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Climate Change Impact on Himalayan Ecosystem: An Assessment of Rishiganga River Basin, Central Himalaya, India

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ABSTRACT

Himalaya is considered to be one of the most ecologically sensitive and fragile areas of the world. The Himalaya region is warming faster than the global average; consequently, climate change poses a fundamental threat to the region and associated environment. At present, there is a severe knowledge gap to know about how mountain ecosystems will respond to these changes. The present study aims to assess the impact of climate change on the Himalayan ecosystem in terms of analysing contrasting meteorological (near-surface air temperature and precipitation) and land cover (fluctuation in snow and vegetation cover) parameters of the Rishiganga River basin (Central Himalaya, India) during 2010-11 to 2019-20 hydrological years. Results suggested that all components of temperature (minimum, maximum and average) were increased significantly at seasonal and yearly scales including summer precipitation. However, amount of the precipitation was substantially decreased during winter and at yearly scale. Furthermore, studies on identifying the cumulative effect of changing contrasting meteorological parameters, residual snow and vegetation cover suggested that the river basin is getting warmer at seasonal and yearly scale, resulting in a decreasing pattern of residual seasonal snow cover and an increasing pattern of vegetation cover (signifying the timber line is shifting towards higher altitude). The study also finds out that fluctuation in residual snow cover with vegetation represents a near-to-inverse relationship. In summary, the presented analysis suggested that the vegetation cover would initially increase in the basin with cryosphere mass retreat. However, most of the plant species would substantially decline and disappear with glacier extinction. The study will be beneficial to understand the mechanism of climate-cryosphere-ecosystem interaction in a changing climate scenario. This will also be helpful to forecast changes in the Himalayan ecosystem and anticipate cascading effects of cryosphere mass retreat on mountain ecosystem services.

Introduction

Changing climate has continuously increased the temperature globally since the last four decades (IPCC, 2021). Recent studies suggested that precipitation patterns are continuously changing due to rising temperature (Meenu *et al.*, 2013; Mala *et al.*, 2019). As a consequence, cryosphere mass is retreating globally and possibly will get extinct within the upcoming decades (Dyurgerov, 2005; Zemp *et al.*, 2015). Furthermore, the globally increased temperature will lead to major environmental changes, especially in the high-altitude regions of the world (IPCC, 2021). The Hindu-Kush-Himalayan region is warming faster than the global average (Yadav *et al.*, 2004; Krishnan *et al.*, 2019). This is altering the glacier boundaries, snow and vegetation cover patterns (Bolch *et al.*, 2012; Singh *et al.*, 2014; Qing-Longa *et al.*, 2017). Changes in the Himalayan cryosphere are crucial for the water storage (Kesarwani *et al.*, 2015a,b). The melt water generated from these glaciers contributes to the total discharge of the north Indian rivers emerging from the Himalaya. Rapid recession of snow and glaciers is not only increasing the risks posed by Cryospheric environment, but also affecting the landscape configuration and long-term future water availability (Carey *et al.*, 2017; Wufu *et al.*, 2021). Additionally, retreating of cryosphere mass exposes the snow-covered area, and these newly exposed terrains are now being colonized by plants. In proglacial environments, the high-altitude plants are highly sensitive to climate warming, changing pattern of precipitation and inherent snow/glacier retreat (Erschbamer, 2007; Dullinger *et al.*, 2012). The deglaciated terrains have been the subject of study as they help to examine the effects of global warming on biodiversity. However, the consequences of cryosphere mass retreat and how ecological networks mediate such impact in the Himalayan region remain poorly understood and quantified. To study the ecological balance in the glaciated areas, it is vital to know the effect of cryosphere mass retreat on the vegetation cover. The study on developing the relationship between vegetation and cryosphere change in the Himalaya is crucial for projecting the ecological dynamics and planning sustainable ecosystem management (Walker & Del, 2003; Erschbamer & Caccianiga, 2016).

Thus, present research work aims to understand the long-term response of vegetation cover with respect to ongoing changes in the Himalayan climate and cryosphere.

