

Climate Change in the Himalayas

Current State of Knowledge

Mahesh R. Gautam
Govinda R. Timilsina
Kumud Acharya

The World Bank
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Environment and Energy Team
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Abstract

This paper reviews the literature on the potential biophysical and economic impacts of climate change in the Himalayas. Existing observations indicate that the temperature is rising at a higher rate in Nepal and Chinese regions of the Himalayas compared with rest of the Himalayas. A declining trend of monsoon in the western Indian Himalayas and an increasing trend in the eastern Indian Himalayas have been observed, whereas increasing precipitation and stream flow in many parts of Tibetan Plateau are noted. Glaciers in both the eastern and western Himalayas are mostly retreating, but the majority of the glaciers in Karakorum are either stable or advancing slowly. Expansion of glacier lakes is reported,

with the highest rate in Nepal and Bhutan. Most literature predicts increases in temperature and monsoon precipitations and decreases in winter precipitations in the future thereby leading to monsoon flooding and increased sediments in stream flow. Available hydrological simulations indicate reduced rainfall and shrinkage of glacier thereby leading to shortage of water supply for power generation and irrigation in winter particularly in highly glaciated basins. Projected economic impacts of glacial lake outburst floods can be substantial on the developed river basin with infrastructures and population centers. However, there is a clear gap in knowledge of economic impacts of climate change in the Himalayas.

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Climate Change in the Himalayas: Current State of Knowledge[#]

Mahesh R. Gautam, Govinda R. Timilsina, and Kumud Acharya[§]

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[§] Mahesh Gautam and Kumud Acharya are, respectively, Post-Doctoral Fellow and Research Professor at Desert Research Institute, Las Vegas, NV and Govinda Timilsina is Senior Economist at World Bank, Washington, DC.

1. Introduction

With the largest snow and ice cover in the world outside the polar regions, the Himalayan region is one of the most important mountain systems in the world and is referred to as the “third pole” (Schild, 2008) and the “water tower of Asia” (Xu et al., 2009). Extending along the northern fringe of the Indian subcontinent, from the bend of the Indus River in the northwest to the Brahmaputra River in the east, the Himalayas directly or indirectly affect lives and livelihood of over 300 million people (Schild, 2008). Through their massive fresh ice reserve, the Himalayas influence flow to thousands of rivers and rivulets that converge into the three main river systems in the region: the Ganges, the Brahmaputra (called Yarlung Zangbo in China), and the Indus (Fig 1).

The Himalayas play a key role on supporting economy of nations like Nepal and Bhutan, which depend heavily on the Himalayas for hydropower, water supply, agriculture, and tourism. For example, Bhutan’s export revenue from hydropower contributed 16.3% of nominal gross domestic product (GDP) or 39% of total exports in 2009/2010 (RMA, 2011). In Nepal, agriculture has remained a key economic sector, contributing about 34% of GDP in 2009 (World Bank, 2011) and employing 93% of the workforce in 2004 (ADB and IFPRI, 2009). Nepal's long term economic development plan centers on hydropower development, although current installed capacity is barely 1.5% of the total 43,000 MW potential. Himalayan States of India and Xizang Province of China also rely on hydropower, tourism, and agriculture for sustaining their economy. All these countries and states have remarkably high potential for hydropower of which only a small fraction has been harnessed. The Government of India released a study (GOI, 2012) showing that the Indian Himalayan states alone have over 70% of India’s hydropower potential in terms of installed capacity greater than 25 MW

The Himalayan region holds significant importance in terms of biological (species) richness, biodiversity, socio-cultural diversity, and wealth. The region is one of 34 worldwide “biological hotspots” (i.e., a natural environment with a high biodiversity containing a large number of endangered endemic species) as identified by Conservation International (CI, 2011). The region’s indigenous people consider the Himalayas sacred and look upon them with reverence. In essence, the Himalayas are both pride and necessity of the region.

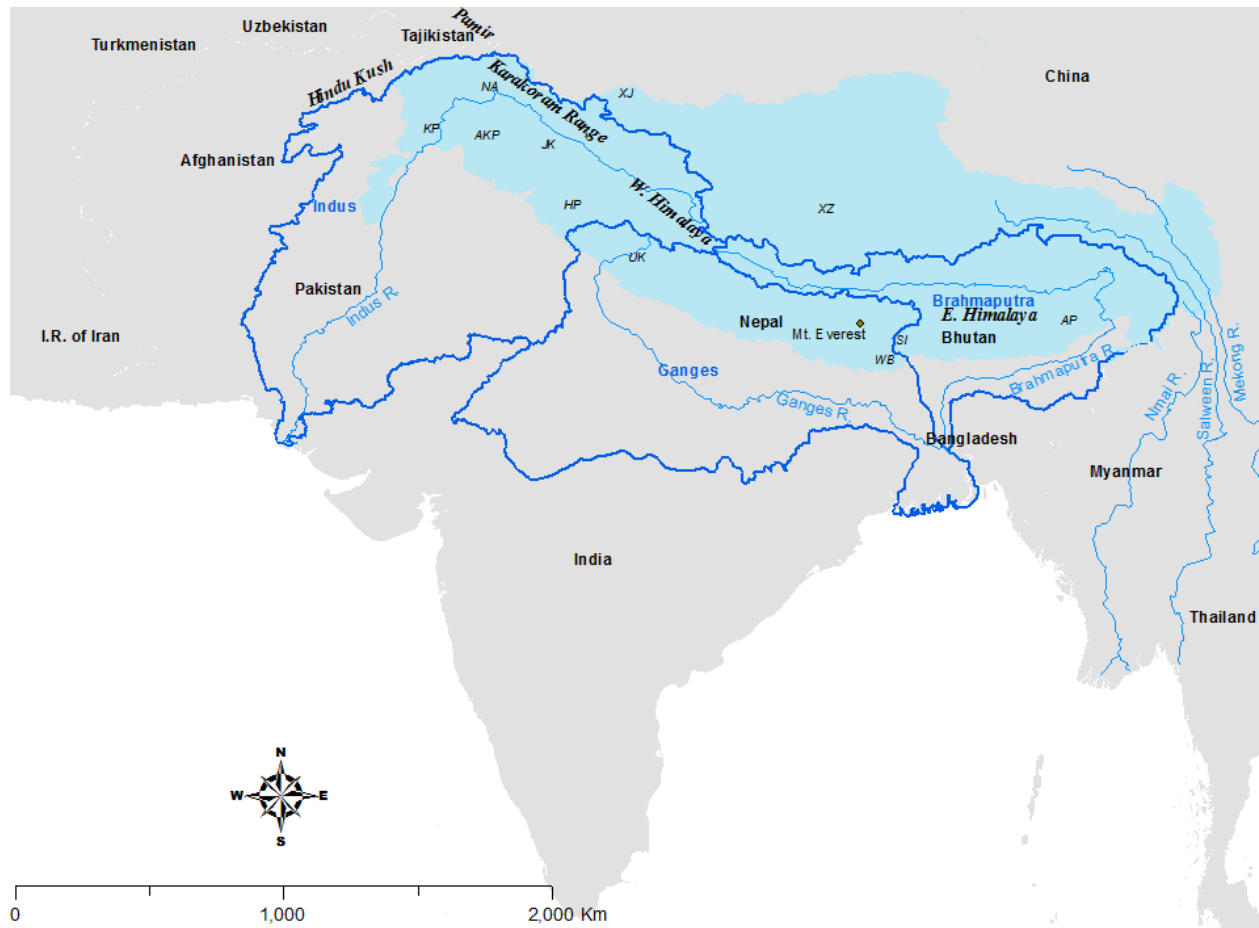


Figure 1 Map Showing the Hindu Kush-Himalayan Region. The coverage of this study is shown in sky blue color. KP: Khyber Pakhtunkhwa, NA: Northern Areas; AKP: Azad Kashmir; JK: Jammu and Kashmir; HP: Himachal Pradesh; UA: Uttrakhand; S: Sikkim; AC: Arunachal Pradesh; XJ: Xianjiang, XZ: Xizang, (Sources: ESRI, ArcWorld and ArcWorld Supplement and ICIMOD).

The fragile landscapes of the Himalayan region are highly susceptible to natural hazards, leading to ongoing concern about current and future climate change impacts in the region (Cruz et al., 2007). Climate change concerns in the Himalayas are multifaceted encompassing floods, droughts, landslides (Barnett et al., 2005), human health, biodiversity, endangered species, agriculture livelihood, and food security (Xu et al., 2009). While there are some reviews of existing literature on climate change observations and physical impacts on some of these aspects, a comprehensive review covering the Himalayan region from all dimensions of impacts is missing. This omission in the literature has fostered an opportune environment for controversies in the past. Specifically, past controversies (Bagla, 2009) are related to glacier retreat, melting,

and regional dependence on glacier melt. While many of these controversies seem resolved at present (Cogley et al., 2010; Inman, 2010), they give some critical insights into the reality. Armstrong (2010) and Kargel et al. (2011) have made excellent contributions toward solving some of the controversies and myths. A comprehensive review not only helps to expose common myths, but also to identify research gaps and areas where scientific investigation is critically important.

Economic development is a key issue in the Himalayan region and analyses of existing knowledge, and gaps in that knowledge, on how key economic sectors will be impacted under climate change is essential. Similarly, given the regional dependence and emphasis on hydropower, it is important to analyze the current economic impact of climate change on hydropower. Thus, this study has two specific objectives: (i) to synthesize the current state of knowledge on climate change impacts on the biophysical system (e.g., temperature, precipitation, snow coverage, streamflow, glacier melt, and ecosystem changes) in the Himalayan region and (ii) to review existing literature on economic impacts of climate change in the region. This study will help identify critical research gaps on the impacts of climate change in the Himalayas.

The study has a broad coverage of both biophysical and economic impacts of climate change on the Himalayas and there exists huge volume of literature on biophysical side. It is beyond the scope of this study to go through every available literature and judge their quality. Instead, we limited our review mostly to peer reviewed journal articles assuming that journals have a rigorous peer-review process and findings of the articles in these journals are credible. Besides, journal articles, we have included reports and articles published by national and international agencies assuming that these agencies are sensitive on knowledge products they produces and results of their studies are credible. However, we have taken every caution to interpret results of the existing studies. For example, many articles were found reporting trends without statistical significance, we have excluded interpretations of such trends. We have also considered other factors to scrutinize reported trends are data type (gridded versus gauged, recorded versus reconstructed), data length, spatial coverage, and analytical techniques. The trend test results are summarized together with information on statistical significance, data type and length. It should be noted that Himalayan hydroclimatological observations are limited; at higher altitude they are very limited. Therefore, caution is required on the interpretation of results based on observations from a few stations. However, until more monitoring networks are

established, existing stations may be the only available means of looking into hydroclimatic trends in the region.

2. Climate Change Observations

2.1 Strong evidence of warming

Temperature data in the Himalayas overwhelmingly show a warming trend, albeit at different rates in different periods depending on the regions and seasons (Table 1). In a very recent regional study using Climate Research Unit's reconstructed temperature dataset (Brohan et al., 2006), Diodato et al. (2011) show that in the last few decades the Himalayan and Tibetan Plateau region have warmed at a rate higher than that in the last century. They show a 0.5 °C in annual average maximum temperature (Tmax) warming over 1971-2005 compared to 1901-1960. Dash et al. (2007) report that the western Indian Himalayas saw a 0.9 °C rise over 102 years (1901-2003). They report that much of this observed trend is related to increases after 1972. Using winter (Dec-Feb) monthly temperature data from 1975-2006, Dimri and Dash (2011) also found a warming trend over the western Indian Himalayas, with the greatest observed increase in Tmax (1.1-2.5 °C). Over the northwest Indian Himalayan region, Bhutiyani et al. (2007) found 1.6 °C warming (0.16° C /decade) in the last century. Singh et al. (2008) observed increasing trends in Tmax and seasonal average of daily maximum temperature for all seasons except monsoon over the lower Indus basin in the northwest Indian Himalaya. Fowler and Archer (2005) report increasing trends in winter temperature during 1961-2000 in the upper Indus basin (Pakistan) with varying warming rates of 0.07-0.51 °C/decade in annual mean temperature (Tav) and 0.1-0.55 °C/decade in Tmax. Increasing winter maximum temperature in the upper Indus basin was also reported by Khattak et al. (2011) who found an increasing warming trend of 0.45,0.42,0.23 °C/decade in Tmax for the upper, middle, and lower regions, respectively, during 1967-2005.

