Climate Change in Uttarakhand: Current State of Knowledge and Way Forward

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Contents

List of Tables

List of Figures

List of Color plates

List of Box Items

Acronyms

AAR	Accumulation Area Ratio
AIS	Agriculture Insurance Scheme
CMSA	Community Managed Sustainable Agriculture
CoP	Conference of Parties
ELA	Equilibrium Line Altitude
FSI	Forest Survey of India
GDP	Gross Domestic Product
GHGs	Green House Gases
GIS	Geographic Information System

GLFOs	Glacial Lake Outburst Floods
GOI	Government of India
GSI	Geological Survey of India
Ha	Hectare
HKH	Hindu Kush Himalaya
IAS	Invasive Alien Species
ICIMOD	International Center For Integrated Mountain Development
IHR	Indian Himalayan Region
INCCA	Indian Network on Climate Change Assessment
IPCC	Intergovernmental Pennell on Climate Change
LIA	Little Ice Age
MAAT	Mean Annual Air Temperature
MoEF	Ministry of Environment and Forests
MPa	Mega Pascal
NABARD	National Bank for Agriculture and Rural Development
NAPCC	National Action Plan on Climate Change
NTFP	Non Timber Forest Produce
NGO	Non Governmental Organization
PAN	Protected Area Network
PRT	Peak Rainfall Time
PTI	Press Trust of India
PSI	People Science Institute
REDD	Reduction Emissions from Deforestation and Degradation
SLEM	Sustainable Land and Ecosystem Management
SRI	System of Rice Intensification
UFS	Uttarakhand Forest Statistics
UCOB	Uttarakhand Organic Commodities Board
VPs	Van Panchayats
WWF	World Wide Fund for Nature
WII	Wildlife Institute of India

Foreword

The Himalayas are considered to be among the most vulnerable to climate change. The 20th century witnessed a consistent warming of the Himalayas. Studies show that the Himalayas have warmed at a faster rate than the global average. The Himalayan glaciers, as noted above, are retreating at a faster rate than the global average. Advanced blooming, migration of species, and changed timings of hibernation and breeding suggests that the climate in the Himalayan region is changing. The northward movement of species and tree line is also widely reported. An increased frequency and intensity of extreme weather events is also noted in the Himalayas. Cloud bursts, intense episodes of rainfall in Uttarakhand and Nepal in June 2013 and delayed but heavy rainfall in Jammu and Kashmir in September 2014 are some of the indicators of climate change in the Himalayas. The impacts of climate change in Himalayas have local, regional and global implications.

This book focus on the impact of climate change in the state of Uttarakhand which lies in the northern extreme of India, in what is known as either the central, or by some descriptions, the eastern end of the western Himalayan region of the country. About 1/6th of the state lies in the foothills or 'plains', with the rest ascending rapidly up, in a steep gradient, till the northern most end lies in the Upper Himalayan tracts, on a boundary shared with China, Nepal and the adjoining Indian state of Himachal Pradesh. It is broadly accepted that the state of Uttarakhand is one of the most ecologically sensitive, fragile and climatically vulnerable state of the country. This geographically, geologically and culturally unique state features high mountains, extraordinary landscapes and major rives of the country provide ecosystem goods and services to the great Gangetic Plain inhabited by approximately 500 million people.

Very little information exists about the responses to different ecosystems to climate change in this state. However, there are clear indications that changes in temperature, rainfall and other climatic variables would have an impact on forests, water regimes, agriculture and hazards; and these would affect the general human well being living in the state and also impact the people downstream. The book synthesizes the available information about the consequences of climate change on important sectors in the state of Uttarakhand. It indicates gaps in knowledge and gives directions for future. I think it is important for the state and its people to have an indepth understanding of these issues in order to adapt and be resilient to climate change. The book is indented to provide inputs to support planners and policy makers, development professionals, civil society and general public at large. People at the helm of affairs need to accept the reality of climate change and make concentrated efforts to more balanced approach while planning for development and economic growth in the state. The information that forms the basis of the book can be used as indicators of change for other Himalayan states and countries as well.

December 15th, 2014

Rajendra Dobhal
Director General
UCOST

Preface

Mountains influence the livelihoods of nearly 40 per cent of people globally. While data on climate change impacts in mountains is sparse, what we have suggests that mountains are among the more vulnerable regions on the planet. As mountains are important providers of ecosystem services and home to wilderness refuges for lowland species in case of climate warming, understanding the impact of climate change on these ecosystems is essential.

The Himalayan region may be particularly sensitive to climate change. There are evidences to indicate that at least parts of the Himalaya are warming at a significantly higher rate than the global average. This is of great concern as (i) the region has more snow and ice than any other region in the world outside the Polar caps, (ii) the Himalaya directly influence climate in much of the South Asia, (iii) the Himalayan glaciers are connected to 9 major river basins, including the Gangetic basin, which alone has about 500 million population.

This report focuses on the Himalayan state of Uttarakhand. Almost 90% of the state is mountainous. The Mountain people who depend on natural ecosystems and ecosystem services for their day to day living are likely to be severely affected by climate change.

Uttarakhand, which had a landscape characterised by scattered, inaccessible and independent settlements, has been transformed over the past few decades. Rapid urbanisation and roadbuilding has increased connectivity and a connection with markets, but has also increased vulnerability by moving away from the self-sufficiency that characterised the communities of this region. An increase in frequency of extreme climate events, likely a consequence of climate change, has led to large losses of life and property – most recently evidenced by the Kedarnath flood of June 2013 which resulted in 5,700 deaths.

This report is an attempt to synthesise information available on climate change for the state of Uttarakhand with relevant examples taken from other Himalayan states and countries. The report is divided into three chapters. Chapter 1 deals with the impact of Climate change on Forests, Chapter 2 highlights the impact on Agriculture and Chapter 3 deals with the status of Himalayan Glaciers with special emphasis on Uttarakhand.

We hope that this report proves to be useful to policy makers and planners and adds to the knowledge scientific community interested in climate change.

Rajesh Thadani

Acknowledgment

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1. Forests of Uttarakhand and the Changing Climate

Forests are one of the most important resource of Uttarakhand and has a direct role in supporting rural livelihoods in the state. Not only do forests meet people's day to day needs for fuel, fodder and timber but they also provide ecosystem services to people living downstream. Uttarakhand supports more than 64.7 percent of forest area and are home of a diverse floral and faunal species. Total forest area is about 34,651 km^2. The forest cover in the state, based on FSI, 2011 data is 24,496 km^2, which is 45.8 % of the state's geographical area. In terms of forest density classes, the state has 4,762 km^2 area under very dense forest, 14,167 km^2 area under moderately dense forest and 5,567 km^2 area under open forest. Reserve forests constitute 71.1 %, protected forests 28.5 %, and unclassified forests, 0.35 % of the total forest area (FSI, 2011). The state has 7418 km^2 under Protected Area Network (PAN), the fourth largest among the Indian Himalayan Region (IHR), comprising 6 national parks and 6 wildlife sanctuaries and two conservation reserves (WII, Dehradun).

The Uttarakhand Himalaya is endowed with rich diversity with forests distributed from sub-tropical to alpine zones. Sal (*Shorea robusta*) forests occur in the foot-hills generally below

1000m elevation, chir pine (*Pinus roxburghii*) forest occurs extensively between 1000-1800m. Oaks are the dominant forest genera (*Quercus leucotrichophora, Q. floribunda and Q. semecarpifolia*) between 1800- 2600m. Deodar (*Cedrus deodara*), a well known timber species forms often mono-dominant patches between 2000-2400m altitude, though many of these are planted. At higher elevations above 2500m blue pine (*Pinus wallichiana*), and fir (*Abeis pindrow*) cover approximately 6% of total forest area (Semwal *et al*., 2007). Above the tree line, which occurs around 3500m, there occur grasslands and meadows locally known as *bugyals*.

Evergreen forests dominate this part of the central Himalaya. Deciduous forests occur only in patches, generally along water courses. From the use point of view, evergreen forests are divided into two groups. There are the forests are dominated by timber species *viz.* sal, deodar and the pine (*Pinus roxburghii* and *Pinus wallichiana),* and then there are forests that have primarily biodiversity, carbon and NTFP values. These include oaks, rhododendrons and lauraceous species. Together, these Himalayan forests provide vital ecosystem services to the densely populated indo-gangetic plains which lie downstream. An assessment conducted by Singh (2007) suggests that the total value of forest ecosystem services flowing from Uttarakhand is about 2.4 billion dollars/yr.

1.1 Climate change and forests of Uttarakhand

From the vulnerability standpoint, forests of the Himalayas are susceptible to fluctuations in climate. The 4x4 Assessment report of MoEF has projected that there will be a change in forest vegetation types with the changing climate patterns (INCCA, 2010). Similarly, the IPCC Fourth Assessment report suggests that the Himalayan Eco-system is particularly at risk with a rise in global temperatures. Given the conical nature of mountains, the bio-diversity that resides at higher altitudes will have less and less place to occupy and will be at increased risk of extinction. Species movement as a result of climate change is further hindered by the extensive fragmentation of forests which have often been reduced to small isolated patches interspersed with settlements and agricultural terraces.

Various studies indicate that climate change might influence forest vegetation in various ways (Korner and Larcher, 1988, and Ravindranath, *et al.,* 2006). Possible impacts of climate change on forest of Uttarakhand might include changing phenological behavior, upward shift of lowland species, change in nutrient dynamics, invasion of alien species, changes in forest soil seed bank and frequency and intensity of occurrence of forest fires.

1.2 Phenology

Plate 1.1 Acorn formation in Banj Oak

It is a well established that phenological behavior, such as flowering, fruiting, germination and the like, is influenced by seasonal and climactic change. As plants and trees are tuned and susceptible to seasonality, any alteration in the phenological timing is an indicator that ecosystems are being influenced by changing climate. Changes in climate may have a significant change in phenophase (bud formation, bud bursting, leafing, flowering, fruiting and leaf senescence and then leaf fall) in the plants. Stern and Roche, 1974 argued that, rapid changes in climate conditions may become unsuitable for some species to complete one or more stages of the life cycle, especially if some climate variables were to change significantly more than other variables. For example, pollen and seed development require minimum heat sums and are sensitive to frosts or heat. Seedlings are particularly vulnerable to short-term droughts, saplings to the presence or absence of sunlight, and mature trees to the availability of soil water in growing-season. As per Kumar *et al.*, 2010, flowering in *Rhododendron arboretum,* an associate of banj oak has shifted by 25 to 30 days and period of leafing by 2 weeks approximately. Changing temperatures also can create an asynchrony with the monsoon and phonological events such as seed fall or germination may occur too early leading to seedling mortality due to dry conditions.

Occurrence of milder winters and hotter summers is likely to intensify summertime drought (Henson, 2006). The process of new leaf production and leaf shedding is synchronized among some dominant evergreen Himalayan tree species during spring. Leaf shedding is often induced by leaf production. In many deciduous species leaves are shed during the peak summer drought, and then start producing new leaves after a few weeks when conditions are still dry. There are Himalayan studies that suggest a greater rise in temperature during winters than summer (Lio and Hou, 1998, Singh et al., 2011). This will narrow down the seasonal temperature variation within an annual cycle and consequently impact species distribution – such as further promoting evergreen species at the cost of deciduous species in the Uttarakhand Himalaya (Singh, 2010).

1.3 Tree water potential

Optimally an increase in temperature induces leaf production in the spring, but slight increase in temperature may induce also intensify droughts by raising evapotranspiration and thereby suppress leafing and/or leaf expansion. A 1999 study from the Kumaun Himalaya indicates that tree water potential in a population of *Quercus floribunda* was affected by the warming. The tree water potential dropped to -5.5 MPa as compared to normal tree water potential, between -2.0 and -2.3 MPa during normal years (Singh and Singh, 2010). This severe drought in 1999 revels reveals that two different populations of *Quercus floribunda* existed in the studied area. One which responded normally and didn't allow water potential to go down steeply and produced leaf in spring, whereas the other which had no such control over the water potential had to wait until the onset of monsoon rain in June for leafing. Physiological data (Thadani, 1999) also indicates similar populations in *Quercus leucotrichophora* with varying phenological differences to drought. Another at Kumaun University in 1999 suggests that banj oak instead of advancing leafing due to rising temperatures, instead witholds leaf production, possibly due to dryer conditions in the spring. The water stress caused by warmer spring hastened seed development as trees were left with insufficient carbon after investing in rapid seed development, withheld the spring time leaf production and produced leaves in several steps, and did not reach their normal quota (Singh and Singh, 2010).

