Analysis of Snow Cover Changes Using MODIS Snow Products and Meteorological Data in the Hunza Region, Karakoram, Pakistan

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1   **Abstract**: The Upper Indus Basin (UIB) is characterized by contrasting meteorological behaviors; therefore, it has
2   become pertinent to understand the meteorological trends at the sub-basin level. Many studies have investigated the
3   snow-covered area along with meteorological trends at the basin level. Still, none have reported the spatial
4   variability of trends and their magnitude at a sub-basin level. This study is conducted to monitor the seasonal trends
5   in the snow-covered area and climatic factors (temperature and precipitation) in the Hunza region of the Upper Indus
6   Basin (UIB). Summer and winter seasons were selected because temperature and precipitation during these two
7   seasons are the key factors for snow cover variation in the region. Mann-Kendall and Spearman methods were used
8   to study the seasonal trends and their magnitude using MODIS snow cover information (2000–2020) and
9   meteorological data. The results showed that during the summer season, SCA and precipitation showed a non-
10 significant (p=0.05) decreasing trend with a value of -0.0095 km²/month and -0.191 mm/month, respectively, while
11 the temperature showed a non-significant increasing trend with a value of 0.315°C/month. While, during the winter
12 season, SCA and temperature showed a non-significant increasing trend with a value of 0.114 km²/month and
13 0.176°C/month, respectively, and precipitation showed a significant increasing trend with a value of 0.436
14 mm/month. In general, the snow-covered areas of the Hunza region have an increasing trend during the winter
15 season, while the summer season has a decreasing trend of snow-covered areas. Based on the results of this study it
16 can be concluded that since the Hunza sub-basin of the UIB is influenced by a different climatological system
17 (westerly system) as compared to other sub-basins of the UIB (monsoon systems), the results of those studies that
18 treat the UIB as one unit in meteorological modeling should be used with caution. Furthermore, it is suggested that
19 similar studies at the sub-basin level of the UIB will help in a better understanding of the Karakoram anomaly.

20   **Keywords:** Upper Indus Basin (UIB); Snow-Covered Areas (SCA); Hindu-Kush Himalayas (HKH), MODIS;
21 Mann-Kendall trend analysis.

1. Introduction

22 Snow Cover is one of the most important land surface characteristics in terms of the global energy budget and the

23 water cycle (Ahmad et al., 2018). The world population is heavily reliant on melt-water resources from glaciers and

24 snow (Lutz et al., 2014). According to Bormann et al. (2018), 17% of the world's population relies on seasonal

25 glacier melt and snowmelt water. According to (Ghulam Rasul, 2011), temperatures are projected to increase

26 globally by 0.6°C between 2001 and 2010. However, the actual temperature rise was 0.93°C, and the increase was

27 even greater in northern Pakistan, where the temperature increased by 1.3°C. As a result, glaciers in the HKH region

28 have retreated and snow has melted. The recent climate warming puts these natural resources at risk; according to

29 the Intergovernmental Panel on Climate Change (IPCC) report titled "State of the Global Climate 2020 WMO-No.

30 1264", between 1880-2020 where the average land and ocean temperature has increased globally by 1.2°C.

31 The Hindu-Kush Himalayas (HKH) region, also known as the "Water Towers of Asia", provides natural freshwater

32 reserves in the form of glaciers and snow, which ensure water distribution in the surrounding mountainous areas and

33 the adjacent plains. The hydrology of the HKH region is primarily driven by glaciers and snowmelt, which sustains

34 rivers and streams in the area (Immerzeel et al., 2010). Furthermore, the pace of glacier retreat in the Himalayan

35 region has increased dramatically in recent decades, which is considered to be a result of global warming

36 (Dyurgerov and Meier, 2005; Ageta et al., 2000). The majority of the glaciers and snow cover in the HKH region is

37 found in Pakistan's Indus Basin catchment, with a total glacier area of 21,192.67 km² (Bajracharya and Shrestha,

38 2011). Pakistan's Indus irrigation network is one of the largest irrigation systems that are vital to Pakistan's economy

39 (Tahir et al., 2015). The agricultural sector is the backbone of Pakistan's economy, which is heavily dependent on

40 water flow in the Indus Irrigation System (IIS) which gets 80% of its inflow from the perennial snow-covered areas

41 of HKH region. The major Tarbela reservoir of the IIS, receiving its primary input from glaciers and snowmelt from

42 the Upper Indus Basin (UIB), provides water to Punjab and Sindh's agricultural areas (Archer et al., 2010). The UIB

43 covers about 200,000 km² area (Atif et al., 2018; Hewitt, 2005) and is split into five sub-basins: Gilgit, Astore,

44 Shigar, Shyok, and Hunza, which acquire around 60% of the meltwater from snow-covered areas (SCA) and glaciers

45 (Tahir et al., 2015). Because the people living downstream rely heavily on these water resources and it's critical to

46 understand how these basins water resources behave.

47 The volume, distribution, and extent of snow are all affected by rising temperatures, making mountain hydrology

48 more sensitive to large-scale changes (Laghari et al., 2012). According to recent studies, snow cover has declined

49 during the previous four decades, particularly in the northern hemisphere (Brown and Robinson, 2011; Choi et al.,

50 2010; Kunkel et al., 2016). In the western United States, a declining trend of snow-covered areas (SCA) was

51 detected based on ground measurements (Pederson et al., 2010; Harpold et al., 2012). Additionally, due to rising

52 temperatures, snowfall across the Himalayan region decreased by approximately 16% from 1990 to 2001 (Menon et

53 al., 2010). Immerzeel et al. (2009) the same pattern was observed between 2000 and 2008. Many scientists say that

54 the snow cover area (SCA) in the HKH region is decreasing (Immerzeel et al., 2009; Gurung et al., 2011b; Shrestha

55 and Joshi, 2011; Maskey et al., 2011; Gurung et al., 2011a), On the other hand, increased SCA has been reported in

56 the western Himalayas and Karakoram (Tahir et al., 2015). Snow cover has also dropped across the Arctic,

57 according to satellite data (Shi et al., 2013). Under global warming, the global snow cover is one of the rapidly

58   changing hydrologic systems, with wide implications for ecological function (Allan and Soden, 2007). Because of

59   the predicted rapid snow cover retreat hindered by the shift of snowmelt runoff from the summer to the winter

60   season, there is a greater risk of winter floods and summer droughts (Ahmad et al., 2018).

61   The Snow-Covered Areas (SCA) of the Hunza region of the UIB have recently received a lot of attention. Many

62   researchers (Bilal et al., 2019; Tahir et al., 2011) utilized meteorological variables along with the satellite data of

63   different spatial and temporal resolutions to carry out the trend analysis of SCA variability of the region. These

64   studies, however, did not take into account the variability of meteorological factors at the Sub-Basin level of the

65   region. Moreover, because it is impossible to establish an observatory in a whole area, meteorological stations offer

66   ground data with a restricted coverage area, therefore, using Remote-Sensing Data is the sole option to evaluate the

67   changes in snow cover in remote locations like the Upper Indus Basin (UIB) (Tahir et al., 2015). However, the

68   investigation was hampered by a lack of data at the high altitude and the availability of data at low altitude in the

69   Hunza region. Many studies have raised this concern (Atif et al., 2018; Bilal et al., 2019; Tahir et al., 2011). The

70   MODIS/Terra Snow Cover 8 Day L3 Global 500 m Grid (MOD10A2) V006 was used to monitor snow cover for 20

71   years from 2000 to 2020. The nonparametric Mann-Kendall and Spearman statistical techniques were used to

72   determine the trend and magnitude of the meteorological variations (temperature & precipitation) in the Hunza

73   region and its correlation with SCA.