Although, studies specific to the eastern Indian Himalaya are not available in the literature, many of the studies discussed above include the eastern Indian Himalaya as part of the greater northeast Indian region. For 1901-2003, Dash et al. (2007) found a rise in Tmax of 1°C over the whole northeast India. The study reports annual average daily minimum temperature (Tmin) increasing after 1972 following a sharp drop of 1.4 °C during 1955-72. Other studies also

report significant warming in the eastern Indian Himalaya. For example, Jhajharia and Singh (2011) show a 0.2-0.8 °C/decade increase in T_{av} , 0.1-0.9 °C/decade in T_{max} , and 0.1-0.6 °C/decade in T_{min} for stations exhibiting warming trend. Immerzeel (2008) reports a basin-wide warming trend similar to global average T_{av} (0.6 °C/100 year for the 1901-2002 gridded dataset) for the Brahmaputra basin in the eastern Indian Himalaya and Tibetan Plateau. The Nepalese Himalaya also saw a warming trend in the last century. Shrestha et al. (1999) reports a trend varying between 0.4 and 0.9 °C/decade in the mean annual maximum temperature across different ecological belts of Nepal, with the high Trans-Himalayan region showing the highest and the Terai (lowland region) showing the lowest. While for the same regions for winter season they reported a trend varying between no trend in Terai to 1.2 °C/decade in the Trans-Himalaya. Tse-ring et al. (2010) report (Table 1) trend similar to that reported by Shrestha et al. (1999) for a slightly different time period. In Bhutan, average temperature in the Himalaya regions increased by 0.5 °C in the non-monsoon season from 1985-2002 (Tse-ring et al., 2010). Several studies report similar higher warming trends for the eastern Himalayas in China (Liu et al., 2006; Liu and Chen, 2000; Wang et al., 2008; Xu et al., 2008; Yang et al., 2011; You et al., 2008; Yunling and Yiping, 2005). Liu and Chen (2000) show a rate of 0.16 °C/decade for the annual mean temperature for 1955-1996. However, analyzing data from 90 stations recently Wang et al. (2008) found increased warming over the whole Tibetan Plateau with a rate of 0.36 °C/decade during 1961-2007. Other studies with proxy temperature data reconstructed from tree ring width have also confirmed warming in the Tibetan Plateau. For example, Liang et al. (2009) reconstructed mean summer temperature (June-August) and found the last decade to be the warmest in the last 242 years (1765-2007) in southeast part of Xizang province of China. Yang et al. (2010) also observe distinct evidence of late 20th century warming in reconstructed annual mean temperature in southwest part of Xizang province of China, although within the range of natural climatic variability in the region.

The Everest (Qomolangma) region in China also exhibits warming at an average rate of 0.234 °C/decade in T_{av} from 1971-2004 (Yang et al., 2006). Higher warming rates of 0.28 °C/decade for annual average temperature are noted in the Chinese side of Brahmaputra basin (Yarlung Zangbo River Basin) during 1961-2005 (You et al., 2007).

Table 1 Summary of Temperature Trend Studies in the Himalayas (NS= Number of stations; DT= Temperature data type (RG= reanalyzed grid; S=Station; M=monthly); SS= Statistical significance)

Region	NS	DT	Trend (°C/Decade)	Analysis Period	SS	References	Remarks
Western Indian Himalaya		RG(M)	Tmax: 0.09	1901-2003	NA	Dash et al. (2007)	Shimla (Himachal Pradesh) and Jammu & Kashmir regions in India
	10	S(M)	Tav, Northwest: 0.11 (A*), 0.14 (W**)	1876-2006	5%	Bhutyani et al. (2010)	
	8	S(M)	Tav: 0.23-0.43 (W); Tmax: 0.06 to 0.17 (W); Tmin: 0.336 to 0.833 (W)	1975-2006	≤5%	Dimri and Dash (2011)	
Pakistan Himalaya (Upper Indus)	4	S(M)	Tav, Northwest: 0.16 (A), 0.17 (W)	1901-2000	5%	Bhutyani et al. (2007)	Shimla (Himachal Pradesh) and Jammu & Kashmir
	1	S(M)	Tmax, Lower Indus: All seasons and year (0.053 to 0.113; 0.139 Annual)	20th century (90-100 years)	5%	Singh et al. (2008)	
	6	S(M)	Tmax: 0.27-0.55	1961-1999	5%	Fowler and Archer (2005)	
Eastern Indian Himalaya	20	S(M)	Tmax: Upper:0.45 (W); Middle:0.42 (W); Lower:0.23 (W)	1967-2005	1%	Khattak et al. (2011)	
		RG(M)	Tmax: 0.1 (A)	1901-2003	NA	Dash et al. (2007)	
	8	S(M)	Tav: -0.2 to 0.8; Tmax: 0.1 to 0.9; Tmin: -0.5 to 0.6	1960s/70s-2000	5%	Jhahaaria and Singh (2010)	
Tibet Autonomous Region		RG(M)	Tav, Bramhaputra Basin: 0.06	1901-2002	NA	Immerzeel (2008)	
	97	S(M)	Tav:0.16 (A), 0.32 (W)	1955-1996	≤5%	Liu and Chen (2000)	Warming after 1950s
	90	S(M)	Tav: 0.36 (A)	1961-2007	5%	Wang et al. (2008)	Pronounced warming after 1998
	1	S(M)	Tav: 0.86 (W), 0.62 (A)	1959-2007	5%	Yang et al. (2011)	
	5	S(M)	Tav: 0.23 (A)- Mt. Qomolangma region, 0.3(A)-Tingri	1971-2004	1%	Yang et al. (2006)	YZR, Regionally averaged trend
Nepal	9*	S(M)	Tav: 0.28(A), 0.37 (W), 0.35(F+), 0.24 (Sp++), 0.17 (Su+++)	1961-2005	5%	You et al. (2007)	Regionally averaged
		RG(M)	Tmax:0.4 to 0.9 (A); NS [#] -1.2 (W)	1971-1994	≤10%	Shreshta et al. (1999)	
		RG(M)	Tamx:0.4-0.9 (A); 0.1-1.2 (W)	1977-2000	NA	Tshe-ring et al. (2010)	

*A=Annual; **W=Winter; +F = Fall; ++Sp=Spring;+++ S= Summer; # NS = Not significant)

All regions showed warming but variably but some studies on the Himalayas in Xizang province of China find higher warming rates at higher altitudes (e.g. Liu et al., 2009; Liu and Chen, 2000; Qin et al., 2009; Thompson et al., 2003; Yang et al., 2011). Similar findings are reported by Shrestha et al. (1999) for Nepalese Himalayas and Khattak et al. (2011) in winter (Dec-Feb) Tmax for Pakistan's upper Indus River Basin.

The rate of warming reported is consistently higher in winter than other seasons in most parts of the Himalayas, namely, the Chinese, northwest Indian, and Nepalese Himalaya (Bhutiyan et al., 2007; 2010; Shrestha et al., 1999; Shrestha and Devkota, 2010). The high mountains and Trans-Himalaya of Nepal exhibit winter warming at the rate of 0.9 °C/decade and 1.2 °C/decade, respectively, as compared to respective annual warming of 0.9 and 0.6 °C/decade in Tmax during 1971-2000 (Shrestha and Devkota, 2010). This seasonal trend (greatest warming in winter, smallest in summer) is also noted by several researchers in the Tibetan Plateau (e.g., Du et al. 2004, Liu and Chen, 2000, You et al., 2008).

Available results from the literature over similar time frames show that the highest rate of warming is in the Yarlung Zangbo River basin (0.29 °C/decade) followed by the northern Mt. Everest region (Mt. Qomolangma; 0.234/decade) during 1971-2004. Warming rates in these regions were higher than both the Chinese average (0.226 °C/decade) and global average (0.148 °C/decade) over the same period (Yang et al., 2006), as well as higher than the all-India average (0.22 °C/decade; Kothawale and Rupa Kumar, 2005) for a slightly different period (1971-2003). In another time frame (1971-2000), the Tibetan Plateau-average trend is 0.24 °C/decade (Wu et al., 2007) and Yarlung Zangbo River basin-average trend is 0.28°C/decade (You et al., 2007). Nepal's warming rate of 0.4-0.9 °C in Tmax (Tse-ring et al., 2010) during the same period is remarkably high, but is not comparable to those reported above based on Tav.

The following tentative conclusions may be drawn based on the above literature review:

(i) The later quarters of the 21st century and recent decades appear to be warmer than earlier periods; (ii) The warming rate is noted to be higher in winter than other periods in the whole region; (iii) The higher altitude Himalayan and Trans-Himalayan zone are reported to be warming at higher rates; and (iv) The Yarlung Zangbo River Basin and Mt. Everest region appear to be warming at higher rates than the rest of the regions.

Despite most literature suggesting a warming trend in the Himalayas, as discussed above, caution is required when comparing or interpreting differences in warming rates over the region.

A noted growing trend on high altitude hydroclimatological observations, however, shows potential for future climate change studies with multi-temporal scale temporal analyses taking into account recurrent large scale climatic cycles.

2.2 Spatial variability in precipitation trends

Unlike temperature, most of the literature reports a lack of spatially consistent long-term trends in Himalayan precipitation. This lack of homogeneity in trends reflects the influence of local thermodynamic and orographic processes (Dimri and Dash, 2011) over large scale ocean-atmospheric processes. Differences in precipitation trends are also observed across seasons.

In a recent study, Bhutiyani et al. (2010) observe a statistically significant downward trend (at 5% significance level) in monsoon and average annual rainfall in the northwest Indian Himalaya (as represented by three stations) during 1866-2006. A similar trend is noted for 1960-2006 over the western Indian Himalaya region (Sontakke et al. 2009) but without any mention of statistical significance. The literature shows intra-regional differences in winter rainfall trends over Western Indian Himalaya. Dimri and Dash (2011) note significantly decreasing winter precipitation (Dec-Feb) in the region for 1975-2006 amid lack of spatially coherent phases among stations. Guhathakurta and Rajeevan (2008) find statistically significant downward trend in winter precipitation (Jan-Feb) in Jammu & Kashmir and Uttarakhand during 1901-2003. In contrast, statistically significant increasing trends are observed in winter precipitation during 1961-1999 in the upper Indus Basin (Pakistan), but no trend is observed during the longer 1895-1999 period, (Archer and Fowler, 2004; Fowler and Archer, 2005). In the same basin, Khattak et al. (2011) find spatially inconsistent and generally statistically insignificant seasonal precipitation trends during 1967-2005; however, they note more increasing than decreasing trends.

Increase in pre-monsoon (March-May) precipitation has been observed over the western Indian Himalaya during 1901-2003 (Guhathakurta and Rajeevan, 2008). Literature on precipitation trends in Bhutan's Himalayan region suggests largely random fluctuations and the absence of trend on annual or seasonal basis (Tse-ring, 2003). Likewise, Shrestha et al. (2000) did not find any significant long-term trend in precipitation data (1959-1994) of the Nepalese Himalaya.

Precipitation in the Tibetan Plateau has increased in most of the eastern and central regions but decreased in the western region during 1961-2001 (Xu et al., 2008). On the Chinese side of the Everest region, Xu et al. (2008) report contrasting precipitation changes in the southern and northern parts: stations in the north show statistically insignificant increasing trends; in the south, a decreasing trend with a sharp drop starting in the early 1990s. In the Yarlung Zangbo River Basin, You et al. (2007) observe decreasing precipitation during 1960s-1980s but increasing thereafter. However, they found mostly increasing trends in the long-term (1961-2005) for annual and seasonal precipitation (not statistically significant in two seasons). A higher rate of increase in annual precipitation was found in the Yarlung Zangbo River Basin (24.6 mm/decade; You et al., 2007) in comparison to the Tibetan Plateau as a whole (11.9 mm/decade; Wu et al., 2007) during 1971-2000. Wu et al. (2007) found a statistically significant upward trend in 69% of 77 observation series mostly from southern stations in the Tibetan Plateau. A recent study in southwest China using 1960-2007 data (Qin et al., 2010) also shows increasing trends in most stations in the Tibetan Plateau in annual, winter, and spring precipitation. Wang et al. (2008) investigated the increasing temperature and rainfall trend in Tibetan Plateau numerically with atmospheric general circulation models and suggested that enhanced warming led to increased rainfall.