Materials and methods

Study area: geographical, geological and climatic setting

The upper Rishi Ganga catchment, a tributary of the Dhauliganga River (basin ID no. 5O 132 07) is located in the Chamoli District of Uttarakhand (Central Himalayan region), covering an area of ~696.21 km^2 between the latitudes of 30°18′16" N to 30°32′16" N and longitudes of 79°40′30" E to 80°02′46" E (Fig. 1). The catchment has 10 major debris-covered glaciers (Nanda Ghunti, Ronti, Bethartoli, Trishul, Mrigthuni Dakshini Rishi, Dakshini Nanda Devi, Uttari Nanda Devi, Uttar Rishi, Changabang and Ramani) with various niche glaciers, hanging glaciers and glacieret having total glaciered area of 262.58 km^2. The snow and glacier-fed catchment is the source of the Rishiganga River, which ultimately joins the Dhauliganga River near Raini village (1940 m a.s.l.) of Joshimath Tehsil. The concave side of the glacier valley faces towards the west, and their crescentic course extends from cirques to the point where glaciers melt, and emanating streams join the Rishiganga River. Geologically, the catchment area belongs to the Vaikrita crystalline group with garnetiferous mica schist and garnet mica schists - well exposed all along the catchment area (Maruo, 1979).

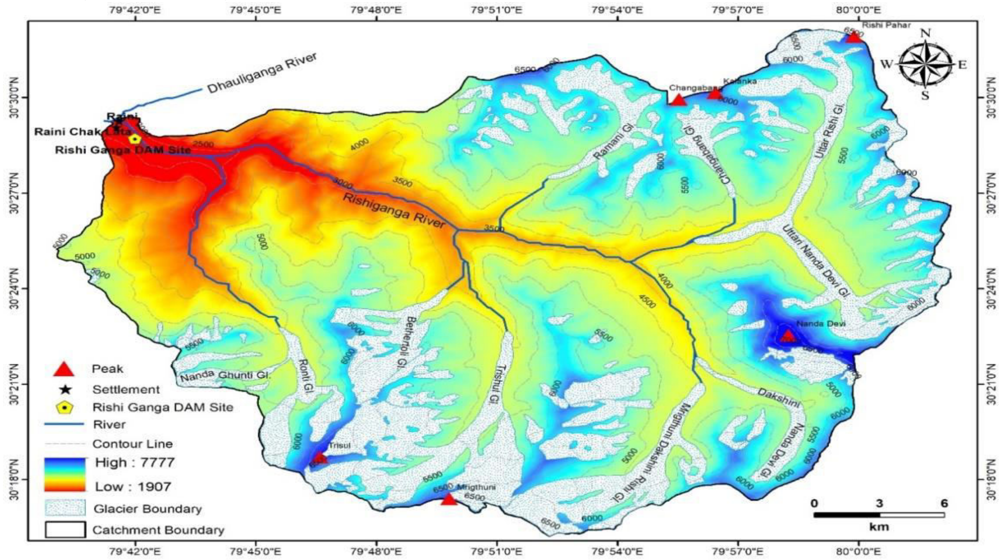

Fig 1. The upper Rishi Ganga catchment (basin ID no. 5O 132 07) located in the Chamoli District of Uttarakhand (Central Himalayan region). Background image: ALOS - PALSAR Digital Elevation Model (DEM) with spatial resolution of 12.5m x 12.5m.

Rishiganga valley occupies a transit zone between the moist Indian Summer Monsoon (ISM) dominated by the Southern Himalaya and the cold, dry Tibetan highlands. Additionally, the mid-latitude west coast also contributes to the winter snowfall which feeds many glaciers in the country. Thus, it is a winter-summer accumulation type river basin which gets precipitation through western disturbance in winter (November–April) and in summer through ISM (June–October) (Owen *et al.,* 1996). The general climate of the study area in winter is dry cold, and in summer it is wet. The cryosphere, landscape dynamics, ecosystems and socio-economic structure of this area are regulated by these weather systems (Pandey *et al.,* 2021). Structurally, the area is very fragile, and the young mountains are vulnerable to the region's severe climatic conditions. Topography-climate interactions are largely responsible for the region's tropical character, which includes abundant biodiversity, rich ecosystem and stunning mountain landscapes.

