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Impact of Climate Change in the Himalayan Region: Drivers, Implications, and Mitigations

Vishwambhar Prasad Sati

ABSTRACT

The impact of climate change in the Himalayan region is enormous. Along with anthropogenic global warming, the consequences of climate change in the Himalaya are enormous. The purpose of this study is to examine the impact of climate change in the Himalayan region. It further analyses the drivers and implications of climate change and explores ways to mitigate its effects. In this paper, data were mainly gathered from the review of literature. Furthermore, observation method was employed to conduct this study as the author visited many parts of the Himalayan region. It was noticed that climate change has effected natural and cultural aspects simultaneously. High variability in rainfall and increase in temperature changed the warming pattern. This was resulted in snow melting, biodiversity loss, shifting of plant species towards the higher elevation, low yield from agriculture fields, and increasing extreme weather events. Sustainable use of natural resources including renewable ones, adopting a green economy, and minimizing physical consumption can reduce carbon emission and can mitigate climate change.

Keyword: Carbon emission; retreating glacier; ecological loss; declining agriculture; climate change; Central Himalaya.

1. INTRODUCTION

Climate of the Earth varies from the equatorial region to the poles and from low elevation to high elevation. Natural forces such as the rotation of Earth on its axis and revolution around the sun, contribute to climate variability. Volcanic eruptions, geothermal energy emission, and solar radiation are the other factors influence climatic patterns of the earth. Due to increase in greenhouse gases (GHGs) mainly after industrial revolution, an increase in anthropogenic global warming was substantial (Stocker et al., 2013). Furthermore, due to carbon emission and the rise in aerosols intensified climate change (Myhre et al., 2013). Allen et al., (2018), estimated a global temperature increase of 1°C since pre-industrial times.

Although climate change is a global phenomenon, it does not occur uniformly across the Earth. Church et al., (2013), observed that the Arctic temperature is rising faster than the global average, and the rate of sea-level rise varies significantly from the equator to the polar regions and from the western to the eastern hemispheres. While climate change impact can be assessed on a global scale, its impact at the regional level is difficult to understand to scientists and policymaker. In the meantime, understanding of accurate regional climate change is essential for effective disaster management and risk reduction strategies (Burkett et al., 2014).

Climate change impact on the environment, economy, and society is significant in the Himalayan region (Ives and Messerli, 1989). The Intergovernmental Panel on Climate Change (IPCC) stated that the warming is significant in the Himalayan highlands, including the Tibetan Plateau (Gao et al., 2003; Yao et al., 2006). Studies indicate that warming in the Himalaya has exceeded the global average of 0.74°C over the past 100 years. Furthermore, the data suggest that warming intensifies with increasing altitude across the Greater Himalayan region. However, the warming trend is not uniform: it is increasing in the northern, central, and eastern Himalaya, while a decreasing trend has been observed in the western Himalayan region (Zhao et al., 2004; Xu et al., 2007).

Climate change impacts in the Himalaya are multifaceted, as the region is among the most vulnerable to its effects. Receding glaciers, downstream flooding, and geohydrological disasters are major consequences of climate change. These will further affect biodiversity, agricultural practices, and livestock farming. Studies suggest that climate change in the Himalayan region will impact the monsoon system and the Western Disturbances. Its effects on river flows, groundwater recharge, natural hazards, and ecosystems will be adverse. Ultimately, it will severely affect the livelihood sustainability of local communities (Sati, 2025).

This study relies on a review of the literature primarily focused on the Himalayan region. It examines rainfall variability and changes, receding snow cover and glaciers, the impacts of climate change on biodiversity, declining agricultural productivity, and the increasing frequency of extreme events. The main research questions addressed are: What are the drivers and consequences of climate change impacts in the Himalayan region? What mitigation measures can minimize these impacts? The study hypothesizes that anthropogenic global warming is the primary driver of climate change in the Himalayan region.

