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MODIS Observed Spatiotemporal Variation of Snow Cover in Zanskar Valley, North-Western Himalaya

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The investigation of variations in the snow cover in response to the ongoing climate change is crucial for the understanding of hydrological and climatological processes in the Himalaya. Apart from contributing significantly to river discharge, the extent of the snow cover influences glacier nourishment, melting dynamics, and the intensity of the summer monsoon. Considering that the meteorological data is often scarce and unevenly distributed in the high mountain region, remote sensing studies become particularly crucial. In this study, we investigate the spatiotemporal characteristics and trends of snow cover percentage in Zanskar valley using the Moderate Resolution Imaging Spectroradiometer (MODIS) eight-day snow cover product (MOD10A2) from 2001 to 2021. Our findings indicate that the proportion of snow cover in the Zanskar valley has not decreased significantly during the last two decades. The annual average snow cover in Zanskar is 68%, with a maximum in the month of March (96%) and minimum in August (32%). Trend analysis showed no change in the snow cover below an altitude of 3500 m above mean sea level (asl) during the study period. The majority of the changes in snow cover percentage occurred between an altitude of ∼4,500 and 5,500 m asl. An overall positive trend in the percentage of snow cover was observed from 2001 to 2021. The snow cover data was also compared to the Climatic Research Unit's (CRU) station interpolated data to look for any substantial contradiction; however any significant incongruity was not observed.

Keywords: snow cover, MODIS, remote sensing, western Himalaya, climate

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INTRODUCTION

Snow cover is an important component of the cryosphere and is inextricably linked to humans because it contributes to the river runoff, influences glacier melting dynamics, and plays a crucial role in the summer monsoon intensity (Pu and Xu, 2009; Bookhagen and Burbank, 2010; Lutz et al., 2016). Snow is the most dynamically active natural material on the planet because it accumulates and melts quickly (Gutzler and Rosen, 1992), contributing to river runoff, which is crucial in high mountain areas. Because it reflects back 80 percent of the sun's radiation falling on it, snow covers play an important role in the earth system's energy balance as well as the water budget. Snow cover has a significant impact on the global and regional climate systems, affecting the plant and animal ecosystems through a series of complex interactions and feedback mechanisms (Barry et al., 2007; IPCC, 2007). Furthermore, because snowfall and snowmelt are directly related to temperature fluctuations, quick response of snow cover's to climate change is one of the most reliable indicators and predictors of climate change (Chen et al., 2015). The Intergovernmental Panel on Climate Change (IPCC, 2007) stated in its 4th Climate Change Assessment Report that the rate of increase in global temperature will reach 0.2 K decade $^{-1}$ in the next 20 years, and that the projected continued rise in global temperature in 2013 suggested that snow cover would be reduced further by the end of the 21st century (IPCC, 2013). Around 45 percent of the land area in the northern hemisphere is covered in snow (Robinson, 2015). The total snow cover area in the northern hemisphere has decreased significantly as a result of climate change (Brown and Robinson, 2011; IPCC, 2013). However, there are significant regional disparities in the response of the snow cover to climate change (warming). As a result, the scientific community has placed a high priority on spatiotemporal monitoring of snow cover (Dye and Tucker, 2003).

Being the highest mountain chain of the world and encompassing huge snow cover and glaciated areas, the Himalayan ranges greatly influences the intensity and path of Indian summer monsoon (ISM) and monsoon variability and has a profound influence on the regional as well as global climate (Brown and Mote, 2009). In addition, the Himalaya plays a critical role in the hydrological resources of South Asia's major river basins. The seasonal melting of snow/glacier ice provides one-third of the annual discharge and nourishes major rivers of the region, which are the source of fresh water and caters millions of people living in the downstream areas (Fowler and Archer, 2005; Lutz et al., 2014). Snow cover and glaciers also play a significant role in winter tourism and many other developmental and recreational activities (Negi et al., 2013). As a result, the scientific community and policymakers place a high value on monitoring and analyzing the distribution and variation of snow cover in the Himalaya. Furthermore, snow cover monitoring has significant ecological implications, as changing snow cover patterns can have an impact on the region's biodiversity and permafrost.

IPCC (2007) has reported an increase in the global temperature by 0.6 ± 0.28°C since 1900 in response to the combined effect of natural and anthropogenic activities. The temperature of the Himalayan region has also increased in tandem with global warming. Negi et al. (2018) have analyzed the long term (1991-2015) winter temperature and precipitation trends in the North-West Himalaya (NWH) and found a rising trend in maximum, minimum and mean temperature in the NWH over a 25-year period, with total increases of 0.9, 0.19, and 0.65°C, respectively. Similarly, in recent decades, air temperatures in the western Himalaya have risen. Similarly, air temperatures in the western Himalaya have also risen in recent decades (Singh et al., 2015). The rising trends in the temperature in the Himalaya have resulted in substantial changes in the in the region's snow cover area and pattern. Gurung et al. (2011) and Immerzeel et al. (2009) found significant regional and year-to-year variation in snow cover in the Himalaya-Karakoram-Tibet (HKT) region over the last decade. Gurung et al. (2011) found a lower decline in Himalayan snow cover between 1990 and 2010 than Menon et al. (2010). They suggest that the snow cover area varies by season and geography, with a rising trend in the western and eastern Hind Kush-Himalaya and a declining trend in the central region. Between 2000 and 2014, Wang et al. (2016) found an increase in snow cover in the Amur River basin. According to Huang et al. (2016), there was little annual change in China's snow cover extent from 2000 to 2014. In a significant study, Wang et al. (2017) found no widespread decline in the snow cover of the Tibetan Plateau between 2000 and 2015. They further explained that the impact of temperature and precipitation on snow cover strengthens as elevation increases. Atif et al. (2015) discovered no significant changes in snow cover area in Pakistan's Upper Indus Basin between 2003 and 2013. Jain et al. (2009), Mir et al. (2015) and Shukla et al. (2017) have all emphasized the significance of topography characteristics in snow cover variability Singh et al. (2014) studied the variations in snow cover for three major Himalayan river basins: the Indus, Ganga, and Brahmaputra from 2000 to 2011, and discovered an increasing trend in the Indus Basin, but a subtle declining trend in the Ganga and Brahmaputra Basins during the same period. Despite this, Shafiq et al. (2018) found an increase in annual mean snow cover area in Kashmir valley between 2000 and 2016. All of these investigations have convincingly demonstrated the variability in snow cover extent across the Himalaya. As a result, it is necessary to investigate trends in snow cover at the local and seasonal scales.

