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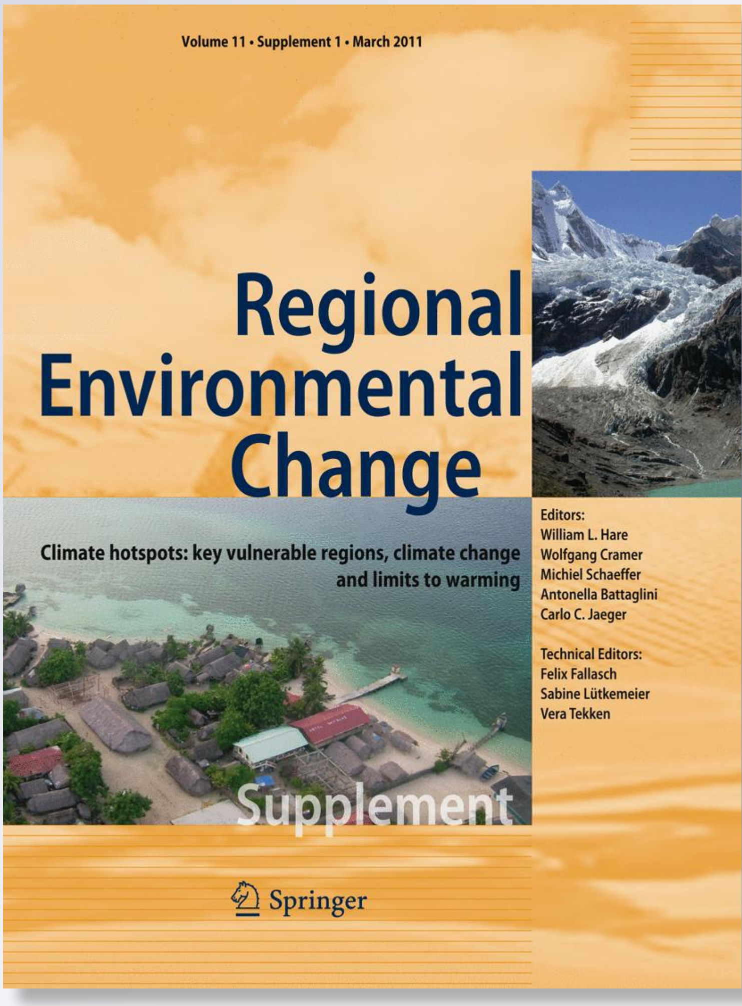

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ORIGINAL ARTICLE

Climate change in Nepal and its impact on Himalayan glaciers

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Abstract Climate change can be particularly hard-hitting for small underdeveloped countries, relying heavily on natural resources for the economy and livelihoods. Nepal is one among these countries, being landlocked, with diverse physiographical characteristics within a relatively small territory and with rugged terrain. Poverty is widespread and the capacity of people and the country to cope with climate change impact is low. The country is dominated by the Asian monsoon system. The main occupation is agriculture, largely based on rain-fed farming practices. Tourism based on high altitude adventures is one of the major sources of income for the country. Nepal has a large hydropower potential. While only 0.75% of the theoretical hydropower potential has been tapped, Nepal can greatly benefit from this natural resource in the future. Climate change can adversely impact upon water resources and other sectors of Nepal. The source of water is mainly summer monsoon precipitation and the melting of the large reserve of snow and glaciers in the Himalayan highlands. Observations show clear evidences of significant warming. The average trend in the country is 0.06°C per year. The warming rates are progressively higher for high elevation locations. The warming climate has resulted in rapid shrinking of majority of glaciers in Nepal. This paper presents state-of-knowledge on the glacial dynamics in the country based on studies conducted in the past in Shorong, Khumbu, Langtang, Dhaulagiri and Kanchenjunga regions of Nepal. We present recent trends in river flow and an overview of studies on expected changes in the hydrological regime due to climate change. Formation, growth and likely outburst of glacial lake are phenomena directly related to climate change and deglaciation. This paper provides a synopsis of past glacial lake outburst floods impacting Nepal. Further, likely impacts of climate change on other sectors such as agriculture, biodiversity, human health and livelihoods are discussed.

Keywords Himalayas · Glacial lake outburst flood · Glacier fluctuations · River discharge · Livelihoods

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Introduction

Nepal is a landlocked country with India bordering on its east, west and southern sides and the Tibetan region of China on the northern side. The region adjacent to the northern border of Nepal is home to 8 of the 10 highest mountain peaks in the world, including Mount Everest (8,848 m) and contains large numbers of glaciers and glacier lakes. These glaciers are huge reservoirs of freshwater in frozen form which maintain a perennial flow of the major rivers of Nepal and also the Ganges in India. As a consequence, changes in the hydrology of Nepalese rivers due to deglaciation could have regional consequences for water resource availability.

A heavy reliance on tourism and agriculture makes Nepal's economy very sensitive to climate variability (World Bank 2002). The country has a population of about 23.6 million, the majority of which live in rural areas. There is a huge disparity with regard to developmental infrastructure between urban and rural areas. Nepal is one of the poorest countries in the world, with 82.5% of the population living below the international poverty line of $2 per day (World Bank 2003). The Human Poverty Index (HPI) value of Nepal exceeds that of all other South Asian countries, except Bangladesh and Pakistan. The poverty index value for rural area is about twice that of urban areas (UNDP 2004).

Eighty percentage of the population practise agriculture as a main occupation to sustain their livelihood. About 20% of total area of the country is being used for agricultural activities. The economy of the nation is overwhelmingly dependent upon agriculture. Despite this situation, agriculture in the country largely relies upon monsoon rainfall because the irrigation system covers only a small area of the country. In addition, Nepal is a major tourist destination: earnings from the tourism sector constitute a significant fraction of foreign earned income in the country.

There are a wide range of natural resources in Nepal, prominent among them being water, which is being continuously provided by the melting glaciers. Shrestha (1985) estimated the theoretical hydropower potential of the country to be 83,000 MW out of which about 50% is estimated to be viable. However, the installed capacity in the country is only 620 MW, which is about 0.75% of the theoretical potential. This is primarily due to lack of financial resources to develop projects, the majority of which have to be developed in remote locations where project costs are often exceptionally high.

Climate change is likely to cause a wide variety of impacts on the environment of the country, with the most prominent impact being on the water resources. Widespread deglaciation in the Himalaya is most likely to change the hydrological characteristics of the rivers fed by glacier melt. Deglaciation will also cause rapid growth of glacial lakes and increase the risk of outburst and subsequent flooding. Other sectors such as agriculture, biodiversity, human health will also be adversely affected by climate change.

