Climate Change Impact and Vulnerability in the Eastern Himalayas – Technical Report 5

ICIMOD

FOR MOUNTAINS AND PEOPLE

Climate Change Impacts on Hazards in the Eastern Himalayas

MacArthur Foundation

Preface

Mountains are among the most fragile environments on Earth. They are also rich repositories of biodiversity and water and providers of ecosystem goods and services on which downstream communities (both regional and global) rely. Mountains are home to some of the world's most threatened and endemic species, as well as to some of the poorest people, who are dependent on the biological resources. Realising the importance of mountains as ecosystems of crucial significance, the Convention on Biological Diversity specifically developed a Programme of Work on Mountain Biodiversity in 2004 aimed at reducing the loss of mountain biological diversity at global, regional, and national levels by 2010. Despite these activities, mountains are still facing enormous pressure from various drivers of global change, including climate change. Under the influence of climate change, mountains are likely to experience wide ranging effects on the environment, natural resources including biodiversity, and socioeconomic conditions.

Little is known in detail about the vulnerability of mountain ecosystems to climate change. Intuitively it seems plausible that these regions, where small changes in temperature can turn ice and snow to water, and where extreme slopes lead to rapid changes in climatic zones over small distances, will show marked impacts in terms of biodiversity, water availability, agriculture, and hazards, and that this will have an impact on general human well being. But the nature of the mountains, fragile and poorly accessible landscapes with sparsely scattered settlements and poor infrastructure, means that research and assessment are least just where they are needed most. And this is truest of all for the Hindu Kush-Himalayas, with the highest mountains in the world, situated in developing and least developed countries with few resources for meeting the challenges of developing the detailed scientific knowledge needed to assess the current situation and likely impacts of climate change.

The International Centre for Integrated Mountain Development (ICIMOD) undertook a series of research activities together with partners in the Eastern Himalayas from 2007 to 2008 to provide a preliminary assessment of the impacts and vulnerability of this region to climate change. Activities included rapid surveys at country level, thematic workshops, interaction with stakeholders at national and regional levels, and development of technical papers by individual experts in collaboration with institutions that synthesised the available information on the region. A summary of the findings of the rapid assessment was published in 2009, and is being followed with a series of publication comprising the main vulnerability synthesis report and technical papers on the thematic topics climate change projections, biodiversity, wetlands, water resources, hazards (this publication), and human wellbeing.

Clearly much more, and more precise, information will be needed to corroborate the present findings. Nevertheless, this series of publications highlights the vulnerability of the Eastern Himalayan ecosystems to climate change as a result of their ecological fragility and economic marginality. It is hoped that it will both inform conservation policy at national and regional levels, and stimulate the coordinated research that is urgently needed.

Andreas Schild, PhD
Director General, ICIMOD

Climate Change Impacts on Hazards in the Eastern Himalayas

Dinesh Pathak, Ananta P Gajurel – Dept of Geology, Tri-Chandra Campus, TU, Kathmandu, Nepal
Pradeep K Mool – ICIMOD, Kathmandu, Nepal

Contents

Introduction 1
Climatic Records and Trends 2
Geomorphology and Geology 4
Present Status of Hazards and Disasters 6
Impact of Climate Change on the Hazard Scenario 10
Gaps in Hazard Research 11
Recommendations for Adaptation Strategies 11
Conclusions 13
References 14
Acronyms and Abbreviations 17
Acknowledgements 18

Introduction

Recent research work suggests that human-induced climate changes, particularly increases in temperature, are taking place in the Eastern Himalayas. Even a slight increase in global average temperature can be accompanied by much greater changes in local and regional climates. Mountains are unique areas in terms of detecting climate change and for assessing climate-related impacts because in the existing system changes occur rapidly with height over relatively short horizontal distances; as do the vegetation and hydrology (Whiteman 2000). Notwithstanding the uncertainties in the timing and exact magnitude of changes predicted in the Himalayan region, it is thought that many natural systems will be affected and their vulnerability to damage will increase. It is also thought that high mountain areas will be subject to greater increases in temperature than elsewhere; glaciers and snowfields will recede; and water supplies will decrease with severe impacts on irrigation and drinking water supplies as well as on supplies of hydroelectricity.

Shifts in monsoon precipitation patterns are expected, leading to the possibility of increased frequency and intensity of droughts and episodes of intense precipitation. These in turn may lead to increases in floods, landslides, and erosion. Increased glacial melt may also lead to increases in the formation of glacial lakes and subsequent glacial lake outbursts. Changes in monsoon precipitation will also have significant impacts on current agricultural practices in the Himalayas.

Biodiversity in mountain areas where migration of species is physically restricted will be threatened by rapid changes in temperature and precipitation. Consequently there could be rapid losses of habitat and genetic diversity from the mountain ecosystem. Iinfrastructure in the mountains and downstream could be threatened. All of these impacts will interact with one another, often in unexpected ways, in some cases resulting in greater impacts, in some cases partially compensating for eachother (Eamer et al. 2007). In many developing countries, there is widespread poverty, poor health, and bad sanitation, in part because of the degradation of the natural environment (Price et al. 2000). If the climate in the Himalayan region changes according to the present predictions, it will have serious consequences on the livelihoods of people in the region.

The Eastern Himalayas (Figure 1) occupy an area of 524,190 sq.km in Bangladesh (0.1%), Bhutan (7.6%), China (6.3%), India (52%), Myanmar (18%) and Nepal (16.1%) (Sharma 2007): from west to east they cover Bhutan, the Zhondian state of Tibet Autonomous Region (China), Arunanchal (Shillong, Itanagar, and Aizwal) in India, Sikkim (India), the Chin and Kachin states of Myanmar, and Nepal. Given the socioeconomic status of the areas involved, therefore, hazards associated with climate change can undermine progress towards sustainable development (IPCC 2001).

In order to minimise the adverse impacts of climate change, significant economic growth is needed in the countries of the Eastern Himalayas so that they are capable of adopting the necessary measures.

In this paper, we have reviewed climate changes and related hazards and their impact on the economy and social life in the Eastern Himalayas. In addition we have also identified the gaps in knowledge about hazards, and approaches to their management that could be adopted in the region.