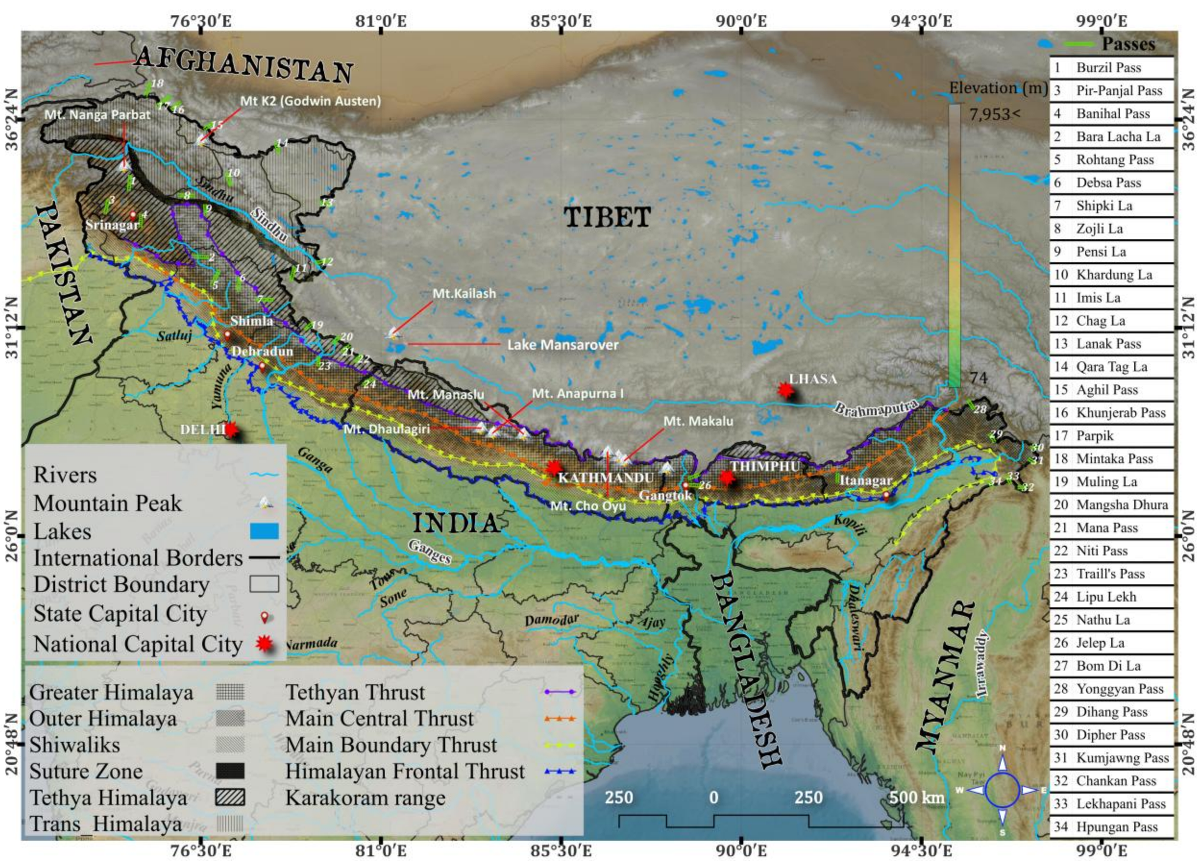

Fig. 1. Location map of the Himalaya

Study Area

This study focuses on the Himalayan region, particularly on the Central Himalaya. The Himalaya is the tallest mountain system in the world, extends from the Pamir Knot in the northwest to Myanmar in the southeast, approximately 2,500 km (Fig. 1). It is ecologically fragile, geologically sensitive, seismically and tectonically highly active, geographically remote, and economically underdeveloped (Sati, 2024). The region is recognized as a global biodiversity hotspot due to its rich biological diversity. It provides vital ecosystem services and supports the livelihoods of over one billion people (Sati, 2023). Furthermore, the Himalaya possesses rich agro-biodiversity, sustaining numerous traditional crop varieties and cultivars. It is also the source of three largest river systems of the world—the Sindhu (Indus), the Ganga, and the Brahmaputra—which collectively forming the extensive and fertile Gangetic Plain. Meanwhile, the Himalaya is highly vulnerable to climate change. Climate variability is high, as temperature is increasing and rainfall is decreasing. It led to high frequency and intensity of natural disasters and caused to human, economic, and ecological losses.

2. METHODOLOGY

The major source of this study was an extensive literature review related to the impact of climate change on rainfall variability, snow cover and glaciers, biodiversity, agro-climatic zones, agriculture, and extreme hazards in the Himalayan region. In addition to secondary sources, primary data were collected through detailed field visits and observations, primarily focused on the Central Himalayan Region. Rainfall variability and change data were obtained from the Indian Institute of Tropical Meteorology (IITM), Pune. Descriptive statistics, regression analysis, and the Mann-Kendall trend test were employed in the data analysis. Data on receding snow cover and glaciers were sourced from the United States Geological Survey (USGS) from 1991 to 2021, at five-year intervals. The author examines the impact of climate change on agriculture, horticulture, and livestock through case studies and household-level surveys. Along with a sample size of 30%, the author used a purposive sampling method to collect data. The State Disaster Management Authority (SDMA), Dehradun, provided data on natural disasters.

3. RESULTS AND DISCUSSION

High Rainfall Variability and Change

Rainfall in the Himalayan region is primarily orographic, leading to significant spatial variability. Consequently, the impacts of climate are primarily influenced by local topographic features (Chalise and Khanal, 2001). During the summer season, from mid-June to mid-October, the region receives rainfall from the Southwestern Monsoon. In contrast, during the winter months of December and January, rainfall and snowfall in the Western Himalaya are brought by Western Disturbances. The Himalayan region has experienced increasing variability in rainfall patterns. Notably, winter precipitation caused by Western Disturbances, originating from the Mediterranean region, has shifted from the traditional months of December and January to February and March (Dimri et al., 2015; Hunt et al., 2018; Krishnan et al., 2019).