2.   Materials and Methods

2.1.   Study Area.

74   The Hunza region of the UIB (8,732.4 km²) is situated in the Gilgit-Baltistan region of Northern Pakistan (Jamill et

75   al., 2022) within a high mountainous area between 74°02′ and 76°00′ East and 35°54′ and 37°10′ North. Hunza is

76   bordered to the Northeast by China's Xinjiang region, to the Northwest by Afghanistan, and to the South by the

77   Nagar district (Nagar 1 in the Southeast and Nagar II in the Southwest). The Water and Power Development

78   Authority (WAPDA), under the Pakistan Snow & Ice Hydrology Project (PSIHP), has deployed two climate stations

79   with precipitation gauges at different elevations: Khunjerab at 4,730 m asl and Ziarat at 3,669 m asl. The climate in

80   Hunza is dry to semi-arid, with two main seasons, Summer from April to August and Winter from September to

81   March. According to 20 years of records (2000–2020) from these climate stations, the annual mean precipitation is

82   180 mm at Khunjerab (4,730 m) and 225 mm at Ziarat (3,669 m) (Atif et al., 2018). Nearly half of the basin area lies

83   above 4,500 m in elevation. Figure 1 shows the Hunza area and drainage basin along with the meteorological

84   Stations, while Table 1 details the basin's key physical characteristics.
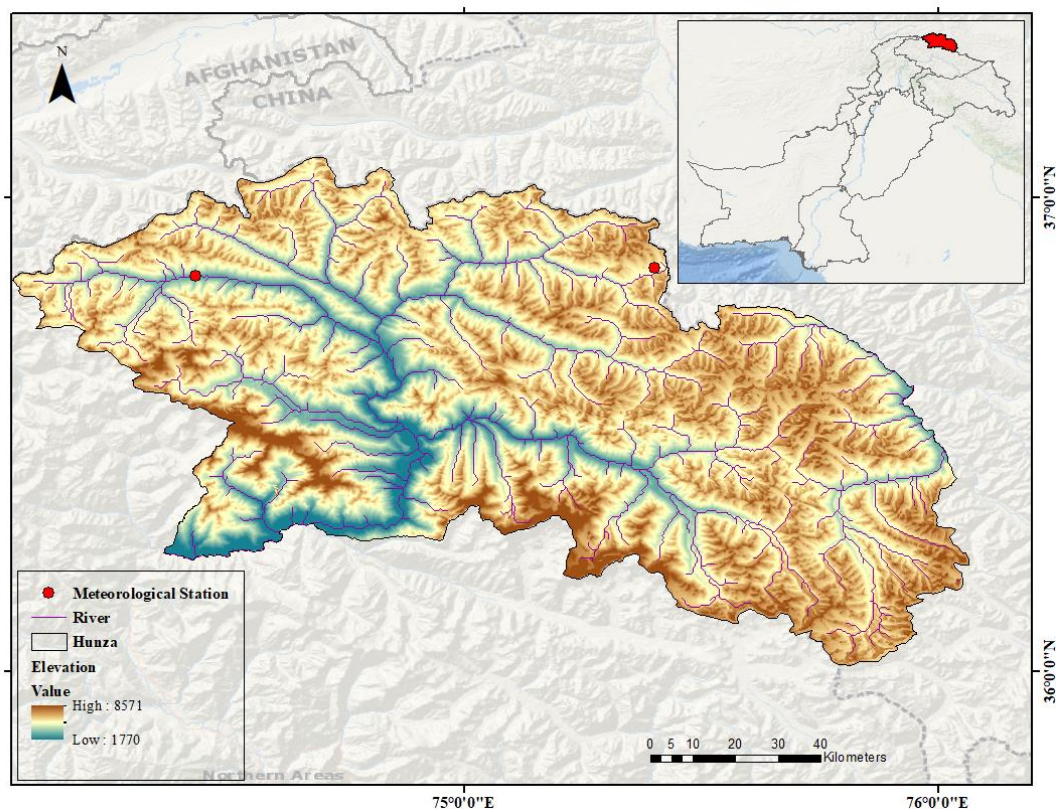
85 Figure 1 Map of the study area along with the installed meteorological stations.

Physical Characteristics	Description
Catchment area	8.732 km^2
Elevation range	1,774-7,774 m
Mean elevation	4,774 m
Latitude	35°54' to 37°10'
Longitude	74°02' to 76°00'
Catchment area above 4500m	62.40%
Dominant land use type	Bare soil with shrubs
Mean Precipitation (2000-2020)	
Khunjerab (4730 m)	163 mm
Ziarat (3669 m)	292 mm

4

86   Table 1 Major physical characteristics of the Hunza region.
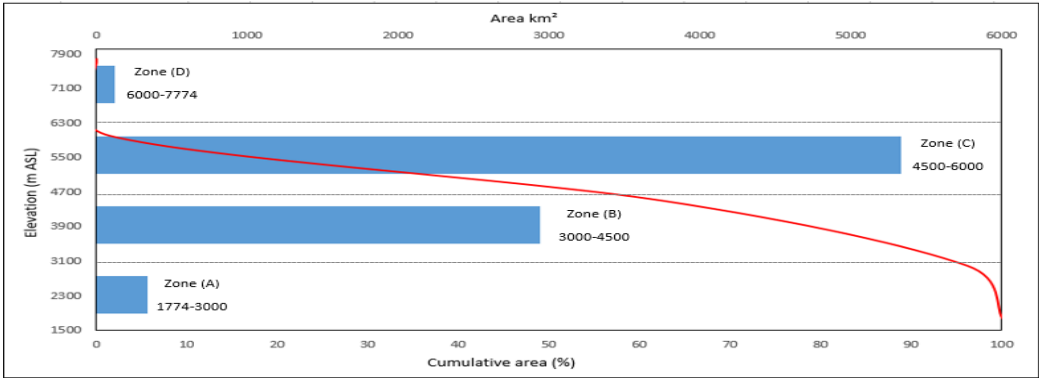
87   Figure 2 Hypsometric curve of Hunza region estimated through digital elevation model (DEM).

Name	Elevation range (m asl)	Mean elevation (m asl)	Land area (km^2)	Land area %
Zone (A)	1774-3000	2387	342.24	3.92
Zone (B)	3000-4500	3750	2937.87	33.64
Zone (C)	4500-6000	5250	5328.04	61.01
Zone (D)	6000-7774	6887	124.28	1.42

88   Table 2 Summary of the hypsometric zones along with the land area percentage.

2.2 Methodology

89   This study has faced challenges due to the lack of data at high altitudes and the availability of data at low altitudes in

90   the Hunza region. Many studies have raised this concern (Atif et al., 2018; Bilal et al., 2019; Tahir et al., 2011). High

91   winds have been observed to cause the underestimation of solid precipitation at high altitudes (Dahri et al., 2016;

92   Ménégoz et al., 2013). However, the MODIS 8-day snow product was used to examine snow cover during 20 years

93   from 2000 to 2020. To identify Snow-Covered Areas across different zones, a study was conducted from 2000 to

94   2020 using supervised classification of Landsat images with a 30m spatial resolution, classifying them into five

95   categories: snow, ice, vegetation, rock, and soil. This was followed by manual digitization to refine snow boundaries

96   and remove artifacts. The nonparametric Mann-Kendall and Spearman statistical techniques were used to determine

97   the trend and magnitude of the meteorological variations in the Hunza region and its association with the SCA. The

98   arithmetic mean of the daily maximum and minimum temperatures is used to get the daily average temperature.

99   Unrecorded data was replaced by interpolating data from the previous and subsequent years. Figure 3 illustrates the

100   Methodological framework of the study.
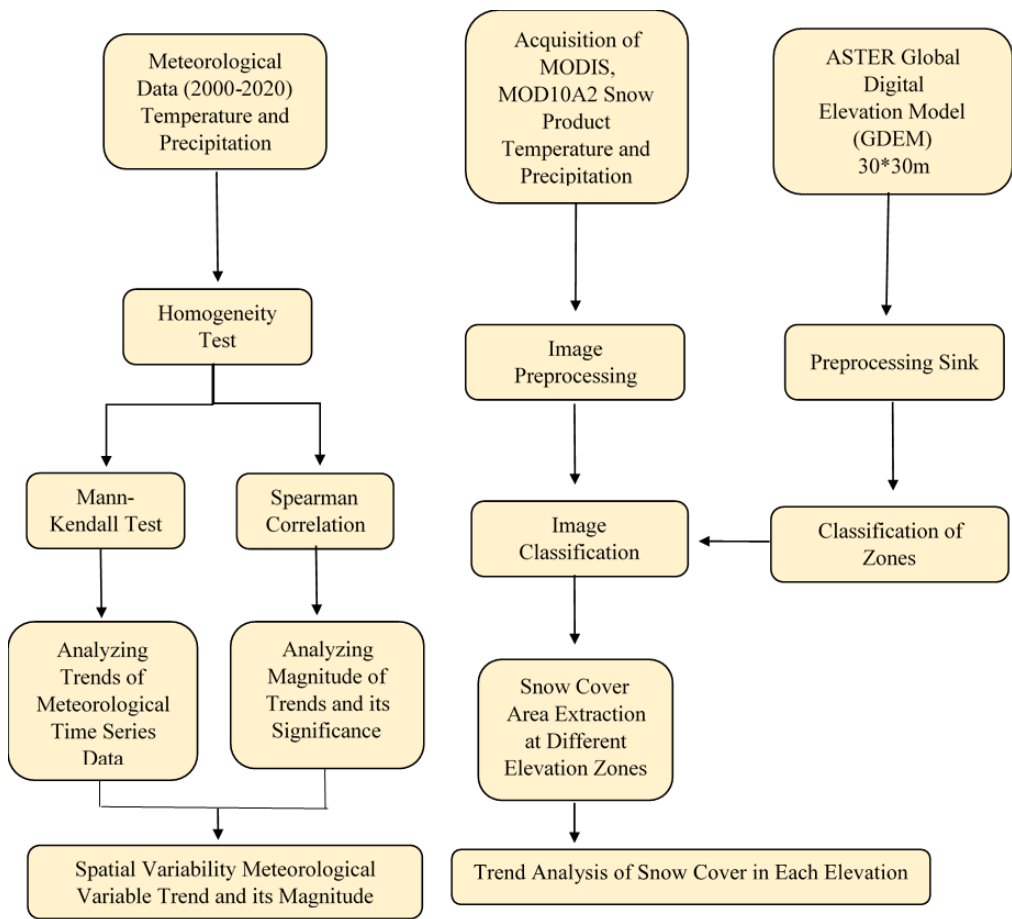
101   Figure 3 Methodological framework of the study.