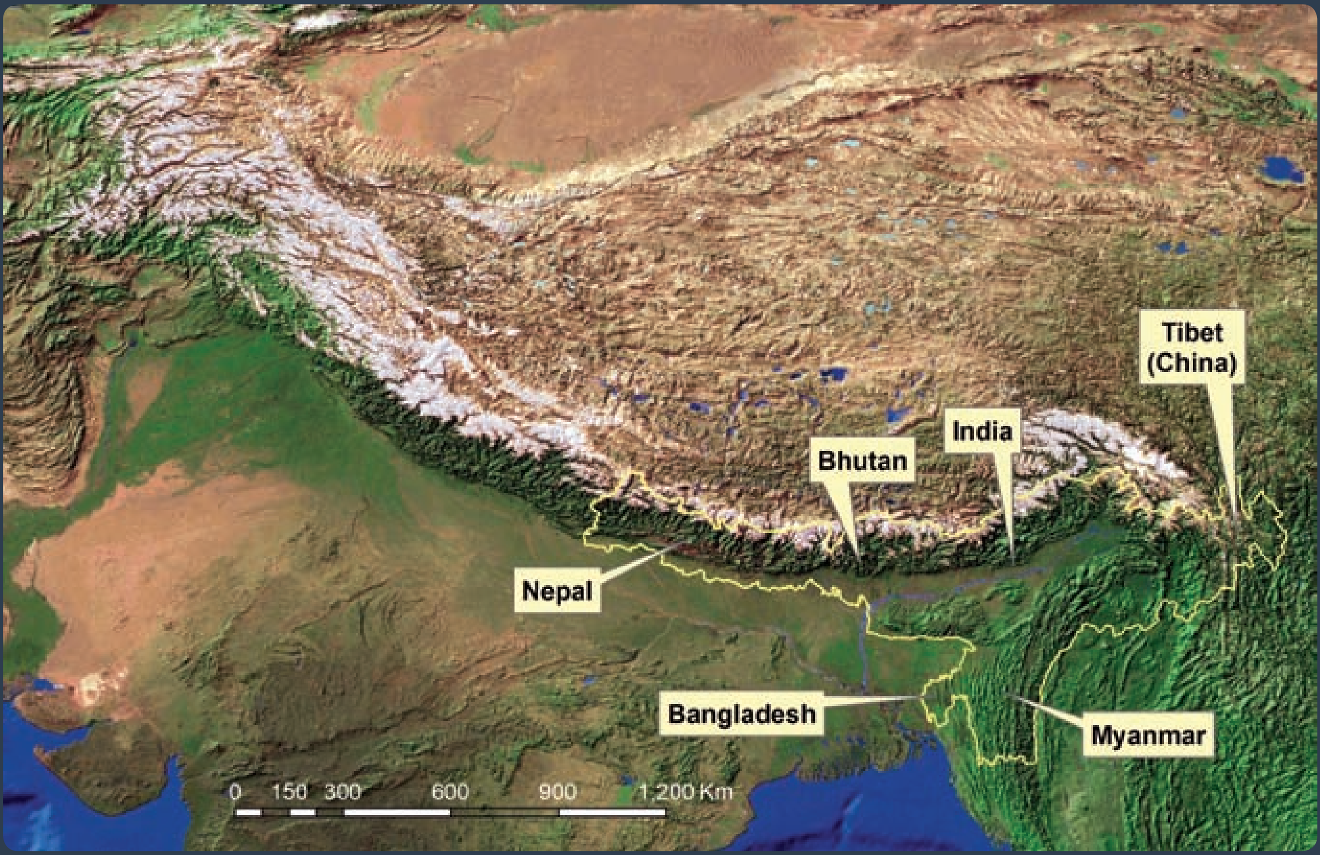
Climate Records and Trends

There is considerable multidisciplinary research literature on the geology and geomorphology of glaciated regions of the Himalayas showing evidence of climate changes over the last millennium. The following sections attempt to examine the effects of both natural and human-induced climate changes.

Paleo- and historical climate records in the Eastern Himalayas

The climate of the Eastern Himalayas is influenced strongly by the Asian monsoon system. The vast Tibetan Plateau is an engine driving the monsoon system by generating a high-altitude region of low pressure cells over southern Asia in response to the heating of the Eurasian landmass (which includes Bangladesh, India, Nepal, Pakistan, and Sri Lanka) in summer, with the hot air replaced by cooler air coming from the Arabian sea and Indian Ocean (Hastenrath 1991). During summer, the monsoon causes intense precipitation over eastern India and the Eastern Himalayas due to the orographic effects of the Himalayas on moist air advancing towards

Figure 1: **Location of the Eastern Himalayas (demarcated by yellow line) within the entire range**



the plateau from the Indian Ocean as a consequence of the low-high pressure gradient: the flow patterns are reversed in winter with cool and dry air dominating over south-central Asia (Johnson and Houze 1987; Murakami 1987, Gregory 1989; Clemens et al. 1991).

Information about past and current records is essential for evaluating the adverse effects of climate change. The variability and trends in the monsoon recorded by past and present records also help in prediction and reduction of climate-related natural disasters. A great deal of research has been published already about the Indian monsoon and its variability in the Himalayas and adjoining regions. Most of the studies carried out focus on continental climatic proxies.

Although the initiation, and subsequent intensification, of the monsoon system is the subject of debate, the results of numeric simulations have led some researchers to propose that it occurred around 30 million years ago (Ma) (Ramstein et al. 1997). Since that time, erosion has intensified, especially in the Himalayan region (France-Lanord and Métivier 2002). The monsoon seems to have changed abruptly in its intensification around 11 Ma as shown by isotope data from freshwater mollusc shells and mammal teeth; and also by the types of paleosol in the Siwalik (Churia) sediments of Nepal (Hisatomi and Tanaka 1994; Dettman et al. 2001). In addition, examination of marine plankton indicates monsoon-related upwelling, presumably from strengthening of seasonal winds in the Indian Ocean by 10-12 Ma (Nigrini 1991; Kroon et al. 1991). Around 7-5 Ma, semi-deciduous forest (C_3 type vegetation) was displaced by monsoon grassland (C_4 type vegetation nourished by warm and moist summers) as a result of an increase in temperature and seasonal precipitation in the Indo-Gangetic plains south of the Himalayas. Evidence for this can be found in changes in oxygen isotope ratios in the paleosols and mollusc shells of Siwalik sediments deposited by the rivers that were ancestors of the modern Indus, Ganges, Brahmaputra, and their tributaries (Quade et al. 1995; Gajurel 2006). Terrigenous organic matter and sediment composition in fan sediments in Bengal transported by the Ganges and/or Brahmaputra river systems also changed at about the same period (France-Lanord and Derry 1994). Among the main causes of late Miocene climate change in the Himalayas, uplift of the Tibetan Plateau and changes in solar forcing are considered to have been major driving mechanisms for the monsoon system (Prell and Kutzbach 1992). Consumption of CO_2 as a result of weathering in the Himalayas is another strong factor (Molnar et al. 1993; Quade et al. 1995). Quantification of CO_2 consumption during weathering in the Himalayas is an important way of learning about the compensation of anthropogenic CO_2 emissions today.

Past glaciation events in the Himalayas are manifested by well-developed moraines. In the following we discuss the results of published research into Quaternary (Pleistocene-Holocene) glacial fluctuations induced by climate change; and studies focusing on landscapes, river valley incisions and alluviation, pollen, and lake sediments and speleothem as climatic proxies. Mostly radiogenic isotope and optically stimulated luminescence (OSL) dating methods have been used to estimate the ages of climate-change events.

Glaciation events in the Himalayas overall were not synchronous with the northern hemisphere ice sheets (Gillespie and Molnar 1995; Clapperton 1990; Owen et al. 1997; Benn and Owen 1998) and were influenced mostly in the eastern part by the South Asian summer monsoon (Benn and Owen 1998; Finkel et al. 2003); i.e., during insolation maxima, the South Asian summer monsoon provides more precipitation as snow at high altitudes to cause a positive mass balance for glacial advances.

On the southern flank of Mount Everest, an area of eight glacial advances is marked by pronounced moraine successions; these 35 ±3 cal ka BP (thousand calendar years before present) and 9.2 ±0.2 cal ka BP glaciation events occurred during periods of increased monsoon precipitation (Finkel et al. 2003). Strong solar insolation at around 40 cal ka BP is also demonstrated by the strongly evaporated characteristic isotope compositions of mollusc shells in the paleo-lake in Kathmandu Valley in the central Himalayas (Gajurel 2006). The extent of glaciation events at 23 ±3 and 16 ±2 cal ka BP of the global Last Glacial Maximum in the area were limited to around 5 km beyond the contemporary ice margin; the glaciation events occurred during reduced precipitation (Finkel et al. 2003). Glacial advances have also been identified at 20-21 and 8-10 cal ka BP in the Kangchenjunga area (Tsukamoto et al. 2002). An earlier glacial advance of 5-6 cal ka BP in the area is also reported by Tsukamoto et al. (2002). Glacial advances in the Gorkha area (Nepal) occurred around 13 cal ka BP, 3 cal ka BP, and <1.7 cal ka BP (Zech et al. 2003), while glaciers advanced a few hundred metres from their present positions at 400-500 ^{14}C yr BP in the Everest area (Muller 1980; Benedict 1976; Fushimi 1978).

