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Research Article

DYNAMICS OF MAXIMUM SNOW COVER AREA AND SNOW LINE ALTITUDE ACROSS NEPAL (2003-2018) USING IMPROVED MODIS DATA

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ABSTRACT

Snow is one of the main components of the cryosphere and plays a vital role in the hydrology and regulating climate. This study presents the dynamics of maximum snow cover area (SCA) and snow line altitude (SLA) across the Western, Central, and Eastern Nepal using improved Moderate Resolution Imaging Spectroradiometer (MODIS; 500 m) data from 2003 to 2018. The results showed a heterogeneous behavior of the spatial and temporal variations of SCA in different months, seasons, and elevation zones across three regions of Nepal. Further, the maximum and minimum SCA was observed in winter (December-February) and post-monsoon (October-November) seasons, respectively. The inter-annual variation of winter SCA showed an overall negative trend of SCA between 2003 to 2018 at the national and regional scales. The SLA was assessed in the post-monsoon season. At the national scale, the SLA lies in an elevation zone of 4500-5000 m, and the approximate SLA of Nepal was 4750 m in 2018. Regionally, the SLA lies in an elevation zone of 4500-5000 m in the Western and Central regions (approx. SLA at 4750 m) and 5000-5500 m in the Eastern region (approx. SLA at 5250 m) in 2018. The SLA fluctuated with the changes in SCA, and the spatio-temporal variations of SLAs were observed in three regions of Nepal. We observed an upward shift of SLA by 33.3 m yr^{-1} in the Western and Central Nepal and by 66.7 m yr^{-1} in Eastern Nepal. This study will help to understand the impacts of climate change on snow cover, and the information will be useful for the hydrologist and water resource managers.

Keywords: MODIS, Nepal, Snow, Snow cover area, Snow line altitude.

INTRODUCTION

Snow is a fundamental constituent of the hydrological processes as it stores water and contributes to snowmelt runoff (Immerzeel *et al.*, 2009). Moreover, snow is the form of precipitation in the high mountainous region, and the dynamics of snow cover determine the glacier mass balance in the Himalaya (Wagnon *et al.*, 2013). The meltwater from ice and snow from the Himalaya are the primary sources of major rivers in Nepal, for instance, the Koshi, Gandaki and Karnali Rivers, and regulate the ecosystem functioning and sustain millions of people downstream (Shrestha *et al.*, 2019; Immerzeel *et al.*, 2020). Snowmelt significantly contributes to discharge and water availability, especially in the spring season (March-April-May) (Armstrong *et al.*, 2019). Thus, monitoring snow cover is essential in the high mountainous region.

It was reported that land snow cover and glacier extent and volume have decreased in the recent decades in response to the climate change (Zemp *et al.*, 2017). Furthermore, trends in temperature and precipitation coupled with different hydrometeorological variables impact the snow cover area (SCA) and subsequently, the snow depth and packs, ultimately affecting the water availability in downstream areas (Mishra *et al.*, 2014; Thapa *et al.*, 2020). Snow cover is a critical element of the cryosphere and weather system, and is an indicator of climate change. Across Himalaya of Nepal, there has been considerable warming from the 1970s (Thakuri *et al.*, 2019) with annual changes in the precipitation (Sharma *et al.*, 2020b; Hamal *et al.*, 2020a). Therefore, in the context of climate change, the study of spatial and temporal snow cover dynamics in Nepal is essential.

