3. Climate Change in Western Himalayas

3.1. Introduction

Climate change is a statistical distribution of weather patterns over periods of time that range from decades to millions of years. Climate change may be limited to a specific region, or may occur across the whole Earth. In recent usage, especially in the context of environmental policy, climate change usually refers to changes in modern climate. Climate of earth varying in nature since the origin of earth, for instance, four great ice periods have covered the large extent of earth surface with ice in Pleistocene period (Kulkarni et al 2004). However, in last few decades, human activities like deforestation, consumption of coal and petroleum have accelerated the green house effects. Recently, Sahu et al (2008) reported that black carbon emission in India has been increased ~61% from 1991 to 2001 which may lead the green house effect in country. Most studies assume that current climatic warming is a result of the increasing green-house gas concentrations into the atmosphere (Hulme, 1999).

During the past decades, climate change in mountain regions has been accepted as an important factor in the understanding of glacier variability (Beniston et al 1997; Haeberli and Beniston, 1998; Calmanti et al 2007). Due to warming of atmosphere, alarming effects such as glacier recession (Kulkarni et al 2005, 2007; Bhambri et al accepted), water scarcity in villages of upper Himalayas (Kulkarni et al 2002, 2007), probability of mass movement activities and Glacier Lake Outburst Floods (GLOFs) (Richardson, 2010) have been increased in Himalayas. Climate studies of Himalayan glaciers have a significant role to understand the
past, current and future behavior of glaciers. Himalayan glaciers are the crucial source of fresh water and hydro-power (Singh et al 2009). Also climate data can be used for mass balance modeling for glaciological purpose (Tangborn, 1999). Thus it is essential to understand future projection about our water resources in the respect of current glacier coverage and climatic trends. The aims of this chapter are (1) appraisal the climate change in Himalayas based on analysis of instrumental weather and proxy climatic records and (2) evaluating air-temperature and precipitation tendency of Mukhim and Bhojbas meteorological stations.

3.2. Climate change – a review
Climate change can occur due to processes (forces) such as variations in solar radiation, deviations in the Earth's orbit, mountain-building and continental drift, and changes in greenhouse gas concentrations. Some parts of the climate system, such as the oceans and ice caps, respond slowly in reaction to climate forcing because of their large mass. Therefore, the climate system can take centuries or longer to fully respond to forces. Climate change can be measured through the long term instrumental records of climatic parameters such as temperature, precipitation data etc. However, in the absence of instrumental weather records climate trends can be constructed by proxy climatic records such as ice cores, tree rings (dendrochronology), corals, and lake and ocean sediments. Climate proxies are preserved physical characteristics of the past that enable scientists to reconstruct the climatic conditions that prevailed during much of the Earth's history.

3.2.1. Climate change studies based on Proxy indicators
3.2.1.1. Dendrochronology
Dendrochronology is the dating and study of annual rings in trees. Dendrochronology dating is a method of dating which makes use of the annual nature of tree growth. Each year trees such as oak put on a layer of new wood under the bark. The thickness of that layer - the tree-ring -
depends on various factors, particularly climate. Conditions favorable to growth will result in a
wide ring; unfavorable ones will produce a narrow one. Generally, trees growing at the same
time and place will show similar patterns of tree-rings. Scientists have estimated many local
climates for past hundred to thousands of year’s using tree rings. By combining multiple tree-
ring studies (sometimes with other climate proxy records), scientists have estimated past
regional and global climates.