Homogeneity Test

102   The Standard Normal Homogeneity Test (SNHT) was used to evaluate the homogeneity of hydrometeorological and

103   snow cover data at a 5% significance level for each station (Kang and Yusof, 2012). Data is considered to be

104   homogeneous when the computed p-value is less than 0.05 (Atif et al., 2018). All the meteorological variables were

105   found to be homogenous.

Trend Analysis

106   For Seasonal Trend Analysis, climatic variables from both these stations were divided into two seasons: Winter

107   (March) and Summer (August), because the trend in temperature and precipitation during these two seasons are the

108   key factors for Snow Cover Variation in the Hunza region (Dimri et al., 2013; Tahir et al., 2015). To find patterns in

109 time series data of the meteorological variables, a non-parametric Mann- Kendall trend test for the seasonal data was

110 used. The MK statistic reveals the nature of a trend, whether it is positive or negative (Mann, 1945; Kendall, 1975).

111 It does not, however, give information on the Slope's Magnitude or the trend line. The size of the trend was

112 estimated using the Spearman correlation method at a 5% significance level (ρ=0.05).

113 The mathematical equations for calculating Mann-Kendall Statistics (S) are as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i)$$

114 (1)

115 Note that if $S > 0$ then later observations in the time series tend to be larger than those that appear earlier in the time

116 series, while the reverse is true if $S < 0$.

117 The variance of S is given by

$$var = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t f_t(f_t-1)(2f_t+5)\right]$$

118 (2)

119 Where t varies over the set of tied ranks and f_t is the number of times (i.e. frequency) that the rank t appears.

120 The MK Test uses the following test statistic:

$$z = \begin{cases} (S-1)/se, & S > 0 \\ 0, & S = 0 \\ (S+1)/se, & S < 0 \end{cases}$$

121

2.3 Data Sets

Topographical Data.

122 The Hunza region is defined using the using the Shuttle Radar Topography Mission (SRTM) Digital Elevation

123 Model (DEM) at a 30-meter resolution (1 arc-second). The STRM DEM was obtained from Earth Explorer and

124 provides detailed elevation data for the Hunza region, though some voids-filled higher elevation data at a resolution

125 of 30-meter resolutions. To address these voids in the STRM DEM were filled using the fill function in ArcMap 10.5.

126 The data was then divided into four distinct elevation zones, each with a mean elevation difference of about 1500

127 meters. The mean elevation of the Hunza basin, determined using an area-elevation hypsometric curve, was

128 calculated to be about 4,774 meters above sea level. This zoning helps in analyzing how the region's topography

129   affects snow cover variations. Figure 2.2 depicts the elevation range and proportionate area (percentage) of each

130   separate zone (A, B, C, and, D).

Snow Cover Data.

131   The MODIS/Terra Snow Cover 8 Day L3 Global 500 m Grid (MOD10A2) V006 was chosen to assess the spatial

132   variability of snow. This dataset was chosen for the study above other data sets because of its appropriate spatial and

133   temporal resolution, as evidenced by prior investigations (Ahmad et al., 2018; Tahir et al., 2011). These images

134   cover a land area of 1200 km by 1200 km and are projected using a sinusoidal map projection (Riggs et al., 2006).

135   The images were projected to the WGS 1984 UTM Zone 43N system in ArcGIS 10.5. To create a monthly

136   composite, the 8-day interval images were combined using ArcGIS's Composite tool. Image quality was further

137   enhanced using interpolation with the Inverse Distance Weighting (IDW) method in ArcGIS. After that, the "extract

138   by mask" tool of ArcGIS was used to demarcate the boundary of the study area and retrieve the area of interest

139   (AOI).
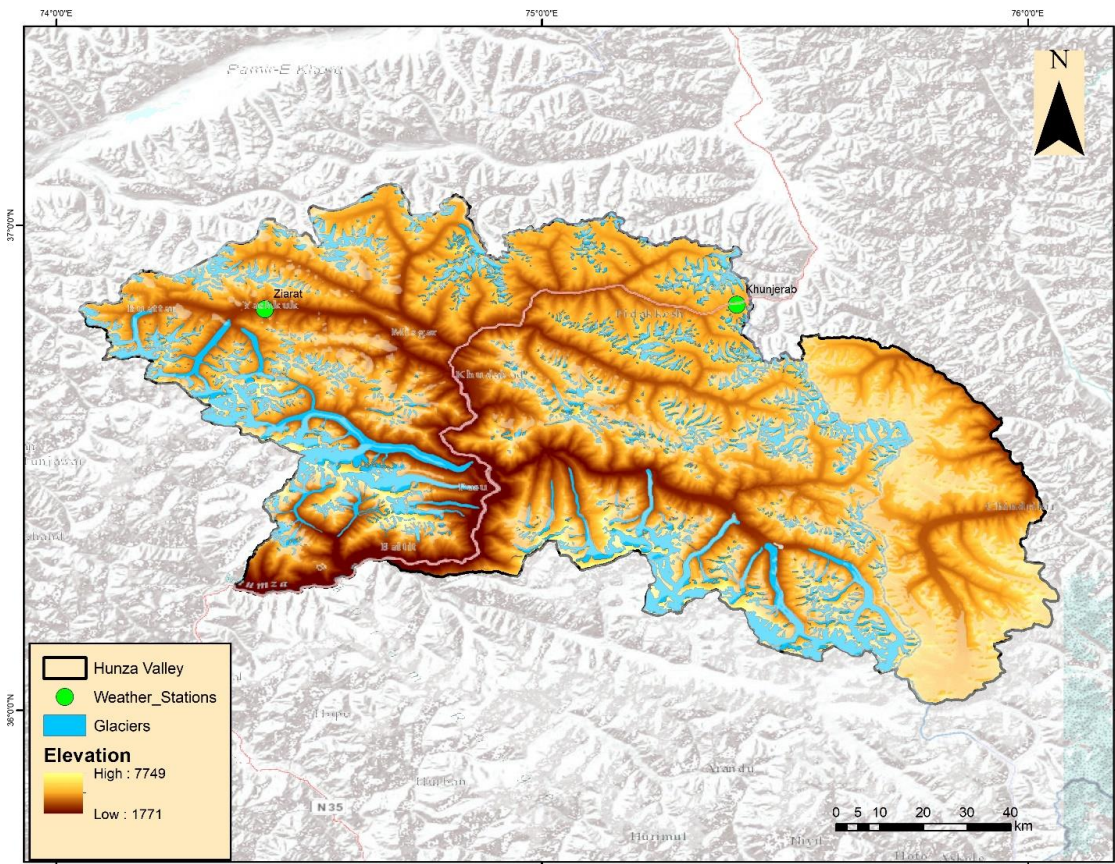
140   Figure 4 shows the altitudinal zones of the Hunza extracted from the Global Digital Elevation Model (GDEM) along
141   with glacier coverage and gauging stations.

Meteorological Data

142   Under the Pakistan Snow & Ice Hydrology Project (PSIHP), the Water & Power Development Authority (WAPDA)
143   made daily temperature, precipitation, relative humidity, and solar radiation data accessible for the two
144   meteorological Stations (Khunjerab and Ziarat) from 2000 to 2020. The Khunjerab station is located at an elevation
145   of 4730 m while the Ziarat station is at an elevation of 3669 m.