Evapo-transpiration induced due to warming can make conditions stressful for many dominant tree species of Uttarakhand. Dry spells of 6-12 days are a common feature in the state. Since species relying on monsoon climates have leaves that are still expanding at the peak of summer drought, their leaf production and leaf cycle can be adversely affected by global warming. In Uttarakhand, many of the dominant species such as *Shorea robusta, Pinus roxburghii,* and the *Quercus spp.* have concentrated early summertime leaf production which induces equally concentrated leaf fall (evergreen with approximately one year life span). These evergreen species function akin to deciduous species that overhaul their canopies to maximize the advantage of favorable months (warm and moist).

1.4 Impact on regeneration of major forest forming species

Many of the dominant tree species in Uttarakhand such as Sal (*Shorea robusta*), Tilonj (*Quercus floribunda*), and Kharsu (*Q.semecarpifolia*) synchronize their seed maturity and seed germination to coincide with the onset of monsoon rainfall (Singh and Singh 2013). In wet conditions these species show varying degrees of vivipary (germination of seeds while they are still on trees). Vivipary however has a disadvantage in that if a germinating seed falls in an unfavorable place at an unfavorable time (such as a rainless week), it has little chance of survival. Early maturation of seeds due to warming may break this synchronization and thereby suppress the regeneration of such species. Already, oak seeds are observed to be larger in size in the summers than in the past, indicating early seed development due of warmer temperatures (Singh and Singh, 2010). Regeneration in sal (*S. robusta*) is known to be a problem, in part because its seeds are ready to germinate by mid-June when the commencement of monsoon is uncertain. The warming-induced early maturation of seeds can easily disrupt this delicate relationship of events (Fig. 1.1) as Sal seeds are viable only for couple of weeks.

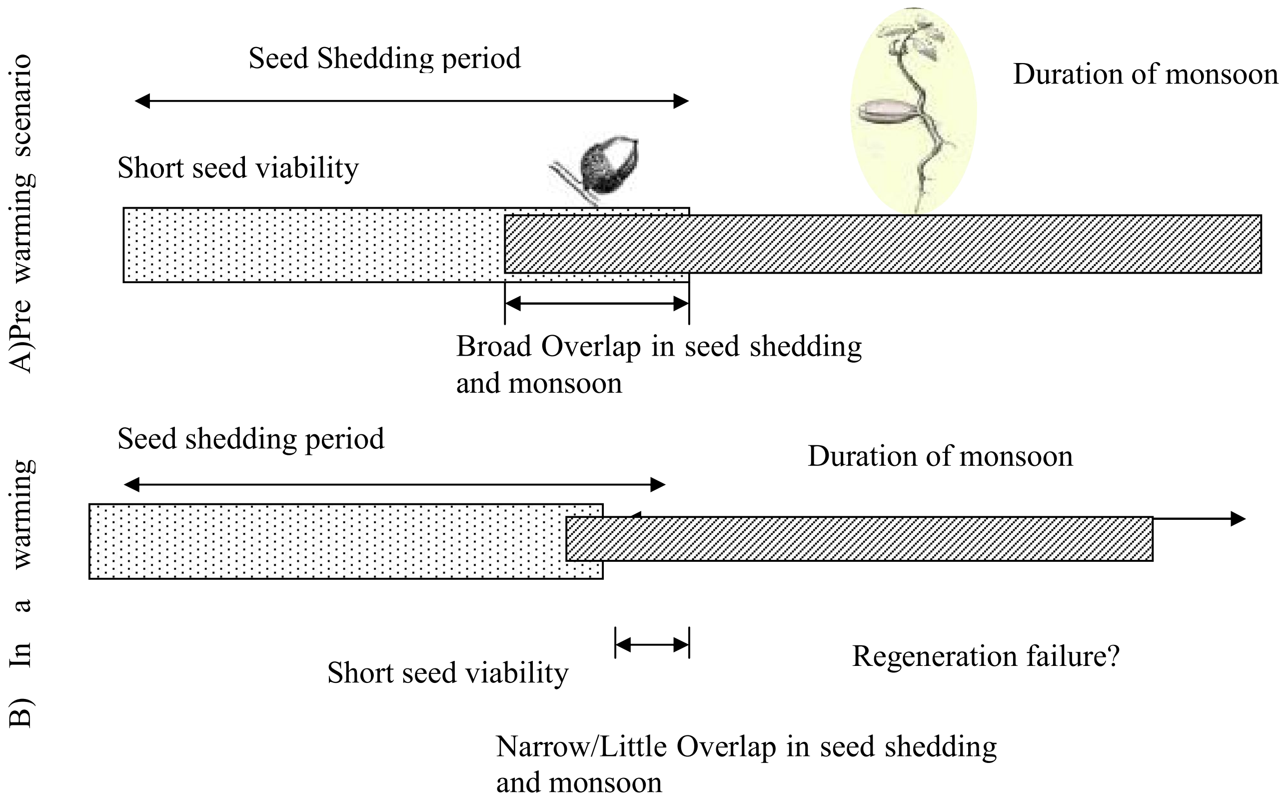

Fig 1.1 Likely impact of climate change on seed germination and regeneration of some major forest tree species of Himalayas. (Adopted from Singh and Singh, 2013)

Upward March of Species

Evidences of upward movement of vascular plants in high Mountains was recently determined in the European Alps. Tree species, such as spruce, have been shifting northwards in latitude and upwards in altitude in response to global warming.

Plate 1.2 Tree line and bushy rhododendrons at Tungnath

The Himalayas provide a large wilderness area with favorable growing conditions up to considerably high altitudes. It has been assumed (Vishnu-Mittre, 1984) that migration of tropical species, including some pines (e.g. *Pinus merkusii*), from lowland areas of South Asia to the Himalaya is indicated to have occurred in the geological past during warmer climate phase. It has also been suggested that many tropical species such as *Bombax ceiba*, and *Butea frondosa* have penetrated into the Himalayan ranges through migration along rivers that have cut deeply into mountains. However, such migration may now be restricted because of a lack of continuity between favorable habitats. Large scale developmental activities in Uttarakhand Himalaya (construction of dams and roads) and conversion of forest land to agriculture have fragmented the landscape. A recent study conducted by Telwala, 2011, in the Sikkim Himalaya (> 4000 masl) suggests that many of the 124 endemic plant species investigated demonstrated a prolonged upward shift over the past 150 years (from 1850 - 2010) with a mean species shift in altitudinal range of 237.9±219.8 masl. The upward shift in species' range was between 100m to 400m in 70% of the species but, in extreme cases, the range shift was 600-800m, About half of the endemic species, showed an upward shift on upper side of their range, leading to an altitudinal expansion on the range.

In general Altitudinal range in several species is squeezed because they are intolerant to warmer temperatures, but are unable to raise their range on the upper margin. The capacity of a species to shift in altitudinal range depends on (i) its tolerance efficiency of warming, (ii) seed dispersal, and (iii) competitive ability (Fig 1.2). Only the species which have efficient seed dispersal and ability to compete effectively with species occurring in higher altitudes would be able to march upward. Because of low pressure and the atmospheric CO_2 concentration in an alpine belt in comparison to low land areas CO_2 fertilization could be an important factor. Species that respond favorably to CO_2 enrichment are likely to out-compete those adapted to low CO_2 concentrations.

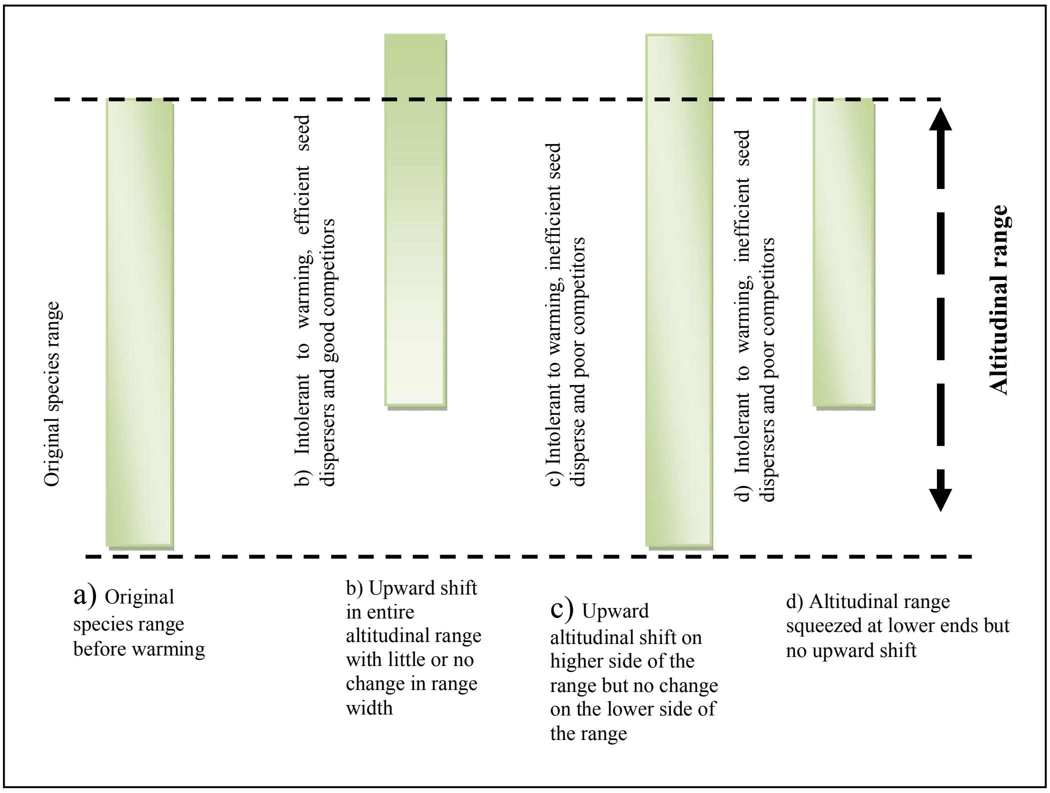

Fig 1.2 Types of species shift due to warming in response to climate change (Adopted from Singh and Singh, 2013)

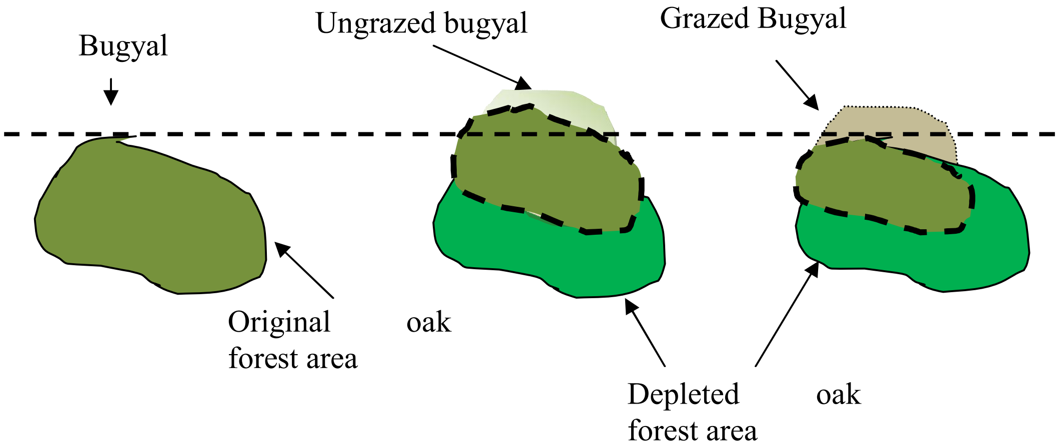

Figure 1.3 Diagrammatic representation of reduction in the original area of brown oak *Quercus semecarpifolia* forest in Uttarakhand in a warming world (Singh and Singh, 2013)

Box 1.1: *Quercus semecarpifolia* vulnerable to Climate Change

Brown oak, *kharsu* oak or *Q.semecarpifolia* a major forest forming oak above 2400 m in the entire east-to west arc of the Himalaya is a highly vulnerable species to climate change., On the lower side, the forests of brown oak are generally surrounded by other oak forests (*Q. floribunda, Q. leucotrichophora*), while on the higher side they have either no space to march upward or have alpine meadows, generally subject to grazing (Fig 1.3). The warming will enable other species to replace its forests at their lower ranges, while grazing in meadows both by livestock and wild animals would not allow seedlings of brown oak to establish and migrate upwards. Seeds of brown oak being viviparous cannot persist until favorable conditions occur. Sharma and Singh (2004) have estimated that an increase of 1^{o}C temperature would reduce the area of brown oak by 40% in Uttarakhand. Since brown oak is a fairly strong light demanding species, it requires large canopy gaps which are also preferred sites for livestock grazing, thereby suppressing its regeneration. The collection of litter from forest floor is expected to combine with warming to increase the rate of seed desiccation, loss of soil moisture and mortality of seedlings

