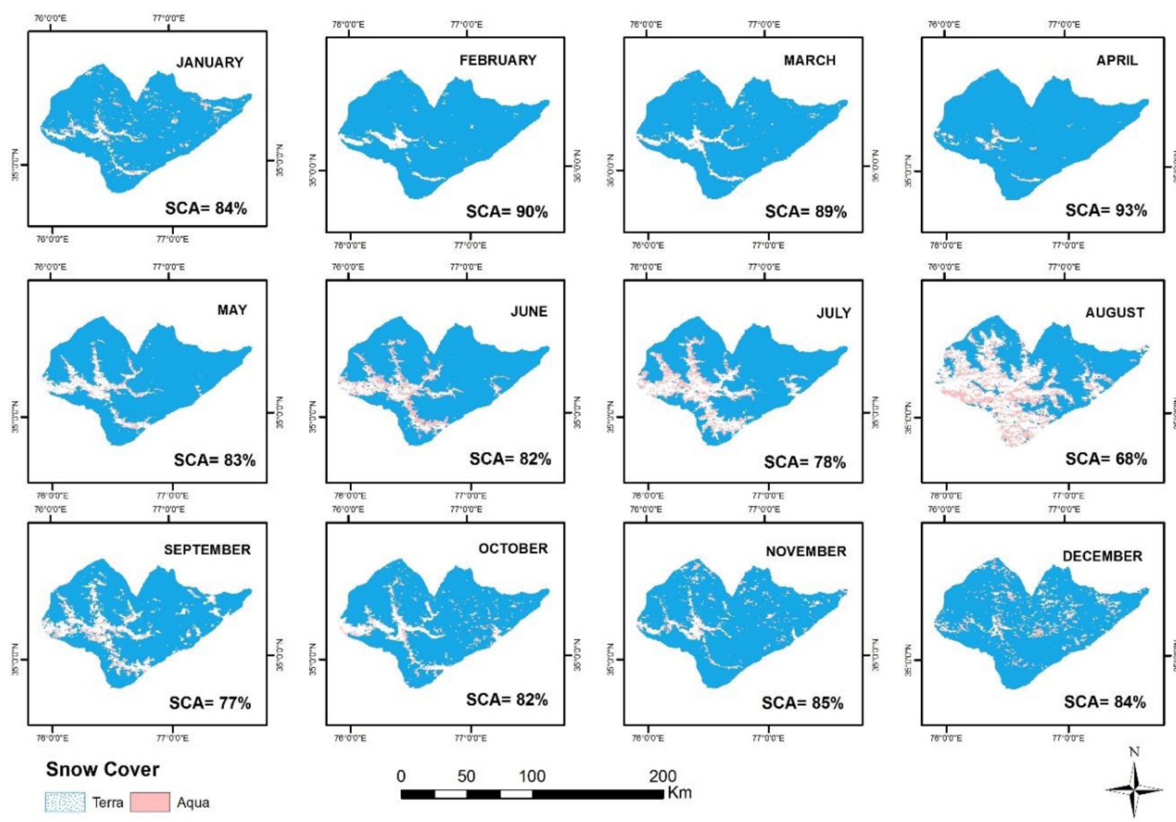

Fig. 6(c). Monthly maximum snow cover area over the last 19-years (2000-2018) in the study basin.