Data	Spatial Resolution	Temporal Resolution	Source
DEM	Grid (30 m)	Fixed	SRTM
Meteorological data	Point	Daily	Water and Power Development Authority (WAPDA)
Snow cover	Grid (500 m)	8-day maximum snow extent	MODIS Terra (MOD10A2)

146   Table 3 represents the summary of the datasets utilized in the research.

3.   Results and Discussion

3.1.   Climatic Trend Analysis

Temperature Trend Analysis

147   The months of April-August and September-March were assessed for temperature analysis, since both are classified
148   as two seasons (summer and winter, respectively) in the Hunza region, from 2000 to 2020. During the summer
149   season, the mean monthly temperature at the Khunjerab station is recorded at 10.22 °C, while the temperature
150   recorded at the Ziarat station is 24.09 °C. While during the winter season, the mean monthly recorded temperature at
151   Khunjerab and Ziarat stations is -4.39°C and 2.69 °C, respectively. Figure 5 represents the trend of mean
152   temperature for both summer and winter seasons from 2000 to 2020. From the figure, it could be seen that the
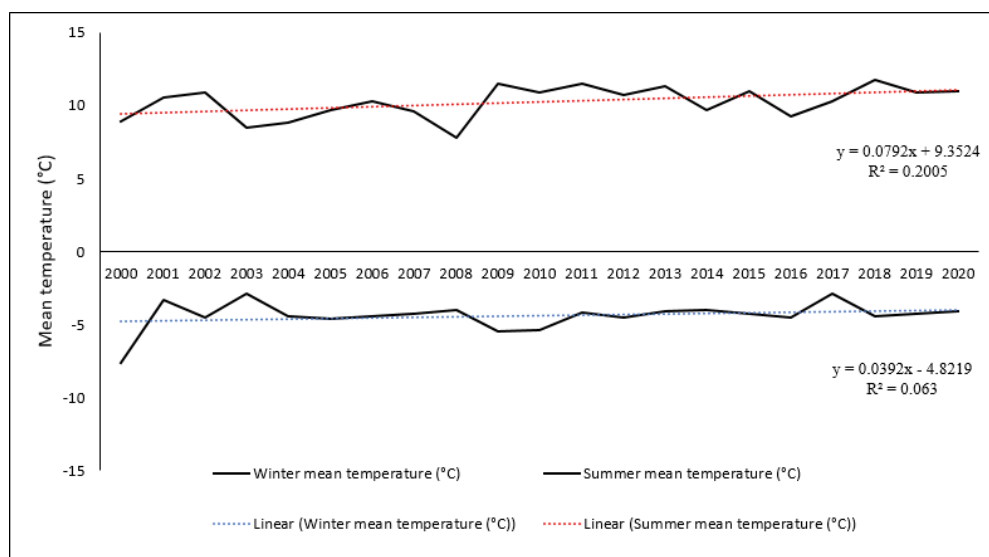153   temperature for both the summer and winter has an increasing trend.

154   Figure 5 Temperature trend in the Hunza region during both summer and winter seasons from 2000 to 2020.

155   The Mann-Kendall (MK) test shows a minute, non-significant increasing trend in winter average temperature, with a

156   rate of 0.176 °C/month, while, on the other hand, the average summer temperature also shows a non-significant but

157   more notable trend as compared to winter temperature, with a rate of 0.315 °C (Table 4). From this result, it could be

158   concluded that, at a seasonal scale, the summer season shows the highest rate of temperature change followed by the

159   winter season. Atif et al. (2018) observed an overall increasing trend in average temperature at the hunza catchment.

	Trend	**p-value**	**Slope °C/month**
Winter	Increasing	0.287	0.176
Summer	Increasing	0.052	0.315

160   Table 4 Summary of temperature trend analysis during both winter and summer sessions.

Precipitation Trend Analysis

161   During the summer season, the monthly precipitation at Khunjerab station was observed at 29.03 mm, while the

162   Ziarat station recorded monthly precipitation at 24.04 mm. On the other hand, during the winter season, monthly

163   precipitation recorded at Khunjerab station was 15.03 mm and 20.49 mm at Ziarat station, respectively. Figure 6

164   represents the general trend of monthly precipitation for both summer and winter seasons from 2000 to 2020. The

165   trend analysis shows that the summer precipitation is gradually diminishing concerning time while the winter

166   precipitation has an increasing trend from the period 2000 to 2020. According to (Hasson et al., 2014), the mean

167 annual precipitation at Khunjerab and Naltar stations within the Karakoram ranges from 200 to 700 mm,

168 respectively.
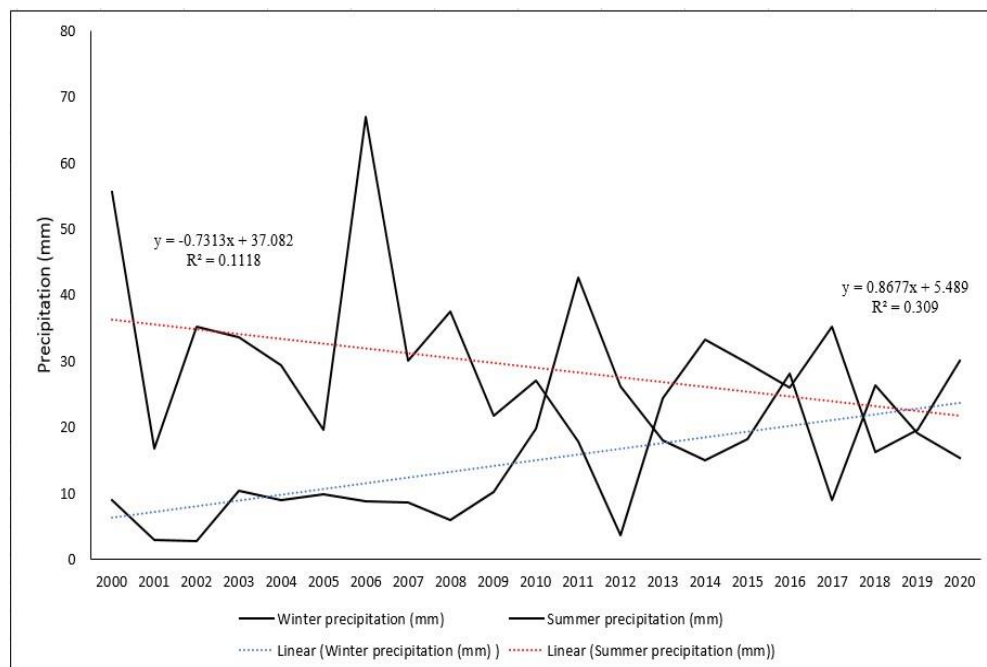
169 Figure 6 Precipitation trend in the Hunza region during both summer and winter seasons from 2000 to 2020.

170 The MK (Mann-Kendall) analysis of precipitation over the Hunza region reveals a significant increasing trend in

171 winter precipitation with a rate of 4.36 mm/month, and decreasing summer precipitation with a rate of -1.91

172 mm/month during the study period (2000-2020) (Table 5). Bilal et al. (2019) and Atif et al. (2018) Seasonal SCA in

173 the UIB is highly dependent on winter precipitation; consequently, an Increasing trend is observed in the

174 precipitation data. According to Tahir et al. (2011), a similar trend of increasing snow cover has been seen in the

175 Hunza basin due to increased winter precipitation. From 1961 to 2000, the Karakoram Mountains are reported to

176 have experienced a decrease in summer temperatures and a significant increase in precipitation (Fowler and Archer,

177 2006).

	Trend	p-value	Slope (mm/month)
Winter	Increasing	0.006	0.436
Summer	Decreasing	0.238	-0.191

178 Table 5 Summary of precipitation trend analysis during both winter and summer seasons.

3.2. Snow Cover Analysis of the Hunza Region

Snow Cover Dynamics during Summer Season

179   Analysis for the summer season shows that the average summer SCA (maximum extent) from 2000 to 2020 was

180   5630.83 km², accounting for 64.4% of the entire study region. During the summer season, the years 2014, 2004, and

181   2009 showed relatively more snow cover, with 6446.59 km², 6255.18 km², and 6138.27 km² in an area on average,

182   respectively of which SCA in 2014 showed the maximum snow cover, with 815.76 km² more area than the overall

183   average (2000-2020). Figure 7 represents the spatial variability of SCA during the summer season from 2000 to