As stated earlier, physical processes influencing precipitation are complex resulting in large variability in observed precipitation trends. While spatial variability in precipitation trends in the Himalayas was commonly noted in the literature, the following tentative conclusions may be drawn based on the reviewed literature. First, monsoon and annual precipitation is increasing in Jammu and Kashmir but precipitation is decreasing in the western Indian Himalayas. Second, winter precipitation is decreasing in the western Indian Himalaya but it is increasing in the upper Indus Basin (Pakistan). Third, there exists no spatially coherent trend in Nepal or Bhutan; and finally, there exists an increasing annual precipitation in the Chinese Himalaya with Yarlung Zangbo River basin showing predominantly upward trend in annual, winter, and spring precipitation.

2.3 Increasing evidence of extreme climatic events

Few limited studies are available that assess trends in climatic extremes of temperature and precipitation in the Himalayas. These studies typically use several climatic indices to detect extremes. Temperature extremes are most commonly evaluated using warm days (percentage

days with $T_{max} > 90$ th percentile), warm nights (percentage days with $T_{min} > 90$ th percentile), cold days (percentage days with $T_{max} < 10$ th percentile), and cold nights (percentage days with $T_{min} < 10$ th percentile).

A study of extreme temperatures (1971-2006) in Nepal revealed that both days and nights are becoming warmer and cold days and nights are becoming less frequent (Baidya et al. 2008). Dimri and Dash (2011) find similar trends in the western Indian Himalayas, where they report an increased number of warm days and decreased number of cold days during 1975-2006. Frequent occurrences of extreme warm years are noted in recent years (6 between 1995 and 2002) in the Brahmaputra River Basin (Immerzeel, 2008). Similarly, in southwest Xizang province of China, most stations showed increasing trends for twelve extreme temperature indices during 1961-2005 (You et al. 2008). Caesar et al., (2011) use daily data to compare trends in climatic extremes in Indo-Pacific regions including the Nepalese and Bhutanese Himalayas. This comparison both across the region and with global trends reveals that, although statistically insignificant, the combined Nepalese and Bhutanese Himalayas show high rates of increase in maximum T_{max} (1.32 °C/decade against 0.29 °C/decade global average) and T_{min} (0.93 °C/decade against 0.33 °C/decade global average). These trends imply that temperature of the hottest day is increasing at a very high rate over the decades.

Trends also exist in precipitation extremes. Baidya et al. (2008) observe an increase in the number of days with more than 50 mm rainfall in Nepal. Analysis of 1961-2006 daily precipitation data from 26 stations across Nepal reveals that precipitation extremes increase in both total precipitation and heavy precipitation events (≥ 50 mm) at 73% of the stations (Baidya et al., 2008). Based on daily data from 1910-2000, Sen Roy and Balling (2004) find an increase in frequency of extreme precipitation events (total precipitation; largest 1, 5, and 30 day totals, number of events with $> 90^{\text{th}}$, 95^{th} , and 97.45^{th} percentiles of precipitation) northwestern Indian Himalaya, a finding that Sen Roy (2009) supports using hourly data from 1980-2002. Sen Roy (2009) reports that the northwestern Himalaya and northern parts of the Indo-Gangetic basin in the Himalayan foothills show increasing trends in precipitation extremes over all seasons (1980-2002). However, Dimri and Dash (2011) find an increasing trend only in maximum number of consecutive dry days (< 1 mm water equivalent of snowfall) in winter (Dec-Feb) at eight stations across the western Indian Himalaya during 1975-2006. Decreasing trends maximum number of consecutive wet days (days with 90^{th} percentile of events with > 1 mm water equivalent of

snowfall) are observed at most of the same stations over the same period (Dimri and Dash, 2011). In Tibetan Plateau, upward trends were noted in the southern and northern regions while downward trends were observed in the central region for most extreme precipitation indices (You et al., 2008).

Using limited data from the Bhutanese and Nepalese Himalayas, Caesar et al. (2011) observe a statistically significant upward trend in R95n index (annual total precipitation when rainfall is >95th percentile). The Bhutanese and Nepalese Himalayas rate of increase in the R95n index is 82.3 mm/decade compared to 4.68 mm/decade global average and 22.66 mm/decade average for the Indian Ocean region (Caesar et al., 2011). Additionally, comparing remotely sensed precipitation data across all regions, Brookhagen (2010) finds that the Himalaya has almost twice as many extreme events as the Ganges Plain or the Tibetan Plateau, regardless of rainfall amount.

In summary, temperature related climatic extremes appear to be increasing across the Himalayas. General increasing trends also exist in precipitation related climatic extremes in Nepal, Bhutan, southern and northern Tibetan Plateau.

2.4 Retreating glaciers, shrinking glacial extent, expanding glacial lakes, and negative mass balance

Glacier retreat and areal shrinkage

Several studies involving field based observations, satellite imagery, and repeat photography have shown that a majority of Himalayan glaciers are retreating. A notable exception is the Karakorum region where some glaciers have shown advancement (Hewitt, 2005). Hewitt (2011) recently outlined important climatic conditions that make Karakoram glaciers different from the rest of the Himalayas. Notable among them include, orographic conditions that enhance precipitation in the source area, an all-year accumulation regime, concentration and role of avalanche, and ablation buffering due to thick debris cover (Hewitt, 2011).

Pandey et al. (2011) analyzed satellite images of 26 glaciers of the western Indian Himalaya from 1975, 1989, 1992, 2001, and 2007, and found all glaciers were retreating (1975-1989/1992, 1989/1992-2001, and 2001-2007). Pandey et al. (2011) note fluctuating retreat rates

with maximum retreat occurring during the 1989/1992-2001 period. Bajracharya and Mool (2010) show that several glaciers in Dudh Koshi basin in Nepal retreated in both 1976-2000 and 2000-2007, while a few glaciers show stability. Temporal variability is observed in the Gangotri Glacier, a well-monitored Indian glacier, which showed no retreat during 2006-2010 (Kargel et al., 2011) despite a high retreat rate in earlier decades (Table 2). Reported retreat rate of many glaciers across the Himalaya also illustrate this variability (Table 2).

Most recently, Scherler et al. (2011) analyzed 286 mountain glaciers from the Hindu Kush, Karokaram, western Indian Himalaya, Tibetan Plateau, West Kunlun Shan, and southern central Himalaya (Nepal, Bhutan, Sikkim, Uttarakhand, and Himanchal) through satellite images from 2000-2008. They found 58% of sampled glaciers in the westerlies-influenced Karokaram region either stable or slowly advancing, while more than 65% of glaciers in the monsoon-influenced regions are retreating with several heavily debris-covered glaciers with low slope at the terminus being stable. Spatially, they found a higher concentration of retreating glaciers (79%) in the western Indian Himalaya and in the northern central Himalaya and West Kunlun Shan (86%) where debris-free glaciers are dominant. In comparison, they found 65% and 73% of sampled glaciers retreating at relatively slower rates respectively in Nepal and Bhutan Himalayas and Hindu Kush where debris-cover is common. They also note that a high rate of glacier retreat is widely observed in the Tibetan Plateau which has the largest concentration of glaciers in China. Ding et al. (2006) analyzed satellite data and found that more than 80% of analyzed glaciers in western China have retreated, losing 4.5% of their combined areal coverage over the past 50 years. While glaciers in the central and northwestern Tibetan Plateau appear relatively stable, glaciers in the mountains surrounding the plateau show extensive areal loss (Ding et al., 2006). Likewise, Yao et al. (2007) analyzed 612 glaciers in the Tibetan Plateau and found that an overwhelming number of glaciers are retreating with retreat rates increasing from 90% for 1980-1990 to 95% for 1990-2005. Recently, Yong et al. (2010) studied glacial change in China's Mt. Qomolangma National Nature Preserve (the Preserve) for 1976-2006 covering four major river basins: Pengqu (Arun), Poiqu (Bhote Koshi – Sunkoshi), Gyirong Zangbo (Trishuli), and Yarlung Zangbo (Brahmaputra). Most of the glaciers in the study area have retreated with rates varying between -9.10 ± 5.87 and -14.64 ± 5.87 ma^{-1} with most retreat occurring at elevations of 4700-6400 m (Nie et al., 2010). They attribute observed retreat to increasing temperature and decreasing precipitation in the study period.

Through digital satellite image analysis, Ye et al. (2006) find that glaciers in China's Naimona'nyi region shrank and retreated, shrinking at average rates of 0.17, 0.19 and 0.77 km^2a^{-1} during the periods 1976-90, 1990-99, and 1999-2003, respectively. Similarly, Nie et al. (2010) observe glacier shrinkage in the Preserve at a rate of 15.6% ($16.7 \text{ km}^2\text{a}^{-1}$) from 1976-2006, occurring mainly at elevations of 4700-6800 m. They find shrinkage in this period was higher on southern slopes (16.8%; Poiqu and Gyirong Zangbo) than on northern slopes (14.4%; Pengqu). They note glacial area shrank at the rate of $16.73 \text{ Km}^2\text{a}^{-1}$ (15.63%) in the Preserve between 1976-2006.

In Nepal, overall glacier area and ice reserve have declined by 21% and 28%, respectively, between 2001 and 2010 (Bajracharya et al., 2011). Bajracharya et al. (2011) also report shrinking (average of $30 \text{ km}^2\text{a}^{-1}$ for 1977-2009) and fragmentation of glaciers, noting that retreating glaciers were only observed below 5800 masl, with the highest rate of retreat at 5000-5500 masl; in central Nepal, they report disappearance of glaciers below 3200 masl.

Bolch et al. (2008 a) analyze changes in glacier area in eastern Nepal (Khumbu Himal) using satellite images of the area (1962, 1992, 2001, 2005) and find that, overall, the region lost ice cover for all four periods considered (1962-2005; 1962-1992; 1992-2001; 2001-2005). Considering the 1962-2005 period, the region is losing ice covered areas at an average rate of 0.12% per year with a higher rate of 0.24% per year for clean ice areas (Bolch et al., 2008 a). Over a longer time frame (1962-2007), Kulkarni et al. (2007) report a 21% overall loss of glacial area in the state after analyzing 466 glaciers using remote sensing. Based on satellite imagery, Kulkarni et al. (2011) studied glacier shrinkage of 1868 glaciers in 11 basins in the Indian Himalaya, where they found an overall reduction in glacier area of 16% from 1962-2002, ranging from 2.7-20% among different basins.

Glacier lake expansion

One impact of increasing temperature over the last centuries in many mountainous environments is retreat of glaciers and formation of moraine-dammed glacial lakes (Evans and Clague, 1994). Bajracharya and Mool (2010) report that overall area of moraine-dammed lakes is increasing in the Nepalese Himalaya.

The eastern Himalaya (Nepal, Bhutan, Sikkim, and sub-basin of Ganges in China) has a large number of glacier lakes compared to the western Indian Himalaya (Bajracharya and Mool, 2010). Komori (2008) studied more than 50 moraine-dammed ice-contact or ice-proximal lakes in the Bhutan-China border region using satellite imagery and concluded 14 lakes were growing over the analysis period (late 1960s-2001). They report higher growth rates on the southern side (35-70m/year; $<0.04 \text{ km}^2 / \text{year}$) compared to the northern side (10-40m/year; $< 0.03 \text{ km}^2 / \text{year}$) of the Bhutan-China border region. Bajracharya and Mool (2010) found that from 1960-2000, 245 small ($<50 \times 50 \text{ m}^2$) lakes disappeared from Nepal's Dudh Koshi Basin, while 24 new lakes were formed. Additionally, 11 supraglacial lakes (lakes formed within the glacier mass) have converted into moraine-dammed lakes and another 34 glacial lakes have grown in size (Bajracharya and Mool, 2010). Gardelle et al. (2010) suggest a 25-45 ha/year rate of growth for glacial lakes in the Nepalese and Bhutanese Himalayas between 1990-2009, contrasting with a relatively stable growth average growth rate of 4 ha/year in the western Indian Himalayas. The study found higher growth rate of glacial lakes in the Everest region during 2000-2009 than 1990-2000 periods, contrasting with Bhutan and Western Nepal Himalayas. In the eastern Indian Himalaya, Kulkarni et al. (2011) report about five-fold increase in Lonak Lake from 23 to 110 ha between 1976 and 2007. In Mt. Qomolangma Nature Preserve in China, Yong et al. (2010) found 64.7% increase in glacial lakes (at a rate of $1.23 \text{ km}^2 \text{ a}^{-1}$) between 1976 and 2006, with a higher rate of change during the 1976-1988 period ($2.9 \text{ km}^2 \text{ a}^{-1}$) over the recent 1988-2006 period. ($0.95 \text{ km}^2 \text{ a}^{-1}$). While, local topography, geological, and glaciological processes determine the biophysical risk due to GLOFs (Watanabe et al., 2009; Reynolds and Taylor, 2004), climate warming can create favorable environment for lake expansion.