In Nepal, few studies have been done on snow cover with different spatial (basin-scale) and temporal coverage. Mishra *et al.* (2014) analyzed the spring and winter snow cover changes in the Kaligandaki River basin focusing on temperature and precipitation changes during the years 2000-2010. Similarly, Thapa *et al.* (2020) analyzed the climatic variables to show their impacts on the snow cover and water availability in the Langtang River basin of Nepal from 2001 to 2012. They reported a constant decrease in snow cover due to an increase in temperature and decrease in precipitation. Maskey *et al.* (2011) studied the inter-annual and monthly/seasonal changes of snow cover in different altitudes of Nepal (>3000 m) concluding that the negative winter trends (3000-6000 m) and increasing autumn trends (>4000 m) would impact on the flow regimes. Nevertheless, these studies were either in basin-scale or did not explicitly study the snowline altitudes (SLAs). SLA is a key metric to show the effects of snow accumulations and ablation, with its dynamics attributed to both climatic variables and topographic effects *(Gurung et al.,* 2017). Moreover, SLA depicts the lowest altitude of perennial snow cover which is often defined as the lowest boundary of SCA after the end of the summer season (Fierz *et al.*, 2009; Krajčí *et al.*, 2014). Girona-Mata *et al.* (2019) reported that the seasonal dynamics of SLA in the Langtang basin from the Landsat imagery (30 m) was controlled by snowfall, snowmelt, and temperature.

In Nepal, maximum snow cover was observed in the winter season (Paudel & Andersen, 2011). During the summer season, snowfall occurs only in the high elevation areas of the Himalaya, which significantly contributes to glacier accumulation; however, due to high temperatures, ablation is significant in the summer season. The snow cover is least during the post-monsoon season compared to other seasons. The variability of the winter snow distribution plays a determining role in the timing and magnitude of spring snowmelt runoff (Shrestha *et al.*, 2012). Hence, in this study, we aim to study the recent status of SCA across different regions of Nepal, analyze the spatio-temporal dynamics of seasonal SCA and, assess the post-monsoon SLA dynamics between 2003 and 2018 in three different regions of Nepal. The findings were expected to be useful for understanding the effects of climate change on snow cover and benefit in water resource and watershed management.

MATERIALS AND METHODS

Study area

The study area, Nepal, is located between 26°22′ to 30°27′ N longitude and 80°40′ to 88°12′ E latitude with the total area of 147,641.28 km^2. The elevation of the country rises from plains in the south to the high Himalaya in the north with varying landscapes, topography, weather, and vegetation. The climatology of Nepal is determined by the South Asian monsoons and the westerlies which are more pronounced in summer (June-September) and winter (December-February) seasons, respectively (Sharma *et al.*, 2020d). Four main types of climate are reported in the country, with the larger area dominated by the temperate climate (Karki *et al.*, 2016). The distribution of precipitation is highly variable, with higher precipitation in the Central regions followed by the Eastern and Western regions (Sharma *et al.*, 2020c). Similarly, precipitation varies with the elevation, i.e., precipitation increases up to 2000 m which decreases further, and moreover, precipitation is in the form of snow in the glaciers and glacial lakes dominant high Himalaya *(Sharma et al.*, 2020a; Khadka *et al.*, 2018; Salerno *et al.*, 2015). Snow cover is maximum when the temperature is low, with snowfall observed even in mountain peaks of 2500m elevation during the winter season over the country. For this study, we divided Nepal into the Western, Central, and Eastern regions based on the major river basins (the Karnali, Gandaki, and Koshi, respectively) and the duration and timing of monsoonal climatology (Fig. 1) (Hamal *et al.*, 2020b).

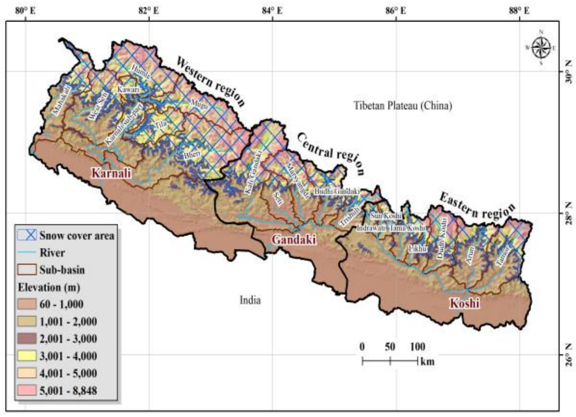

Fig. 1. The study area, Nepal divided into three regions and 19 glacierized sub-river basins. The blue gridded box in the map shows the maximum snow cover area in 2018

Data Source

We used the combined 8-day maximum snow extent product derived from Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) version 6 and a glacier inventory (RGI 6.0), named MOYDGL06*, developed from 2002 to 2018 covering the high mountains of Asia (Sher & Thapa, 2020). These products are improved versions, where overestimation and underestimation of snow from clouds are removed by combining two snow products (i.e., from Aqua and Terra sensors) and seasonal, temporal, and spatial filters were applied, respectively.