1.6 Biodiversity responses to the climate change

As per the fourth IPCC Report (2007), by the end of this century, climate change will be the main cause of biodiversity loss. If there is an increase of the average global temperature by 1.5-2.5^0 C, approx. twenty to thirty percent of known plants and animal species may be threatened to extinction. Himalayan forests are endowed with a varied range of biodiversity because of varied micro-climates, and ecological conditions. These factors have resulted in a high degree of genetic diversity in terms of crop and livestock species and their wild relatives. Altitudinal gradients and ecological zones provide plants with different exposures over short distances in the Himalayan region. The topography is a varied and a fragmented mosaic of habitats or genetic 'islands in the sky'. The link between climate change and biodiversity is poorly understood (ICIMOD, 2009). Climate change can impact biodiversity either directly through altering the physiological responses of species or indirectly by altering interspecific relationships (Woodward, 1987; Tallis, 1990; Peters and Lovejoy, 1992). Whenever these changes lead to habitat degradation, biodiversity will be adversely affected (Peters and Lovejoy, 1992; Vitousek, 1994). Climate change together with other pressures on ecosystems produces a significant threat to biodiversity due to the following reasons:

i) Climate change, combined with other causes of habitat degradation, may locally decrease species diversity (Peters and Darling, 1985; Rind, 1995). Disturbance also may create opportunities for pioneer species, which will become more abundant (Myers, 1993) and, over time, replace many species that are slower growing and require more stable conditions. In some cases, this may lead to a temporary increase in species diversity (e.g., Lugo, 1988; Mooney, 1988; Vitousek, 1988).

ii) Species may become permanently extinct when local extinction cannot be reversed by reimmigration from surrounding areas. This problem would be most severe where the climate changes from being favorable to being completely unsuitable (Peters, 1992), rendering "sanctuaries" into "traps" (Myers, 1993). Thus, an increasing fragmentation of habitats in combination with climate change may cause significant and irreversible species loss.

Studies from valley of flowers in Uttarakhand revealed that *Rhododendrons* and other woody species have already begun to invade alpine meadows (Singh and Thadani, 2011). As herbs are replaced by woody species, several associated changes may occur. For example there would be fewer lichens and mosses under the shade of woody plants (Olofsson, 2006). Subsequently, allocations of biomass to under-ground parts and mycorrhizal fungi are likely to change. Many species may migrate from ~~east~~ to west in search of cooler habitats, but due to their island like distribution and anthropogenic pressure; their natural movement would be impeded. This applies particularly to species such as *Q. semecarpifolia*. Warming temperatures would have implications also for small animals that cannot easily migrate, such as the tiny rodent-like animal Pika (*Ochotona* spp.).

1.7 Litter decomposition and Nutrient dynamics

Soil nutrient dynamics can be affected by a slight change in the optimal temperature. It is speculated that rising mean temperature will subsequently lead to faster decomposition. However, as temperatures rise, soil moisture may well become a limiting factor thereby slowing decomposition rates. Climate change could enhance the supply of nutrients to plants in the mountains, for instance, increasing root and mycorrhizal growth and thereby increasing access to soil phosphorus and enhancing nitrogen fixation by legumes. On the other hand, the more important considerations are likely to be nutrient leaching and soil erosion wherever tree cover is lost (because of droughts or fire) or removed (by logging, clearing, or grazing) especially where high-rainfall events occur in hilly areas and immobilization of nutrients in soil organic matter may take place in response to elevated CO_2.

1.8 Invasive alien species (IAS) induced by climate change

Ecosystems are already changing and presumably a new ecological order will arise in the future. Changes in the climate pattern also favor the diffusion of invasive alien species which are considered to be second to habitat destruction as a threat to global biodiversity and ecosystems. Invasive alien species are able to conquer new territories when changed eco-climatic zones become favorable for their breeding. Future biodiversity scenarios show a steady rise in the number of invasive alien species in many regions. Alien invasive plants often replicate faster by vegetative means (roots, stolons etc) and are usually more responsive to increases in atmospheric

CO_2 concentrations (Rogers et al., 2008). Biological invasions are a widespread and significant component of human induced global environmental change. Invasive alien species may have the advantage in elevated CO_2 conditions, and out-compete the local species in migration to higher ranges. Already, *Lantana camara*, *Eupatorium* spp. and *Parthenium* spp., have spread over large areas in the mountains and along roads and rivers in Uttarakhand Himalaya. Being an early successional species they would take advantage of human perturbations and natural disturbances, such as rainfall induced lanslides.

1.9 Forest carbon stocks and sequestration rates

Over the last few years forests and forestry have been the focus of international climate change debates and negotiations. The international scheme known as "Reduction Emissions from Deforestation and Degradation of forests and enhancement of forest carbon stocks" (REDD+) was agreed to be included in post 2012 climate framework in Cancun in 2010. REDD+ is a scheme intended to compensate developing countries for protection and enhancement of forest carbon stocks through international fund mechanisms. The developing countries are required to scientifically prove their forest carbon wealth in order to take advantage of the scheme. Researchers involved in forest carbon measurements know that it is difficult to accurately measure the carbon stock of even a small forest area. Outmoded inventories and lack of methodology and labor intensive measurements are the major problems behind accurate measurements of carbon stocks and sequestration rates. In this section an attempt is made to provide an estimate of carbon stocks and sequestration rates of major forest forming species of the Indian Himalayan state of Uttarakhand.

The Uttarakhand forest department has classified the forest area under the domination different species occurring in the state (Table 1.1) (UFS, 2011-12). On the basis of the data provided by the state forest department and previous studies conducted on biomass of forest under different tree species a more reliable estimate of forest carbon stocks in Uttarakhand is presented. Biomass estimations used in the data are based on species specific allometric equations developed in the past, except for *Abies pindrow and Picea smithiana* for which volume based equations were used. 50 percent of the biomass was considered as carbon present in the tree (Singh et al. 2011). The analysis revels that approximately 348.2 million metric tonnes of carbon is stored in the forest of Uttarakhand, of which 25.3 percent is *Shorea robusta* (Sal) forest, 24.8 percent is *Quercus leucotrichophora* (Banj oak)forest and 12.6 percent in *Pinus roxburghii* (Chir pine) forests and 32.9 percent is stored in miscellaneous mixed forests respectively. The average carbon sequestered by the forest of Uttarakhand is 3.12±0.4 $tha^{-1}yr^{-1}$ the maximum carbon sequestration rate is reported for the *Eucalyptus spp* 5.99±1.9 $tha^{-1}yr^{-1}$ while minimum was reported for *Pinus wallichiana* forest 1.25±0.3 $tha^{-1}yr^{-1}$ (Singh et al. in press). Approximately 5.9 million metric tons of carbon is added to the forest every year through sequestration by trees. The data/extrapolation used here has its limitations, as most of the previously developed allometric equations were developed for intact forests and do not capture carbon reduction due to forest degradation, site variability and environmentally enhanced rates of tree growth due to warming in temperatures. Labor intensive and time consuming measurements for better spatial data also acts as hurdle in a in a mountainous terrain of Uttarakhand. Moreover, the 1982 Supreme Court ban on green felling above 1000 m leaves us with no solution but to rely on previously developed equations for estimating biomass and carbon stocks of the state as getting permissions to cut trees, even for research purposes, is extremely difficult.

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Table 1.1 Area and biomass of major forest species of Uttarakhand

Species	Area (km^2)	Average biomass tha^{-1}	References
Miscellaneous mixed	6143.6	373.9 ±59.2	Rawat and Singh, 1988, Rana *et al.* 1989, Skutsch, 2011
Pinus roxburghii	3943.8	223.7 ±46.2	Chaturvedi and Singh, 1982, Rana *et al.* 1989, Raikwal, 2008, Skutsch, 2011
Quercus leucotricophora	3830.9	451.3 ±56.8	Raikwal, 2009 and Singh 2009
Shorea robusta	3130.5	564.6 ±124.7	Rana *et al.* 1989, Singh *et al.* 2006
Abies pindrow and Picea smithiana*	924.6	130.42	Manhas *et al.* 2006
Eucalyptus spp*	214.1	43.5 ±11.2	Joshi *et al.* 2013, Singh, 2011
Tectona grandis*	202.1	164.1	Negi *et al.* 1995
Cedrus deodara*	187.8	370.2	Sharma, 1988
Pinus wallichiana*	185.5	183.5	Skutsch, 2011

Dalbergia sissoo	151.1	73.2 ±22.9	Singh *et al.* 2011, Lodhiyal and Lodhiyal 2003, Joshi *et al.* 2013
Acacia catechu*	58	10.45	Joshi unpublished
Cupressus torulosa	29.7	321 ±82	Adhikari *et al.* 1998

(*no replicate) *Abies pindrow and Picea smithiana* value of temperate forest of Uttarakhand Himalaya is used

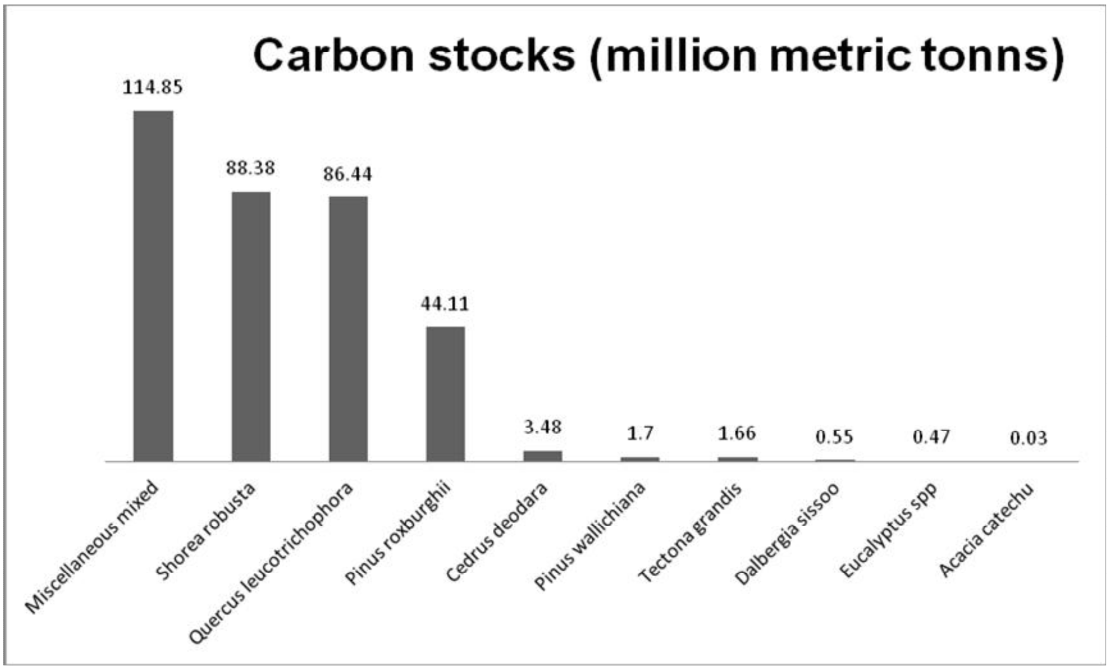

Figure 1.4 Species wise carbon stocks

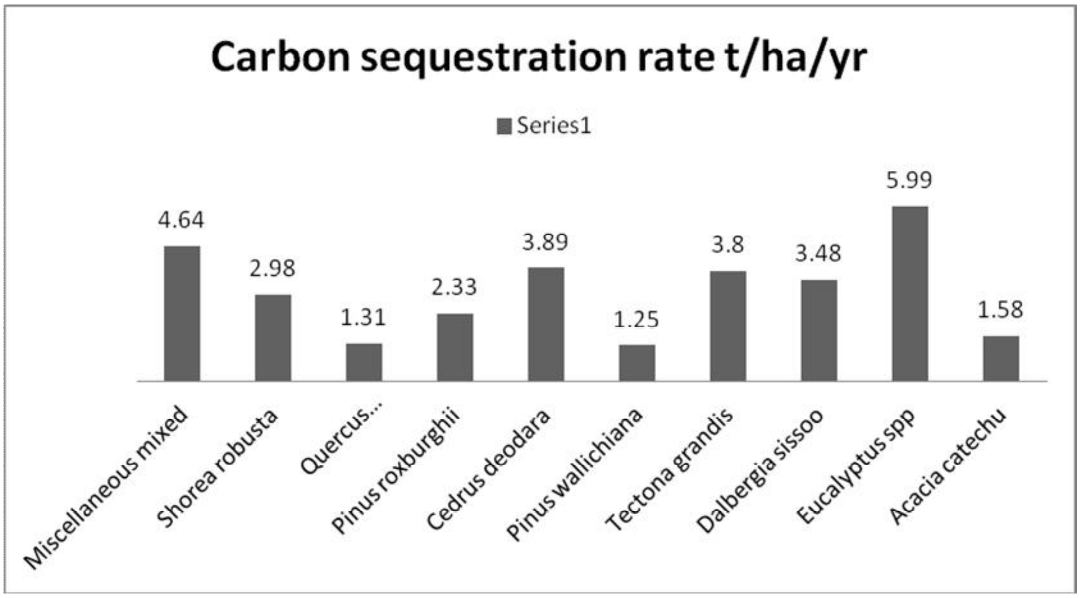

Figure 1.5 Carbon sequestration rates of major species of Uttarakhand Himalaya
(values obtained from Skutsch, M., 2011, Singh, V.,2011, Raikwal, D., 2009, Singh, V.,2009, Joshi et al. 2013)