Himalaya, along with the Karakoram and Tibetan Plateau is a very large and complex mountain ecosystem with high topographic and climate heterogeneity (Wambulwa et al., 2021), therefore understanding the snow cover area variation in each part of the range is critical for understanding the climatic signals. Many studies on snow cover area variability in the Himalayan and neighboring regions have been undertaken; however, additional research is required to investigate the ongoing variations in snow cover because the trends and patterns of snow cover distribution are geographically uneven. In this context, we aim at examining the variation of snow cover area in the Zanskar valley (NWH). Zanskar valley has been chosen purposefully due to the reported contrasting response of glaciers to climatic changes and it location in a climatologically sensitive transitional zone (Nathawat et al., 2008; Kamp, 2009; Pandey et al., 2011, 2012; Ghosh and Pandey, 2013; Ali et al., 2020; Taloor et al., 2021). As far as the glaciers in this region are concerned, some are retreating, while others are stagnant and only a few are reported to be advancing (Kamp, 2009; Pandey et al., 2012). Furthermore, the location of Zanskar valley is thought to be significant since it is located in a transitional climatic zone defined by the Karakoram range in the north, which is dominated by western disturbance (WD), and the Pir Pnjal range in the south, which is dominated by ISM. Being in the transitional climatic zone, any change in the intensity of winter (WD) or summer (ISM) weather patterns would have a significant impact on snow and glacier response, providing an opportunity to investigate the current role/contributions of weather systems in snow/glacier dynamics. As a result, deciphering climate signals from snow cover patterns may be important in comprehending the region's diverse glacier behavior

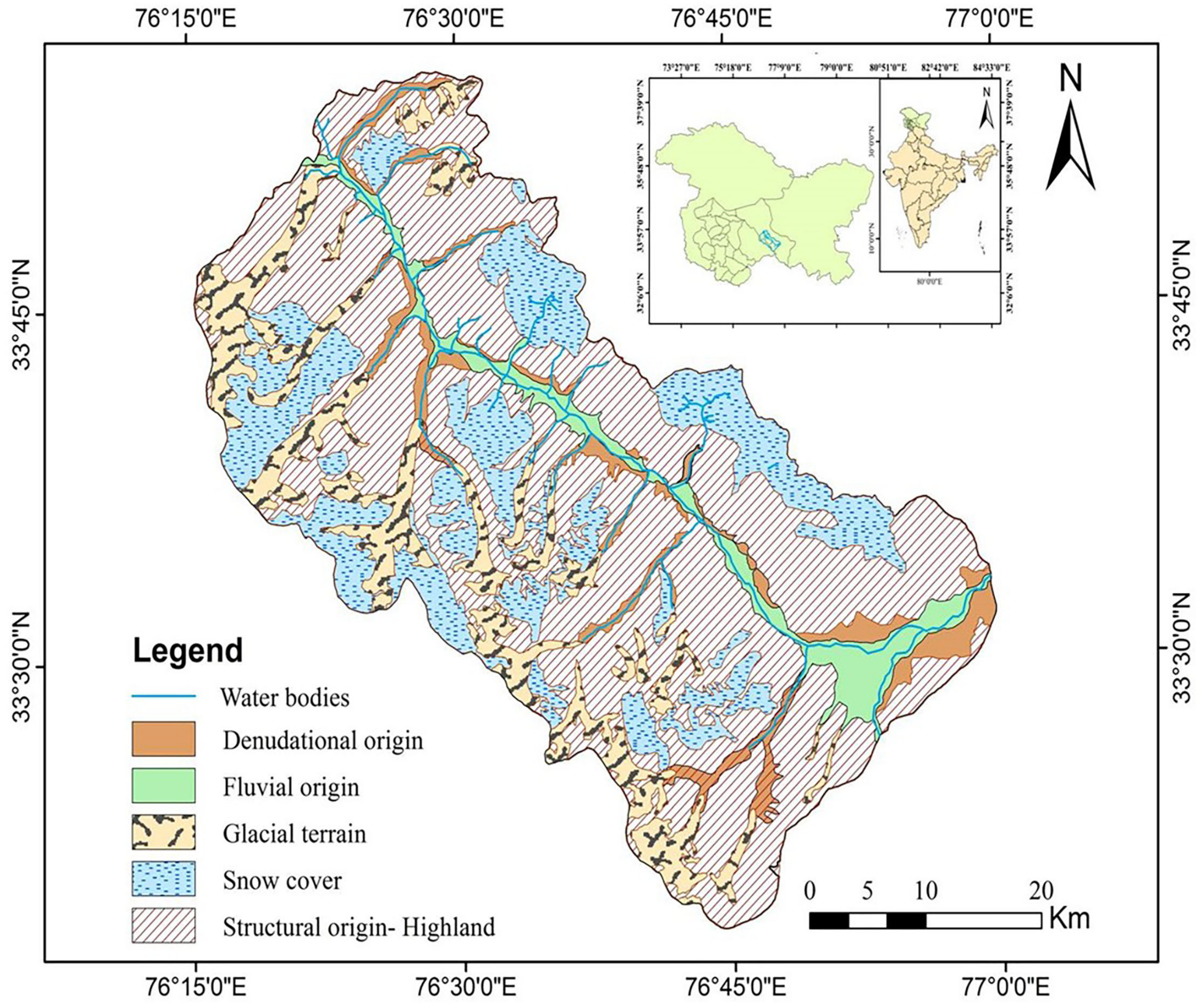

FIGURE 1 | The geomorphological map of the Zanskar valley along with it location. The map highlights water, sediments, glaciers and the snow cover. The insets show the NW Himalaya and the location of Zanskar valley in the region.

as well. Furthermore, quantification and monitoring of snow cover variability is critical for water resource domains. Winter snow and glacier melt are the principal sources of water in this region. According to research (Sabin et al., 2020), the Himalaya is warming faster than the Indian land mass, resulting in increased glacier melt, early snowmelt, and permafrost thawing, which is affecting the region's socio-economics. Understanding the critical significance of snow in many sectors necessitates quantifying and monitoring the region's snow cover area. Since the region's snow observatories are few and unable to provide accurate information on the distribution of snow cover underlying at various elevation ranges, space-based observed snow cover data from the Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day composite (MOD10A2) product has been used and analyzed for the years 2001 to 2021 to provide the most recent snow cover conditions.

STUDY AREA

The study area - Zanskar Valley – is located in the north-western Union Territory of Ladakh, India (**Figure 1**). The study area is situated between the greater Himalayan range in the southwest and the Ladakh range in the northeast and extends between latitudes 33° 18′ to 33° 53′ (N) and longitudes 76° 18′ to 76° 45′ (E),. The total area investigated in this study is approximately 2,156 km^2, with an altitudinal range of 3,450 and 6,500 m asl. This altitudinal range is primarily composed of the high mountains containing a significant amount of snow, ice, and glaciers, including Haptal, Yaranchu, Shimling, Mulung, Kanthang, Denya, Durung Drung (Koul, 2017). Zanskar Valley extends from Penzila-La, which is considered as the gateway to Zanskar and stretch up to Padam, headquarter of Zanskar region. The Zanskar valley is located in the shadow zone of Great

Himalaya and hence has a distinct climatic characteristic. The winters are very harsh (cold) with mean minimum temperature ranging from −15 to −35°C from November to May, while summers are short lasting only from June to September with temperature ranging from −8 to 25°C (Koul, 2017). The major amount of precipitation brought to the region is by the