Furthermore, climate change impacts have highly influenced the Rishiganga River basin. Due to continuous increasing temperature and variable precipitation rate, glaciers of the basin are experiencing rapid recession after 1990. Since 1980-2017, total glacierized area in the basin is lost by 26 km^2 (Kumar *et al.,* 2021). During this period, the equilibrium-line-altitude (ELA) varied between 5200 and 5700 m a.s.l. (Kumar *et al.,* 2021). Recently, the Rishiganga River basin experienced a massive flood (Sain *et al.,* 2021) on February 07, 2021 (Fig. 2).

The Raini village of the basin was hit severely by the sudden burst of a tremendous discharge of a flash flood ripping off the valley along the downslope of Raunti stream, Raini, Tapovan and so on. The plausible causes of this catastrophe were detachment of a sizeable rock mass and overlying hanging glacier in the Raunthi catchment (Shugar *et al.,* 2021).

This activity had dammed the Rishiganga River and led to the devastation of roads, bridges and various hydropower projects over downstream. The large-scale devastation resulted in huge human and economic loss in the region.

Fig 2. (a) Damaged under construction barrage site of Tapovan-Vishnugad hydropower project at Tapovan village (520 MW, owned & operated by National Thermal Power Corporation Limited-NTPCL), (b) confluence zone of Dhauliganga and Rishiganga rivers at Raini village (c) Rishiganga hydropower project (13.2 MW, owned & operated by Kundan Group, New Delhi) at Raini village, and (d) flood level during the disaster at Vishnu Prayag site (1458 m a.s.l.).

Climatic Records

Long-term contrasting meteorological records (near-surface air temperature and precipitation) of the Rishiganga River basin were extracted from the World Climate Research Programme (WCRP)-CORDEX (Coordinated Regional climate Downscaling Experiment) dataset for South Asia region during 2010-11 to 2019-20 (10 years), at daily scale. The data series was alienated as per the hydrological year (01 November to 31 October of the following year), and at seasonal scale, the dataset is further divided into two seasons – (i) winter (01st October of preceding year to 30th April of following year), and (ii) summer (01st May to 31st October). To understand the climate variability in near-surface air temperature and precipitation, statistical methods were used to analyse these datasets and identify the seasonal and annual trends of series.

Ancillary and Geospatial Dataset

Topographical map of the Rishiganga River basin is covered under map number NH 44-6 (1:2,50,000 scale) of Army Map Services (AMS), U.S. Army United States (prepared in 1955). This map was used for extracting the basin information and other geographical parameters. The Landsat series (spatial resolution of 30.0m x 30.0m) of satellite images were used for identifying the changes in snow and vegetation cover over the study area during end of the accumulation (preferably March/April) and the ablation (preferably October/November) seasons. For studying the snow and vegetation cover, satellite images of Landsat-5 MSS (Multispectral Scanner) & TM (Thematic Mapper) were used for the period of 2010-11, while Landsat 8-OLI (Operational Land Imager) / TIRS (Thermal Infrared Sensor) were used for the period of 2012-13 to 2019-20. Due to high cloud cover/new snowfall issues in the LANDSAT series of satellite image for the studied region, snow cover analysis could not be performed for the periods of end of accumulation season of 2011-12 and 2012-13, and in ablation season of 2011-12 and 2017-18. Similarly, vegetation cover analysis could not be performed during end of the ablation season of 2011-12. Additionally, ALOS - PALSAR Digital Elevation Model (DEM) with spatial resolution of 12.5m x 12.5m was used for extracting the elevation, slope, and aspect parameters of the catchment.