1.10 Forest Degradation:

In the Uttarakhand Himalaya, forest degradation occurs due to human induced small scale chronic disturbance. The removal of leaves, growing tips and young branches as a result of lopping for fuelwood and fodder results in a significant loss of productivity, lowered growth rates and decreased carbon sequestration. Disturbance to the understory, through removal of leaf litter (to be used as compost fertilizer) and grazing of seedlings by cattle, and trampling leading to soil compaction also greatly impact forest structure. Low intensity human induced fires (encouraged by locals to promote grass growth) are common and again damage regeneration. Species such as oak are most impacted as these are most prone to both branch pruning and understory disturbance. The high calorific value and good burning properties make oak wood a preferred wood for cooking and heating; the leaf fodder is generally regarded as favourable for cattle, and the fallen leaves of oak decompose to an excellent quality manure for fertilizing fields. Traditional agriculture in this region is heavily reliant on forests in particular for nutrient inputs. Up to 10 units of energy from forest ecosystems are required to obtain 1 unit of grain energy from the agro-ecosystem (Singh and Singh, 1992).

These chronic disturbances impact species selection at the regeneration stage, and changes carbon sequestered through lowered leaf biomass and through impacts on mycorrhizal growth, root productivity and carbon presence in the soil (Santer *et al.,* 2003). These changes become all the more significant in the current scenario, where – as a result of climate change – there is likely to be migrations and geographical shifts in the ranges of species. Disturbed environments will hinder the migration of certain species while encouraging others.

Plate 1.3 Undisturbed banj oak forest

Plate 1.4 Degraded Banj Oak forest

Singh, (2009) studied the impact of chronic disturbances on Banj oak forest of Uttarakhand Himalaya, the study observed that the biomass stocks of degraded forest[1] 327 tha^{-1} in comparison to 530 tha^{-1} in undisturbed forest[2]. While the carbon sequestration rate was 1 $tha^{-1}yr^{-1}$ in comparison to 5 $tha^{-1}yr^{-1}$ for the undisturbed forest. Degradation in soil was observed by a low soil organic carbon content and litter decomposition rates, the soil organic carbon content of degraded forest was approximately 40% lower than the undisturbed forest in the top 0-10 cm layer. In 365 days the litter decomposition rates of a degraded forest was approximately 45% as compared to 78% for undisturbed forest. In another study Raikwal, (2009) found that the fine root biomass (0-20cm layer) of a degraded forest was significantly lower (144.40 kg ha^{-1})

[1] High Lopping, High Litter removal and High grazing
[2] No Lopping, No litter removal, moderate grazing

compared to an undisturbed forest (347.95 kg ha^{-1}), while the and the mycorrhizal density was 3 times lower than the undisturbed forest.

1.11 Forest Fires:

Fire is a common feature in the forests of Uttarakhand. Most of these fires are attributed to man-made reasons and are most often lit to encourage better growth of grass for fodder, though accidental fires (mot often the result of a carelessly thrown cigarette or beedi) and arson are not uncommon. The preponderance (and increasing spread) of conifers, steep slopes, inaccessibility, lack of modern equipment-techniques and budgetary constraints complicate the task of forest fire control in the state. Vast tracts of forest lands between 1,000 and 1,800 m range are covered by chir pine (*Pinus roxburghii)*. The National Remote Sensing Agency, report that in the hills of Kumaun and Garhwal fires in 1999 season impacted around 22.64% of the forest area (5085.6 sq. km.) of which 1225 sq. km. got severely burnt. Prior to this, in 1995, forest fires affected 19.32% of the total forests cover of the state. Generally the frequency of forest fires is 2-5 years, while 11% of forests of the region experience fire every year (Semwal et al 2003). With the changing climate lengthening of fire season, increase in frequency and severity of forest fires in fire prone areas is expected.

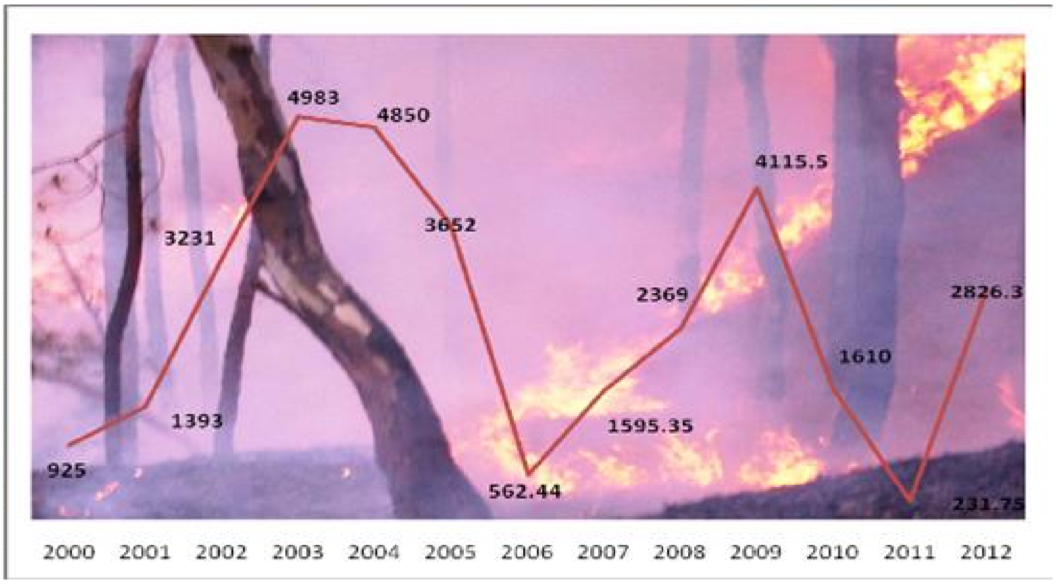

Figure 1.6 Fire affected area (ha) in Uttarakhand 2000-2012

Climate induced droughts, and an apparent reduction in late spring/ pre-monsoon rainfall locally known *"Chooti barish"* may further aggravate forest fire events in the region.

Research on forest fires is lacking; nevertheless, management of fuel type and fuel load, in addition to fire lines and increasing awareness among local people could be used to help protect forests from bigger fire events. Control burning, previously advocated as a solution, may not be an advisable practice in face of climate change as huge amount of black carbon is released in the atmosphere through this mechanism of fire suppression. Alternate strategies, such as the utilization of pine needles *(pirul)* as an alternate source of energy (pine needle briquetting) can help reduce the fuel load from the forest floor, though the ecological impact of large scale *pirul* collection are not well understood. Apart from this, plantations of fodder grasses such as Napier and *Thysolenea spp* under Pine forest canopy will not only reduce fire events but also meet the fodder requirements of local people and likely discourage arson. Involving the local community in reporting and management and provide economic incentives in return has long been suggested as a strategy to curb fire events and inculcate a greater sense of ownership among community members over the forest

1.12. Adaptation to climate change

The policy of Reduced Emissions from Deforestation and forest Degradation (REDD) first proposed in UN conference of parties (CoP 13), Bali in 2007 is under consideration at various international forums. This mechanism offers financial incentives to developing countries for conservation of standing carbon stocks in forests and to reduce emissions from the forests. Later in CoP 15, (Copenhagen, 2009) this mechanism was expanded to REDD+ to include the role that conservation, sustainable management of forests and the enhancement of forest carbon stocks can play in reducing emissions from the forestry sector. REDD financing can be used to support the Van Panchayats of Uttarakhand for conservation, sustainable management and enhancement of the forests in Uttarakhand. Financial incentives would not only reduce pressure from the forests and mitigate the effects of climate change but also build community resilience by investing in modern technology.

1.13 Way forward

A large portion (64.7%) of the states geographical area is under forests. These contribute significantly both to rural livelihoods as well as a myriad of ecological benefits and ecosystem services. Yes, there is a paucity of research by research institutions, universities and funding agencies to understand the repercussions of climate on these valuable asset that extend over a large part of the state.

Data on climate change in relation to forests of Uttarakhand is limited, most research conducted in the state on the forest responses to climate change are largely speculative and based on experience of senior scientists or on models which rely on uneven and inadequate data. Studies on forest require time series of data which are unavailable. Past studies conducted in the region can provide some useful information if remeasured, however locating exact sites to observe changes is a difficult task. Nevertheless, a recent initiative taken by the senior scientists of Uttarakhand on Coordinated projects on different aspects of climate change funded by the Department of Science and Technology may throw some light on the impacts of climate change. Meteorological data is difficult to access, because of the high costs involved in procuring data (which is not open access) and also deficiency of weather stations particularly at higher altitudes. Without proper meteorological information and long term studies the research on the responses of climate change on forestry would be restricted to sheer guess work. Concrete and long term research involving different state agencies is required on different aspects of forestry to substantiate the impacts of climate change on forests in the state.

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2. Possible Impacts of Climate Change on Agriculture

Agriculture is strongly linked with climate. In the mountains, where fields are mostly unirrigated, temperature and rainfall patterns are all the more important in determining crop selection and productivity. Changes in regional climate are will thus impact agricultural systems (Gronall, 2010). Impacts of climate change will vary from one region to another. In areas where temperatures are already close to the physiological maxima of crops i.e. tropical regions, heat stress and water loss due to evapotranspiration may lead to decline of yields while areas in mid and high latitudes the suitability and productivity of crops are expected to increase (Olesen et al. 2007). The same has also been concluded by the IPCC Fourth Assessment report with low[3] to medium confidence[4]. While an increase in temperature may at first appear to be beneficial for cold mountain areas, further study is needed as rainfall and not temperature is typically limiting

[3] "Low confidence" means particular finding has about 2 out of 10 chance of being correct.
[4] "Medium confidence" means about 5 out of 10 chances of being correct.

to productivity in the Himalaya and hence a better understanding of change in precipitation patterns is key to understanding Himalyan agricultural productivity.

Some of the well established direct impacts of climate change include; changes in mean temperature which may require adjustments to current practices of agriculture in order to maintain productivity; extreme weather events, including higher incidence of heavy rainfall, which may lead to short or long term productivity losses. Even small changes in rainfall pattern in the growing season can lead to a marked change in productivity of crops (Lobell and Bruke 2008), short term temperature extremes especially in the phases of plant development can also result in reduction of yield (Wheeler et al., 2000). Similarly droughts, both due to low rainfall or due to deficiency in soil moisture and increased plant water stress may result in crop failure or lowered yields (Li et al, 2009). Heavy rainfall events on the other hand may completely wipe out entire crops over wide areas or excess water can lead to soil water logging, anaerobicity and reduced plant growth (Gronall, 2010). Long terms impacts occur if the topsoil is washed away, which is a common result of extreme rainfall in heavily sloping areas.

Indirect effects of climate change may be experienced by changes in incidences of pests and diseases. Newman (2004) and Stanley & Johnson (2008) have reported an increase in weevil larvae and aphids under elevated CO_2 conditions, whereas Zohu et al., (1995) have reported wider dispersion of aphids under higher temperature conditions. Climate change may also lead to changes in water availability due to changes in upstream conditions – the melting of glaciers for example can deprive downstream areas of much needed irrigation water during the summers. While globally, Irrigated agriculture is only 20 percent yet it meets 40-45 percent of the food requirements (Doll and Siberet 2002). Water for irrigation is often extracted from rivers which depend upon distant climate conditions for example, the agriculture along the Gangetic plains rely to a certain extent on the rainfall in the upper reaches of the Ganga basin.