The data (MOYDGL06*) was downloaded from the Pangaea repository (Muhammad & Thapa, 2019). These products contain pixels of 500 m × 500 m with snow and glaciers; thus, we used snow pixels derived from MODIS data (Sher & Thapa, 2020). In the 8-day maximum snow product, a pixel was classified as snow if snow cover was observed at least once in 8 days (Riggs *et al.*, 2015). Besides, we used the Shuttle Radar Topography Mission Digital Elevation Model (SRTMDEM, 30 m) data for topographical analysis which were downloaded from the National Aeronautics and Space Administration's (NASA) web portal (https://urs.earthdata.nasa.gov).

Methods

The improved products had snow and non-snow pixels with six values; glacier ice captured by MODIS was presented as 200, snow converted to no snow as -200, no snow from clouds converted to snow as 210 and no snow as 0, and debris-covered and debris-free glacier as 240 and 250, respectively. Here, firstly, the snow (200 and 210) and non-snow pixels (-200, 0, 240, and 250) from the improved MODIS products were converted to values of 1 and 0, respectively (Fig 2). Since the 8-day MODIS products start on the first day of the year, recurring each other eight days up to the first few days of the next year (Thapa *et al.*, 2020), these products were separated into different months depending on the days that falls in the respective months. Secondly, the monthly maximum snow product for each month was obtained by combining the 8-day products that fall in each month using the maximum overlay statistic in the ArcGIS Desktop. This means that the largest value of the input (1 ∨ 0) was considered to derive the maximum monthly snow extent products, i.e., the final product will have a pixel as snow if it has snow on any day of that month (Fig. 2).

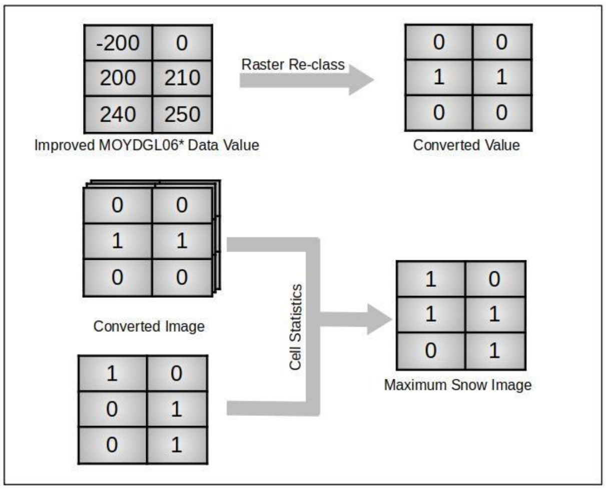

Fig. 2. The snow (200 and 210) and non-snow (-200, 0, 240, and 250) pixels in the improved MODIS product (MOYDGL06*) used in this study were reclassified to values of 1 and 0, respectively. The maximum snow cover image in each month, season, and year were obtained by combining the images using cell statistics. *denotes merged product from Terra and Aqua sensors

This method is similar to the method applied to produce 8-day MODIS product, where pixel was classified as snow if snow occurs at least once in 8 days (Riggs *et al.*, 2015). Similarly, seasonal maximum snow products were obtained by combining the monthly products for pre-monsoon (March-April-May), monsoon (June-July-August-September), post-monsoon (October-November), and winter seasons (December-January-February) to study the SLA and SCA dynamics. Though these are comparatively improved products than original MODIS products, the uncertainty exist, and some non-snow pixels were misclassified as snow due to topography, climate, image quality, and methodological constraints (Sher & Thapa, 2020). Thus, for national scale investigation, we used the simple elevation threshold to discard snow below 3500 and 2500 m pixels in the summer/post-monsoon and other seasons, respectively to minimize the misclassified snow pixels from clouds. Additionally, snowfall does not occur or if occurred will have no significant hydrological impacts below these elevations in the study area (Maskey *et al.*, 2011).

