CORRELATING CLIMATIC SHIFTS WITH SNOW COVER DYNAMICS OF HUNZA AND NAGAR DISTRICTS USING GEOSPATIAL TECHNIQUES

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DEDICATION

We dedicate this thesis to our beloved parents who stood by our side and supported us wholeheartedly

ABSTRACT

Pakistan is contributing to GHG emissions slightly however, under the massive impact of Climate Change. The cryosphere of Pakistan involves Hindukush, Karakoram, and Himalayan (HKH) mountain ranges, the source of water for river Indus and its tributary running towards the lowland rivers. The Snow cover area(SCA) has a paramount significance, any disturbances can lead to disasters and catastrophes. Keeping everything in mind, a study has been conducted to assess SCA of Hunza and Nagar distircts from MODIS snow cover area product and linkage with climatic data including temperature maximum, minimum and rainfall. The results direct a diminishing trend of the SCA of these districts. The annual temperature is increasing by one degree Celsius. The precipitation shows increasing trend over years. Years 2021 and 2022 are under influence of triple-dip La Nina. The correlation analysis of SCA with all parameters displays a positive correlation with rainfall and a negative with temperature. The conclusion drawn from this study shows a rise in temperature leads to the decrease in SCA which can result in flooding risks and water scarcity in low-lying areas.

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ABBERVIATIONS

CS	Coordinate System
DC	Data collection
GHG	Green House Gases
IDW	Inverse Distance Weight
mm	Millimeter
MODIS	Moderate Resolution Imaging Spectroradiometer
NDSI	Normalized Difference Snow Index
SCA	Snow cover area
SPSS	Statistical Package for the Social Sciences
TIFF	Tag Image File Format
UTM	Universal Transverse Mercator
WGS	World Geodetic System

CHAPTER 1

INTRODUCTION

The world is seeing particularly severe impacts of climate change. The melting of glaciers and snow is influenced by shifts in the climate. Global warming is leading to increased heat on the earth and altering the functionality of snow and water systems. In recent decades, the average temperature in the Arctic has increased at a rate that is twice as fast as the global average (Sakai & Fujita, 2017). Strong Arctic warming is further supported by the widespread melting of sea ice, glaciers, and snow cover as well as the rising temperatures of permafrost. An early warning of the environmental and socioeconomic significance of global repercussions is given by these changes in the Arctic (Zhang, et al., 2010). Also, the Arctic has important natural resources like fish, gas, and oil that will be affected by climate change. The rise in global sea levels is attributed to the melting glaciers in the Arctic. Due to continuous increases in the concentrations of greenhouse gases in the Earth's atmosphere, these climatic trends are predicted to accelerate this century. Global effects will follow from these changes in the Arctic (Corell, 2006).

Water supplies from glacial ice and seasonal snowmelt are essential to about 17% of the world's population (Gurung, et al., 2011). Water availability downstream in Asia's major river basins is influenced by the dynamics of the snow cover in the Tibetan Plateau and the High Himalayas, especially during the beginning of the cropping season in the spring, as well as in the fall and following the monsoon season (Barnett, et al., 2005). The duration, number of days per year the snow is on the ground, and the amount of the snow cover has a crucial role in the ecology and hydrology of the environment. It affects the sink potential of many areas as well as greenhouse gas emissions. Even though there have historically been a lot of variations and fluctuations regarding the snow cover changes, there are serious worries that future climate change will lead to a major decline in the amount, quantity, and spatial extent of snow cover.

Through its reflectivity, surface radiation balance, and energy balance, snow cover (SC), which is essential to the cryosphere, significantly affects the local climate. SC has a significant impact on the exchange of energy between the land surface and the atmosphere. Therefore, it is crucial to the regional and global climate systems (Mukhopadhyay & Khan, 2014). The districts of Hunza and Nagar in the Karakoram region are under threat from climate change, just like other mountainous areas of the world. That being said, the effects of climate variability vary amongst the three mountainous areas of northern Pakistan (Shafique, et al., 2018)**.** By the end of the twenty-first century, it is predicted that spring snowfall in the northern hemisphere will be decreased by 7%. In the Greater Himalayas, there are numerous reports of rapidly declining glaciers in addition to declining snowfall. There are also reports of faster glacier retreats in the Hindukush region's eastern region (Zamir & Masood, 2018)**.** Recent research revealed that the mass balance of the glaciers there was either positive or unchanged, especially in the Karakorum mountains. Some of the glaciers in the HKNP region have thickened, according to a study based on fieldwork conducted between 1997 and 2002. As a result, anomalies in the expansion of glaciers and snow cover occur in the Karakoram region, and glaciers retreat at the edges of adjacent regions. To evaluate the effects of climate change on snow covers and glaciers, the area offers a unique observational location (Bibi, et al., 2019)**.**

Approximately 75% of the freshwater on Earth is stored in glaciers, which are a crucial part of the climate system. Nonetheless, because of their closeness to populated areas, mountain glaciers are more significant in terms of usable water (Tahir, et al., 2017). Monitoring the unusual activity of snow and glacier-fed regions helps us track the snow levels and their impact on stream water. This can aid us in improving the management of water resources (Shrestha & Aryal, 2011). Changes in snowfall are primarily influenced by fluctuations in weather conditions such as temperature, precipitation, and rainfall. This is particularly precise in remarkably high mountain ranges. According to Shrestha and Aryal (2011), slight weather changes can have a significant effect on the accumulation and melting of snow in specific regions (Azmat, et al., 2016). The weather has been changing a lot in the last 50 years, with more rain and higher temperatures. This, along with changes in snow cover, has put areas downstream at risk for floods, and not having enough food and water (Maurer, et al., 2003)

1.1 Significance of snow cover

In addition to being a significant source of stream runoff and regulating soil processes, seasonal snow cover affects weather and climate (Easterling, 2011). A few significant consequences of snow cover are widespread; they have an impact on the entire world, specific continents, or significant subcontinents (Hasan, et al., 2012). Mountainous areas depend heavily on snow for a variety of reasons, including the environmental aspects of the native plant and animal life as well as the production of hydropower and water (Wipf, et al., 2009).

Because snow has a higher albedo and a lower thermic conductivity than other materials, it is an essential part of the climate and can control atmospheric and hydraulic processes (Arif, et al., 2023). Snow has a significant role in controlling hydrology because it provides high-altitude basins with ice melt during the summer and acts as a reservoir and source of freshwater (Immerzeel, et al., 2010). The best example of this is found in the Indus Basin, where water is primarily obtained from the seasonal melting of snow following a protracted dry season that lasts from October to March. This is because, during the winter, the Indus Basin receives most of its precipitation in frozen states from the northern Hindukush region (Barnett, et al., 2005). Furthermore, it should be noted that the examination of snow cover is crucial for both seasonal water availability forecasts and for calibrating the distributed hydrological patterns (Fowler & Archer, "Conflicting Signals of Climatic Change in the Upper Indus Basin,", 2006). Together with creating streamflow, snow cover, and glaciers are crucial to the mountainous region's hydropower production, winter tourism, climate, strategic planning, and a host of other economic and leisure endeavors and cooperation on transboundary waterways (Jain, et al., 2009).

1.2 Climate change and snow cover changes

A critical component of the climate system is the amount of snowfall that occurs throughout the year. It is not just an expression of the general circulation in the atmosphere; it also modifies and interacts with air masses above it (Akhtar, et al., 2020). Often, this leads to the amplification and stabilization of circulation anomalies, which in turn bring unusual weather. Understanding the distribution and quantity of snow on the ground is key to advancing weather forecasting and enhancing models for predicting long-term weather patterns. In addition, the presence of snow cover may be a key factor in influencing changes in the climate. Moreover, it could be a crucial element impacting the interaction between the climates of the Earth's northern and southern hemispheres (Rees & Collins, “Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming,”., 2006).

Climate factors that affect snowfall events include air temperature and precipitation, both of which can be affected by climate change (Gurung, et al., 2017). The patterns of snowfall are changing due to climate change, resulting in modifications to the amount of snow cover, its depth, the way it accumulates, and when it starts to melt on the ground (Viste & Sorteberg, 2015). An investigation by Immerzeel et al. (2010) examined how snow and glacier melt contributed to current, and projected climate change scenarios, and concluded that the HKH's glaciers and seasonal snow cover are already being impacted by global warming; the Indus basin's mean upstream water supply has decreased by 8.4%. The mean annual snowfall in the Indus basin is predicted to decrease by 30–50%, between 2071 and 2100, which simulates future climate change scenarios (Immerzeel, et al., 2010). The main sources of precipitation that contribute to groundwater include snowfall, glacier melting, and rainfall (Sakai & Fujita, 2017).

The mountainous regions in Pakistan have also been observed to be rapidly warming up in recent years, which is consistent with unconventional global warming and climate change. This warming has resulted in a significant decrease in the annual mean snowfield area; in the Karakoram region, a reduction in the snowfall of about 16 percent was noted between 1990 and 2002 in the Himalayan region (Paull, et al., 2015). However, it has also been observed in recent years that the snow cover area is increasing. A similar pattern of snow reduction from 2000 to 2008. Similarly, for the years 2000–2010, with certain localized anomalies, an increase in the snow cover area (SCA), suggested a considerable ice cap reduction. With more precipitation and colder temperatures, UIB, in contrast, displays a different aspect of climate variation. The area has been the wettest for the last thousand years, according to precipitation trends based on tree ring observations, which confirm this climatic condition (Dong & Menzel, 2016).

1.3 Snow Cover Changes in Pakistan

Pakistan's economy depends heavily on surface water, and the country's extensive Indus Basin River System provides water that is mostly used for agriculture (Immerzeel, et al., 2013). The northern parts of Pakistan, which make up the upper catchments and are home to three of the biggest mountain ranges in the world, the Himalayan, Karakoram, and Hindu-Kush (HKH), are primarily responsible for the flows in the Indus Basin River System (Bookhagen & Burbank, Towards a complete Himalayan hydrologic budget: the spatiotemporal distribution of snow melt and rainfall and their impact on river discharge.). Pakistan is renowned for having five thousand glaciers, the largest of which is the Siachen Glacier, the second largest in the world (Hall & Riggs, 2007). Freshwater is stored in glacier snow and ice throughout the winter, and when the ice melts in the summer at elevated temperatures, the water is released into rivers. With agriculture accounting for 21% of the country's GDP, Pakistan is more economically dependent on these systems (Rasul, et al., 2011).

For the country's river networks, the snow cover in northern Pakistan is regarded as the water tower. Sea level rise and significant climatic changes are predicted as a result of significant variations in snow cover and the retreat of these regions. Understanding how the snow and ice cover behaves is crucial (Ahmad, et al., 2020). When the snow and ice in the HKH mountain ranges melt, a lot of water goes into the Indus River at Tarbela Dam. Based on past research, areas with a lot of snow above 4,000 meters make up most of the water in the Upper Indus Basin (UIB) (DR Archer., 2003).

Several studies have indicated that the UIB has more ice and snow compared to other icy regions, due to cooler summers and snowier winters. All of the glaciers in the Central Karakoram Range are expanding, according to Hewitt, (2005) (Hewitt, 2005). Numerous climate stations in the Karakoram region demonstrated a declining trend in summer mean air temperature (July–September), which is crucial for glacier melt, between 1961 and 2000. Hussain et al. reported a similar downtrend in temperature during the region's monsoon and pre-monsoon seasons (Fowler & H.J). Tahir, et al., (2011) found that the Hunza River's water flow decreased because the summer temperatures got cooler and the winter rainfall increased, based on a study of snow data from remote sensing. This variation may also have an impact on regional water management for various uses, including drinking, irrigation, and hydropower generation. As a result, in future scenarios with reduced resource availability, unsustainable water use conditions may result (Tahir, et al., 2011).

1.3.1 Contributing factors in changes to snow cover

The two main climate variables that have a significant impact on various physical processes within the hydrological cycle and dynamics of snow cover changes are temperature and precipitation. Thus, assessing the correlation between these variables is crucial to comprehending snow cover behavior in any given area. Temperature and precipitation variations have a major influence on the SCA. Regional dynamics of snow cover are significantly impacted by changes in temperature and precipitation. The unusual behavior of the catchments fed by glaciers and snow (cryosphere) in recent times. To improve water resource management, several researches provide a chance to track variations in the amount of snow cover and how it affects yearly stream flows. In addition to influencing whether precipitation falls as rain or snow and how quickly snow melts on the ground, temperature also has an impact. The total area covered in snow can vary along with temperature and patterns of precipitation.

Several climatic variables, including temperature, wind speed, solar heat, and precipitation influence the development and movement of snow and glaciers (McCarthy, 2001). Over several decades of global warming, variations in the mass of glaciers and the hydrological cycle are linked. Snow cover distribution is influenced by some major factors, including climate change.

1.3.1.1 Precipitation and snow cover changes

The volume, intensity, and form of rainfall are all changing globally. The quantity of precipitation and temperature, which are linked to meteorological conditions, determine snow coverage and continuity (Ansari, et al., 2019). Future water access and management may become more challenging if the area is covered by snow cover shifts, as increased runoff and flooding are expected to occur. Studies on the implications of climate change for snow-impacted hydrologic systems have been conducted since 2001 (Javadinejad, et al., 2020). A significant amount of uncertainty exists in the forecasting of snowmelt runoff due to incomplete data on temporal and spatial variability of rainfall (Boral, 2019).

Two of the world's major precipitation systems, the South Asian monsoon, and the mid-latitude westerlies, primarily feed the mountainous Karakoram region of northern Pakistan. During winter and summer seasons, the high mountains in the area combine with mid-latitude westerly circulations, which are the South Asian monsoon, to ensure substantial rainfall. These circulation systems are critical to the formation of glaciers and the maintenance of permanent snow covers in this area, as several researchers have noted (Athar, 2018). Nearly 60–70% of the region's yearly snowfall is provided by the mid-latitude westerly systems, which have an influence on the region's western and northern ranges, central Karakoram, and the eastern portion of the Hindukush mountains in the winter and spring (Atif, et al., 2018). The remaining 1/3 of the region's snowfall is provided by the South Asian monsoon, which has the greatest effect on the eastern and southern mountains during the summer. The management of water resources downstream is severely impacted by even small variations in the frequency and intensity of these two systems that bring about precipitation (Waqas & Athar, 2019).

In the Hindukush Northern Pakistan region, it was also observed that spring precipitation is declining, and summer and winter precipitation is rising. Inconsistent patterns in the recorded precipitation in the same area from 1967 to 2005 were discovered in another study (Anjum, et al., 2019). While few weather stations in the eastern Hindukush and northwest Karakoram showed an increase in precipitation. No significant changes in precipitation over the entire region from 1980 to 2009 were found (Butt & Iqbal, 2009).

1.3.1.2 Temperature and snow cover changes

A solid grasp of temperature and precipitation patterns is fundamental to climate assessment. As a result, when studying climate, many factors need to be considered. But in climatic research, temperature and precipitation are crucial and multifaceted, especially when it comes to different environmental hazards. With rising temperatures over the past few years, the region has seen an increase in rainfall. Additionally, it was discovered that monthly mean maximum temperature indices showed increasing trends between 2007 and 2011 while the rainfall has been decreased (Afsar, et al., 2013).

The winter precipitation has increased, and the summer mean and minimum temperatures have decreased since the early 1990s, according to analyses. Even though summer precipitation does not regularly increase, the latter is the result of more summer storms, as many locals have reported, in the Hindukush and Karakoram, northern regions of Pakistan. Lower critical temperatures for these high-altitude glaciers are consistent with global warming effects, but rising winter temperatures are not. While temperatures and snow cover are major constraints, solar radiation is the primary cause of ablation. The amount of ice that melts from seasonal snow cover and temperatures above zero determine ablation losses.

A study conducted by Butt & Iqbal, (2009), in Pakistan's districts of Hunza and Nagar, revealed the climatic variability in snow-covered areas. The amount of Northern Pakistan that is covered in snow was estimated using NDSI (Rees, et al., 2005). According to the study, the summer of 2006 saw a rise in temperature over the summer of 2000, while the winter of 2006 saw a decrease over the winter of 2000. This pattern led to the conclusion that, while temperatures decreased from winter 2000 to 2006, they increased from summer 2000 to summer 2006. This pattern demonstrates how crucial a factor in the snow cover area is the daily temperature. Yet, a variety of other factors influence the distribution of snow cover (Dozier, 2006). When we examine the SCA between 2000 and 2006, we find that there was no significant shift in the SCA during these six years. The research also showed that, between 2000 and 2006, summer temperatures rose sharply while winter temperatures fell, a sign of extreme summer and winter weather. Snowmelt in the early spring is a result of rising temperatures, which also alters runoff volume and timing (Nolin & Liang, 2010). Freshwater, the natural system, hydropower production, and agriculture are all impacted by variations in snowmelt patterns. In the winter, as temperatures rise, more rain rather than snow falls. Again, an increase in temperature is linked to the greater amount of snow cover in high-elevation areas relative to low-elevation areas (Brown, 2000).

1.3.1.3 Topography and snow cover changes

Numerous studies that have focused on the impact of elevation have emphasized the importance of topography in the distribution of snow cover (Liu, et al., 2017) One example is when Zheng, et al., (2017) conducted a study in 2017 on the variations in snow coverage at various elevations on the Tibetan Plateau. The study revealed that the majority of the snow accumulation occurs in elevated areas and has a prolonged duration. Jain, et al., (2009) conducted a study that focused on the variations in snow cover across different areas of the Himalayas. It was discovered that snow cover is undergoing varying changes at varying elevations (Jain, et al., 2009). By distributing the incoming solar radiation, local topographic features such as slope, aspect, and elevation have a major impact on the amount of snow cover (Saydi & Ding, 2020). Elevation is the primary factor to be studied due to its critical impact on local microclimates, particularly in mountainous areas. Due to lower temperatures and the tendency for precipitation to increase with elevation, snow accumulation is more common in high mountainous areas (Zheng, et al., 2017)**.**

By varying the amount and duration of sun exposure at a particular place, the aspect and slope of the terrain have an impact on the amount of solar radiation that reaches the surface. Steeper slopes typically have less snow than flatter slopes due to gravity, windward slopes receive more snow than leeward slopes due to the direction of incoming water vapor, and sunward aspects typically have shorter snowfall durations than shaded slopes (Liu, et al., 2015).. To examine the characteristics of snow cover and their variability, topographic influences must therefore be quantitatively considered. Aspect and slope are important topographical features in the area and are strongly associated with the distribution of snow cover, particularly in rocky areas. Due to the stronger sun radiation on the south-facing slope's surface, snow accumulation there was more susceptible to temperature increases than on slopes facing north (Zhou, et al., 2005)**.** However, there are few pertinent studies and little research on the function of slope gradients in the distribution of snow cover. A topographic effect is produced by the relationship between elevation, aspect, and slope. Therefore, a more thorough investigation is required to clarify the relationship between the features of the snow cover and the properties of the terrain (Zhang, et al., 2017)**.**

1.4 Geospatial techniques for snow cover monitoring

Satellite remote sensing is an effective tool for observing remote and inaccessible regions. Recent advancements in technology and the wide array of sensors available have increased the significance of utilizing satellite observations for monitoring snow cover (Winiger, et al., 2005). Multiple methods are employed to map snow cover using different sensor variations. Snow maps can improve snow modeling and enhance the accuracy of predicting the water content in snow. As a result, many studies conducted worldwide have focused on the potential of spatial observation of snow and its role in snowmelt modeling. Numerous research works have examined the possibilities of remote sensing to track snow cover in Pakistan's northern regions (Archer, 2003).

Geospatial techniques have been widely applied to cryosphere changing aspects in mountainous regions worldwide to investigate snow-changing phenomena. The snow product of the MODIS has been validated as a potential tool for modeling snowmelt runoff and snow variation in high-altitude regions (Immerzeel, et al., 2009). The increased spatial resolution of MODIS snow cover maps also makes it possible to observe the effects of vegetation, aspect, elevation, and land use more clearly. Tekeli, et al., (2005), evaluated MODIS snow coverage using ground-based observations and stated that also in a river basin with rough topography, the estimated snow cover was accurate (Tekeli, et al., 2005). Several studies have utilized the MODIS snow product in the snow melt runoff model to predict stream flow in snowmelt-dominated regions with a notable degree of accuracy. The impact of SCA on river runoff in the UIB was exposed by using MODIS, input data of snow cover to the hydrological runoff model, the runoff could be accurately predicted (Sirguey, et al., 2009).