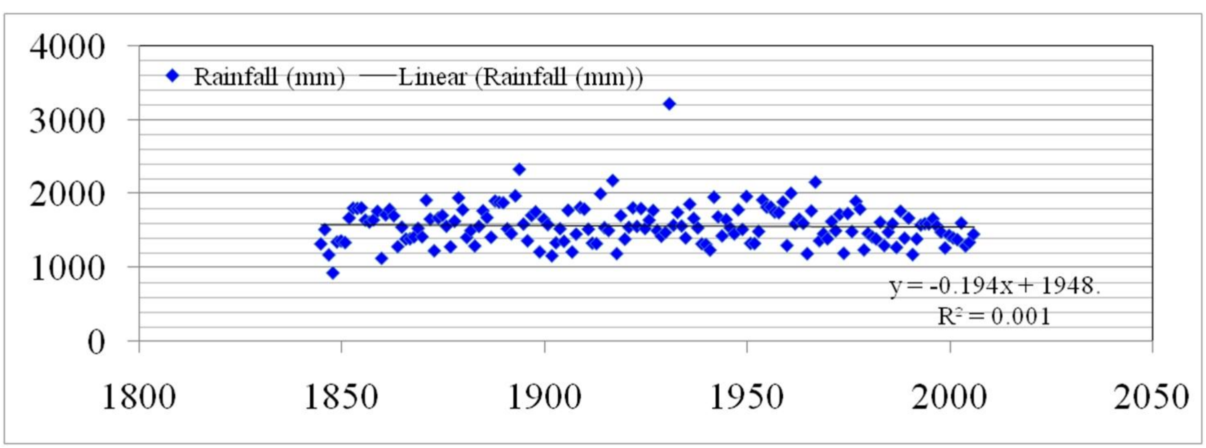

Fig. 2. Annual average rainfall in the Himalayan region

In the recent past, frequency, intensity, and duration of monsoon rainfall is highly variable. Rainfall variability depicts that the duration of monsoon rain has decreased from four months to three months, whereas, its intensity increased, resulting to an increase in natural disasters. Over the past 161 years, the annual average rainfall showing a decreasing trend with high interannual variability (R^2 value = 0.001) (figure 2).

The analysis of seasonal rainfall analysis in the Himalayan region reveals varying trends across different seasons. There are four rainfall seasons in a year: (1) January and February, (2) March, April, and May, (3) June, July, August, and September, and (4) October, November, and December. During January and February, winter precipitation from Western Disturbances used to be intense; however, in recent years, this pattern has shifted toward March, April, and May, with reduced intensity and an overall decreasing trend. In the winter season of 2024–25, the Western and Central Himalayan region received scanty precipitation, resulted in drought situation. Meanwhile, rainfall in March, April, and May has shown an increasing trend, although this period historically received very little rain.

July, August, and September are typically the peak monsoon months. However, in recent years, rainfall during this period has declined notably in volume. Despite this, the intensity of rainfall events has increased, with frequent and intensified cloudbursts leading to debris flows and flash floods—both of which have become more severe and widespread across the Himalaya (Sati, 2022). Similarly, the rainfall trend has increased during October, November, and December (Fig. 3).

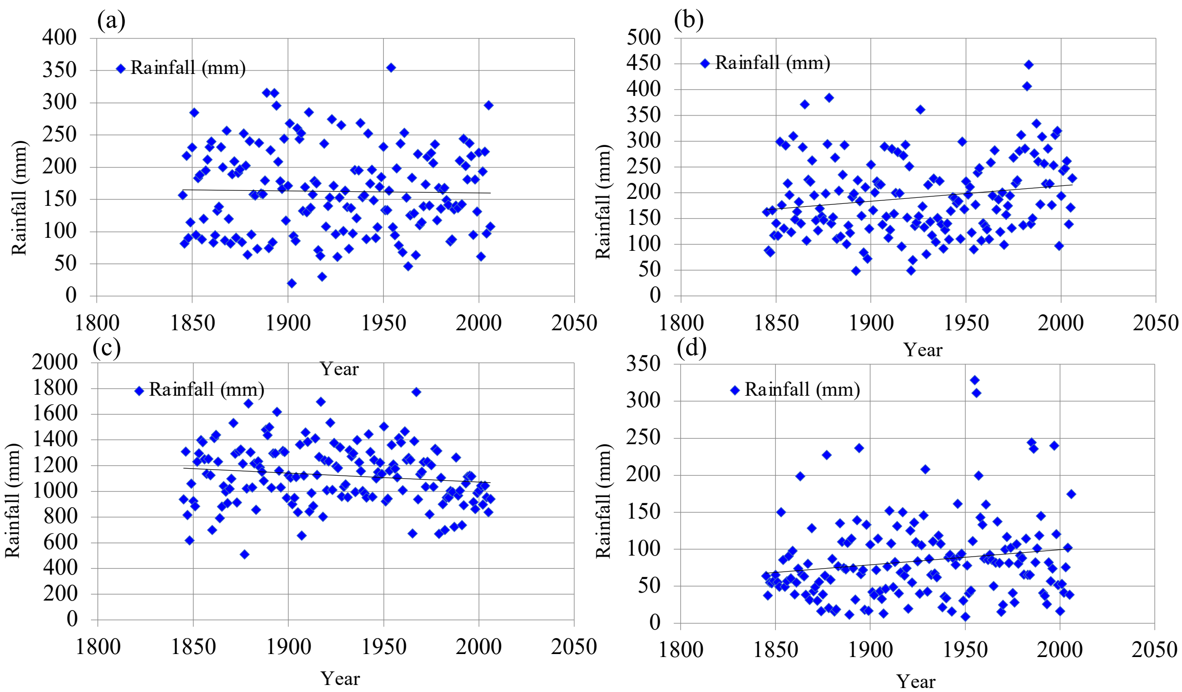

Fig. 3. Seasonal average rainfall variability, (a) January and February, (b) March, April, and May, (c) June, July, August, and September, (d) October, November, and December