Physical and climate factors affecting vulnerability to climate change

Nepal is situated between latitudes of 26°22′ to 30°27′ north and longitudes of 80°04′ to 88°12′ east. The shape is roughly rectangular and oriented almost parallel to the axis of Himalaya. The east–west length is about 800 km, while the average north–south width is 140 km. The total area of the country is 147,181 km^2. Nepal is divided into five major physiographical regions (Fig. 1): Terai Plain, Siwalik Hills, Middle Mountain, High Mountain (consisting of the Main Himalayas and the Inner Himalayan valleys) and the High Himalaya.

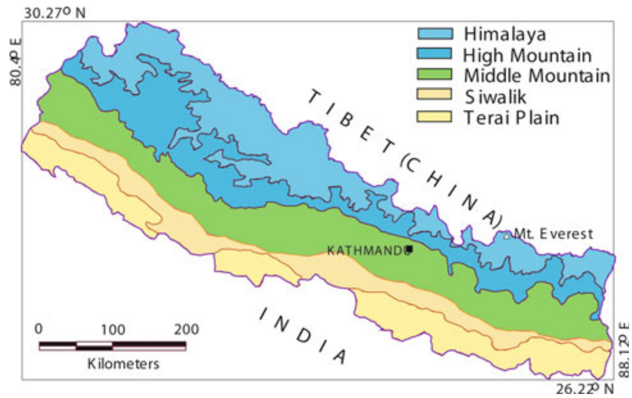

Fig. 1 Physiographical regions of Nepal

Terai Plain Is the northern most limit of the Indo-Gangetic plain. This region extends nearly 800 km east to west and 30–40 km from north to south with an elevation range from 100 to 200 m above sea level (a.s.l.). It is generally flat with minor relief caused by river channel shifting and down-warping of the basin.

Siwalik Hills Commonly known as Churia Hills, the Siwalik abruptly rises from Terai and ends with the beginning of middle mountain range. The elevation in the Siwalik ranges from 700 to 1,500 m a.s.l.

Middle mountains Also known as the Mahabharat Range, the elevation of Middle Mountain Range varies from 1,500 to 2,700 m a.s.l and extends throughout the length of Nepal. It is the first great barrier to the monsoon winds which produces the highest precipitation on its southern slopes due to orographic effects.

High mountains The region lies further north of Middle Mountains, and its elevation ranges from 2,000 to 4,000 m a.s.l. It has an average width of 50 km and extends from east to west in the form of a strip. The region has a cool temperate climate.

High Himalaya The hills of the High Mountains rise slowly to the north and ultimately make the snow-capped High Himalaya. The elevation ranges from 4,000 to 8,848 m a.s.l, with the highest peak being Mount Everest. Eight of the highest peaks of the world are located in this region. The region is mostly occupied by glaciers, snow peaks, rocky slopes, talus and colluvial deposits. It has an extremely rugged terrain with steep slopes and deeply cut valleys.

Principally, Nepal falls within a subtropical climate zone. However, due to its unique physiographical and topographical distribution, it possesses enormous climatic and ecological diversity within a north–south span of about 140 km. The climate types ranges from subtropical in the south to arctic in the north. The climate of Nepal is essentially dominated by the south-easterly monsoon which provides most of the precipitation during the rainy summer months (June to September). Monsoonal precipitation is the most important climatic element for agriculture as well as water resources development of the country. The average precipitation in the country is 1,768 mm (Shrestha et al. 2000). Depending on the location, about 70-85% of the annual precipitation in the country occurs during this period (Singh 1985; Ives and Messerli 1989).

In general, the onset and retreat of south-easterly monsoon is associated with the change in the direction of seasonal winds and the northward and southward shift of the Intertropical Convergence Zone (ITCZ). Nepal receives heaviest precipitation when the position of ITCZ is close to the foothills of Himalaya. Precipitation is also heavy when the monsoon depressions forming over Bay of Bengal pass through the country. The south-eastern part of Nepal receives the first monsoon rainfall, which slowly moves towards west. There is a marked variation of monsoon precipitation amount from east to west, as well as from south to north. The contribution of the monsoon precipitation is substantially greater in the south-eastern part of the country compared to the north-west. Besides, due to the extreme topographical variation, precipitation varies significantly from place to place both in local scale as well as in macro scale. The approaching monsoon winds are first intercepted by the foothills of Churia range, where heavier rainfall occurs. The rainfall increases with altitude on the windward side and sharply decreases in the leeward side. Lumle (1,642 m a.s.l.) lying south (windward side) of the Annapurna range in Nepal Himalayas receives about 5,000 mm of annual rainfall, whereas Jomsom (2,750 m a.s.l.) lying north (leeward side) of it receives only about 250 mm of rain per annum. The summer monsoon precipitation occurs in solid form in the higher altitudes, which plays a vital role in nourishing large numbers of glaciers, especially those situated in eastern and central Nepal, the majority of which are summer accumulation-type glaciers.

The winter precipitation is caused by the westerly weather systems. The associated systems are commonly known as westerly disturbances which have their origin over the Mediterranean Sea. The low pressure system formed there is steered and swept eastwards by the westerly winds aloft. These disturbances bring snow and rain during winter and spring, most significantly in the north-western part of the country. Winter precipitation contributes significantly to the annual total precipitation in Nepal's north-west. It plays a major role in the mass balance of glaciers in western Nepal, while playing a secondary role in the glaciers of eastern and central Nepal (Seko and Takahashi 1991). Although the winter precipitation is not as impressive in volume or intensity as the summer monsoon precipitation, it is of vital importance in generating water flows for agriculture. Most of the winter precipitation falls as snow and nourishes snowfields and glaciers and generate melt water during the dry season between February and April.

The maximum temperature of the year occurs in May or early June. Temperature starts decreasing from October and reaches the minimum in December or January. As temperature decreases with height, the sharp altitudinal gradients in the topography of the country have resulted in significant spatial variation in temperature. The Terai belt is the hottest part of the country where maximum temperatures cross 45°C. The highest temperature ever recorded is 46.4°C in Dhangadhi, a town in far western Terai, in June 1995.

There are more than 6,000 rivers and rivulets flowing in Nepal. According to their origin, Sharma (1977) divides the rivers of Nepal into antecedent, subsequent and consequent rivers. The classification draws its significance from the development of the Himalayan system. The four major river basins that originate from the snow clad Himalayas are the Mahakali, the Karnali, the Gandaki and the Koshi (Fig. 2). The Babai, the West Rapti, the Bagmati, the Kamala, the Kanaka and Mechi are all rivers originating from the Middle Hills and meet with the four main rivers of Nepal. Of similar origin are several other rivers such as Andhi Khola, Ridi, Rosi, Pikhuwa, East Rapti, Trijuga, which meet the four main rivers within Nepal. Numerous rivers originate from the Siwalik and flow through Terai. A large annual fluctuation is characteristic of Nepalese rivers, which closely follows the annual precipitation cycles.