The spatial and temporal arrays can be identify of snow cover over sizable regions of inaccessible terrain by remote sensing, which yields important information about a vital aspect of the hydrological cycle (Adam, et al., 2009). Out of all river basins, the Indus is most reliant on snow and for water resources its ice melt, with substantial portions being covered in snow for extended periods of the year. However, using geospatial techniques in remote sensing, observers have noted an increasing trend from west to east in the snow cover over the years (Kour, et al., 2015). Many researchers have used MODIS data to examine the level of snow covering the ground. The Landsat ETM+, on-site snow measurements, and Google Earth pictures were used to improve the accuracy of the MODIS NDSI value for estimating how much of the ground is covered by snow. MODIS daily (MOD09GA), and (MOD09A1), 8-day products were also used to investigate the variations in snow cover over some time through regression analysis. The MODIS satellite captures images of the Earth from a great distance.- Different hues are employed to depict phenomena such as weather patterns and geographic attributes (Gafurov & Bárdossy, 2009). The snow cover on a map is represented by the MODIS/Terra L3 with temporal resolution of 8-day (MOD10A2) with wavy lines and spatial resolution of 500 meters. This satellite studies cloud images and stores data on the deepest snow cover over 8 days in a specific format, including image details. The MODIS system can help researchers and policymakers better understand how much snow is covering glaciers and affecting rivers. This information can help manage water resources and make future implications regarding snow cover distribution (Dong & Menzel, 2016).

1.5 Review of Literature

Around the world, climate change is having a significant impact on the cryosphere; in the Hindukush, Karakoram, and Himalayan (HKH) regions, in particular, this is endangering the region's water supplies. To address this issue, a study was conducted in District Hunza from 2003 to 2018 by Moazzam, et al., (2023) to extract the snow cover area (SCA) using the upgraded MODIS snow cover product.

The altitude, slope, and aspect of the topographic parameters were correlated with SCA using ASTER GDEM data. The impact of climate change on SCA was investigated by acquiring climatic data from the Climate Research Unit (CRU), average monthly also with yearly rainfall as well as temperature data. Based on monthly and annual SCA trends, the results showed that a declining trend of Hunza district. Average monthly and yearly temperature is increasing at a speed of 0.31 degrees Celsius and 0.10 degrees Celsius, correspondingly, while precipitation is declining at a rate of 2.90 mm/month and 5.73 mm/year (Banerjee, et al., 2021).

Due to changes in precipitation and temperature, SCA has been shown to exhibit high seasonal variability. When it comes to accumulation, the elevation zones 3–5 show the maximum snow cover area, and when it comes to depletion, zones 4 and 5 show the maximum snow cover area. In addition to the slope aspects that face north and northeast, slope zones 3 and 4 have the greatest amounts of snow cover. There has been a strong correlation found between monthly, annual, and seasonal SCA and climatic parameters. This research leads to the conclusion that SCA melting is facilitated by rising temperatures and falling precipitation, which may result in flooding and a shortage of water in areas downstream (Moazzam, et al., 2023).

Data in high-altitude regions are scarce, so there is a great deal of uncertainty regarding the condition and future of Pakistan's Karakoram glaciers. Considering their behavior differs from that of the eastern Himalayas, they are assumed to be less susceptible to climate change. The Hunza River Basin in Karakoram, one of the eight subbasins of the Upper Indus Basin, has a glacial ice area that is subject to decadal temporal changes, which are measured in this study. A relationship between estimated values of precipitation, temperature, runoff, and changes in the glacial ice area has been attempted to be explored (Mazhar, et al., 2021).

It makes use of both field-based and satellite-based methods. Eight glacial ice subregions in the Hunza River Basin have three years' worth of maps showing the hypsometry of glacial ice (2010, 1989, 2002, and 2003). The glacial ice-covered area has decreased, as indicated by the results, by 20.47 percent, with the lowest elevation bands showing the greatest reduction. The reason glacial ice in the Karakoram is behaving differently from the near-global indication of glacial ice changes remains unsolved at this time. Finding explanations for this unusual behavior will require high-altitude climate data (Baig, et al., 2018).

Snow and glacier melting in the mountains are important for the Upper Indus Basin in Gilgit Baltistan, including the districts of Hunza and Nagar. The water system of the Indus Basin relies on the amount of snow-covered land. This is crucial for both hydropower and agriculture in the region (Coles, et al., 2017). Bilal, et al., (2019) utilized a unique instrument to observe the range of snow change in the Gilgit-Baltistan region over the past

18 years. Between 877 and 8564 meters above the sea, five elevation zones were created within the study area. SCA in the UIB is marginally rising, in contrast to research on cryosphere, worldwide. Additionally, each elevation zone's SCA is slightly increasing, according to elevation-based SCA analysis. Nonetheless, regions above 5000 m ASL contain a substantial concentration of snow (Jin, et al., 2019). The strong connection among SCA and rain, the data of rain shows a similar pattern. - The sun has been shining increasingly with each passing month, causing a slight decrease in the average temperature and an increase in rainfall and humidity. This is the conclusion drawn from analyzing the climate data. The small rise in SCA in the study area is mainly because of these patterns, as well as the increase in global rainfall, winter winds from the west, and precipitation caused by mountains. Despite the limited observation time, the findings expanded the understanding of escalating snow and the glaciers in the Hindukush Karakoram (Bilal, et al., 2019).

The Indus River gets most of its water from the melting snow and ice from the mountains in China, India, and Pakistan. People residing in the Indus Plain rely heavily on this water source for their everyday needs. They require it for irrigating their fields, for drinking purposes, and for generating electricity (Forsythe, et al., 2012). It is substantial to monitor the amount of water that is flowing in the river. Hussain, et al., (2019), Hussain and his team studied how the ice and snow in the northwest part of the Upper Indus Basin, also called the Gilgit Basin, affects the amount of water flowing in the river. A special camera known as a moderate-resolution imaging spectroradiometer was provided with the eight-day snow data from 2001 to 2015, which was used to study the SCA in the catchment.

From 1995 to 2013, the data from ground stations was analyzed to see how air temperature and rainfall change each year and with the different seasons. The amount of snow and ice stayed about the same throughout the year, but in the fall, there was less snow and ice. The average temperature and rainfall were going up, with the highest increase being 0.05 degrees Celsius per year and 14.98 millimeters per year (Young & Hewitt, 2008). Additionally, for the hydro-meteorological data we computed the Pearson correlation coefficients to determine any potential relationships. The average temperature and the amount of water running off were strongly related negatively. The connection between SCA and precipitation data was not strong. The Gilgit River flow mostly comes from melted snow instead of rain. The SCA went down a little during the study, which shows that global warming may have affected the mountainous area (Hussain, et al., 2019).

The snow in the Hunza River Basin is crucial for the people living downstream as it supplies them with clean water. The changing weather has a big effect on the ice and snow. These glaciers can cause floods and sudden movements of ice and water due to changes in the weather. This can affect people who live downstream. It is essential to monitor these glaciers and snow masses. This study provides a method for studying certain glaciers in the Hunza River area (Hakeem, et al., 2014). Research by Ali, et al., (2021) utilized various technologies including Landsat, digital maps, and remote sensing to gather information. A total of 27 glaciers were identified in HRB from 1990 to 2018. On the other hand, there was a big decrease in glacier size from 1994 to 1999, with about 3.126 square kilometers lost each year on average (Baig, et al., 2018). The glaciers in HRB were not changing as much as the glaciers in the Hindukush, Himalayan, and Tibetan Plateau regions. Glaciers on steep slopes were melting faster than those on gentle slopes, and glaciers below 5000 meters above sea level were also changing a lot. HRB has experienced a cooling trend and higher precipitation from 1995 to 2018. The glaciers experienced significant growth between 2009 and 2015 due to increased snowfall in the winter and autumn. Glacial ice at extreme elevations and latitudes experienced significant transformation due to climate change from 1990 to 2018. The glacier experienced increased melting due to rising summer temperatures, but it could also be expanding during the winter and fall as a result of greater snowfall and rainfall (Ali, et al., 2021).

The Himalayan, Karakoram, and Hindu-Kush mountain ranges (HKH) are thought to be losing snow and glaciers. Because of this, the accessibility of water for people living downstream is seriously affected. Arif, et al., (2021) found that the tendency of the snow cover in Gilgit Baltistan (GB), northern Pakistan, varied over time in 2021 (Robinson & Frei, 2000). MODIS images for the years 2000 to 2020 were used to calculate the Normalized Difference Snow Index (NDSI) and estimate the snow-covered area (SCA). The main sub-basins of Gilgit Baltistan (GB) are Hunza, Astore, Sakardu, Shigar, Gilgit, Diamir, Shyok, and Ghanche. The majority of the glaciers in GB are found in Hunza and

Skardu. Within GB, there was an annual variation in snow cover of 10 to 80 percent. Almost eighty percent of the area was covered in snow during the accumulation season, which runs from December to February, and sixty to seventy-five percent during the melting season, which runs from July to September. In 2009, there were approximately 57687.85 km2 of maximum and 12083.40 km2 of minimum SCA detected. The findings indicate that the Snow Cover Area has slightly fluctuated over time. The snow fluctuation is depicted by the Mann-Kendall trend. However, Mann Kendell observed a negative trend for glacier peaks but a positive trend for glacier surges. (Arif, et al., 2021).

1.6 Problem Statement

For a considerable amount of time, Pakistan's glaciers have been retreating and losing snow mass, but after 1990, they began to accelerate slightly. Over the past few years there have been balanced budgets in the Karakoram glacial ranges, the snow cover area, which was decreasing previously has been increasing, and glaciers are melting due to global warming and also climate change, which have displayed some irregularity (anomalies) for a considerable amount of time (Gardelle, et al., 2012).

The literature states that the peak snow cover in the Hunza sub-basin is typically observed in December and January. The variation in snow cover ranges from 40 to 50 percent. The minimum snow cover period is from 2008 to 2012, and the maximum snow cover period is from 2009 to 2018 (Arif, et al., 2023). Due to rising summer temperatures, the melting period lasts from March to late August. The months of December and January are known to have the highest snowfall in the Nagar sub-basin. The range of snow cover variability is 40–80%. The lowest period of snow cover is from 2007 to 2016, while the maximum periods are from 2009 to 2018. Because of the rising summer temperatures, the melting period lasts from March to August (Karl, et al., 2010). Given the correlation between the snow covers and the expected mass runoff of collected snow, it is expected that the basins at high-elevation will have less snow cover area at higher slopes. In contrast, because a larger portion of these glaciers extend to warm mountain regions, less snow cover is assumed at lower inclinations in the snow-fed basins. Because of the region's conflicting nature, and the climate change shifts, snow covers are difficult to evaluate. In the Upper Indus Basin, the evaluation of the snow cover has become challenging at both the native and sub-basin levels due to the absence of minimum-distance high-elevation meteorological stations. Any assessment of the snowfall regions is impossible due to the harsh and severe climate and topography of the Hindukush, Karakoram, and Himalayas (Bhambri, et al., 2013).

Furthermore, due to the ever-changing nature of snow, proper spatial-temporal resolution is necessary for both evaluation and mapping. Snow mapping is now possible even in remote areas, by utilizing data geospatial tools, from combined Remote Sensing (RS) and GIS (Geographical Information System) techniques. For assessing snow caps in difficult-to-reach places, satellite remote sensing has proven to be the most effective approach. (König, et al., 2001). Therefore, the goal of the present study is to correlate the climatic shifts with the snow cover distribution and to see the trends of snow melting, in the districts of Hunza and Nagar, Northern Pakistan using geospatial techniques.

1.6.1 Research Objectives

This study aims to assess the dynamic of snow covers in the districts of Hunza and Nagar, Northern Pakistan, and its connection with the climatic parameters by means of satellite products.

1 Assessment of Hunza and Nagar District's snow cover area trends over the past two decades.

2 Investigating the climatic parameters that are strongly correlated with the snow cover area trends.

CHAPTER 2

METHODOLOGY

2.1 Study area

Both the districts Hunza and Nagar lies between the geographical location 36˚51' 38.359" N, to 35˚55' 22.231" N and 76˚0' 45.354" E to 73˚59' 26.466" E, with average height of about 3000m. The approximate total area covered by these districts is 14305.07 km (Abbas, 2016).

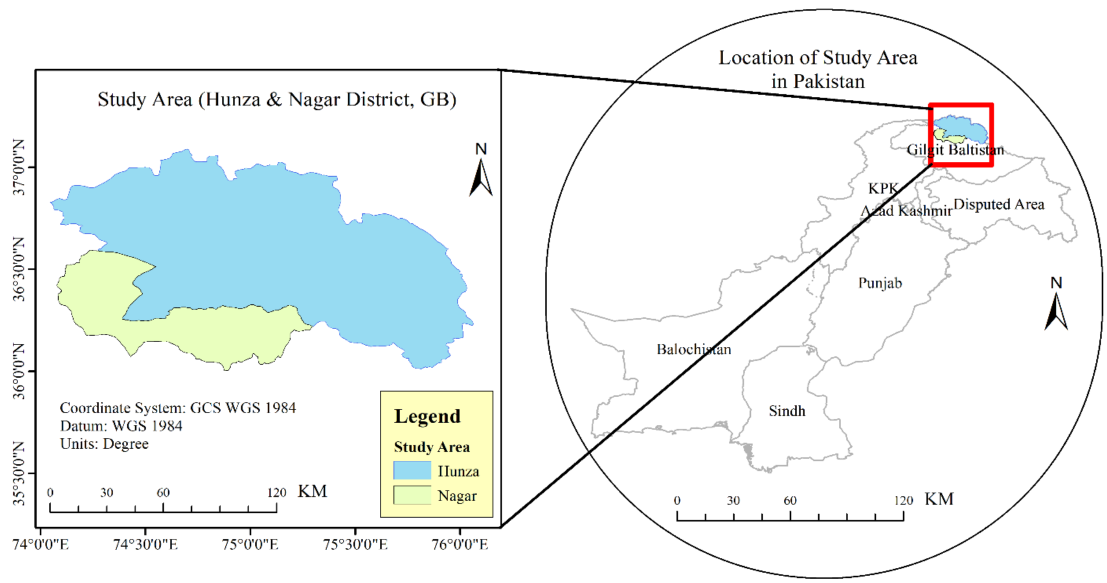

Figure 2.1 Study area map

The topography of Hunza and Nagar districts is rugged and harsh. This uneven landscape is covered with rocks and trees having mountains abundant heterogeneous peaks, valleys and deep ravines, giving panoramic sights of natural beauty. The glaciers, lakes and streams in this region are the source of fresh water to low-lying Indus plain areas.

Most of the glaciers in this area are the main source of water, feeding the Hunza Nagar River. Climate with mean minimum 16 °C and maximum 36.5 °C temperatures (Shafique, et al., 2018). The yearly average rainfall in the month of November is 2.1 mm minimum and maximum in April about 28.3mm, overall yearly is 136.2mm (Afsar, et al., 2013).

2.2 Data collection

Spatial data was collected of Hunza Nagar Districts, Gilgit Baltistan of over a period of 18 years (2006-2022). Data was obtained from the years 2006, 2011, 2016, 2021, 2022. High resolution imagery data files were downloaded from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite for analysis and representation of snow cover.

Table 2.2 Chronological log of data collection (DC) events through MODIS satellite

Sr.no	Year	Months of DC	Satellite	Product	Spatial Resolution	Temporal Resolution	Rainfall(mm) Temperature(°C)
1.	2006	January-December	MODIS	MOD09A1	500*500m	8 days	Nasa Power
2.	2011	January-December	MODIS	MOD09A1	500*500m	8 days	Nasa Power
3.	2016	January-December	MODIS	MOD09A1	500*500m	8 days	Nasa Power
4.	2021	January-December	MODIS	MOD09A1	500*500m	8 days	Nasa Power
5.	2022	January-December	MODIS	MOD09A1	500*500m	8 days	Nasa Power

2.3. Downloading the data files

Quantitative analysis was employed to analyze data for Hunza and Nagar, which was acquired from MODIS AρρEEARS. MODIS AρρEEARS is an application helps to access the data and transform it in required form efficiently.

2.3.1 Extracting the Shape file

To extract the shape file, the Arcmap 10.4.1 was used. Using the Pakistan map file, the specific area of interest was marked on the "attribute table of that file". After extracting the required area, both the districts were merged. The shape file was ready and stored in the required drive, this shape file will be uploaded in Modis AρρEEARS application to get the data files.

2.3.2 Uploading shape file to download data files

The shape file for the study area was then uploaded on Modis AρρEEARS under the option "Extract" then "Area". After completing this step another screen will appear. Upload the shape file, enter "start and end date" of the data required according to the need. Select the layers to be included in area for snow cover, layers of band 4 and 6 are requisite. File format is "GeoTiff" and projection is "Geographic". Request is submitted to AρρEEARS to get the access to data files. The downloaded was saved to a designated folder on the computer, on a local disk such as D or E preferably. Images of band 4 and 6 were downloaded. The spatial resolution of images is 500*500m and the temporal resolution is 8 days, after every 8 days this satellite captures images.

2.4 Calculating NDSI

The Normalized Difference Snow Index was calculated to find out the extent of snow cover area. This calculation involves, subtracting band 4 that is green spectral band and band 6 was shortwave infrared then dividing the result by the sum of both bands. This calculation was executed in Arcmap, using "raster calculator". This procedure was applied to all the Images with temporal resolution of 8 days of every month, across each year.

Formula:

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

$$\mathbf{NDSI} = \frac{\mathbf{Band4} - \mathbf{Band6}}{\mathbf{Band4} + \mathbf{Band6}}$$

2.4.1 Arithmetic Monthly mean of NDSI

The monthly average of NDSI was computed by summing the daily values. Each month contains four images. The NDSI was aggregated by adding and then divided by the total number of days of that month. This arithmetic mean of each month, across every year was calculated by using the "raster calculator" in Arcmap.

2.5 Vectorization

The monthly mean of NDSI is stored in raster form. To extract the snow cover area, data was converted from raster to vector data in the form of polygons. In Arcmap, start with search "raster to polygons" a small screen will appear. Now proceed to convert files of monthly mean of each month individually.

2.5.1 Calculation of area of polygons

Right-click on the monthly mean polygon file then navigate to "Attribute table". On attribute table highlight the Grid code that represents snow area. In this case, grid code of value 1. Now export this data to create a separate file. Further steps will be applied on this exported data.

To identify snow cover area, area of polygon is determined. Initially to determine area, Coordinate system was changed by selecting "Layers". Right-click then navigate to "Properties", and select "CS". In the CS, opt for "Projected Coordinate System". A list of projections will appear, where selected "UTM". From there, select the option "WGS 1984", then click on "Northern hemisphere", and finally, click on "UTM Zone 43N".

These steps will facilitate to calculate the snow cover area. Now Right-click on any monthly file. Open attribute table, add field named "Area_sqkm". Then right-click on this field, opt for "Calculate Geometry", then choose units "sqkm", press OK. Area for each month is calculated. Right-click on field named "area_sqkm", click on statistics. Sum area of polygons will appear. Transfer area of every month of each year into excel file.

2.6 Downloading climatic data

Climatic data such as Rainfall(mm), Temperature maximum and minimum(**°C)** was downloaded from Nasa Power. The first step is to note 6 different latitudes and longitudes from the study area. This step contributes to get data more precisely. Later, average of these six different locations was taken. Nasa Power provides meteorological data used in climatic researches. These satellites are sufficiently providing accurate and reliable data.

Metrological data with temporal resolution of one-month was collected for 2006-2022 years. The csv files of this data was downloaded. Data was obtained using this link https://power.larc.nasa.gov/data/.

2.7 Inverse distance weight (IDW) mapping

Inverse distance weight interpolation was used to estimate the unidentified values of climatic data for the study area. To perform this step, click on search bar then type "IDW". Now, click on IDW spatial analyst. A small tab will appear. Enter the csv file containing all the six latitude and longitude coordinates, climatic data of all these coordinates (precipitation, wind speed, temperature maximum and minimum) in the "input point features". Then select every climatic parameter one by one in "Z value field". Now, opt for "Environments", set the "Processing extent" to study area and then mask "raster analysis" to study area. This will create the maps of each parameters indicating areas will the high to low values of each parameter. The color differences will indicate the values variation. IDW maps are shown in Appendix C.

2.8 Correlation Analysis

The correlation analysis is primarily done to associate the association between variables. Correlation analysis was completed using Statistical Package for the Social Sciences software (SPSS). On SPSS software window, click Analyze present on the main menu. Then opt for, "Correlate" then "Bivariate". As this analysis involves more than one variable. A small tab will appear from there select the variables that are snow cover area and all the climatic parameters. Select "Pearson coefficient" and "Two-tailed" test of significance. Click "ok". The results will appear.