Table 2 Glacier Retreat Rates for Selected Glaciers

Glacier	Country/State	Observation Period	Average retreat or advance rate (m/yr)	Reference
Gangotri	Uttarakhand/Western Indian Himalaya	1935-1971 1971-2004 2004-2005 2006-2010	-26.50 -17.50 -12.10 stable	Bali et al.,2011 Bali et al.,2011 Kumar et al.,2008 Kargel et al., 2011
Pindari	Uttarakhand/Western Indian Himalaya	1845-1906 1906-1958 1958-1966 1966-2007	-26.23 -20.0 -7.62 -6.39	Bali et al., 2011
Tipra	Uttarakhand/Western Indian Himalaya	1962-2008	-14.41	Mehta et al., 2011
Dokriani	Uttarakhand/Western Indian Himalaya	1962-1995	-16.67	Dobhal et al.,2004
Kangriz	North West Indian Himalaya	1910-2007	stable	Raina, 2009
Siachin	North West Indian Himalaya	1862-1909 1909-1929 1929-1958 1958-1985 1985-2004 2004-2005	15.42 -2.5 -14 stable -3 stable	Ganjoo, 2010
Imja Glacier	Nepal/Eastern Himalaya	1976-2000 2000-2007	-34 -74	Bajracharya and Mool, 2010
Langdak	Nepal/Western Himalaya	1976-2000 2000-2007	-9 -44	Bajracharya and Mool, 2010
W. Chamiang	Nepal/Eastern Himalaya	1976-2000 2000-2007	-42 -21	Bajracharya and Mool, 2010
Rongbuk	TAR/Mt. Qomolangma Nature Preserve	1960-2000	-7.5	Yao et al., 2007
Middle Rongbuk	TAR/Mt. Qomolangma Nature Preserve	1976-2006 1966-1997 1997-2001	-14.64±5.87 -8.7* -9.1*	Nie et al., 2010 Ren et al., 2004
East Rongbuk	TAR/Mt. Qomolangma Nature Preserve	1976-2006 1966-1997 1997-2001	-9.10±5.87 -5.5* -5.56*	Nie et al., 2010 Ren et al., 2004
Far East Rongbuk	TAR/Mt. Qomolangma Natural Preserve	1976-2006 1966-1997	-13.95±5.87 -7.4*	Nie et al., 2010 Ren et al., 2004
Reqiang	TAR/Mt. Qomolangma Natural Preserve	1976-2006	-65.95±5.87	Nie et al., 2010
Naimona'nyi Glacier (Gurla Mandhata)	TAR/North west corner of Nepal (Western Nepal Himalaya)	1976–2006	-4.8	Yao et al., 2007

*summer measurements

Climate change and glacier dynamics

There is now general agreement among scientists that unlike thickness (mass balance), which immediately responds to climatic changes, flow rate and glacial length (glacier retreat) have longer response times (Kargel et al., 2011). Response times of most Himalayan glaciers are in the range of 10-200 years (Armstrong, 2010; Kargel et al., 2011) and the largest Himalayan glaciers are responding to changes that occurred as many as 100 years ago (Thompson et al., 2011). With a few exceptions, field measurements of Himalayan glacier retreat are short, and thus available data may not be adequate to capture decadal or multi-decadal climate variations, as suggested by Fujita and Nuimura (2011) and Kargel et al. (2011). Climatic factors, such as precipitation amount and type (e.g. summer versus winter accumulation), albedo (Koul and Ganjoo, 2010), and temperature (which effects glacier retreat by controlling the position of the equilibrium line – a theoretical line that divides the accumulation and ablation zones) (Venkatesh et al., 2011), and non-climatic factors (e.g. debris cover, slope, aspect, elevation) both modulate glacier retreat (Scherler et al., 2011). Scherler et al. (2011) point to the role of debris cover in reducing retreat rate: several debris-covered Himalayan glaciers show stable snouts despite rapidly losing mass (Bolch et al., 2011; Scherler et al., 2011).

Unlike glacier retreat or advance, glacier mass balance (i.e., change in thickness/volume) is the direct and immediate response to annual atmospheric conditions (Haeberli and Hoelzle, 1995; Kargel et al., 2011). The existing literature documents negative mass balance across the Himalayas.

Most recently, Fujita and Nuimura (2011) report comparative analysis of three small, relatively debris-free glaciers in Nepal, varying between 0.5 and 0.8 meter water equivalent per annum (m w.e.a^{-1}). They found considerable thinning (negative mass balance) in the two glaciers in the humid climate in recent decades. Higher mass loss rates in the humid region are attributed to the glaciers' lower altitude, which makes them more sensitive to small changes in temperature and surface albedo (Fujita and Nuimura, 2011).

High-resolution satellite data shows that glaciers in Everest Region have been losing mass since 1970 (Bolch et al., 2011). From 1970-2007, all ten glaciers in the region lost mass at an average rate of $-0.32 \pm 0.08 \text{ m w.e.a}^{-1}$. Interestingly, the thick debris-covered parts of these glaciers lost mass at a still higher rate of $-0.39 \pm 0.07 \text{ m w.e.a}^{-1}$ (Bolch et al., 2011). The greatest mass loss is observed at Imja/Lhotse Shar, although this is partly attributed to lake-induced ice

loss by calving. In most glaciers, mass loss is observed at mid-ablation zones with negligible loss at glacier termini. Likewise, based on the radioactive isotope analysis of ice cores from a high altitude (6050 masl) Naimona'nyi Glacier, located near northwest corner of Nepal in the Chinese Himalaya, Kehrwald et al. (2008) concluded no net mass accumulation since 1950.

In the Spiti/Lahaul region in Himachal, most glaciers show distinct thinning at low elevations, even on debris-covered tongues (Bertheir et al., 2007). Overall annual mass loss of -.7 to -0.85 m w.e.a⁻¹ is observed during 1999-2004 (Bertheir et al., 2007), ranging up to -1.0 m w.e.a⁻¹ in Chhota Shigri Glacier (2002-2006; Wagnon et al., 2007). Negative mass balance is also observed in Garhwal Himalaya (Uttarakhand Himalaya) (0.32 m w.e.a⁻¹; 1992-2000) (Dobhal et al., 2008). In contrast, some Karakorum glaciers have not shown a change in mass (Matsuo and Heiki, 2010), and some show positive mass balance (Hewitt, 2005). On a larger spatial scale, based on Gravity Recovery and Climate Experiment (GRACE) satellite observations, Matsuo and Heki (2010) found that average ice loss from Asia's high mountain region during 2003-2009 has been twice as fast as the average loss rate over the previous four decades.

Recently, black carbon has received greater attention as a factor triggering accelerating glacial mass loss in the Himalayas. Black carbon is produced by incomplete combustion of biomass, coal and diesel fuels (Kaspari et al., 2011). Ramanathan et al. (2007) suggest that warming trends in Asia are amplified by black carbon. Kaspari et al. (2011) show that black carbon concentrations have increased approximately threefold from 1975-2000 relative to 1860-1975 in the high elevation regions of the Himalaya. While atmospheric black carbon causes glacial melting through warming related to light absorption, black carbon deposited on snow and ice accelerates melt through reduced surface albedo (Kaspari et al., 2011). Xu et al. (2009) suggest that black carbon deposited on Chinese glaciers is an important factor contributing to observed rapid glacial retreat. Through numerical experiments, Lau et al. (2010) found that heating of the troposphere by elevated dust and black carbon aerosols in the boreal spring can lead to widespread enhanced land-atmosphere warming and accelerated snowmelt in the Himalayas. Based on atmospheric observations at the Nepal Climate Observatory-Pyramid (NCO-P) at 5079 masl, Yasunari et al. (2010) estimate black carbon concentration on snow surface and perform numerical experiments suggesting accelerated glacier mass loss on Yala glacier (Nepal) and related impact on water availability.

In summary, a larger percentage of glaciers was noted to be retreating with highly variable retreat rate. Some glaciers notably in upper Indus were reported to be advancing. Available a few studies suggest negative mass balance in high altitude glaciated region.

Following Kargel et al. (2009) glacial dynamics in the Hindu Kush-Himalaya region could be summarized by dividing the region into four zones. Zone-1 covers Afghanistan's Hindu Kush region (Kargel et al., 2009) where glaciers are relatively stable or show very slow retreat (Scherler et al., 2011). In contrast, Zone-2 glaciers (Northwestern Himalaya in India, Karakoram, and Pamir) show both retreat and advances: retreat is generally observed in the Pamir Mountains, while Karakoram glaciers have retreated, advanced, and surged (Hewitt, 2005). Zone-3 glaciers (covering Himalayas in western India, southwestern part of Xizang province of China and western Nepal) show variable rates of retreat over different periods of time (Table 2). Zone-4 glaciers (eastern Nepal, Bhutan, Sikkim and southeast part of Xizang province of China) are characterized by the formation of many large glacial lakes since 1960s (Watanabe et al., 2009) and rapid disintegration of many glaciers. Many Zone-4 glaciers are not retreating but are rapidly losing mass (Bolch et al., 2011).

As glacier retreat generally does not respond to year-to-year climate variation, it may not be an indicator of the climate warming and change. The negative mass balance, shrinking areal extent and expanding glacier lakes and increasing temperature observed widespread in most parts of the Himalayas, however, may be due to climate warming as suggested in the literature.

2.5 Mixed streamflow trends

Streamflow trends can result from both climate and land use changes, and thus requires precipitation and temperature data for climate change attribution. Either upward or downward streamflow trends can have big implications for water availability and flood risk. Bhutiyani et al. (2007) note a significant increase in the number of high-magnitude flood events in rivers of the northwestern Indian Himalayas in the last three decades, as well as increasing trends in annual maximum flood in three of four basins. Khattak et al. (2011) find an increasing trend in winter and spring streamflow at 100% and 50% of eight considered hydrometric stations in the upper Indus Basin, Pakistan, respectively. With no observed trend in winter precipitation but a positive trend in winter maximum temperature, Khattak et al. (2011) attribute observed streamflow trends

to the temperature increase. No spatial patterns in Nepalese streamflow trends during 1965-1995 are apparent (Gautam and Acharya, 2012): observed trends in central and eastern Nepal are almost evenly divided between upward and downward; however, observed trends in western Nepal (Karnali-Mahakali River Basin) are mostly downward. Seasonally, a higher percentage of observed upward trends in pre-monsoon and winter average flow is noteworthy given potential snowmelt contribution to many studied sites in low flow periods; no trends are observed in the post-monsoon season (Gautam and Acharya, 2012).

On the Tibetan Plateau, Yao et al. (2007) note an increase of 5.5% in river runoff attributable to glacial melting, and an even higher increase (13%) in the surrounding Tarim River Basin. Significant increasing trends in streamflow over annual and wet season periods (May-October) are seen in Niyang River Basin, southeast part of Xizang province of China (Zhang et al., 2011). Zhang et al. (2011) attribute these trends to accelerated glacier melting based on both insignificant trends in annual precipitation and significant decreasing trends in wet-season water temperature. Streamflow in Lhasa River increases with two change points (1970, early 1980s) followed by an upward trend in the last 20 years due to increasing precipitation in summer and increasing temperature in winter (Lin et al., 2008).

In summary, increased contribution to streamflow of glacial and snowmelt in response to warming temperatures are noted as causes for the upward trend in streamflow in low flow periods and in areas of low precipitation (e.g. Tibetan Plateau and Indus basin).