Proxy records also provide detailed temporal and spatial information concerning climate change in the Himalayas. Many sediment deposits of glacial origin are the source of mass wasting and fluvial and glacial erosion. Fluctuations in sediment deposits and discharge of water into the rivers are caused by variations in precipitation and glacial ice melt. Bedrock incisions and valley alluviation for the short term reflect the climatic responses of the area. In the Marsyangdi river, Nepal, Pratt-Sitaula et al. (2004) identified a major channel sedimentation with a monsoonal maximum at ca. 50-35 cal ka BP. At around 9 cal ka BP, sediment about 80 m thick filled the river valley during a period of strengthened South Asian monsoons. Such remarkable variations of sediment supply (fluvial vs. debris flow) and water discharge in Himalayan river valleys during the late Pleistocene to Holocene era are attributed to climatic variations (Monecke et al. 2001). Moreover the sediments could have been produced by deep-seated landslides and/or catastrophic debris flows of great magnitude (Fort 2000).

Temporal and geographical variability in the monsoon during the Holocene age are well preserved in the sediments of Lunkaransar and Didwana lakes in Rajasthan. These lake sediments show that there was no significant precipitation from the northwestern Indian summer monsoon prior to about 10,000 years ago (10 cal ka BP), as shown by the results of the general circulation model of 18,000 years ago (Manabe and Hahn 1977). Lunkaransar lake was desiccated about 5 cal ka BP (Enzel et al. 1999), whereas Didwana Lake became dry at about 2.5 cal ka BP (Bryson and Swain 1981). Around 6 cal ka BP, monsoon intensification was five times that of today (about 200 mm) in the Lunkaransar area (Bryson and Swain 1981).

A reduced monsoon precipitation record between 2,300 and 1,500 years ago and elevated summer monsoon precipitation thereafter, was identified from the mineralogical records of the Siddha Baba cave, Nepal, by Denniston et al. (2000). A thousand years later, dense, optically clear calcite layers deposited from 1550 ±5 AD to 1640 ±20 AD indicate a less-evaporative cave environment and suggest moister and/or cooler conditions, possibly related to climatic changes associated with the onset of the Little Ice Age (Denniston et al. 2000).

Recent climate records

Increased concentration of greenhouse gases in the atmosphere due to anthropogenic activities leads to warming of the earth's atmospheric system, while aerosols reduce surface warming. Global warming is manifested by decreases in snow cover, lesser extent of sea ice in the northern hemisphere, thinner sea ice, shorter freezing seasons for lake and river ice, glacial recession, decrease in the extent of permafrost, increases in soil and borehole temperature profiles, and rises in sea level. Global average air temperature is increasing and mountain glaciers and snow cover have declined on the average in both hemispheres and in the Himalayas. Here, we briefly review the evidence for climate change, particularly in the Eastern Himalayas.

The Eastern Himalayas are subject to the southwest monsoon in the summer and the northeast monsoon in winter. Climate and weather in the mountains are extremely variable and influenced by altitude, latitude, topography, orientation, and continental position (Barry and Chorley 1992). Instrumental meteorological records show a global warming trend of 0.74°C in a 100-year period (1906-2005) (IPCC 2007). In contrast the higher Himalayan data from Nepal over the period from 1977-1994 show an increase in temperature of up to 0.06°C per year, which is greater than the global trend (Shrestha et al.1999).

Warming in the Himalayas is demonstrated by the increased rate of glacial recession and the resultant formation of new glacial lakes in the high Himalayas (e.g., Mool et al. 2001a).

The recorded rate of glacial retreat varies across the Himalayas. One reason is the variability in monsoon intensity (Karma et al. 2003). Within basins, the orientation and position of a glacier, different meteorological conditions in the valleys, and amount of debris and distribution on and in the glacial mass, all play a role, as does the irregular carving of glaciers at the glacier end where the solid phase of water comes into contact with the liquid phase (Ageta et al. 2001). Research is needed to decipher the controlling mechanisms and determine the causes of these changes in glacial melt velocity. In some cases the rate of retreat has increased in recent years. Gangotri glacier in the western Himalayas (India) showed a more rapid rate of retreat after the seventies, increasing from 15 m/yr from 1935 to1976, to 23 m/yr from 1985 to 2001. The rate of retreat of the Imja glacier in Nepal almost doubled after 2001. One of the causes of acceleration in glacial retreat is probably the increased warming trend in the High Himalayas (Shrestha et al. 1999).

Geomorphology and Geology

Geomorphology

Geographically, the east-west trending Eastern Himalayan region turns south at the bend in the Brahmaputra River in upper Assam and generally runs approximately north and south in Bangladesh and Myanmar.

The Eastern Himalayas can be broadly divided into the following distinct, geomorphologic units from south to north as proposed by Upreti (1999); Alam and Tshering (2004); and Konagaya (2005) as follows.

- Southern foothills with inner valleys (200 to1,500 masl)
- Mahabharat range (1,000 to 3,000 masl)
- Midlands (200 to 2,500 masl)
- Fore Himalayas (2,500 to 4,000 masl)
- High Himalayas (4,000 to 8,848 masl)
- trans-Himalayas with inner valleys (2,500 to 4,500 masl)

The southern foothills suddenly rise from the plains from a height of about 100 m to reach 1,500 m. East-west elongated inner valleys, also called 'dun valleys', are located within this zone. The inner valleys are densely populated. The climatic regime is very similar to that of the plains. The first orographic barrier of the outer Himalayas, also called the Mahabharat range, rises rapidly to about 3,000 m. The topography of the area is rugged and steeper in the western part than in the eastern part. The relatively mature and subdued geomorphic zone to the north of the Mahabharat Range is known as the Midland zone. The altitude of the area varies from 200 to 2,500 m and contains a large number of wide river valleys and intermontane basins: it is a densely populated zone. To the north of the Midlands are the Fore Himalayas with altitudes ranging from 2,500 to 4,000 m. The Fore Himalayan zone is denoted as the Central Mountain zone in Bhutan. The high-altitude area of the Fore Himalayan zone is covered by snow during winter. The High Himalayan zone with heights ranging from 4,000 to 8,848 m includes peaks such as Annapurna, Manaslu, Mount Everest, and Kangchenjunga. Most of the glaciers, glacial lakes, and snow peaks are found in this zone. The trans-Himalayas contain inner valleys ranging in height from 2,500 to 4,500 m. The mountainous ranges in the eastern part of the East Himalayas (Bangladesh, east India, and Myanmar) have north-south directed trends. The mountain area in Bangladesh reaches a height of 1,003 m.

Geology

Geologically, the main remarkable features are the continuity of tectonostratigraphic relationships and major tectonic structures such as the Main Frontal Thrust, Main Boundary Thrust, Main Central Thrust, and South Tibetan Detachment along the Himalayan range (Gansser 1964; Le Fort 1975; Valdiya 1980; Stöcklin 1980; Schelling and Arita 1991). Geologically, the Eastern Himalayas up to the bend in the Brahmaputra can be divided from south to north, into four major tectonic zones — the Siwalik zone, Lesser Himalayan zone, Higher Himalayan zone, and Tibetan-Tethys zone. Each zone has its own historical geotectonic characteristics.