Snow Cover Mapping

To delineate the presence of snow over the study area during end of the accumulation and the ablation seasons, standard method of Normalized Difference Snow Index (NDSI) was used. For images of Landsat 5, band 2 (Green) and band 5 (SWIR) were used, whereas for Landsat 8, band 3 (Green) and band 6 (SWIR) were used to calculate NDSI using the following formulation suggested by Dozier (1989) and modified by Hall *et al.* (1995) -

$$NDSI = \frac{Green - SWIR}{Green + SWIR} \qquad (1)$$

Vegetation Cover Mapping

To determine the vegetation cover over the catchment during the end of the ablation season, Normalized Difference Vegetation Index (NDVI) was used. To calculate NDVI, band 3 (Red) and band 4 (NIR) of Landsat 5 were used, however, for Landsat 8, band 4 (Red) and band 5 (NIR) were used using the following formulation suggested by Kriegler *et al.* (1969).

$$NDVI = \frac{NIR - \mathrm{Re}\,d}{NIR + \mathrm{Re}\,d} \qquad (2)$$

Results & Discussion

Analysis of Climatic Records

Daily records of minimum (T_{min}), maximum (T_{max}) and average (T_{avg}) near-surface air temperature of the Rishiganga River basin were analysed for the hydrological years of 2010-11 to 2019-20 (10 years), at daily scale. In case of T_{min}, it was observed that T_{min} ranged from (-) 2.71 ± 7.83°C to (-) 1.87 ± 7.74°C with an average value of (-) 2.33 ± 7.93°C (Fig. 3a). However, T_{max} varied between 4.24 ± 6.43°C and 5.41 ± 6.75°C having an average value of 4.82 ± 6.81°C (Fig. 3b). The near-surface average temperature of the basin fluctuated in the range of 1.01 ± 6.37°C to 1.88 ± 6.58°C with an average value of 1.45 ± 6.59°C (Fig. 3c). To identify the fluctuations of near-surface air temperature and its confirmation, trend line analysis was performed at yearly and seasonal scales. Results suggested that average T_{min} experienced a sharp rise of (+) 0.40°C in winter season followed by (+) 0.38°C yearly and (+) 0.36°C in summer. Similarly, T_{max} was observed to be increased by (+) 0.54 °C in summer followed by (+) 0.53°C yearly and (+) 0.49°C in winter season. However, T_{avg} experienced an increase of (+) 0.43°C in summer followed by (+) 0.32°C yearly and (+) 0.21°C in winter season. Normalizing the trend line results of seasonal and annual fluctuations of near-surface air temperature (T_{min}, T_{max}, T_{avg}) represented that T_{max} experienced the highest significant changes at seasonal and yearly scales followed by T_{avg} and T_{min}. Furthermore, analysis of precipitation records at seasonal and yearly scales suggested that total winter precipitation varied between 1483 ± 14.83 and 2576 ± 17.06 mm with an average value of 2032 ± 16.72 mm (Fig. 3d). Similarly, in the summer season, total precipitation fluctuated in the range of 1458 ± 13.04 to 2731 ± 18.66 mm having an average value of 2093 ± 16.95 mm. However, at a yearly scale, changes in total precipitation were observed between 3427 ± 14.61 and 4923 ± 19.29 mm with an average value of 4124 ± 16.97 mm. Trend line analysis of seasonal and yearly precipitation records suggested that the Rishiganga River basin experienced a sharp decrease in total winter precipitation by 512 mm followed by 83 mm in yearly total precipitation. However, in the summer season a sharp rise of 429 mm in total precipitation was observed.

These facts represent that the contrasting meteorological parameters (near-surface air temperature and precipitation) of the Rishiganga River basin that governs the basin ecosystem were changed significantly during the study period. In previous studies, increasing trend of near-surface air temperature and decreasing trend of winter precipitation over the high-altitude regions of the Himalaya were also observed (Archer & Fowler 2004; Bhutiyani *et al.,* 2009; Kesarwani, 2015; Kour *et al.,* 2016; Shafiq *et al.,* 2018; Sahu & Gupta, 2020).

