

Climate and topographic controls on snow cover dynamics in the Hindu Kush Himalaya

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ABSTRACT: Snow governs interaction between atmospheric and land surface processes in high mountains, and is also source of fresh water. It is thus important to both climate scientists and local communities. However, our understanding of snow cover dynamics in terms of space and time is limited across the Hindu Kush Himalaya (HKH) region, which is known to be a climatically sensitive region. We used MODIS snow cover area (SCA) data (2003–2012), APHRODITE temperature data (2000–2007), and monthly long term in-situ river discharge data of the Gandaki (1968–2010), Koshi (1977–2010) and Manas (1987–2004) basins to analyse variations among four basins. We gained insights into short term SCA and temperature, long term discharge trends, and regional variability thereby. Strong correlations were observed among SCA, temperature and discharge thereby highlighting the strong nexus between them. Temporal and spatial snow cover variability across the basins is strongly coupled with the variability of two weather systems: Western Disturbances (WD) and Indian Monsoon System (IMS), and strongly influenced by topography. Manifestation of these variability in terms of downstream discharge can have repercussion to water based sectors: hydropower and agriculture, as low flow seasons is seen affected. This study adds to our knowledge of snow fall and melt dynamics in the HKH region, and intra-annual snow melt contributions to downstream discharges. The study is limited by short span of data and it is desirable to perform a similar study using data representing a much longer time span.

KEY WORDS snow; Hindu Kush Himalaya; Himalaya; climate change; MODIS

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1. Introduction

The ‘Himalaya’, a term coined by the ancient pilgrims of India meaning ‘abode of snow’, owes its name to snow (Saraf and Choudhury, 2006). In recent years, the relevance of snow has become more scientific than aesthetic due to its role in climate change and as a source of fresh water, which has a direct effect on economic development and social wellbeing (Cao and Liu, 2005). The albedo of snow (clean, fresh, dry snow) is as high as 0.9 in some parts of the light spectrum, meaning that 90% of the incident radiation is reflected back to the atmosphere (Munneke *et al.*, 2009). The low thermal conductivity and high albedo of snow insulates the Earth’s surface from incoming solar energy (Weller and Holmgren, 1974), thereby strongly affecting climate change (Vavrus, 2007). The role of snow in energy exchange and climate change has resulted in its recognition as an essential climate variable (ECV) by the Global Climate Observation System (GCOS). Snow exhibits a close negative relationship with atmospheric temperatures (Brown, 2000; Hosaka *et al.*, 2005) and thus is often used as proxy indicator of

climate change (Robinson, 1987; Kropacek *et al.*, 2010). Because the relationship between air temperature and precipitation affects the occurrence of snow fall (Bednorz, 2004) and both temperature and precipitation are affected by climate change, which is pronounced at higher elevations, the changing climate is altering temporal and spatial patterns of snow fall. Changes in snow fall patterns are manifested in changes in snow cover area (SCA), snow depth, and shifts in snow accumulation and timing of melting on the ground. These changes will have serious consequences in downstream areas because both water balance and peak runoff in cold regions are strongly affected by snow accumulation in drainage basins (Pomeroy, 2002). Changes in water balance and peak runoff will have implications downstream in terms of access to water resources for drinking, irrigation, hydro-power and hydro-based industries.

The Hindu Kush Himalaya (HKH) region is the source of water in 10 major drainage basins, which support a population of more than 1.3 billion (Jianchu *et al.*, 2007), who are dependent on glacial and snow melt to support life and livelihoods. Country like Bhutan, one of the smallest economies in the world, has its economic development tied to hydropower resources, with 17.61% of its GDP being derived from it (NEC, 2012). Snow cover and associated changes have a direct bearing on rangeland productivity

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(Buus-Hinkler and Tamstorf, 2006; Shang *et al.*, 2012; Paudel and Andersen, 2013), and these changes threaten the livelihoods of mountain residents, many of whom are nomadic. Rangeland covers approximately 60% of the HKH region and supports many communities in the high mountains, where livelihoods are derived from pastoral production (Sharma *et al.*, 2007).

Research on snow cover in the HKH region in general indicates a decrease in SCA (Immerzeel *et al.*, 2009; Shrestha and Joshi, 2009; Gurung *et al.*, 2011b; Gurung *et al.*, 2011a; Maskey *et al.*, 2011). In contrary studies (Tahir *et al.*, 2015) have reported an increase in SCA in the western Himalaya and the Karakoram area. These differences indicate that snow cover variability is high as it is affected by micro-climates, and research on snow therefore needs to be performed at an appropriate scale to capture micro-climatic effects. Although much is at stake, our understanding of the spatial variability of snow accumulation and melt (altitude, east to west) is limited by a lack of research on an appropriate scale in the HKH region. The bulk of these studies have a regional to sub-regional focus (Zhang *et al.*, 2004; Dahe *et al.*, 2006; Li *et al.* 2008; Zhang *et al.*, 2010; Gurung *et al.* 2011b; Maskey *et al.*, 2011; Jin *et al.*, 2015; Singh *et al.*, 2014), and catchment level research is even more sparse (Jain *et al.*, 2009; Kulkarni *et al.*, 2010; Sharma *et al.*, 2012).

This paper attempts to explain snow fall and melt patterns based on SCA variations in time and space at the catchment level across four comparable basins (the Jhelum, Gandaki, Koshi and Manas basins) spread across the Himalaya range from east to west. An attempt was also made to compare SCA with temperature and discharge to shed light on temperature-snow-discharge nexus.