Table 1: Trends of decadal and seasonal average rainfall

Seasons	**Z**	**P**	**Q**	**Trends**
Jan and Feb	-0.50	0.62	-5.09	Insignificant decrease
Mar, Apr, and May	0.77	0.44	11.64	Insignificant increase
Jun, Jul, Aug, and Sept	-1.40	0.16	-102	Insignificant decrease
Oct, Nov, and Dec	1.85	0.06	15.03	Insignificant increase
Total	-1.31	0.19	-61.45	Insignificant decrease

Note: Z= Mann-Kendall/modified Mann-Kendall test statistics, P= Probability Value, Q= Sen's Slop; Level of significance 0.05

The Mann-Kendall Test and slope analysis of trends in seasonal average rainfall in the Himalayas depict an insignificant decrease and increase during 1845-2006 (Table 1). The rainfall seasons (1) January and February and (2) June, July, August, and September experienced an insignificant decreasing trend with magnitudes of -5.09 and -102 per decade, respectively. On the other hand, in March, April, and May, the rainfall increased insignificantly. The situation was the same in three months of October, November, and December. Moreover, the overall decadal trend for the entire study area showed an insignificant decrease during the recorded period, with an average magnitude of -61.45 per decade.

Receding Snow Cover and Glaciers

Mountains provide 50% of the global river runoff. Approximately one-sixth of population of the Earth depends on glaciers, seasonal snow, and water for domestic and agricultural needs. Climate change impact will be tremendous on glaciers, snowpacks, and farming practices (Barnett et al., 2005; Graham et al., 2007). There are 16,000 glaciers in the Himalayas. As depicted in the fourth IPCC report, (2007), climate change has resulted in high rates of snowmelt rate in the Himalayan region. Glacial Lake Outburst Floods (GLOFs) are threatening to mountain areas. About 204 glacial lakes have been identified as potentially dangerous in the Himalayan region (ICIMOD, 2007).

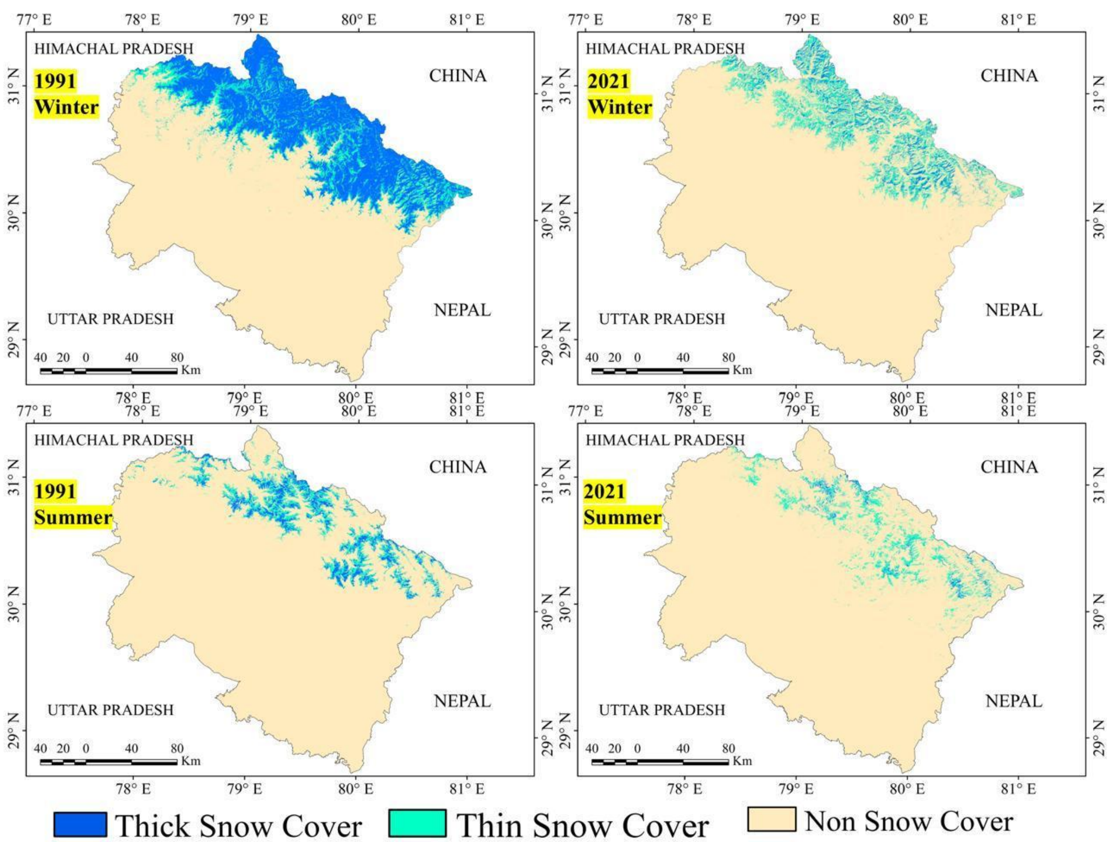

Fig. 4. Changes in thick and thin snow cover in the Central Himalaya.