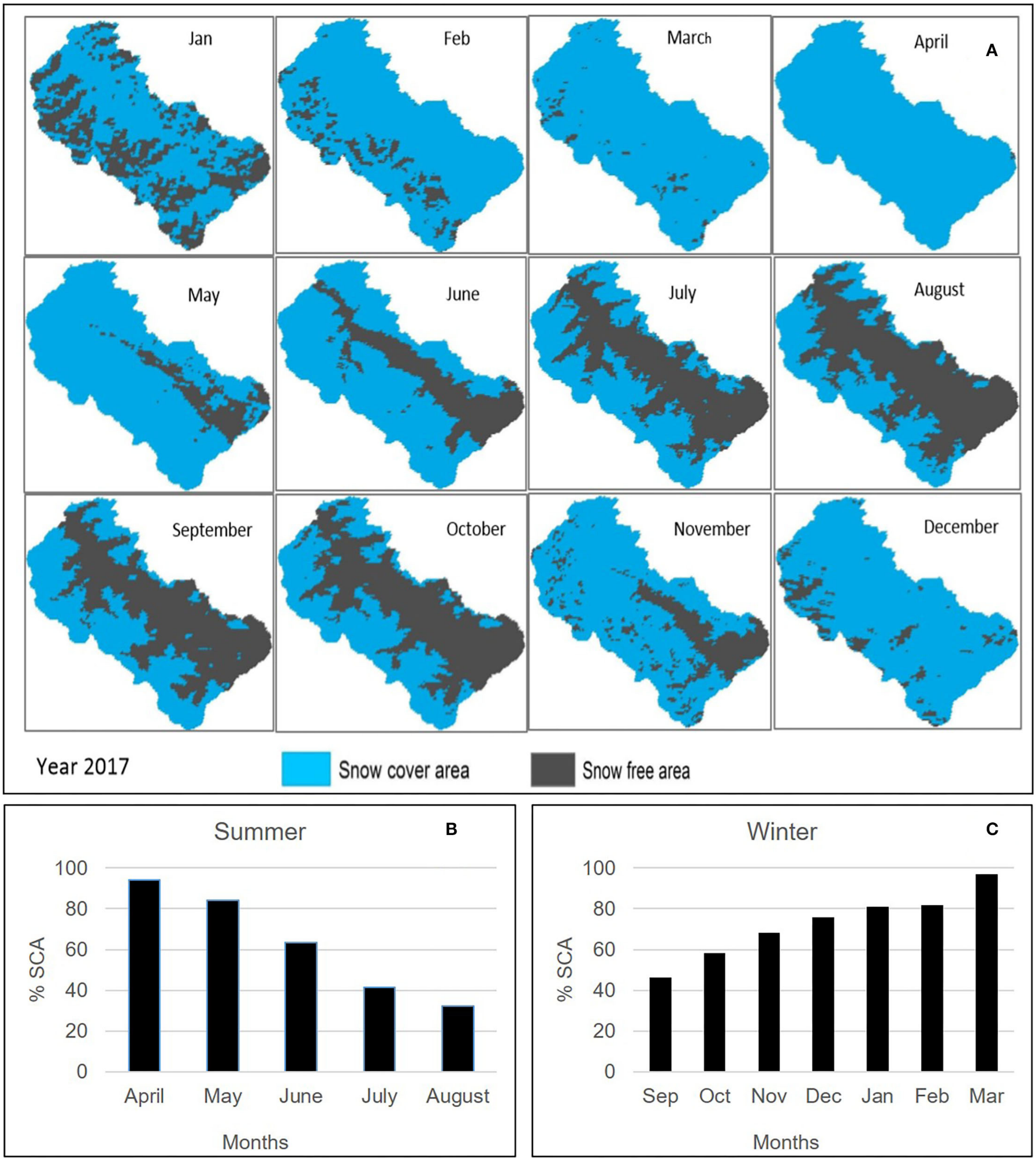

FIGURE 2 | (A) Monthly snow cover area distribution map of Zanskar valley from January to December for the year 2017; **(B)** Average snow cover during ablation season i.e., summer consisting of April-May-June-July and August months; **(C)** Average snow cover during accumulation i.e., winter season including months from October to March.

Mediterranean influences of the mid-latitude westerlies. The majority of winter precipitation falls in the form of snow (Fort, 1983). The glaciers located on the Zanskar Valley's southern flank are larger in number than those on the northern flank. The glaciers on the southern flank flow northeast, and because of the lower solar radiation and the presence of cold air masses, their size is noticeably larger than the glaciers on the northern flank (Raina, 2016). Raina (2016) has discussed in details about the role of the slope and orientation in the growth of glaciers in Zanskar Valley.

Datasets and Methods

MODIS Eight-Day Snow Products

The MODIS snow cover product has been available from the National Snow and Ice Data Center of the United States (NSIDC) since March 2000. In MODIS' snow mapping algorithm, the Normalized Difference Snow Index (NDSI) is used to differentiate between snow and non-snow areas based on reflectivity in visible and near-infrared ranges (Hall et al., 1995). The NDSI uses the reflectance of MODIS band 4 (0.545–0.565 μm) and band 6 (1.628–1.652 μm) and a threshold value of >0.4 to differentiate between snow and non-snow regions. Level−3 eight-day snow cover data (MOD10A2) with a spatial resolution of 500 m were used in this study. MOD10A2 is a composite of MOD10A1 data collected over 8 days, from day one to day eight, and compiled in such a way that the product has maximum snow cover and minimal cloud cover. Several studies have found that MODIS 8-day maximum snow products (MOD10A2) and ground observations are in reasonable agreement (Wang et al., 2008). Furthermore, as compared to the daily snow cover product MOD10A1, MOD10A2 has a lower cloud coverage in the data (Xie et al., 2009). In MOD10A2, different pixel values represent distinct ground objects: 0 represents missing data, 1 represents no decision, 11 represents night, 25 represents no snow, 37 represents lake, 50 represents cloud, 100 represents lake ice, and 200 represents snow (Riggs et al., 2006). If snow cover is detected on any of the 8 days, the pixel will be labeled as snow; however, if cloud cover is detected on all 8 days, the pixel will be labeled as cloud cover. As a result, the MOD10A2 product provides highly reliable data that is being be used to accurately investigate the spatial and temporal variation of snow cover over the Himalayan region. For this study, a total of 17 years of MOD10A2 datasets were obtained, spanning the dates of February 26, 2000, and December 31, 2021. In the ArcGIS 10.5 environment, the sinusoidal projection of MOD10A2 datasets was converted to the Universal Transverse Mercator (UTM) Zone 43 projection on the World Geodetic System (WGS84). The trend analysis of snow cover variation employed scenes with less than 15% cloud cover of the overall research area. Instead of using the data, if the cloud cover for a specific day was greater than 15%, the snow cover for that date was replaced by linearly interpolating the prior and next available cloud-free photos (Shukla et al., 2017). Snow and non-snow-covered pixels were separated on the re-projected images, and a binary map with only two classes was generated. The monthly snow-covered regions were calculated using the average of the 8-day snow cover maps for each month, for each investigated elevation class, aspect, and slope range.

TABLE 1 | Percentage (%) Snow cover area (SCA) distribution for different aspect and slope classes.

Aspect	%SCA	Slope	%SCA
N	8.66	0–10	10.25
NE	9.02	10–20	15.22
E	10.01	20–30	18.13
SE	8.56	30–40	17.26
S	6.95	40–50	10.54
SW	7.48	50–60	4.20
W	10.28	60–70	0.83
NW	10.72	70–80	0.03

Aster Gdem

For the terrain analysis of snow cover area in the Zanskar valley, Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) 30-m spatial resolution Global Digital Elevation Model Version 2 (GDEMV2) (jointly produced by Ministry of Economy, Trade, and Industry, Japan and United States NASA) was used. Since June 2009, ASTER GDEM, which was created, using ASTER near infrared (NIR) band stereo-pairs, has been available to researchers all over the world. The ASTER GDEM is made up of 22,600 1° by 1° tiles that cover land surfaces between 83°N and 83°S. Pre-production estimated (but not guaranteed) accuracies for this global product were 20 at 95% confidence for vertical data and 30 m at 95% confidence for horizontal data. The ASTER GDEM meets the pre-production accuracy predictions in most cases, according to preliminary validation studies. The GDEM was re-sampled to match the resolution of MOD10A2 data for carrying out various terrain analyses.

Climate Data

The MODIS observations were compared to station interpolated precipitation and temperature data obtained from the Climatic Research Unit (CRU-TS 4) for the period 2000-2020. CRU is a gridded climate dataset with 0.5° latitudinal and longitudinal grid cells that include six independent climate variables (mean temperature, diurnal temperature range, precipitation, wet-day frequency, vapor pressure and cloud cover) derived from monthly meteorological observations made at various meteorological stations around the world (Harris, 2013). In this study, we have only analyzed precipitation and temperature data for Zanskar valley.