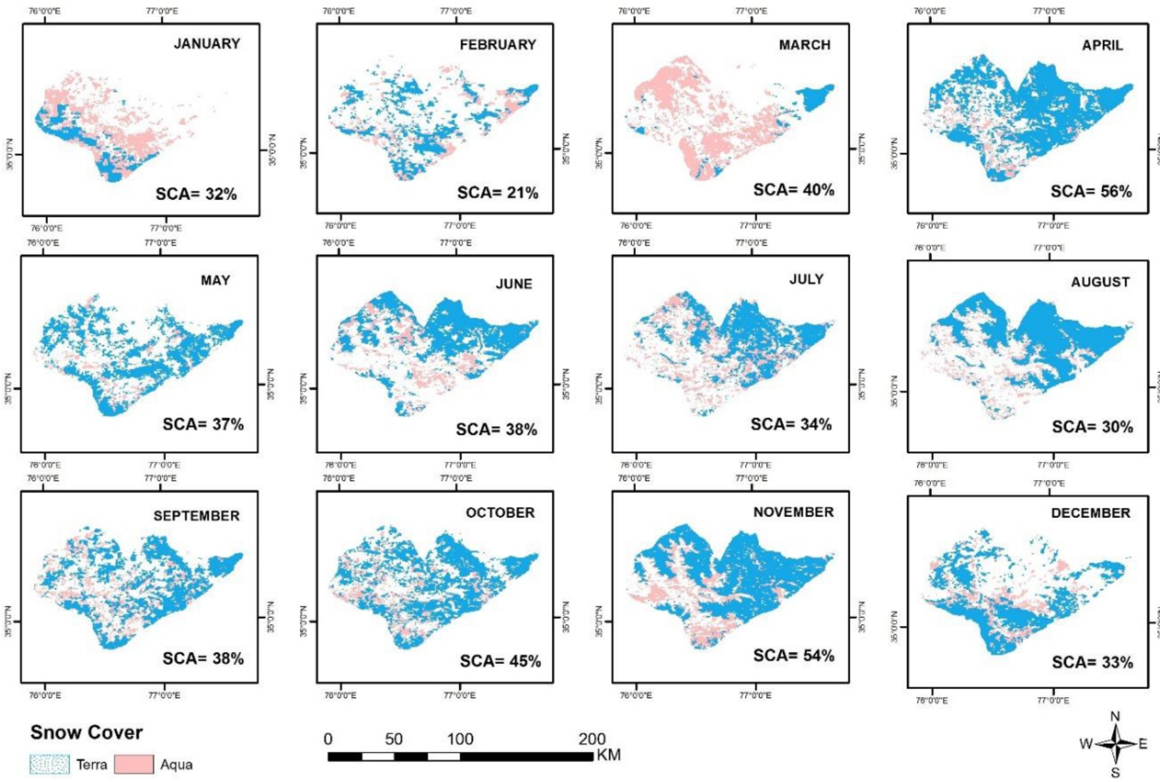

Fig. 6(d). Monthly minimum snow cover area over the last 19-years (2000-2018) in the study basin.

5. Meteorological stations data

Data from a specific climate station within the study area was used to reveal the pattern of climate. The daily temperature and precipitation data from high-altitude meteorological station located at Hushey within watershed of Shayok for a period from 2000-2018 was collected from water and power development authority (WAPDA), Government of Pakistan. Linear trend analysis of Maximum temperature, minimum temperature, and Total precipitation is presented in Figure 7.

5.1. Correlation of SCA and climate data

SCA was correlated with climatic parameters (Precipitation, maximum temperature, and minimum temperature) to further understand the relationship between SCA and climate parameters.

5.2. Maximum temperature

At High altitude basins like Shayok, the overall temperature remains very low because snow covers the region throughout the year. Temperature has an inverse correlation with SCA. In the correlation graph of Figure 7(a), it can be observed that as maximum temperature is increasing, snow cover extent is decreasing and vice versa. In summers when the temperature rises it causes the snow to meltdown, and in winters decrease in temperature results in snow accumulation.

5.3. Minimum temperature

With the rise in maximum temperature, minimum temperature has also increased and hence has a negative correlation with snow-covered area as trend is shown in Figure 7(b).

5.4. Precipitation

Most of the precipitation in UIB occurs in Winters and Spring in the form of snow in high altitudes and rainfall in low altitudes due to westerlies circulation originating mostly from the Mediterranean and Caspian Sea. The increasing trends of precipitation continuously feed the high altitudes with snow. Precipitation has a direct relationship with SCA. It increases as the precipitation increases. Analysis suggests a positive correlation of precipitation and SCA as shown in Figure 7(c).