Elevated CO_2 in the ambient air can also affect plant physiological process such as photosynthesis and transpiration (Field et al. 1995). The physiological impact of CO_2 varies between species through different pathways of photosynthesis (C_3 and $C_{4)}$. In C_3 crops, RuBisCO is not CO_2 saturated in current atmospheric conditions, so rising CO_2 concentrations in the atmosphere will increase the net uptake of carbon and eventually growth. In C_4 plants RuBisCO is already saturated. Thus rising CO_2 concentrations will confer no significant physiological advantages and only a marginal increase in productivity is expected (Long et al 2004). However, even if CO_2 increases are stabilized or even completely halted, a certain level of global warming is nonetheless expected (IPCC, 2007). While stabilizing CO_2 would curb the positive impacts of CO_2fertilization, the impacts of climate change would still increase (Gornall, 2010) and impact productivity.

Projections of the IPCC Forth Assessment Report suggested regional changes in the global distribution of hunger. India and Bangladesh are among the world's ten countries most vulnerable countries to food crises and hunger induced by climate change. High losses of agriculture production are suggested, ranging from 20-40 per cent decline in agricultural productivity.

Agriculture contributes nearly 17.1 percent of Gross Domestic Product (GDP) of India. During 2008-09, the production of food grains was estimated to be around 233.88 million tones, including 99.15 and 80.58 million tonnes of rice and wheat, respectively. It has been projected that by 2020, food grains requirement will be almost 30-50% more than the demand during 2000 AD (Paroda and Kumar, 2000). Indian agriculture is facing challenges from several factors such as increased competition for land, water and labor from non-agricultural sectors and increasing climatic variability. The latter, associated with global warming, will result in considerable seasonal / annual fluctuations in food production. All agricultural commodities even today are sensitive to such variability. It has also been projected that there is a probability of 10-40% loss in crop production in India by 2080- 2100 due to global warming (Bhoomiraj et al 2010) despite some beneficial aspects of increased CO_2. A recent meta-analysis of CO_2 enrichment experiments in fields has shown that in field environment, 550 ppm CO_2 will lead to an increase of 8-10% in yield in wheat and rice, up to 15% in soybean, and almost negligible in maize and sorghum (Long *et al*., 2005). There are a few Indian studies on this theme and they generally confirm a similar trend of agricultural decline with climate change (Saseendran *et al*. 2000). Projections indicate the possibility of loss of 4-5 million tonnes in wheat production with every rise of 1^oC temperature throughout the growing period with current land use (Aggarwal, 2008). As an example, in March 2004, temperatures were higher in the Indo-Gangetic plains by $3-6^oC$, which is the equivalent to almost 1^oC per day over the whole crop season. As a result, wheat crop matured 10-20 days earlier and wheat production dropped by more than 4 million tonnes in the country (Samra and Singh 2004). Losses were also very significant in other crops, such as mustard, peas, tomatoes, onion, garlic, and other vegetable and fruit crops. Similarly, the drought of 2002 led to reduced area coverage of more than 15 million hectares of the rainy-season crops and resulted in a loss of more than 10% in food production (Shamra and Singh 2004).The projected increase in these events could result in greater instability in food production and threaten the livelihood security of farmers leading to distress migration and various social implications. A simulation analysis indicats that maize yields in monsoon may be adversely affected due to rise in atmospheric temperature; though increased rainfall can partly offset these loses. However, spatio-temporal variations in projected changes in temperature and rainfall will lead to differential impacts in the different regions (Byjesh *et al*., 2010). Analysis on sorghum indicates that the yield loss due to rise in temperature is likely to be offset by projected increase in rainfall. However, complete amelioration of yield loss beyond 2°C rise may not be attained even after doubling of rainfall (Srivastava *et al*., 2010). While the above review indicates gross effects of climate change on crops in India, there are several special ecosystems that while ecologically and economically important are not analysed for agricultural. These include the Himalayan ranges. Agriculture in the Himalaya is multi-dimensional ranging from rice-based agriculture, horticultural crops, plantations, fisheries and dairy. Changes in climate - increasing temperatures, possibly erratic rainfall, change in frost events and glacier melt will influence hill agriculture in ways that are as yet unclear.

2.1 Uttarakhand: Agriculture at a Glance:

Agriculture has been the mainstay of rural livelihoods of the state of Uttarakhand. The contribution of agriculture to the state's gross domestic product is about 31 percent (Planning commission, 2009) and the population dependent on agriculture for their livelihood is reported more than 70 percent (Planning commission, 2009) engaging about 65 percent of the total workforce, though recent studies indicate a sharply declining trend. Wheat and paddy are the staple food crops of the state and most agricultural activities are concentrated upto 2000m elevation. The gross cropped area in Uttarakhand is 1,289,000 ha and the net sown area is estimated to be 76,7571 ha with the cropping intensity 156 percent which is higher than the national average of 135 percent (Planning Commission, 2009). Small size of land holdings (against the national average of 1.57 ha , the average holding in Uttarakhand is only 0.95 ha), (State Focus paper NABARD, 2010-11) is an important characteristic feature of agriculture in

Uttarakhand (Table 2.1)The cultivated land size per person per year is about 1260m^2, which is much lower than the global or national average.

Plate 2.1 Terrace Farming; peculiar to mountain agriculture

As per census-2011 the decadal population growth rate of the state was 84.89 lakh in 2001 and 101.17 lakh in 2011. 69.5 percent of the population lives in villages, where agriculture and animal husbandry remain the major sectors to sustain their livelihoods. Apart from this, there are a number of Industries, which directly and indirectly depend upon raw material from agriculture. Although, the area under cultivation of food grains in the state has increased from 0.98 m ha to 1.03 m ha between 2000-01 and 2005-06, the yield has declined from 1742 kg/ha to 1548 kg/ha for the same period (Agriculture Statistics at a Glance, 2007). Lower yields can be attributed to lack of irrigation (90% of area is rain-fed) scattered land holdings, tough terrain, inadequate improved technology, uncertainty in climatic conditions and lack of credit and market facilities. The reduction of agriculture production may be in part be a result of climate change, though outmigration, increased aspirations and a lack of interest among the younger generation to undertake agriculture as a livelihood option are also reasons behind the decline in agriculture production.

Table 2.1: Distribution of land holdings in Uttarakhand

Classification of Holdings	Holdings		Area	
	Nos (in '000ha)	% to total	Ha ('000)	% to total
< = 1 ha	628	70.6	243	28.8
1 to < = 2 ha	158	17.8	221	26.2
>2 Ha	103	11.6	380	45.0
Total	**889**	**100**	**844**	**100**

Source: State Focus paper NABARD, 2010-11

2.2 Climate change related issues to Agriculture in Uttarakhand

Rugged mountains, steep slopes, an immature topography highly vulnerable to landslides and erosion pose serious limitations to agricultural activities. Various climate change studies indicate that marginal and small farmers will be worst-hit due to climate change as they already face enormous social and economic tribulations. The people of Uttarakhand like other mountain regions of the world will not only face problems of food security but are also likely to be affected by the erratic weather patterns experienced in past few years. Without doubt one of the major consequences of climate change is going to be the change in crop selection and increase in the altitudinal range of cultivated land. Delay in snowfall and early snow melt may encourage people to cultivate crops in alpine meadows both legally and illegally. Crops such as potato may expand to become a regular feature at what are now Alpine altitudes. Sporadic cultivation of potato in alpine meadows can be seen even at present

Box 2.1. Signs of change from Kullu valley of Himachal Pradesh

Apple production has declined after peak production in the 1988–1989 seasons. Apple cultivators (35,000 families) of the valley perceive that over the years the amount of snowfall has decreased, and that it occurs later than before. Not surprisingly, the farmers look at climate change primarily in relation to the decrease in their apple production, and as a 'deviation from the weather cycle ideal to apple production' (Vedwan and Rhoades, 2001). Due to the change in snowfall the chilling hours for apple trees are reduced, affecting the time of its bud-break. Early snow (December to early January) is preferred for its favorable effect on bud-break as well as on soil moisture. It provides a chilling period of about 10 weeks below 5^{o}C, which is required to meet the internal conditions necessary for bud-break in apples in springtime (Abbott, 1984). Late snow (in late January and February), which is less durable, more watery and transitory, restricts bees' activities, including pollination of apple flowers (Singh et al, 2011).

The Press Trust of India (PTI), 2010 reports that the Peak Rainfall Time (PRT) has shifted from July-August to August-September and winter precipitation extended till February whereas, cloud bursts have become a regular phenomenon in the recent past. In 2010 cloudbursts destroyed 30% of the crops in Uttarakhand. Some anecdotal accounts based on people's perceptions of climate change are given below:

- Increased warming in snowfall period, lower periods of snow on ground
- Decline in apple yield and upward shift of apple zone due to less snow fall
- Successful cultivation of cabbage/pea/tomato in higher elevations

- Shortening of maturity periods of winter (rabi) crops
- Increased pest infestation
- Less rains during March-May - abandonment of millets like *Panicum milliaceum* and decline yield of *Amaranthus*
- Shift of monsoon upto October damage the mature crops which leads decline in yields
- Shift of winter period delaying the sowing period of winter crops and decline in most of the rabi season crops

Much of the evidence for climate change however remains anecdotal and it is difficult to separate the signal from noise due to the short time period involved and natural fluctuations in climatic patterns which can mask actual patterns. Nonetheless, a definite change in climatic patterns over the past 50 or so years appears to exist

Table 2.2 Positive and negative effects of climate change/ warming in Uttarakhand Himalaya

Positive	Negative
CO_2 fertilization*, productivity enhancement of C_3 crops – wheat and soya bean Marginal enhancement in productivity of C_4 crops – millets, maize, sugarcane etc Suitability of crops to grow in higher altitudes	Increased evapotranspirational losses may severely affect rain-fed agriculture – particularly important when moisture limits productivity. Increased mortality of crops due pest and disease Intensified heavy droughts and heavy precipitation may lead to crop damage Frequent climate hazards may lead to loss of agricultural land and development of fear psychology

*While CO_2 fertilization effect could be positive it is likely to be negated by the adverse impacts of climate change.

Box 2.2. Crop yields and Climate Change

Crop yields are heavily dependent on the weather - particularly in rain fed conditions. The impacts of climate change on mountain agriculture based on farmers perceptions are documented below (Negi & Palni, 2010):

- Reduced availability of water for irrigation
- Extreme events and shift in the rainfall regime resulting in failure of crop germination and fruit set
- Increase in invasion of weeds into croplands
- Increased frequency of insect pest attacks.
- Decline in crop yield

Uttarakhand has been a rich repository of agro-biodiversity with over 40 different crops, and hundreds of planted cultivars comprising of cereals, millets, pseudo-cereals, pulses and tuber crops (Agnihotri and Palni, 2007). *Baranaja* (a mixed cropping pattern of 12 crops) is among the best examples of agriculture diversity of Uttarakhand region (Ghose and Dhyani, 2004) which provide insurance against absolute crop failure and capture the heterogeneity of the environment. Such traditional cropping patterns have declined by 60% due to social, economic and climatic influences and many crop cultivars are at the brink of extinction (Maikhuri *et al* 1997).

Erratic rainfall patterns and increasing solar radiation also impacts agriculture by changing the geographical distribution of areas suited to different crops. An upwards altitudinal shift in cropping has been reported in cash crops like apple, rajma, potato and carrot. Some projections speculate on an increase of night time temperature (Dimri and Dash, 2011) which may not only lead to decrease in production of some crops such as rice, but also reduce the winter killing of pests, hereby decreasing crop yields. High temperature, increased humidity and warmer temperatures in from lower regions (500-1500m asl) may provide favourable condition to pests and insect diseases. Diseases like rust and blight in cereals and potato appear to be on the rise, while legumes like *Phaseolus spp*. May be increasingly infected through the soil borne insects such as *Coleoptera* species (locally known as *Uksa/Kurmula)*. These insects damage the crops in early stage of seed germination (Maikhuri *et al* 2008). High temperature, increased humidity and milder winters provide favourable conditions for *Coleoptera* and the damage to crops could be even more severe. Hailstorm events in high altitude areas of Uttarakhand are also shifting from March to as late as May and these increase damage to various fruit crops at the flowering and early fruit stage. According to an estimate, around 50-60 per cent of the apple crops in parts of the State were destroyed in the year 2011 due to hailstorms (The Hindu, 2011)**.**

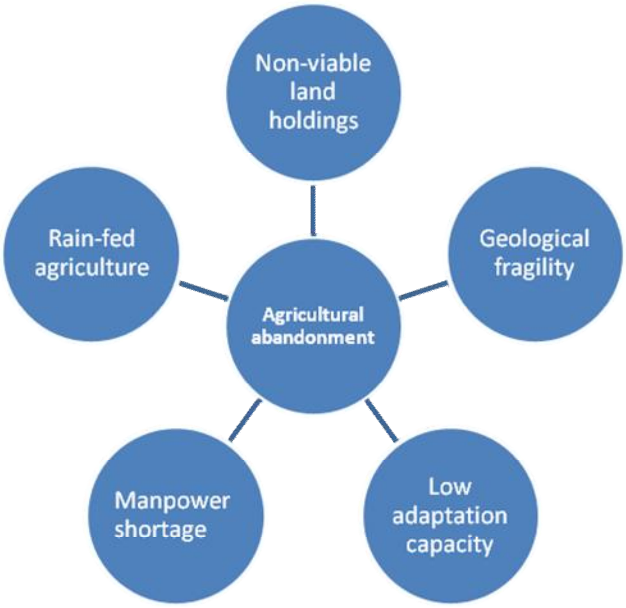

Figure 2.1 Factors which may combine with adverse climate effects and possible impact (Even if the climate change risk become less severe, small agricultural land holdings, shortage of manpower will lead to agricultural abandonment with the slightest deviation in climatic patterns, while growing cash crops in certain pockets would be possible, by and large climate change would combined with other factors would discourage farmers to continue with the present farming practices.).