The Siwalik zone is separated from the Indo-Gangetic Plain by the Main Frontal Thrust along which the rocks of the Siwaliks override the sediments of the plains in the south and the Main Boundary Thrust (which is a tectonic plane bringing the older rocks above the rocks of Siwaliks) in the north. These two thrusts are the most active major geological structures and they have generated stress on the rocks of the surrounding thrust zone making the mountains more fragile and unstable. Landslide hazards around these zones are mostly related to the activities of these thrust faults. Likewise folds and faults sap the strength of the mountains. The Siwalik zone is composed of Mio-Pliocene rocks, predominantly mudstone, sandstone, and conglomerates.

The Lesser Himalayan zone located in the hanging wall of the Main Boundary Thrust consists of meta-sedimentary rocks belonging to the Precambrian-Oligocene era with overriding rocks of crystalline nappes and klippen. The crystalline rocks of the Higher Himalayas are thrust over the Lesser Himalayan rocks. They are composed of gneiss, schist, quartzite, and marble. The overlying sedimentary rocks from the Cambrian to the Cretaceous age belong to the Tibetan-Tethys zone. The main rocks in this zone are sandstone, limestone, and shales. The contrasting topography in Nepal and Bhutan and its relationship with geology and structure has been explained by differing tectonic and erosional histories (Duncan et al. 2003). The geomorphology is a result of the interaction of tectonic, climatic, and denudational processes.

The hilly area covering Bangladesh, east India (Assam, Tripura, and Mizoram), and Myanmar lies in the Western Fold Belt of the Indo-Burman Orogeny. Tectonically the belt lies in the Arakan range bounded by the Arakan Trench in the west and Kabaw Fault in the east (Tapponnier and Molnar 1975). It is composed of Miocene-Pliocene rocks. The sandy-argillaceous sediments are folded into NNW-SSE trending anticlines and synclines. This belt consists mainly of the intercalation of shale, claystones, siltstones, and sandstones with occasional intra-formational conglomerates.

Present Status of Hazards and Disasters

Hazards in the HKH related to hydrometeorological conditions, and thus potentially subject to impacts as a result of climate change, can be loosely grouped into hydrological (especially precipitation-related) hazards, which include storms, cloudbursts, floods, landslides, mudflows, and avalanches; droughts and related disasters such as extreme temperatures and wildfires; wind and thunderstorms and related disasters, such as lightning bolts. Adverse effects on human activities resulting from glacial processes, whether direct or indirect, can also be regarded as hazards (Reynolds 1992).

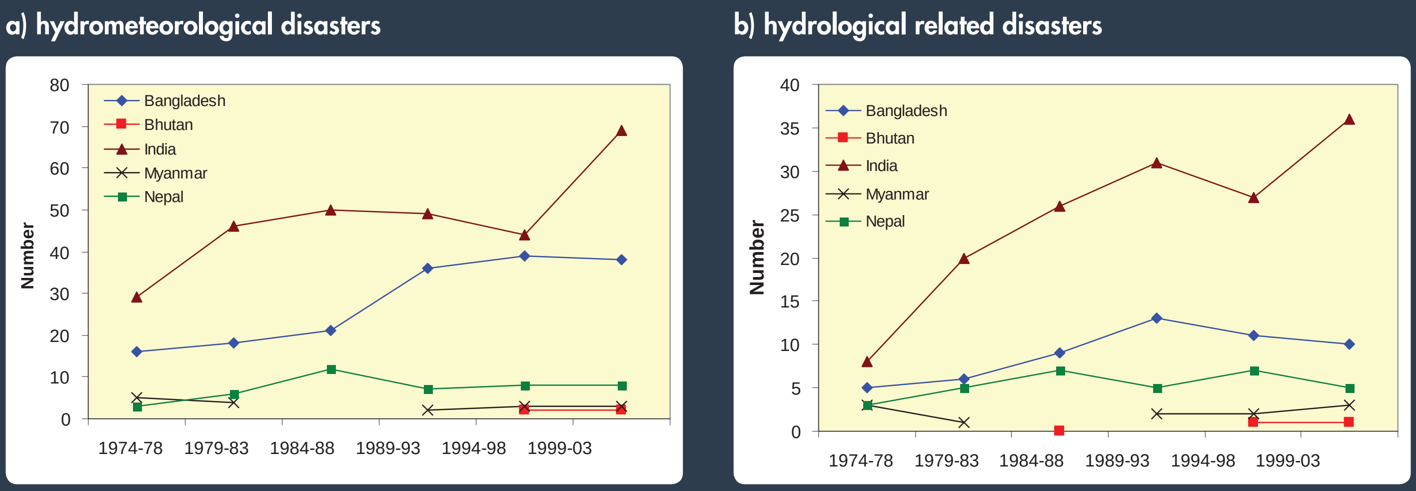
There are very few good data on occurrences of hazards and disasters and their impact on people in the Eastern Himalayas. One of the few long-term data sets is that on natural disasters published by the Centre for Research on the Epidemiology of Disasters (CRED) (Guha-Sapir et al. 2004). The CRED data (Guha-Sapir et al. 2004) can be used to show relative changes and increasing trends in disasters resulting from hydrometeorological conditions between 1974 and 2003 in the Eastern Himalayan countries (Figure 2). However, these data are for the whole of each country, not just the Himalayan part, and show aggregated data for a whole range of natural disasters and all locations, whether mountains or plains. Hydrometeorological disasters are more frequent in whole country statistics because they include typhoons and cyclones. A large country will also suffer from more disasters in total than a small country. Similarly, the impact of floods, for example, is likely to be greater in the plains, whereas landslides will have a greater effect in mountain areas, although cloudburst events in mountain areas can also impact the plains (Figure 3).

Hydrological-related hazards

Steep, sloping, and unstable mountain terrain; extreme relief; and the relatively young mountain chain of the Himalayas, cause the whole region to be vulnerable in economic and ecological terms. The fragile geological structure of the Himalayas facilitates mass wasting more frequently when intense precipitation occurs. Intensification of rainfall in mountain areas can overwhelm the water storage capacity and trigger hill slope failures, leading to loss of life and property in the communities clinging to the steep Himalayan hillsides (Gabet et al. 2004). Scouring of river banks during the monsoon season, even in trans-Himalayan valleys, can render the inhabitants of the area vulnerable (Figure 4).

Rock avalanches and landslides can create landslide damming incidents in the narrow and deep river valleys of antecedent Himalayan rivers (Figure 5). Such events are highly hazardous for the surrounding areas and equally dangerous to the inhabitants, agricultural lands, and infrastructure located in the valleys downstream. Landslide dams in the narrow river valleys can cause impacts of greater magnitude than the initial landslide event (Korup 2005). In September 2003, the valley of Tsatichhu River in Lhuentse, eastern Bhutan was dammed by a huge rock avalanche and landslide and impounded

Figure 2: **Total number of hydrometeorological and related disasters in Bangladesh, Bhutan, India, Myanmar, and Nepal (1974-2003)**



a) hydrometeorological disasters

b) hydrological related disasters

Data source: CRED (2004)

Figure 3: **Impact of flash flood due to the 1993 cloudburst event in the headwater area of Malekhu khola in the Mid Zone of Nepal: half of a bridge on the Prithvi Highway in the plains was washed away. A new bridge can be seen In the background**

Figure 4: **Braided river pattern of the Kali Gandaki river during a period of low flow in May 2003. In the monsoon, full discharge in the river triggers bank collapse due to scouring, rendering Kagbeni village in the alluvial fan of Kagbeni khola, extremely vulnerable**

Figure 5: **Breached landslide dam in the Kali Gandaki river at Thaple Pairo village**