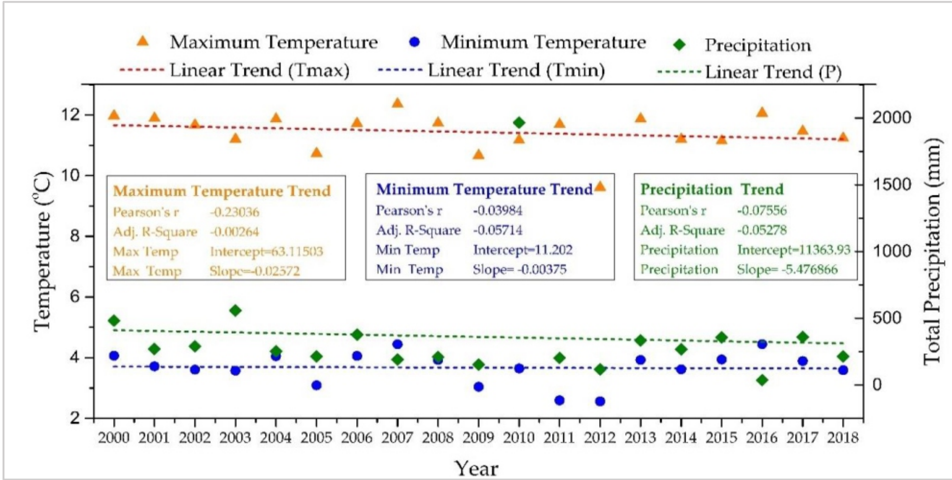

Fig. 7. Linear trend analysis of Maximum temperature, minimum temperature, and Total precipitation.

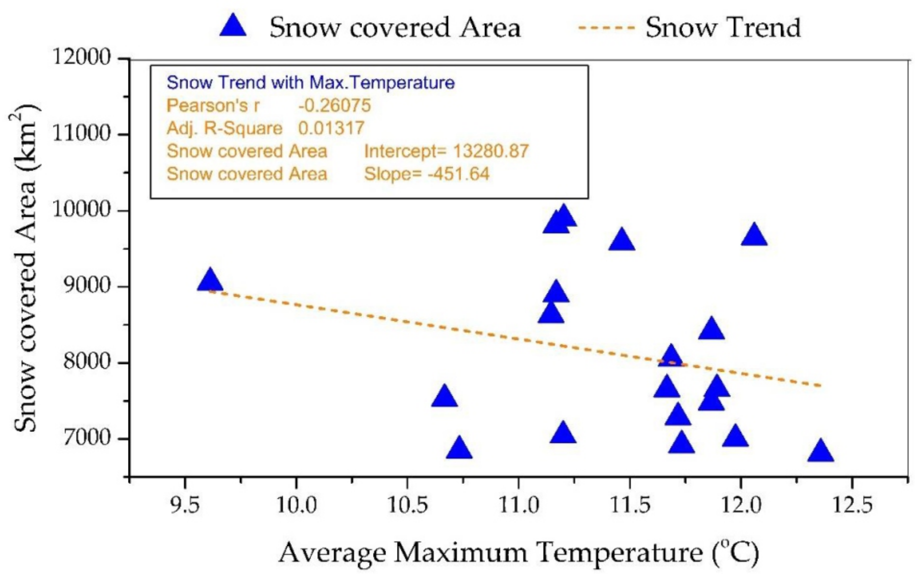

Fig. 7(a). Correlation of maximum temperature and snow-covered area.

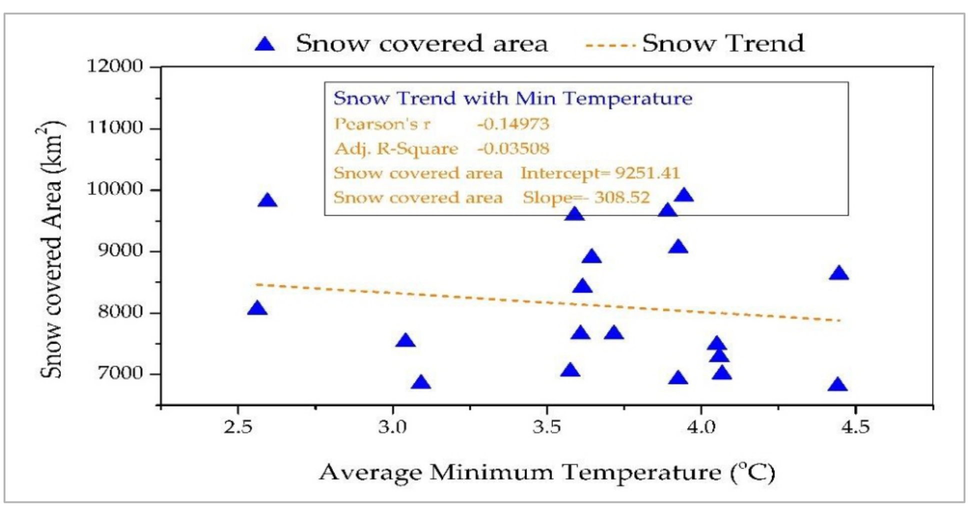

Fig. 7(b). Correlation of minimum temperature and snow-covered area.