The timing of discharge coincides closely with seasonal maxima and minima of precipitation at basin scales (Fig. 3). Discharge maxima generally occur in August, coinciding with the peak in monsoon. About 75% of the annual volume of water leaves the respective watershed during the monsoon season (June–September). Minimum values occur during the months of January–May (Alford

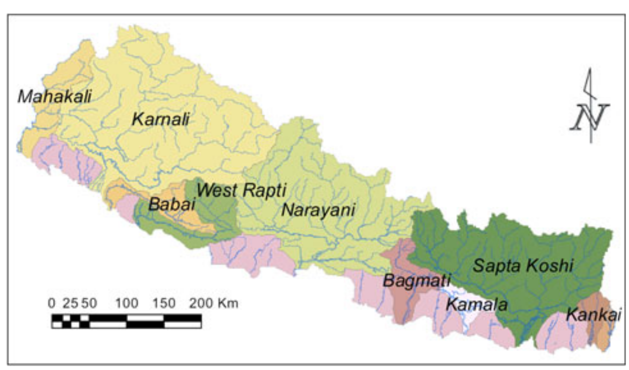

Fig. 2 River basins of Nepal

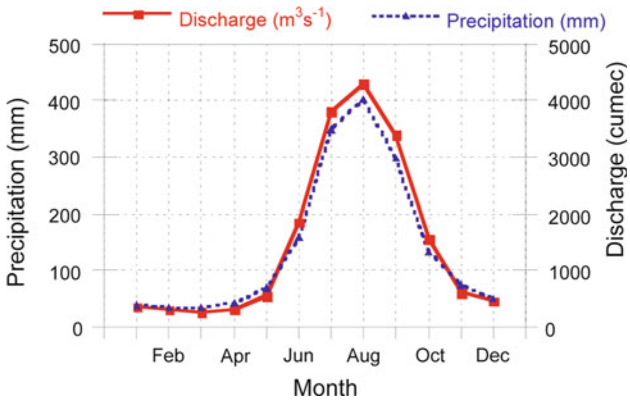

Fig. 3 Hydrograph of discharge at Chatara (Sapta Kosi) and precipitation. *Source*: Bhusal (1999) and Alford (1992)

1992). All the major rivers of Nepal are perennial and cater for a significant amount of water flow throughout the year. Snow and glacier melt is the important contributor to the flow of these rivers. All the rivers of Nepal ultimately flow into the Ganges in India. Alford (1992) suggests that the low flow contribution of Nepalese rivers to the Ganges could be as high as 70%. It is further suggested that Nepalese rivers modulate the flow of the Ganges. The snow and glaciers of Nepal Himalaya therefore carries a regional importance for water resources (Fig. 4).

Climate plays a large role in the water resources of the country. Changes in precipitation and temperature brought by climate change could affect run-off. This in turn affects the potential water utilization and the benefits of establishing or continuing to operate water resource projects. It may also affect demand for electricity, although the influence of climate change on demand would probably be quite low. Extreme events such as Glacial Lake Outburst Floods (GLOFs) have the largest potential effect on water resources projects. The force of a GLOF is so great that an entire plant can be wiped out in a very short period, as happened during the 1985 GLOF at Khumbu in the eastern Nepalese Himalaya.

Climate concerns can span a variety of timescales, ranging from seasonal to inter-annual variability. In the coming years, water resources planners will certainly have to incorporate measures to adapt to climate change.

Observed changes in Nepal

Analysis of observed temperature and precipitation data in Nepal is limited. One of the reasons behind this is the relatively short length of records, about 30 years. From available studies, it has been found that temperatures in

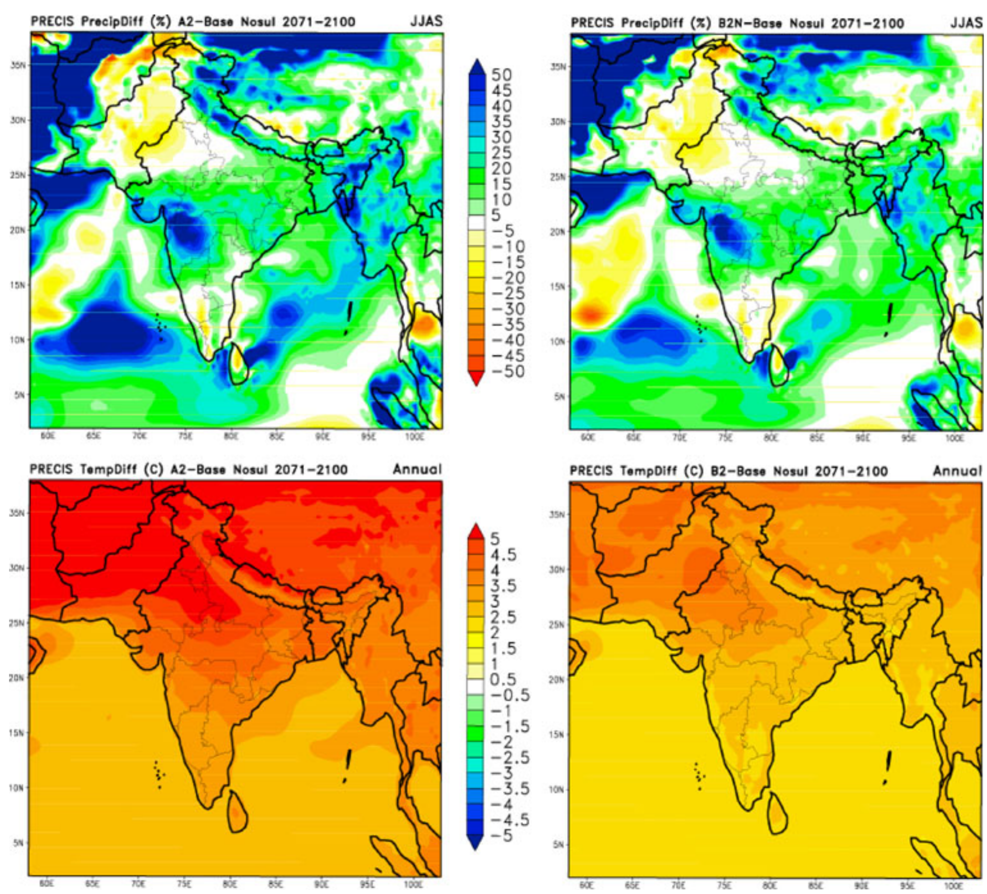

Fig. 4 Projections of changes in monsoon precipitation (*top*) and average annual temperature (*bottom*) by the end of the twenty-first century for emission scenario SRES-A2 (*left*) and B2 (*right*) (Rupa Kumar et al. 2006)