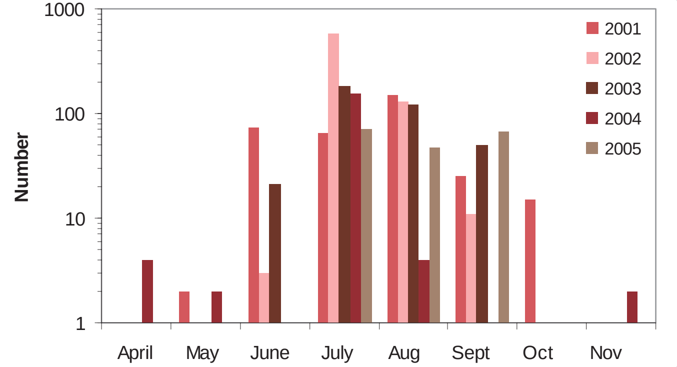
Table 1: **Flood and landslide disaster data for Nepal from 1994 to 2006**

	People			Families affected		Houses destroyed	
Year	Dead	Missing	Injured		Animal Loss	Completely	Partly
1994	49	-	34	3,697	284	569	416
1995	203	-	57	128,540	1,535	5,160	15,820
1996	258	-	73	36,820	1,548	14,037	14,392
1997	78	-	21	5,648	103	994	796
1998	273	-	80	33,549	982	13,990	0
1999	209	94	92	9,768	309	2,220	318
2000	146	351	14	11,167	na	4,357	1,961
2001	196	45	88	7,901	377	2,995	939
2002	441	21	265	38,859	2,024	13,956	4,204
2003	232	58	76	7,167	865	2,683	334
2004	131	11	24	14,238	495	2,552	1,132
2005	141	20	31	2,088	360	1,090	12
2006	114	30	39	18,385	9,980	2,946	388

Source: Home Ministry, Government of Nepal of 4-7 x 10^6 cu.m of water at full lake level (Dunning et al. 2006). Catastrophic collapse of the landslide released a flood wave with a peak discharge of 5,900 cu.m/sec 35 km downstream (Dunning et al. 2006).

Table 1 shows another example of the impacts of hydrological disasters: deaths of people and animals, and other damage, from floods and landslides, between 1994 and 2006 in Nepal, as recorded by the Ministry of Home Affairs. The number of families affected annually by hydrometeorological disasters ranged from 4,000 to nearly 130,000 and deaths from 49 to 441. Livestock losses were much higher than human losses. Losses in terms of dead, missing, and injured people were rare outside the monsoon months of June, July, August, and September (Figure 6). Similarly major landslide events over a 30-year period (1971-2000) in Nepal were found to be concentrated in the higher summer monsoon precipitation zone (Shrestha et al. 2000; Nadim et al. 2006). This illustrates the impact of these events in an area covering 16% of the Eastern Himalayas. Similar impacts are likely in the remaining area although the micro-hydrometeorological characteristics within the region differ as do the sociogeographical conditions.

Figure 6: **Monthly variation in the number of dead, missing, and injured people from floods and landslides in the period 2001 to 2005 in Nepal**



Data source: GoN (2006) and Nepal Red Cross Society (2006)

Cryosphere-related phenomena

There are various types of risk phenomena related to snow and glaciers. Ice and/or snow avalanches can significantly affect communities living at high altitude. One of the more dramatic risks is that of glacial lake outburst floods (GLOFs). As glaciers retreat, glacial lakes can form between the frontal moraine and the retreating glacier. These lakes have a potential to breach their moraine dams, and suddenly release a huge amount of water and debris, known as a glacial lake outburst flood (or GLOF). The outburst has a potential for generating extensive destruction in the valley downstream, destroying infrastructure such as hydropower installations, roads, and others, and rendering communities in the river valley areas vulnerable. Discharge rates from GLOFs in the Himalayas can reach 30,000 cu.m/sec (Richardson and Reynolds 2000). In general, an average lake of 0.02 sq.km contains 6x10^5 cu.m of water (Bajracharya et al. 2007). The impact of such an outburst depends on the physical character of the dam, the lake size and depth and the rapidity of its drainage, and the nearby surroundings (Ives et al 2010).

Recorded past GLOF events include 15 in Nepal, six in Tibet AR, and five in Bhutan (WECS 1987; Yamada 1998; Watanabe and Rothacher 1996; Mool 2001). Glacial lakes in the Himalayas have been growing rapidly since the Little Ice Age and there is a concern that the frequency of GLOFs could increase as a result of accelerated glacial thinning and retreat.

Fluctuations in glacier volumes lead to fluctuations in water resources, and this can lead to increased volumes of meltwater in rivers (during excessive melting) and/or reduced volumes if the glaciers shrink markedly or disappear. Problems with water resources linked to glacial wasting threaten the livelihoods (and lives) of farmers in the hills and plains, and threaten the viability of the growing number of hydropower projects in the region.

Changes in snow and ice

In the Eastern Himalayas significant amounts of snowfall at high altitudes in the summer, and a large part is rapidly lost by melting (Owen et al. 1998). Surface hydrological discharge of snowfed rivers is affected to a significant degree by fluctuations in the glacial mass of the Himalayas. As the glaciers retreat, less precipitation will be stored in the form of snow and ice and more will immediately flow into the river systems. This means both an increase in the risk of flooding and landslides close to the time of precipitation, and an increase in the risk of water shortages during the later dry season.

Impact of Climate Change on the Hazard Scenario

The hazard-related elements in mountains most sensitive to climate change are water resources, glacial lakes, inundation, and landslides. However, increases in hazard levels can be related to many factors, not only climate change. These include, for example, environmental degradation and landuse change. Hence, care must be taken when analysing disasters with respect to climatic factors.

Climate change is projected to compound the pressures on natural resources and the environment: pressures associated with rapid urbanisation, industrialisation, and economic development will increase. Likewise, endemic morbidity and mortality due to diarrhoeal diseases primarily associated with floods and droughts are expected to rise in East, South, and Southeast Asia due to changes in the hydrological cycle (IPCC 2007). It has been predicted that, by the 2050s, the supplies of freshwater in Central, South, East and Southeast Asia will decrease, particularly in large river basins.

Future scenarios of climate change in mountain regions are not easy to determine due to the low spatial resolution of climate models. Nevertheless, as an approximation, the scenarios in surface air temperature and precipitation relative to the baseline period of 1961-1990 indicate that surface warming will be of the order of 1.4±0.3°C in the 2020s, 2.5±0.4°C in the 2050s, and 3.8±0.5°C in the 2080s, considering the combined effect of greenhouse gases and sulphate aerosols (Lal et al. 2001). The scenario of temperature and precipitation change in the Eastern Himalayas using 20-year observational data (1981-2000) also predicts significant changes (Shrestha and Devkota 2010). The highest mean temperature increase of 3.2°C is projected during winter (December – February) and post monsoon (September – November) and the lowest increase of up to 2°C during the pre-monsoon period (March-May), and indicates annual mean temperature increases of 2.9°C by the middle of the 21st century. The area-averaged increase in surface air temperature is likely to be most pronounced over boreal Asia and least in Southeast Asia in all seasons (Lal and Harasawa 2001).

The climate model also projects an increase in rainfall during the monsoon, with a 7% increase in monsoon precipitation over the Eastern Himalayas by the middle of the 21st century, and an increased intensity of extreme rainfall events. These are expected to cause an increase in the frequency and intensity of natural disasters such as floods, landslides, and others in parts of Bangladesh, India, and Nepal (Lal et al. 2001). Changes in the intensity and pattern of the monsoon have already left direct and indirect impacts on the communities in the mountains and adjacent plains, particularly through floods, landslides, and drought.

The potential risk to human lives and activities in the Himalayas from glacier-related phenomena may have increased with climate change. The glacial lakes in the Himalayas are growing in both number and size and bigger floods than heretofore are conceivable (Reynolds 1998; Yamada 1998). Overall, hazards from flash floods, riverine floods, breached landslide-dam floods, and GLOFs are likely to increase. Each of these is associated with morbidity and mortality in the generally poorly-prepared populations.