Various approaches were proposed to derive the SLA from remotely sensed data. Seidel et al. (1997) used the statistical concept to draw snowline (i.e., zone with at least 50 % SCA) using Landsat Thematic Mapper in Rhône-Sion basin of Switzerland, while Prantl et al. (2017) used Terrestrial Laser Scanner to study SCA/SLA dynamics. Meanwhile, Girona-Mata *et al.* (2019) utilized a high-resolution Landsat images to delineate snowline and developed an improved method at a basin scale. In this study, we adopted the statistical concept to draw SLA from SCA in three regions of Nepal. This method is promising and straightforward for a large study area. Moreover, World Meteorological Organization (WMO) has recommended using elevation zones (or bands) to represent the SLA, as it is challenging to represent the exact snowline at a specific altitude due to topographic and climatic constraints (UNESCO, 1970). Since the resolution of MODIS data used was 500 m, we longitudinally divided the study area into 500 m elevation zones and recorded the snow area. The SLA was determined as the average elevation of the upper and lower value of the elevation zone, where SCA exceeded 50 % of the total area of that zone.

RESULTS AND DISCUSSION

Recent SCAs in Nepal

Spatial and temporal variation of the SCAs was observed in different months and elevation zones across three regions of Nepal in 2018 (Fig. 3). The maximum SCA (~33 % of the country's area) was observed in February and the minimum (~14 % of the country's area) in October. Maximum SCA was observed in February over Western and Central regions, while in March over the Eastern region. Regionally, the highest SCA was observed in the Western region, followed by the Central and Eastern regions. This was because of more pronounced westerly in the western region (Hamal *et al.*, 2020a) and snowfall in high elevation areas during the winter season. In March, retreating westerlies and advancing monsoon mix to bring high snow in Eastern and other regions. Seasonally, the winter season marked the highest SCA followed by pre-monsoon, monsoon, and post-monsoon seasons, respectively. It is worthy to note that the snow accumulation and ablation co-occur at the higher elevation in monsoon season (June-September) and hence Nepalese glaciers are known as summer accumulation type glaciers, and subsequently minimum SCA was observed in the post-monsoon (October-November), after the melt season. Thus, this season is favorable for identifying the transient SLA across Nepal. The uncertainty of the snow cover area was calculated as a product of the LRE (linear resolution error, i.e. pixel resolution) and the perimeter (l) of the area. The uncertainty of 2018 SCA in January, February, March, April, May, June, July, August, September, October, November, and December are ~18, ~14, ~15, ~19, ~19, ~31, ~24, ~22, ~31, ~35, ~31, ~18 %, respectively, of total SCA.