RESULTS AND DISCUSSIONS

Snow Cover Characteristics in Zanskar Valley

The distribution of snow cover in Zanskar valley exhibits significant spatio-temporal heterogeneity. The percentage snow cover area has been estimated as the ratio of pixels recognized as snow and the total number of pixels (multiplied by 100). On the basis of distinct weather conditions, a year in Zanskar valley has four distinct seasons i.e. winter (November-December-January-February), Spring (March-April-May), Summer (June-July-August), and Autumn (September-October), with dates that correspond to traditional categorization. These four seasons can be divided into two glacial seasons: accumulation (September, October, November, December, January, February, and March) and ablation (April, May, June, July, August). For clarity, the accumulation and ablation seasons are now referred to as the winter and summer seasons, respectively, in the manuscript.

The seasonal variation in the snow cover area in Zanskar as observed from the analysis of the results was very distinctive (**Figure 2A**). In the month of March, snow cover reached a peak

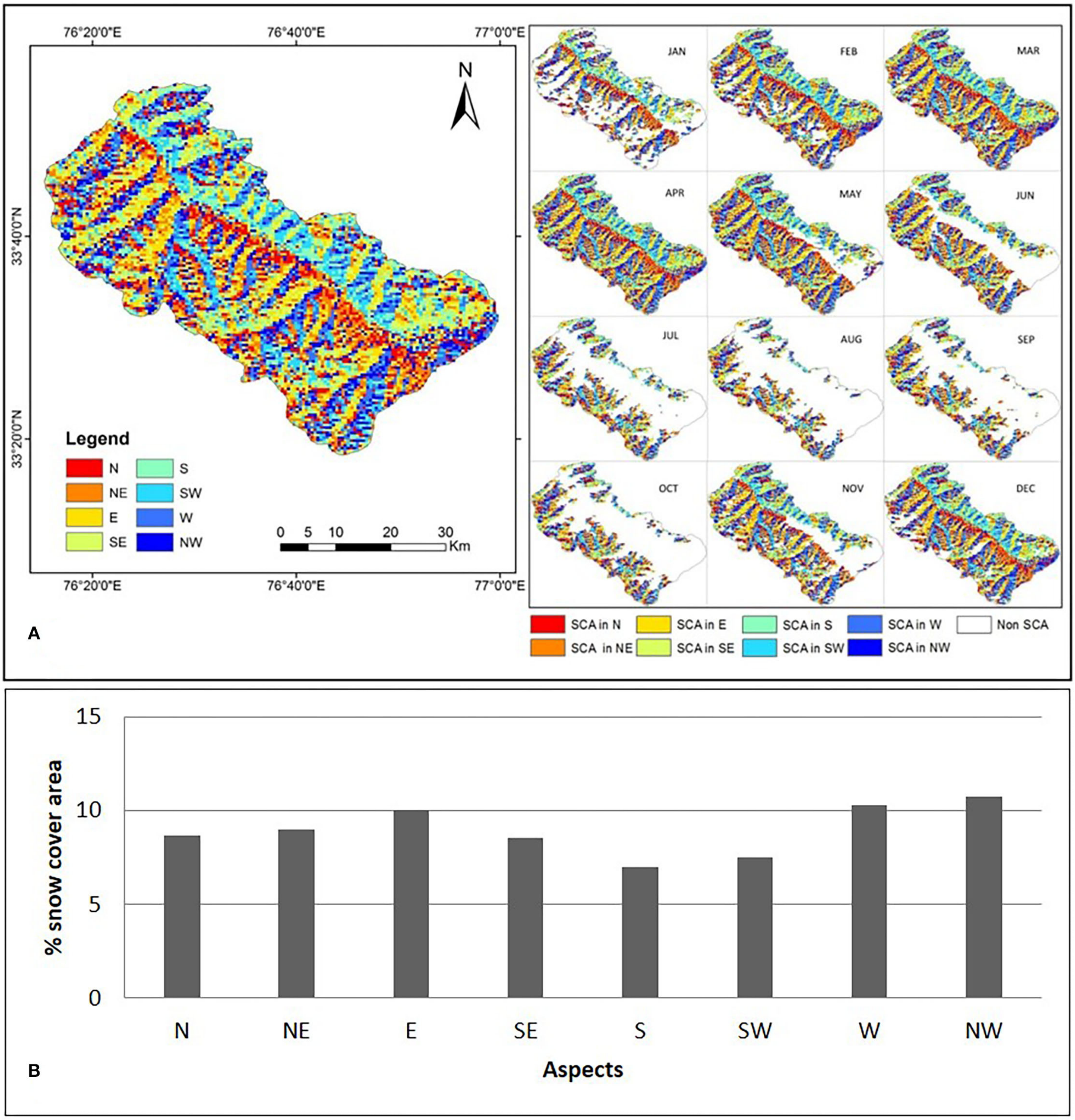

FIGURE 3 | (A) Monthly distribution of snow cover for different aspect classes; **(B)** Mean Snow cover % in each aspect class in Zanskar valley.

of around 96 percent of the valley's total area. The snow began to melt in April, but a substantial percentage of it remained, approximately 94 percent, decreasing to 84 percent in May. Our findings are in accordance with suggestions of a maximum snow cover extent in the Himalayas at the start of spring (Immerzeel et al., 2009; Bookhagen and Burbank, 2010). The occurrence of maximum snow cover during the start of spring is ascribed to maximum snowfall and rainfall rates in the Himalaya during the spring, which is also associated to maximum snow depth (Ménégoz et al., 2013).

After May, the snow melts more quickly and reaches a nadir in August, covering just 32% of the valley's total area, leaving only high peaks and glaciers to hold the snow. Snow begins to accumulate again in September and gradually increases until a sudden rise in March (**Figure 2B**). In September, around 46% area of the region is covered with snow (**Figure 2C**), which