2. Study sites

The study sites consisted of four comparable trans-boundary basins spread across the Himalaya range (Figure 1); the sites were selected to represent micro-climatic variations across the range. From west to east, these basins are the Jhelum basin, which is part of the greater Indus basin; the Gandaki and Koshi basins, which are parts of the greater Ganges basin; and the Manas basin, which is part of the greater Brahmaputra basin. The Jhelum basin, located in the Western Himalaya, is influenced by westerlies, whereas the other three basins in the Central (Gandaki and Koshi) and Eastern (Manas) Himalaya are influenced by the Indian Summer Monsoon (ISM). These basins listed in descending order of size are the Koshi (88 605 sq. km), Jhelum (50 858 sq. km), Gandaki (44 665 sq. km) and Manas (29 638 sq. km) basins (Figure 2). Mean elevations in descending order are 4408 m asl in the Koshi basin, 4065 m asl in the Gandaki basin, 3756 m asl in the Manas basin and 3077 m asl in the Jhelum basin (Figure 2). Hypsometric integral (HI) values, which range from 0.48 (Jhelum) to 0.50 (Koshi, Gandaki, Manas) indicate that all four basins are at a mature stage (Singh *et al.*, 2008; Ramu and Mahalingam, 2012).

3. Data and sources

3.1. Snow data

In situ snow stations are sparse in the Himalaya in general and more so on the southern flank. Even where available, the station data represent a point, are often not representative of a large area, and thus are not appropriate for basinwide snow analysis. Alternatively, remote sensing provides continuous (spatially and temporally) snow information useful for spatio-temporal variability analysis at various geographic levels. One remote sensing derived data that has become almost a *de facto* standard for snow cover research and has been widely used (Immerzeel *et al.*, 2009; Shrestha and Joshi, 2009; Gurung *et al.*, 2011b, Gurung *et al.* 2011a; Maskey *et al.* 2011) is the moderate resolution imaging spectroradiometer (MODIS) snow product. There is a suite of MODIS snow products consisting of a sequence of products beginning with the 500-m-resolution swath product (Hall *et al.*, 2002; Hall and Riggs, 2007), which is made available for public use by the National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (DAAC). Daily snow products produced by MODIS sensors onboard two satellites, the Terra (MOD) and Aqua (MYD), have been available since February 2000 and July 2002, respectively. The MODIS snow algorithm has been described by Hall and Riggs, 2007. The accuracy of MODIS products reported by many researchers based on comparisons with *in situ* data (Klein and Bernet 2003; Simic *et al.*, 2004; Parajka and Bloeschl 2008; Wang *et al.*, 2008) is as high as 94–95%, although the accuracy is low (<39%) where the snow depth is less than 4 cm (Wang *et al.*, 2008). MODIS snow products has been found suitable and used for such basinwide analysis (Barman and Bhattacharjya, 2015).

In this study, binary snow information from Level 3 MODIS snow products obtained by Terra (MOD10A1) and Aqua (MYD10A1) during overpasses in the morning (approximately 0445 GMT) and afternoon (approximately 0745 GMT), respectively, and available at daily temporal resolution was used. The MOD10A1 and MYD10A1 snow products are tile gridded product in the sinusoidal projection and measure approximately 1200 x 1200 km (10°x10°) (Riggs *et al.*, 2006). The daily MODIS snow products available in hierarchical data format (HDF) were first re-projected into the Lambert equal-area projection system prior to conversion to a GIS-friendly format (GeoTIFF) using the MODIS reprojection tool (MRT). Instead of using already available daily MODIS snow products, which are limited by cloud pixels, the daily products were generated using moving 8-day composites. Cloud pixels were thereby replaced by information from their corresponding cloud-free pixels, which resulted in a cloud-filtered daily snow product.

3.2. Temperature

To develop a spatially explicit representation of temperatures for comparison with the SCA in the four basins, the Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE)