Soil erosion is another problem in Uttarakhand. Much of the state is mountainous with steep slopes and fragile soils that are highly prone to erosion especially during the monsoon season. Crop fields along river beds are fertile and productive but such areas are also prone to erosion and mass wasting. The State of Uttarakhand is losing fertile soil at a rate that is 10 times higher than the national average. Land degradation is therefore a serious problem in Uttarakhand with up to 1.6 million hectares facing varying degrees of degradation (SLEM–Home page http://slem-cpp.icfre.gov.in/worldbank1.html). Intensity of precipitation (concentrated rainfall) and extreme dryness (longer drought periods) are likely causes attributed to the land degradation in Uttarakhand. Such changes also affect the agriculture sector more drastically and lead to morbidity among the workforce dependent on it (Singh and Chaturvedi, 2012) (Fig. 2.1). Uttarakhand has a low cropping area of

Plate 2.2 Agriculture along river beds more susceptible to seasonal floods

about 7.93 lakh ha (14%) and a majority of the net sown area is rainfed (State Action Plan-2012). Rainfed agriculture is extremely sensitive to climate change and likely to be impacted by erratic rainfall patterns observed over the years (Ramay, 2011). A study from north-East India, Kumar *et al* (2011) investigated how climate change would affect crop productivity and reported that by 2030 the production of irrigated rice would increase by up to 5% but that the rainfed areas would show a 10% decline in productivity.

2.3 Adaptation and Mitigation mechanisms

Adaptation and Mitigation are two broad mechanisms through which climate change can be addressed. Adaptation aims at increasing the capacity of people and ecological systems to adjust to climate change and to increase resilience to these changes, whereas mitigations deal with the measures that aim at decreasing GHG emissions.

Box 2.3. National Mission for Sustainable Agriculture:

A key goal of India's National Action Plan on Climate Change, 2008 (NAPCC), in the context of climate change aims to support climate adaptation in agriculture through the development of climate resilient crops and appropriate agricultural practices

As Uttarakhand has a low per capita carbon emission, the possible impact of mitigation measures is limited and hence adaptation may be the focus. However, many adaptation options also result in an often unintentional drop in the emissions, and thus act as an effective mitigation strategy too.

Improved soil and water conservation is reported to be most useful strategy in face of climate uncertainty in mountain area (Kandpal and Negi, 2003). Certain simple steps can be undertaken to improve soil and water conservation:

- No tillage farming
- Promotion of perennial grasses in degraded areas.
- Plowing against hill slope for water retention
- Mulching seed beds of vegetables to avoid killing by frost
- Relay cropping, lentil sown (broadcast sowing) about a week prior to harvest paddy
- Sowing of presoaked paddy seeds to minimize irrigation demand for germination
- Value addition of local fruits and vegetables.
- Introduction of intercrops with assured market demands will provide higher income to the villagers.
- Initiatives to facilitate storage, transportation and providing quality seeds and train villagers to conserve water for irrigation.

Table 2.3 Adaption mechanisms to address climate change in Uttarakhand

Adaptation	
Instrument	**Preparation**
Diversified Agriculture System	More copping potential against extremity of climate
Conservation Agriculture	It involves high and sustained production levels while concurrently conserving the environment
Improve water use efficiency	Drip and sprinkler irrigation and retention of moisture through multistoried and relay cropping
Rainwater harvesting	Conserve rainfall in rainy months
Organic farming	Promote green manuring- less use of chemical fertilizers
Adaptation research	Improve varieties, pest surveillance, diversified farming and breeding
Improve micro-climate	Induce shelterbelts, wind-breaks, organic mulches and mixed cropping
Pre warning system	As warning and advice should be issued promptly to ameliorate the adverse effects of climate change
Agriculture Insurance Scheme (AIS)	Observed decline in the share of agriculture in GSDP (29% in 1999-2000 to 15.8% in 2008-09) can be boosted through AIS
Mitigation	

Minimize Emission	➢ Efficient use of nitrogen to reduce N_2O emission ➢ No Tillage ➢ Efficient use of livestock feed to reduce amount of methane produce ➢ GHG and management - Minimize environmental footprints from rice cultivation by using techniques like System of Rice Intensification (SRI)

Box 2.4. Conservation of traditional cropping system to address climate variability and high costs

Some of the community-led programmes like ***Beej Bachao Andolan*** with scientific expertise from ***gene campaign*** are working together to bring back traditional seeds to address climate unpredictability and high costs. Mixed crop farming is successfully reported from the state in which '***Barah Naja***' or 12 crops farming is done prior to the kharif season. This practice of mix farming is based on the principle of crop cycling and practiced in many regions of the state. Under this practice, the seeds are sown in mid-May to mid-June and harvested in mid-September to mid-October and the fields are left fallow after that, and are prepared again at the end of March. Paddy and barnyard millet are the kharif crops and harvested by end September whereas in rabi season, wheat barley and masur dal is grown and harvested by end April. Such practice provides nutritional requirements of the farmers and more or less free from pests and diseases. Moreover, ragi, oilseeds and pulses showed resistance against drought, as ragi needs only one shower to germinate. This successful model of Uttarakhand is supported by '***Beej Bachao andolan***' and directly deals with the conservation of traditional/local seeds.

The above-said approaches may help in adapting to present climate change scenario and lower the carbon emissions at the same time. However, practically scaling-up the sustainable agricultural practices in Uttarakhand is often questioned due to outmigration and the lack of dissemination of locally appropriate technologies.

Some successful initiatives are required in the state and learnings from initiatives such as Community Managed Sustainable Agriculture (CMSA) in Andhra Pradesh and System of Rice Intensification (SRI) in Tripura, Orissa and Tamilnadu. These initiatives have provided new knowledge to deal with climate change without big, costly 'techno-fixes' (GOI Monitor Desk , 2012). Innovative and knowledge based experiments are conducted across the country and it is imperative that Uttarakhand state learns from these experiments and initiatives to better adapt to climate change and lower the GHG emissions from the sector. Some excellent work has been done by local NGOs such as Peoples Science Institute (PSI) on promoting aspects of SRI and the Uttarakhand Organic Commodities Board (UOCB) in sustainable organic farming - but the successes have not been replicated or scaled up.

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3. Status of Himalayan Glaciers

The Himalayan cryospheric system is the largest outside the polar region and is associated with a number of hydrological and climatic regimes, extending from cold-arid regions of the Ladakh to humid monsoon climate of the north-eastern Himalayas (Mani, 1981). This region which covers eight countries across Asia is home to some of the world's largest and most spectacular glaciers and snow fields. These glaciers and snowfields are the source of numerous large Asian river systems, including the Indus, the Ganges and the Brahmaputra, which provide water for over 800 million people. The surface water of these rivers and associated groundwater constitute a significant strategic resource for all of Asia.

It is estimated that there are around 12,000 glaciers in the Himalaya (Kaul, 1999; ICIMOD, 2001) and the area under glaciers is estimated at 33,000 km^2 (Kaul, 1999; Rai and Gurung, 2005). The Indian Himalayan Glacier System with 9575 glaciers (Singh et al., 2009), is the third largest glacier system on earth and holds the largest reserves of freshwater in the form of snow and ice outside the polar regions (GSI, 2001). The Himalayas are thus also referred to as the 'water towers' of Asia and a 'third pole' of the earth. The distribution of glaciers is uneven from East to West with respect to altitude, latitude, precipitation and aspect. The maximum concentration of glaciers is in NW Himalaya. The length of glaciers varies from 1-72 km and these extend between altitudes ranging from 3700 to 6000 m. The snow line

(ELA) altitudes are; 4100 m in Kashmir, 4800 m in Himachal, 5050 m in Garhwal and 5300 m in Sikkim (GSI, 2001).

The glaciers of the Indian Himalayas are spread over different river basins including the Indus, Ganga and Brahmaputra. Inventories of the Himalayan glaciers by the Geological Survey of India (GSI) reveal that the Bhagirathi sub-basin has the largest glacierised area of about 755 km^2 with as many as 238 glaciers including the Gangotri glacier (26-30 km). In comparison, the Brahmaputra basin has nearly 161 glaciers although it occupies a much smaller glacierised area of about 223 km^2. Some of the other important glaciers found in the Himalayas include Siachen (72 km), Zemu (26 km), Milam (19 km), Kedarnath (14.5 km) and Dokriani (5.5 km) (WWF, 2005).The snow and glacier covered area in the Indus, Ganga and Brahmaputra river basins is given in Table 3.1 and their distribution across the States in Table 3.2. The basin/ sub-basin wise distribution of glaciers in India is given in Table 3.3. Distribution and area covered by glaciers in the Bhagirathi basin is given in Table 3.4.

Table 3.1 Snow and Glacier covered areas in the Indus, Ganga and Brahmaputra River Basins

Basin Name	Basin area, km^2	Glacier area, km^2	Glacier area, %	Population, 10^6
Indus	1,139,814	20,325	1.78	211.28
Ganges	1,023,609	12,659	1.24	448.98
Brahmaputra	527,666	16,118	3.05	62.43

Source: NAP, 2012

Table 3.2 Snow and Glacier covered areas in the Indian Himalayan Glacier System

State	Glaciers	Area (km2)	Average Size (km2)	Glacier%
J&K	5262	29163	10. 24	61.8
Himachal	2735	4516	3.35	8.1
Uttarakhand	968	2857	3. 87	18.1
Sikkim	449	706	1.50	8.7
Arunachal	162	223	1.40	3.2

Source: Gupta and Dobhal, 2011

Table 3.3 Distribution of Glaciers - Basin wise in India

Glaciers in India – basin wise distribution					
Basin/Sub-basin	Total basin area (km^2)	Number of Glaciers	Glacierised area (km^2)	Glacierised area (%)	Largest Glacier in the Basin
Jhelum	12,362	133	94.18	0.76	Kolahoi
Satluj (Partly)	2,831.47	224	420.60	14.85	Baspa-Bamak
Bhagirathi	750,207	238	755.43	10.06	Gangotri
Tista	7,172.21	449	705.54	9.84	Zemu
Brahmaputra	54421.77	168	223.37	0.41	Subansiri

Source: Kaul, 1999

Table 3.4 Distribution of Glaciers in Bhagirathi Basin.

Bhagirathi Basin, Garhwal Himalaya

1.	Total basin area (km^2)	7502
2.	Number of glaciers	238
3.	Glacierised area (km^2)	755
4.	Glacierised area (%)	10
5.	Distribution of glaciers	
	a. Area wise (Numbers)	
	< 1km^2	147
	>1 <5 km^2	61
	>5 <10 km^2	17
	>10 <15 km^2	4
	>15 km^2	9
	b. Length wise (Numbers)	
	<1 km	70
	>1 km	136
	>5 km	32
6.	Total ice volume (km^3)	67.02
7.	Largest Glacier	
	Area (km^2)	143.58
	Length (km)	30

Source: Dobhal, 2010

3.1 Glaciers in Uttarakhand

The Uttarakhand Himalaya stretches for about 325 km between Kali Ganga in the east and Tons-Yamuna valley in the west and covers an area of 53,204 km^2. There are 1439 glaciers in Uttarakhand Himalaya covering a total area of 4060 km^2. These glaciers have been further sub-divided in the following mountain ranges: Nanda Devi Group, Dauliganga Group, Kamet Group, Gangotri Group, Satopanth Group and Bandarpunch Group. The glacier inventory for Uttarakhand Himalaya using remote sensing techniques has been prepared by the Wadia Institute of Himalayan Geology and ICIMOD (Table 3.5).