2.6 Limited observations of ecosystem changes

The Himalayan region is severely data-deficient in terms of observations of climate change impacts on ecosystem and biodiversity (IPCC, 2007). Globally, many endemic terrestrial, marine, and freshwater species are facing risk of extinction (Rosenzweig et al., 2007): the same should generally be valid for the Himalaya region as well.

Most local studies on trends and observed impacts of climate change on ecosystem and biodiversity are limited to perception studies. Tse-ring et al. (2010) document several observed impacts of climate change on biodiversity in the eastern Himalaya, but no literature is cited and many stated impacts appear to be subjects of further research. NBC (2011) describes perceptions of biodiversity change in Bhutan and relates them in the context of climate change. Related perceptions in Nepal (Tse-ring et al., 2010) largely point to changes in ecotone, reduced biodiversity, and new or proliferation of existing invasive species because of climate change.

Tree line shift is a potential indicator of climate-driven ecosystem changes in mountain regions (Guisan et al, 1995). Tree line position is strongly correlated to various climatic parameters and is highly sensitive to climate change, making it a useful indicator of climate change (Grace et al., 2002). Panigrahy et al. (2010) reports a shift of around 300 m in tree line elevation since 1960 using satellite data of the Nanda Devi Biosphere Reserve in Uttarakhand, although the data quality has been questioned (Bharati et al., 2011). Another study in the western Indian Himalayas records an upward shift of tree line species at 19 and 14 m/decade on south and north slopes, respectively (Dubey et al. 2003). INCCA (2010) discusses an uncited systematic study of climate change impact on 11 multipurpose tree species in Himachal (western Indian Himalayas) that notes substantial shifts in critical phenophases (e.g. leaf emergence, flower initiation and growth period etc.) over an eight-year period. In a related study using repeat photography of Baima Snow Mountain in China's Yunnan Province, the tree line moved up 67 m in elevation and 270 m upslope from its 1923 location (Baker and Moseley, 2007). These local observations in the Himalayas generally agree well with observations in other mountain regions, such as the Swiss Alps (Gehrig-Fasel et al., 2007).

In the Bhutanese Himalaya, high frequency of pine die-back (five counts from 1992-2008) is associated with periods of higher temperature and lower rainfall (NBC, 2011; Wangda et al., 2009). Similarly, although most forest fires in the region are human-caused (GFMC, 2011), increasing fire frequency and related losses are likely caused by higher fire vulnerability due to prolonged dry winter conditions (BAP, 2009). Other observations in Bhutan also point to increasing climate influence on forest fires, including a large forest fire in a region with no known prior fire experience in 1998-1999 (BAP, 2009), and a temporal correlation between higher incidences of forest fire and low rainfall (e.g. 2004-2005). Although no detailed information is available in the Nepalese or Indian Himalayas, the trend is expected to be similar to that observed in Bhutan.

Climate change can impact at species level by altering reproduction, migration pattern, and frequency and severity of pest, invasive species, and disease outbreaks (Campbell et al., 2009). Similarly, climate change can create favorable environments for colonization by invasive species in terrestrial and fresh water ecosystems (Campbell et al, 2009). Apparently, there are no published systematic studies or data on species-level impacts of climate change in the Himalayas.

2.7 Climate-sensitive agriculture in the Himalayan region

Climate change and variability can affect food and water security in the Himalayan region, largely due to lack of adequate storage systems (natural or manmade). Agriculture in the Himalayan region is mostly rain-fed (about 60 %; World Bank, 2007), and therefore vulnerable to changes in rainfall timing and frequency.

Besides water availability, crop yield depends on a number of biophysical processes and variables (e.g. thermal stress, humidity, solar radiation, nitrogen stress, ozone, and fertilization effect of CO₂) and their complex, nonlinear interactions (Challinor et al., 2009). The relationships between crop yield and these variables are complicated by several factors such as uncertainties in interrelationship among variables (Sheehy et al., 2006), lack of data from realistic controlled field studies (IRRI, 2011), and study scale (Challinor et al., 2009), among others. For example, increased temperature, reduced solar radiation, and water stress can outstrip the fertilizing effect of CO₂ on crop yield in some regions (Cruz et al., 2007). There are concerns that rising CO₂ and temperature, as well as other climatic parameters such as humidity, might offset the potential increases in crop yield by increasing pest infestations (Gornall et al., 2010).

Scientific observations and studies on climate change impacts on agriculture in the Himalayan region are extremely limited and mainly focus on climate sensitivities. One recent study reports a decline in apple yields in some parts of Himachal Pradesh because chilling requirements essential for proper flowering and fruiting are not met (Raina et al., 2009). In Nepal, winter crop yield in 1997-1998 was significantly reduced (11-38% of the previous 10-year average) due to severe sky overcast and associated drop in solar radiation (MoPE, 2004). In Nepal, good rice yield is correlated with timely and adequate monsoon rainfall: in 2006, poor monsoon rainfall led to a 30% drop in rice production in eastern Terai, while heavy rainfall and flooding in western Nepal reduced production by the same amount (Regmi and Paudyal, 2009). Another study in Nepal showed maize yield was reduced 13 out of 32 years during 1974-2005 when pre-monsoon rainfall was much lower than normal (Nayava and Gurung, 2010).

2.8 Climate sensitive epidemics and other natural disasters

2.8.1 Human health

Limited reviews exist on the impact of climate change on human health in the greater Himalayan region [e.g. Ebi et al. (2007) for Hindu-Kush Himalayas, Majra and Gur (2009), Dhiman et al. (2010), and Bush et al. (2011) for India]. Ebi et al. (2007) identify climate-related health risk, synthesize country reports, and discuss climate-related health issues in the Hindu Kush-Himalayan regions. Majra and Gur (2009) discuss the nexus between climate change and human health and why India should be concerned. Bush et al. (2011) discuss potential health impacts of climate change in India (heat stress and air pollution, waterborne disease, and vector-borne diseases with focus on malaria) and recommend further research in climate change and health sectors. Dhiman et al. (2010) present several literature examples suggesting re-emergence of vector-borne diseases in the Indian Himalayas, as well as discuss the threat of vector-borne diseases in India vis-à-vis climate change and emphasize the need for preparedness.

Bouma et al. (1996) found increasing incidence of falciparum malaria in northwest Pakistan in the 1990s, which they attributed to regional increases in temperature, humidity and precipitation. Recent studies show that water- and vector-borne diseases closely follow seasonal rainfall patterns in Nepal (Khatiwada and Rimal, 2007; Pemola and Jauhari, 2006; Regmi et al., 2008). Nepal's initial communication to United Nation's First Communication for Climate Change (UNFCCC) notes longitudinal trends of malaria, kala-azar and Japanese encephalitis (MoPE, 2004). MOPE (2004) reports an upward trend in kala-azar incidence in Nepal, as well as emergence in new areas. Annual total malaria cases increased from 1963-1985, but then declined due to mitigation measures (MoPE, 2004). An upward trend was also seen in annual total Japanese encephalitis cases, which was likely caused by rising temperature Nepal (MoPE, 2004). Bhutan showed similar patterns in total malaria cases (Tschering and Sithey, 2008): an upward trend increasing from 518 cases in 1965 to 39,852 cases in 1994 followed by a downward trend as mitigation measures were applied. Statistical analysis with limited data (ten years) of malaria cases, rainfall, and temperature shows a positive association between malaria cases and change in temperature in Bhutan (Tschering and Sithey, 2008). Eriksson et al. (2008) report incidences of malaria in high altitude villages of Nepal and China's Yunnan province. Dengue is another

tropical disease relevant to the Himalayas. Dengue was first reported in 2004 in both Bhutan (Tschering and Sithey, 2008) and Nepal (Pandey et al., 2004).

2.8.2 Natural Disasters

The Himalayas is subject to extreme temperature, weather events, and variable precipitation patterns. Extreme weather and climate events are an important cause of mortality and morbidity in the region. Flood accounted for 35% of natural disasters during 1975-2005 in South Asia (Shrestha, 2008). In Nepal, data from 1980-2010 shows that floods, landslides, and epidemics (in order) are the main causes for disaster-related human loss. Four types of floods are possible in the Himalayas: riverine floods, flash floods, glacial lake outburst floods (GLOF), and breached landslide-dam floods. Flash floods are common in the foothills, mountain borderlands, and steep coastal catchments. Similarly, the International Disaster Database (EM-DAT) showed that storms and floods were the first two major causes of disaster-related human loss in Bhutan over the last thirty years (1980-2010).

One impact of warming climate in many mountainous environments is glacial retreat and formation of moraine-dammed glacier lakes (Evans and Clague, 1994). Moraine-dammed glacier lakes are the most hazardous type of glacier lakes (Yamada and Sharma, 1993) as moraines can burst for several reasons such as sudden increased water volume; surge waves generated by glacier calving, snow, ice or rock avalanches into the lake; earthquake; piping; and overtopping of dams (Kattlemann, 2003). Moraine-bursting events usually occur in the summer monsoon when temperature is high and inputs to the glacier lake can have multiple sources.

Of the many recorded GLOF events in the region (Bajracharya et al., 2007), several have caused severe socio-economic damages. In 1981, the Zhangzhangbo GLOF in China destroyed a large section of the China-Nepal road, a power station, and a bridge, with losses totalling more than USD 3 million (Bajracharya et al., 2007). The Dig Tso outburst in 1985 destroyed several infrastructures, land, shops, and the nearly completed Namche Hydropower plant worth USD 3 million (Vuichard and Zimmermann, 1987). In 1994, the Luggye Tso GLOF in Bhutan caused loss of property (Richardson and Reynolds, 2000) and more than 20 lives (Bajracharya et al., 2007). A huge landslide in 2000, resulting from snow and ice damming the Yigong River (tributary to the Yarlung Zangbo River) caused 30 deaths and more than USD 22 Million of property damage in Arunachal Pradesh (ICIMOD, 2010).

Recently, Bolch et al. (2008b) and ICIMOD (2011) identified potentially dangerous glacial lakes in Nepal. Bolch et al. (2008 b) categorized hazard as low, medium, and high. Lakes in Imja Glacier and Chukung Glacier are rated as medium hazard; lakes southwest of Baruntse and Hunku Glacier are rated as low to medium hazard lakes (Bolch et al., 2008 b). Watanabe et al. (2009) detailed Imja Tsho's evolution from 1956-2007 and gave details on the Imja GLOF risk. Similar monitoring and risk assessment studies have been carried out in the Bhutanese Himalayas (Ageta and Iwata, 1999; Ageta et al., 2000; Fujita et al., 2008, Komori, 2008; Komori et al., 2004; Leber et al., 1999). Based on field investigations and inventory in the middle section of the Chinese Himalaya, Xu and Feng (1994) reported 139 moraine-dammed glacier lakes, of which 34 were identified as dangerous. They identified ice avalanches from advanced glacier tongues and ablation of dead ice beneath moraine ridges as potential GLOF triggers.

3. Future Climate Projections

3.1 Temperature

Global Climate Model (GCM) projections point to a warmer Himalayan region in the future with warming likely to be above the global average. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) presents temperature and precipitation projections for South Asia, derived from a dataset of 21 GCMs, suggest a median increase of 3.3 °C by 2100 for the A1B SERS scenario (a “middle of the road” estimate of future conditions; Nakićenović et al., 2000), with increases in both daily minimum and maximum temperatures (Christensen et al., 2007). As Christensen et al. (2007) point the largest warming is expected on the Tibetan Plateau and the higher-altitude Himalayan regions: 3.8 °C during the next 100 years. For South Asia, the median warming varies seasonally from 2.7 °C in June-August (monsoon) to 3.6 °C in December-February (winter). For the same scenario, the seasonal variation in the simulated warming in Xizang province of China ranges from 3.6 °C in March-May to 4.1 °C in December-February.