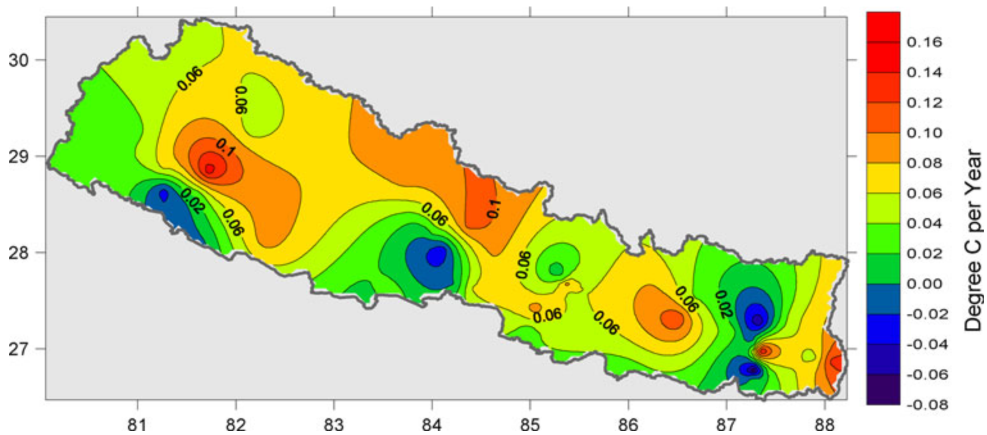

Fig. 5 Spatial distribution of annual mean—maximum temperature trends in Nepal for the period 1977–2000

Nepal are increasing at a rather high rate. Shrestha et al. (1999) analysed 49 stations in Nepal and found that the warming was consistent and continuous after the mid-1970s (Fig. 5). They found that the average warming in annual temperature between 1977 and 1994 was 0.06°C year^{-1}. Warming is more pronounced in the higher altitude regions of Nepal such as the Middle Mountains and Himalaya, while the warming is significantly lower, or even lacking, in the Terai and Siwalik regions. Further, warming in the winter is more pronounced compared to other season (Table 1). The early analysis of Shrestha et al. (1999) was extended with more recent data, and it was found that the warming trend is still continuing and that the rate of warming has not decreased (Fig. 6). Until 2000, the two warmest years in Nepal were 1999 and 1998. The widespread warming in the country is thus is in broad agreement with projections made by climate models.

Similar analysis on precipitation data does not reveal any significant trends, although precipitation in Nepal is found to be influenced by, or correlated to, several large scale climatological phenomena, including ENSO (Shrestha et al. 2000).

Warming similar to that observed in Nepal is also observed in Tibetan Plateau. Liu and Chen (2000) have shown that in Tibetan Plateau, warming is more pronounced in higher altitude stations than in lower ones. A recent study suggested that the progressively greater warming in the higher altitude regions is a general phenomenon of the whole Hindu Kush–Himalaya region (Shrestha 2009).

Glacier fluctuations

There are 3,252 glaciers in Nepal covering a total area of 5,323 km^2 (ICIMOD and UNEP 2001). Since glaciers are excellent indicators of climate change (e.g., Oerlemans 1994; Oerlemans and Hoogendoorn 1989), the Nepalese glaciers provide a good opportunity to study the impact of global climate change in this region. Studies of glaciers on a regular basis started in Nepal in the early 1970s. Since then, several glaciers in Hidden Valley of Dhaulagiri region, Langtang region, Khumbu region and Kanchenjunga region have been studied (Fig. 7). Some results of the glacier fluctuation studies are presented below.

Shorong Himal

Glacier AX010 in the Shorong Himal (27°42′N, 86°34′E; Fig. 7) is one of the most studied glaciers in Nepal.

Table 1 Regional mean maximum temperature trends for the period 1977–1994 (°C/year)

Regions	Seasonal				Annual
	Winter December–February	Pre-monsoon March–May	Monsoon June–September	Post-monsoon October–November	January–December
Trans-Himalaya	0.12	0.01	0.11	0.1	0.09
Himalaya	0.09	0.05	0.06	0.08	0.06
Middle mountains	0.06	0.05	0.06	0.09	0.08
Siwalik	0.02	0.01	0.02	0.08	0.04
Terai	0.01	0.00	0.01	0.07	0.04
All Nepal	0.06	0.03	0.05	0.08	0.06