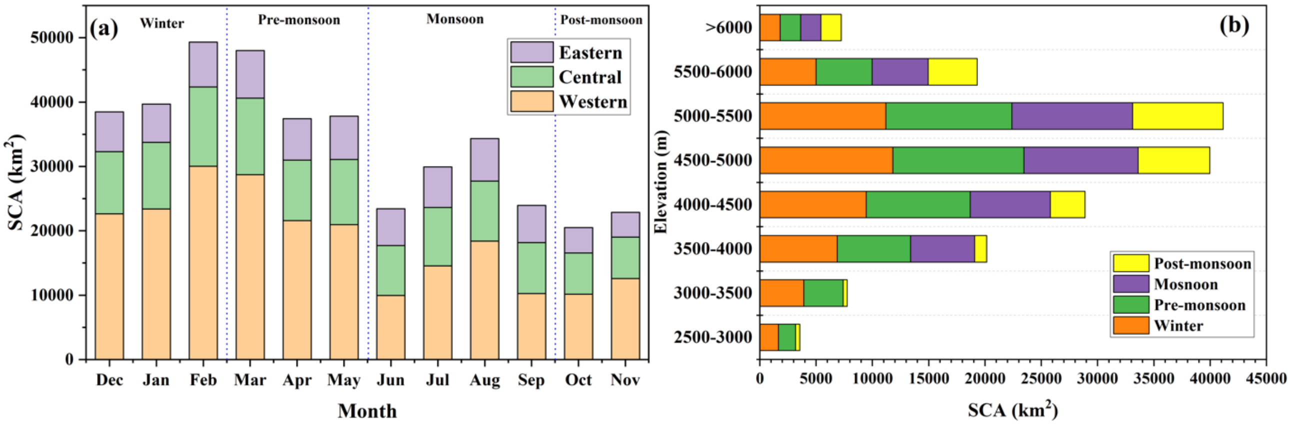

Fig. 3. Variation of maximum SCA in different months (a) and elevation zones (b) across three regions of Nepal in 2018

The percentage of 2018 SCA are ~62, ~81, ~96, and ~100 % in the elevation zones 2500-3000, 3000-3500, 3500-4000, and >4000 m, respectively. It should be noted that since we computed the maximum SCA by stacking maximum snow products (refer methodology section, Fig. 2), the elevation wise SCA depends upon the seasons. The results showed that SCA in different elevation zones varied with the season (Fig. 3b). Moreover, the frequent clouds in summer were often misclassified as snow due to the poor ability of the algorithm to discriminate cloud and snow cover pixels (Sher & Thapa, 2020). In contrast, the other seasons are relatively cloud-free, and the accuracy of the SCA assessment was high. For future studies, it is recommended to assess the SCA based on the topography (aspect, slope) and land cover as they control the SCA (Mishra *et al.*, 2014).

Seasonal variation of SCAs in the 2003-2018 periods

The seasonal climatology was studied by using maximum seasonal snow cover products from 2003 to 2018. The result revealed that the winter season received the maximum snowfall (the highest SCA) followed by pre-monsoon, monsoon and post-monsoon seasons, respectively (Fig. 4). At the regional scale, it followed a similar pattern of seasonal SCA climatology. The highest SCA was observed in the Western region in all seasons, followed by central and eastern regions, respectively. However, it is worthy to note that the area of these three regions is not equal, i.e., the Western region is larger than the Central and Eastern. Moreover, seasonal variation was studied from maximum seasonal snow products, i.e., the pixel with snow cover in any one month of the season was considered into the final seasonal product. Thus, this method may have some bias in representing the real ground SCA as the data used, and the applied methodology did not distinguish snow cover duration. In a mountainous country like Nepal, a large spatial and temporal variation of snow cover is mainly determined by local topography and climate, circulations of monsoon, and westerly wind system (Hamal *et al.*, 2020a; Mishra *et al.*, 2014).

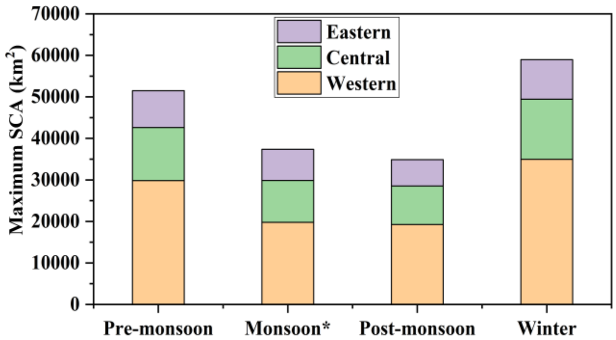

Fig. 4. Variation of maximum seasonal SCAs of Nepal in the 2003-2018 period. *Misclassification of pixels as snow from cloud cover is relatively high

Trends of maximum winter SCAs from 2003 to 2018

The maximum winter SCAs of a particular year were obtained from products of December of the preceding year and January and February of that year. The results showed the inter-annual variation of SCA with an overall negative trend of SCA at the national and regional scales (Fig. 5).