Despite general consensus on importance of GCM projections, due to their large spatial scale (e.g. hundreds of kilometers) they are not able to capture local or regional information, such as orographic features and summer monsoon considered extremely important in the

Himalayas (Lucas-Picher et al., 2011; Rupa Kumar et al., 2006). Regional Climate Models (RCMs) refine the spatial scale (e.g. 50 km) and are thus better suited for more realistic projections in daily climatic extremes (Christensen et al., 2007). With the climate large-scale information from GCM, RCM can be applied over a limited regional area for high resolution climate model output (Rummukainen, 2010). Despite their usefulness, the RCMs also have their own set of limitations (Rummukainen, 2010). One important limitation is the high computational cost. For this reason, the region lacks dedicated program like North American Regional Climate Change Assessment Program for climate modeling in North America (Mearns et al., 2009) using multiple GCMs and RCMs. The reliance on few climate models grossly underestimates modeling uncertainties thus limiting their use in climate change adaptation planning.

The most widely used RCM in the region is *Providing Regional Climates for Impacts Studies* (PRECIS), which is based on the Hadley Centre's regional climate modeling system with the HadCM3/HadAM3 as a driving GCM. The PRECIS simulation for 2071-2100 (Rupa Kumar et al., 2006) with increased greenhouse gas concentrations and sulfate aerosols generally appears to agree with IPCC AR4 results. The simulation shows an all-around warming over the Himalaya including Tibetan Plateau and the Indian subcontinent. The warming seems to be more pronounced over high altitude areas in the northern parts of India, Nepal and Bhutan. The annual rise in mean surface air temperature for the region ranges from 3-5 °C in A2 scenario, and 2.5-4 °C in the B2 scenario. Further analysis of climate change projection maps in Rupa Kumar et al. (2006) reveals that temperatures increase more during pre-monsoon and winter months compared to monsoon and post-monsoon months over the Himalayan region, which is in agreement with IPCC AR4 GCM ensembles. Extremes in maximum and minimum temperatures were also projected to increase in the future.

In a recent study, Shi et al. (2011) report results of applying a high-resolution regional climate model (RegCM3) using the SRES A1B scenario over the Yarlung Zangbo-Bramhaputra River Basin for 1948-2000 and 2001-2100. They estimate temperature increases of 2.8 °C annually, 3.3 °C in winter, and 2.3 °C in summer for 2041-2060 over 1981-2000 temperatures.

3.2 Precipitation

Unlike temperature, precipitation projections by GCMs are less consistent, reflecting the greater uncertainty associated with precipitation. Precipitation projections for South Asia show a

5% decrease in median precipitation in the winter months (December-February), a 9-15% increase March-November, and an 11% increase on an annual basis over the end of the century (Christensen et al., 2007). Over the Tibetan Plateau, a 10% median precipitation increase is simulated on annual basis, 19% in winter, and 4-10% increase in other seasons (Christensen et al., 2007).

Precipitation projection maps from the PRECIS regional simulation study (Rupa Kumar et al., 2006) reveal that western Nepal, Uttarakhand, Himachal, and Bhutan will receive higher monsoon precipitation in 2071-2100 compared to base precipitation. In contrast, the scenarios indicate 0-5% reduction in monsoon precipitation in northern Nepal and 0-15% reduction in some parts of the Chinese Himalayas north of Nepal. Moderate increases are simulated in the rest of the Himalayas. Seasonal precipitation scenarios show variations in winter precipitation with reduced precipitation in lowland and hill areas of the Nepalese and Indian Himalayas, increased precipitation in the region's high mountainous belt, and generally very large increase over the Tibetan Plateau. Pre-monsoon precipitation is projected to increase significantly in lowland regions, and moderately in most of the region. Post-monsoon precipitation is also projected to increase with Bhutan, Sikkim, central and eastern Nepal, and adjoining areas in China seeing the largest increase. Similarly, results from Shi et al. (2011)'s RegCM3 model results using the SRES A1B scenario over the Yarlung Zangbo-Bramhaputra River Basin for 1948-2000 and 2001-2100 suggest a nominal increase of 0.8% and 1% but a substantial decrease of -27.6%, respectively on regional mean change in annual, summer, and winter precipitation.

Another study in Nepal (APN, 2005) uses an ensemble of 13-GCM projections and also shows the country is expected to be wetter annually ($6.22 \pm 6.56\%$) and in monsoon ($14.98 \pm 9.74\%$), but drier in winter ($-17.58 \pm 2.53\%$) by 2080. Other projections available for the region (Agrawala et al., 2003 for Nepal; Gao et al., 2008, 2011 for Tibetan Plateau; MoPE, 2004 for Nepal; Krishna Kumar et al., 2004, Rajendran and Kitoh, 2008, and Moors et al., 2011 for India; Tse-ring et al., 2010 for Bhutan, among others) generally agree with increased annual or seasonal temperature and annual precipitation, but vary for seasonal precipitation projections.

Very recently, Revadekar et al. (2011) produced future projections of precipitation extremes over the region using PRECIS and standardized indices. Their analysis also showed an increase in annual precipitation towards the end of the 21st century consistent with other studies (Revadekar et al., 2011). In general, extreme precipitation was projected to increase substantially

over a large area in the Himalayan region (with the exception of Jammu & Kashmir) with heavy maximum daily rainfall in monsoon season. Projections for the post-monsoon season are similarly intense in central and eastern Nepal, Bhutan, and Sikkim Himalaya, and similar but less intense in the rest of the region. Maximum daily precipitation is projected to remain largely unchanged or decline in Bhutan, Sikkim, and Nepal, but to increase moderately in Himachal, Jammu & Kashmir, and Arunachal. Barring Uttarakhand, daily precipitation extremes in the pre-monsoon season is projected to increase over the whole region with the largest increase in Arunachal. The simulation indicated increase in frequency of heavy precipitation (days with ≥ 10 mm rain) events towards the end of the 21st century mostly in monsoon season over the whole region (Revadekar et al., 2011).

A recent regional climate model (COSMO-CLM) application by Dobler and Ahrens (2011) projects increased rain day intensity with increasing green house gases emissions and perceptible water in the atmosphere, but reduced rain day frequency during summer monsoons in the Himalayas from the period 1971-2000 to 2071-2100. The results in Dobler and Ahrens (2011) show substantial increases in monsoon precipitation in upper Indus basin region but decreases in the central and western Tibetan Plateau.

Despite some differences in the projections, in general, the literature point towards : a) enhanced warming especially in the high Himalayas and Tibetan Plateau; b) increased temperature in winter compared to other seasons; c) general agreement between climate projections and historical temperature trends (seasonality, higher temperature change at high altitude); d) increased monsoon precipitation and reduced winter precipitation at many areas, although at spatially varying rates; e) spatially varying changes in seasonal precipitation (in terms of magnitude and direction); f) increased frequency and magnitude of daily precipitation and temperature extremes.

4. Projected Climate Change Impacts

4.1 Impact on glacier melting and streamflow

Much of the literature on hydrologic simulation aims to find the sensitivity of streamflow and glacier to climate warming by using step increases in temperature. Hydrologic simulation studies in glaciated basins in Nepal point towards increased flow (Fukushima et al., 1991, Braun et al., 1993; Shilpakar et al., 2009) with a consequent potential threat of GLOFs under a

temperature rise up to 3 °C. A study done on a high-altitude sub-basin of Satluj River Basin (tributary to Indus River Basin) revealed an increase in runoff up to 18% from snowmelt and 38% from glacier melt for 2 °C warming (Singh and Kumar, 1997). Singh and Bengtson (2004) report a three year simulation with 1-3 °C rise in temperature in the Satluj River Basin and show reduction in melt in snowfed basin but increase in galcierfed basin. On the contrary, in another tributary in the same basin, however, Rathore et al. (2009) report about 40% reduction in glacier extent, 5-19% reduction in snow extent, and 8-28% reduction in seasonal streamflow with 1 °C rise in temperature for 2004-2040. Temperature rise is expected to increase streamflow in the short term in some Chinese rivers due to increased glacier melt (Yao et al., 2007). Climate sensitivity analysis in a glacier-dominated region in the Niyang River Basin in the Tibetan Plateau indicates high sensitivity of streamflow to climate change, particularly temperature change (Zhang et al., 2011). Simulations with unchanged precipitation showed annual streamflow increase by an average of 65 mm per 0.5 °C temperature increment (Zhang et al., 2011).

Rees and Collins (2006) carried out a comparative study evaluating climate change impacts on two hypothetical conceptual catchments representing glaciological features similar to Batura Glacier in Karakoram and Langtang Glacier in the Nepalese Himalaya using a 0.06 °C year⁻¹ climate warming (for 150 years starting 1990) and time-varient glacial extent. Results for subcatchments with more than 50% glacial area showed an increase in streamflow, which peaked at 2050 and 2070 with 150% and 170% of intial flow and stabilized to lower values with the disappearance of glaciers in 2086 and 2109 respectively in the west (Batura) and east (Langtang) glaciers (Rees and Collins, 2006). In another basin scale study, the flow in upstream areas (≥ 2000 masl) was projected to decrease by 8.4% in Indus, 17.6% in Ganges, and 19.6% in Brahmaputra basins in 2046-2065 compared to 2001-2007, showing the relative importance of glacier melt contributions (Immerzeel et al., 2009). Immerzeel et al. (2009) used climate warming scenarios with the SRES A1B emission and a mass-balance based glacier evolution scenarios. Projected future precipitation increases in the region are expected to compensate for streamflow reduction due to declining glacial contributions (Immerzeel et al., 2009).

In a recent study of climate change impacts on the hydrology of the Langtang River catchment (360 km²), Immerzeel et al. (2011) applied five GCMs to a high-resolution combined cyrospheric-hydrologic model under SRES A1B and found that both downscaled precipitation

and temperature were projected to increase (average temperature by $0.06\text{ }^{\circ}\text{C y}^{-1}$; precipitation by 1.9 mm y^{-1}). Under multimodel average climatic conditions, Immerzeel et al. (2011) project glaciers to shrink and retreat (32% by 2035 and 75% by 2088) resulting in reduced glacier melt contribution to streamflow; however, the loss in glacier melt contribution is compensated by increased baseflow and runoff leading to an increase in total runoff of 4 mm y^{-1} . Immerzeel et al. (2011) suggest this high-altitude mid-sized catchment is representative of the southern slopes of the central and eastern Himalayas with dynamic, moderate-sized glaciers often characterized by debris covered tongues. These studies show that changes in streamflow will largely be determined by future precipitation patterns.

Literature on the exact contribution of glaciers to streamflow is uncertain, resulting in several conflicting statements. This is partly due to lumping glacier-melt and snowmelt together as meltwater. Meltwater is thought to account for about 10% of annual streamflow in Nepal (Sharma, 1977) with rivers of western Nepal receiving more meltwater than those in eastern Nepal (Kattelmann, 1993). Motoyama et al. (1987) found that glaciers act as water reservoirs and are the source of total winter flow (4% of annual discharge) in glacial basins of Langtang Valley. Recently, Alford and Armstrong (2010) empirically estimated the contribution of glacier meltwater as 2-30% (4-32 % as inferred from Figure 8 of Alford and Armstrong, 2010) in eight rivers in Nepal. Studies from the Indian Himalaya mostly give an account of lumped meltwater (combined snow and glacier melt) contribution to streamflow (Hasnain, 2002; Kumar et al., 2007; Singh et al., 1997; Singh and Jain, 2002; Singh et al.; 2008). Other recent studies (Immerzeel et al., 2010; Kaser et al., 2010) have also lumped snow and glacier melt together. Thus, the exact role of glacier melt to total streamflow should not be confused with that of the total meltwater. Similarly, a distinction must be made between annual and seasonal contributions to understand the role of glaciers more clearly.

Alford and Armstrong (2010) suggest a 4% contribution of glacier meltwater to the annual volume of water flowing to Ganges from Nepalese river systems. Considering the annual volume of water stored in Himalayan glaciers (3375 Km^3), and the combined annual discharge of the Indus, Ganges and Brahmaputra rivers (1263 Km^3), and assuming annual thinning of Himalayan glaciers (0.5 ma^{-1}), Kargel et al. (2011) showed that negative mass balance contributes 15 km^3 (about 1.2% of the total annual flow) of water annually. Immerzeel et al. (2010) found that total meltwater (from glaciers and snow) accounts for 151%, 10% and 27% of

total discharge in the downstream areas in the Indus, Ganges and Brahmaputra, respectively. In a similar study, Kaser et al. (2010) estimate the contribution potential of glacier meltwater to discharge of major river systems in the world. In the Himalayan region, the Indus River has the largest (55%), the Brahmaputra the lowest (17%), and the Ganges a moderate (33%) annual contribution of glacier melt to runoff.