The Eastern Himalayas are comprised of complex basins that have both seasonal snow and permanent snowfields and glaciers. The hydrological response of a basin consisting of permanent snow and glaciers will be different from that of a basin receiving seasonal snow only. For the complex basin, melt runoff from the portion of the basin that becomes snow-free will be reduced during winter, but runoff from the glaciated part of the basin will increase (Singh and Bengtsson 2003). The resultant impact of climate change on total streamflow depends on the relative contributions from the upper glaciated zone and the lower groundwater storage of each basin. The reduction in total streamflow due to the impact of climate change will threaten the efficacy of water management. Moreover, populations depending on water from snow- and glacier-fed mountain rivers for hydropower, surface irrigation, and agriculture a likely to suffer in the future.

Exploitation of water resources through hydropower generation and irrigation is important for the development of Himalayan countries. Thus water-induced disasters jeopardise the economic status of the countries.

The increase in frequency of disasters due to climate change, and the resultant impact on human systems in the Himalayan region, are critical as the area is home to a large proportion of the global population. The impact of climate change on various sectors needs to be assessed. Proper records of disasters in the Eastern Himalayan countries are needed. Data should be collected systematically on the frequency and distribution of various disasters with respect to location in mountainous areas.

This information is needed as a basis for developing appropriate adaptation measures for climate change, and implementing appropriate mitigation actions against climate change related disasters in order to reduce the risk of economic loss and threat to lives in the Himalayan countries.

Gaps in Hazard Research

Inter- and multidisciplinary approaches, which include the natural, social, health, and engineering sciences, are important in mountain research. A concerted effort to improve research and long-term monitoring is required in order to address the gaps in our knowledge about what is happening to ice and snow and hazards in general, and their effects on the climate, biodiversity, and human wellbeing. Likewise, integrated model-based studies of environmental change in the Himalayan region, including variations in the monsoon, are urgent. More clarity is needed concerning future changes in weather patterns.

There is a paucity of data and publications on observed extreme weather events such as cold days and nights, hot days and nights, heat waves, and frequency of heavy precipitation events in the region. Projections of relative changes in runoff by the end of the 21st century are less reliable for lower latitudes, especially those in the monsoon region (IPCC 2007). Further research is needed in the following areas:

- The locations of glacial hazard areas in the Eastern Himalayas and their potential threats; this is needed for decisions on national investments in large projects.
- Snow avalanche forecasting and risk mapping
- The vulnerability of local people to natural disasters such as avalanches, GLOFs, landslides, and debris flows; and ways to reduce these by limiting human activities in zones where there are potentials for natural hazards.

Recommendations for Adaptation Strategies

People in the region have adapted by changing livelihood, agricultural, and cultural practices to cope with the uncertainty of climate change, variability, and extremes: they have even accepted enormous losses. Although cultural norms affect people's adaptive choices, new occupations and livelihood practices which are socially and culturally unacceptable have been adopted, in some cases in response to climate-related changes and stress (ICIMOD 2009). Social networks and local institutional support with good governance and planning are vital for enhancing adaptive capacities for collective water management, equitable distribution of irrigation facilities, livestock management, communal grazing, and development of infrastructure for flood management and water security (ICIMOD 2009). For example, the water distribution system in an environment of persistent drought in Mulkhow, Pakistan, is determined according to the extent of the land being irrigated, incorporating day- and night-time routines depending on the geographical location and potential for loss through evaporation. Similarly, the social code of conduct plays a vital role in management. In addition, attention is paid to the affect of short-term gains which can have long-term effects on society. National institutional support is essential during formulation of new policies in order to increase the effectiveness of adaptive measures.

Extreme weather conditions can result in disasters; policymakers should focus on adaptation to the risks posed by climate change, and preparation for disasters. Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account damage from climate change, co-benefits, sustainability, equity, and attitudes to risk (IPCC 2007). It is understood that neither adaptation nor mitigation alone can avoid all climate-change impacts; however, they can complement each other and together can significantly reduce the risks from climate change (IPCC2007).The following adaption strategies are identified.

- Policy and strategy
- Institutional capabilities
- Adaptation measures

Policy and strategy

Some hazard issues have international dimensions, hence, managing risks of such extreme hazards requires intergovernmental cooperation. The key development sectors that are directly affected by climate change are human health; water supply and sanitation; energy; transport; industry, mining, construction; trade and tourism; agriculture, forestry, fisheries; environmental protection, and disaster management (World Bank 2006).

Policy responses should lead to coordinated action by government and non-government organisations towards protecting the environment in the mountains and uplands and helping local populations adapt to changing ecological, economic, and health-related impacts. Policies should also aim to convince key global actors such as the World Trade Organization (WTO) to take mountain issues into consideration in the planning of future trade accords and commercial practices. Recognition of the adverse impacts of climate change and extreme events on future development, and incorporation of this recognition in policy and strategy documents are the approaches taken by governments in the countries covering the Eastern Himalayas.

Adaptation and disaster-risk reduction activities should be integrated into climate risk management. Even though climate change is a long-term environmental problem, it should be treated as a major economic and social risk to national economies. Therefore, it is necessary to address it through reducing vulnerability over the short term in order to reduce the possibility of long-term impacts.

Adaptation activities should be integrated into existing development programmes (Alam and Regmi 2004). Participation of and cooperation from different stakeholders such as government policy makers, implementing agencies, development partners, the private sector, and communities are required. Policies should mainstream adaptation activities in sectoral activities: policies, efforts, and strategies adopted to cope with the impacts of hazards should be modified to address the integrated impacts caused by climate change.

Institutional capability

Although governments in the region have established bodies to study and address climate-change issues, several aspects need strengthening. Improvements are needed in gathering and sharing information and data; public-government partnerships need strengthening; inter-departmental coordination should be improved; and better regional collaboration should be undertaken. Most importantly, focus should be given to the development of technical expertise and human resources.

Up-to-date scientific data on climatic parameters and their impacts should be collected in a systematic manner in collaboration with government agencies, academia, and local-level partners so that adaptation and mitigation measures can be established. Data banks can be kept up to date by sharing the data among partner countries in the region. In this way it will be possible to construct regional climatic models for understanding the climate mechanism. Listing appropriate parameters and analysing them should be the first step towards devising effective adaptation measures.

School science and local-level awareness programmes can be advantageous for local communities since they can become directly involved in the choice of suitable adaptation measures (Eriksson et al. 2009).

A tool for screening climate risks should be prepared for quick risk assessments of development projects. The tool should assess whether projected climate changes might increase or reduce risks, thus assisting planners to make appropriate decisions. This is especially important in the case of hydropower projects which have a lot of scope in mountain countries such as Nepal and Bhutan and offer great opportunities for national development. Identifying the appropriate type of hydropower project (run-of-the river or storage) is a step towards the sustainability of hydropower projects. Other options for water storage (ponds, lakes, and aquifer recharges) should be identified with reference to the geographical regions and be implemented in the context of hydrological, geological, and climatic parameters.

Adaptation measures

There are many techniques that can contribute towards better environmental planning and management, notably tools for pollution control, waste reduction, transport planning, environmental impact assessment, capacity studies, strategic environmental plans, and state of the environment reports. Options and measures for adaptation can be categorised broadly as soft measures and hard measures. Soft measures are improvement in observation and forecasting, development of early warning systems, mapping of hazards and vulnerabilities, community awareness and participation, and conservation of forests and water.

Adaptation measures should focus on capacity building and work on reducing the impacts of climate change: they include climate forecasting for agriculture and livestock production; integrated natural resource management plans; exploration of current coping responses adopted by communities facing climatic extremes; analysis of droughts; examination of the impacts of floods and mass movements; and providing appropriate response mechanisms in a variable and changing climate.