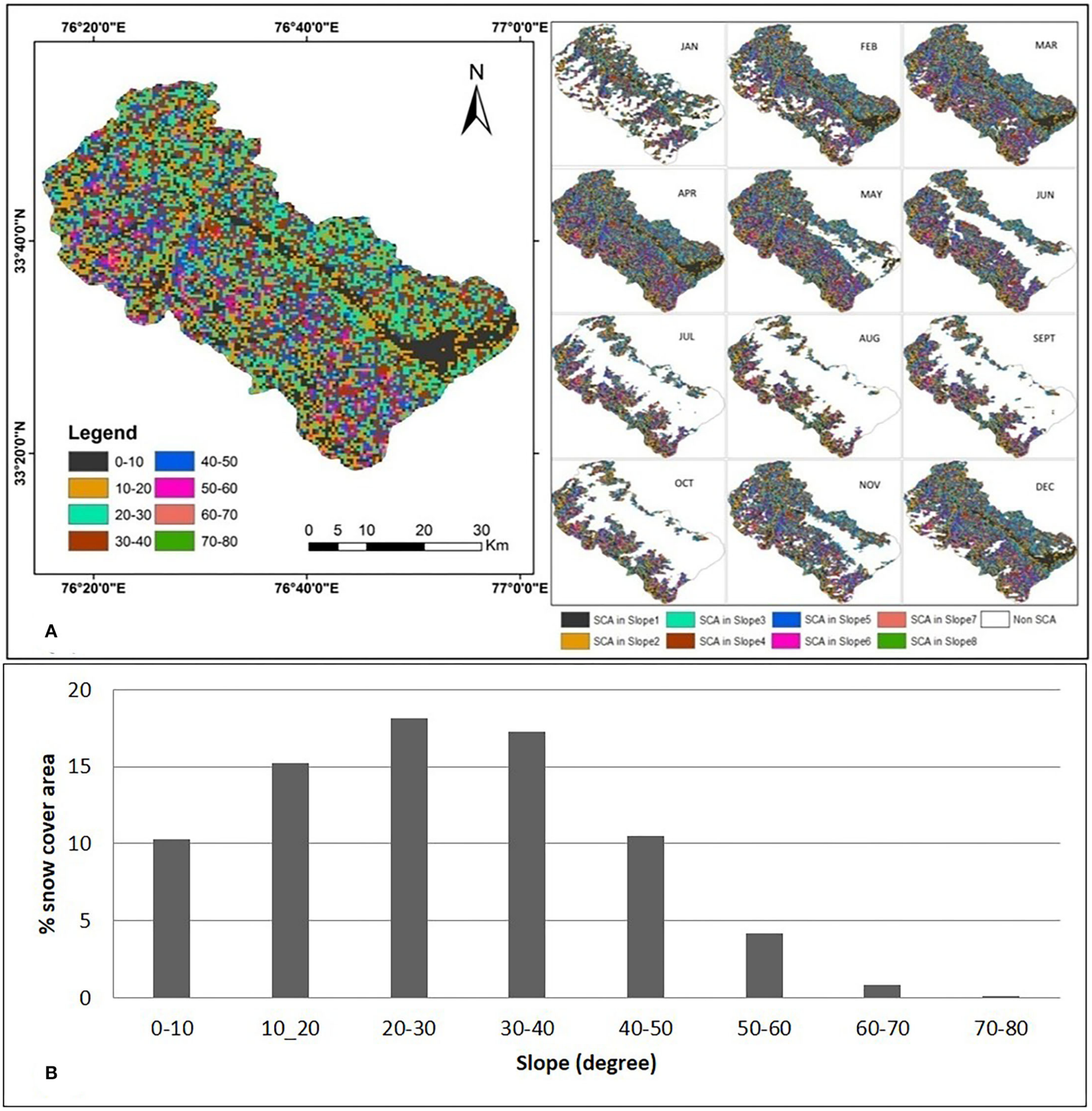

FIGURE 4 | (A) Monthly snow cover distribution is different slope classes in Zanskar Valley; **(B)** percentage of mean snow cover in different slope classes in Zanskar valley.

gradually increased and reached a maximum in March, covering 96% of the total valley's area. The ablation is more gradual than the accumulation of snow in the valley.

The average annual snow cover in Zanskar was 67% during the research period. According to Shafiq et al. (2018), the Kashmir Himalaya has the least snow cover in July and the most in January, owing to the congruence of western disturbances and the cold season in the north-western Himalaya. However, the present study revealed that the, least snow cover in Zanskar valley is in August and maximum in the March. This would imply that the snow accumulation/ablations dynamics in the Himalaya are determined by factors other (like geographical location, extant weather system) than elevation (Banerjee et al., 2021). These findings appear to contradict predictions that the duration of seasonal snow cover in the Himalayan region will shorten and snow cover will melt faster than it does now, resulting in a water deficit in spring and early summer (Lemke et al., 2007). However, given the Himalaya's continuously rising temperature trend, the foregoing predictions, such as rapid snowmelt, decreased snow cover, and more glacier retreat, cannot be ruled out.

The aspect-wise distribution of snow in the Zanskar valley is depicted in **Table 1** and **Figures 3A,B** for eight aspect classes. Results revealed that the maximum percentage of snow cover in the valley was in the north-western orientation followed by north-eastern side. The aspect-wise analysis of the snow cover in the basin clearly demonstrated that the basin is dominated by westerlies in the winter, which could explain why the northern slopes have the most snow cover. Furthermore, this could be attributed to the fact that slopes with southern orientations receive more sun radiation, which accelerates snow melt and results in reduced snow cover area (Sharma et al., 2014; She et al., 2015; Banerjee et al., 2021). Similar aspect wise snow cover was also observed in upper part of Satluj basin by Shukla et al. (2017). Therefore, it is evident that the dominant orientation of the valleys and slopes determine the snow cover area to a large extent.

Another topographical parameter that has a significant impact on snow cover distribution is slope. The majority of the snowfall in the Zanskar valley occurred on slopes ranging from 10 to 40 degrees. The 20–30° slope range has the highest proportion of snow cover, accounting for 18% of total snow cover area. The slopes above 70° had minimum snow cover area, and the steepness of the surface where snow could not accumulate is implicated (**Figure 4**, **Table 1**). This would imply that the slope-aspect orientation play an important role in influencing land surface processes such snow deposition, solar irradiation, surface energy balance, and surface temperature (Jain et al., 2009; Sharma et al., 2014; Kour et al., 2016; Banerjee et al., 2021). Similar snow

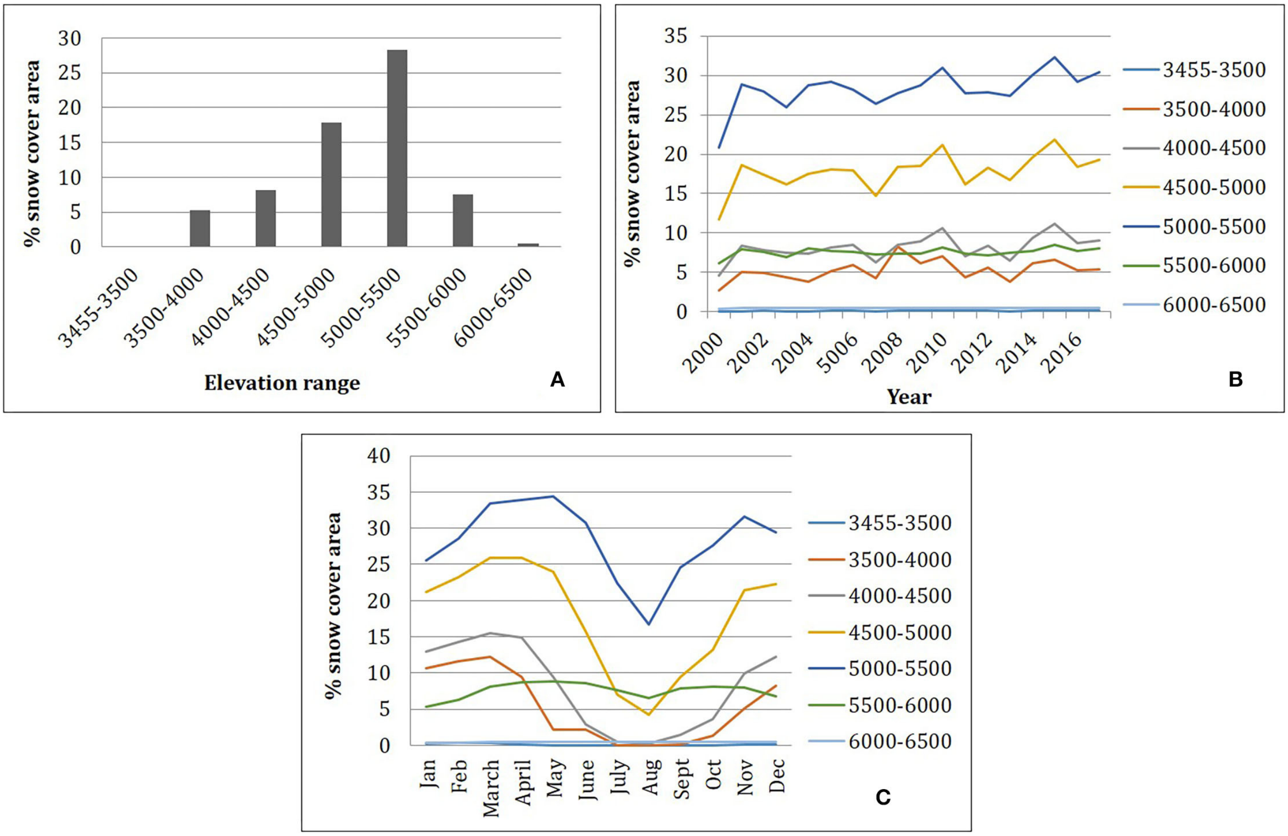

FIGURE 5 | Snow cover distribution under each altitude zones, **(A)** average snow cover area at 500 m altitude interval; **(B)** the annual variation in the snow cover area at each altitudes; **(C)** the monthly variation in the snow cover area for different altitudes.

cover distribution was also reported by Shukla et al. (2017) for Satluj basin.