184   2020.
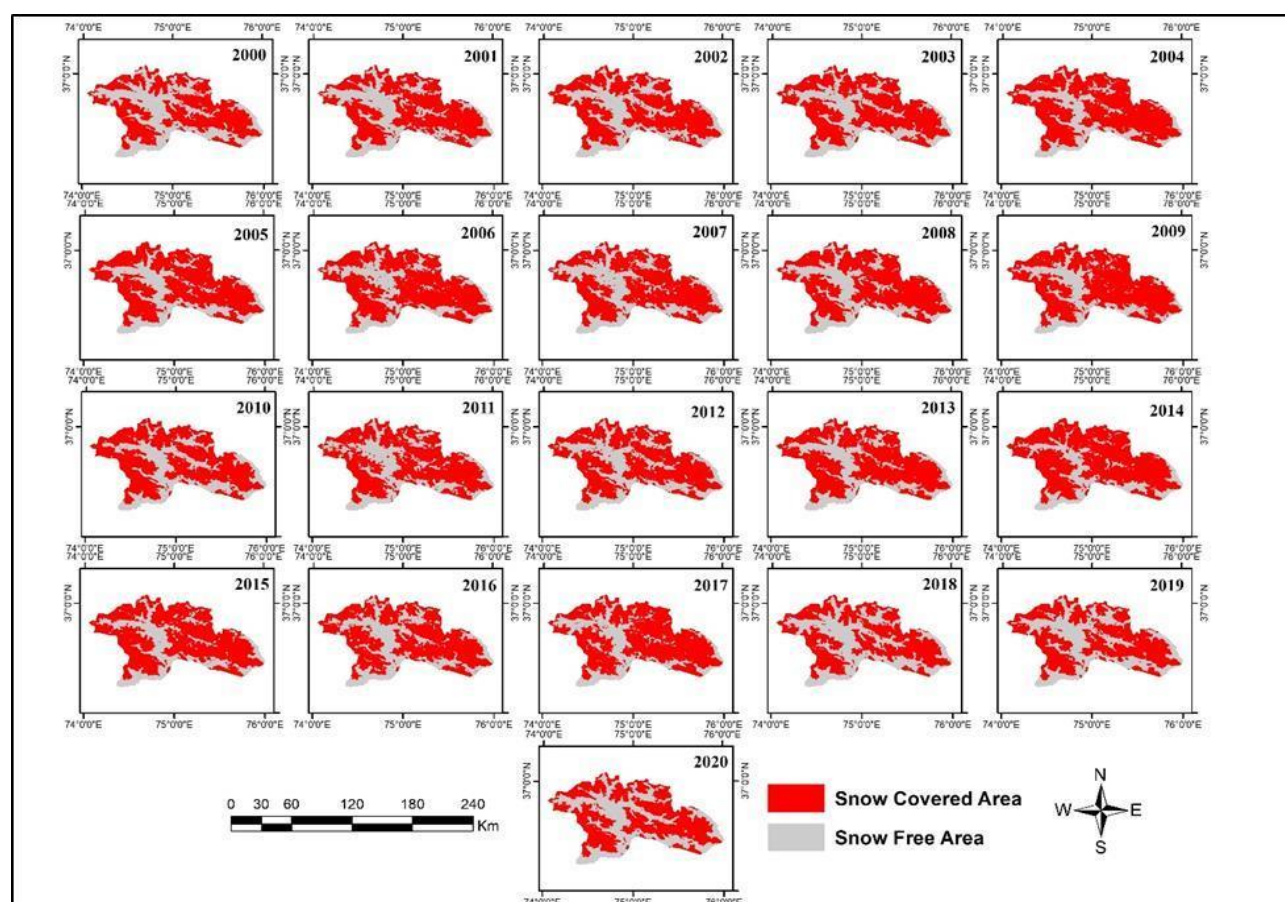
185   Figure 7 Spatial variability of snow cover during the summer season from 2000 to 2020.

186   The trend analysis of SCA during the summer season is shown in Figure 8 SCA analysis during the summer season

187   represents a non-significant declining trend for the period of 2000 to 2020. Tahir et al. (2011) the Snow cover area is

188   at a minimum 30–40 % in the summer (July to September). This declining trend in SCA is also observed in the

189   previous studies conducted for the Hunza region (Bilal et al., 2019).

$y = -0.0865x + 65.428$

$R^2 = 0.0108$
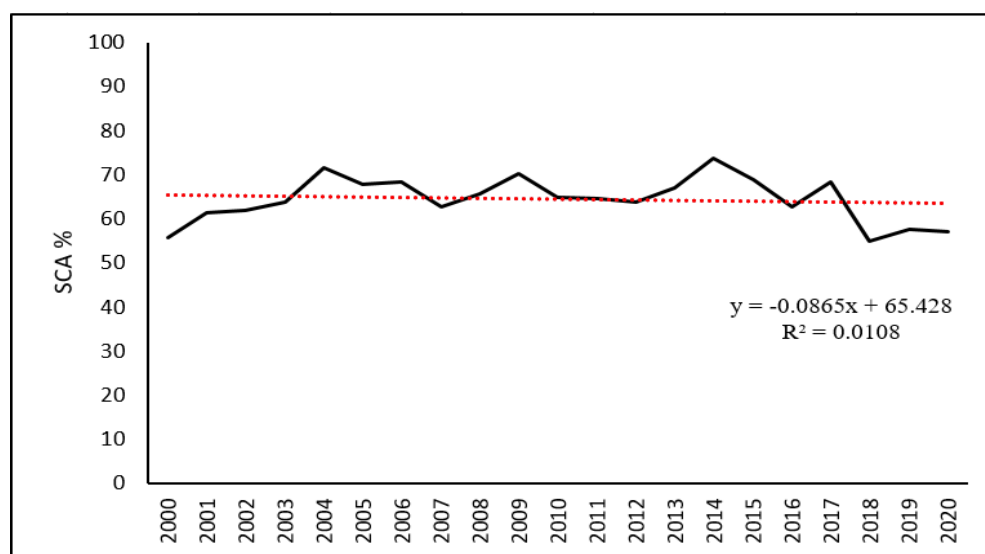
190   Figure 8 Trend analysis of snow-covered area during the summer season (2000-2020).

Snow Cover Dynamics during Winter Season

191   Analysis for the winter season shows that the average winter SCA (maximum extent) from 2000 to 2020 was

192   8126.61 km², accounting for 93% of the entire study region. During the winter season the years 2009, 2005, and

193   2018 showed relatively more snow cover, with 8419.89 km², 8338.28 km², and 8355.22 km² in an area on average,

194   respectively of which SCA in 2009 showed the maximum snow cover, with 293.28 km² more area than the overall

195   average (2000-2020). Figure 9 represents the spatial variability of SCA during the winter season in the Hunza region

196   from 2000 to 2020.
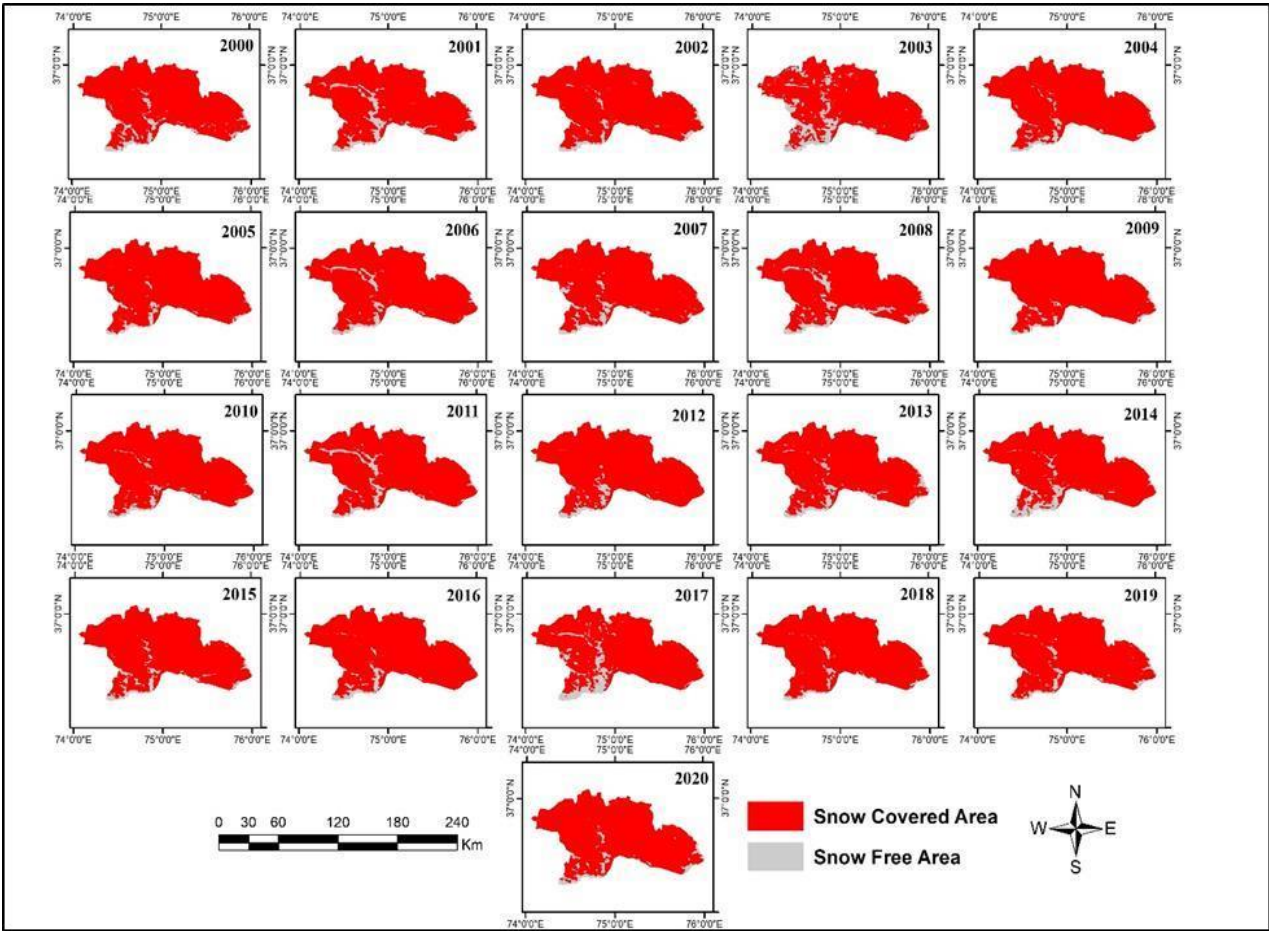
Figure 9 Spatial variability of snow cover during the winter season from 2000 to 2020.