Dendrochronology technique was developed by the astronomer A. E. Douglass, the founder of
the Laboratory of Tree-Ring Research at the University of Arizona during the first half of the
20th century. In India, tree-ring research started by the pioneering work of Chowdhury (1939,
1940a, b) in the early 1940s, who worked on the wood anatomy in association with the tree
phenology to identify tree rings. Unfortunately, his work was not continued until the late
1970s. Successful attempts in dendrochronology for the Indian region were made by Pant
(1979). He concluded that trees of the Himalayan zone are suitable for dendroclimatic
research because their well-defined growth rings display a very prominent response to
temperature. Pant and Borgaonkar (1984a) studied the tree rings in chir pine (Pinus
roxburghii) of the Kumaon (Uttarakhand) region in relation to the salient features of year-to-
year variation and long-term changes in rainfall and temperature of the region. Bhattacharyya
et al (1988) reported that the samples taken from Cedrus deodara and Pinus gerardiana at
lower altitudes in the dry inner valleys of the Pir Panjal Range, south of Kashmir, exhibit a
high age (up to 500 years), high mean sensitivity and good intra-and inter-species correlations
based on six coniferous species in the western Himalayas. Borgaonkar et al (1994) presented a
reconstruction for summer precipitation at Srinagar starting at A.D. 1775 using tree-ring
chronologies of P. smithiana and A. pindrow. Similarly, Borgaonkar et al (1996) reported a
significant relationship between pre-monsoon summer (March-April-May) climate
(temperature and precipitation) and Cedrus deodara chronologies from the western Himalayan
region. Thus, the possibility of using tree-ring chronologies from subalpine sites to reconstruct spring and early summer temperatures, or even whole summer temperature and precipitation, demonstrates that dendroclimatology is a tool to study the effect of climate variability on systems such as crops, rivers and glaciers in the western Himalayas.

Singh and Yadav (2000) presented 410 year old (AD 1590–1999) ring-width chronology of Himalayan pine (Pinus wallichiana) based on large replication of samples derived from a pure, mixed age stand growing on thick soil with almost even topography near Chirbasa, Gangotri. The chronology showed abrupt surge in tree growth during the late 20th century, with the highest growth indices recorded in the 1990s. Strong correlation noted between tree growth and winter temperature showed that the winter warmness is one of the main factors responsible for the twentieth century growth surge. This growth surge is closely associated with the area vacated by the Gangotri Glacier. Low growth prior to the 1950s reflecting cooler conditions indicated that the glacier should had been stationary for a long time with some episodic advances. Yadav and Singh (2002) presented reconstruct of mean spring (March–May) temperature variations back to A.D. 1600 based on network of 12 tree-ring width chronologies of Himalayan cedar (Cedrus deodara) from the western Himalayan region. The most noticeable feature of the temperature reconstruction is the long-term cooling trend since the late 17th century that ended early in the 20th century. The warmest 30-year mean for the 20th century recorded during 1945–1974 in this study. Singh et al (2004) reported 1198-year long (A.D. 805–2002) ring width chronology of Himalayan cedar (Cedrus deodara) from a site in Bhaironghati, Garhwal Himalayas. The ring-width chronology showed strong indirect relationship with mean monthly temperature from February to May strong temperature signal present in the series showed the potential of such long-term chronologies in developing climatic reconstructions useful for evaluating the recent climatic changes under the background influence of increasing concentration of greenhouse gases.
Figure 3.1 Important climatic stations in western Himalayas.
Bhattacharyya et al (2006) described the potentiality of tree ring data of Birch (Betula utilis) for the analysis of Himalayan glacial fluctuations. Tree rings of Birch growing along moraines around Bhojbasga, close to the snout of Gangotri Glacier. This study found that the growth of Birch has negative relationship with temperature of January, March and April, and direct relationship with precipitation of March, April and June, and temperature of February. In addition, increased tree growth in recent years has also been recorded coinciding with the rapid retreat of Gangotri Glacier.

As above discussion indicate that tree ring studies can be used for study climate variability in recent past. However, there are multiple climate and non-climate factors that impact tree ring width. Climate factors that affect trees include temperature, precipitation, sunlight, and wind whereas non-climate factors include soil, fire, tree-to-tree competition, genetic differences, logging or other human disturbance, disease, various types of mass movement activities. Some species of ant which inhabit trees and extend their galleries into the wood, thus destroying ring structure.

3.2.1.2. Pollen
All flowering plants produce pollen grains. Their distinctive shapes can be used to identify the type of plant from which they came. Since pollen grains are well preserved in the sediment layers in the bottom of a pond, lake or ocean, an analysis of the pollen grains in each layer can tell what kinds of plants were growing at the time the sediment was deposited. Pollen typically is the most abundant, easily identifiable, and best preserved plant remains in sediments and sedimentary rocks.