Source Shrestha et al. 1999

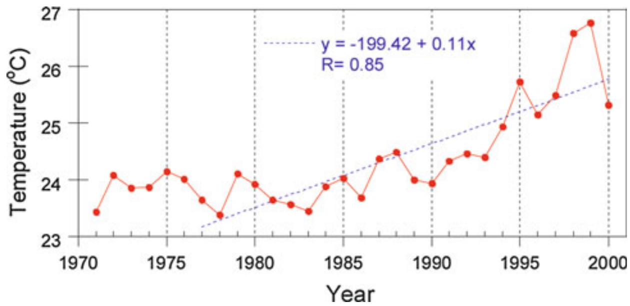

Fig. 6 All Nepal annual mean-maximum temperature trend for the period 1977–2000

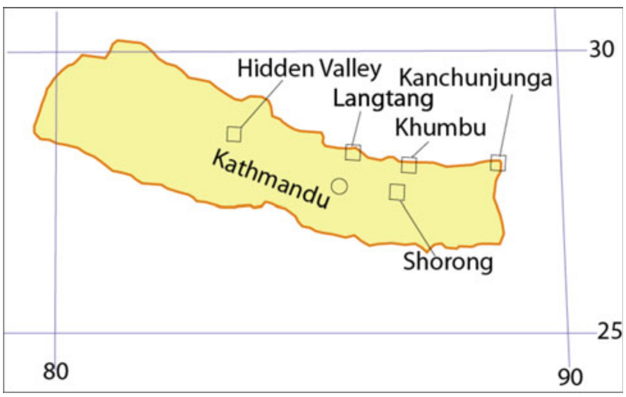

Fig. 7 Glacier study areas in Nepal

Changes in glacier terminus area have been monitored intermittently between 1978 and 1995 and every year thereafter until 1999. The aerial extent of the glacier was measured intermittently in 1978, 1996 and 1999 by topographical survey (Fujita et al. 2001). The retreat from 1978 to 1989 was 30 m, which is equivalent to 12 m thinning of the glacier surface. Kadota and Ageta (1992) used these results to establish a relationship between climate and the retreat of the glacier. They applied a simple model using climate (temperature and precipitation) data from glacier-free areas (Chialsa and Kathmandu). According to this analysis, the surface air temperature around the glacier terminus increased less (0.1°C year^{-1}) than in the glacier-free area (0.2–0.4°C year^{-1}). Kadota et al. (1996) reapplied the model with additional data and found that the retreat after 1989 is much larger than for the period 1978–1989 and derived higher surface temperature at the glacier terminus (4,958 m a.s.l.; +1.4°C). The study predicted the shrinking tendency to continue and to accelerate in the future, even if climate condition remains unchanged. Recently, Glacier AX010 was resurveyed. The results of the survey showed that the glacier surface is remarkably close to what was predicted by Kadota et al. (1996). The glacier terminus had further retreated by a further 14 m after 1998 (Fig. 8).

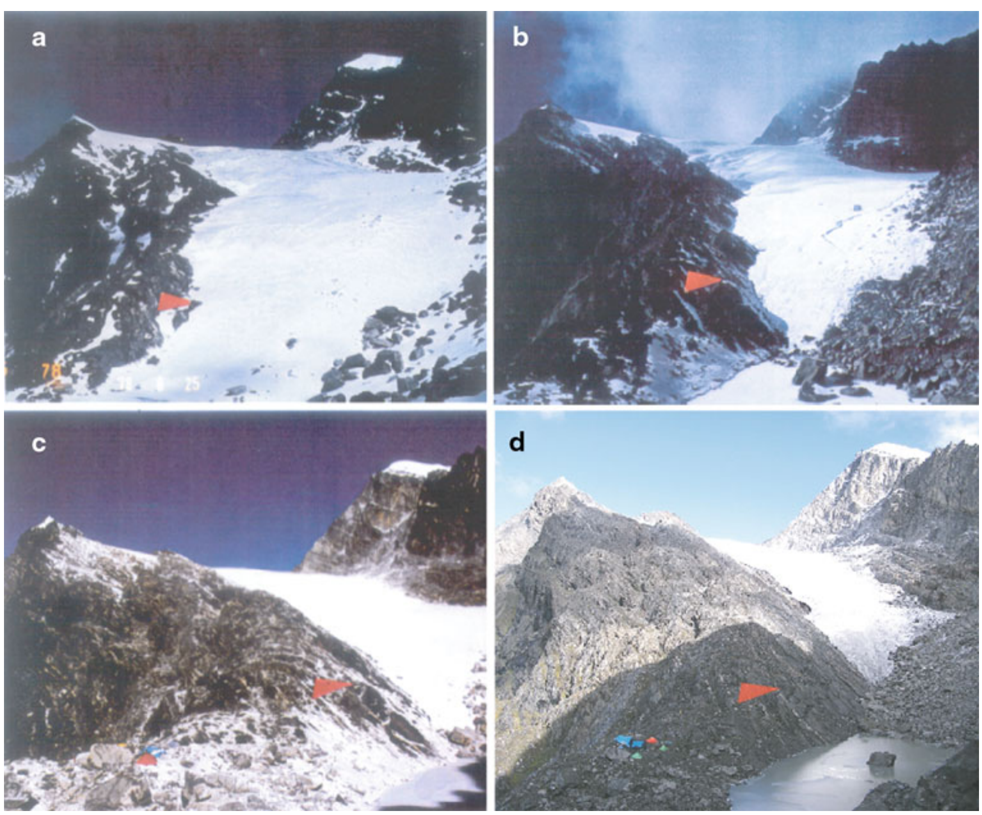

Fig. 8 Glacier AX010 (shoring) in **a** 1978, **b** 1989, **c** 1998 and **d** 2004

Khumbu Region

Khumbu Glacier is a large debris-covered glacier in the Khumbu Region, about 15 km long, which drains mainly from the West Cwm between Mt. Everest and Lohtse. The bare ice zones (ice pinnacles) in the glacier are gradually shrinking (Seko et al. 1998). The surface of the glacier lowered about 10 m throughout the debris-covered ablation area in the period 1978–1995 (Kadota et al. 2000). Indications of a slowing down of ice flow were also detected, which means the shrinkage may accelerate even if the ablation condition remains unchanged. Naito et al. (2000) developed a model coupling mass balance and flow dynamics of debris-covered glaciers and applied it to the Khumbu Glacier. The model predicts the formation and enlargement of a depression in the lower ablation area about 5 km upstream of the terminus, which could transform into a glacier lake in the future.

Yamada et al. (1992) reviewed terminus fluctuation of seven clean type glaciers in Khumbu for the period 1970s to 1989. A majority of the glaciers have retreated in the range of 30–60 m in the observed period. An expedition organized in 2004 found the majority of glaciers in Khumbu Region continuing to shrink at a rather fast rate, while some smaller glaciers have begun to disappear.

Langtang region

Yala glacier is the most studied glacier in the Langtang region. The glacier terminus was surveyed in 1982 (Ageta et al. 1984). The glacier fluctuation was studied both by photogrammetry and by ground survey. Fujita et al. (1998) surveyed the Yala glacier terminus in September 1994, May and October 1996 and found that the retreat rate and surface lowering have accelerated in recent years.

A transverse profile of the Lirung glacier, with its debris-covered lower part, was surveyed in 1987 and in 1989. There is no major change in the profile; however, photographs taken at different times show a clear retreat of the glacier. There is an indication that the upper steep part and lower flatter part will separate in the near future. Data from a station close to the glacier show annual temperature rising at the rate of 0.27°C year^{-1}. However, this is a quite high rate, and the relatively short record length may not provide true assessment of the climatic trends prevailing in that region.

Dhaulagiri region

Rika Samba Glacier (28°50′N 83°30′E) is the most studied glacier in Hidden Valley, Kali Gandaki Basin. The terminus position was surveyed initially in 1974 (Nakawo et al. 1976) and thereafter intermittently in 1994 (Fujita et al. 1997), 1998 and 1999 (Fujita et al. 2001). Photographs taken in different years and a topographical survey of the glacier show clearly that the glacier is retreating (Fig. 9). The glacier terminus retreated by 20 m in the period between 1974 and 1994. A study on temperature trends at 7 stations in Kali Gandaki Basin showed an average warming of 0.025°C year^{-1}.