Climate change is altering the risks of disaster and can lead to adaptation. An effective adaptation strategy could be improvement in local capacities to adapt to climate change through limiting environmental hazards or their consequences on health. Social processes generate unequal exposure to risk by making some people more vulnerable than others. These inequalities exist in every society and more so in the Himalayan region. The multifaceted nature of disasters in which climate-related processes coalesce with environmental degradation, conflict, disease, and poverty bring about and magnify the loss and damage caused by natural hazards. Socioeconomic development and institution-building are important ways of reducing the vulnerability associated with disasters. The vulnerability of the Eastern Himalayas is associated closely with changes in the water regime. Several adaptation options and measures are possible. Regarding management of disasters related to climate change, in addition to the short-term approach to response and recovery, long-term goals such as improving awareness, preparedness, and risk reduction are essential. Disaster risk reduction through vulnerability reduction is the major aspect of adaptation to impacts of climate change. Capacity-building of local communities through community-based approaches using critical assessment of their strengths and weaknesses is necessary as capacities vary from community to community and according to geographical region.

Hard measures include engineering projects to reduce vulnerability and are more expensive than soft measures. These include mitigating GLOF risks, expanding irrigation and storage, and promoting reservoir hydropower instead of run-of-the river for electricity generation so that supplementary water supplies are available for domestic and agricultural use during dry seasons.

Integrated adaptation measures should incorporate improved public health programmes to meet increasing threats from disease resulting from climate change: such measures should be included in regional development plans.

Conclusions

There is evidence of climate change in the Himalayas as in other parts of the world. In the past, the region has experienced several warming and cooling events such as those of the Last Glacial Maximum and the Little Ice Age. The Eastern Himalayan region is influenced strongly by the Asian monsoon system. Changes in the intensity and pattern of the monsoon in mountain areas can lead to increases in natural hazards such as floods, landslides, and drought; this increase is facilitated by the fragile geological structure of the mountains. Climate change in mountain areas can lead to a reduction in the area of glaciers and snowfields; resultant reductions in water sources may have severe impacts on irrigation and drinking water supplies as well as on the reliability of hydroelectricity generation.

The potential risks to humans and their activities from glacier-related phenomena such as glacier lake outburst floods are likely to increase. Several lakes in the Himalayas have the potential to burst catastrophically.

There appears to be an increasing incidence of disasters related to hydrometeorological influences, especially changes in rainfall patterns. However, there is a lack of data and publications on observed extreme weather events such as cold days and nights, hot days and nights, heat waves, and frequency of heavy precipitation events, which limits making projections for the region as a whole.

Detailed field-based hazard assessment on the effects of climate change and delineation of vulnerable areas located in complex geographical and climatic regions is necessary.

The lack of systematic and standardised data collection on disasters in the countries of the Eastern Himalayas makes long-term planning for disaster preparedness and response difficult. In addition, the region has limited climatological records in terms of the temporal and spatial adequacy to characterise and uncover significant changes in physical and biological systems. There is an urgent need for research in various aspects related to climate change. A representative model of the regional climate system should be generated as a foundation for future planning.

Management of risks from extreme hazards requires coordination among communities involved with climate change, disasters, and development so that disaster management can be improved. In totality, a holistic approach to the problems faced currently by many mountain regions is necessary. Sufficient finances, networking to share important information, and promoting public awareness are important in terms of formulating an appropriate response to climate change. Integrated adaptation measures should be implemented in order to define and facilitate specific adaptations and policy options to meet the anticipated impacts of climate change.

References

Alam, M; Regmi, BR (2004) *Adverse impacts of climate change on development of Nepal: Integrating adaptation into policies and activities*, Working paper No 3. Dhaka: Bangladesh Centre for Advanced Studies

Alam, M; Tshering, D (2004) *Adverse impacts of climate change on development of Bhutan: Integrating adaptation into policies and activities*, Working paper No 2. Dhaka: Bangladesh Centre for Advanced Studies

Bajracharya, SR; Mool, PK; Shrestha, BR (2007) *Impact of climate change on Himalayan glaciers and glacial lakes: Case studies on GLOF and associated hazards in Nepal and Bhutan*. Kathmandu: ICIMOD

Barry, R; Chorley, R (2003) *Atmosphere, weather, and climate* (6th edn). London: Routledge

Benedict, JB (1976) 'Khumbu glacier series.' *Nepal: Radiocarbon* 18:177-178

Benn, D; Owen, L (1998) 'The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: Review and speculative discussion.' *Journal of the Geological Society* 155(2):353-363

Bryson, RA; Swain, AM (1981) 'Holocene variations of monsoon rainfall in Rajasthan.' *Quaternary Research* 16(2): 135-145

Caine, N; Mool PK (1982) 'Landslide in the Kolphu Khola drainage, middle mountains, Nepal.' *Mountain Research and Development* 2(2):157-67

Chikita, K; Jha, J; Yamada, T (2001) 'Sedimentary effects on the expansion of a Himalayan supraglacial lake.' *Global and Planetary Change* 28(1-4):23-34

Clapperton, C (1990) 'Quaternary glaciations in the southern Hemisphere: An overview.' *Quaternary Science Reviews* 9(2-3):299-304

Clemens, S; Prell, W; Murray, D; Shimmield, G; Weedon, G (1991) 'Forcing mechanisms of the Indian Ocean monsoon.' *Nature* 353(6346):720-725

Guha-Sapir, D; Hargitt, D; Hoyois, P (2004) *Thirty years of natural disasters 1974-2003: The Numbers*. Belgium: Université Catholique de Louvain

Denniston, RF; González, LA; Asmerom, Y; Sharma, RH; Reagan, MK (2000) 'Speleothem evidence for changes in Indian summer monsoon precipitation over the last 2300 years.' *Quaternary Research* 53(2): 196-202

Dettman, DL; Kohn, MJ; Quade, J; Ryerson, FJ; Ojha, TP; Hamidullah, S (2001) 'Seasonal stable isotope evidence for a strong Asian monsoon throughout the past 10.7 my.' *Geology* 29(1):31-34

Duncan, C; Masek, J; Fielding, E (2003) 'How steep are the Himalaya? Characteristics and implications of along-strike topographic variations.' *Geology* 31(1):75-78

Dunning, SA; Rosser, NJ; Petley, DN; Massey, CR (2006) 'Formation and failure of the Tsatichhu landslide dam, Bhutan.' *Landslides* 3(2): 107-113

Eamer, J; Lambrechts, C; Prestrud, P; Young, O (2007) 'Policy and perspectives.' In Eamer, J (ed) *Global outlook for ice and snow*, pp 215-228. Nairobi: UNEP

Eriksson, E; Xu Jianchu; Shestha, AB; Vaidya, RA; Nepal, S; Sandström, K (2009) *The changing Himalayas: Impact of climate change on water resources and livelihoods in the greater Himalayas*. Kathmandu: ICIMOD

Enzel, Y; Ely, LL; Mishra, S; Ramesh, R; Amit, R; Lazar, B; Rajaguru, SN; Baker, VR; Sandler, A (1999) 'High-resolution Holocene environmental changes in the Thar Desert, northwestern India.' *Science* 284(5411): 125

Finkel, RC; Owen, LA; Barnard, PL; Caffee, MW (2003) 'Beryllium-10 dating of Mount Everest moraines indicates a strong monsoon influence and glacial synchroneity throughout the Himalaya.' *Geology* 31(6): 561-564

Fort, M (2000) 'Glaciers and mass wasting processes: their influence on the shaping of the Kali Gandaki valley (higher Himalaya of Nepal).' *Quaternary International* 65/66: 101-119