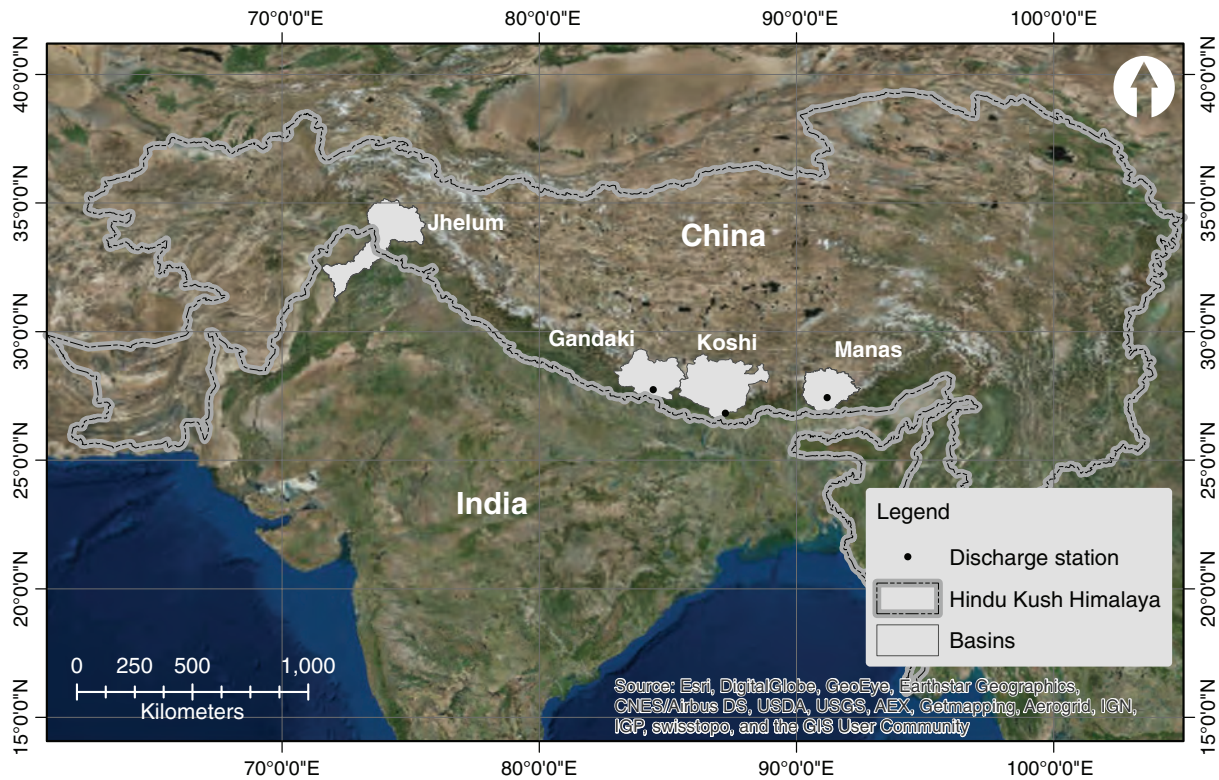


Figure 1. Map showing the locations of the four basins (Jhelum, Gandaki, Koshi and Manas).

daily temperature dataset of 2000 to 2007 was used. The APHRODITE gridded daily mean temperature data (product version V1204R1) at a 0.25° spatial resolution available in netCDF (nc) format was first converted to GeoTIFF format. The gridded daily temperature raster file was clipped based on basin boundaries (shape files) and re-projected to create a Lambert equal-area projection. The gridded temperature datasets were resampled to a 500-m resolution using the cubic convolution technique to make them consistent with the snow cover data. Temperature statistics were extracted in table format for the basins as a whole and for 1000-m elevation zones.

3.3. Discharge

River discharge data from three downstream stations corresponding to the Gandaki (Narayan Ghat station along Narayani river), Koshi (Chatara-Kothu station along Sapta Koshi) and Manas (Autsho station along Kuri Chu) basins (Figure 1) were used. These data were from stations operated by the Department of Hydrology and Meteorology (DHM) of Nepal and Department of Hydro-Met Services (DHMS) of Bhutan. Stations capture 70, 61 and 10% of the surface flow of Gandaki, Koshi and Manas basins, respectively. Although these stations are not located at the drainage basin outlets, these stations were best alternative available for the analysis.

3.4. Topographic

Topography is an important factor in snow cover distribution. This paper describes an attempt to study the variations

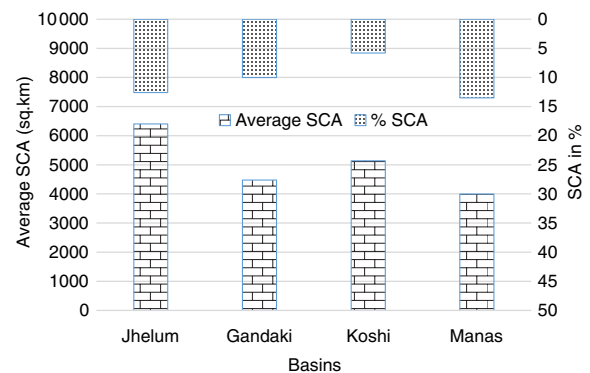


Figure 2. Average SCA and SCA% in the four basins.

in SCA and temperature between basins and topographic zones. We used a commonly used, freely available topographical dataset, the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) available at a 90-m spatial resolution. This DEM was first re-projected to create a Lambert equal-area projection and then resampled at a 500-m spatial resolution to make it consistent with other data layers. Delineation of the drainage basins was performed using the 90-m-resolution SRTM DEM.

4. Methodology

4.1. Snow cover area analysis

We analysed trends spanning 10 years (2003–2012), referred as the short-term SCA trend, for the entire basins,

Table 1. Physical characteristics of the four basins.

Watershed	Area (sq. km)	Elevation (m)			Average Decadal SCA (sq. km)	Hypsometric Integral
		Minimum	Maximum	Mean		
Manas	29 638	7	7519	3756	3999.60	0.50
Koshi	88 605	8	8825	4408	5138.85	0.50
Gandaki	44 665	18	8148	4065	4476.47	0.50
Jhelum	50 858	120	6275	3077	6402.53	0.48

in each 1000-m elevation belt, and for different slope aspects. Linear regression is one of the most widely adopted (Pu *et al.*, 2007; Wang *et al.*, 2008; Immerzeel *et al.*, 2009; Gurung *et al.*, 2011a) approaches, and SCA trends were analysed using linear regressions at the 95% confidence level. As a measure of the statistical significance of the observed trends, we used the *P*-value test, which is a statistical method of testing one or more hypotheses. Linear regression was performed on the average SCA% in 10 individual years to evaluate the short-term trend. Because the topography has a strong effect on snow accumulation and melting (Jain *et al.*, 2009), similar regressions were developed for each 1000-m elevation belt and for various slope aspects (N, NE, E, SE, S, SW, W, NW) to characterize the spatial variability. Spatial resolution (500 m) of MODIS snow product is found to be adequate to perform elevation and aspect based snow cover analysis (Table S3, Supporting information). Because it is important to analyse seasonal dynamics, average SCA% statistics were generated for four seasons (winter, i.e. December–March; spring, i.e. April–May; summer, i.e. June–August and autumn, i.e. September–November) following schema adopted by Immerzeel *et al.*, 2009 and Maskey *et al.*, 2011.

Intra-annual variability is important for water users like hydropower sector and farming community to understand the changes and adapt, average monthly SCAs spanning a 10-year period were plotted, and variations within individual months were captured by standard deviations (SDs) using 10 sets of monthly average SCAs.

4.2. Temperature analysis

The daily temperature statistics extracted from resampled (500 m) daily gridded APHRODITE temperatures spanning 2000 to 2007 were averaged over various time periods (annual, monthly and seasonal) and geographic areas (entire basins, elevation zones and aspects). Linear regression at the 95% confidence level was used to analyse short-term temperature trends (annual, seasonal and monthly). Correlations between basinwide daily temperatures and SCA and in individual elevation belts were analysed using a nonparametric measure of association called Kendall's tau-b correlation (τ). Similar to Spearman's (ρ) and Pearson's (r) product moment correlation it measures relationship between two variables.