One of the indicators of climate change in the Himalayas is the receding of glaciers. The Himalayas possess some of the most significant snowpacks and glaciers in the mountain ranges of the world, feeding the three major river systems—the Sindhu, Ganga, and Brahmaputra. Climate change has a significant impact on the Greater Himalayan region, which is known as the Roof of the World. The rapid reduction in glaciers has profound future implications for downstream water resources. Recently, Himalayan glaciers have been receding faster than the global average, according to a study by Dyurgerov and Meier, (2005). Two main factors are causing glacier retreat in the Himalayas: decreased precipitation and increased temperatures. If warming and drying continue, glacier loss will accelerate (2003; Sati, 2022). Studies on Himalayan glaciers reveal that, in the coming decades, glaciers in the Himalayas will continue to retreat, and smaller glaciers may disappear (IPCC, 2007). Qin, (2002) observed that by 2050, a 2°C increase in temperature would lead to a 35% reduction in glaciers and increased runoff in the Himalayan region. Glacier retreat will destabilize slopes and increase landslides (Ballantyne and Benn, 1994; Dadson and Church, 2005). Additionally, it will lead to flash floods (Hewitt, 2005).

The mass loss of Himalayan glaciers is higher than the global average in recent decades (Kaab et al., 2012; Zemp et al., 2005). Westerlies influenced these glaciers, which decrease from west to east, and the Indian monsoon, which decreases from east to west (Bookhagen and Burbank, 2010). A study showed that glacier loss in the Himalayas ranged from 1% to 14%. The Gangotri glacier of the Garhwal Himalaya retreated by 1,500 meters since 1935. The Alaknanda Basin in the Central Himalayas has experienced a 10% loss of snow over 15 years (Kulkarni and Karyakarte, 2014). It has further accelerated runoff and led to extreme water scarcity for people living in upstream areas (Kumar and Prabhu, 2012). Furthermore, high climatic variability and glacial melt have significantly impact on groundwater recharge and ecosystem health in downstream areas (Lepcha et al., 2021).

A study conducted by Banerjee et al., (2024), shows that both thick and thin snow cover in the central Himalayas from 1991 to 2021 was significantly reduced (Fig. 4). The reduction in snow cover due to human interference was significantly high in Gaumukh glacier, Alkapuri glacier, Ralam glacier, and Milan glacier. The snow cover volume maxima and minima exhibit both increasing and decreasing trends. From 1991 to 2001, the snow volume maxima and minima increased, after which they decreased significantly (Fig. 5), indicating receding glaciers with high variability.