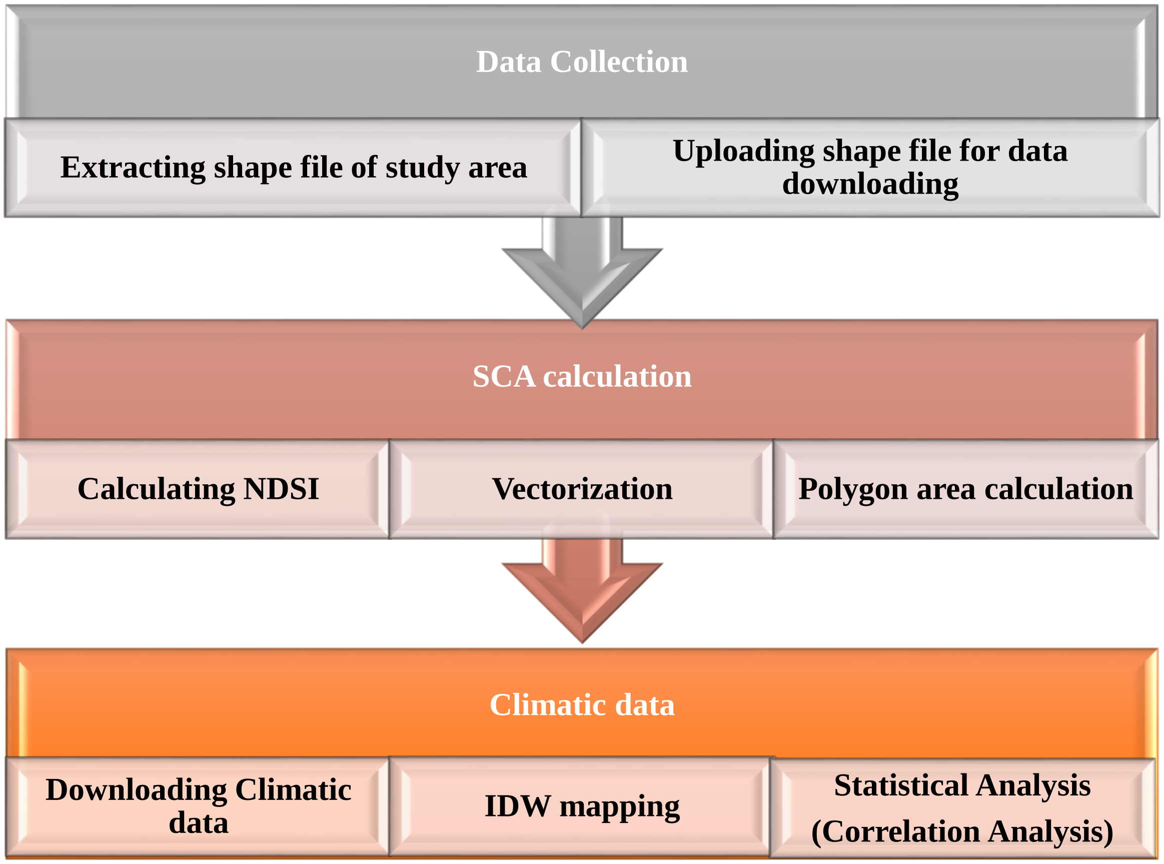

Figure 2.2 Methodology flow diagram

CHAPTER 3

RESULTS AND DISCUSSIONS

The snow cover area of both districts was calculated and climatic data was downloaded to understand snow cover trends. The final product provides an overview of the snow cover area of Hunza and Nagar from years 2006, 2011, 2016, 2021 and 2022. The snow cover area of each year is calculated using basic geometry and statistics tools of Arcmap 10.4.1 software and have been graphically represented. The climatic data was compared with snow cover area using Correlation Analysis on SPSS software.

The data was accumulated from 2006-2021,2022 and after accumulated from year 2022 to check if any changes are occurring after a year.

3.1 Year 2006

The year 2006, as seen through the satellite imagery had a total yearly snow cover area of 9217.13km^2. This year will be compared with the subsequent years to identify the parameters and snow cover variations up to 2022.

Snow cover area is compared with all the climatic parameters one by one with the help of line graphs.

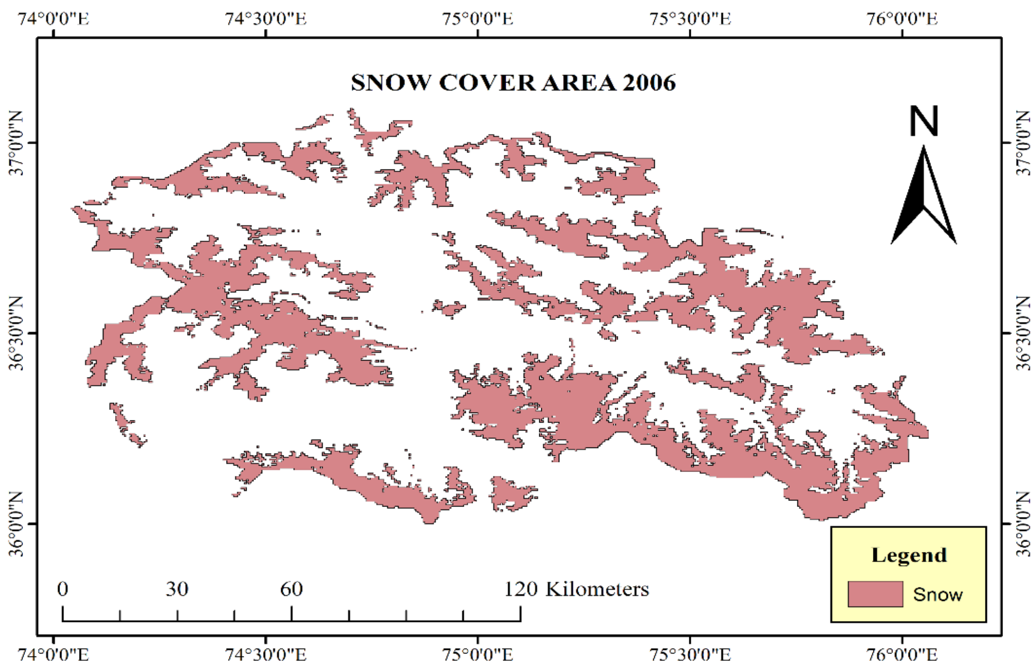

Figure 3.1(a) Study area snow cover map 2006

3.1.1 Results of 2006

In 2006, the month receiving most of the rainfall are January, August, November and December as shown in the figure 3.1(a). March to August are considered snow melting month. This study area snow cover is declining from may until September. The minimum temperature recorded this year is -32 °C and maximum temperature is 16 °C, respectively (fig 3.1c).

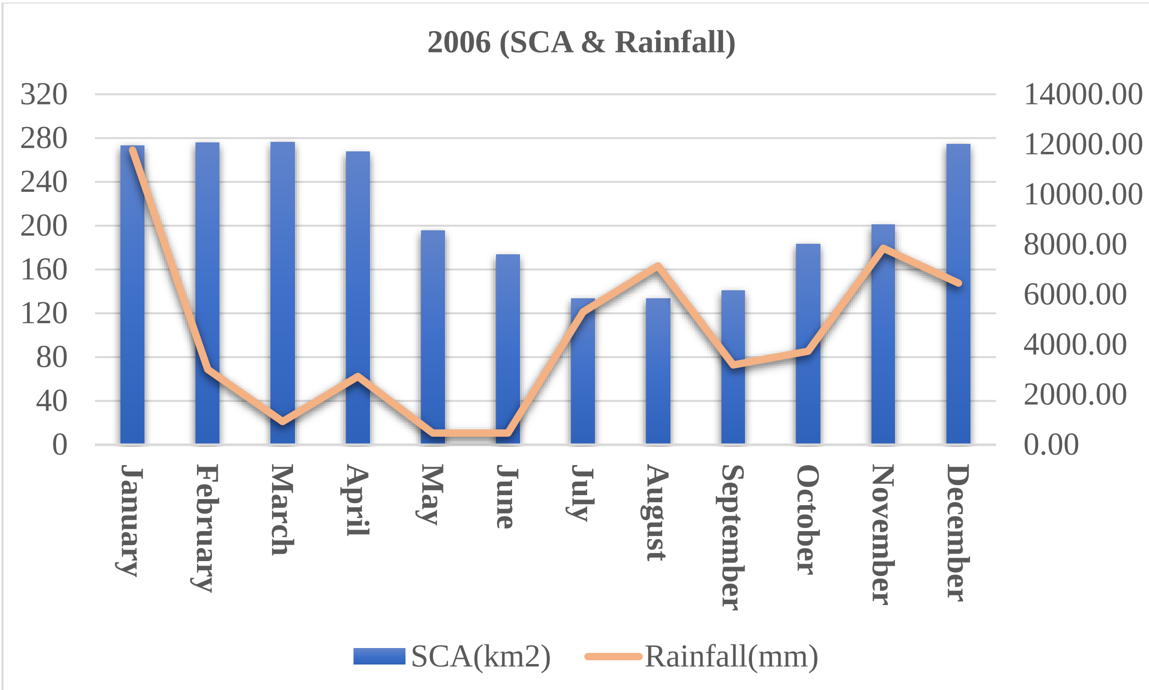

Figure 3.1(b) 2006 SCA and Rainfall

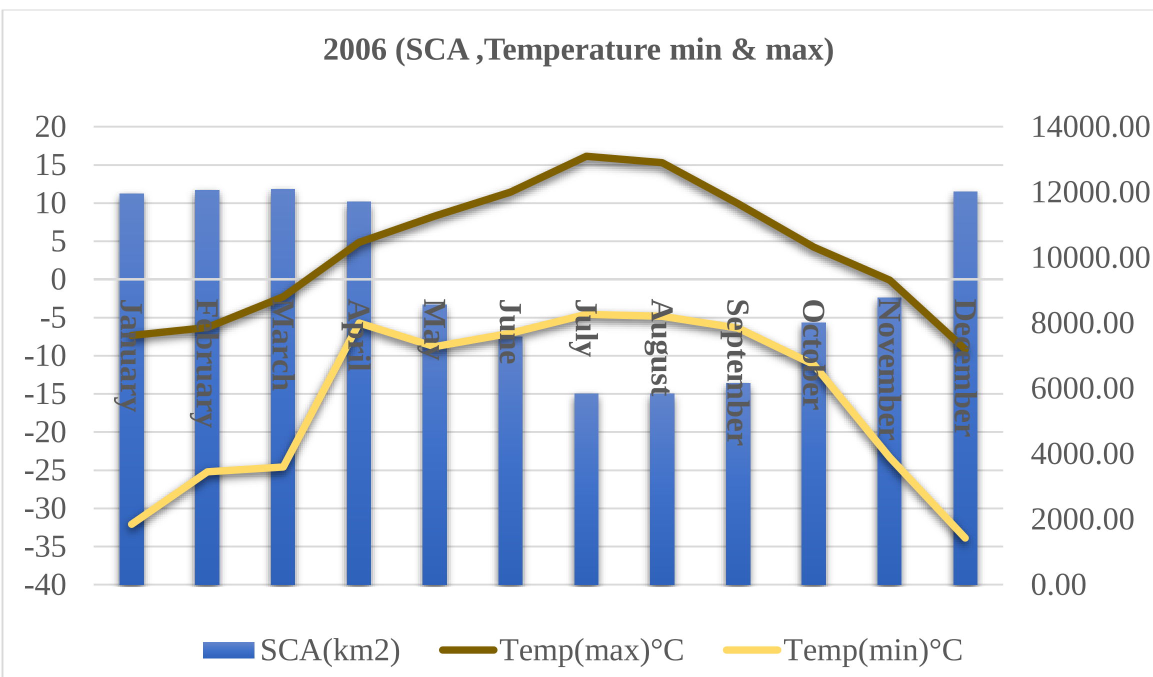

Figure 3.1(c) 2006 SCA, Temperature minimum and maximum

3.2 Year 2011

In 2011, significant changes in snow cover area and rainfall were perceived. This year demonstrates that rainfall has decreased so does the snow cover area. Snow cover has decreased more in 2011 during melting months than 2006.

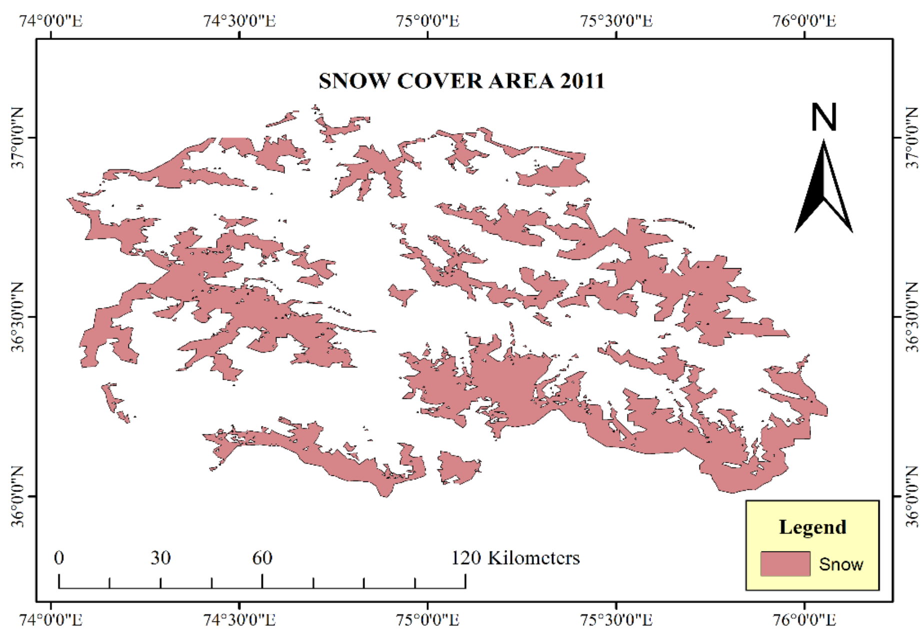

Figure 3.2(a) Study area snow cover map 2011

3.2.1 Results of 2011

The annual rainfall received was 746.28mm, which is relatively very low than rainfall (1211mm) in 2006. Snow cover area reduced to 8985.85km^2 this year. No such changes in the temperature maximum. The minimum temperature was increased to -29.35 °C.

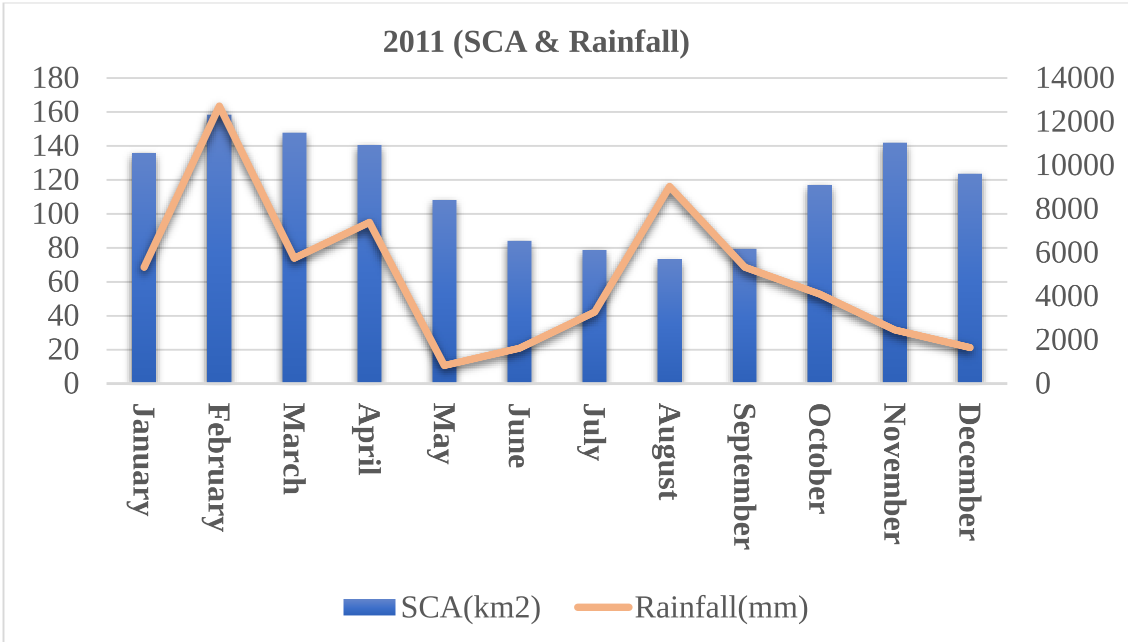

Figure 3.2(b) 2011 SCA and Rainfall

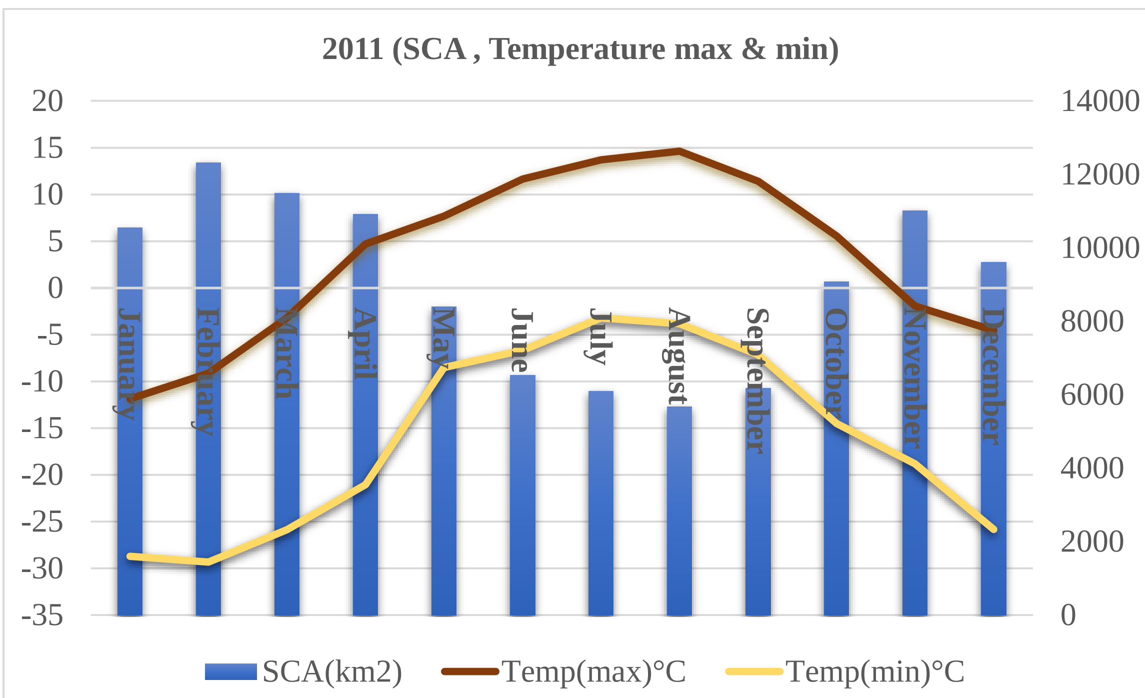

Figure 3.2(c) 2011 SCA, Temperature minimum and maximum

3.3 Year 2016

In 2006, the snow cover area decreased in melting months than of years 2006 and 2011. An increase in maximum temperature was noted in June and July.

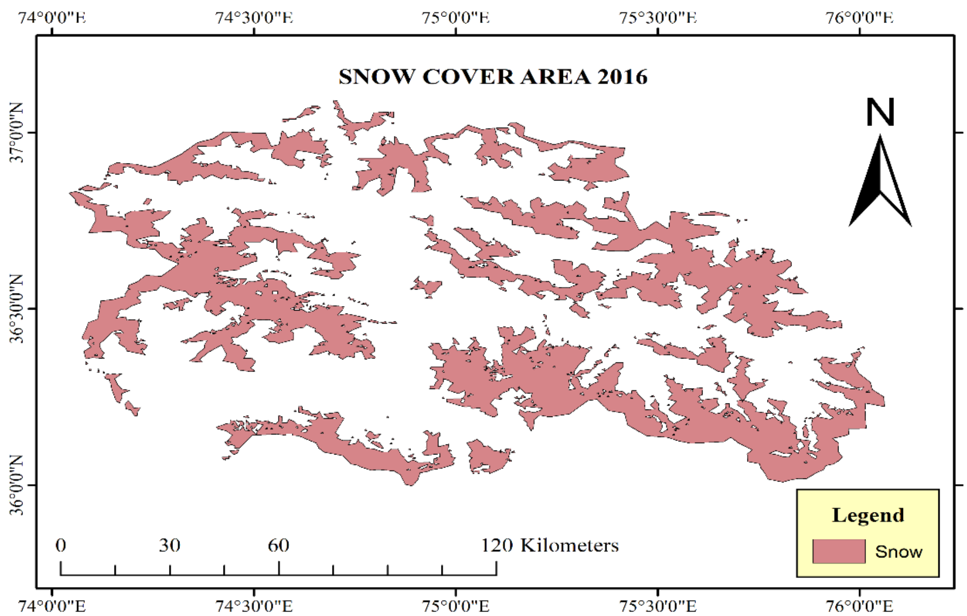

Figure 3.3(a) Study area snow cover map 2016

3.3.1 Results of 2016

The annual rainfall received was 1283.69mm, which is relatively higher than last two years. The maximum temperature of 17.16 °C was recorded in month of July. As rainfall was increasing, on the other hand snow cover area decreased.