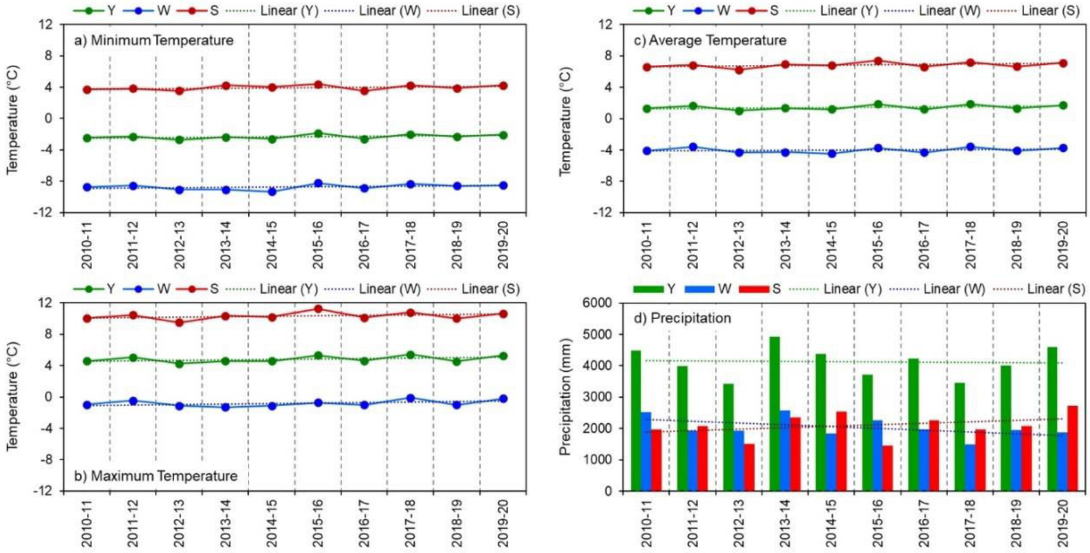

Fig 3. Components of near-surface air temperature – (a) minimum (T_{min}), (b) maximum (T_{max}), (c) average (T_{avg}), and (d) precipitation records at seasonal (winter - W; summer - S) and yearly (Y) scales of the Rishiganga River basin, Central Himalaya (Uttarakhand), India for the hydrological years 2010-11 to 2019-20 (10 years). Trend line analysis was used to calculate the linear fluctuations in near-surface air temperature and precipitation records at seasonal and yearly scales.

Seasonal Snow Cover

The seasonal snow cover area (SCA) plays an important role in the Himalayan region to maintain the river runoff. Information on changes in SCA on a spatio-temporal basis will be helpful for better and efficient utilization of water resources and understanding the impact of climate change. In the present study, snow cover changes in the Rishiganga River basin were analysed during end of the accumulation and the ablation season of 2010-11 to 2019-20 hydrological years. At the end of the accumulation season, total average residual SCA was observed to be 74.96 % of the basin area (521.85 km^2) during the study period (Fig. 4a). The maximum annual SCA was found in 2013-14 as 86.82 % (604.47 km^2) with minimum being 59.65% (415.30 km^2) in 2014-15. Trend line analysis of changes in residual SCA during the end of the accumulation season suggested that SCA showed a negative trend and decreased by 26.6 km^2 in the basin during the studied period. This decreasing trend of residual SCA during the winter in the Rishiganga River basin may be attributed to increase near-surface air temperature.

Furthermore, during the end of the ablation season, the average residual SCA was 22.74% of the river basin (158.31 km^2) from 2010-11 to 2019-20 (Fig. 4b). The hydrological year 2019-20 experienced minimum residual SCA of 15.71% (109.35 km^2) while year of 2010-11 experienced maximum residual SCA of 31.74% (221.02 km^2). Results of the trend line analysis represented that residual SCA was decreased by 29 km^2 during the end of the ablation season. A strong correlation was also observed between fluctuations in SCA and near-surface air temperature which represented the fluctuations in SCA over the Rishiganga River basin is highly sensitive to change in temperature. In previous studies, decreasing trend of residual winter snow cover and increasing trend of minimum near-surface air temperature over the high-altitude regions of the Himalaya were also observed (Archer & Fowler 2004; Bhutiyani *et al.,* 2009; Kesarwani*,* 2015; Kour *et al.,* 2016; Shafiq *et al.,* 2018; Sahu & Gupta, 2020).