Several studies have been reported on peat bogs in the higher central Himalayas and Himachal Pradesh (Kar et al 2002; Rühland et al 2006; Chauhan, 2006). For instance, Rühland et al (2006) used high-resolution pollen and diatom proxies from a peat deposit in the Pindar valley of higher central Himalayas. These proxies enabled them to reconstruct high-resolution climate
for the last 3 millennia in the periglacial areas of Himalayas. Pindar valley witnessed an abrupt ecosystem turnover towards a wetter state in the last two centuries. This exceeded changes recorded over the last three millennia. This was contrary to expectations because, no correlation between recent proxy changes and summer monsoon precipitation was seen. However, relationship with the pollen proxy with winter climate data has been recorded. Recent wetness (unprecedented) was taken as the evidence to mark warming at higher elevations. This resulted in increased seasonal runoff and associated climatic feedbacks in the snow and ice-melt region. Chauhan (2006) deduced short-term climatic variability and contemporary vegetation shifts, tree-line changes and glacier movement in the alpine belt of Himachal Pradesh during late Holocene. Pollen analysis of 1 m sediment core from Naychhudwari Bog (Himachal Pradesh) indicated that around 1300 to 750 years BP, the alpine belt of this region experienced warm and moist climate. The glaciers receded and the tree-line ascended to higher elevations. Around 750 to 450 years BP, intermittent deterioration and amelioration of climate occurred. From 450 years BP onwards, the glaciers advanced and consequently the tree-line descended under the impact of cold and dry climate in the region. Kar et al (2002) presented Pollen analysis of a 1.25 m sediment profile from an outwash plain at Bhojbasa (3800 m a.s.l.) near Gangotri Glacier and linked with glacial fluctuations during the past 2000 years. Around 2000 years BP, open Juniperus–Betula forest occupied the area vacated by the glacier, revealing comparatively cooler and moist climate than the one prevailing at present. Subsequent increase of local arboreal taxa (Juniperus, Betula, Salix) and extra local elements (mainly Pinus) around 1700 years BP, indicates further amelioration of climate, i.e. increase of both precipitation and temperature in this region. Around 850 years BP there is a shift in the vegetation pattern, with sharp increase in Ephedra and other steppe elements notably Artemisia and Asteraceae. This indicates a trend towards drier climatic conditions, which is also evidenced by a decrease in Ferns and Potamogeton and in recent
times, climate again reverted to warm and moist, and due to increase in temperature, resulting in the retreat of snout to higher elevations. Thus, Pollen is a good proxy technique for reconstruction of past climate and associated phenomena.

3.2.2. Recent climatic trends based on instrumental records

Few studies (Singh et al 2005; Singh and Kumar, 1996; Arora et al 2008; Bhutiyani et al 2007; Shekhar et al 2010) have been carried out on climate change in western Himalayas based on weather instrumental records due to absence of high altitude metrological observatories. In India, Indian Meteorological Department (IMD) is the leading agency who is involved in the establishment of metrological observatories and collection of climatic data on the regular basis. After the independence of India, IMD has established several metrological observatories (Figure 3-1). Central water commission (CWC) and Snow and Avalanche Study Establishment (SASE) are other leading government agencies who have established manned and automatic weather stations in western Himalayas under river water development projects, power projects, and avalanche monitoring projects respectively. Almost all the metrological observatories in Indian Himalayas established at less than 4000 meter height. Due to this reason very less information about climate of high Indian Himalayan region is available.

The climate over the high altitude of Himalayas varies greatly over short distance due to elevation, aspect, vegetation cover and Rain shadow zone. Some studies have estimated climate trends based on statistical analysis of climatic data. Pant and Borgaonkar (1984b) studied the climate of the hill regions of Uttar Pradesh using annual rainfall data of six stations and temperature data at one station, for a period of about last century. They found the rainfall at the six stations is significantly correlated, indicating that the inter-annual variability has good spatial coherence. Recently, Kothawale and Kumar (2005) reported that all India mean annual temperature has shown significant increasing trend of 0.05°C / 10 year during the
period 1901-2003 and recent period 1971-2003 has shown increased warming trend of 0.22°C/10 year, which is mostly due to unprecedented warming during the last decade. In addition this study also noticed rising temperature during monsoon session. Instrumental meteorological records of some stations of western Himalayas clearly indicate that winter temperature has been increased during last century (Pant et al 2003). They found that maximum trend occur in winter temperature at Srinagar (1.4), Mukteswar (1.3), followed by Mussoorie (0.4), Lah (0.3), Shimla (0.2) and Dehradun (0.1).