4.3. Discharge

Two different levels of analysis are done using discharge data. Several studies indicate good correlation between SCA and discharge (Yang *et al.*, 2003; Yang *et al.*, 2009; Chevallier *et al.*, 2014; Delbart *et al.*, 2015). Monthly average SCA and discharge data were plotted for Gandaki (2000–2010), Koshi (2003–2010) and Manas (2006–2007) basins to analyse correlation. In order to understand long term (inter-annual) discharge trend linear regression analysis was done using monthly average, monthly minimum and monthly maximum discharge for Gandaki (1968–2010), Koshi (1977–2010) and Manas (1987–2004). Similarly month wise discharge trend and standard deviation (SD) was analysed to analyse intra-annual variability. Since Narayan Ghat station captures 70% of the snow melt in Gandaki basin, correlation (τ) between monthly average SCA at every 1000m elevation above 3000m asl and monthly average discharge was analysed, using data span from 2000 to 2010.

5. Results and discussion

5.1. Inter-annual cyclicity of SCA

The Jhelum basin which lies at the higher latitude (Figure 1) despite its lesser relief has highest average decadal SCA (6402.53 sq. km) and the Manas basin with average SCA of 3999.60 sq. km has the least (Table 1). In terms of SCA in percentage of total basin area, the Manas and Koshi basins with 13.49% and 5.79% are highest and lowest respectively. The short-term SCA trend in these basins is largely negative and statistically not significant except in Manas (Table 2). Similar observation has been reported from this region by other studies and has attributed to high degree of SCA variability and shorter temporal span of data (Immerzeel *et al.*, 2009). Positive SCA trend in western Himalaya has also been reported by others (Singh *et al.*, 2014; Tahir *et al.*, 2015), may be due to increase in winter precipitation as a result of stronger westerly circulation (Archer and Fowler, 2004; Hewitt, 2005). A similar positive SCA trend is also reported from western China from 1951 to 1997 (Dahe *et al.*, 2006). The observed rate of SCA decline is however not consistent, a case of high spatial variability in terms of snow response to climate change across the Himalaya. It is observed to be highest in the Manas basin and is inferred to be comparable in the Gandaki and Koshi basins (Table 2). The observed tendency of SCA decline is found consistent

Table 2. Summary of short-term trends of SCA (2003–2012) and temperature (2000–2007) based on MODIS and APHRODITE data, respectively. The bold values represent statistically significant trends at the 95% confidence level.

	Jhelum		Gandaki		Koshi		Manas	
	SCA	Temp	SCA	Temp	SCA	Temp	SCA	Temp
Winter	0.079576	0.0006	-0.2955	0.0019	-0.1943	0.0014	-0.8448	0.002
Spring	0.023091	0.0004	-0.0878	0.0019	-0.0257	0.002	-0.2251	0.0025
Summer	0.035879	-0.0001	-0.0292	0.0006	-0.0235	0.0003	-0.0016	0.0006
Autumn	-0.07982	-0.0034	-0.3539	-0.0022	-0.1738	-0.0022	-1.6318	-0.0022
Annual	0.019455	0.002	-0.2010	0.003	-0.1110	0.003	-0.6287	0.005