Table 3.5 Glaciers of Uttarakhand (Sah et al., 2005).

S. N.	Basin	No. of Glaciers	Area (km^2)	Volume (km^3)
1	Tons	102	162.58	17.43
2	Yamuna	22	10.4	0.45
3	Bhagirathi	374	921.46	129.93
4	Bhilangana	19	112.84	13.48
5	Mandakini	40	81.64	5.98
6	Alaknanda	457	1434.56	170.37
7	Pindari	43	158.99	15.01
8	Ramganga	7	6.74	0.322
9	Goriganga	128	561.35	69.18
10	Dhauliganga	135	373.19	34.6
11	Kutiyanghi	112	236.24	18.64
Total		1439	4060.04	475.43

3.2 Recession of Glaciers in Uttarakhand

Studies indicate that the rate of recession and volume change are irregular for glaciers across the Himalayan arc. This is attributed to the variations in micro-climate and physiography. Out of more than 5000 glaciers in the Indian Himalayas, only 11 glaciers have been monitored for their mass balance and nearly 100 glaciers have been monitored routinely for shifting of snout position of the glaciers. The recession trends of some the glaciers are given in Table 3.6. The Gangotri glacier is receding rapidly with the rate of retreat during the period 1962-1991 being about 20 m/yr. The enhanced rate of retreat is attributed to the increased anthropogenic interventions.

Table 3.6 Recession trends of some Himalayan glaciers

Name of Glacier	Period of Observation	Period (in years)	Recession (in m)	Average recession rate (m/yr)	Source
Milam glacier	1848-1996	148	2472	16.7	Vohra
Pindari glacier	1845-1966	121	2840	23.5	Vohra
Gangotri glacier	1935-1996 1996-1999	61 3.5	1,147 76	18.8 22.2	Vohra Naithani et al
Tipra bank glacier	1960-1987	27	100	3.7	Vohra
Dokriani glacier	1962-1991 1991-2000	29 09	480 161.15	16.5 18.0	Dobhal Gergan
Chorabari	1992-1997	05	55	11	Swaroop et al
Shanklup	1881-1957	76	518	6.8	Vohra
Poting	1906-1957	51	262	5.1	Vohra
Dunagiri	1992-1997	05	15	3.0	Swaroop et al
Burphu	1966-1997	31	150	4.8	Srivastava et al
Chorabari	1992-1997	05	55	11	Swaroop et al
Bhrigupanth	1962-1995	33	550	16.7	Srivastava et al
Tipra Bank	1960-1987	27	100	3.7	Vohra

Source: Nainwal et al., 2008

3.3 Glaciers and River Flow Regimes

River systems originating from the Himalayan region are fed in part by melting of snow and ice stored in the glaciers and this helps the rivers maintain a healthy level of stream flow all round the year. Snow and glacier melt together with monsoonal precipitation determines the headwater flow regimes of large parts of the Himalayas, including central and eastern Himalayan tributaries of River Ganga and Brahmaputra. Studies reveal that snow and glacier melt contribution is very significant in many of these Himalayan Rivers. On average, annual snow and glacier melt contribution is estimated to be 60% in Satluj river at Bhakra dam (Singh and Jain, 2002), 49% in Chenab river at Akhnoor (Singh et al., 1997) and 35% in Beas river at Pandoh (Kumar et al., 2007).

Studies indicate that glaciers in the Himalayan region are in a general state of recession since 1850's (Mayewski and Jeschke, 1979; Vohra, 1981; Dobhal et al., 2004; Kulkarni et al., 2007) with few exceptions in the Karakoram region, which are advancing (Hewitt, 2005). As the glaciers retreat the amount of snow and ice melt may not be enough, especially during the critical summer season and other periods of low flow, and base flows may fall to a level where agriculture and human settlements are very adversely impacted. As the storage capacity of glaciers declines, short-term flood risks would increase. This would be followed by decreasing water flows in the medium and long term. Both these consequences of glacier melt would threaten food production in some of the world's most densely populated regions. The watersheds of the area are characterised by complex hydrology and the magnitude of the contribution of glacial meltwater to the total water supply in these rivers is not clear. This paucity of information and data in tandem with the implications of accelerated rates of glacial retreat have not allowed for a precise characterisation of impacts of glacial wastage for downstream populations. Non availability of water, and projections of population growth have led to concern over possibilities of negative impacts from changes in the availability of water supplies in the coming decades (Vaux et al., 2012).

The current understanding regarding the impact of glacier shrinkage on the river flow variations is discussed in the IPCC (2007a) which stated that "*as these glaciers retreat due to global warming, river flows are increased in the short term, but the contribution of glacier melt will gradually decrease over the next few decades*" and "*the enhanced melting of glaciers leads at first to increased river runoff and discharge peaks and an increased melt season*" (IPCC, 2007b). However, considering the diverse climatic and hydrological regime of mountain glaciers across the world, such a uniform river flow response to glacier melting needs further evaluation. The Himalayan region itself has three dominant climatological regimes, which include areas experiencing monsoon and winter precipitation, areas dominated by winter precipitation from western disturbances and cold-arid regions (Vohra, 1981). Therefore, glacier's role in influencing the flow regimes of the rivers along the Himalayan arc would vary considerably.

Glaciers are thus natural buffers of hydrological seasonality and play an important role in the flow regime of these rivers by releasing meltwater during summer and early autumn in particular. They are not only a local water resource in the mountains but also influence runoff into lowland rivers, recharge riverfed aquifers, and contribute to global sea-level change; in the H-K region (Immerzeel et al., 2010), regional climates are heterogeneous, and the socioeconomic importance of glacier meltwater varies over the H-K; they are a major source of stream flow in parts of the H-K having little summer precipitation, especially the Karakoram and northwestern Himalaya, but is less important in monsoon-dominated regions with abundant summer precipitation (Radić and Hock, 2010). This spatial variability influences meltwater regimes, thus affecting the availability of water for hydropower generation, agriculture, and ecosystems (Moors et al., 2011). Glacier change – advance or retreat - also brings about a change in risks due to glacial hazards, not least from glacial lake outburst floods (GLOFs).

3.4 Glaciers and Climate Change

Glaciers develop where mass gain (e.g., by snowfall and avalanches) exceeds mass loss (e.g., by melting and calving). Lower temperatures and greater snowfall favour mass gain (accumulation); conversely, higher temperatures favour mass loss (ablation). The sum of accumulation and ablation over any period is the mass budget. Mass is transferred by glacier flow from the accumulation area, at high elevation, to the ablation area at low elevation. If ablation dominates over several years, the mass flux is reduced and the glacier starts to retreat. Conversely, if net annual accumulation (positive balance) dominates for a long time, the glacier increases flow speed and eventually advances. Because the response of the terminus to a change in climate is delayed by flow dynamics, current changes in terminus position are integrated reactions to past climate changes. Glacier response times vary; the larger and slower (flatter) the glacier, the longer the delay under equal climatic conditions. Glaciers are one of the most obvious, and seemingly simple, indicators of climate change. However, glaciers themselves are physically complex and spatially diverse. Glacier data in the Himalayas and surrounding mountains are very sparse, limited mostly to terminus location data that do not comprehensively describe overall conditions of the glaciers (Armstrong 2010).

Glacier retreat provides a clear indication of a global climate that has been warming since the Little Ice Age (LIA), which occurred from approximately 1650 to 1850 (Oerlemans, 2005). Globally, evidence left by glacier moraines shows the maximum extent of these glaciers during the LIA and quantifies the fact that glaciers have been retreating since this period in response to a warmer climate. There is now clear evidence that the retreat of glaciers in many locations of the world has accelerated in recent decades (Zemp et al., 2008). However, glacier systems at the highest elevations, 4000-7000 m, have not responded to recent climate warming in the same way as glaciers that extend to lower elevations, simply because glaciers at higher elevations remain below freezing during much of the year, even in the presence of a warmer climate. Therefore, one cannot always make direct comparisons and extrapolations from the well-studied lower elevation glaciers to the more poorly observed higher elevations of the Himalayan region (Armstrong, 2010).

3.5 Regional Variations of Himalayan Climate

The climate in H-K is strongly influenced by the varying dominance of the Asian monsoon and winds from the west (Bookhagen and Burbank, 2010; Vaux et al., 2012; Raina, 2010; Dobhal, 2010, Thayyen and Gergan, 2010). The westerlies are a more important moisture source in the northwest: about two-thirds of the high-altitude snowfall in the Karakoram is due to westerly cyclones, mainly in winter, whereas in the southeast more than 80% is provided by the summer monsoon (Bookhagen and Burbank, 2010). The mountains block transfer of most moisture to the Tibetan plateau; hence, precipitation decreases sharply northward in both the monsoonal and the westerly regimes. The mean elevation of H-K glaciers, a rough proxy for the equilibrium line altitude (ELA), is ~5360 m above sea level (asl), with the highest values in the central (~5600 m) and the lowest in the western Himalaya (~5150 m) (Bolch et al., 2012).

As discussed earlier, due to lack meteorological data, little is known about the regional horizontal and vertical distribution of precipitation, especially at high elevations. Short records suggest precipitation of 1600 to 1800 mm year^{-1} in the southwestern Karakoram near 5000 m asl (Winniger et al., 2005). Himalayan precipitation records show little or no trend with time (Shrestha et. al., 2005), whereas winter precipitation has increased in the Karakoram (Shekhar et al., 2010). Weather station data indicate recent warming in the Himalaya but not in the Karakoram (Shekhar et al., 2010; Shrestha et al., 1999). Nearly all stations are far below the lower limit of glaciers, and some are affected by progressive urbanization, so that it is uncertain whether these trends are also valid for the glaciers. At the highest long-term weather station in the Himalaya, Tingri (4300 m asl), north of Mount Everest, mean annual air temperature (MAAT) increased by ~0.03 K year^{-1} during 1959 to 2007, with greater warming in winter than in summer (Yang et al., 2011). This warming rate may be greater than the global average. In contrast, the MAAT in the Karakoram decreased—a global anomaly-mainly due to the decrease of summer temperatures (Shekhar et al., 2010).

3.6 Characteristics of Himalayan Glaciers

Himalaya experiences diverse climate and hydrology from west to east (Fig. 1), dominated by S-W Indian monsoon in summer and mid-latitude westerlies known as western disturbances in winter (Upadyaya, 1995; Mani, 1981; Benn and Owen, 1998; Lang and Barros, 2004). While S-W monsoon decline in strength from east to west along the Himalayan arc, western disturbances weakens as it move from west to east (Gupta, 1983). As a result of the changing meteorological regimes, hydrology of the glaciers and glacier fed rivers, east of Chenab basin are highly influenced by the summer monsoon and these glaciers are considered as summer accumulation type glaciers (Ageta and Higuchi, 1984; Vohra, 1981). This large region of the Himalaya constitutes the headwater regions of Ganga and few tributaries of River Indus and Brahmaputra. In contrast, the winter snow precipitations from western disturbances dominate large areas of Indus River systems (Quincey et al., 2011). In India, the State of Jammu and Kashmir is representative of this meteorological regime where monsoon activity is very low. Another unique glacio-hydrological system in Indian Himalaya is the cold-arid region of the Ladakh, which extends from Tibet to India. In this area, water from melting of glaciers and permafrost sustains the stream flow and water requirement of the population.

The very steep and rugged terrain above the glaciers leads to considerable accumulation by snow avalanching in H-K, especially for Karakoram glaciers, complicating the definition of accumulation areas and the calculation of responses to climatic changes (Hewitt, 2011; Bolch et al., 2011). Himalayan glaciers are largely confined to narrow valleys and the geometry and slope of the valley makes them more dynamic; they are invariably covered with debris (moraine) and hence less vulnerable to solar radiations (Dobhal, 2004). Debris cover, along with seasonal snow (Bhambri and Bolch, 2011), complicates delineation of the glaciers, and different measures and definitions of the numerous tributaries of the larger glaciers make length and area determination difficult. The large proportion of low-elevation glacier area in the western Himalaya may in part be a result of extensive debris cover. Bolch et al., 2012, estimate that total debris cover in H-K is ~10%. This percentage is important, because thick debris, which retards surface melting, is concentrated on the low-lying tongues where most melting is expected. However, many completely debris-covered glacier tongues have very low flow velocities or are stagnant (Scherler et al., 2011; Quincey et al., 2009) and are thus subject to additional melt processes.