Vegetation Cover Analysis

In order to study the fluctuations in vegetation cover area (VCA) over the Rishiganga River basin at a spatio-temporal scale, the method of Normalized Difference Vegetation Index (NDVI) was used during end of the ablation season of 2010-11 to 2019-20. VCA in the basin was found to be higher in the downstream and some part of the middle portion of the valley (Fig. 5). Further, in the middle portion of the valley, seasonal change in VCA was maximum. Fluctuations in VCA was in the range of 8.72 (1.25% of the basin area) to 65.93 km^2 (9.47% of the basin area) with an average yearly fluctuation of 31.22 km^2 (4.48% of the basin area) during the study period. The lowest VCA was observed during the hydrological years of 2013-14 while the highest one was in 2014-15. The area with high vegetation cover was concentrated in the western portion of the valley followed by the southwest (SW) and the northwest (NW) region. However, VCA was found to be relatively small in the north (N), northeast (NE), east (E), southeast (SE) and south (S) portions of the valley.

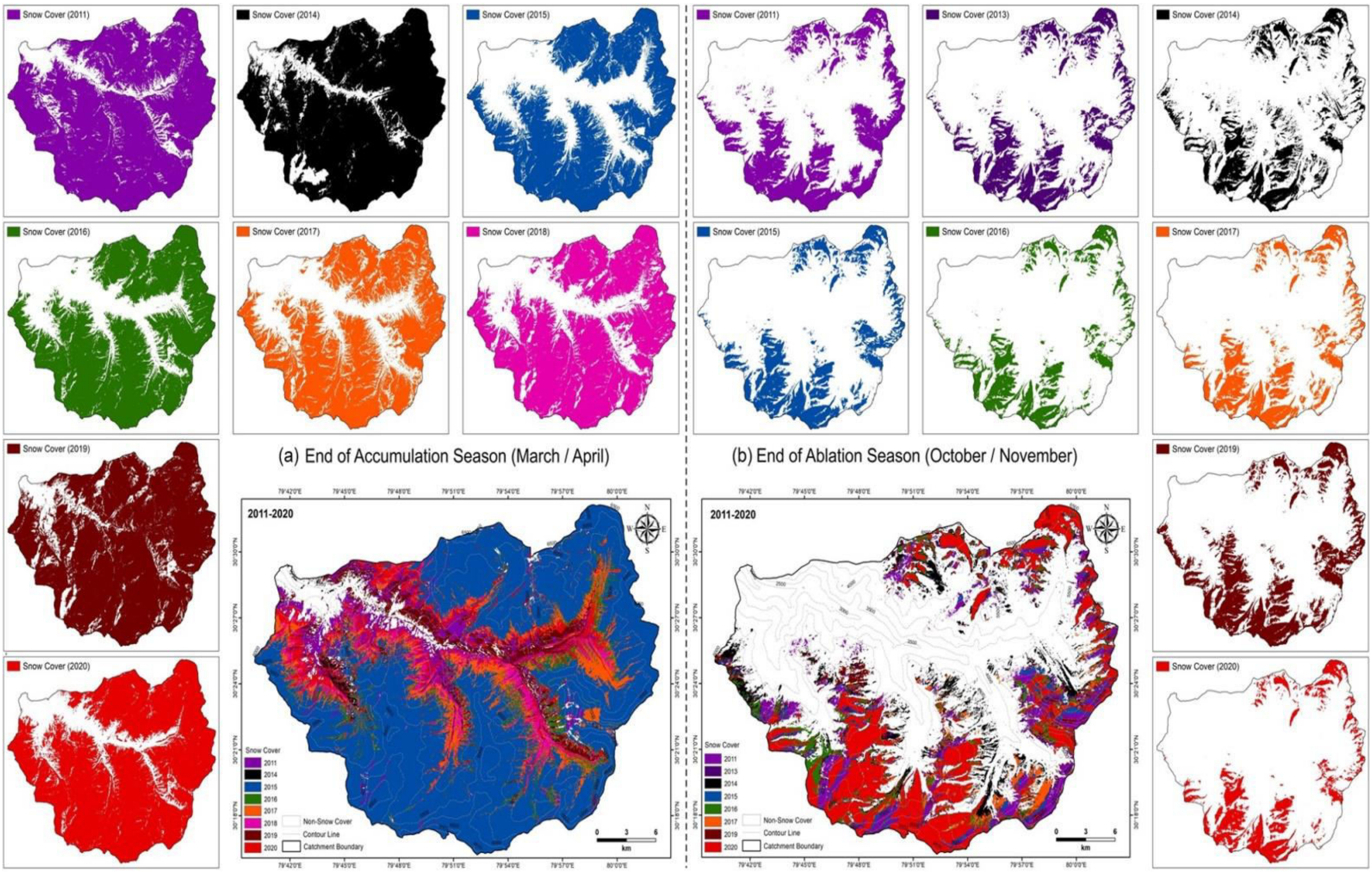

Fig 4. Seasonal snow cover variability (2011-2020) of the Rishiganga River basin during a) end of accumulation (March/April) and b) ablation (October/November) seasons of 2010-11 to 2019-20 hydrological years. Snow cover analysis could not be performed during the periods of end of accumulation season of 2011-12 and 2012-13, and ablation season of 2011-12 and 2017-18 due to high cloud cover/new snowfall issues in the LANDSAT series of satellite image for the studied region.