Altitudinal Distributions of Snow Cover Area

Zanskar valley has a complicated topography as the valley stretches between 3,450 and 6,500 m asl altitude range. The hypsometric analysis of the valley revealed that most part of the valley lies between the altitude ranges of 4,500 and 5,500. Only a small portion of the area lies above 6,000 m asl and below 3,500 m asl. Because of the undulating terrain, it is important to investigate the spatial heterogeneity of the snow cover trends at different altitudes zones. To analyse the topographical diversity of snow cover distribution and trends in variance, the entire valley was divided into 7 classes at 500 m intervals ranging from 3,500–6,500 m asl. As seen in **Figure 5A**, the majority of the snow falls between 4,500 and 5,500 meters above sea level on a yearly basis. On an annual average scale, less than 1% of the land was covered by snow above 6,000 m asl and below 3,500 m asl. The trend analysis revealed that the snow cover area did not vary considerably below 3,500 m asl during the study period. A similar trend was observed above the elevation of 6,000 m asl where no substantial change in snow cover area was found. There was a slight increasing trend in snow cover area above 3,500 m asl. The increasing trend was distinct at elevations above 4,000 m asl. In general, the region has a constant to increasing trend in snow cover. The altitude wise snow cover % variation has been shown in **Figure 5B**.

Above 6,000 m asl, altitude-wise monthly snow analysis revealed almost minimal changes in snow cover throughout the year. In July and August, almost all of the snow melts below

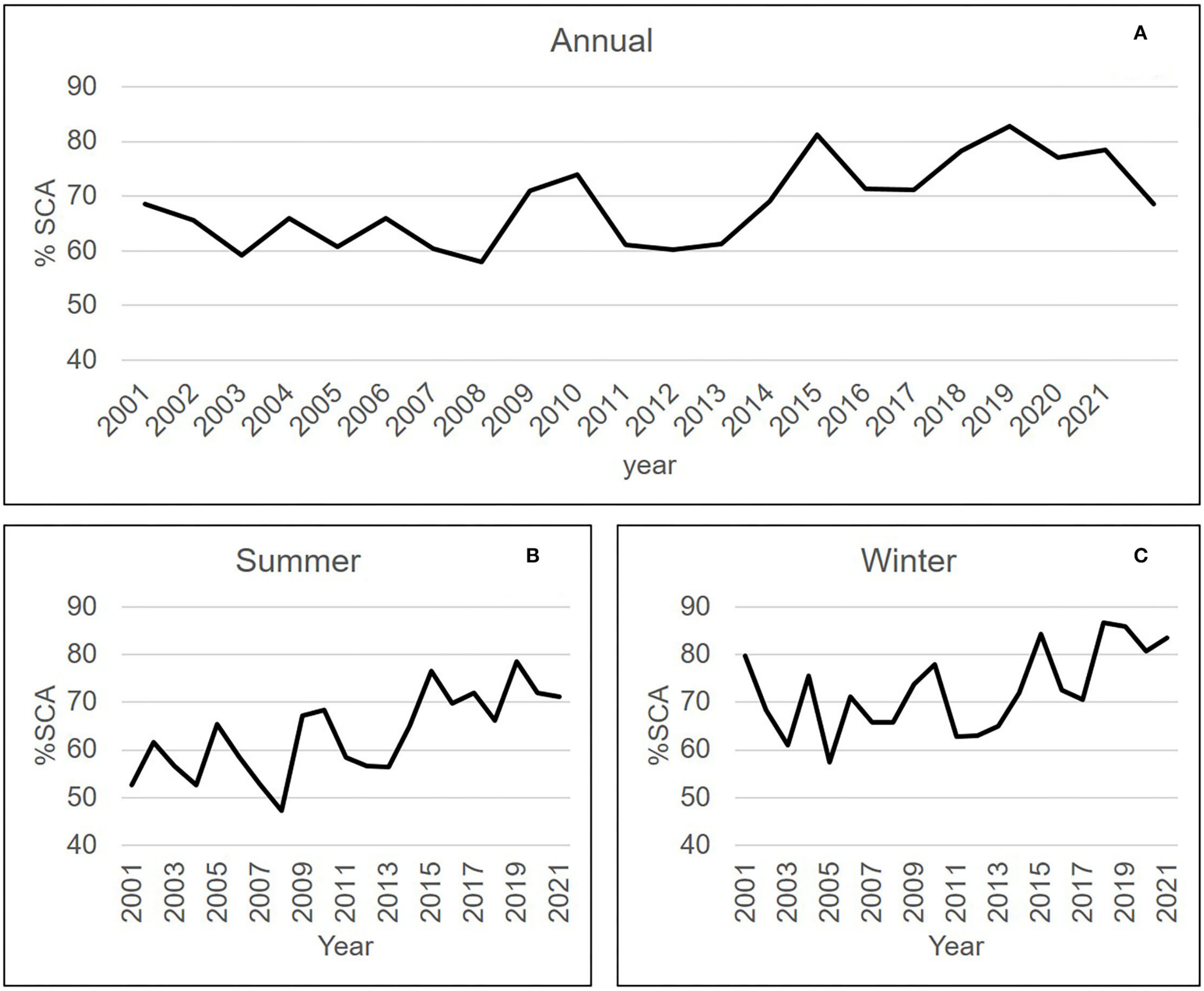

FIGURE 6 | (A) Annual average of snow cover variation from 2001 to 2021; **(B)** average snow cover variation for ablation season (AMJJA) and; **(C)** average snow cover variation for accumulation season (SONDJFM).

4,500 m asl. In July and August, between 4,500 and 5,000 m asl, about 5% of the terrain remained snow covered. Above 5,000 m asl, there is a persistent snow cover area with limited melting in the summer. In the last two decades, the elevation range between 5,500 and 6,000 m asl has shown the least seasonal change in snow cover area (**Figure 5C**).

Annual Snow Cover Distribution and Trends

Observational data from the northwest Himalaya show a significant warming during the winter season (Negi et al., 2018). However, as shown in **Figure 6A**, the snow-covered area over the Zanskar valley did not show any decline over the last two decades between years 2001 and 2021. The annual average snow cover area in the valley showed an increasing tendency with positive trends both in ablation season (April, May, June, July, August: AMJJA) (**Figure 6B**) and accumulation season (September, October, November, December, January, February, March: SONDJFM) (**Figure 6C**), with summer being more distinctive than winter. The year 2015 had the highest average annual snow cover, with snow covering roughly 82% of the valley. In the year 2003, the minimum snow cover was recorded to be 59 %. Years 2005, 2007, and 2012 showed relatively lesser snow cover area, while the years 2010, 2015, and 2018 showed higher snow cover area. High snow cover in the year 2015 has also been confirmed in the study conducted by Choudhury et al. (2021) for north-western Himalaya. We didn't include the year 2000 because the snow product was only accessible after February 2000.