Glaciers with large accumulation areas have been known to reach velocities of 100 to 200 m $year^{-1}$, decreasing gradually toward their termini, while those with small and steep accumulation areas have speeds >50 m year^{-1} only in the zones beneath their rock-ice headwalls (Kaab, 2005). In contrast to this rather homogeneous regional pattern, which is typical for the central and eastern Himalaya, glacier speeds in the Karakoram vary greatly in time and space (Bolch et al., 2012). Glaciers in close proximity, in similar topographic settings, and with similar sizes and shapes have very different speeds at a given time, which points to a range of dynamical sensitivities and instabilities (Dobhal, 2004; Copland et al., 2009). Particularly in the Karakoram, many glaciers surge for reasons that are not directly related to climate (Heid and Kaab, 2011). The number of glacier surges has almost doubled since 1990, which might be linked to positive mass budgets in this region in the recent period (Copland et al., 2011).

3.7 General Changes in Himalayan Glaciers

Changes in length changes measured for more than 100 glaciers in H-K (Bhambri and Bolch, 2009) suggest that most Himalayan glaciers have been retreating since the mid-19th century, except for 1920 to 1940, when about half the records show stationary or advancing tongues (Mayewski and Jeschke, 1979). Some large glaciers have advanced or been stable recently in the northwestern Himalaya and in the Karakoram (Bolch et al., 2011). In the Trans-Himalayan region of Ladakh, small high-altitude glaciers in the Transhimalaya of Ladakh had a shrinkage rate of ~0.4% year^{-1} from 1969 to 2010 (Schmidt and Nusser, 2012). In the Indian Himalaya, shrinkage rates are regionally variable: ~0.2 to ~0.7% year^{-1}, 1960s to 2001–2004 [11 Indian catchments, (Kulkarni et al., 2011)]; 0.12 +/- 0.07% year^{-1}, 1968 to 2007 [Garhwal Himalaya, (Bhambri et al., 2011)] and ~0.3% year^{-1}, 1963 to 1993 [Bhutan, (Karma et al., 2003)]. Where measured, the debris-covered area has increased, indicating increasing debris production, reduced glacial transport capacity, or negative mass balances. Most studies investigating more than one time period show faster shrinkage rates in later periods. Notwithstanding the variability and the uncertainties, a consistent picture emerges of net area loss in recent decades in most parts of the Himalaya.

Measurements of the annual mass budget are relatively few and short-term (Bolch et al., 2012). All budgets are negative on average with only a few positive years. Typical values vary from –0.32 m year^{-1} water equivalent (w.e.) (Dokriani Glacier, 1992 to 2000) to –0.67 +/- 0.40 myear^{-1} w.e. (Chhota Shigri Glacier, 2002 to 2010) (Azam et al 2012). A space-borne geodetic assessment for 1999 to 2004 in Lahaul/Spiti (Western Himalaya) revealed substantial mass loss on several heavily debris-covered tongues (Berthier et al., 2007). These measurements suggest that the mass budget over large parts of the Himalaya has been negative over the past five decades, that the rate of loss increased after roughly 1995 (Bolch et al., 2012), but also that the spatiotemporal variability is high. Monsoon-affected glaciers are more sensitive to temperature change than winter-accumulation–type glaciers (Fujita, 2008) because the temperature increase directly reduces solid precipitation (i.e., snow accumulation) and extends the melting period. Without a snow cover in summer, surface albedo is much lower and melt is further increased.

Since glaciers in the Himalaya are located closer to the Tropic of Cancer, they receive more heat than the Arctic and temperate climate mountain glaciers, and hence they are very sensitive to the rising temperature or climate variability both at regional and global levels (WWF, 2009). The responses of various glaciers are different due to variations in mass balance and the climate change impacts they face. Both a short-term perturbation in inputs as well as a long-term change in precipitation can affect glacial retreat.

Some of the studies carried out in the Indian Himalayas clearly point out an increase in glacial melt (Kumar et al., 2007). For instance, the Baspa basin of Himachal Pradesh has shown an increase in the winter stream flow by 75% as compared to the rate in 1966. This exhibits synchronicity with the rise in average winter temperatures in the area, possibly illustrating the impacts of global warming in the form of increased snow ablation, which in turn has augmented the stream flow (Kulkarni and Bahuguna, 2002; Kulkarni et al., 2002). Climate change impacts are also visible in the mass balance study of the Chhota Shigri glacier in the Chandra valley of Himachal Pradesh. The study shows that there has been a decrease in the Accumulation Area Ratio (AAR) of the glacier and it has had a negative mass balance in the years 2002-2005 (Kumar et al., 2007, Berthier et al., 2007).

3.8 Impacts of Glacier Changes in the Indian Himalaya

3.8.1 River Flow

Glacier change affects the hydrological cycle. A negative annual mass budget yields a surplus of runoff from glacier ice, whereas a positive budget yields a deficit of runoff because snow has gone into storage on the glacier. When glacier ice (as opposed to winter snow) is lost in the long term, the annual hydrograph evolves toward that of an equivalent glacier-free catchment. The relative importance of this loss of glacier ice necessarily decreases downstream, but it differs fundamentally under different precipitation regimes (Kaser et al., 2010).

The glacio-hydrological regimes of the Himalaya are characterized by differences in spatial and temporal distribution of precipitation and runoff (Thayyen and Gergan, 2010). In areas dominated by winter snowfall (Karakoram), peak glacier runoff contributes to the otherwise low flow conditions, governed by lower precipitation in summer (Fig. 2a); in areas dominated by the summer monsoon (Himalaya), peak glacier runoff contributes to the peak river flow in July and August months (Fig. 2b); in the cold-arid regions of the Ladakh, annual discharge peak occur in the month of July and August (Fig. 2c), mainly due to higher glacier melting during the period.

The "Himalayan catchment" is defined as glacier catchments experiencing snowfall in winter and monsoon precipitation in summer with peak discharge from the glacier contributing to the crest of the annual stream flow hydrograph. The Himalayan catchment is one of the three distinct glacio-hydrologic regimes of the Himalaya. Other two are the winter snow dominated Alpine catchment and cold-arid region of the Ladakh. The hydrological characteristics of the "Himalayan catchment" ensures that the highest runoff in a stream always occur as a result of high precipitation and glacier component in the stream discharge is highest during the years of low summer runoff. Hence under normal circumstances glacier melting would not lead to high discharge or floods in a "Himalayan catchment". Therefore, warming induced initial increase in discharge and subsequent decline is a response limited to the glacier degraded component of runoff and not necessarily translated as river flow response in all glacio-hydrological regimes as suggested by the IPCC (2001) and IPCC (2007a, b).

The runoff contribution from glacier imbalance is relatively minor in the wetter monsoonal catchments of the Ganges and Brahmaputra but more substantial in the drier westerly dominated headwaters of the Indus (Immerzeel et al., 2010). The contribution of snow and glacier melt runoff in different Indian Himalayan Basins is given in Table 3.7.

Table 3.7 Contribution of Snow and Glacier melt runoff in Indian Himalayan Basins

River	Site	Avg. Snow and Glacier melt contribution to Annual Flows
Chenab	Akhnoor	49%
Satluj River (Indian part)	Bhakra Dam	60%
Ganga River	Devprayag	30%

Projections of the diminishing contribution of seasonal snow to annual runoff indicate reduced maximum flows in spring and an increase by over 30% of the glacier contribution to total runoff (Barnett et al., 2005). Unlike in regions with winter-accumulation–type glaciers, where an earlier peak of spring snowmelt is expected, the monsoon-influenced Himalaya will maintain peak discharge in summer even with strongly reduced glacier sizes (Immerzeel et al., 2010). Runoff from less glaciated catchments will probably decrease, especially in the central and eastern Himalaya, as glaciers continue to shrink (Rees and Collins, 2006).

3.8.2 Glacial Lakes

Valley glaciers generally have supra-glacial ponds and moraine dammed lakes. As the glacier retreats it leaves a large void behind (Report of Expert Committee on Glaciers, 2006). The formation and disappearance of new supraglacial lakes is a natural phenomenon. However, an increase in the number and area of supraglacial lakes on the glacier surface can be linked with high rates of ice melting or excess downwasting of the glaciers (Hasnain et al). The coalescing of the small lakes results in large glacier lakes that store huge quantities of water and sediment. These glacier lakes can be bounded by the terminal moraine of the glacier, forming moraine-dammed or ice-margin lakes. The glacial moraine boundary consists of soft and loose material. In the central and eastern Himalaya, lake growth has been observed in recent decades, with much larger absolute growth rates in the east, while in the drier northwest, total lake area decreased (Xin et al., 2008).

The moraine walls that act as dam are structurally weak and unstable and undergo constant changes due to slope failures and slumping and there exists the danger of catastrophic failure, causing glacial lake outburst floods (GLOFs). These events are characterized by sudden release of huge amount of lake water that rushes along the stream channel downstream in the form of dangerous flood waves. The propagation of GLOF surges triggers landslides and bank erosion that temporarily block the surge waves and result in a series of surges as the landslide dam breaches (Report of Expert Committee on Glaciers, 2006). Discharge rates of such floods are typically several thousand cubic meters per second. In Uttarakhand Himalayas there are 127 glacial lakes of varying sizes, the total area of which is around 75 km^2. Therefore, the possibility of the state being affected by GLOF cannot be ruled out. As the glaciers continue to recede in the Uttarakhand Himalaya, the formation of moraine dammed lakes and their eventual collapse cannot be ruled out. Some of the larger glacier lakes will perhaps need to be monitored on a regular basis, especially during the monsoon season.

3.8.3 Glacier Advance

Advancing glaciers may also cause threats if they dam tributary valleys, turning them into new lake basins. The risk related to glacial lakes in the H-K, in contrast to some other mountain regions such as the Alps or Andes, is characterized by the particularly large lake volumes and associated long outburst flood reaches rather than by a high population concentration close to the lakes.

Other than these, in the changing global climate scenario, other area of concern with respect to the Indian Glacier System and glacier systems elsewhere in the HKH region relate to; (i) the contribution of glaciers to runoff, (ii) the projection of glacier changes, (iii) the variability of glacier changes within the region, (iv) the influence of debris cover on glacier melt, (v) and the role of ice and snow avalanches in the glacier mass budget. These uncertainties can be mainly attributed to deficient information (for example, about total glacier area and mass); lack of measurements, both of climatic forcing agents and of the glaciers themselves (mass budgets and length changes); and the use of unsuitable or uncertain data, such as imagery with extensive seasonal snow or maps drawn from such imagery.

Although generally temperatures are increasing and these increases are likely to accelerate in coming decades, spatial variability and gaps in observational data mean that it remains unclear what specific manifestations of climate change will be in specific places — including where and how quickly glaciers might retreat and what the cumulative impacts on the hydrological system of the region will be (Vaux et al., 2012). Moreover, it is difficult to separate the effects of changes in glacial wastage from other factors. These factors include changes in the timing and amounts of monsoonal rain and seasonal snowmelt, snow and ice dynamics, the effects of aerosols and black carbon, and the role of tectonic activity in destabilizing glaciers.

3.9 Conclusions

Though there is substantial scientific uncertainty, snow and glacial melt will likely continue to be important sources of water in the region and there will be several climatological, glaciological, and hydrological factors that control the rate, volume, and timing of snowmelt and icemelt. Monitoring systems will be critical to implementing effective adaptation solutions and improving water management systems (Vaux et al., 2012). Scientific evidence shows that most glaciers in the Himalayan region are retreating, leading to concerns that, over time, normal glacier melt will not be able to contribute to the region's water supply each year. Glaciers in the eastern and central regions of the Himalayas appear to be retreating at rates comparable to glaciers in other parts of the world. There is uncertainty in projections of future changes in precipitation, but shifts in the location and intensity of snow and rain could also impact the rate of glacial retreat. Variations in climate; in the timing, amount, and type of precipitation; and in glacial behaviour and dynamics mean that it is challenging to determine exactly how retreating glaciers will affect water supply in each location. Overall, retreating glaciers over the next several decades are unlikely to cause significant changes in water availability at lower elevations, which depend primarily on monsoon rains. However, for high elevation areas, current glacier retreat rates, if they continue, could alter streamflow in some basins. Glacial meltwater can act as a buffer against the hydrologic impacts of a changing climate, such as drought. Thus, water stored as glacial ice could serve as the Himalayan region's hydrologic insurance. Although retreating glaciers would provide more meltwater in the shorter term as the glacier shrinks, the loss of glaciers could become problematic over the longer term.

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