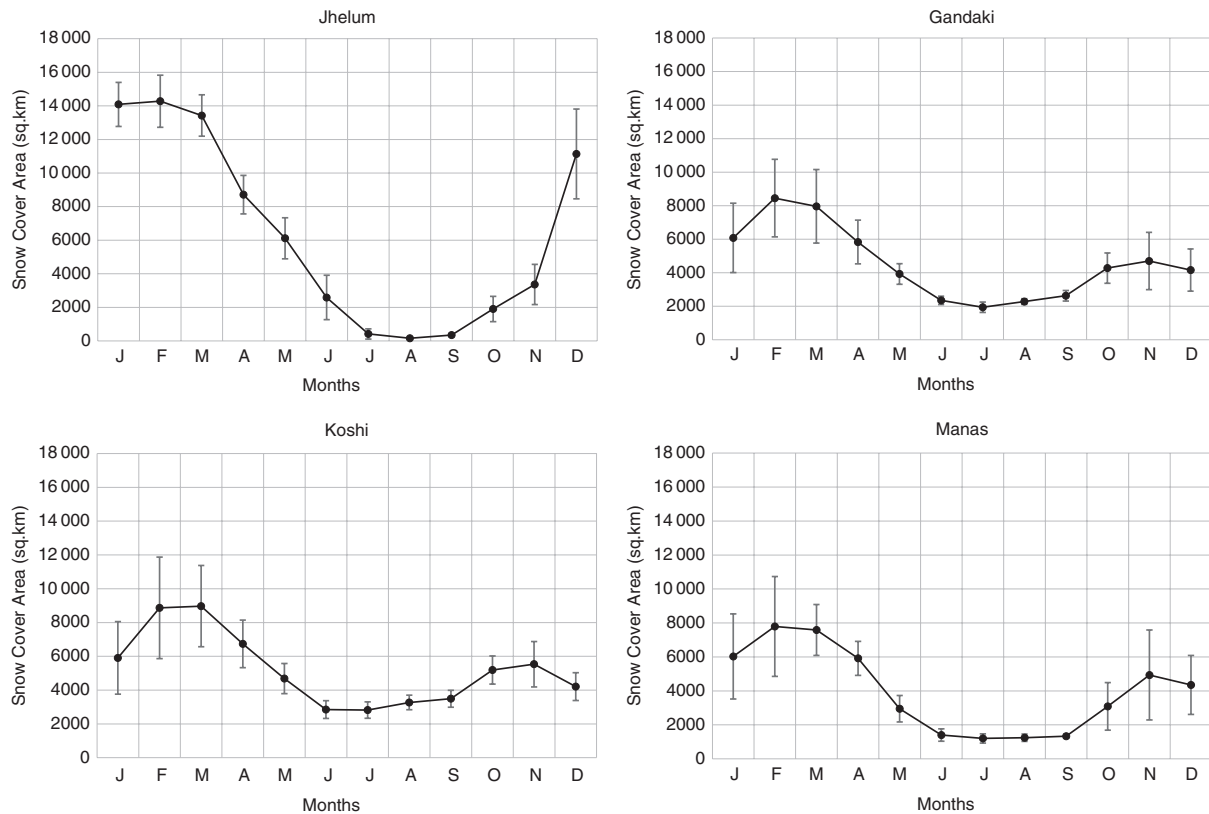


Figure 3. Monthly average SCA and standard deviation (SD) from 2003 to 2012.

across all elevations in all four basins except between 2000–3000 m in Jhelum basin (Table S1). Observed decreasing SCA trend is statistically significant between 4000–7000m in Manas basin and 6000–7000m in Gandaki basin. Similar short term SCA trend analysis based on aspect also indicated decreasing tendency in all aspect except in case of Jhelum basin, and statistically significant in case of Manas basin (Table S2).

The observed short term SCA trend is consistent with observed short term temperature trend. Inter-annual temperature in all the basins indicates an increasing trend which is statistically significant except for Jhelum basin. This is in agreement with a positive long-term (1972–2002) temperature trend in the HKH region and vicinity reported based on the CRU TS 2.1 (Immerzeel *et al.*, 2009). The observed temperature increase is found across all elevation and aspect (Tables S1 and S2). However, Manas basin has the highest rate of short-term temperature increase while it is comparable for Koshi and

Gandaki basins, indicating a case of spatial variability. Jhelum basin indicate increasing tendency and at rate lowest amongst the four basins. Intra-annual variability by way of seasonal trend analysis shows increasing trend for all seasons except autumn temperature (Table 2).

Inferring on positive annual temperature trends in the Gandaki and Koshi basins, in conjunction with observed negative inter-annual SCA trend in the Manas basins, the region in general has experienced a decade of decreasing snow cover. This observation is consistent with trends from this region reported earlier from Nepal (Ojha, 2009; Shrestha and Joshi, 2009), and the upper Indus basin (Immerzeel *et al.*, 2009).

5.2. Intra-annual variation in SCA

Intra-annual variability as manifested by monthly and seasonal SCA variation shows conspicuous differences between the Jhelum basin and the other three basins (Figure 3), manifestation of influence from different

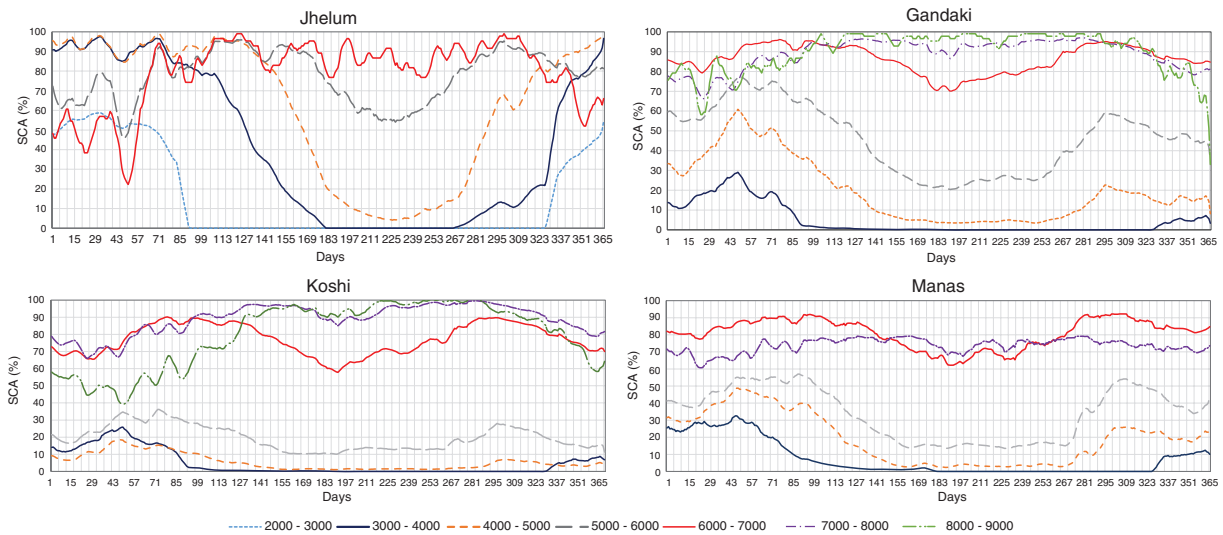


Figure 4. Variations in the SCA% (as a percent of area of each individual elevation belt) during 8-day periods of the year in various elevation zones, based on data from 2003 to 2012.

Table 3. Associations between daily SCA and daily temperature (2000–2007) in the four basins as expressed by Kendall’s tau-b correlation coefficient (τ). The τ values are significant at the 0.01 level.

Domain	Jhelum	Gandaki	Koshi	Manas
2000–3000	−0.68			
3000–4000	−0.56	−0.60	−0.56	−0.57
4000–5000	−0.51	−0.55	−0.50	−0.55
5000–6000	−0.08	−0.55	−0.41	−0.56
6000–7000		−0.26	−0.14	−0.31
7000–8000		0.45	0.43	
>8000		0.23	0.52	
Entire basin	−0.62	−0.53	−0.46	−0.57

weather systems. The Jhelum basin is affected by western system known as Westerly Disturbances (WD) originating over Mediterranean and Black Sea area (Hatwar *et al.*, 2005). The WD is dominant winter system which results heavy snow fall in Western Himalaya. Other three basins receive snow mostly from the ISM during summer and partly also from WD during winter. Characteristics of Nepalese Himalaya being fed by summer and winter snowfall was why it was referred as ‘summer accumulation type’ glaciers (Ageta and Higuchi, 1984).