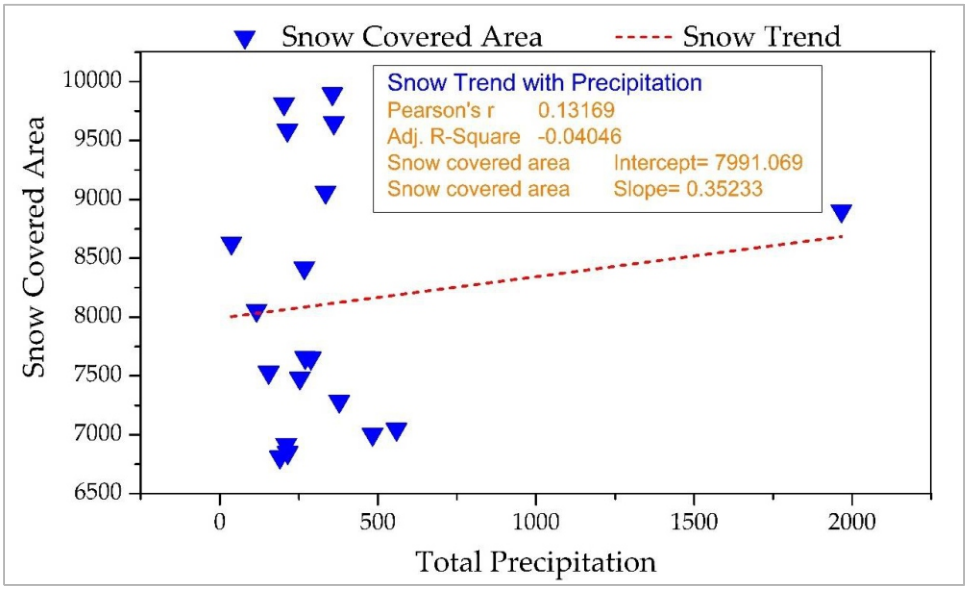

Fig. 7(c). Correlation of precipitation and snow-covered area.

6. Discussion

Over the past few decades, the warming of earth is observed due to concentration of carbon dioxide (CO2) and other greenhouse gases in the atmosphere, which has increased global warming (Stocker et al., 2013). The Himalayas glaciers and snow cover which are very sensitive to climate conditions have observed major snow cover changes in shape of retreating and losing mass in recent decades (Diodato et al., 2012; Immerzeel et al., 2009; Menon et al., 2010). However, the UIB observed contrasting signatures of climate variability conditions that include cooling temperatures and stable glaciers (Fowler & Archer, 2006). Subsequently, the Karakoram glaciers, in particular, have experienced stable, and majority of them have advancing features during the period of 2000-2012 (Bolch et al., 2012; Gardelle et al., 2013). In this context, the status of snow cover is unknown and needs to be investigated at each basin level of UIB in detail. This investigation will assist to avoid uncertainties in the current and future management of water resources in downstream population. The decadal comparison between 2000-2009 and 2010-2018 in terms of SCA, temperature, and precipitation is shown in Figure 8. There is a shift in pattern of SCA accumulation (Maximum SCA) from March and April to April and May.

Similarly, there is a change in increasing trend of maximum extent in SCA from September to December (Shifted from October to November and December). This shift pattern depends on the rate of precipitation occurred in the snow accumulated season and the seasonal temperature. For Temperature the variation seems to be minor for both decades, but precipitation shows a great variation because huge amount of precipitation occurred in 2010 which resulted in floods and heavy rainfalls (Hashmi, 2012). This shift of one month in decreasing trend from March to April and May will contribute to decreased in availability of freshwater in downstream resulting in creating problems in management of water. This investigation highlights the importance of study of each glacier and river basin in detail for long term with consideration of regional and global climate patterns to draw accurate conclusions about the trends of SCA change in UIB. Consequently, these conclusions will be helpful to manage water resources or any other SCA related hazardous situation. Further, our investigations and observations validate the reliability of the MODIS products to study snow cover change and its correlations which substantiate observed trends in previous studies.