More specific analysis revealed a consistent trend in snow cover area during summer months, with snow cover being stable throughout the season. During the winter, however, there was a significant variability in the snow cover area. Except for March, all the winter months from September to February exhibited significant variability in the snow cover area. The most significant variability in snow cover area was found in the month of October. The overall trend analysis suggested stagnant to a mild rise in snow cover area during winter (September to January). Nonetheless, the snow cover area in the months of March and December has decreased somewhat during the previous two decades. The monthly snow cover percent area fluctuations in the Zanskar valley during summer and winter are depicted in **Figures 7A,B**, respectively. Mild to significant increase in the snow cover area has also been reported by Shafiq et al. (2018) for Kashmir Himalaya, Choudhury et al. (2021) for entire north western Himalaya in the recent decades.

Snow cover area (SCA) trend analyses were carried out at different scales for the period 2001–2021 and summarized in **Table 2**. The one sample *t*-test (OriginLab software) shows a positive SCA trend in all the three calculated time frames i.e. annual, accumulation and ablation. It is observed that an overall increasing trend in annual SCA at a rate of ∼0.845 km^2/year is present in the Zanskar valley. On a seasonal scale, the statistical analyses reveal that the accumulation season has a significant increasing trend in the SCA (with a rate of ∼0.983 km^2/year) while that for the ablation season is 0.74 km^2/year, which is not very significant.

TABLE 2 | Significance analysis of snow cover trends.

Duration	Trend	Slope (km^2/year)	*F*-value	*p*-value
Annual	Increasing	0.845	15.96	0.0007
Accumulation	Increasing	0.983	18.74	0.0003
Ablation	Increasing	0.74	7.4	0.01

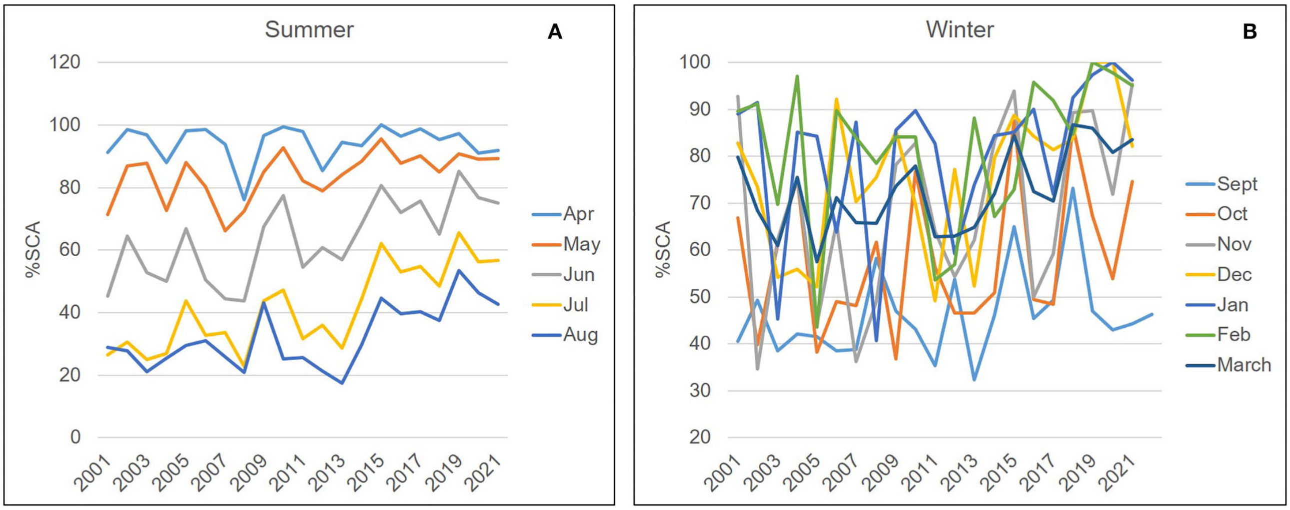

FIGURE 7 | (A) Monthly snow cover variation during ablation season from 2001 to 2021; **(B)** Monthly snow cover variation during accumulation season from 2001 to 2021.

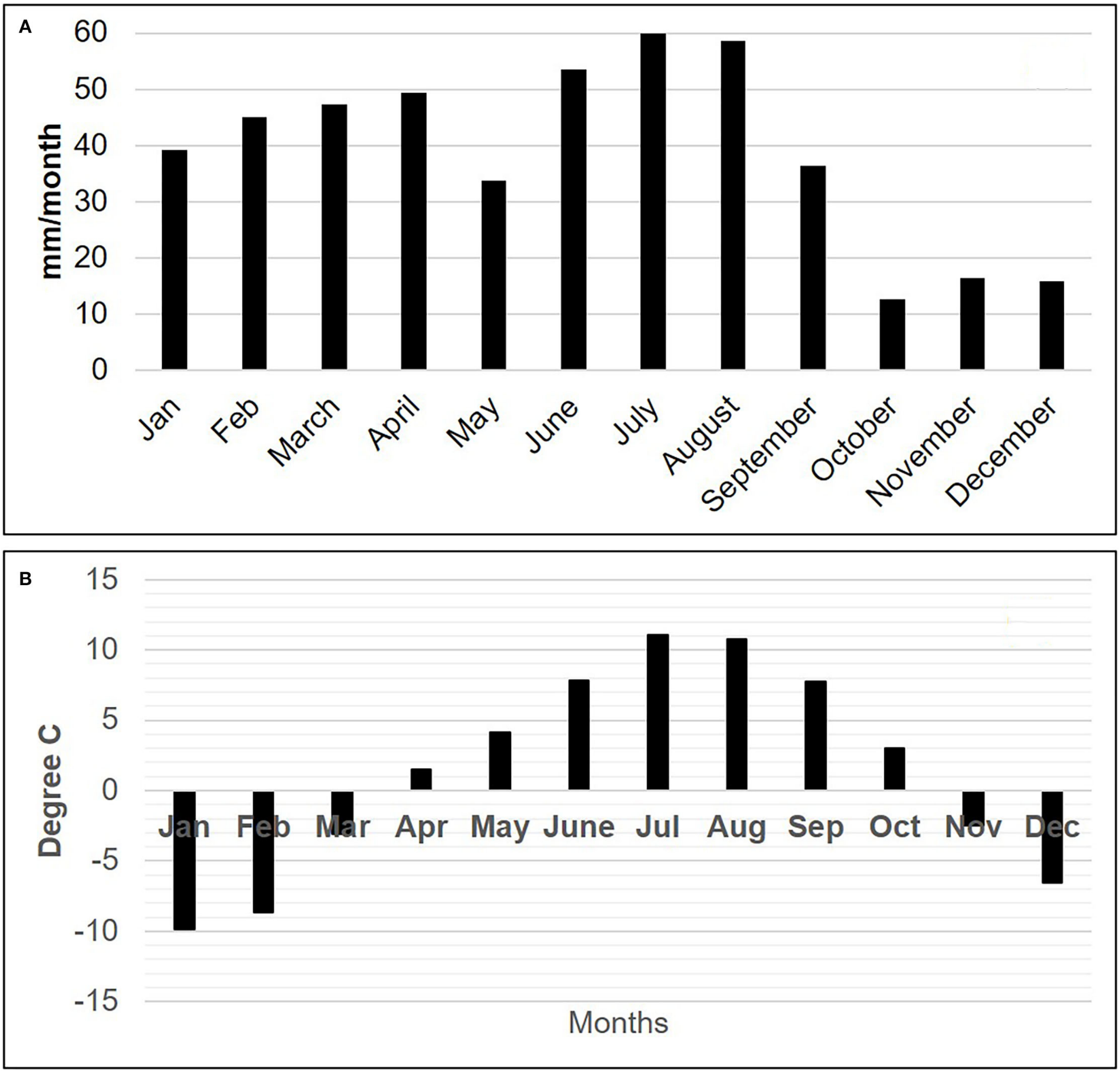

FIGURE 8 | Month wise (average 2000-2020) CRU TS **(A)** precipitation of the Zanskar region and; **(B)** temperature of Zanskar region.