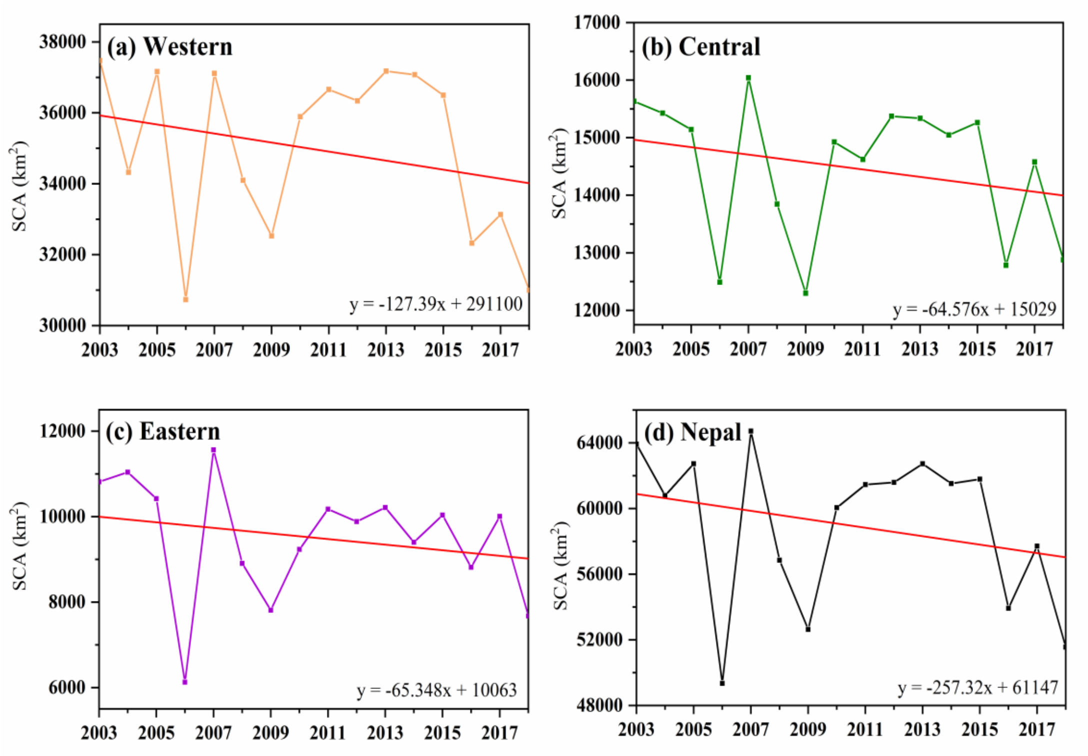

Fig. 5. Trends of maximum SCA over Western (a), Central (b), Eastern (c), and Nepal (d) from 2003 to 2018

Figure 6 (a) shows the spatial changes in snow cover, revealing that snow cover has decreased between 2003 and 2018. Minimum and maximum SCA was observed in 2006 and 2007, respectively, in all three regions of Nepal (Fig. 5). Similarly, the years 2006, 2009, 2016, and 2018 marked the lowest SCA in all the regions. The western region experienced a higher downward trend of SCA (slope = -127.39 km^2/year) compared to other regions. Figure 6 (b) shows the winter SCA in sub-basins of Nepal, revealing the maximum SCA in the Bheri basin and minimum in the Likhu basin.

Moreover, the northern part of all basins was covered by snow. Though ~3 % of the total annual precipitation occurred during the Winter season (DJF), the minimum temperature at this season (the minimum temperature at high Himalaya and hilly regions falls below -5 and 5 °C) favored the maximum snowfall (DHM, 2017). Moreover, the snow accumulated in the winter season contributed to runoff and water availability in the spring season (MAM) (Armstrong *et al.*, 2019); however, high SCA was also distinct in spring seasons (Fig. 4), which was the result of low temperatures in March at hilly and mountainous regions and the mixture of advancing monsoonal wind and retreating westerlies bringing snowfall (DHM, 2017). Thus, the study of maximum winter SCA dynamics is essential for water availability and hydrological studies.