Despite the different weather systems, all four basins experience maximum snow fall during winter month which is seen to peaks either in February (Jhelum, Gandaki and Manas basins) or March (Koshi basin). Similarly month with lowest SCA is during summer months: in August (Jhelum basin), July (Gandaki and Manas basins) and June (Koshi basin). Figure 4 shows intra-annual variability of SCA using 8-day average SCA% in each 1000-m elevation belt. The SCA% increases with elevation and there is marked increase above 6000m asl which is very prominent in the Gandaki, Koshi and Manas basins. The intra-annual variation is strong below 6000 m asl, which has also been observed in Nepal (Maskey *et al.*, 2011).

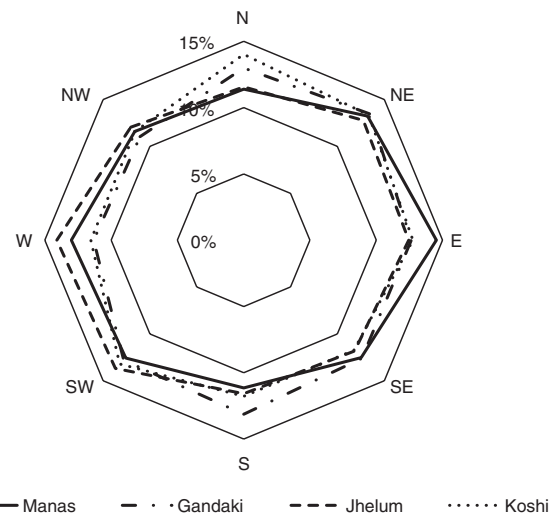


Figure 5. Radar chart showing SCA distribution (average SCA% over 2003–2012) in the four basins based on aspect.

Above 7000 m asl, the SCA% is much greater in summer than in winter in all four basins. This pattern has also been reported in Nepal and has been attributed to greater cloud cover in summer than in winter (Maskey *et al.*, 2011).

The SDs of the monthly SCAs represent the degree of variation for each individual month during the 10-year period. The SD plot (Figure 3) shows that the variation is greater during winter months, consistent with report from Nepal (Maskey *et al.*, 2011) and Loess Plateau, China (Jin *et al.*, 2015). The SD is greatest in February in the Gandaki, Koshi and Manas basins and is greatest in December in the Jhelum basin, a case of spatial variability.

5.3. Relationship between SCA and temperature

The inverse correlation between SCA and temperature is well established (Bednorz, 2004; Hosaka *et al.*, 2005; Gurung *et al.*, 2011b; Maskey *et al.*, 2011; Barman and

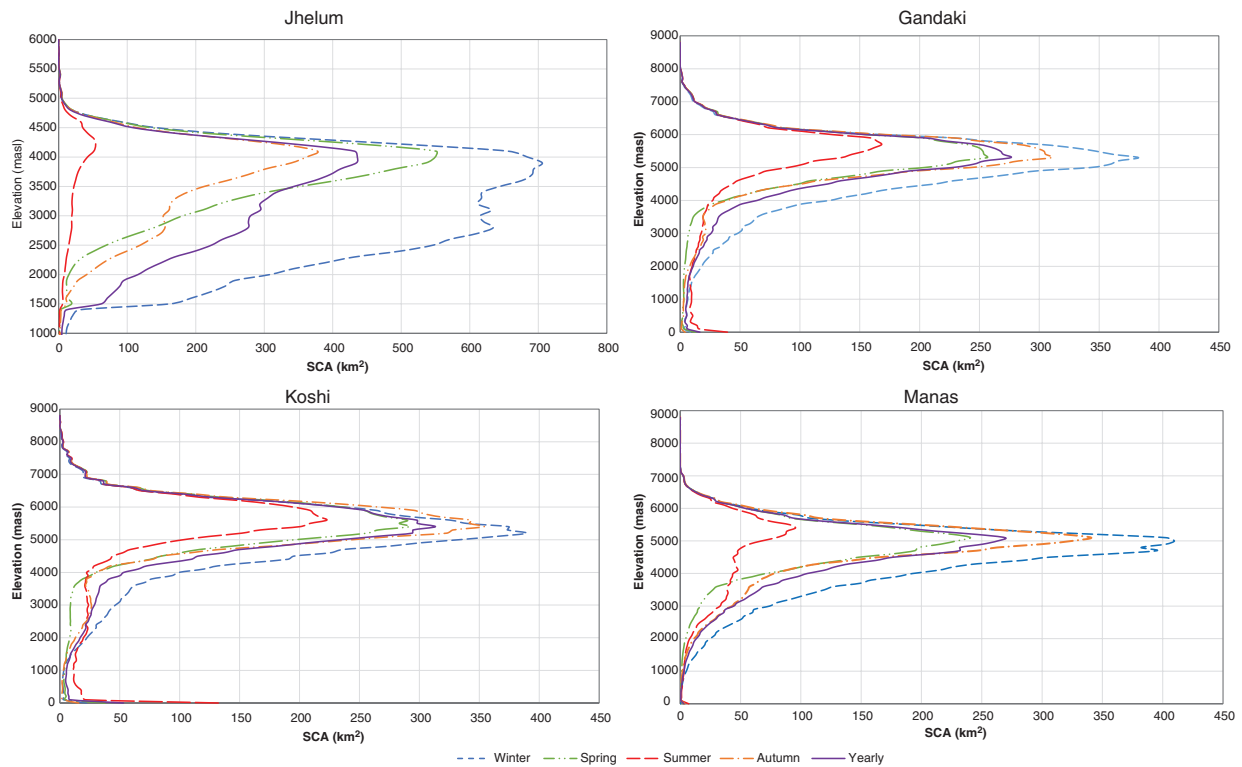


Figure 6. Hypsographic curves showing the distribution of SCA across elevations in the four basins.