From the perspective of distribution, vegetation cover in the valley was in a flaky manner. The seasonal changes in VCA were quite different and generally dependent on SCA. However, the overall performance of VCA in the valley was in an increasing trend from the northwest to the southwest which represents that the timber line in the basin is shifting towards higher altitude.

Snow-Vegetation Interactive Processes

The relationship of vegetation cover with snow-glacier metrics strongly depended on the altitude and associated climatic conditions (Asam *et al.,* 2018). Retreating of available cryosphere mass (snow and glacier) in the Rishiganga River basin will expose new terrains in the near future and develop space for vegetation to grow. However, continuous increase in vegetation cover over the snow-glacier fed catchment will be responsible for generating more warming of the surrounding atmosphere and faster melting of cryosphere mass; resulting in pushing back the snow and glacier to their extinction. The present study suggested that fluctuation in snow cover with vegetation represents a near-to-inverse relationship.

Furthermore, previous studies in the alpine cryosphere environment showed that at first the vegetation cover and associated biodiversity would increase (Raffl *et al.,* 2006) with the cryosphere mass retreat in the high-altitude regions. However, this phenomenon holds true only as long as the cryosphere regime is not vanished, once it disappears, most of the vegetation will also not survive (Cauvy-Fraunié & Dangles, 2019; Losapio *et al.,* 2021). Even for the plant species who will be in the category of *"winners,"* the *"victory"* will not be taken for granted due to the negative impacts of changing climate and rising competition (Losapio *et al.,* 2021).