The trend analysis of SCA during the winter season is shown in Figure 10 SCA analysis during the winter season represents a minute, non-significant increasing trend for the period of 2000 to 2020.
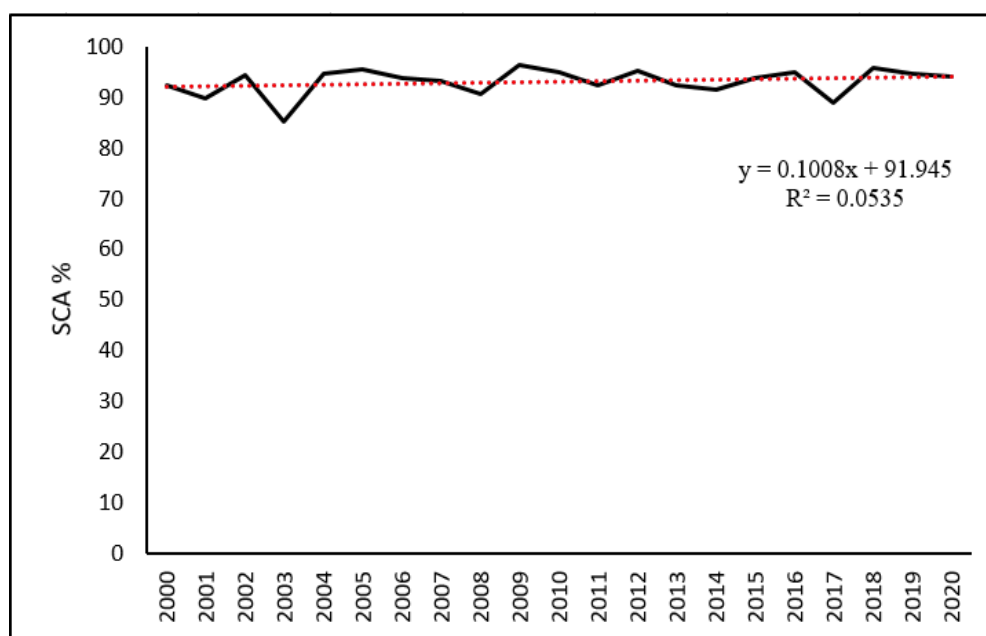
Figure 10 Trend analysis of snow-covered area during the winter season (2000-2020).

The Mann Kendall (MK) test shows a statistically significant increasing trend in winter SCA, with a rate of 0.114 km²/month. About 98% of the area of the Hunza basin lies above an elevation of 2000 m and about 32.5% of the Hunza basin area is located above 5000 m where the temperature remains well below freezing throughout the year, and which receives comparatively more snow due to the westerly system at this altitude. This could be the reason for the slight increase in snow cover and the advancement of some glaciers in the Hunza basin (Atif et al., 2018). According to Tahir et al. (2011), a similar trend of increasing snow cover has been seen in the Hunza basin due to increased winter precipitation. 32.5% of the Hunza Basin region is located above 5,000 meters above sea level, and the seasonal variation in snow cover ranges from 38 to 43%. At this altitude, temperatures remain below freezing throughout the year and precipitation tends to increase. This may be the reason for the increase in snow cover in the Hunza basin and the advance of some glaciers. (Hewitt, 2005; Archer and Fowler, 2004) also concluded that the increase in snow cover and the advancement of glaciers is due to the increase in winter precipitation due to the influence of westerly winds. While, on the other hand, a decreasing trend in summer SCA is observed at a rate of -0.0095 km²/month (Table 6). A positive SCA trend and a decreasing temperature trend during the winter season and a negative SCA trend and an increasing temperature trend during the summer season have also been observed in previous studies (Bilal et al., 2019; Tahir et al., 2011).

	Trend	p-value	Slope km^2 /month
Winter	Increasing	0.487	0.1142
Summer	Decreasing	0.976	-0.0095

15

216   Table 6 Summary of SCA trend analysis from 2000 to 2020.

3.3.   Zone-wise Snow-Covered Area Analysis

217   **Elevation Zone (A).** Between 1774 and 3000 meters above sea level, covering a total area of 342.24 km² (3.91

218   percent). During the winter season, around 32% of this zone is covered in snow. Figures 11 represent the snow cover

219   dynamics of elevation zone (A) during summer and winter, respectively. The analysis reveals no significant trend in

220   snow cover during the summer season, while the winter session shows an increasing trend, consistent with previous

221   studies (Bilal et al., 2019; Atif et al., 2015)
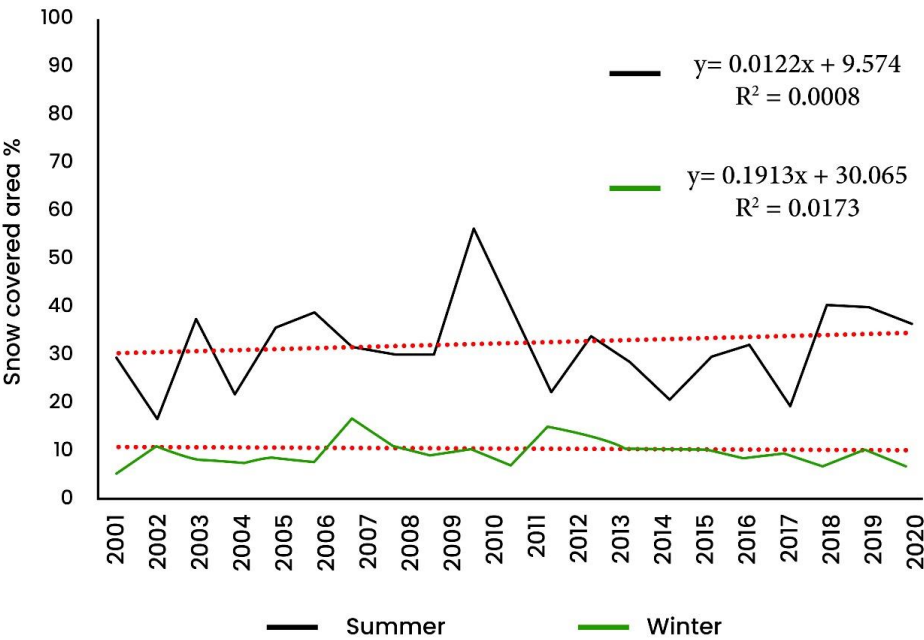
222   Figure 11 Snow cover variability in zone (A) during the winter season and summer session.