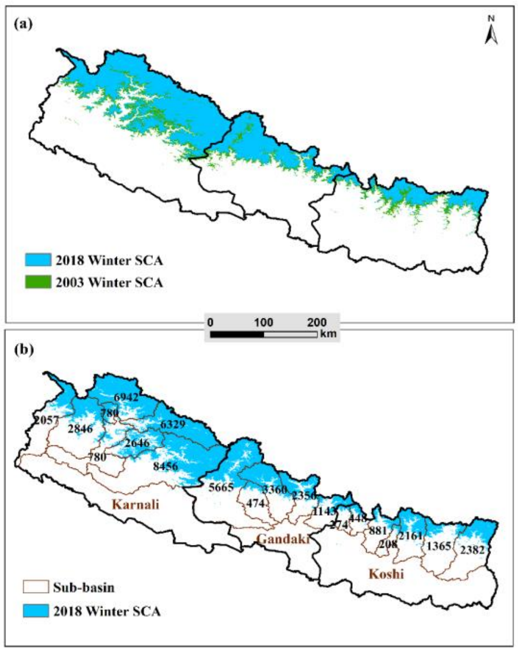

Fig. 6. (a) Spatial changes in winter SCA between 2003 and 2018. (b) Numbers in the figure represents absolute 2018 winter SCA (km^2) in sub-basins of Nepal. Refer to Fig. 1 for the name of the respective glacierized sub-basins

SLAs across different regions of Nepal

The SLA was derived from the SCA of the post-monsoon season. The results revealed the inter-annual and regional dynamics of SLA in different regions of Nepal (Fig. 7). At the national scale, the SLA was in the elevation zone of 4500-5000, with approximate SLA being 4750 m in 2018. The SLA was in an elevation zone of 4500-5000 in the Western and Central regions (approx. SLA at 4750 m) and 5000-5500 m in the Eastern region (approx. SLA at 5250 m) in 2018. SLA fluctuated with the dynamics of SCAs, and spatio-temporal variation of SLA was observed in three regions of Nepal from 2003 to 2018. The result showed the upward shift of SLA by 33.3 m yr^{-1} in the Western and Central Nepal and by 66.7 m yr^{-1} in the Eastern Nepal. In the Western region, SLA fluctuated between 3750 and 5250 m, as depicted in Fig. 7 (d). The mean SLA in Eastern (~4469 m) was higher than Western (4438 m) and Central (4344 m) regions. This implies permanent snow cover was at a higher elevation in the Eastern region compared to the Central and Western regions. This study focused on large-scale national and regional investigation; thus, we derived the SLAs from the maximum snow products and discarded the factors, such as snowfall, snowmelt, and temperature that control the snow cover and subsequently the dynamics of SLA (Girona-Mata *et al.*, 2019). It is recommended that future study should focus on exploring the dynamics of SCAs and SLAs coupling the relation with climatic and topographic factors and large-scale ocean-atmospheric patterns.