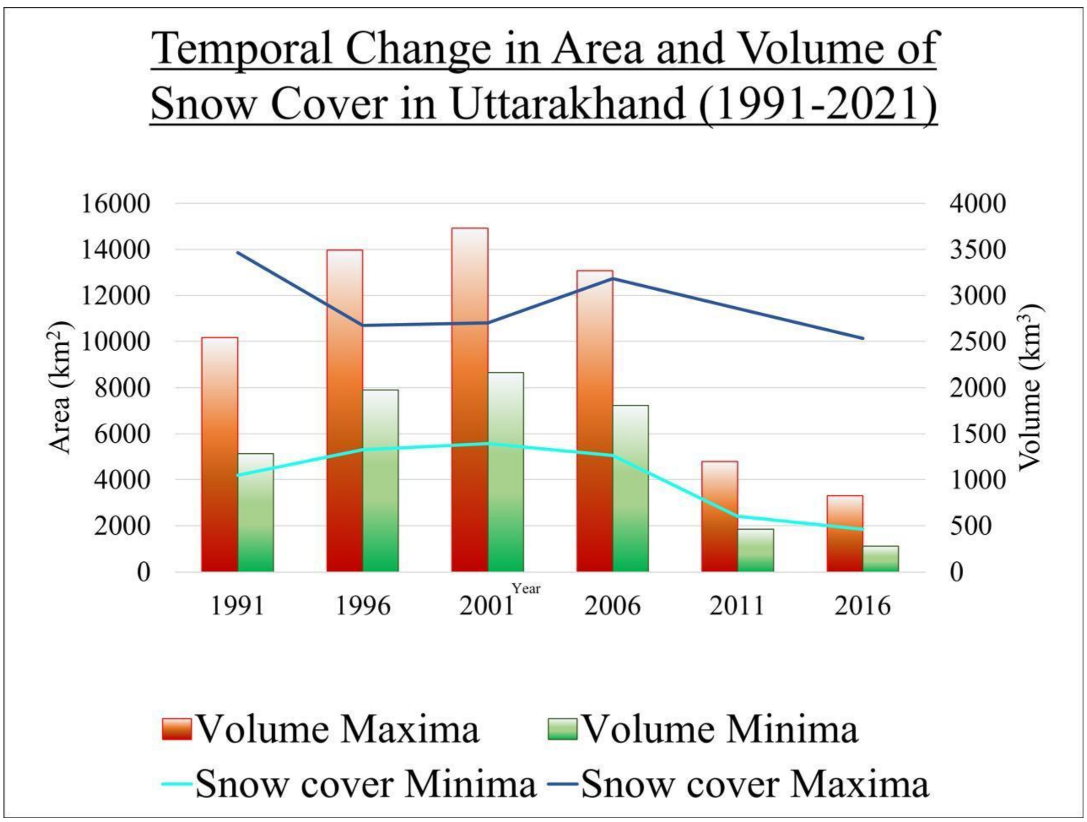

Fig. 5. Temporal change in area and volume of snow cover in Uttarakhand (1991-2021).

Climate Change and Biodiversity Loss

The Himalayas have rich biodiversity, ranking fourth among 36 global biodiversity hotspots, 60th among 200 global eco-regions, and 330 crucial biodiversity and bird areas (Kotru et al., 2020). They provide crucial ecosystem services, including carbon sequestration, water storage, biodiversity maintenance, and food security to highland pastoral communities (Ingty, 2021). The Himalayas are the source of the world's major river systems, supporting ecosystem goods and services for more than one billion people, upstream and downstream. Similarly, mixed-oak forests in the Himalayan region provide significant socio-cultural ecosystem services when managed by local communities (Dorji et al., 2019). However, habitat loss and declining biodiversity have led to a substantial loss of ecosystem services. In the Nepal Himalaya, the value of greenhouse gas sequestration reduced to 74%, a 60% reduction in carbon storage, a 94% reduction in nature-based recreation, and an 88% reduction in water quality (Peh et al., 2016).

Climate change has high impact on the distribution of natural vegetation and ecosystems (Wilkes, 2008). Recently, the Himalayas have been experiencing significant warming (Shrestha et al., 2012), with an increase in global mean temperature (Lamsal et al., 2017). Global warming has a substantial effect on the Himalayan ecosystems (Xu and Wilkes, 2004). Decreasing biodiversity and climate change have greatly affected ecosystem functions in the Himalayan region (Pires et al., 2018). Degradation of forestland due to warmer and drier climates will be a future problem (Dirnbock et al., 2003). The tree line is rising from 5 to 10 meters per decade in the eastern Himalayas (Baker and Moseley, 2007). The Himalayan region is facing significant biodiversity loss due to human interference and climate change.

Human-induced activities affect more than 9 million faunal and floral resources worldwide (Cardinale et al., 2012). Several plant species have shifted to the higher altitudes due to warming (Shrestha et al., 2012). Furthermore, climate change leads to biodiversity loss and changes in ecosystem processes, further leading to decrease in ecosystem productivity (Balvanera et al., 2014; Arneth et al., 2020). In addition, climate warming drives land-use changes across the altitudinal gradient, constraining biodiversity and ecosystem functions, resulting in lowering ecological resilience. It has become one of the most substantial drivers of biodiversity loss in the Himalayas. Climate warming will have substantial effects on biodiversity loss and reduced ecosystem services (Dolezal et al., 2020; Hector and Bagchi, 2007).

The biodiversity of the Himalayan region is highly sensitive to climate change. The author observed that pine forests are invading the mixed-oak forest regime (Fig. 6), therefore, mixed-oak forest area has decreased. Shift of pine forest to higher elevation is more affective on the sun-facing slopes. The trend is similar to agro-biodiversity as the area and production under apple fruits have decreased and citrus fruits are already minimized from the valley regions and middle altitudes (Sati, 2024).

Fig. 6. Pine trees are invading mixed-oak forests in the Paukhal area of the Tehri district. *Photo: By author*

The Himalayan region is also rich in agro-biodiversity, with hundreds of agricultural and horticultural crop races/cultivars grown at different altitudes. The Barahnaja system prevails here, where 12 or more crops are grown in a single agricultural field. Traditional crops are highly adaptable to climate change in the Himalayan region. However, the area under conventional crops has decreased. Monocropping, such as paddy cultivation, requires large amounts of water, and due to the drying up of many conventional water sources, water scarcity is a growing concern. It has led to decreased water supply to paddy fields in the valleys. Crop yield may decrease by 30% due to rising temperatures and water stress in the future (UNDP, 2006). The impact of climate change on water resources and farming systems has become more intensive.