223   **Elevation Zone (B).** The zone (B) covers a total area of 2937.87 km² (33.64 percent). WAPDA has established only

224   one weather station in this zone, the Ziarat meteorological Station (3669 m). This zone has more persistent snow

225   cover as compared to zone (A) due to the higher elevation. According to (Bilal et al., 2019), a clear shift is

226   observable in snow accumulation and snowmelt periods in Zone (B) as compared to zone (A)   The SCA data

227   analysis of this zone also shows similar results as zone (A). The SCA during the summer season from 2000 to 2020

228   shows a linear trend while the SCA in the winter season shows an increasing trend. Tahir et al. (2011) the increasing

16

229   trends of precipitation continue to feed the high altitudes, particularly zone C, and result in the form of expanding

230   snow cover in the area. Figure 12 represents the trend of SCA in zone (B) during the summer season and winter
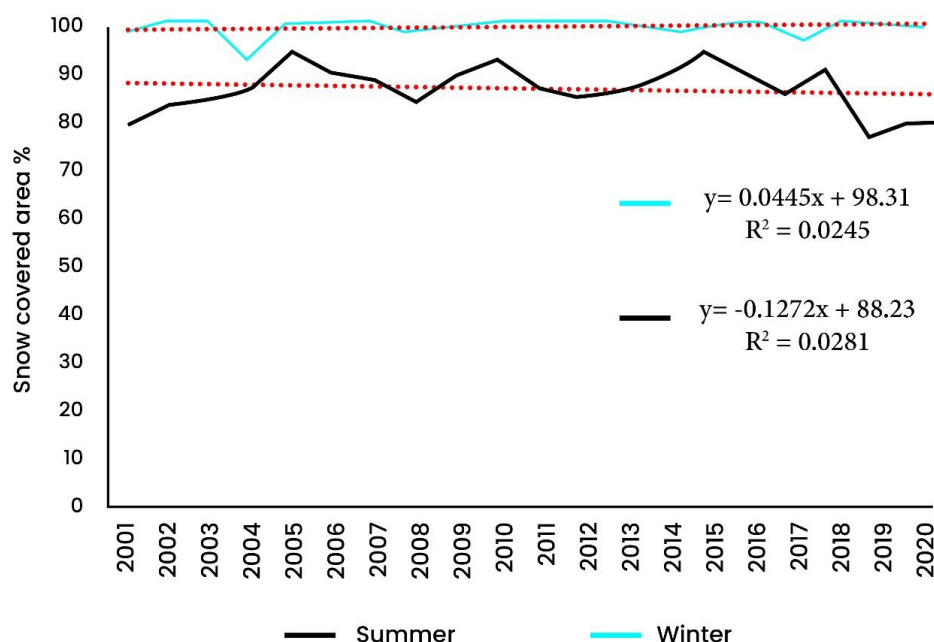
231   season, respectively.

Figure 12 Snow cover variability in zone (B) during the summer season and winter session.

233   **Elevation Zone (C).** is the most central zone, with only one meteorological station (Khunjerab station). The annual

234   temperature ranges from -3°C in March to 10°C in August. SCA is more persistent in this zone than in zones (A) and

235   (B) due to the higher elevation and lower mean temperature. In this zone the SCA trend analysis revealed a

236   decreasing trend during the summer season, while the SCA trend during the winter season is non-significant and

237   linear to some extent, as represented in Figure 13. According to (Tahir et al., 2011) The tendency for snow

238   accumulation shows a marked increase during peak snow periods from November to February across all altitudinal

239   zones, with the most notable increase observed in the elevation above 4500 meters above sea level in zone C. During

240   the minimum snow cover periods from June to September, a slight upward trend is also apparent in zone C. A

241   similar non-significant increasing trend was also observed in the zone (C) (Tahir et al., 2015).
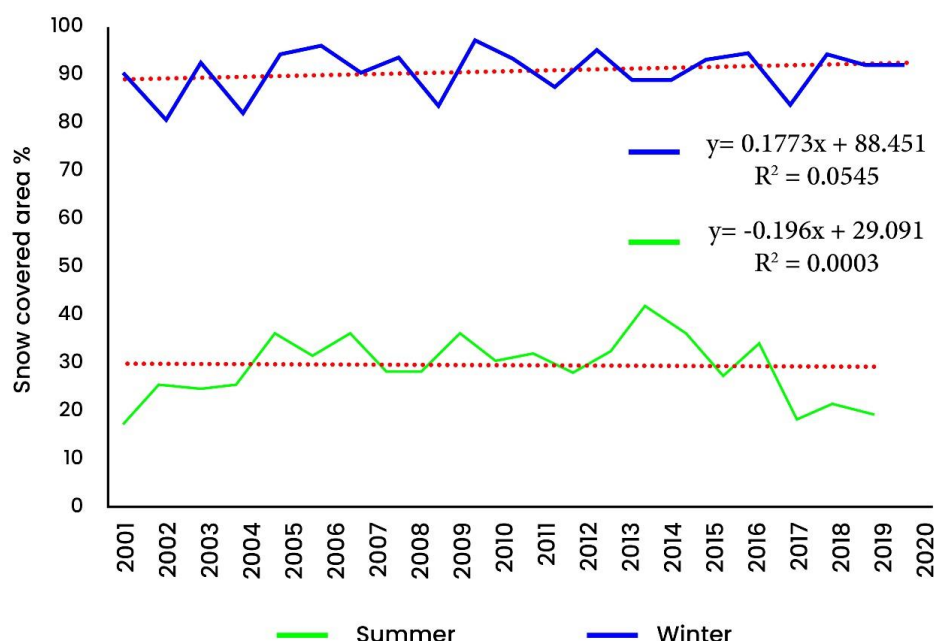
Figure 13 Snow cover variability in zone (C) during the summer season and winter session.

Elevation Zone (D). With a mean elevation of 6887 meters above sea level, Zone (D) is the highest elevation zone. Throughout the year, more than 90% of the land is covered with snow (Bilal et al., 2019). Over the previous 20 years, analysis of monthly data revealed no trend during the winter season because the entire area of this region is snow-covered during the winter season, while during the summer season, the snow-covered area persists because of the higher elevation and low levels of temperature throughout the year as represented in figure 14. According to (Bilal et al., 2019) SCA data further suggest significant increasing tendency during snow accumulation (τ=+0.062, p<0.05 S=+0.004% yr-1) and snowmelt (τ=+0.181, p<0.05, S=+0.08% yr-1). Apart from the years 2016 and 2017, SCA over this region, for the summer month shows homogeneity and a non-significant decreasing trend, as represented in Figure 14.
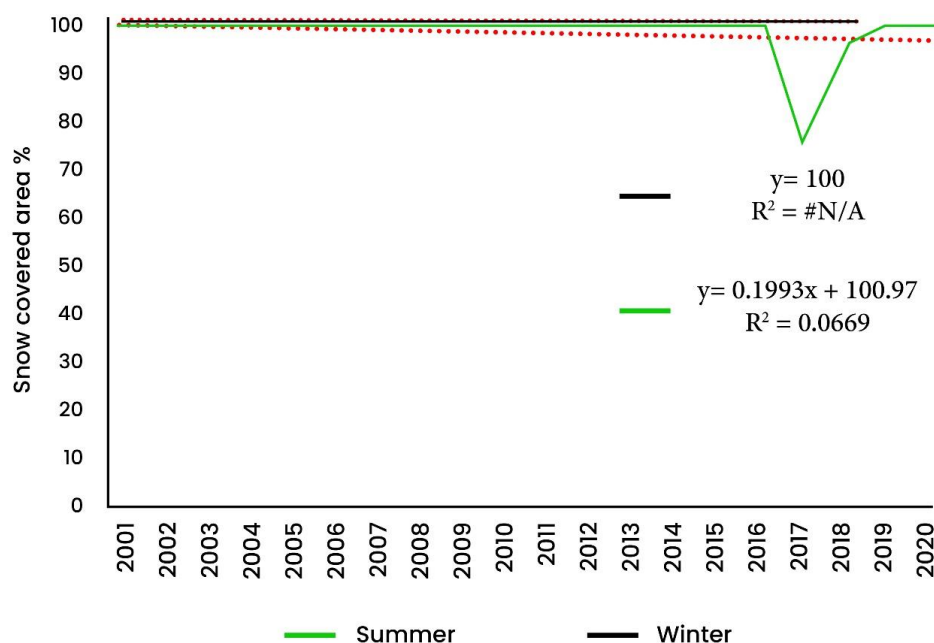
252 Figure 14 Snow cover variability in zone (D) during summer session and winter session