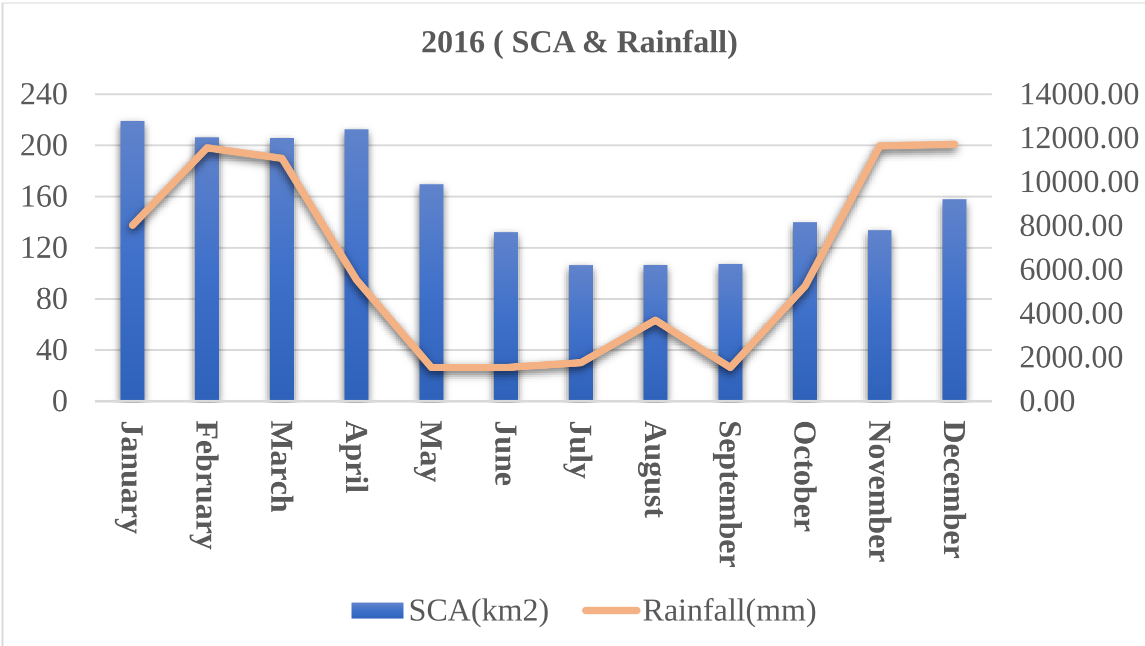

Figure 3.3(b) 2016 SCA and Rainfall

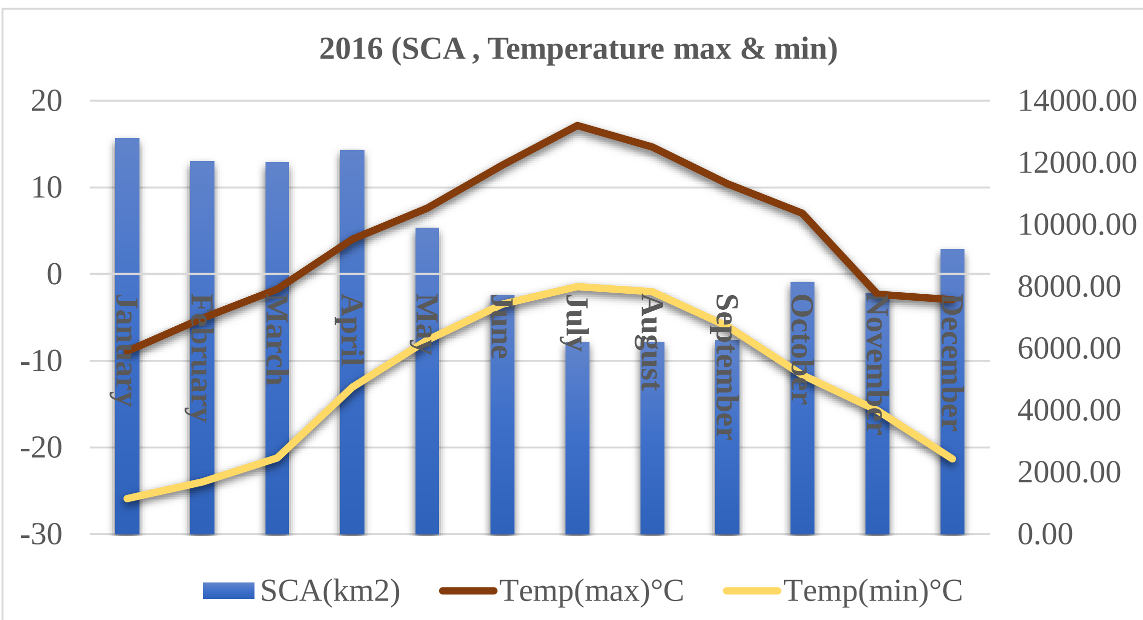

Figure 3.3(c) 2016 SCA, Temperature minimum and maximum

3.4 Year 2021

This year shows the notable increase in the annual snow cover area compared to previous years. Concurrently, the amount of rainfall received is increasing, indicating climatic conditions are changing. Additionally, the maximum temperature is the same as previous year 2016.

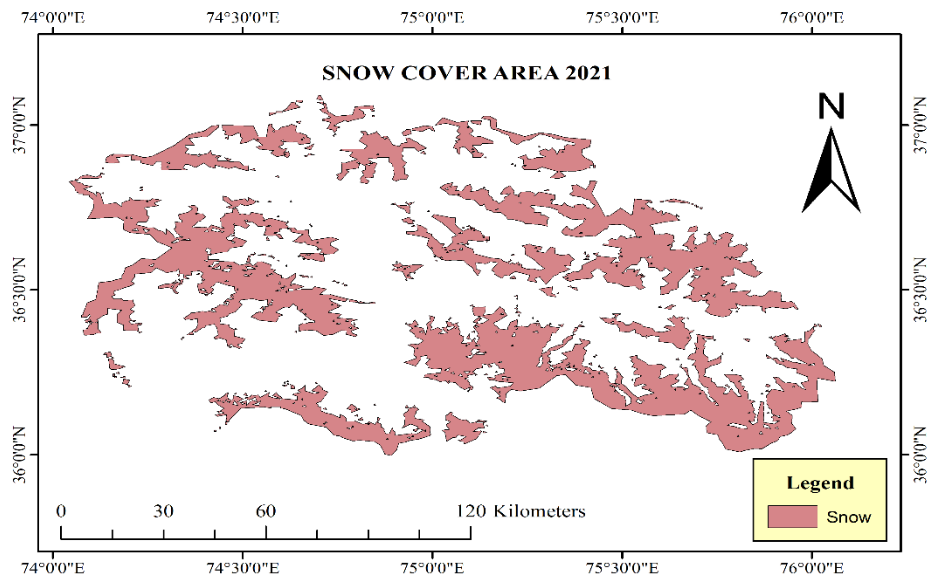

Figure 3.4(a) Study area snow cover map 2021

3.4.1 Results of 2021

As maximum temperature is rising during summer months, a substantial decrease in snow cover area was observed. Notable increase in rainfall has been observed during April, May, June and July. underscoring the weather patterns dynamics. In year 2016, the rise in temperature has showed no changes in rainfall. However, this year, showed an increase in rainfall while the temperature not varying.

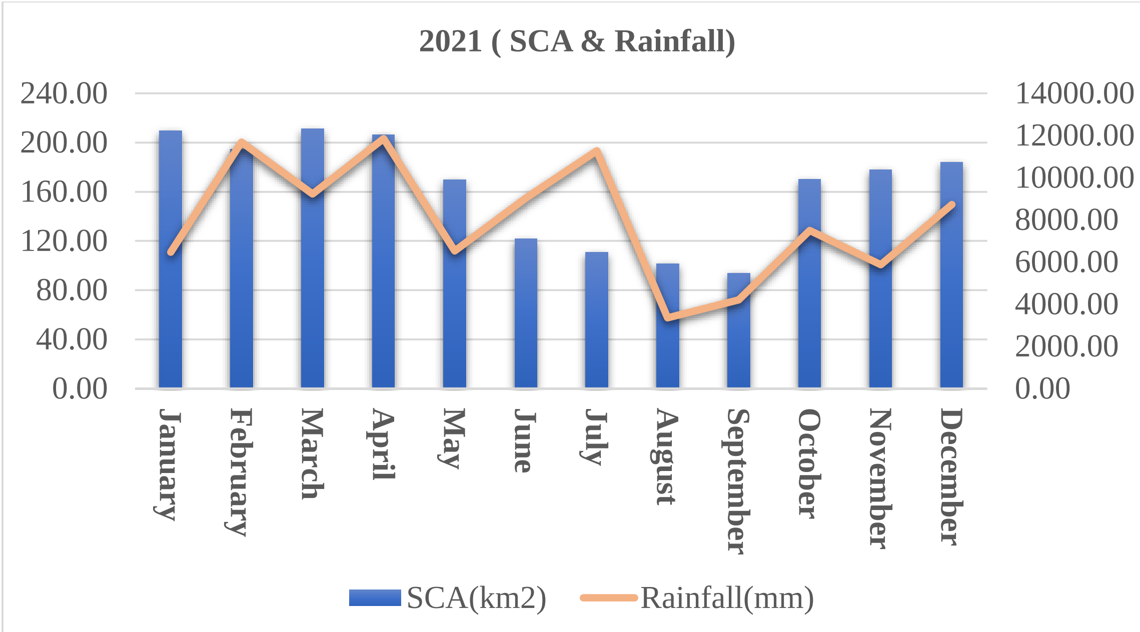

Figure 3.4(b) 2021 SCA and Rainfall

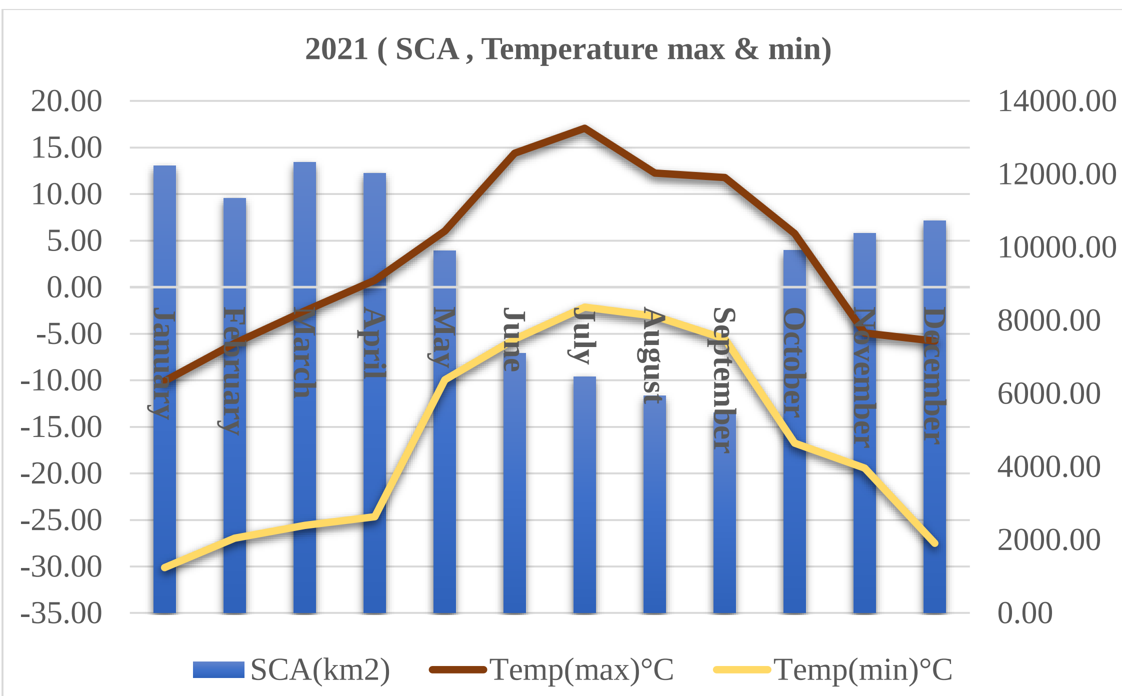

Figure 3.4(c) 2021 SCA, Temperature minimum and maximum

3.5 Year 2022

Years following 2016 showing snow cover anomalies, a sudden increase in rainfall leading to snow cover area increase, showing fluctuations in snow cover at different times.

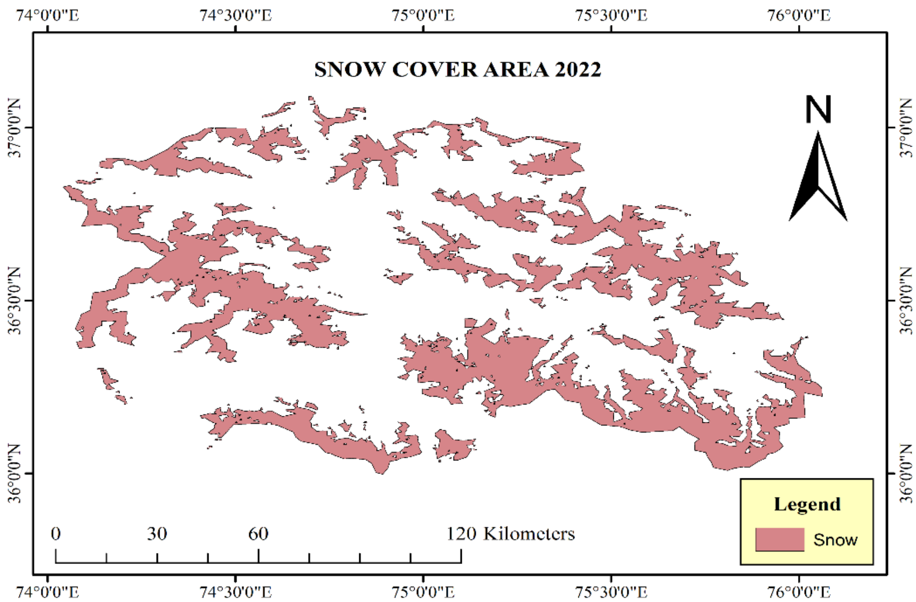

Figure 3.5(a) Study area snow cover map 2022

3.5.1 Results of 2022

The rainfall in years 2021 and 2022 during summer months has shown substantial increase than the preceding years. In comparison with 2021, this year has experienced a decrease snow cover area. There a minor increase in overall temperature.

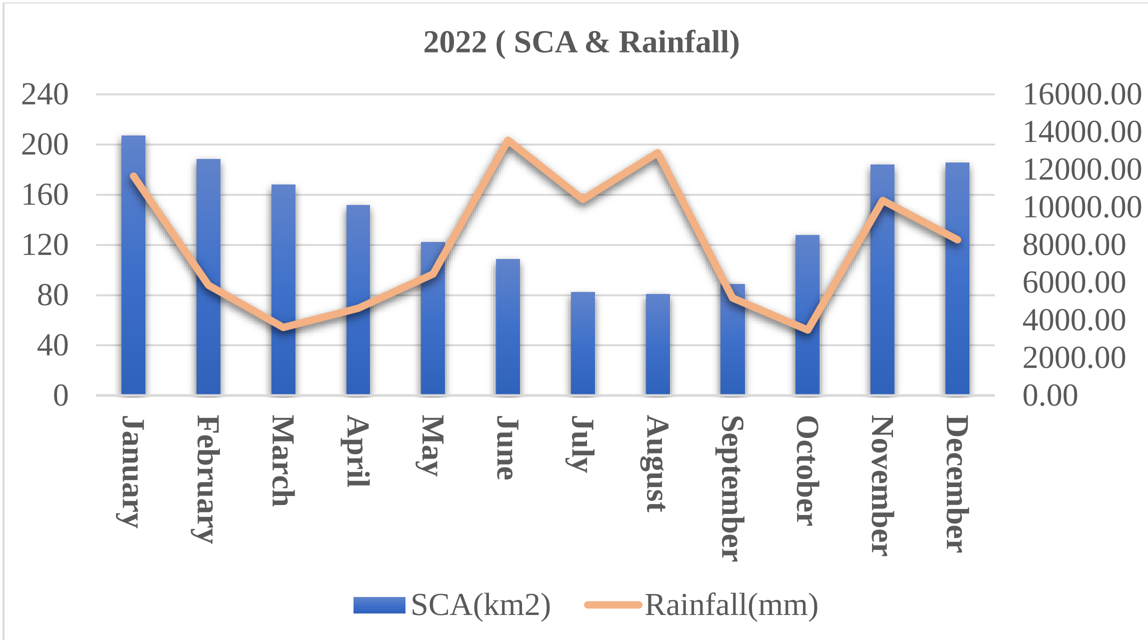

Figure 3.5(b) 2022 SCA and Rainfall

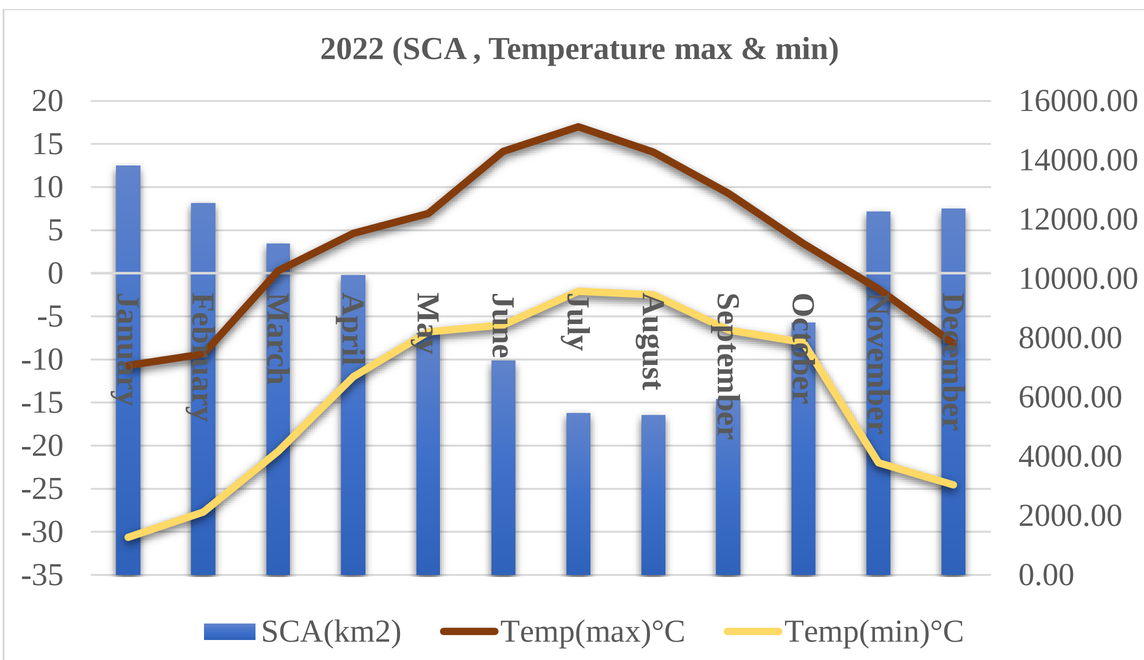

Figure 3.5(c) 2022 SCA, Temperature minimum and maximum

3.6 Rainfall trends over years

To comprehend the rainfall trend, the linear slope-intercept of a linear equation is used.

$$\mathbf{Y = mx + c}$$

"Y" indicates the dependent variable that is Rainfall, "x" indicates the independent variable that is perhaps months and years.

"m" is the slope line, indicating rainfall changes. "c" is y-intercept showing the initial value of rainfall at the beginning point.

The positive value of m, indicates the positive correlation. The slope value shows the rain is increasing over these decades.