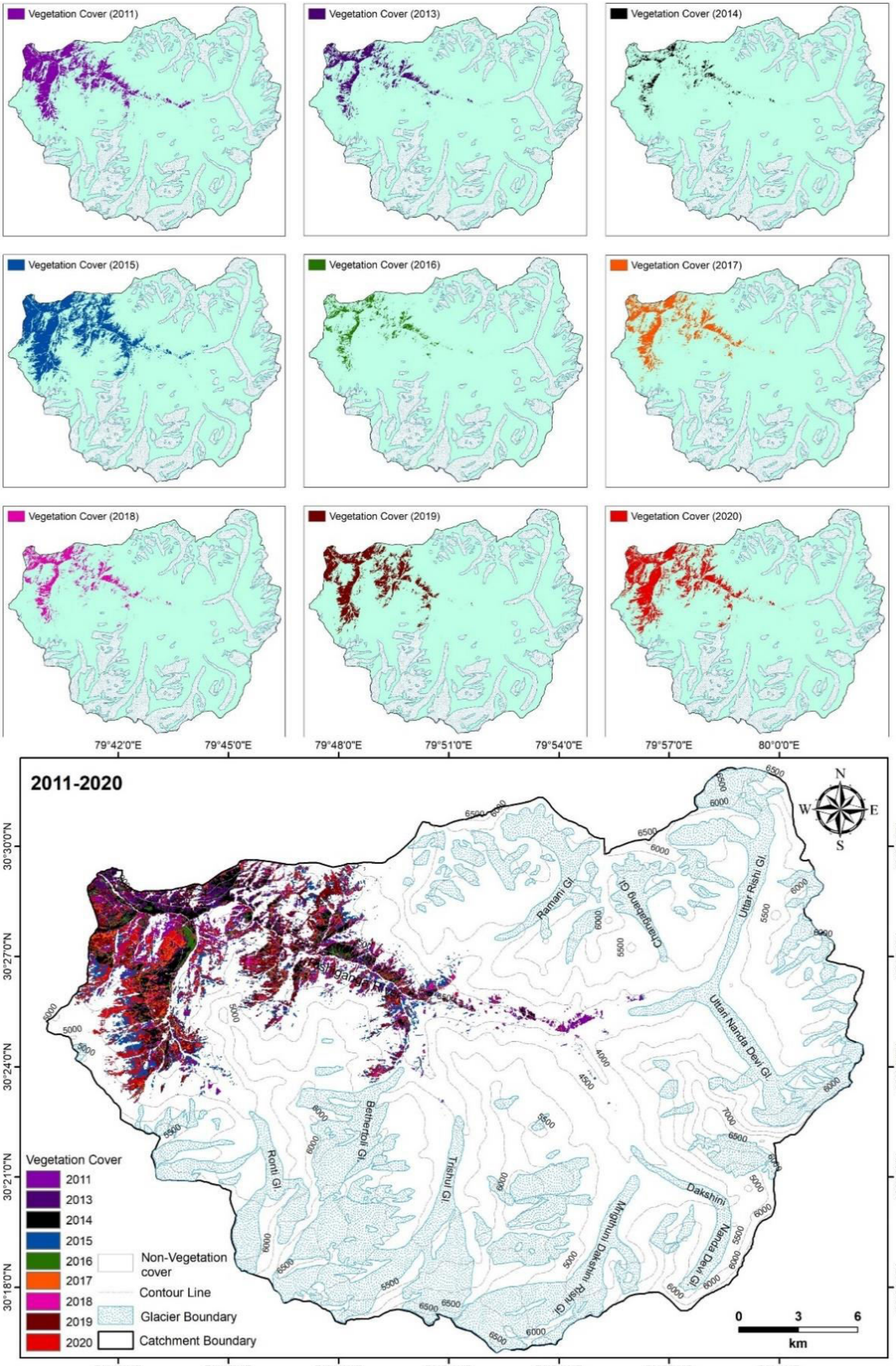

Fig 5. Seasonal vegetation cover variability of the Rishiganga River basin during the end of accumulation (March/April) and ablation (October/November) seasons of 2010-11 to 2019-20 hydrological years. Vegetation cover analysis could not be performed during end of ablation season of 2011-12 due to high cloud cover issues in the LANDSAT series of satellite image for the studied region.

Conclusion

In the present study, the Rishiganga River basin (Central Himalaya, India) is studied in terms of identifying the impact of climate change on the Himalayan ecosystems. Long term records (2010-11 to 2019-20; 10 years) of contrasting meteorological (near-surface air temperature and precipitation), and land cover (fluctuation in snow and vegetation cover) parameters of the basin were analysed. Results of the study suggested that all components of temperature (minimum, maximum and average) were increased significantly at seasonal and yearly scales including summer precipitation. However, amount of the precipitation was substantially decreased during winters and at yearly scale. Furthermore, studies on identifying the cumulative effect of changing contrasting meteorological parameters, residual snow and vegetation cover suggested that the river basin is getting warmer at seasonal and yearly scale, resulting in a decreasing pattern of residual seasonal snow cover and an increasing pattern of vegetation cover (signifying the timber line is shifting towards higher altitude). The study also finds out that fluctuation in snow cover with vegetation represents a near-to-inverse relationship. In summary, although the vegetation cover will initially increase in the basin with cryosphere mass retreat, most of the plant species will substantially decline and disappear with glacier extinction.

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