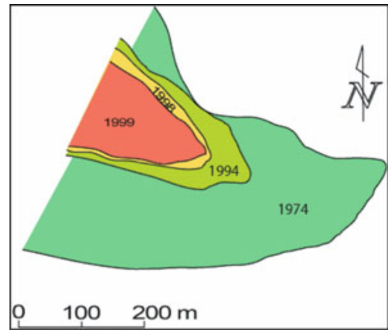

Fig. 9 Terminus retreat of Rika Samba Glacier, Hidden Valley

Besides Rika Samba, six other glaciers in the region were measured in 1994 using altimeter measurements and compared with observations from 1974 (Fujita et al. 1997). It was found that glacier retreat was a general trend in Hidden Valley.

Kanchenjunga region

Asahi and Watanabe (2000) studied glacier fluctuations in the Ghunsa Khola basin of Kanchenjunga area. Out of 57 glaciers, 50% had retreated, 38% were stationary and 12% were advancing between 1958 and 1992.

River discharge

A comprehensive analysis of trends in river flow is not yet available and what follows is a preliminary analysis of river discharge. Trends in rivers of three categories (large outlet rivers, southern rivers and snow-fed rivers) are examined here. Among the large rivers, Karnali and Sapta Koshi show a decreasing trend, although the record of Sapta Koshi is quite short. In contrast, another large river, Narayani (Kali Gandaki), shows an increasing trend. Southern rivers do not show any trend. All of the three snow-fed rivers examined here show a declining trend in discharge. It is clear that trends observed in river discharge are neither consistent nor significant in magnitude, with the ambiguity due to short record lengths and high inter-annual variability in discharge data. A separate study suggests that the number of flood days and consecutive days of flood events appears to be increasing (Shrestha and Shresta 2003).

Glacier lake and outburst floods

There are 2,315 glacier lakes of various sizes, the total area of which is 75 km^2 (ICIMOD and UNEP 2001). The formation and growth of glacier lakes are a phenomenon closely related to the deglaciation in Nepal. Valley glaciers generally contain supra-glacial ponds. Due to a warming climate, these ponds grow bigger and merge. The ponds fill the depressions earlier occupied by glacier ice. The dams holding these are structurally weak and unstable and undergo constant changes due to slope failures, slumping, etc. and possess the danger of catastrophic failure, causing glacier lake outburst floods (GLOFs). Principally, a moraine dam may break by the action of some external trigger or by self-destruction. A huge displacement wave generated by a rockslide or snow/ice avalanche from the glacier terminus into the lake may cause the water to overtop the moraines, create a large breach and eventually cause dam failure (Ives 1986). Earthquakes may also be one of the factors triggering dam break depending upon its magnitude, location and other characteristics. Self-destruction is caused by the failure of the dam slope and seepage from the natural drainage network of the dam.

A GLOF is characterized by a sudden release of a huge amount of lake water, which in turn rushes down the stream channel in the form of dangerous flood waves. These flood waves comprise of water mixed with morainic materials and cause devastating consequences for downstream riparian communities, hydropower stations and other infrastructure. The severity of flood wave depends upon the amount of water released, breach characteristics, debris load and on basin characteristics of the watershed. Discharge rates of such floods are typically several thousand cubic meters per second.

The record of past disastrous GLOF events in Nepal is shown in Table 2. Although GLOF events are not new in Nepal, they attracted the attention of the scientific community and government only when a disastrous GLOF occurred at Dig Tsho Glacier Lake on 4 August 1985 in the Langmoche valley of Khumbu region in eastern Nepal (Ives 1986; Yamada 1998). It caused serious damage to the nearly completed Namche Hydropower Project, washed away big area of cultivated land, bridges, houses including livestock and inhabitants along its path downstream. The flood waves lasted for about 4 h and released about 6–10 $\times$ 10^6 m^3 of water (Ives 1986). Since then, the Government of Nepal has considered GLOF as a threat to the development of water resources of the country and has given attention to GLOF studies.

Tsho Rolpa is the largest glacier lake in Nepal occupying an area of 1.76 km^2. This lake was in the form of a cluster of small supra-glacier ponds in the late-1950s, which merged and grew to its present stage into one large lake (Fig. 10). Based on the rapid growth of the lake, rapid fast degradation of terminal and lateral moraines holding lake water, melting of fossil ice inside the moraine, seepage of lake water from the end moraine and rapid ice calving from glacier terminus, it is suggested that there is a high risk of a GLOF from Tsho Rolpa Lake. This is the only lake in Nepal, where some mitigation work and an early

Table 2 List of GLOF events affecting Nepal

Date	River basin	Name of lake
450 years ago	Seti Khola	Machhapuchhare, Nepal
August-1935	Sun Koshi	Taraco, Tibet
21-September-1964	Arun	Gelaipco, Tibet
1964	Sun Kosi	Zhangzangbo, Tibet
1964	Trishuli	Longda, Tibet
1968	Arun	Ayaco, Tibet
1969	Arun	Ayaco, Tibet
1970	Arun	Ayaco, Tibet
3-September-1977	Dudh	Koshi Nare, Nepal
23-June-1980	Tamur	Nagmapokhari, Nepal
11-July-1981	Sun Koshi	Zhangzangbo, Tibet
27-August-1982	Arun	Jinco, Tibet
4-August-1985	Dudh Koshi	Dig Tsho, Nepal
12-July-1991	Tama Koshi	Chubung, Nepal
3-September-1998	Dudh Koshi	Sabai Tsho, Nepal

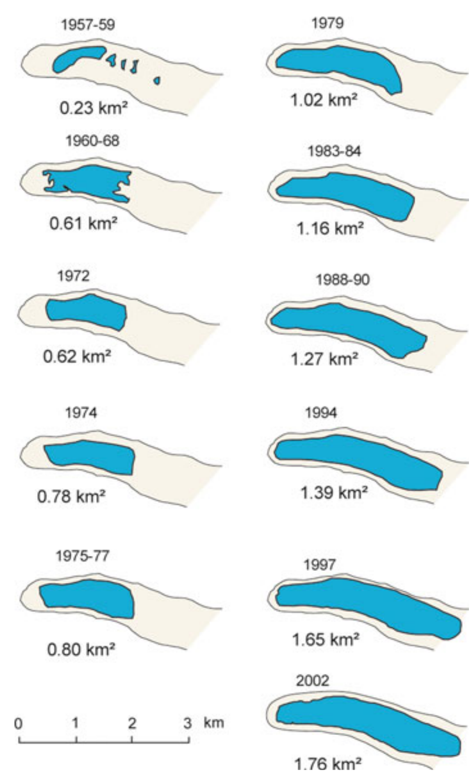

Fig. 10 Growth of Tsho Rolpa Glacier Lake

warning scheme has been implemented (Rana et al. 2000; Shrestha et al. 2001). The other glacier lakes listed as dangerous are Imja, Lower Barun and Thulagi Lakes. ICIMOD and UNEP (2001) identified altogether 20 lakes in Nepal as potential dangerous lakes, although many of these need field verification.