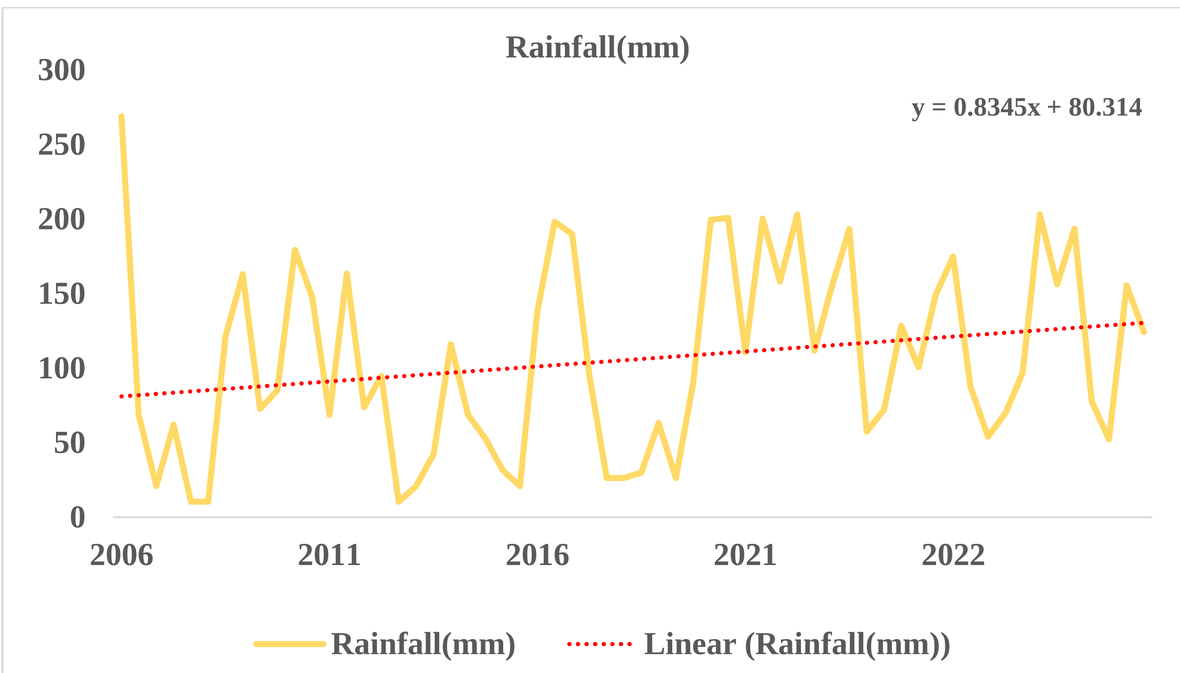

Figure 3.6 Rainfall trends

3.7 Temperature Maximum trends over years

To comprehend the temperature maximum trend, the linear slope-intercept of a linear equation is employed.

$$Y = mx + c$$

“Y” indicates the dependent variable which is Temperature maximum, “x” indicates the independent variable that is perhaps months and years.

“m” is the slope line, indicating temperature maximum changes. “c” is y-intercept showing the initial value of temperature maximum at the beginning point.

The positive value of m, indicates the positive correlation. The slope value shows the increasing over these decades.

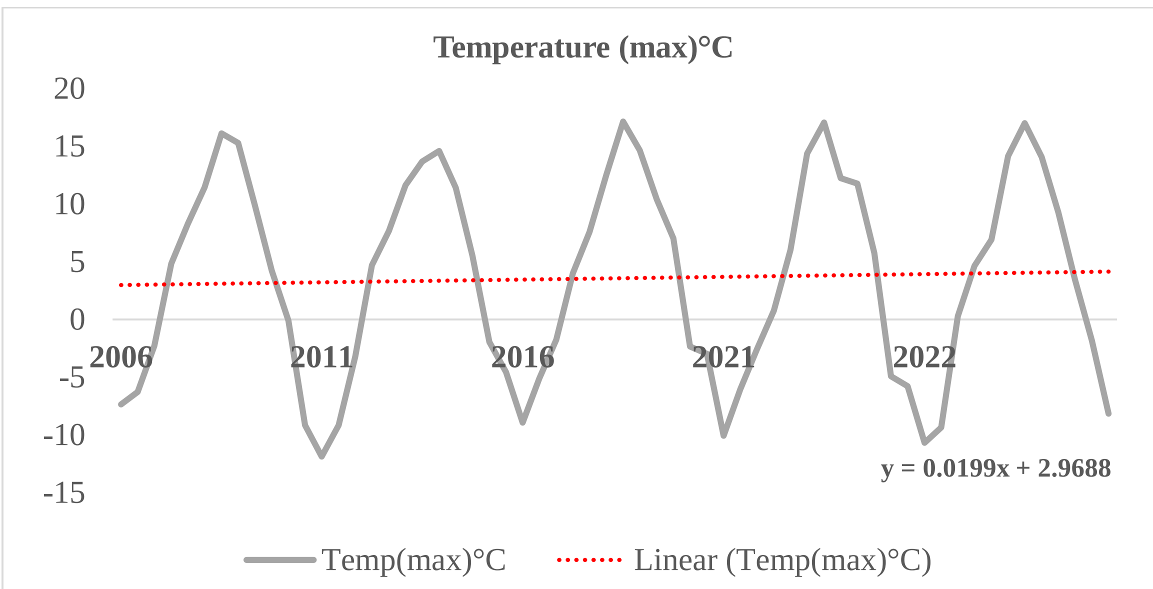

Figure 3.7 Temperature Maximum trends

3.8 Temperature Minimum trends over years

This climatic parameter is understood utilizing the same slope-intercept of a linear equation.

$$Y = mx + c$$

"Y" indicates the dependent variable which is Temperature minimum, "x" indicates the independent variable that is perhaps months and years.

"m" is the slope line, indicating temperature minimum changes. "c" is y-intercept showing the initial value of temperature minimum at the beginning point.

The positive value of m, indicates the positive correlation. The slope value shows the increasing over these years this indicates increasing value of temperature minimum.

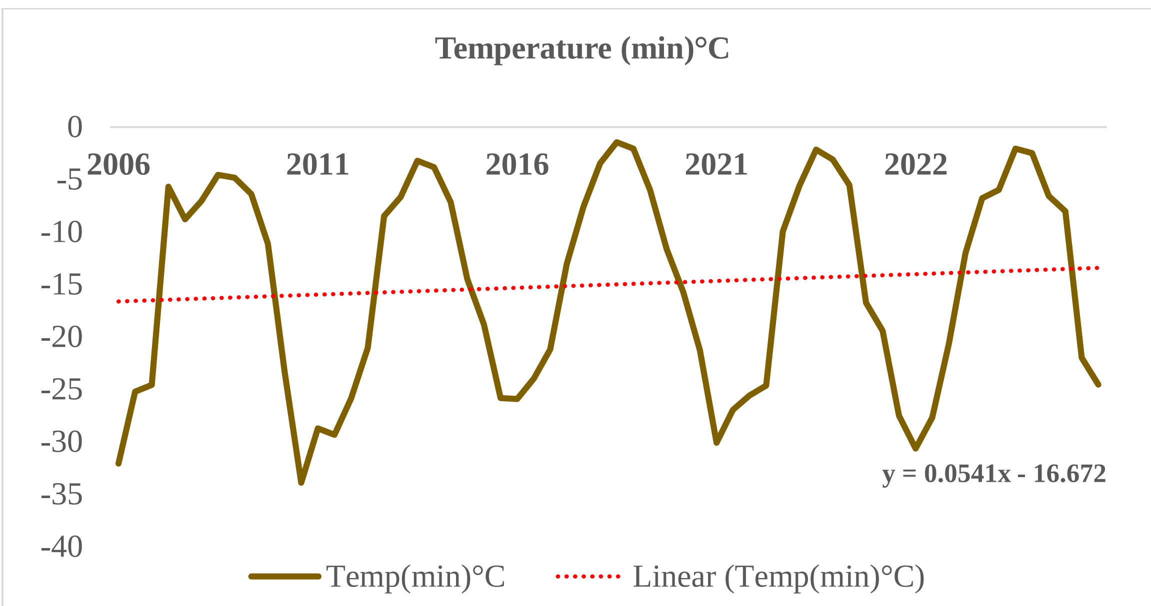

Figure 3.8 Temperature Minimum trends

3.9 Snow cover area changes over years

To identify the changes of snow cover area over the years, each year is divided into snow falling months and snow melting months. The changes will explain if the snow is melting with increasing rainfall or not.

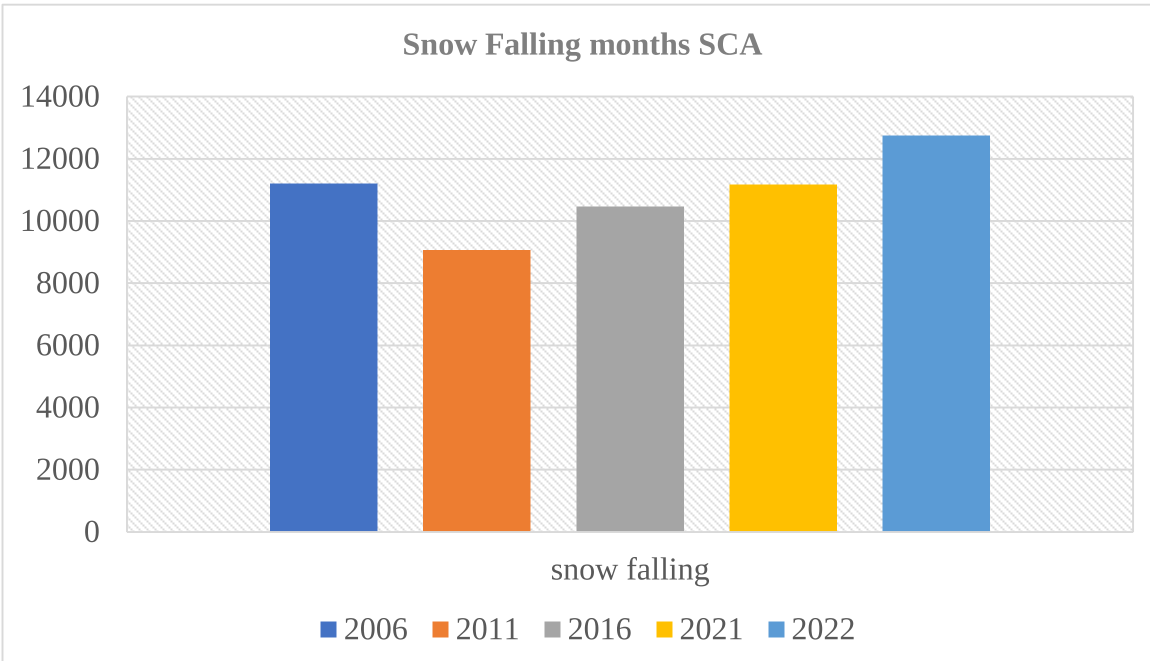

Figure 3.9(a) Snow Falling months SCA

The falling months typically starts from mid of November to mid of February. During 2006-2011, less snow fall has been observed. During 1989-2016, decline in winter was observed in Northern Pakistan (Hussain, et al., 2019). SCA in 2021 and 2022 has increased. The western disturbances also influence the sudden winter rains in northern parts of Pakistan. These are indicators of human based activities (Rebi, 2023). During 2021-2022, Pakistan was facing triple-dip La Nina.

The melting months are April, May, June, July and August. The increasing changes show melting only during 2006-2016, rest of the years are showing, comparatively lower melting.

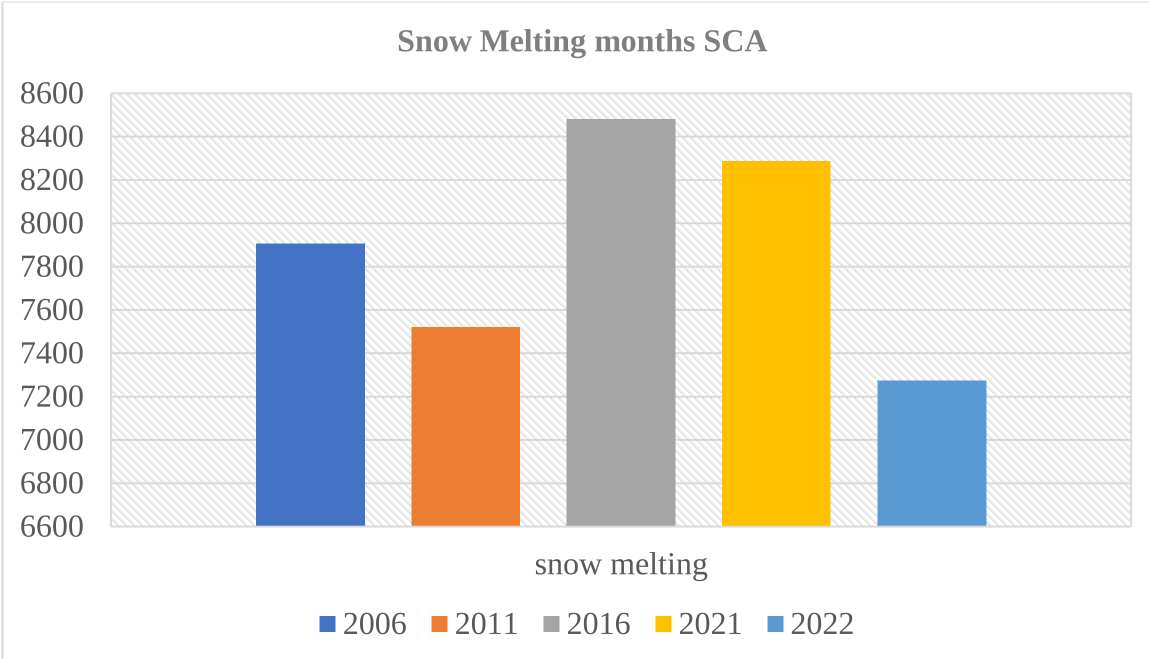

Figure 3.9(b) Snow melting months SCA

(Minora, et al. 2013) They analyzed climatic data and SCA through MODIS satellite depicts slight decrease in summer temperature and increase in supra-glacial debris coverage (debris such as rocks, soil etc. buried in snow) results in reduction of snow melting during 2001-2010. The results also display low melting in 2006-2011. The results show that the districts has a declining trend SCA till year 2021 on annual time scale for the reason mean temperature is increasing, respectively rainfall is decreasing. High variability in SCA has been observed due to temperature and rainfall variation. Years 2021 and 2022 are facing the impacts the of triple-dip La Nina, there SCA are also influenced by it.

The figure below (3.9.c) shows declining trend in SCA over the past few years. The correlation analysis is run to compare the SCA trend with climatic parameters.

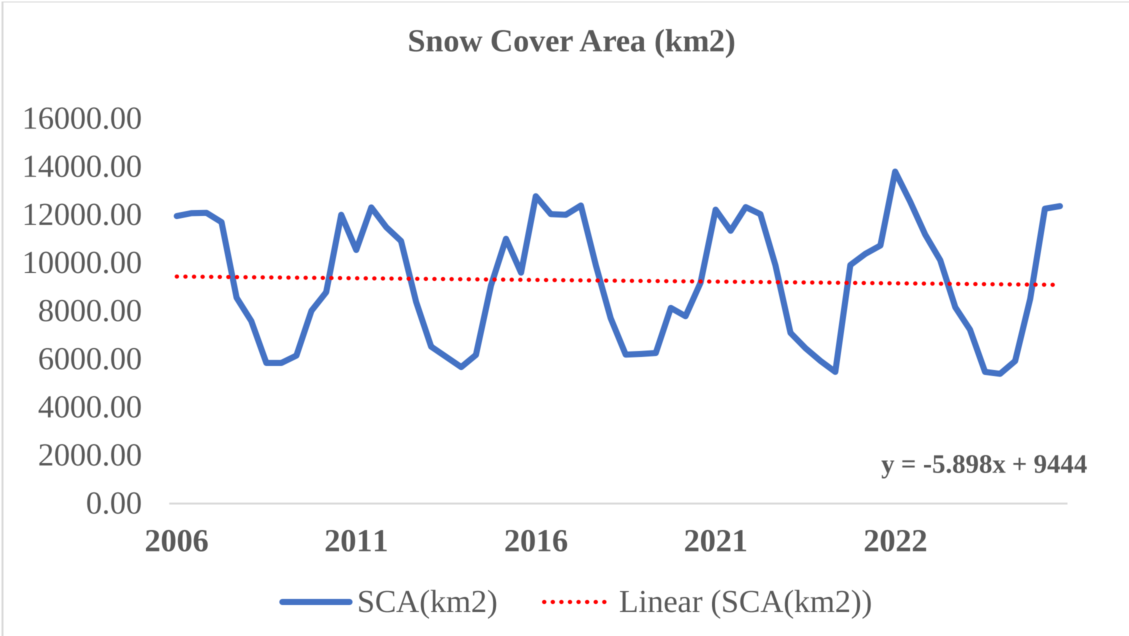

Figure 3.9 (c) Snow cover area (km^2)

3.10 Statistical Analysis of snow cover area and climatic parameters

Statistical analysis such as Correlation Analysis is applied to evaluate the relationship between two quantitative variables. The aim is to determine to what extent changes in one variable can affect the other variable. Correlation analysis deals with the association of variables, not causation.

The Pearson Correlation Coefficient on the other hand is a specific measure of correlation analysis. The linear relation between two variables is quantified using Pearson coefficient. The values of Pearson coefficient lie between -1 and +1. With the help of a table 3.10(a) below the range of coefficient values is discussed. Value is denoted by "r".

Table 3.10 (a) Range and output of correlation analysis

Sr.no	Range	Output
1.	$0<r<1$, (i.e. r = +0.23, 0.98 etc.)	Positive correlation
2.	$-1<r<0$, (i.e. r = -0.15, -0.78 etc.)	Negative Correlation
3.	r = +1	Perfect positive
4.	r = -1	Perfect negative
5.	r = 0	No Correlation

Correlation coefficient interpretation is done with the help of the table 3.10(b). If the size of correlation lies between 0.9 - 1.0 then the correlation is very high and strong. Similarly, if the size is between 0.70 to 0.9 the relation is high. The rest of the sizes of correlation are discussed in the table 3.10 (b). If the values of in negative, indicates if one variable increases the other decreases.

Table 3.10 (b) Interpretation of correlation analysis

Size of Correlation Analysis	Interpretation
0.9 to 1.0 (- or +)	Very high (positive or negative) correlation
0.7 to 0.9 (- or +)	High (positive or negative) correlation
0.5 to 0.7 (- or +)	Moderate (positive or negative) correlation
0.3 to 0.5 (- or +)	Low (positive or negative) correlation
.00 to 0.30 (- or +)	Negligible (positive or negative) correlation

3.10.1 Results of Correlation Analysis

The Correlation analysis tells positive robust correlation between SCA and rainfall. Particularly, instance when the SCA was diminished in 2011 overlap with the reduction in rainfall. On the other hand, in leading years' concurrent increase in SCA is also related with increasing rainfall. The statistical significance of results is highlighted by a p-value, if the value of $p<0.01$ (as illustrated in table 3.10.c) shows great significance. The relation between SCA and rainfall is estimated significant as the value is less than 0.01. The positive value indicates as rainfall increasing SCA also surpassing.

Temperature and SCA displays a negative correlation, increase in one corresponds a decrease in other variable. The value of $p> 0.01$, indicating no significant correlation among these variables (as illustrated in table 3.10.c). Maximum and minimum temperature exhibits an upward trend, as shown in Figures 3.7 and 3.8; however, no apparent direct linkage with SCA. The rise in temperature does not appear to be associated with rainfall. The correlation might not show direct significance but the increase by 0.9 degree Celsius in 2001-2010, the northern Pakistan faced the increase of 1.3 °C (Rasul, et al., 2011). The rise in temperature of one degree Celsius, need increase of 25-35% in rainfall to balance the melting change (Raper, 2000); (J, 2005).

The increase in rainfall is related La Nina. Pakistan facing triple-dip La Nina from 2020-2022. In Asia, Pakistan was in the grip of heavy rainfall (Jeong, 2023). La Nina is a climatic pattern in the Pacific Ocean. Warm water in the central Pacific Ocean becomes cooler than the normal, causing the warm water to reach Asia.

The years 2021, 2022 shows increased rainfall during march to august. When Pakistan is facing triple-dip La Nina. A climate model called state-of-the-art-ocean-atmosphere revealed that the unusual weather pattern, marked by a strong negative Indian Ocean dipole(IOD), was influenced by triple-dip La Nina. The combination of IOD and La Nina heavily affected the rainfall patterns in Pakistan (Jeong, 2023).