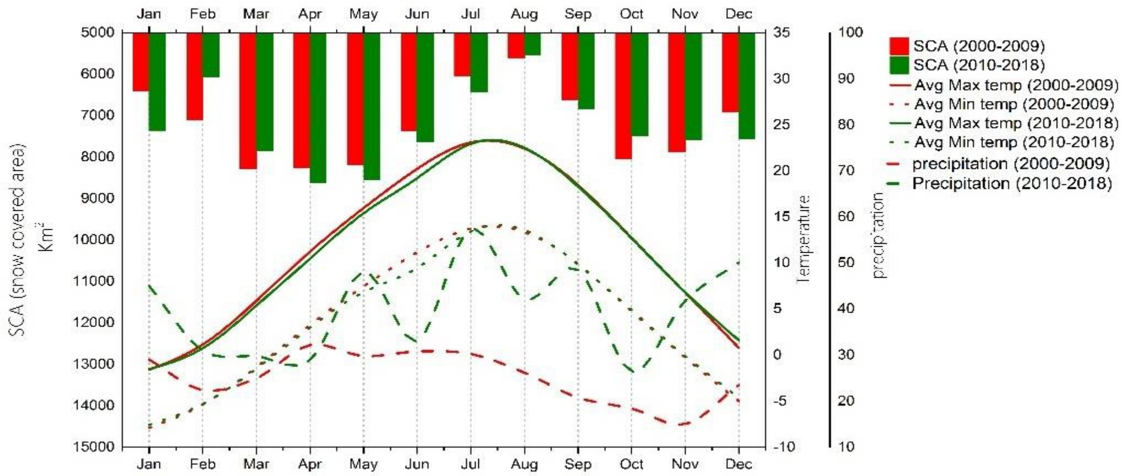

Fig. 8. SCA, along with Climate data (Temperature & Precipitation) for two decades.

7. Conclusion

The Shayok River basin situated in the high elevations of Eastern Karakorum is one of the main basins fed by Indus Rivers of Indus. In this basin Inflow of rivers in subject to the amount of snow and accumulated ice and the energy influx associated to mean temperature. Assessment of snow cover variability over the Shayok river basin was examined using remotely sensed spaceborn data and observations of meteorological, and following statements were drawn:

1. MODIS high-resolution snow mapping products (MOD10A2 & MYD10A2) have provided an excellent opportunity to define details in the spatial and temporal snow cover distribution in the area. It suggests that the use of the MODIS snow products is effective for the mapping of snow cover change. Furthermore, these products are free of cost and easy to treat as our results of correlations of SCA with temperature and precipitation substantiate the observed trends from past studies to assess the SCA in the Shayok river basin.
2. Variable trend of snow-covered area is revealed over the basin based on MODIS snow cover data during 2000–2018. Deviation in snow accumulation and melting is observed in the basin, but mostly maximum snow accumulation has been occurred in spring over two decades. Moreover, there is an indication of slight increasing trend of SCA in 2015 and then a decreasing trend in snow cover; however, to reach a definite conclusion, a longer time series of data needs to be examined.
3. Investigation of annual, monthly, and seasonal snow cover shows that the snow cover change has a highly positive correlation with precipitation and highly negative correlation with temperature; therefore, it is important to achieve accurate climate data to understand snow extend efficiently. Further the climate data estimation methods (e.g., installing more climate data stations) should be upgraded in complex terrains.
4. This study helps to improve the needs stated earlier in (Haq et al., 2016; Hasson et al., 2015; Hasson et al., 2013) which indicated that a comprehensive study should be conducted in high-altitude glacier and snow-fed un-gauged sub-catchments (e.g. Shayok and Shingo) of UIB to understand complex hydrological regime within the UIB.

Acknowledgement

We are thankful to WAPDA for providing climate data and National Snow and Ice Data Center (NSIDC), USA, for providing MODIS datasets.

Author's contribution

Laila and Aftab Ahmed Khan, proposed the main concept, involved in write up, and preparation of figures. Garee Khan, assisted in *data processing, Karamat Ali, collected field data. Syed najam Ul Hassan, helped in review and analysis of data, javed Qureshi and Irfan Ullah Jan have contribute in proof read of the manuscript and technical review before submission.*

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