The station interpolated temperature and precipitation data from CRU TS from 2000 to 2020 have also been analyzed which revealed that on average the area receives ∼40 mm of rain per month, with the highest precipitation in July (60 mm) and the lowest in October (12 mm). The precipitation from ISM occurs from June to September. Westerlies are major weather systems in the winter, bringing substantial amounts of snow from January onwards. According to CRU statistics, the month of August has the most precipitation (**Figure 8A**), which also happens to be the end of the ablation season. This was also obvious in the CRU temperature data (**Figure 8B**). The Zanskar's average annual temperature is below zero degrees Celsius from November to March and rises to positive levels from April to October. Because the largest snow cover occurs in March and April, despite CRU data showing good precipitation in August, the Zanskar valley is influenced mostly by western disturbances. Higher temperatures in July and August, as well as decreased snow cover, indicate that the summer monsoon is causing more rainfall in the basin than snowfall.

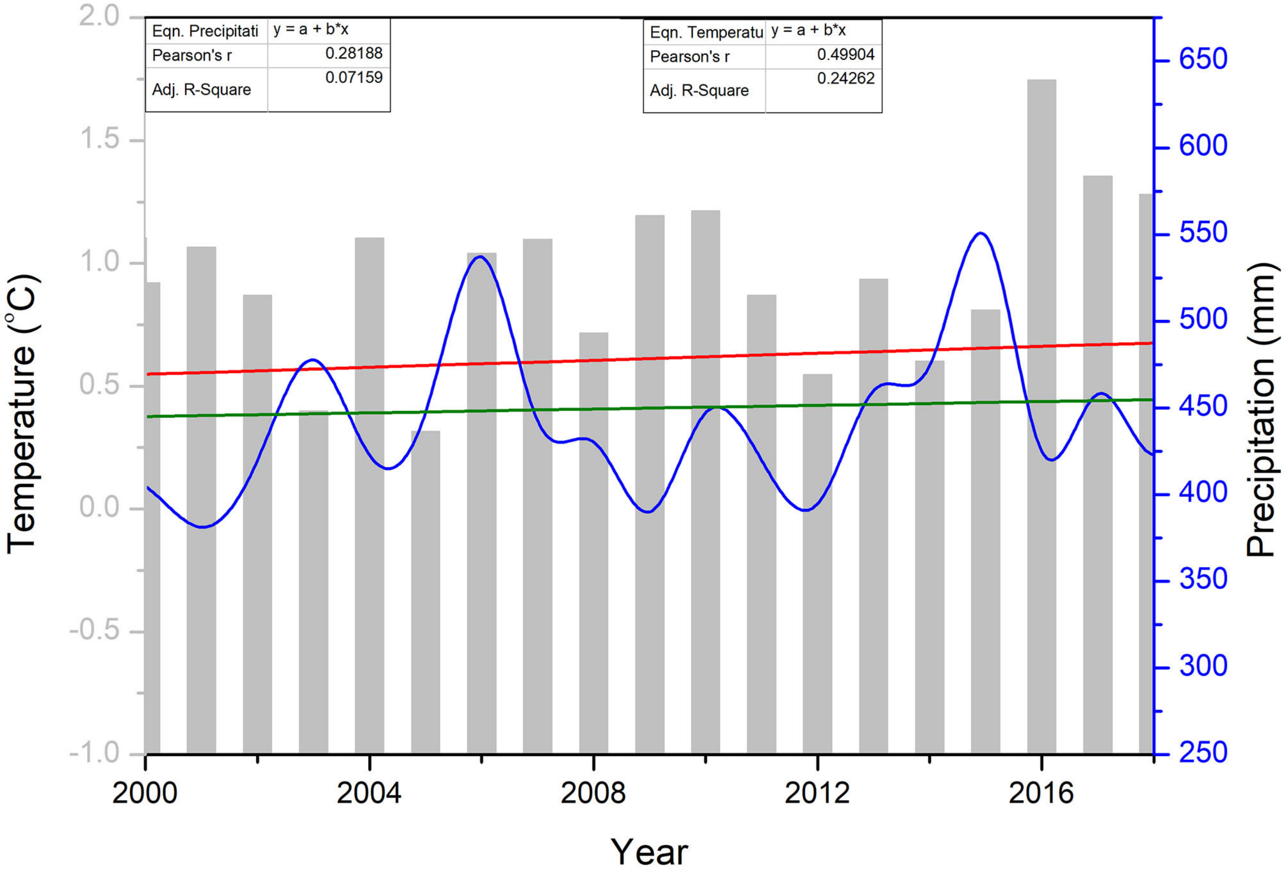

FIGURE 9 | Line plot of CRU TS-4.03 data showing precipitation and temperature from 2000 to 2020.

The linear plots of CRU TS annual average precipitation and temperature data both revealed rising trends (**Figure 9**). The increased precipitation from CRU data corresponded to the MODIS-derived snow cover in the Zanskar valley. Sabin et al. (2020) also indicate rising temperatures in the western Himalaya. Because temperature and snow cover are inversely connected, higher temperatures in Zanskar would logically favor a reduction in snow cover (Choudhury et al., 2021). However, despite rising temperatures, the snow cover in Zanskar is increasing. According to Sabin et al. (2020), this could be linked to an increase in the synoptic-scale activity of western disturbances (WDs).

CONCLUSION

Using the MODIS MOD10A2 product, we evaluated the spatiotemporal characteristics and fluctuations of snow cover area in the Zanskar valley between 2000 and 2017. In contrary to popular belief, we discovered no change to a growing trend in the variation of snow cover area in the Zanskar valley, north-western Himalaya, despite the prevalent impression that snow cover area is decreasing in mountainous locations as a result of global warming. However, the time series was only 20 years long, which was insufficient to identify any discernible trend; so, we do not claim that the valley is less vulnerable to climate change. Our study's key findings are presented below:

(i) Snow covers 67 percent of the total area of the Zanskar valley on an annual basis.
(ii) The annual average snow cover was found to be highest in the year 2015 (80%) and lowest in the 2007 (59%).
(iii) The monthly average snow cover area was found to be highest in March (96%) and lowest in August (28%).
(iv) Snowfall in the Zanskar Valley begins in September and ends in April.
(v) In the valley, the majority of the snow cover remains on slopes ranging from 10 to 40 degrees and the northern aspects of the valley has maximum snow cover whereas the southern aspect has less snow cover area.
(vi) The snow cover area above 4,000 m asl show a distinct increasing trend, however, no change in snow cover was observed beyond 6,000 m asl.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

PP and SNA have conceptualized the work, analyzed the data, and prepared the draft of the manuscript. HK has downloaded the data, processed the data, and prepared the maps. PKC has provided guidance on the progress of the work and contributed in the writing of the manuscript significantly. All authors contributed to the article and approved the submitted version.

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