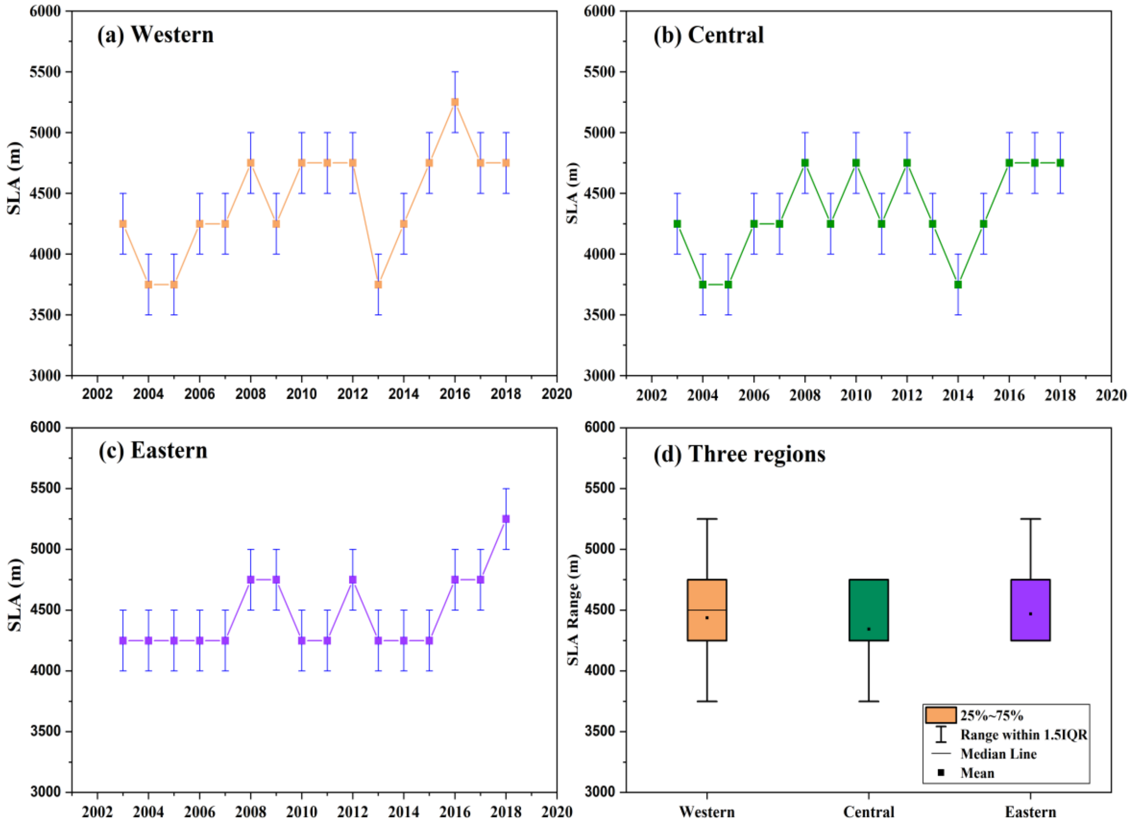

Fig. 7. Dynamics of SLA in Western (a), Central (b), and Eastern (c) regions of Nepal from 2003 to 2018. The error bar represents the elevation zones in which SLA can fluctuate. (d) Box plot of the SLA in three regions between 2003 and 2018

CONCLUSIONS

This study investigated the nation-wide snow cover area (SCA) and snow line altitude (SLA) dynamics from 2003 to 2018. The results revealed the heterogeneous SCA in different months, seasons, and elevation zones across three regions of Nepal in 2018. Maximum SCA was observed in winter (DJF), which was slightly higher than in the pre-monsoon (MAM) season. We analyzed the winter SCA dynamics as the low temperature in this season favor the maximum snowfall. Moreover, precise SCA can be obtained in the winter since the cloud cover is in the lowest ratio than in the summer season, which minimizes the misclassification of clouds as snow pixels.

The results showed the variation of winter SCA in each year with an overall negative trend of SCA at national and regional scales. SLA was observed in the post-monsoon season which recorded the lowest SCA as compared to other seasons. The result showed the upward shift of SLA by 33.3 m yr^{-1} in Western and Central Nepal and by 66.7 m yr^{-1} in Eastern Nepal. The mean SLA in Eastern (~4469 m) was higher than Western (4438 m) and Central (4344 m) regions. SLA determines the permanent snow areas and has great significance in determining water availability and the status of glaciers in high mountains. The results of this study gave information on the latest status of the SCAs and the variation of SCAs and SLAs for the 15 years (2003-2015) in the context of ongoing climate change. The information provided in the present study was expected to support the climate analysts, hydrologists, glaciologists, and watershed managers.

AUTHOR CONTRIBUTIONS

N. Khadka developed the concept and wrote the original draft. N. Khadka and S. K. Ghimire processed the data. All the authors participated in the analysis, discussions, review, and writing of the manuscript.

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