Table 3.11 (c) Results of correlation analysis

		SCA	Temp (max)	Temp (min)	Rainfall
SCA	Pearson Correlation	1	-0.214	-0.051	.992**
	Sig. (2-tailed)		0.729	0.935	0.001
Temp (max)	Pearson Correlation	-0.214	1	0.771	-0.196
	Sig. (2-tailed)	0.729		0.127	0.752
Temp (min)	Pearson Correlation	-0.051	0.771	1	-0.059
	Sig. (2-tailed)	0.935	0.127		0.925
Rainfall	Pearson Correlation	.992**	-0.196	-0.059	1
	Sig. (2-tailed)	0.001	0.752	0.925	
** Correlation is significant at the 0.01 level (2-tailed).					

CONCLUSIONS

1. The extent of SCA is identified by utilizing the satellite MODIS in Hunza and Nagar districts. A distinguishable decline in the trends of SCA is observed, with extensive melting in year 2016. These melting trends has the potential to pose serious threats to low-lying areas and inhabitants there. Significantly, the melting fails to provide usable water resources but adversely affect the quality of water, intensifying water scarcity and risks of flood.
2. Climatic parameters related to snow is mainly rainfall, according to correlation analysis. The rise in temperature is attributed to global climate change. The rise in temperature causing melting in 2006-2016. The precipitation increase in 2021 and 2022 are not indicating excess SCA decrease but high potential to flooding risks. Rainfall increase in 2021 and 2022 is directly linked to Triple-dip La Nina as the increase is recorded from march-august. The global climatic impacts provide the clue that he frequency of La Nina might increase.

RECOMMENDATIONS

1. The proper monitoring system for assessment of SCA and glacial range is important to take precautionary measures and mitigation steps before the onset of hazard and risk. Implement policies that solely promotes mitigation in northern areas.
2. The increasing rainfall and SCA trends are causing the increasing probability of floods in Pakistan. Pakistan has high vulnerability to floods. Proper water management and early warning systems from such events are utmost footsteps for the security of the inhabitants and people in low-lying areas.

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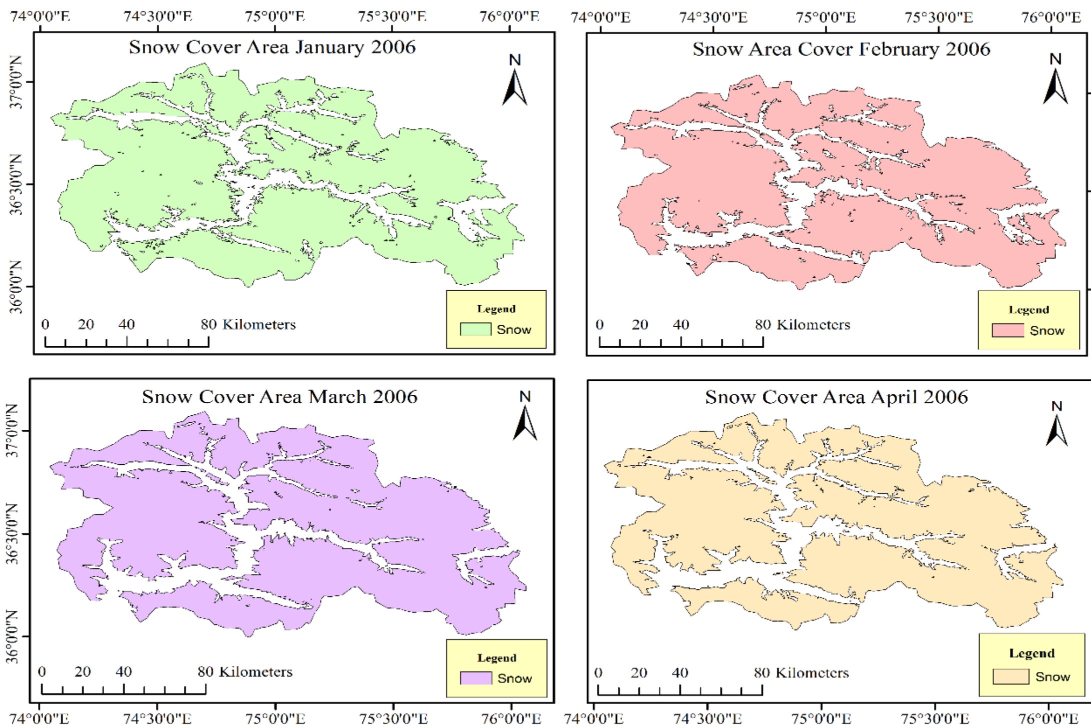
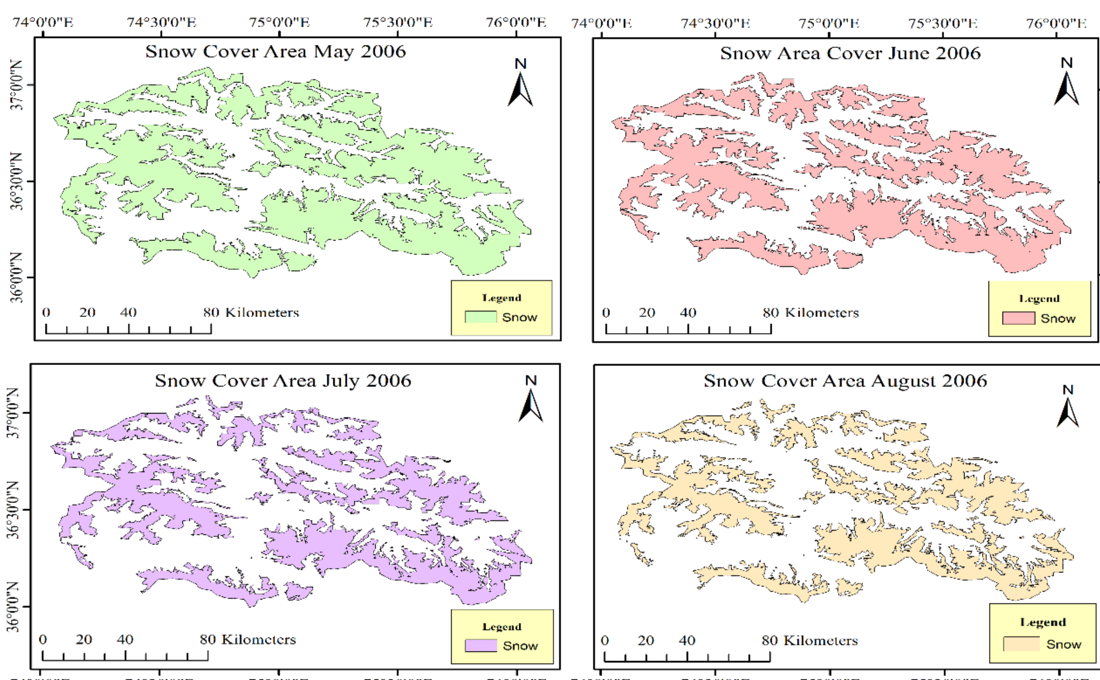
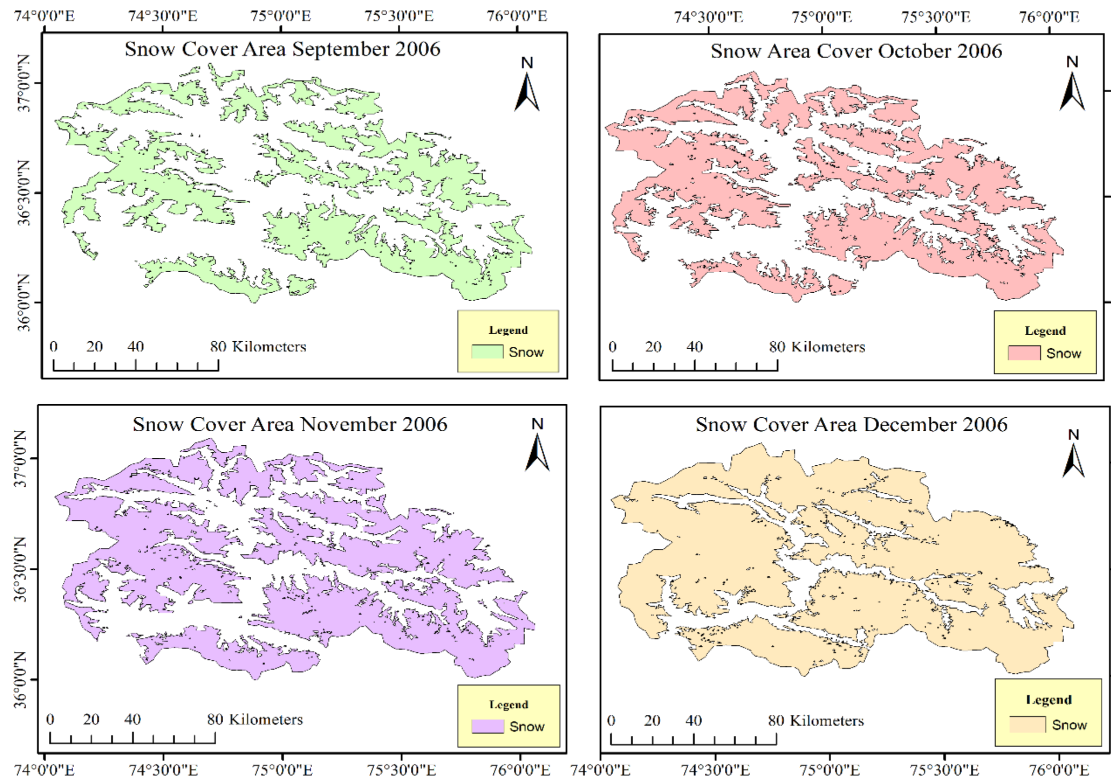
Appendices