In the Himalayan region, studies on the impact of climate change on biodiversity loss are limited. Decreasing precipitation and increasing temperatures, caused by the retreat of Himalayan glaciers due to warming in recent decades, are leading to the shift of fauna from lower altitudes to higher altitudes (Sigdel et al., 2021). The Himalayan flora is highly sensitive to climate change, and warming in the high-altitude regions will impact ecosystem functions in the future (Behera et al., 2019). Telwala et al., (2013), stated that 87% of 124 endemic species have experienced a shift to higher altitudes. Climatic warming has impacted species richness and diversity (Bhattacharjee et al., 2017), along with changes in tree-line ecotone species. Betula utilis (Himalayan birch) has been shifting towards the Eastern Himalayas, with a declining trend in the west (Hamid et al., 2018). The early flowering of Rhododendrons in the Himalayan region indicates a warming trend and the impact of climate change.

Declining Agriculture

In the Himalaya, agriculture is the prime economic activity, the main occupation, and a significant source of the economy (Wani, 2011; Sati, 2023). However, its contribution to GDP is minimal and is further declining (Economic Survey, 2019). Agriculture characterises fragility, marginality, inaccessibility, and poor infrastructural facilities. Approximately 76% of the total cropped area is grain-dominated (Pratap, 2011), and it remains self-sufficient without any commercial use (Pandey et al., 2016), alongside low production of subsistence cereals (Khanal, 2018). The terrain is rough and rugged with small landholdings (Pathania, 2010). Recently, agricultural land has been shrinking, and irrigation facilities are inadequate, leading to low crop production. Driving forces such as frequent disasters, poor planning, lack of technological advancement, and dependency on monsoon rains impact cropping patterns (Fatima and Hussain, 2012). Topsoil and fertile soil erosion due to excessive rain, steep slopes, and fragile landscapes further contribute to low crop productivity (Mahapatra et al., 2018; Mandal and Sharda, 2011). The economic status of the majority of farmers is medium to low (Roy et al., 2013). High variability and changes in climatic conditions—such as increasing temperatures, decreasing precipitation, and extreme weather conditions—have significantly impacted the agricultural systems of the Himalaya (Swiderska, 2022; Bolch et al., 2019). It has reduced water availability for irrigation, instability in crop yields, and failure of rainfed farming systems (Negi et al., 2012; Ramesh et al., 2017). Approximately 50% of the population suffers from food insecurity and malnutrition in the Himalayan region (Rasul et al., 2019). Similarly, about 38% of farming families face transitory food insecurity (IMI, 2019; Sharma and Sharma, 1993).

The author conducted a case study of eight villages in the Chamoli, Pauri, Tehri, and Uttarkashi districts of the Central Himalaya. He observed that, except for a few crops, the area, production, and productivity of all crops decreased substantially from 2000 to 2020 (Table 2). He observed the same trend in fruit crops.

Table 2. Change (%) in Area and Production under Different Crops (2000–2020)

A. Food and Commercial Crops			
Crop	Area (%)	Production (%)	Productivity (%)
Paddy	−61.4	−81.7	−52.3
Wheat	−58.5	−87.3	−69.0
Barley	−35.6	−35.6	No change
Millets	−32.5	−73.2	−59.8
Pulses	+6.3	−72.7	−75.2
Oilseeds	+162.7	−73.9	−90.6
Potato	−11.4	+76.1	+100.0
Total	−17.3	−53.2	−42.4
B. Fruit Crops (Plants in Number)			
Fruit	Area (%)	Production (%)	Productivity (%)
Apple	−62.1	+660.6	−33.1
Peach	−44.8	−86.9	−69.7
Malta	−6.7	−39.2	−62.0

Lemon	−29.4	−5.3	−14.9
Walnut	−30.1	−55.9	−35.1
Total	−44.4	+473.3	−52.8

Source: By author

The farmers in the Central Himalaya cultivates cereal crops using traditional methods. The cultivation is carried out on the narrow patches, thus, the production and productivity are nominal (Micevska et al., 2008). However, it remains a significant source of income and a livelihood option (Meena and Sharma, 2015). A large population (above 70%) is dependent on practicing agriculture (Alam and Verma, 2007; GoU, 2014), with marginal farmers constituting 90% of the total farming community. Agriculture contributes 11% to the Central Himalaya's Gross State Domestic Product (GSDP) (Rahul et al., 2010). Several factors affect crop production and productivity, with low arable land, rough and rugged terrain, rain-fed agriculture, inaccessibility, high soil erosion, low soil fertility, mono-cropping, and climate change being prominent. Crop diversity is rich, with more than 30 crop races/cultivars, of which, many are likely to extinct due to climate change (Das, 2021). TERI (2018) stated that climate change will have considerable implications for agriculture implications in the coming 30 years. A sustainable agricultural approach is needed to increase the production and productivity of crops.