Long-term trends in the maximum, minimum and mean temperatures over the northwestern Himalayas during the 20th century suggest a significant rise in air temperature in the northwestern Himalayas, with winter warming occurring at a faster rate (Bhutiyan et al 2007). This study also noticed that significant warming started in the late 1960s, with the highest rate of increase between 1990 and 2009. Dimri and Ganju (2007) simulated wintertime temperature and precipitation over the western Himalayas by a regional climate model. However, Fowler and Archer (2006) showed some conflicting results based on upper Indus Basin (UIB) data, they reported a decreasing trend in mean annual temperature since the 1960s that has become more pronounced since the 1970s. In contrast, they found an increasing trend in mean winter (December–February) temperature during 1960–2000. The changing trends of temperature and precipitation over the western Himalayas were examined by Dimri and Kumar (2008), who calculated the number of warm and cold events during winter (December–February) for 1975–2006. This study found a trend of increasing temperature and decreasing precipitation at some specific locations. Observational studies also reported that the area of spring snow cover across the western Himalayas has been declining and the snow has been melting faster from winter to spring since 1993, which may be due to climatic warming (Kripalani et al 2003). Singh et al (2005) used temperature (May to October) from 2000 to 2003 (four years) for the understanding of temperature trend of upper
Bhagirathi Basin. However for the high-quality understanding of climate of Himalayan terrain long term climatic data is required. Borgaonkar et al (2004) studied climate variability on Gangotri Glacier based on instrumental records of Pooh climatic observatory (1978 - 1991). Data was available only for November to April month. This study found increasing trend in both maximum and minimum temperatures in November to April months except January maximum temperature. One study on Nepal Himalayas reported that maximum temperature trends increased ranging from 0.06°C to 0.12°C per year in most of the middle mountain of Himalayas (Shrestha et al 1999). Above review suggest that temperature is increasing in western and central Himalayas during the last few decades. However, to my knowledge there are no published studies addressing Garhwal Himalayan glacier changes and influencing climate variables such as air-temperature and precipitation.

3.3. Temperature and precipitation variability in Garhwal Himalayas

The Snow and Avalanche Study Establishment (SASE) established a manned metrological observatory at Bhojbasa near Gangotri Glacier, Garhwal Himalayas which has been functional from December, 1999. SASE has also established three automatic weather stations at Bhojbasa, Kalindipass and Nandanban (DST website). Monthly average maximum and minimum temperatures ($T_{\text{MAX}}$ and $T_{\text{MIN}}$) and precipitation data for Mukhim station from 1957 to 2005 (except 1962, 1963, 1967, 1983 and 1984) were acquired from IMD (Figure 3-1). Mean monthly climate data (temperature and snowfall) of Bhojbasa station from 1999 to 2008 was acquired from Snow and Avalanche Study Establishment (SASE), Government of India. Monthly data were used to obtain average indices for annual and seasonal (December to February—DJF; June to August—JJA) variables of temperature ($T_{\text{MIN}}$ and $T_{\text{MAX}}$) and precipitation. Data from Tehri and Mukhim stations have an overlap of 22 years. A non-parametric Mann-Kendall test was used for determination of statistical significance trend, and
magnitudes of the trend were obtained by linear regression analysis (Racoviteanu et al. 2008a; Sansigolo and Kayano, 2010). A correlation analysis was carried out to verify trend results from Mukhim station and to determine whether it is possible to transfer data from Mukhim station (longer time series) to Bhojbas station (shorter time series).

The annual and JJA TMIN indices of Mukhim show significant cooling trends (tau = -0.50) of -0.072 °Cyr⁻¹ and -0.19 °Cyr⁻¹ from 1957 until 2005 while the TMIN of DJF shows no trend. In contrast, the annual (+0.05 °Cyr⁻¹), DJF (+0.1 °Cyr⁻¹) and JJA (+0.06 °Cyr⁻¹) TMAX display a significant warming trend. There is a slight, but no significant decrease in precipitation mainly due to summer precipitation (Table 3-1; Figure 3-2).

Table 3-1 Temperature and precipitation trends for the 1957–2005 period for the Mukhim station is based on the Mann–Kendall nonparametric test.