In a study in the eastern Indian Himalayas (Brahmaputra River Basin), Immerzeel (2008) simulate a sharp increase in the occurrence of average and extreme downstream discharges, especially in the monsoon season, using an empirical rainfall-runoff model fed with projected seasonal increase in temperature and precipitation (Immerzeel, 2008). Recent preliminary modeling results by Gosain et al. (2011) agree with Immerzeel (2008) findings. Gosain et al. (2011) simulate increased surface runoff (28-48%) under both B2 and A2 scenarios in 2080 along with projected increases in precipitation (14-23%), snowmelt (29-32%), groundwater recharge (19-31%), potential evapotranspiration (11-20%), water yield (23-39%), and sediment yield (39-95%), but reduced snowfall (7-12%). Similarly, with PRECIS-generated scenarios under B2 and A2 scenarios, the upper BRB saw increased precipitation (9-17%), snowmelt (30-33%), groundwater recharge (36-57%), surface runoff (19-32%), water yield (26-42%), but reduced snowfall (7-12%) over the base period (Gosain et al., 2011). In comparison, Koshi basin was found to be more sensitive to climate change under similar climate change scenarios (Gosain et al., 2010). Gosain et al. (2010) project increased precipitation (2-10%), snowmelt (74-76%), groundwater recharge (48-79%), surface runoff (48-69%), potential evapotranspiration (21-36%), water yield (49-70%), and sediment yield (91-123%), but reduced snowfall (19-23%) over the base period under the considered scenarios.

From these three studies, the climate change concern in the Brahmaputra River Basin and Koshi Basin appear to have excess water with implications for flooding and inundation of heavily populated floodplain areas in the areas. Increased sediment load due to higher number of flood events has consequences for water quality, human health, agriculture, and functioning and operational life of water structures. Increased sediment yield will be a major challenge in an already high sediment-laden river. High potential evapotranspiration compared to rainfall (4 to 10 times higher) implies a drier basin state. Higher snowmelt rate and reduced snowfall suggest reduced accumulation of snow in glaciers. The impacts to these basins will be far-reaching,

potentially affecting agriculture, biodiversity, hydropower production, water quality, and siltation.

All these studies point in similar direction, suggesting relatively low annual meltwater contribution to the Ganges and Brahmaputra. Clearly, there is a need for better understanding of seasonal and monthly dynamics of snow and glacier melt at various spatial scales from the practical standpoint of water resources management under climate change and glacier melting. Both small-basin and regional-scale analysis are important as regional-scale hydrology cannot serve the planning needs of water resources managers at smaller basin scale. Currently, approaches for assessing meltwater contribution involve a range of uncertainties that need to be better quantified. There is a need for supplemental analysis with alternative approaches for quantifying uncertainties or the range of meltwater contribution.

4.2 Impacts on agricultural production

Regional crop modeling studies have shown that under future climate change scenarios substantial losses are likely in rain-fed wheat in South and South-East Asia (Fischer et al., 2002). For example, a 0.5 °C rise in winter temperature would reduce wheat yield by 0.45 tonnes per hectare in India (Lal et al., 1998; Kalra et al., 2003). Similarly, another study suggested a 2 to 5% decrease in yield potential of wheat and maize for a temperature rise of 0.5 to 1.5 °C in India (Aggarwal, 2003). Modeling by the Indian Agricultural Research Institute suggests a reduction of 4-5 million tonnes of wheat production due to 1 °C rise in temperature throughout the growing period even after considering carbon fertilization effect (Aggarwal, 2008). Taking CO₂ fertilization effect in to account in the M-GAEZ crop model (Fischer et al., 2002), Masutomi et al. (2009) project a net reduction in average rice production in India under all emission scenarios during 2020s (3.4-4.2%), and under A1B and A2 scenarios during 2050s (0.1-0.5%) and 2080s (3-4.9%) compared to 1990s; these rates are much smaller than those projected for Nepal. Masutomi et al. (2009) project reductions in rice productivity in Nepal for 2020s (6.1- 7.7%), 2050s (10.4-20.7%), and 2080s (18.7-34.6%) from the baseline 1990s. In Bhutan, however, Masutomi et al. (2009) project an increase in rice productivity for the 2020s and 2050s (up to 15.8% increase), but a decline for the 2080s (-12.9%) depending on the emission scenarios (A1B, A2, and B1).

There is a conspicuous lack of studies in other regions in the Himalaya. A Department for International Development (DFID) systematic review (Knox et al., 2011) on projected impacts of climate change on food productivity on Africa and South Asia reports a single article for both Bhutan and Nepal. While the report indicates India is widely studied (15 sources), most of them exclude the Indian Himalayas (Knox et al., 2011). Similarly, although literature on future impact of climate change on agriculture in China is increasing, the Xizang province is either aggregated with other regions (You et al., 2009) or skipped (Tao et al., 2008).

4.3 Impacts on human health

Published information on possible health consequences of climate change in mountain regions is extremely limited. Most available literature on future projection is speculative. Many sources (e.g. Ebi et al., 2007; ICIMOD, 2010) suggest the likelihood of spreading vector-borne pathogens as new habitats become available at altitudes that were formerly unsuitable, increasing prevalence of diarrheal diseases with changes in freshwater quality and availability, and increased weather related impacts and food security concerns.

McMichael et al. (2004) find through a regional human health impact assessment using Hadley Center GCM projections that climate change induced risk on health outcomes will more than double by the year 2030 in some regions. The study found that in Bhutan, Nepal and India (region SEAR-D), the risks to human health due to flooding and malnutrition would be highest, followed by a modest increase in diarrhea and malaria (McMichael et al., 2004). For China (region WPR-B), flood and malaria related risks were projected to increase, and diarrhea and malnutrition risks are projected to increase and decrease, respectively, but nominally (McMichael et al., 2004). However, future projections of health impacts due to climate change are uncertain (Kolstad and Johansson, 2011; McMichael, 2006; Patz et al., 2005).

Few studies have modeled vector-borne disease expansion under climate change in the Himalayas, and those available are mostly limited to malaria (Sarkar, 2011). Bhattacharya et al. (2006) project country-wide malaria expansion in India under HadRM2 projections of daily temperature and relative humidity run under the IS92a emission scenario. They considered three different classes of temperature transmission windows (between 15-35°C) for two malaria parasite species and a transmission window of relative humidity (55-90%), and found that Himalayan states will become malaria prone in the 2050s.

In a recent study, Dihman et al. (2011) applied PRECIS under the A1B emission scenario for projecting malaria expansion into 2030s with a focus on the Indian Himalayas. With the transmission windows for temperature as 18-32 °C and a relative humidity >55%, Dihman et al. (2011) not only find an increase in the number of open months (months favorable for malaria vector survival and transmission) in 2030s as compared to baseline (1961-1990), but also opening of transmission windows in some Himalayan states where they are non-existent earlier. This finding that Indian Himalaya is projected to be more vulnerable in the future (Dhiman et al., 2011) has implications for both Nepal and Bhutan. In Nepal, MoPE (2004) suggests temperatures 22-32 °C are very favorable for malaria vectors to develop and complete their cycle. Similarly, Japanese encephalitis thrives at the average annual temperature range of 23-26 °C, while kalazar occurs mainly in summer season due to optimum breeding environment (MoPE, 2004); thus, climate warming may have implications for these diseases' vectors to shift upland as increasing temperature makes higher altitudes more favorable. However, there are no reported modeling efforts or other studies for such impact assessments.

4.4 Impacts on biodiversity

Research on climate change impacts on ecosystem, forests and wildlife in the Himalayas are notably lacking (Xu et al., 2009, Scheidegger et al, 2011). Most recently, Charturvedi et al. (2011) used a dynamic global vegetation modeling approach (Kucharik et al., 2000) to assess the impact of projected climate change on forest ecosystems in India under SRES A2 and B2 scenarios. Most mountainous forest (including sub-alpine, alpine, dry temperate, and moist temperate forests) were susceptible to climate change impacts, which Charturvedi et al. (2011) attribute to higher rates of climate change at higher elevations. Additionally, forests in northwestern Indian states are highly vulnerable to projected climate change (Charturvedi et al., 2011). Recently, an ICIMOD study (Tse-ring et al., 2010) did an integrated analysis of current vulnerability of biodiversity and ecosystem services considering exposure, sensitivity, and adaptive capacity in the eastern Himalayas (east of Kaligandaki Nepal to northwest Yunnan in China). Tse-ring et al. (2010) identified the Terai belt in southeast Nepal as highly vulnerable, together with other vulnerable regions such as the Brahmaputra Valley, the lower Gangetic plain of northeast India and a few highly localized sites. The most vulnerable ecosystem identified included the Brahmaputra Valley's semi-evergreen forests (Tse-ring et al., 2010). MoPE (2004), based on the Holdridge model under 2xCO₂, projected that Nepal's current 15 forest types

(under existing 1xCO₂ condition) will reduce to 12 forest types. The report indicates changes in vegetation pattern in 38 out of 80 meteorological stations considered in the study (MoPE, 2004). Using Atmosphere Vegetation Integrated Model (AVIM20) under SRES B2 scenario, Wu et al. (2007) analyzed ecosystem vulnerability with a set of indices based on net primary production of vegetation. The vulnerability of the Tibetan Plateau ecosystem at baseline period (1961-1990) increases in all considered periods between 1991 and 2080. Climate change impact assessments in Bhutan are mostly limited to a few local observations and perceptions and speculate potential future impacts based on studies elsewhere (NBC, 2011).

4.5 Impacts on hydropower

Climate change could impact hydropower for the Himalayan regions in multiple ways. First, a projected increase in monsoon rainfall and rainfall extremes in the region (APN, 2005; Rupa Kumar et al., 2006) is expected to increase sediment load in streamflow with potentially severe impacts on the operating life of hydropower plants (e.g. reduced live storage and turbine life). Sediment loads in Himalayan rivers are already very high. Second, many small or micro hydropower systems could be damaged or washed away due to floods (riverine or GLOFs). Both temperature and monsoon precipitation projections have negative implications for GLOF risks. Increased temperature would contribute to expansion of both supra- and pro-glacial lakes, leading to favorable conditions for large scale damage (Richardson and Reynolds, 2000). Increased monsoon rainfall would increase glacier melt contribution and GLOF risk (Rathore et al., 2009).

Climate change impacts on hydropower will largely depend on future precipitation. Studies with medium- and large-sized catchments with unchanged or increasing future precipitation showed reduction and increase in river discharge. If the projected drier winter period flow (APN, 2005) were considered as a future scenario, it would imply a reduction in river discharge. Small-scale hydropower generators and countries with run-of-river hydropower systems would be more vulnerable to reduced dry season flow under climate change. Both Nepal's and Bhutan's hydropower systems are mainly run-of-river and thus vulnerable to reduction of streamflow.

While both temperature and precipitation changes would impact hydropower generation, one study (Rathore et al, 2009) has shown that even without a reduction in precipitation, a 1°C rise in temperature alone may reduce the contribution of glacier melt to streamflow in a tributary

of Sutluz river by 40% and thus reduce streamflow and hydropower potential by 8-28% by 2040. Streamflow reduction was highest during the monsoon (28%), moderate during winter and post-monsoon seasons (about 20%) and least during pre-monsoon season (Rathore et al, 2009). Considering the future projection of reduced winter precipitation, impacts on winter streamflow might be much higher in later part of the century, particularly for small catchments.

5. Economic Impacts of Climate Change

An economic impact assessment covers both benefits from and damage of climate change to production sectors (e.g. agriculture, forest, electricity generation, and fisheries), service sectors (e.g., tourism, hotel and restaurants and health), and households (e.g., household income). This type of assessment could also include impacts on non-market sectors (e.g. biodiversity and ecosystem services) and social effects (e.g. poverty, large-scale dynamics related to human values and equity) (Watkiss et al., 2005). Although a large number of studies have been carried out on economic assessment of climate change impacts in the various regions of the world, no such study is available for the Himalayan region.