Mitigation work is extremely expensive, and it is not possible to implement mitigation work in all dangerous lakes. Moreover, mitigation work cannot completely exclude the possibility of a GLOF. It is certain that GLOFs will have strong negative impact on the development efforts of Nepal, especially in the water resources sector.

Effects of projected climate change

The Intergovernmental Panel on Climate change (IPCC) assessment reports provide a comprehensive review of climate models results in terms of temperature and precipitation projections (IPCC 2001; Christensen et al. 2007). Climate models show greater than average warming in the South Asian region in summer. There is a general consistency among the models in their output for winter, while the agreement is less for summer. In contrast, the consistency among models in precipitation predictions, as well as the significance of projected changes, is low both for the winter as well as for the summer seasons (Christensen et al. 2007). General circulation models tend to not perform well over the high altitude regions of concern here, and regional climate models have been found to perform better (Christensen et al. 2007).

Recently, the Indian Institute of Tropical Meteorology (IITM) high resolution climate scenarios for the South Asian region based on a regional climate model PRECIS (HadRM3 Providing Regional Climates for Impacts Studies—Rupa Kumar et al. 2006). These scenarios indicate a decrease in monsoon in the northern parts of the country and increase in the southern parts (Fig. 4). Nepal is projected to warm on average by 3.5–4°C in these scenarios. The IPCC AR4 found that warming in South Asia is projected to be at least 2–4°C by the end of the century (Christensen et al. 2007). There is a clear elevational gradient in warming rates in the Himalayan range (e.g., Bhutan, Nepal, and Himachal Pradesh) similar to that in the observed historical temperature data.

An earlier projection set of projections for Nepal was made using the SRES B2 scenario by Agrawala et al. (2003) using the MAGICC/SCENGEN model (Wigley 2003) selecting the set of 7 recent GCMs that best reproduced observations over Nepal. As with the more recent projections, a significant and consistent increase in temperature was projected for Nepal for the years 2030, 2050 and 2100 across the various models. This analysis also shows somewhat larger warming in winter months than the summer months, consistent with more recent assessments (Christensen et al. 2007). The projected warming above the baseline average (1961–1990) is 1.2°C for 2030, 1.7°C for 2050 and 3.0°C for 2100. This analysis also agrees with the IPCC analysis in the projection of precipitation change, i.e. less significant change and high standard deviation among the model results (Table 3). Similar analysis was done for Nepal under the National Communication for the UNFCCC. The results of this analysis are also largely consistent with PRECIS and OECD results (Ministry of Population and Environment 2004).

However, there have been very little research conducted in the Nepalese Himalaya to quantify the possible impact of climate change induced deglaciation on various sectors such as river discharge, GLOFs, landslides and their eventual effects on agriculture and livelihoods. Almost all the studies conducted so far are subjective in nature.

River discharge

Model predictions on the effect of climate change on stream flow vary regionally and between climate scenarios, largely following projected changes in precipitation. In South Asia, HadCM3 shows increase in annual run-off

Table 3 GCM Estimates for temperature and precipitation changes in Nepal

Year	Temperature change (°C)			Precipitation change (%)		
	Mean (SD)			Mean (SD)		
	Annual	DJF	JJA	Annual	DJF	JJA
Baseline average (mm)				1,433	73	894
2030	1.2 (0.27)	1.3 (0.40)	1.1 (0.20)	5.0 (3.85)	0.8 (9.95)	9.1 (7.11)
2050	1.7 (0.39)	1.8 (0.58)	1.6 (0.29)	7.3 (5.56)	1.2 (14.37)	13.1 (10.28)
2100	3.0 (0.67)	3.2 (1.00)	2.9 (0.51)	12.6 (9.67)	2.1 (25.02)	22.9 (17.89)

Source: Agrawala et al. (2003)

ranging from 0 to 150 mm year^{-1} by the year 2050, relative to average run-off for the period 1961–1990, while the older version, HadCM2, projects decrease of up to 250 mm year^{-1}. These climate models are unable to highlight the details on seasonal variations in run-off, although it is generally suggested that due to higher evaporation and decrease in glacier mass, the low flows are likely to decrease with unfavourable consequences (Cruz et al. 2007). Analysis on run-off variations due to climate change at smaller geographical scales is lacking.

In 2001, a project called SAGARMATHA (Snow and Glacier Aspects of Water Resources Management in The Himalaya) was initiated with the primary objective of assessing the seasonal and long-term water resources in snow- and glacier-fed rivers originating in the Hindu Kush–Himalayan region and to determine strategies for coping with the impacts of climate change induced deglaciation on the livelihood of people in the region (e.g., Rees and Collins 2004; Sullivan et al. 2004).

For this project, a regional hydrological model was developed which provides estimates of seasonal and annual run-off for a grid cells at a 20 km by 20 km. The model was applied for a baseline climatology for a 30-year period as well as 4 incremental scenarios of increasing temperature, 2 incremental scenarios of increasing temperature with increasing precipitation, 2 incremental scenarios of increasing temperature but decreasing precipitation and one climate model-based scenario, based on output from the HadRM2 regional climate model (RCM). The output of the regional hydrological model, representing the distribution of runoff at a 20 km by 20 km resolution, was translated into river flows, and comparisons were then made between baseline flows and those from the various scenarios to analyse how the surface water resources availability of rivers may be affected by climate change.

In Nepalese Himalaya, the model was applied to the catchment of Kali Gandaki-Narayani river system in the eastern region of Himalaya. The decadal mean flows in this catchment increase for all scenarios, with the most extreme temperature scenario attaining a peak flow increase of between +30 and +90% over the base line some 50 years, or more, into the 100-year model run. The decadal mean flow of Kali Gandaki-Narayani river system increases gradually, as ice at the lower elevations of glacier is exposed more slowly to melting and for less time. It takes longer for the ice at the lower elevations to deplete, which, in turn, causes the peak in flows to be delayed for many decades. In Modi River at Kusma in the upper reaches of Kali Gandaki-Narayani river system, decadal mean winter flows increase gradually throughout the 100-year model run, to a maximum increase of over +10% versus the baseline winter flow by decade 10, with warming increased at 0.06°C year^{-1}. While the relative changes are less in winter, any variation in water availability in this traditionally dry period could have serious impacts for water users.