Increasing Incidences of Disasters

The Himalaya is one of the most fragile landscapes (Byers et al., 2018) and is prone to severe climate-induced disasters. Geohydrological disasters such as glacial and cloudburst-triggered landslides, flash floods, debris flows, rockfalls, extreme weather, and land submergence are common, frequent, and intense (Wang et al., 2014; Sim et al., 2022). The intensity of these disasters has been accentuated by human-induced activities and climate change (Sati, 2014). These disasters disrupt entire landscapes (Sati, 2013; Das et al., 2006) and cause significant loss of life and property (IPCC, 2012; Singh, 2014). Furthermore, the overall impact of these disasters on ecosystems, the environment, and the economy is enormous (Stoffel and Corona, 2014). In the Central Himalayan region, geohydrological disasters are especially widespread (Sati, 2019; Devi, 2015; Bhambri et al., 2016). Numerous disasters in recent years have devastated entire landscapes (Allen et al., 2023). Natural disasters, primarily driven by climate change, such as flash floods, landslides, and forest fires, have also led to the abandonment of arable land.

The author studied the types of hazard events and their frequency in the Central Himalaya from 2020 to 2023. A total of 183 disaster incidents occurred during these three years. Landslides had the highest frequency, accounting for 34.5%, followed by flash floods (26.5%) and cloudbursts (14%). The frequency of other disaster incidents was less than 10%. The distribution of disaster incidents over the years was as follows: 98 incidents in 2022, 51 in 2023, and 34 in 2020-2021 (Table 3).

Table 3: Types of disaster events and their frequency (2020–2023)

Type of disasters	2020–21	2022	2023	Average (%)
Land Submergence	2.9	1.02	0	1.3
Extreme Weather	5.9	1.02	5.9	4.3
Rock Falls	5.9	11.22	11.8	9.6
Debris Flows	17.6	6.13	5.9	9.9
Cloudbursts	11.8	20.4	9.8	14.0
Flash Floods	29.4	26.53	23.5	26.5
Landslides	26.5	33.67	43.1	34.4
Total Incidents	34	98	51	183

Source: By author

4. CONCLUSION

The impact of climate change on the Himalayan region is substantial, affecting rainfall patterns, glaciers, biodiversity, agriculture, and climate-induced disasters. In the past decades, the area has experienced significant variability and changes in annual and seasonal rainfall. Himalayan glaciers are melting at the high rate, with a reduction of about 30% in snow cover in the Central Himalaya over the past three decades. Climate change has resulted in biodiversity loss, declining ecosystem services, and a decrease in agricultural productivity. In addition, the frequency and intensity of geohydrological disasters, such as landslides, flash floods, and debris flows, have been increased, with climate change further exacerbating these events.

The Himalaya, often called as the 'Third Pole' due to vast snow cover, and the 'Water Tower of Asia' because of plenty of water. However, abundance snow cover and water resources are facing unprecedented challenges due to climate change. The Himalaya with its rich biodiversity and ecosystem services is highly vulnerable to environmental disturbances. The region is ecologically fragile, geologically sensitive, and seismically and tectonically active, which makes it particularly susceptible to the impacts of climate change.

The consequences of climate change in the Himalayas are evident, with an increase in the frequency of landslides, glacial lake outburst floods (GLOFs), and other geo-hydrological hazards. Climate change is affecting the natural environment, threatening natural resources, and adversely affecting food security and livelihoods in the region. In addition, the displacement of people due to climate-induced events affected human health and mindset, leading to socio-economic struggles.

Global warming in the Himalayan region has resulted in rising temperature, high variability in rainfall, and melting of glaciers. Furthermore, it has led to shifts in snow cover and decreased water availability, which in turn have reduced crop yields, threatening food security. The events of floods and landslides are increasing, leading to lives, infrastructure, and livelihoods.

Due to warming, the agro-ecological zones are shifting, leading to the loss of habitat in many areas. Many endemic and economically important species are at risk. The author observed that apple cultivation at 2000 m altitude is no longer viable, and apple-growing areas have shifted to above 2200 m in the Central Himalaya. Since the human population is mostly concentrated at around 2000 m altitude, apple cultivation has decreased. Due to this economic loss, people from the Central Himalaya have migrated to urban areas in the plains. As a result, many traditional cultural practices have also been affected. In some areas where water availability is adequate and arable land is sufficient, farmers have initiated coping strategies such as crop diversification, community forestry, and ecotourism. Integrating traditional knowledge with modern innovations in farming systems can help mitigate climate change.

The highland areas and the communities living there, are highly vulnerable to climate change. It is essential to plan climate action at national and regional levels, keeping mountain specificities and communities challenges. Adopting community-based participatory approach and nature-based solutions will help in building resilience against climate change. Crop suitability analysis and agricultural diversification will ensure food security. Selection of crops according to changing agro-climate along with altitudinal gradient will further mitigate the risk of high rainfall variability, water scarcity, and climate change. To address energy needs and reduce dependency on fossil fuels, the construction of micro-hydro projects, solar energy farms, and the adoption of clean energy solutions can promote sustainable development.

Long term studies on climate change in the Himalayan region are crucial. It will help in understanding trends and predicting future challenges. These studies can assist in policy and decision-making. Framing and implementing suitable strategies will protect the fragile ecosystems of the Himalaya and will enhance livelihoods of rural communitie. These actions will be essential for ensuring the long-term sustainability of the region in the face of climate change.

Informed consent

Not applicable.

Ethical approval

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

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Data and materials availability
All data associated with this study are present in the paper.

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