3.4. Seasonal Temperature and Precipitation Correlations with SCA

253 Figures 15 and 16 represent the correlations of SCA variability along with the variations in the meteorological
254 parameters for both the winter and summer seasons respectively. The years depicting high SCA values are in good
255 agreement with low- temperature observations and high precipitation. During the winter season, a sudden increase in
256 precipitation was experienced after 2008-2009 which started to diminish from 2011. However, during the winters of
257 2002-2003, a peak in temperature was detected as compared to the other years, with a sudden dip in snow cover
258 during the year 2003 despite significant precipitation. The sudden fall in SCA during 2003 despite high precipitation
259 indicates that temperature has a stronger correlation with snow cover compared to precipitation. Similarly, another
260 slightly increase in temperature was observed during 2016, and the 2017-time period, for which the year 2017 also
261 shows a sudden dip in SCA. The overall analysis shows, that the snow cover during the winter season is not much
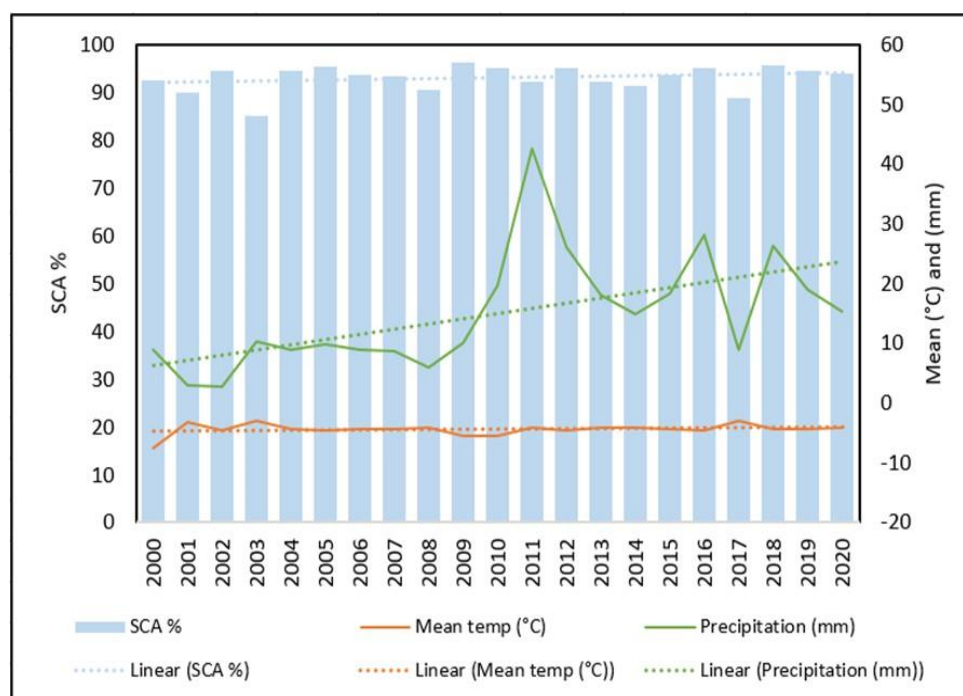262 variable and has a non-significant increasing trend at a minute level (Figure 15).

Figure 15 Snow cover variability in correlation with meteorological parameters during the winter season.

While, during the summer season, prior years 2014, 2004, and 2009 showed relatively more snow cover 6446.59 km², 6255.18 km², and 6138.27 km² respectively in an area on average which also correlates with the variations in temperature and precipitation along the Hunza region. From Figure 16 it could be concluded that the year 2014 has the maximum level of SCA because during the year temperature has a minute lag but the precipitation value has risen, thus both these factors positively affect the snow cover resulting in the maximum level of SCA during this year. The years 2018 and 2019 show less SCA as compared to other years because the temperature during these years has slightly risen and the precipitation has also decreased. So, both these factors adversely affect the SCA resulting in the low extent of SCA (Figure 16).
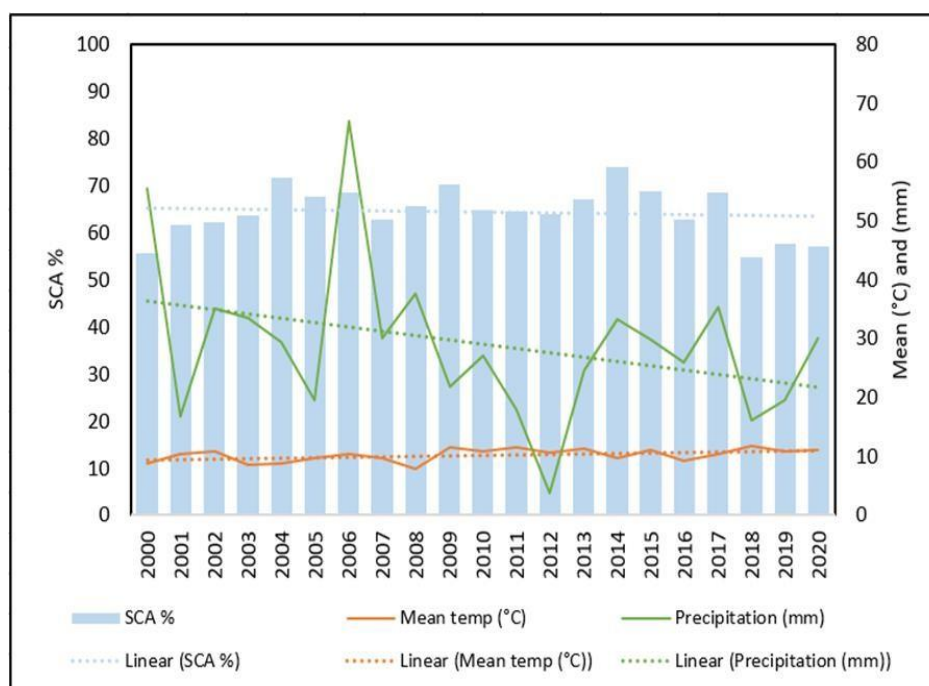
Figure 16 Snow cover variability in correlation with meteorological parameters during the summer season.

The strength of the SCA's correlation with temperature and precipitation was evaluated using Spearman's Correlation Method. The analysis shows a significant, strong negative correlation between SCA and seasonal mean temperature, with a correlation coefficient (r) of -0.804 for the winter season and -0.511 for the summer season over the past 20 years (Table 7). This implies that SCA and temperature are inversely proportionated. Figures 15 and 16 illustrate that the enhanced SCA coincides with decreased temperature and increased precipitation over the Hunza region.

	Winter	Summer
Temperature	-0.804	-0.511
	P<0.0001	P=0.620
Precipitation	0.371	0.182
	P=0.099	P=0.428

Table 7 Spearman's Correlation coefficients between SCA (maximum extent) and climate variables over Hunza during 2000–2020.

4. Summary

281   The Hunza sub-basin in the Upper Indus Basin (UIB) shows a substantial rise in snow-covered Area (SCA) above
282   4500m asl, standing in contrast to global snow cover patterns. Using MODIS satellite data (MOD10A2) and
283   meteorological data from 2000 to 2020, this study analyzed SCA trends and their relationship with temperature and
284   precipitation, supported by Mann-Kendall and Spearman correlation tests. The region experiences two distinct
285   seasonal snow periods: the summer season from April to August, during which the snow covers about 64% of the
286   area; and the winter season from September to March, during which snow covers about 93% of the total area. This
287   30-35% variation in snow-covered areas (SCA) contributes considerably to the continuous Indus River flow.
288   Generally, at the Sub-Basin Scale, the SCA of the Hunza region shows a non-significant advancing trend with a rate
289   of 0.114 km²/month during the winter season, while the SCA during the summer season shows a slightly decreasing
290   trend. This characteristic of SCA variability during both seasons can be attributed to the variations in the climatic
291   variables. During the winter season, the temperature trend of the Hunza region shows a minute level of increase with
292   a rate of 0.176 °C/month, but the amount of precipitation shows a significant increasing trend from 2000 to 2020,
293   which has ultimately resulted in the advancing trend of SCA during winter months. Apart from the significantly
294   increasing trend of precipitation, SCA is not progressing at a much greater extent during the winter season because
295   the temperature has a wide effect on SCA as compared to precipitation, canceling out the large increase in
296   precipitation. Similarly, during the summer season, the temperature trend shows a minute level of increase with a
297   rate of 0.31 °C/month, but at the same time, precipitation also has a decreasing trend that results in the decline of
298   SCA during this season. The precipitation levels during the winter increased due to Westerly circulation to the
299   Hunza region. The area receives precipitation in the form of snow due to its greater elevation, especially during the
300   winter season. The high elevation of the Hunza region, an increase in global precipitation, orographic precipitation,
301   the first encounter of winter westerly disturbances, increasing temperature, a shorter snow-melt season, and an
302   increase in relative humidity are all factors that contribute to the advancing snow cover and glaciers of the region.

Data Availability

Author Contributions

307   All authors contributed equally from the introduction to the conclusion under the supervision of the principal
308   investigator (PI). The study was completed through collaboration among all authors. Dr. Garee Khan supervised the
309   study and helped with graphs, maps, and manuscript writing, Mr. Muqeet Ahmed developed the main research
310   concept, conducted the study, and worked on graphs, maps, and manuscript writing, Mr. Shehzad Ali contributed to

Competing Interests

Disclaimer

Acknowledgements

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