The results have shown impacts of deglaciation to vary considerably within the region and within catchments. Highly glaciated catchments and those (catchments) where melt water contributes significantly to the run-off have been shown to be most vulnerable to deglaciation. However, catastrophic water shortages forecast by some experts are unlikely to happen for many decades, if at all. Rather, some upper areas may benefit from increased water availability for the foreseeable future. Based on these results, the threat that all of the regions' glaciers will soon disappear would seem ill-founded. It has to be noted here that the model is spatially rather crude and the results should not be taken as conclusive. Furthermore, it is not able to predict changes in seasonal variability and changes in hydrological regime, which are very important.

Elsewhere in Himalaya, Singh and Bengtsson (2005) studied the impact of warmer climate on melt and evaporation for rain-fed, snow- and glacier-fed basins in the western Himalayan regions. Hydrological processes were simulated under current climatic conditions using a conceptual hydrological model, which accounts for the rainfall run-off, evaporation losses, snow and glacier melt. Based on the future projected climate scenarios in the study region, three temperature increase scenarios above the base period were adopted for quantifying the effect of warmer climate ($T + 1$°C, $T + 2$°C and $T + 3$°C). For a $T + 2$°C scenario, annual melt was reduced by about 18% for the studied snow-fed basin, while it increased by about 33% for the glacier-fed basin.

Livelihoods

A livelihood impact study was conducted for downstream communities due to deglaciation resulting from climate change. While the hydrological component of the project provides a regional model for the whole Hindu Kush–Himalayan region, and on the water resources of the Indus, Ganges and Brahmaputra river basin, the livelihood impact study was restricted to selected communities within the Kali Gandaki river corridor in the western region of Nepal.

It was found that the Kaski and Parbat districts located in the upper part of the corridor will be considerably influences by any change in run-off due to deglaciation. In the middle part of the corridor, the Baglung, Parbat, Gulmi and Syangja districts may experience high to moderate impacts, with Palpa and Tanahu in the lower part of the corridor are likely to be less affected. In the far downstream areas, impacts will be less marked. It was found that any changes in hydrological regimes can have serious consequences to hydroelectric projects. The study showed that the traditional water mills used by local people for various purposes (e.g. grinding grains, power.) might be adversely affected, especially those that are seasonally operated. The study also found various irrigation schemes along the river corridor vulnerable to climate change. Similarly, fishing an important mean of subsistence will undoubtedly be affected by deglaciation in the upper catchment. Water in the region also has important religious and spiritual uses. There are altogether 22 traditional places, commonly known as *ghats*, along the Modi/Kali Gandaki river corridor, which are used for religious bathing and cremating. Changes in run-off, either increases or decreases, may cause inconvenience and increased risk for local people.

Effects on other sectors

The Initial National Communication of Nepal to the United Nations Framework Convention on Climate Change (UNFCCC 1992) provides a comprehensive analysis of possible impacts of climate change on different sectors of Nepal (MOPE 2004). A brief discussion of the most important impacts is presented below.

Agriculture

In an agrarian country like Nepal, with a staggering increase in population and food demand, even a slight decline in annual food production is a matter of great concern. Although the majority of the people depend on agriculture, this sector is adversely affected by the loss of fertile soil due to soil erosion, landslides and floods. Soil loss is one of the major causes of decline in agricultural production in Nepal. The negative effects of climate change may further aggravate this situation. It has been suggested at that with a 4°C temperature combined with a 20% precipitation rise, there could be marginal yield increase rise, between 0.1 and 7.5%, and beyond that yield will continue to decline. However, temperature increase has mixed effect in the case of wheat as the actual yield of wheat has increased in the western region with the rise of temperature and declined in other regions. Temperature increase has a negative effect on maize yield. Though temperature rise has a more negative effect to maize yield, the trend is similar to wheat.

Natural forest, biodiversity and wildlife

Forests are important natural resources of Nepal as the majority of people use forest products such as firewood, food, fodder, timber and medicines. The extensive utilization of, and increasing demands for, forest products have led to a decline both in area and in quality. Further, global warming may cause forest damage as their climatic zones move leading to changes in their composition and extinction of species. The impact of this situation could affect directly not only the environment of Nepal but also the lives of a majority of people. Nepal is renowned worldwide for its biodiversity but this could be seriously threatened by climate change. Tropical wet forests and warm temperate rain forests would disappear, and cool temperate vegetation would turn to warm temperate vegetation. Vegetation patterns would be different under the incremental scenario (at 2°C rise of temperature and a 20% rise of rainfall) than the existing types. Climate change will also have direct impacts on wildlife. Furthermore, migration of vegetation zones and declines in biodiversity will have further adverse impact on wildlife.

Health

The risk of malaria, *kalaazar* and Japanese encephalitis outbreak is suggested under climate change scenarios for Nepal. Particularly, subtropical and warm temperate regions of Nepal would be more vulnerable to malaria and *kalaazar*. Similarly, an increase of temperature would make the subtropical region of Nepal more vulnerable to Japanese encephalitis.

Conclusion

Climate model projections are highly variable concerning projections for the South Asian region. The IPCC AR4 projections on temperature change are consistent and significant with projected mean temperature increase of 1.4 and 5°C by 100 over the 1901–1950 period for the range of SRES scenarios (Christensen et al. 2007). Over the Tibetan plateau region, warming is projected to be 2.1–7.5°C for the same period and range of scenarios (Christensen et al. 2007). Overall, increase in precipitation is projected; the magnitude of change is low (Christensen et al. 2007). Change in run-off projections generally follows precipitation, although it is highly variable with models. Observed trends in temperature generally agree with climate model results and show significant warming in last decades. More warming is observed in high altitudes compared to low elevations. No significant trend is found in precipitation.

The warming in the Himalayas is having great impact on the glaciers. There is an overwhelming evidence of rapid deglaciation in the Himalayas. As glaciers are an important source of water to the rivers of Nepal, as well as India, especially during dry seasons, widespread deglaciation is certain to have an impact on a regional scale on water resources. As run-off variation is directly related to glacier conditions, continued deglaciation is certain to have an impact on run-off in the future. Model results, however, are not consistent in predicting run-off change across the Himalayan region, although a lot of improvement in modelling is needed so that the whole suite of hydrological characteristics of Himalayan Rivers can be predicted. Preliminary analysis of river flow data, however, does not show any consistent trend at present. This could be due to rather short length of discharge records. It is therefore wise to prepare for the worst.

Glacial lake outburst floods are a problem for water resource development. It is timely to make vulnerability assessment of different development sectors and devise adaptation plans. Some "no regret" adaptation measures may be implemented in the near future. There is a need for a comprehensive physical and socio-economic risk assessment of climate change in the region.

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