Appendix A: Monthly SCA maps of all years

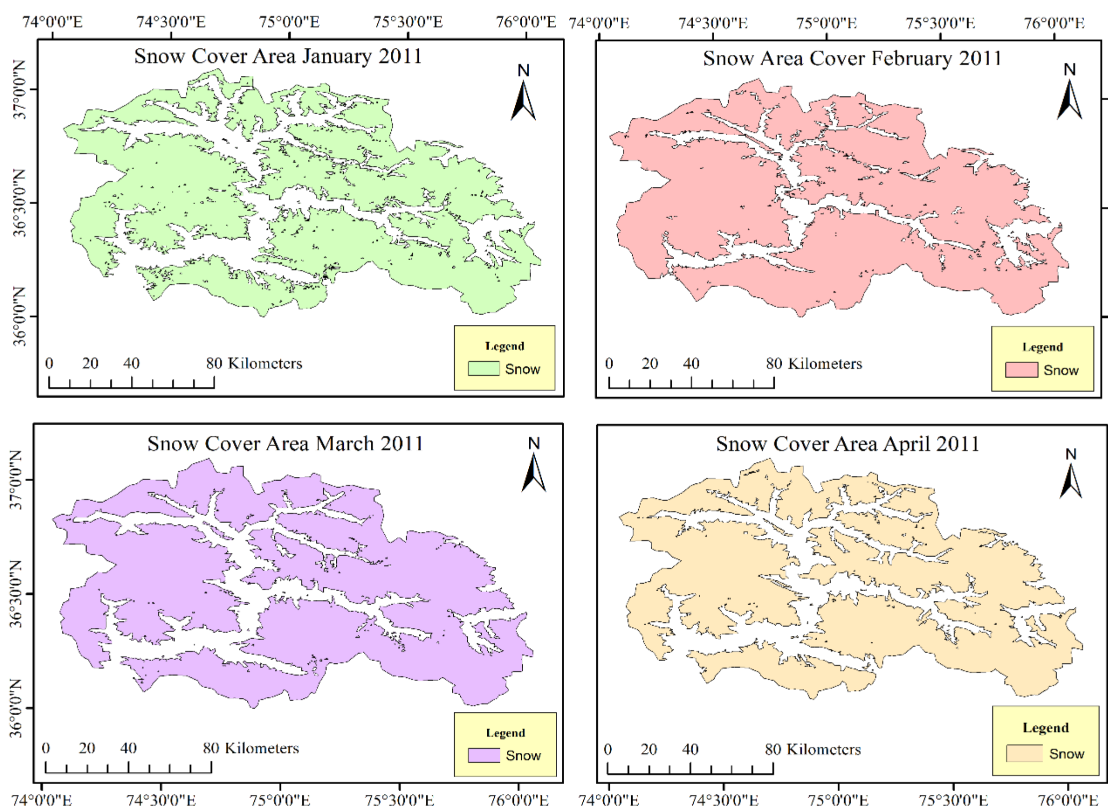
Appendix A1: Monthly SCA maps of 2006

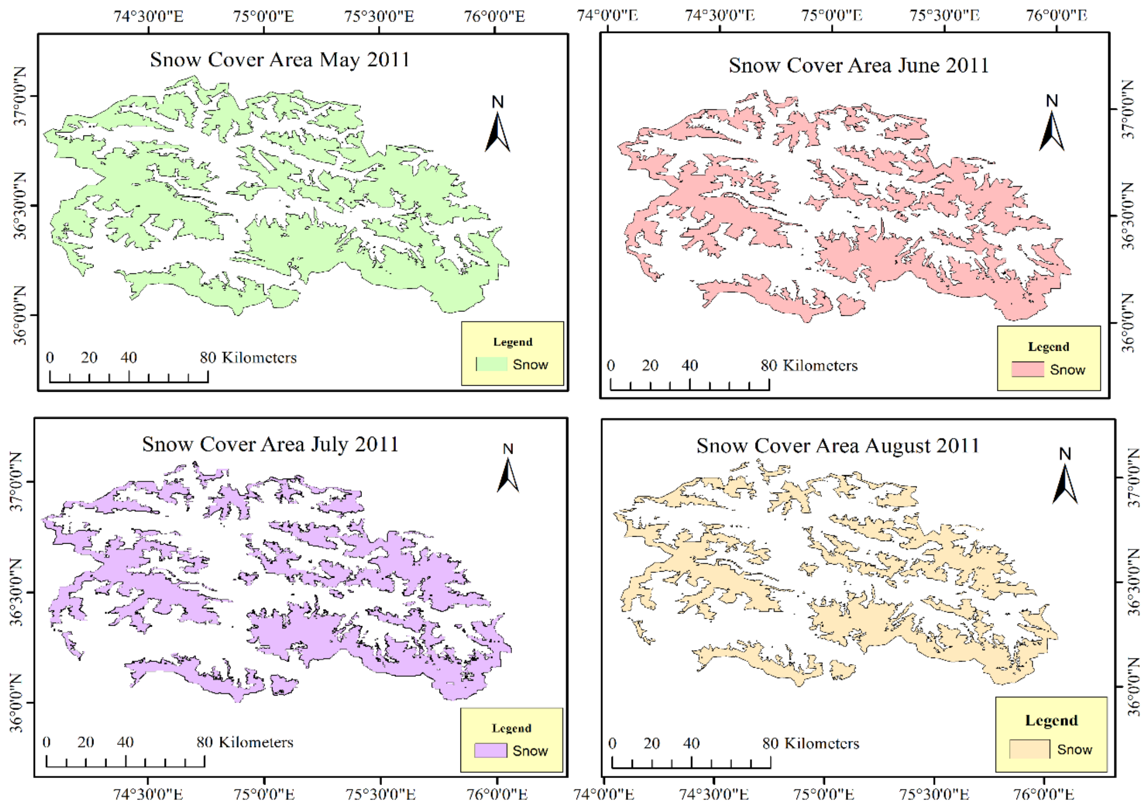


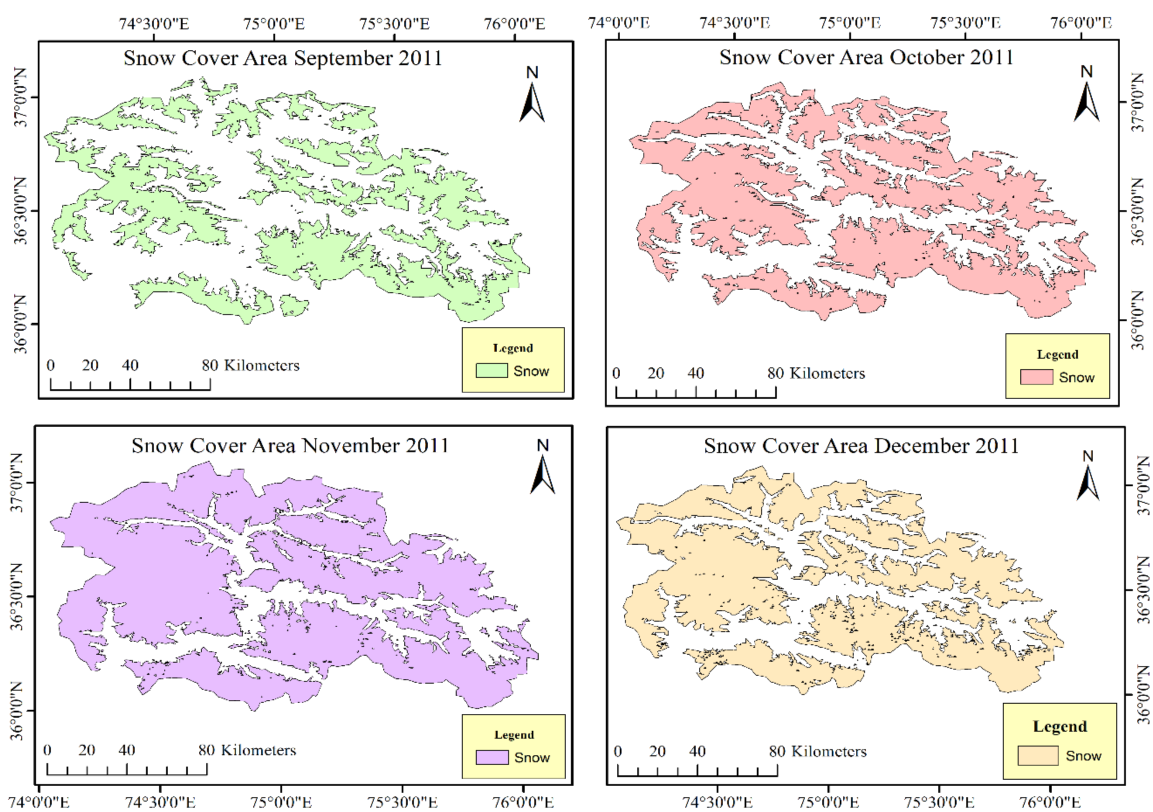




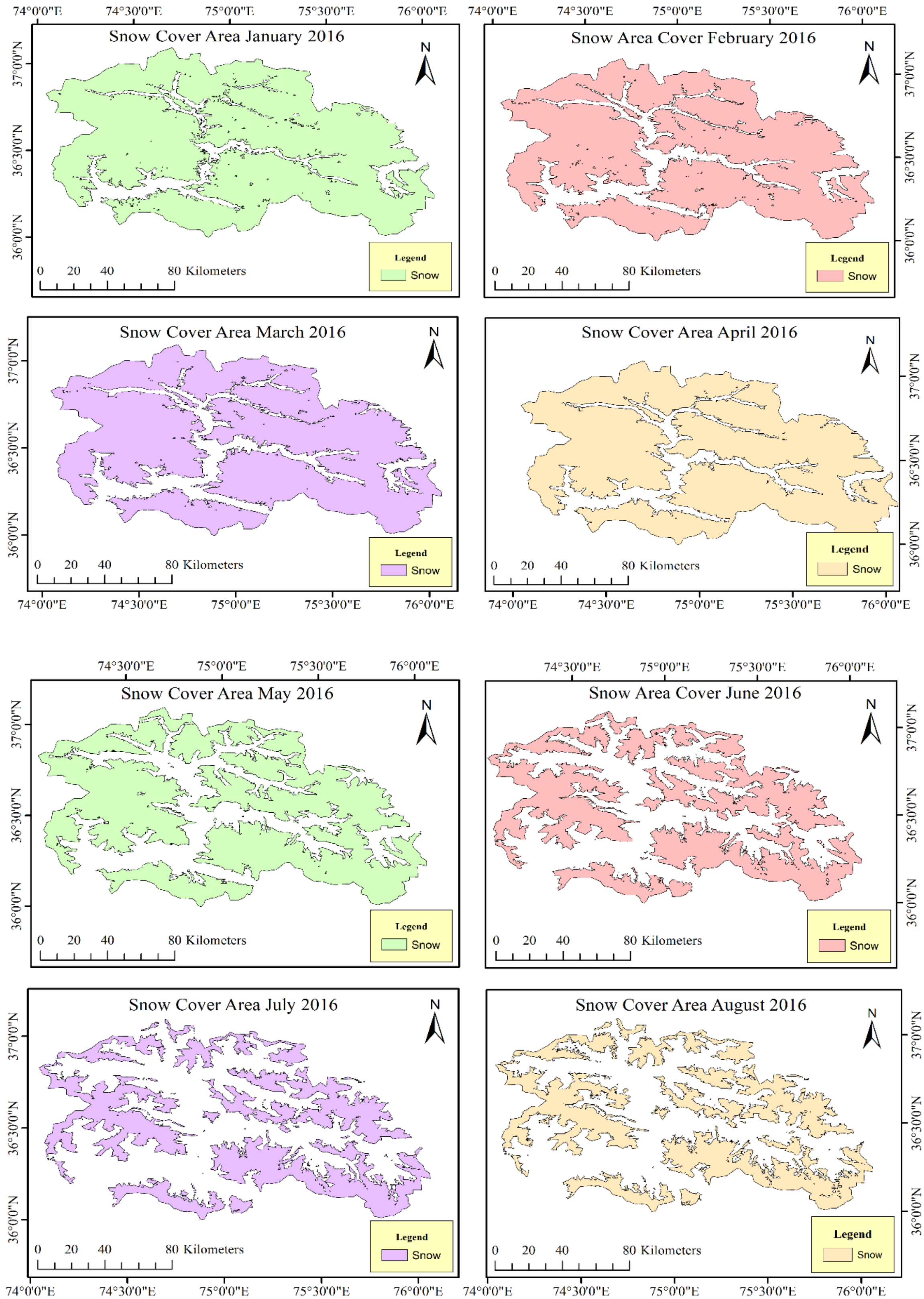
Appendix A2: Monthly SCA maps of 2011

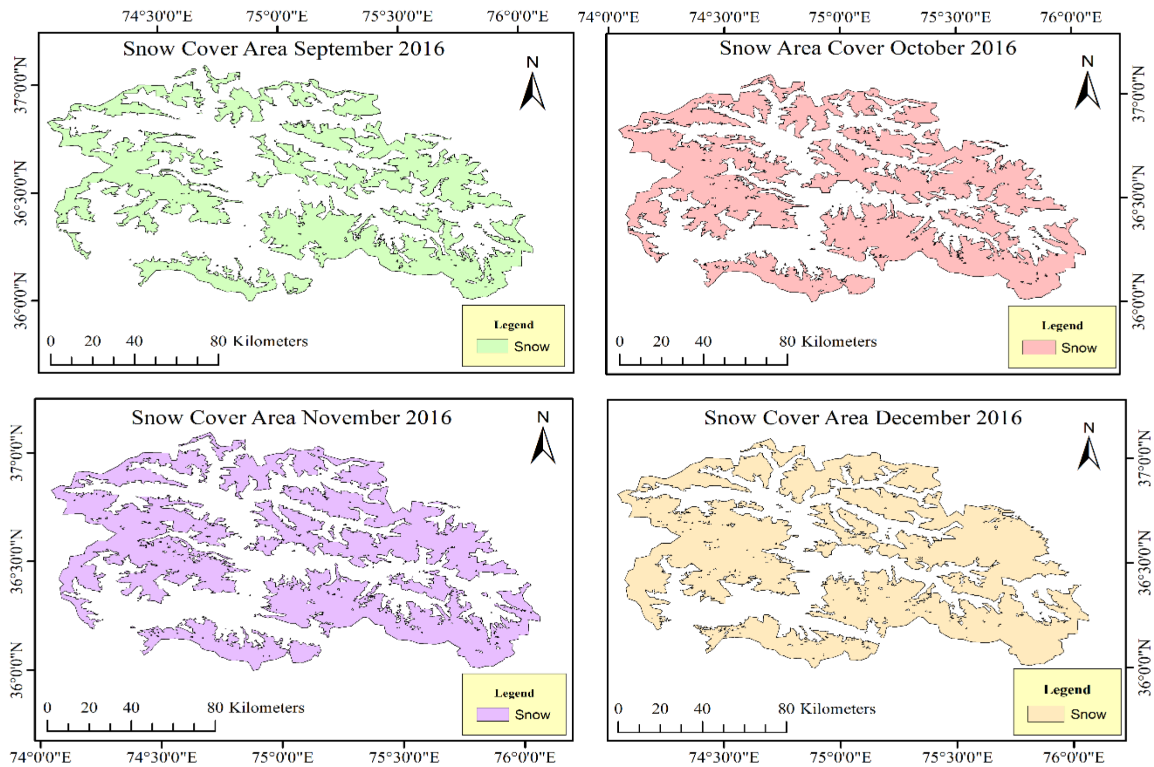



Snow Cover Area May 2011
Snow Cover Area June 2011
Snow Cover Area July 2011
Snow Cover Area August 2011
Legend
Snow
0 20 40 80 Kilometers
N
74°0'0"E
74°30'0"E
75°0'0"E
75°30'0"E
76°0'0"E
36°0'0"N
36°30'0"N
37°0'0"N

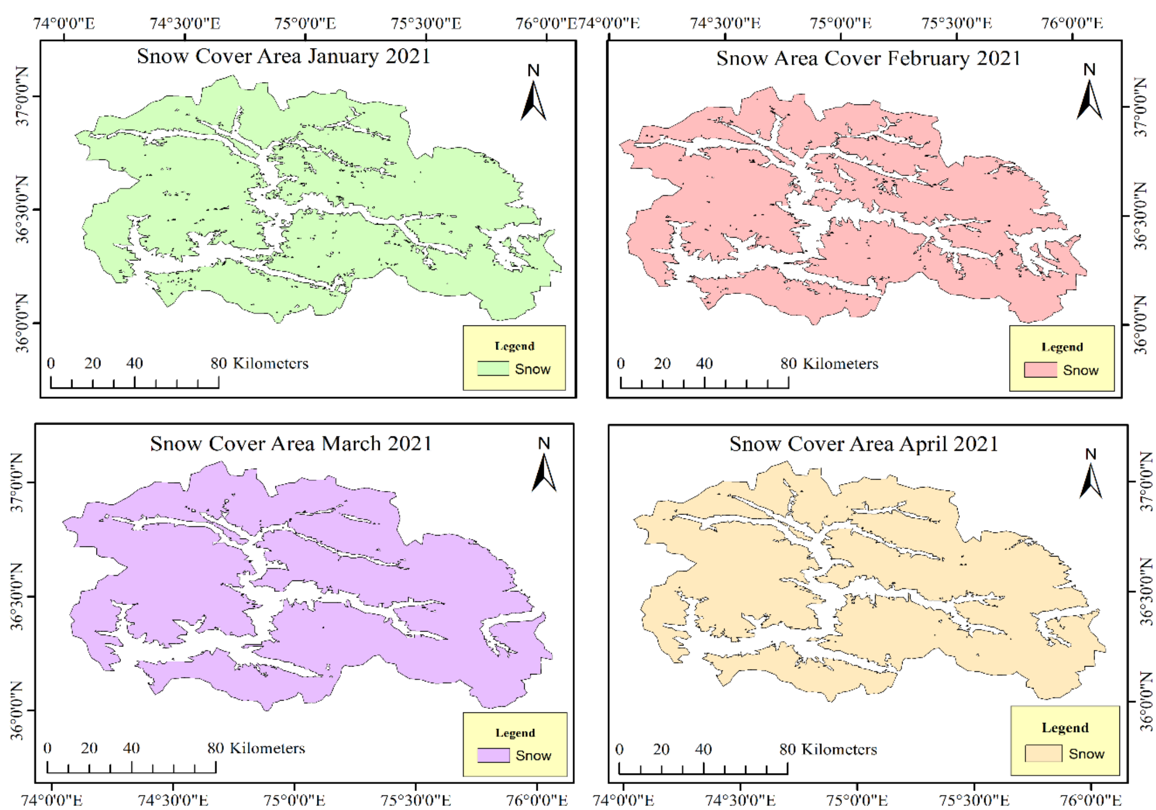

Snow Cover Area September 2011
Snow Cover Area October 2011
Snow Cover Area November 2011
Snow Cover Area December 2011
Legend
Snow
0 20 40 80 Kilometers
N
74°0'0"E
74°30'0"E
75°0'0"E
75°30'0"E
76°0'0"E
36°0'0"N
36°30'0"N
37°0'0"N

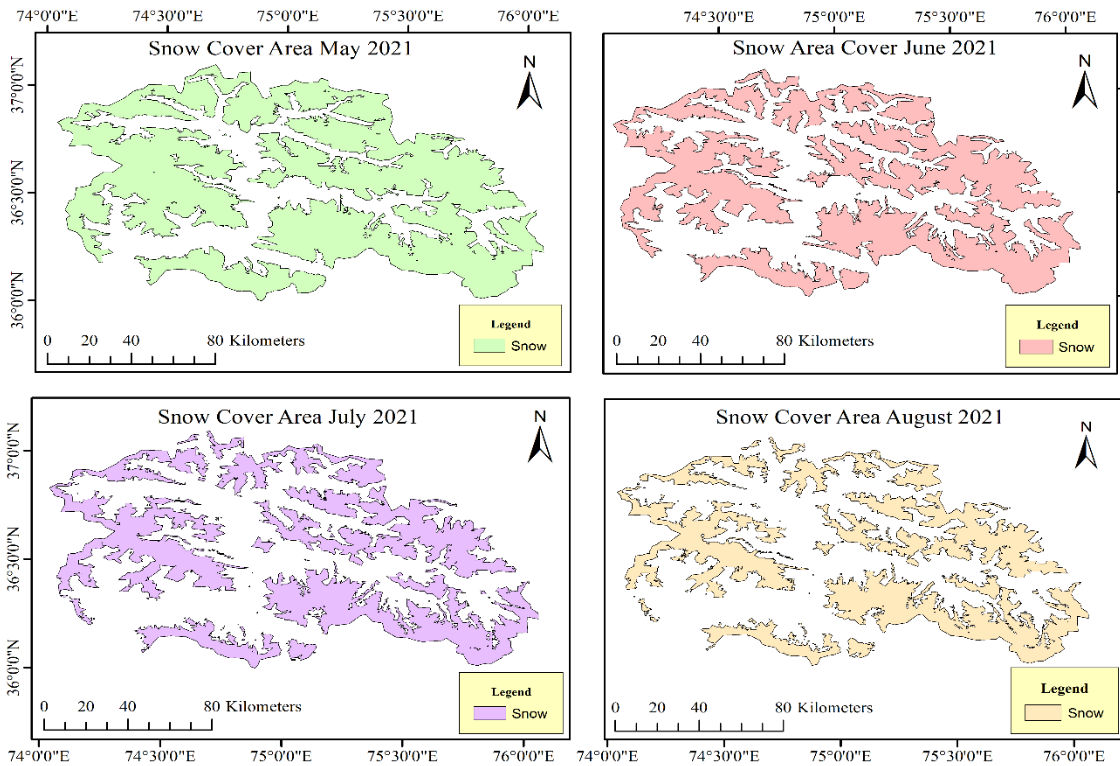
Appendix A3: Monthly SCA maps of 2016

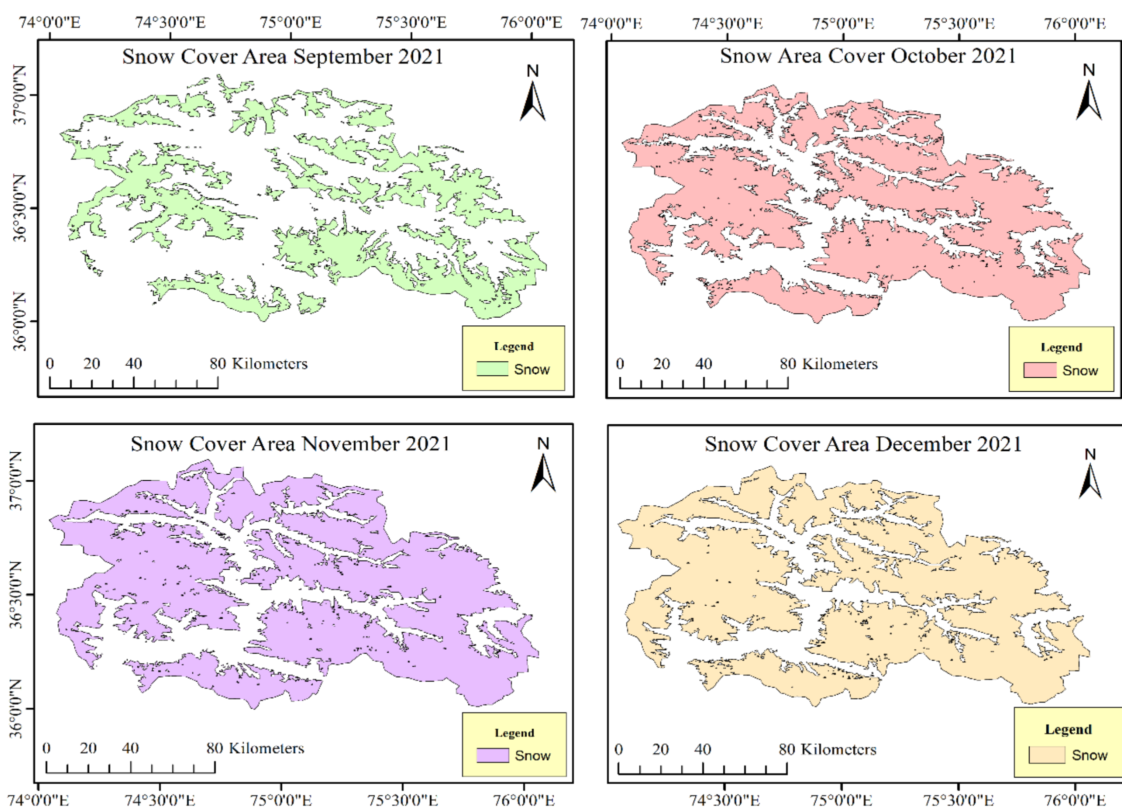




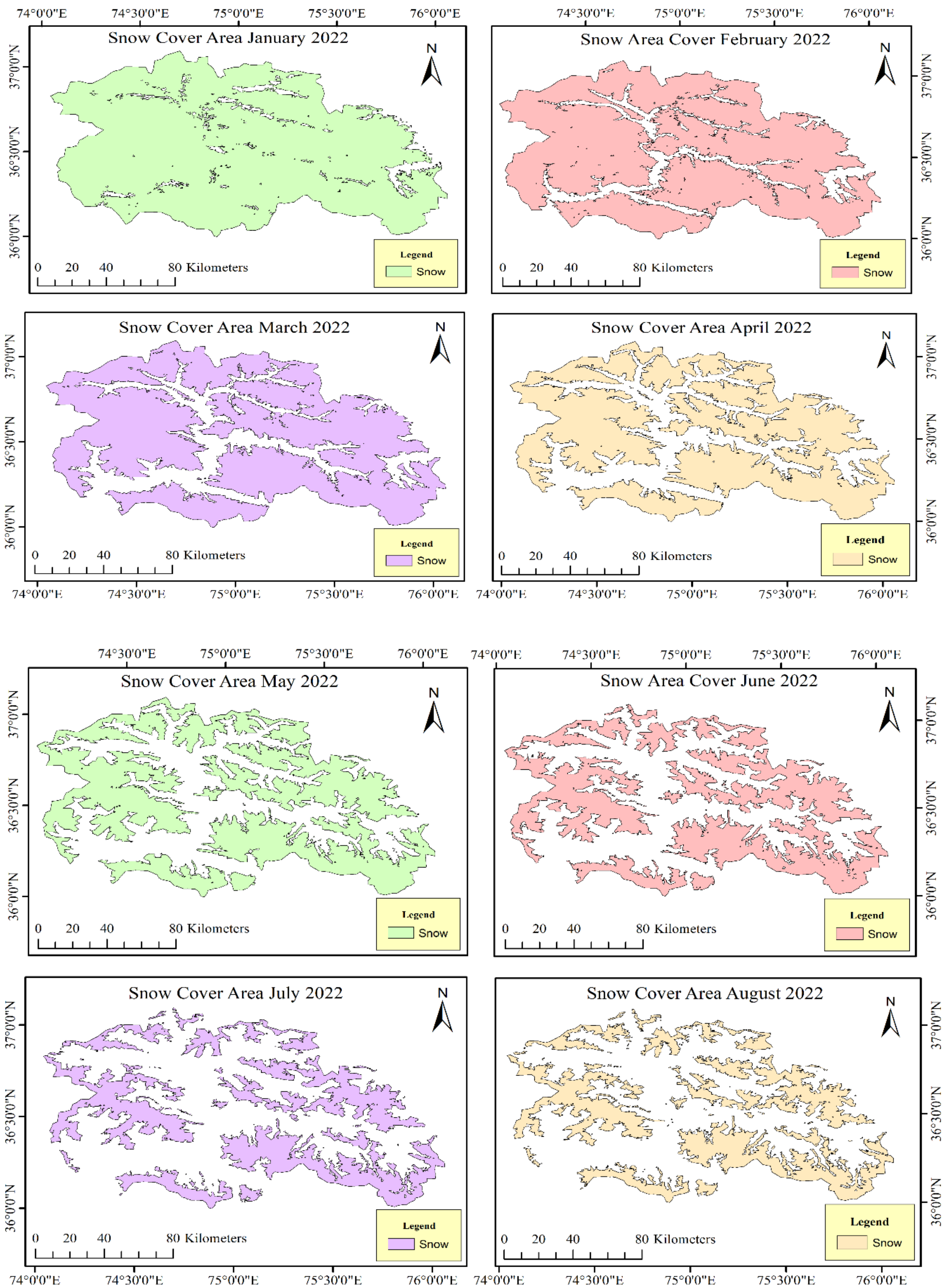
Appendix A4: Monthly SCA maps of 2021

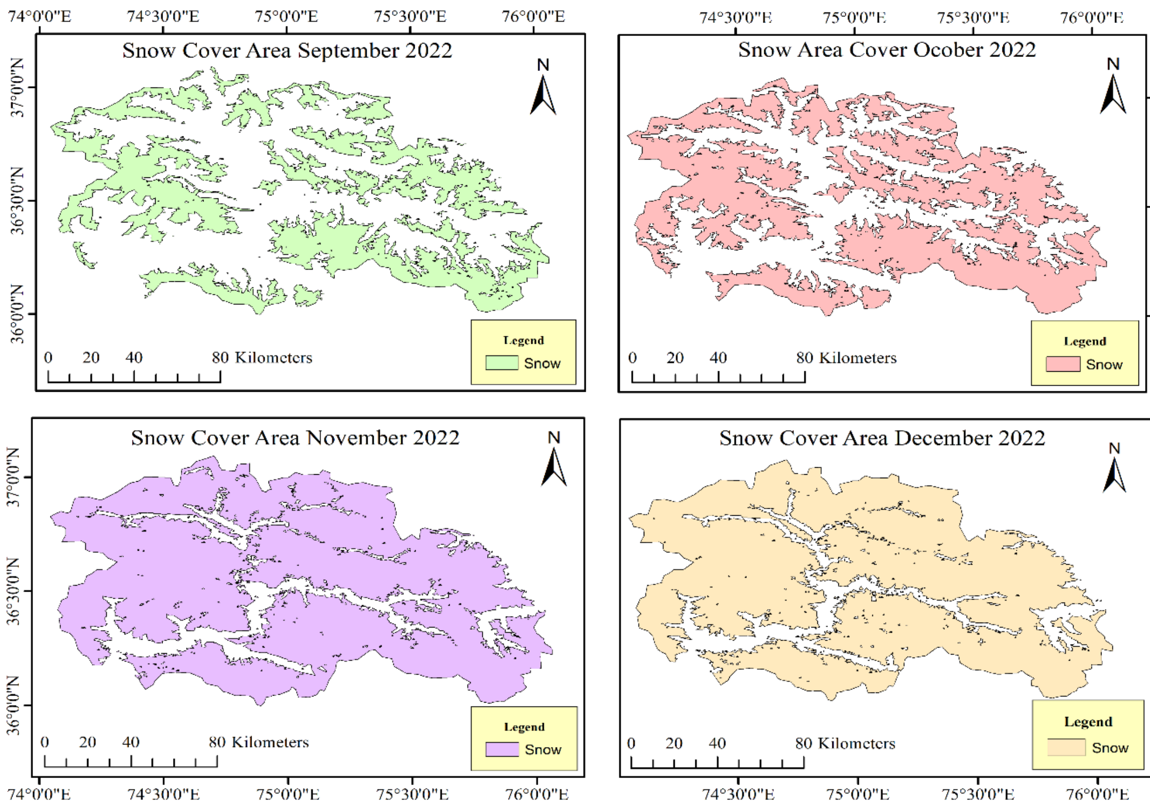



Snow Cover Area May 2021
Snow Area Cover June 2021
Snow Cover Area July 2021
Snow Cover Area August 2021
Legend
Snow
0 20 40 80 Kilometers
N
74°0'0"E
74°30'0"E
75°0'0"E
75°30'0"E
76°0'0"E
37°0'0"N
36°30'0"N
36°0'0"N