<table>
<thead>
<tr>
<th></th>
<th>tau correlation coefficient</th>
<th>Z</th>
<th>p</th>
<th>Mann–Kendall results</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ΔT °Ca⁻¹</td>
</tr>
<tr>
<td>Annual TMIN</td>
<td>-0.499</td>
<td>-4.824</td>
<td>0.0000</td>
<td>-0.072</td>
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<td>Annual TMAX</td>
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<td>4.441</td>
<td>0.0000</td>
<td>0.057</td>
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<td>-0.104</td>
<td>0.9170</td>
<td>0.003</td>
</tr>
<tr>
<td>DJF TMAX</td>
<td>0.441</td>
<td>4.309</td>
<td>0.0000</td>
<td>0.10</td>
</tr>
<tr>
<td>JJA TMAX</td>
<td>0.473</td>
<td>4.513</td>
<td>0.0000</td>
<td>0.06</td>
</tr>
<tr>
<td>JJA TMIN</td>
<td>-0.590</td>
<td>-5.636</td>
<td>0.0000</td>
<td>-0.19</td>
</tr>
<tr>
<td>Annual Precipitation</td>
<td>-0.029</td>
<td>-0.263</td>
<td>0.7926</td>
<td>-</td>
</tr>
<tr>
<td>DJF Precipitation</td>
<td>0.094</td>
<td>0.909</td>
<td>0.3634</td>
<td>-</td>
</tr>
<tr>
<td>JJA Precipitation</td>
<td>-0.097</td>
<td>-0.920</td>
<td>0.3574</td>
<td>-</td>
</tr>
</tbody>
</table>

The mean annual temperature of Mukhim shows an insignificant decreasing trend (-0.006 °Cyr⁻¹) in study period. The JJA TMIN indices of Mukhim and Tehri station of overlapping 22 years data show cooling trends of -0.109 °Cyr⁻¹ and -0.088 °Cyr⁻¹ respectively during 1957 to 2005. There is no correlation between Bhojbas and Mukhim climate data for five years of
overlapping data (2000 – 2005). Meteorological data of Bhojbas indicate that annual $T_{\text{MIN}}$, $T_{\text{MAX}}$, DJF $T_{\text{MIN}}$ and JJA $T_{\text{MAX}}$ increased from 1999 to 2008 whereas DJF $T_{\text{MAX}}$ and JJA $T_{\text{MIN}}$ decreased during similar period. Solid precipitation (snowfall) increased during same period. However, meteorological results of Bhojbas are statistically not significant due to the short time period.

Garhwal Himalayas obtain precipitation from the southwest monsoon in summer and westerlies during winter season. This distinguishes the region from eastern and Karakoram Himalayas. Our study area (Bhagirathi and Alakananda catchments) has few climate observatories at higher altitude (e.g. Mukhim and Tehri) with breaks in long term climate data series. The observation of weather conditions near the Gaumukh is limited to summer period in previous studies (Singh et al 2005; Singh et al 2007). The present study shows significant increasing trend in the annual $T_{\text{MAX}}$ but decreasing trend in the annual $T_{\text{MIN}}$ during the study period. Shekhar et al (2010) also reports an increase of 2.8 °C in annual $T_{\text{MAX}}$ from 1984/85 to 2007/08 in western Himalayas while annual $T_{\text{MIN}}$ increased by about 1 °C during similar period in western Himalayas. The present study notices significant decreasing trend in the JJA month’s $T_{\text{MIN}}$ of Mukhim station. The Tehri station data support these findings. Similarly, summer cooling has been reported in some parts of the western Himalayas and Upper Indus basin during the latter part of the twentieth century (Yadav et al 2004; Fowler and Archer, 2006). The present study reports significant increasing trend in the winter month’s $T_{\text{MAX}}$ of Mukhim station (Table 3-1). Alike Bhutiyani et al (2007) show winter months mean $T_{\text{MAX}}$ of north western Himalayas has significantly increased by ~3.2 °C during last two decades.
Figure 3-2 Climate parameters of Mukhim station, Garhwal Himalayas: (a) mean $T_{\text{MAX}}$ and $T_{\text{MIN}}$ of DJF and JJA from 1957 to 2005, (b) mean annual $T_{\text{MAX}}$ and $T_{\text{MIN}}$, (c) mean minimum and maximum precipitation of DJF and JJA and (d) annual mean precipitation. (DJF – December, January and February; JJA – June, July and August).