Bhattacharjya, 2015), whereas the spatial variability across elevations is not well understood. Table 3 shows the correlation (τ) between the daily average temperature and daily SCA of individual basins during the period between 2000 and 2007. The correlation is negative in all four basins and is statistically significant at the 0.01 confidence level. The strongest correlation is observed in the Jhelum basin ($\tau = -0.62$), and the weakest correlation is observed in the Koshi basin ($\tau = -0.46$). Spatial variability is explicit with stronger but negative correlation in lower-elevation belts than lower and positive correlation in higher-elevation belts. The 7000m asl elevation marks the transition from negative to positive correlation which has also been reported in Nepal. This pattern may be due to temperatures being well below critical above 7000 m asl, and as a result small changes in temperature do not lead to perceptible changes in SCA (Barman and Bhattacharjya, 2015). The other possible reason could be ablation at higher elevation due to wind erosion and sublimation.

5.4. Relationship between SCA and topography

Topography has a major effect on weather and climate in the Himalaya, and elevation and aspect therefore play important roles in the SCA distribution (Jain *et al.* 2009; She *et al.*, 2015). We analysed elevation and aspect wise SCA distribution to shed light on topographic control on SCA distribution. Figure 5 presents a radar chart showing the distribution of SCA% based on aspect. The Jhelum and Manas basins receive maximum snow fall on their west- and east-facing slopes, whereas north- and south-facing slopes receive the maximum snow fall in the

Gandaki and Koshi basins. This pattern is observed during all seasons.

A strong correlation between elevation and SCA% is observed as indicated by a high coefficient of determination (R^2) in all four basins: Jhelum (0.96), Gandaki (0.92), Koshi (0.83) and Manas (0.84) (Figure S2). Variations in SCA% with every 100-m increase in elevation were calculated and were found to be 1.9% in the Gandaki basin, 1.6% in the Koshi and Jhelum basins, and 1.5% in the Manas basin. Figure 6 is a hypsography curve showing yearly and seasonal SCA across every 100 m elevation belts. SCA is maximum in winter in all the basins across all elevation belts. The difference in seasonal SCA is very prominent below 6000 m in the Gandaki, Koshi and Manas basins, which confirms the observation shown in Figure 4. In the Jhelum basin, this critical elevation is much lower: 4700 m asl.

5.5. Relationship between SCA and stream flow

Snow melt is particularly important for sustaining river flows during winter and spring months, when glacial melt is impeded by lower temperatures. Snow melt and thus SCA is therefore important for future water security, particularly during dry winter months (Stewart, 2009; Immerzeel *et al.*, 2010). Studies have indicated a strong correlation between SCA and downstream discharge (Yang *et al.*, 2009; Delbart *et al.*, 2015). Figure 7 shows a plot of average monthly SCA versus average monthly discharge from the Gandaki, Koshi and Manas basins. The plot shows an inverse relationship between the SCA and discharge in all three basins. Correlation (τ) between

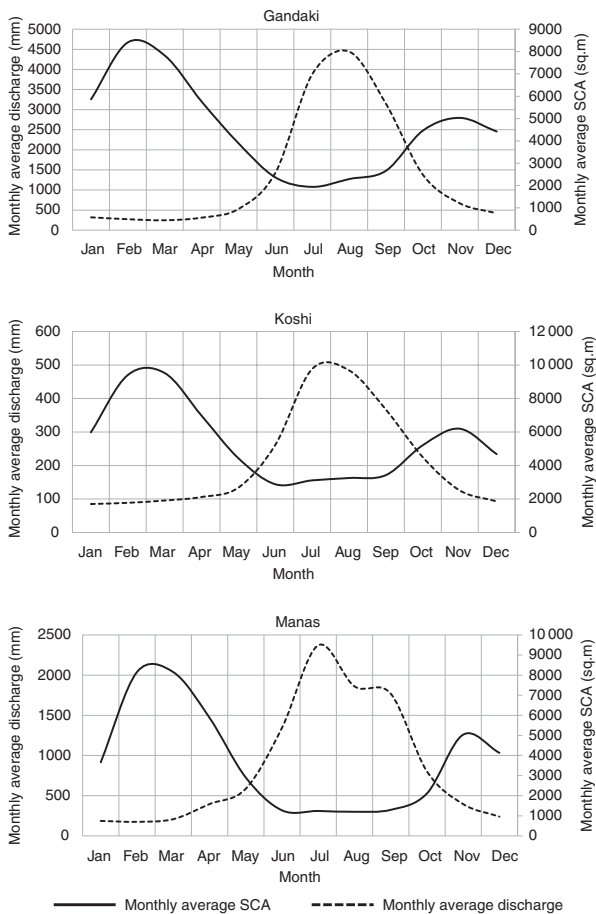


Figure 7. Monthly average SCA in and discharge from the Gandaki (2000–2010), Koshi (2003–2010) and Manas (2006–2007) basins.

average SCA at different elevation belts and average discharge was analysed for Gandaki basin where the station captures variability of snow melt over 70% of the basins area. The analysis (Table 4) showed stronger positive correlation in lower elevation and vice versa, which may indicate greater contribution to river discharge from snow at lower elevation. The elevation at which the transition from positive to negative correlation between SCA and discharge is varying across seasons, indicating contribution of snow cover from different elevation for different seasons. The contribution of snow melt to river discharge is confined to elevation below 5000 and 6000 m in winter and spring, respectively. Due to warmer temperature during summer contribution from snow is from all elevations but with decreasing significance with elevation.