Snow Cover Area September 2021
Snow Area Cover October 2021
Snow Cover Area November 2021
Snow Cover Area December 2021
Legend
Snow
0 20 40 80 Kilometers
N
74°0'0"E
74°30'0"E
75°0'0"E
75°30'0"E
76°0'0"E
37°0'0"N
36°30'0"N
36°0'0"N

Appendix A5: Monthly SCA maps of 2022





Snow Cover Area September 2022
Snow Area Cover Ocober 2022
Snow Cover Area November 2022
Snow Cover Area December 2022
Legend
Snow
0 20 40 80 Kilometers
N
74°0'0"E
74°30'0"E
75°0'0"E
75°30'0"E
76°0'0"E
36°0'0"N
36°30'0"N
37°0'0"N

Appendix B: Tables of yearly data of SCA and climatic parameters

Appendix B1: 2006

Month	SCA (km2)	Temp (max)°C	Temp (min)°C	Rainfall (mm)
January	11959.39	-7.34	-32.09	268.91
February	12070.47	-6.28	-25.22	68.54
March	12092.79	-2.29	-24.58	21.1
April	11700.09	4.85	-5.69	62.2
May	8556.90	8.3	-8.81	10.54
June	7583.35	11.455	-7.05	10.54
July	5841.89	16.125	-4.57	121.3
August	5844.55	15.29	-4.84	163.19
September	6156.57	9.93	-6.38	72.75
October	8016.63	4.23	-11.15	85.23
November	8783.76	-0.09	-23.31	179.29
December	12005.21	-9.14	-33.9	147.62
Mean/Sum	9217.63	3.75	-15.63	1211.21

Appendix B2: 2011

Month	SCA (km2)	Temp (max)°C	Temp (min)°C	Rainfall (mm)
January	10548.18	-11.875	-28.72	68.56
February	12318.55	-9.14	-29.35	163.48
March	11487.7	-3.2	-25.875	73.83
April	10915.17	4.7	-21.05	94.93
May	8390.24	7.68	-8.51	10.54
June	6526.24	11.65	-6.68	20.74
July	6103.14	13.69	-3.21	42.18
August	5674.16	14.61	-3.82	116.01
September	6178.01	11.42	-7.15	68.56
October	9071.01	5.55	-14.51	52.75
November	11013.37	-1.95	-18.82	31.62
December	9604.53	-4.55	-25.84	21.08
Mean/Sum	8985.85	3.21	-16.12	764.28

Appendix B3: 2016

Month	SCA(km2)	Temp (max)°C	Temp (min)°C	Rainfall (mm)
January	12780.42	-8.92	-25.92	137.76
February	12037.06	-5.1	-23.98	198.18
March	12002.21	-1.75	-21.2	189.84
April	12394.96	4.02	-13.05	94.93
May	9895.49	7.6	-7.61	26.37
June	7706.23	12.57	-3.47	26.36
July	6195.02	17.16	-1.44	30.09
August	6214.17	14.66	-2.05	63.28
September	6254.03	10.41	-6.01	26.36
October	8135.36	7.03	-11.64	90.11
November	7790.06	-2.34	-15.74	199.56
December	9192.48	-2.96	-21.31	200.85
Mean/Sum	9216.46	4.37	-12.79	1283.69

Appendix B4: 2021

Month	SCA(km2)	Temp (max)°C	Temp (min)°C	Rainfall (mm)
January	12225.35	-10.08	-30.11	110.75
February	11345.92	-6.04	-26.96	200.39
March	12320.51	-2.57	-25.59	158.21
April	12030.02	0.76	-24.66	203.27
May	9907.61	6.03	-9.95	111.86
June	7100.14	14.38	-5.59	154.76
July	6460.36	17.06	-2.15	193.37
August	5933.31	12.25	-3.09	57.49
September	5468.79	11.78	-5.54	72.05
October	9913.02	5.77	-16.76	128.44
November	10384.05	-4.92	-19.44	100.62
December	10734.73	-5.77	-27.50	149.52

Mean/Sum	9485.32	3.22	-16.45	1640.73

Appendix B5: 2022

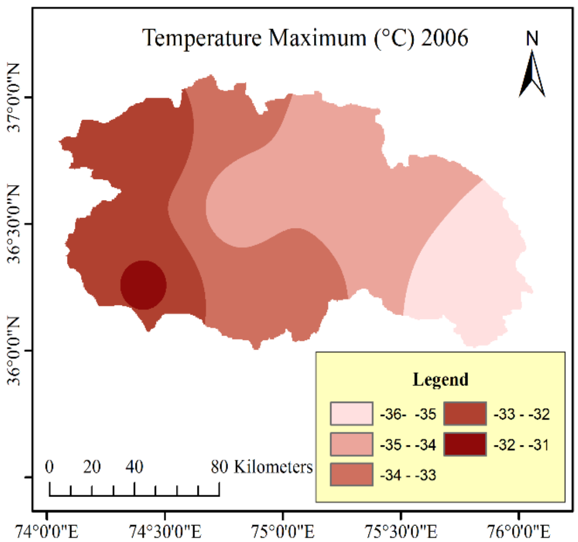
Month	**SCA (km2)**	**Temp (max)°C**	**Temp (min)°C**	**Rainfall (mm)**
January	13808.28	-10.69	-30.64	174.79
February	12557.10	-9.34	-27.7	87.81
March	11182.44	0.3	-20.66	54.15
April	10118.74	4.65	-11.99	69.63
May	8155.98	6.93	-6.8	96.87
June	7231.02	14.15	-5.99	203.32
July	5471.54	17.01	-2.07	156.17
August	5394.29	14.07	-2.5	193.58
September	5926.16	9.28	-6.57	77.68
October	8514.52	3.46	-8.04	52.32
November	12261.87	-1.82	-22	155.54
December	12363.07	-8.14	-24.55	124.22
	9415.42	3.32	-14.13	1446.08

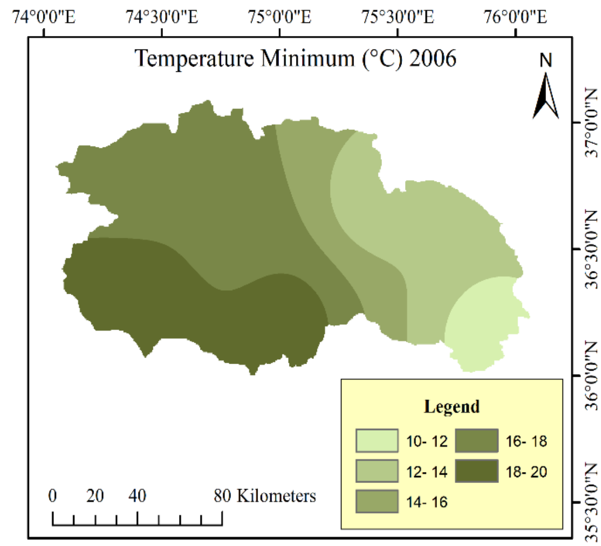
Appendix B6: Snow falling and melting months' data

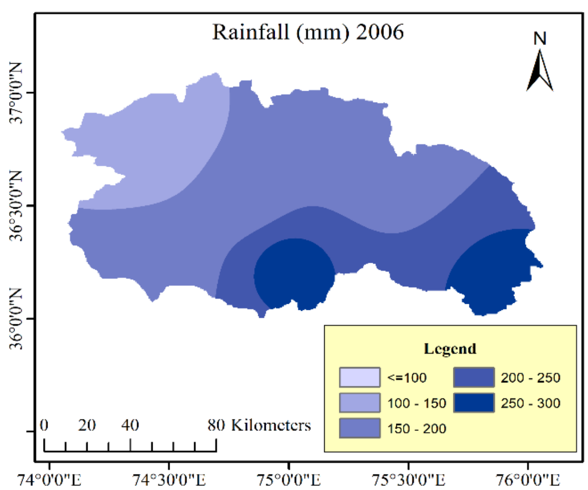
Year	**snow high (kgm^2)**	**snow melting (kgm^2)**
2006	11204.71	7905.36
2011	9067.22	7521.79
2016	10450.01	8481.17
2021	11172.51	8286.29
2022	12747.58	7274.32

Appendix C: Climatic parameters maps of each year

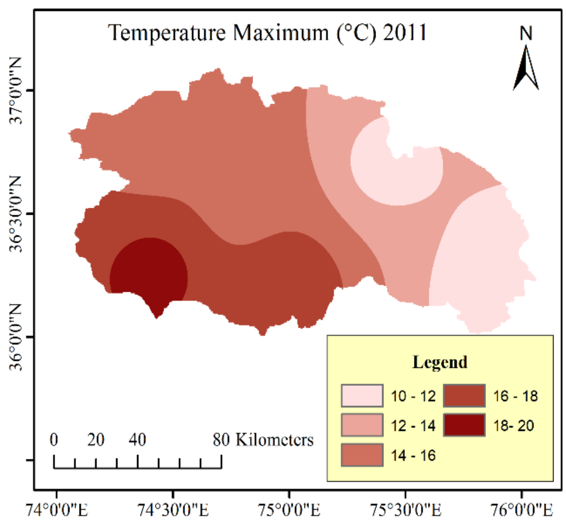
Appendix C1: 2006

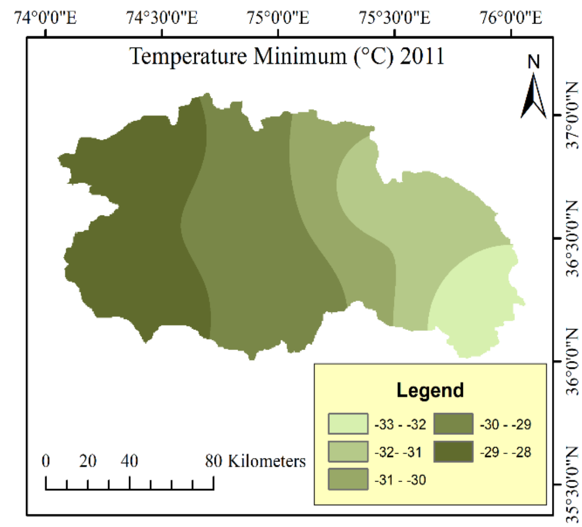


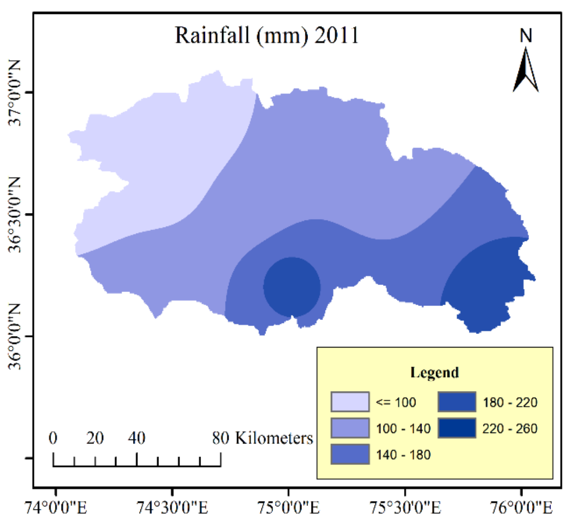




Appendix C2: 2011







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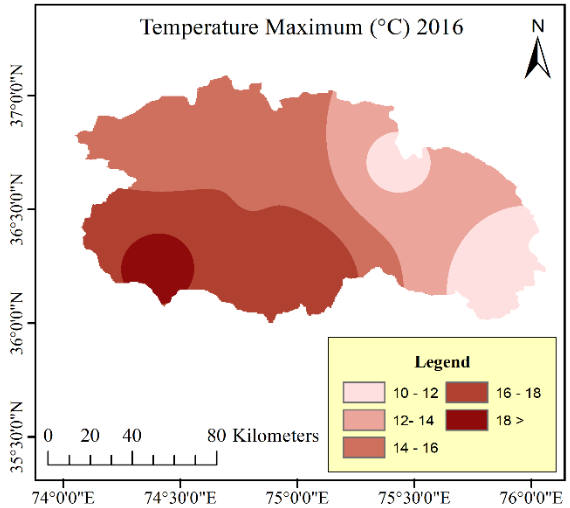
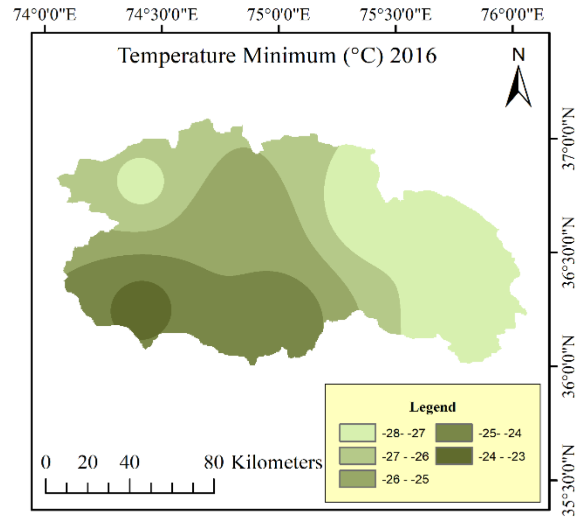
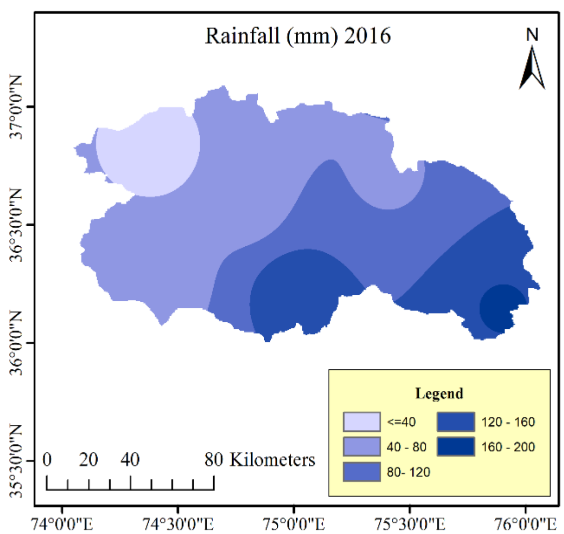
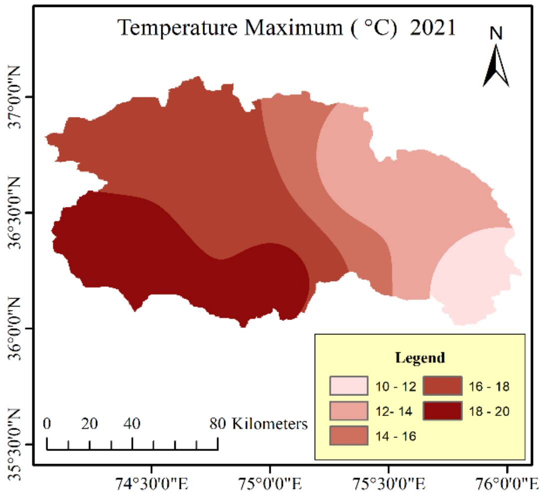
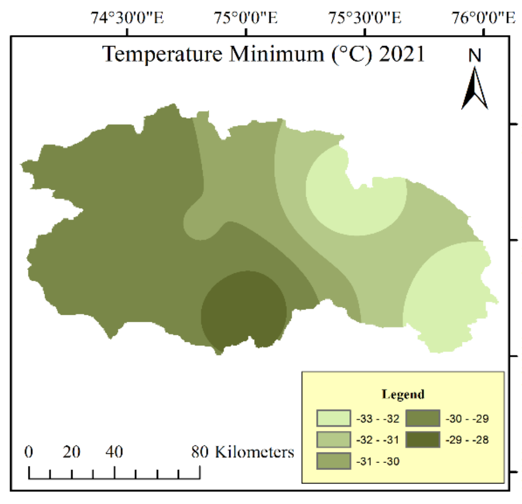


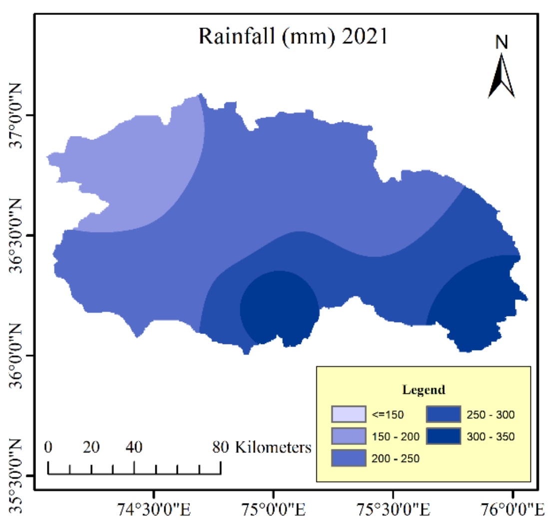




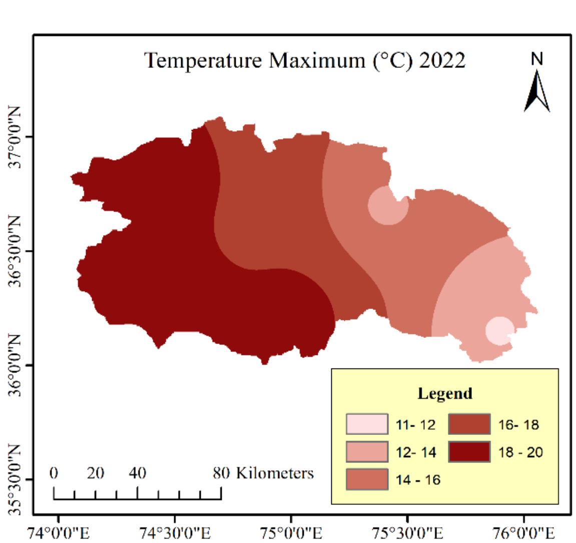
Appendix C4: 2021

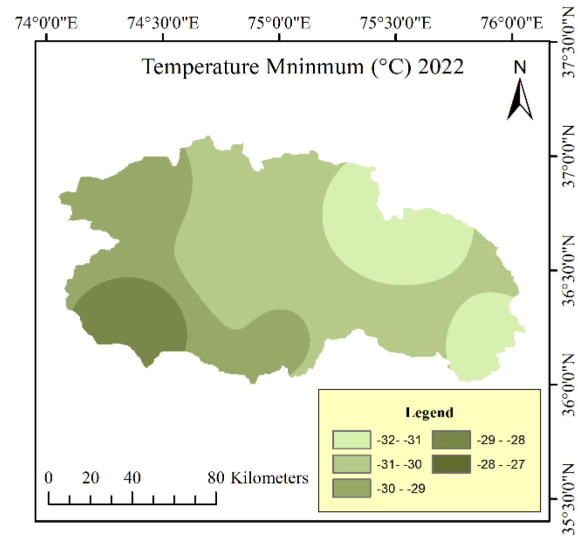


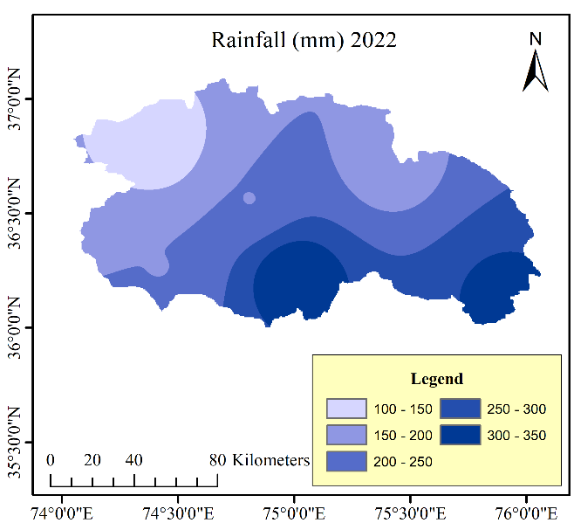




Appendix C5: 2022







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