One notable aspect of the Himalayan region considered in this study is the important role of agriculture, hydropower, and tourism (Table 3) in the economy at present and in the future. In one study, Agrawala et al. (2003) made preliminary assessments of climate change impacts on several sectors in Nepal based on biophysical risks by considering four criteria (certainty of impacts, timing, severity of impact, and importance) and ranked the sectors accordingly (Table 3). Agrawala et al. (2003) reported water resources and hydropower as the most important sectors under future climate change scenarios. Given the similar socio-economic contexts in the region (Table 2), their analysis for Nepal should also be applicable to other Himalayan regions.

Table 3a: Status of Hydropower and Economy in the Himalayan Region

Country/State/Region	Potential	Installed maximum	Key present and potential future economic sectors ⁵
Nepal¹	43,000	633	Agriculture, tourism, remittance, hydropower
Bhutan²	23,760	1,488	Agriculture, forestry, hydropower and related services and industries, tourism
India³	148,701	32,782	
Arunachal Pradesh³	50,328	405	Agriculture, Tourism, mining, forest, hydropower
Sikkim³	4,286	570	Agriculture, mining, forest, hydropower, construction tourism
Uttrakhand³	18,175	3,226	Tourism, horticulture and floriculture, bio technology, and hydropower
Himachal³	18,820	6,193	Agriculture, Horticulture, Tourism, hydropower
Jammu & Kashmir³	14,146	2,340	Agriculture, horticulture, Tourism, hydropower
Xizang Province⁴	110,000	150	Agriculture, Tourism, Construction and hydropower

1 USAID, 2009; 2 World Bank, 2010 (2010 Bhutan Economic Update); 3 CEA, 2011; 4 Climate Connect, 2010; 5 Compiled from various sources

Table: 3b Attributes of Climate Change Impacts on Resources (Agrawala et al., 2003)

Resources/Sector	Rank	Certainty of impact	Timing of impact	Severity of impact	Importance of resource
Water resources and hydropower	1	High	High	High	High
Agriculture	2	Medium-low	Medium-low	Medium	High
Human health	3	Low	Medium	Uncertain	High
Ecosystems /Biodiversity	4	Low	Uncertain	Uncertain	Medium-high

In the Himalayan region, almost all of the existing economic assessments are limited to agriculture in India (Dinar, 1998; Kumar and Parikh, 2001) and China (Wang et al., 2009). A notable exception is the work of Cline (2007) which includes a fairly detailed global analysis with results for several countries and regions in the Himalayas, which will be discussed later.

5.1 Economic impact on agriculture

A recent economic analysis by Thapa and Joshi (2011) uses a Ricardian approach (Mendelsohn et al., 1994) to evaluate climate sensitivity of Nepalese agriculture shows varied responses of net farm income to climatic variables during 1977-2006. Thapa and Joshi (2011) note six key findings on climate sensitivity of farm income: a) marginally increasing annual precipitation could cause farm income to increase significantly in the hilly (temperate zone) region, but decrease significantly in lowland areas and insignificantly in the mountains (alpine zone); b) marginally increasing temperature (average annual) causes negative impacts in the lowlands and positive but statistically insignificant impacts in the hills and mountains; c) net farm income is likely to increase with good monsoon (summer precipitation) and relatively low temperature; d) marginally increasing precipitation during summer and winter would increase net farm income; and e) relatively low precipitation and high temperature seem to have positive impact on net farm income during the fall and spring seasons (harvesting seasons for rice/maize and wheat, respectively). Although important, the study is limited by models that explain only 10-11% of variability in the net farm income.

The findings of Thapa and Joshi (2011) on potential negative impacts of future climate on Nepalese farm yield/income appears to be in agreement with the earlier results of Cline (2007), who projected declining net farm income at the national level under climate change. About 17% reduction in farm output from 2003 level is projected for Nepal by 2080 (Table 1) under SRES A2 scenario using four GCMs (Cline, 2007). Consideration of the carbon fertilization effect, however, compensates for the higher loss due to temperature rise and limits the income reduction to 5% (Cline, 2007).

Information on similar climate impacts on agriculture for the Indian Himalaya is not available. However, using Mendelsohn et al. (2001)'s Ricardian climate impact model for agriculture in India without considering the carbon fertilization effect, Cline (2007) found about 60% reduction in farm yield (90% reduction in net income) for northeast and northwest India by 2080.

Future projection of economic impacts (as farm output) in the region using combined Ricardian and agronomic models (with appropriate weights) based on projected temperature and rainfall (based on six GCMs under six SRES A2 emission scenarios) is shown in Table 4 (Cline, 2007). India would face the highest loss in farm output (about 30%), followed by Nepal (5%)

even when the carbon fertilization effect is taken into account (Cline, 2007). When considering the carbon fertilization effect, the loss would be about 34% in northeast and 19% in northwest India (Cline, 2007). Xizang province of China fairs better, with projected gains in farm output of about 21% assuming carbon fertilization and 5% without carbon fertilization effect (Cline, 2007).

The positive impact on agriculture in the Tibetan Plateau is also reported by Wang et al. (2009). On a provincial level analysis using the Ricardian method, Wang et al. (2009) found irrigated farms are likely to benefit from warmer temperatures with conspicuous gains in the Tibetan Plateau (128-381 USD/ha/°C). The effect of a precipitation increase on irrigated farms, however, is modest (1-65 USD/ha/°C) for Tibetan Plateau as well as other parts of Chinese Himalayas. The impact on rain-fed agriculture shows sharp contrast to the irrigated farms (Wang et al., 2009). The marginal effect of temperature increases on rain-fed agriculture in most parts of the Tibetan Plateau is a net loss at a rate of 0-165 USD/ha/°C. The marginal precipitation effect is beneficial to rain-fed farms in the whole Tibetan Plateau (1-65 USD/ha/°C).

Table 4. Impact on farm output under climate change (Cline, 2007)

Country	Farm Area (1,000 ha)	Output per ha (2003 USD)	Output (millions of 2003 USD)	Temperature (°C, annual average)		Precipitation (mm, annual average)		Change in output (% change from 2003)	
				Present 1961-90	Future 2070-99	Present 1961-90	Future 2070-99	Without Carbon fertilization	With Carbon fertilization
India	170,115	777	132,140					-38.1	-28.9
Northeast	64,870	777	50,389	20.54	24.54	3.51	4.23	-43.9	-35.5
Northwest	37,528	777	29,151	23.55	27.52	1.58	1.97	-42.5	-33.8
Southeast	42,767	777	33,220	26.76	30.06	3.05	3.42	-29.1	-18.5
Southwest	24,950	777	19,381	26.23	29.32	3.04	3.47	-31.9	-21.7
Nepal	3,294	728	2,399	12.9	17.13	3.64	4.57	-17.3	-4.8
Tibetan Plateau	1,226	788	966	-1.45	4.15	1.13	1.53	4.8	20.5

In summary, despite inherent uncertainties, the reported literature (both agronomic and Ricardian model studies) suggests generally negative impact of climate change on agricultural yield and income. However, as the region's agriculture is mostly rain-fed, future impacts will be largely determined by future water management strategies.

5.2 Economic impact of GLOF

A few micro-level economic assessments related to GLOF were reported in Nepal. ICIMOD (2011) compares the potential economic impact of GLOFs in three major glacier lakes in Nepal (Imja, Tso-Rolpa and Thulagi) with the 1981 GLOF in Bhotekoshi-Sunkoshi. Considering the potential tangible damage due to modeled and maximum flood heights of past GLOF events (worst case scenario), they found net potential economic damage of 11.9-35.5, 1.9-8.8, and 407-415 Million USD, for the three lakes, respectively, at present value (ICIMOD, 2011). When proposals for potential hydropower projects at these sites are considered, the damage due to GLOF would be USD 8.98 billion for Imja Tsho, 2.4 billion for Tsho Rolpa, and 2.2 billion for Thulagi unless risks are mitigated (ICIMOD, 2011). Following a similar approach, Shrestha et al. (2010) estimated the total value of properties exposed to GLOF risk to be USD159 million at Limu Chimi Lake, Sunkoshi Basin, and USD197 for high flood scenarios. Thus, the extent of future economic damage due to GLOF will be largely determined by the socioeconomic development status. While such analysis was not available for other regions in the study area, economic damage potential would be high in most of the Himalayan states in view of the current and potential future hydropower development.

6. Concluding Remarks

This study attempts to shed some light on climate change impacts on the Himalayas by presenting a review of the existing literature. Based on the review of several reported hydro-climatic trends and observed temperature and precipitation patterns in the region, our study finds strong evidence of warming over the whole Himalayan region. The rate of warming, however, varies across sub-regions and across seasons. High altitude regions such as Trans-Himalayas in Nepal and Tibetan Plateau in China are warming at a higher rate than lowland areas. Warming rates are generally higher in winter than other seasons. Although patterns in precipitation trends are missing both spatially and temporally, a general decline in monsoon precipitation is noted in the western Indian Himalaya, while precipitation increases in the eastern Indian Himalaya and China. Moreover, we found growing evidence of increasing frequency of climatic extremes (both precipitation and temperature) in the region, especially in the mountainous regions. Like precipitation, there is a general lack of spatial patterns in streamflow trends in the southern Himalayan region, but streamflow trends in China, north of Himalaya, are generally increasing,

attributable to both increasing precipitation and glacier melting due to temperature increases. Our review shows that, overall, glaciers are losing mass in both eastern and western Himalaya, but not in the Karakorum region where some glaciers have positive mass balance.

While several glacier lake outburst floods (GLOFs) have occurred historically in the region, threats appear to have increased due to the increasing number of expanding lakes and the formation of new ones. Literature suggests 25-45 ha/year growth of glacial lakes in the Nepal and Bhutan from 1990-2009, which far exceeds the growth rate of the western India, which averaged at 4 ha/year. Several future climate projections suggest a warmer region, generally agreeing with observed trends in terms of seasonality (winter projected to be warmer), and higher temperature change at high altitude (Tibetan Plateau and high Himalayan region seeing more temperature rise). GCMs/ RCMs project increased monsoon precipitation, reduced winter precipitation, highly variable seasonal precipitation patterns, and increased frequency and magnitudes of daily precipitation and temperature extremes. A high-resolution RCM indicates an increase in frequency of heavy precipitation events (days with ≥ 10 mm rain) during monsoon in the whole Himalayan region.

Earlier literature was dominated by climate change sensitivity analysis and impact studies particularly with respect to temperature increase. Simulations of temperature increase while keeping precipitation unchanged suggest reduced glacier extent, increased snow and glacier melt, initial increase but eventual decline in streamflow, and increased threat of GLOFs. The literature shows a higher sensitivity to climate change of Karakorum glaciers than Himalayan glaciers, with meltwater contribution to streamflow higher in the former due to aridity. While in the long run deglaciation is a concern for streamflow under projected climate change, the severity will be largely determined by future precipitation. Despite inherent uncertainties of future precipitation scenarios, as well as data and modeling uncertainties, the existing studies point towards higher monsoonal streamflow and thus an increased threat from floods in the future. Other potential negative impacts of potential climate change include increased surface runoff in wet periods and less streamflow in dry seasons. Depending on the area-altitude curve and future precipitation, long-term impacts on dry season streamflow could be significant, particularly for small, upland, glaciated catchments. In small basins with significant glaciated area, the threat of GLOFs depends on local topography, geologic, and glaciologic conditions.

We found that climate change simulation studies for agriculture were mostly limited to India but largely excluded the Indian Himalayan states. Available literature projects reduced potential agricultural yield in India under climate change. In Nepal, however, similar agronomic crop simulations reveal an increase in rice yield with temperature up to 4 °C. Based on actual net farm output or income, however, this finding was negated by other available studies.

Based on the limited available studies, we found that economic impacts of climate change on India as a whole would be severe. For parts of Xizang province of China considered in our study, the marginal impact on net crop output would be either highly beneficial (irrigated farm) or mostly beneficial or less damaging (rain-fed). In view of the current and potential future hydropower development in our study area, there appears to be very high damage potential for GLOF. Literature shows projected risk of GLOF under climate change scenarios for Nepal would vary depending on socio-economic status of the site. Despite the importance of hydropower and agriculture in the study region, a comprehensive evaluation of economic impact was conspicuously missing. Therefore, further assessments would be needed on the economic impacts of climate change, particularly on hydropower and agriculture, the two most important economic sectors in the study area.

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