5.6. Discharge trend

Long term discharge trend was also analysed using monthly average, monthly maximum and monthly minimum for Gandaki (Narayan Ghat station) and Koshi (Chatara-Kothu station), and monthly average discharge for Manas (Autsho station) basins. Span of data used was different: 1970–2010 for Gandaki basin, 1968–2010 for Koshi basin and 1987–2004 for Manas basin. None of the long term discharge trend was statistically significant thus was not conclusive. However, tendency is largely

Table 4. Associations between seasonal average SCA and seasonal average discharge in Gandaki basin expressed by Kendall's tau-b correlation coefficient (τ).

Altitude belt (m)	Winter	Spring	Summer	Autumn
3000–4000	0.5	0.182		
4000–5000	0.5	0.182	0.929	–0.143
5000–6000	0	0.036	0.786	–0.214
6000–7000	–0.071	–0.182	0.429	–0.357
7000–8000	–0.214	–0.109	0.286	0.286
>8000	–0.286	–0.423	0.231	–0.154

of increasing except for average and minimum discharge for Koshi basin (Figure S3), and increasing in case of maximum discharge and decreasing in case of average and minimum discharge for Koshi basin (Figures S2, S3 and S4). Month wise trend (Table 5) showed decreasing tendency in general except for July (Gandaki and Koshi basins) and August (Koshi basin). The trend is statistically significant for October, November and December for Gandaki basin and December for Koshi basin, and seen to decrease from October to December. The SD of month wise discharge indicates higher variability during high flow months (May to October) and vice-versa. This may be attributed partly to higher observed variability in monsoon system (Smadja *et al.*, 2015). Average monthly discharge plot (Figure S5) shows highest average discharge for August in all three basins, while lowest average discharge for Manas basin is in January and for Gandaki and Koshi basins in March.

6. Conclusions

Based on the analysis of MODIS snow cover data from 2003 to 2012, the Himalayan region has experienced decline of SCA, a trend found consistent across all elevation belts and aspects. The statistically significant negative correlation between SCA and temperature indicates that this trend is partly a result of increasing temperatures. However, there are spatial and temporal variations, which is important to understand to be able to develop region-specific adaptation interventions. The east–west variability seen in Jhelum basin in Western Himalaya and other three basins is due to difference in weather system. Jhelum basin is predominately dependent on winter snow fall showered by WD, and characterized by high degree of inter-annual and intra-annual variability compared to other three basins.

Topography has strong effects on the snow distribution and snow melt processes, as indicated by the high correlation coefficient (R^2) between SCA and elevation. The correlation between SCA and temperature is inverse and stronger at lower elevations. Topography has also influence on intra-annual and seasonal SCA variability, with stronger variability observed below 6000 m asl. This may introduce greater variability (less stability) to winter and spring (low flow) season discharge as snow melt contribution to discharge is confined to snow from

Table 5. Long term monthly trend (liner regression) and standard deviation of discharge from stations in Gandaki (1968–2010), Koshi (1977–2010) and Manas (1987–2004) basins. Bold values represent statistically significant trend at 95% confidence level.

Basin		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Gandaki	Trend	-1.06	-0.65	-0.57	-0.64	-1.81	-0.67	4.36	-0.08	-5.20	-6.10	-2.36	-1.63
	SD	56.22	41.54	45.01	55.77	98.53	256.61	606.40	484.59	379.42	203.64	104.04	63.12
Koshi	Trend	-0.87	-0.47	-0.42	-0.58	-3.33	-2.60	6.19	12.33	-2.55	-5.75	-2.80	-2.10
	SD	49.01	43.44	45.88	52.38	104.16	269.89	723.56	675.29	540.99	180.53	79.58	55.66
Manas	Trend	-0.13	-0.04	-0.45	-0.05	-2.89	0.41	-0.47	11.61	-1.85	-2.99	-0.75	0.53
	SD	3.47	4.28	4.28	11.69	41.98	39.28	68.58	178.82	60.16	36.82	14.92	10.61

elevation below 5000 and 6000 m, respectively. It is also to note that month wise long term discharge trend indicates decline during low flow months.

This study indicates that it is critical to understand the nexus between climate, snow and water because future water security issues will have many inter-related adverse consequences, threatening the very existence of human civilization. There is a need for better research into the impacts of climate change in alpine environments using long-term data derived from remote sensing and *in situ* stations. There is a general lack of high-elevation hydro-climatic stations in the Himalaya region, and it is imperative to fill this gap if we are to unravel the complex climate-snow-water nexus and develop adaptations. The findings from this study will help advance our understanding of these alpine processes and complexities and help lead to better strategy on water resource management.

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Supporting information

The following supporting information is available as part of the online article:

Figure S1. Liner regression between elevation and snow cover area percentage (SCA%).

Figure S2. Long term discharge trend (linear) of stations in Koshi (1997–2010) basin using monthly average (top), monthly minimum (middle) and monthly maximum (bottom) discharge value.

Figure S3. Long term discharge trend (linear) of stations in Gandaki (1968–2010) basin using monthly average (top), monthly minimum (middle) and monthly maximum (bottom) discharge value.

Figure S4. Long term discharge trend (linear) at Autsho station in Manas basin using monthly average discharge from 1987–2004.

Figure S5. Monthly average discharge of the Gandaki, Koshi and Manas basins at selected stations. The monthly average are based on data of different temporal span: Gandaki (1968–2010), Koshi (1977–2010) and Manas (1987–2004).

Table S1. Short term snow cover trend (2003–2012) and temperature trend (2000–2007) for every 1000 m elevation band.

Table S2. Aspect based short term snow cover trend (2003–2012) and temperature trend (2000–2007) for four basins: Jhelum, Gandaki, Koshi and Manas.

Table S3. Table showing numbers of AVHRR and MODIS pixels in each elevation belt (top) and aspect (bottom).

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