France-Lanord, C; Derry, LA (1994) 'δ^{13}C of organic carbon in the Bengal Fan: Source evolution and transport of C_3 and C_4 plant carbon to marine sediments.' *Geochimica et Cosmochimica Acta* 58(21):4809-4814

France-Lanord, C; Métivier, F (2002) 'Le message sédimentaire: Un enregistrement des relations entre surrection, érosion et climat.' In Avouac, JP; De Wever, P (eds) *Himalaya-Tibet: le choc des continents,* pp 114-122. Paris: CNRS et Muséum National d'Histoire Naturelle

Fushimi, H (1978) 'Glaciations in the Khumbu Himal.' *Sepyo* 40: 71-77

Gabet, EJ; Burbank, DW; Putkonen, JK; Pratt-Sitaula, BA; Ojha, T (2004) 'Rainfall thresholds for landsliding in the Himalayas of Nepal.' *Geomorphology* 63(3-4): 131-143

Gajurel, AP (2006) *Etude sédimentologique et géochimique (isotopes stables) des bassins syn-orogéniques de l'Himalaya du Népal (Siwaliks et bassin de Kathmandu)*. Doctoral thesis, Université Joseph Fourier, Grenoble, France

Gansser, A (1964) *The geology of the Himalayas*. London: Interscience

Gillespie, A; Molnar, P (1995) 'Asynchronism of mountain and continental glaciations.' *Reviews of Geophysics* 33: 311-364.

GoN (2006) *Disaster data of Nepal*. Kathmandu: Government of Nepal, Home Ministry

Gregory, S (1989) 'Macro-regional definition and characteristics of Indian summer monsoon rainfall, 1871-1985.' *International Journal of Climatology* 9: 465-483

Guha-Sapir, D; Hargitt, D; Hoyois, P (2004) *Thirty years of natural disasters 1974 -2003: The numbers*. Brussels: Centre for Research on the Epidemiology of Disasters (CRED)

Hanisch, J; Delisle, G; Pokhrel, AP; Dixit, AP; Reynolds, JM; Grabs, WE (1998) 'The Thulagi glacier lake, Manaslu Himal, Nepal: Hazard assessment of a potential outburst.' In Moore, D; Hunger, O (eds) *Proceedings of the 8th International Congress, International Association for Engineering Geology and Environment, 21-25 September 1998, Vancouver, Canada*, pp 2209-2215. Vancouver: Tire-A-Art Offprint

Hastenrath, S (1991) *Climate dynamics of the tropics*. Dordrecht: Kluwer Academic Publishers

Hisatomi, K; Tanaka, S (1994) 'Climatic and environmental changes at 7 and 7.5 Ma in the Churia (Siwalik) Group, west central Nepal.' *Himalayan Geology* 15:161-180

ICIMOD (2009) *Local responses to too much and too little water in the Greater Himalayan region*. Kathmandu: ICIMOD

Metz, B; Davidson, O; Swart, R; Pan, J (eds) (2001) *Climate change 2001: Mitigation* – Contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

IPCC (2007) *Climate change 2007: The physical science basis* – Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, summary for policymakers. Cambridge: Cambridge University Press

Johnson, RH; Houze, RA (1987) 'Precipitating cloud systems of the Asian monsoon.' In Chang, CP; Krishnamurti, TN (eds) *Monsoon meteorology, pp 298-353*. Oxford: Oxford University Press

Karma, A; Ageta, Y; Naito, N; Iwata, S; Yabuki, H (2003) 'Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalayas.' *Bulletin of Glaciological Research* 20: 29-40

Konagaya, Y (2005) 'Characteristics of natural hazards in Bhutan.' In Yoshida, M; Upreti, BN; Bhattarai, TN; Dhakal, S (eds) *Natural disaster mitigation and issues on technology transfer in south and southeast Asia*, proceedings of the JICA regional seminar October 2004, pp 25-41. Kathmandu: Tribhuvan University, Department of Geology

Korup, O (2005) 'Geomorphic hazard assessment of landslide dams in South Westland, New Zealand: Fundamental problems and approaches.' *Geomorphology* 66: 167-188

Kroon, D; Steens, T; Troelstra, SR (1991) 'Onset of monsoonal related upwelling in the western Arabean Sea as revealed by plantonic foraminifers.' In Prell, WL; Niitsuma, N (eds) *Proceedings of the Ocean Drilling Program, Scientific results,* pp 257-263. Texas: College Station

Lal, M; Harasawa, H (2001) 'Future climate change scenarios for Asia as inferred from selected coupled atmosphere-ocean global climate models.' *Journal of the Meteorological Society of Japan* 79(1): 219-227

Lal, M; Harasawa, H; Murdiyarso, D (2001) 'Asia.' In McCarthy, JJ; Canziani, OF; Leary, NA; Dokken, DJ; White, KS (eds) *Climate change 2001: Impacts, adaptation, and vulnerability* – Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, pp 533-590. Cambridge: Cambridge University Press

Le Fort, P (1975) 'Himalayas: The collided range-present knowledge of the continental arc.' *American Journal of Science* 275A: 1-44

Manabe, S; Hahn, DG (1977) 'Simulation of the tropical climate of an Ice Age.' *Journal of Geophysical Research* 82: 3889-3911

Molnar P; England, P; Martinoid, J (1993) 'Mantle dynamics, uplift of the Tibetan Plateau, and the Indian Monsoon.' *Reviews of Geophysics* 31(4): 357-396

Monecke, K; Winsemann, J; Hanisch, J (2001) 'Climatic response of Quaternary alluvial deposits in the upper Kali Gandaki valley (West Nepal).'*Global and Planetary Change* 28:293-302

Mool, PK; Bajracharya, SR (2003) *Inventory of glaciers, glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of the Himalayan region: Tista Basin, Sikkim Himalaya, India.* Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu

Mool, PK (1995) 'Glacier lake outburst floods in Nepal.' *Journal of Nepal Geological Society* 11:273-280

Mool, PK (2001) *Glacial lakes and glacial lake outburst floods,* Mountain Development Profile No 2. Kathmandu: ICIMOD

Mool, PK; Bajracharya, SR; Joshi, SP (2001a*) Inventory of glaciers, glacial lakes, and glacial lake outburst floods: Monitoring and early warning systems in the Hindu Kush-Himalayan regions – Nepal*. Kathmandu: ICIMOD

Mool, PK; Bajracharya, SR; Joshi, SP (2001b*) Inventory of glaciers, glacial lakes, and glacial lake outburst floods: Monitoring and early warning systems in the Hindu Kush-Himalayan regions – Bhutan*. Kathmandu: ICIMOD

Muller, F (1980) 'Present and Late Pleistocene equilibrium line altitudes in the Mt. Everest region - An application of the glacier inventory.' In *Proceedings of the World Glacier Inventory Workshop,* at Riederalp, Switzerland, IAHS-AISH Publication N. 126: 75-93. Wallingford (UK): IAHS

Murakami, T (1987) 'Effect of the Tibetan Plateau.' In Chang, CP; Krishnamurti, TN (eds) *Monsoon meteorology,* pp 235-270. Oxford: Oxford University Press

Nadim, F; Kjekstad, O; Domaas, U; Rafat, R; Peduzzi, P (2006) 'Global landslides risk case study.' In Nadim, F; Kjekstad, O; Domaas, U; Rafat, R; Peduzzi, P (eds) *Natural Disaster Hotspots Case Studies,* pp 21-77. Washington: The World Bank

Nakawo, M; Rana, B (2003) 'Estimate of ablation rate of glacier ice under a supraglacial debris layer.' *Geografiska Annaler* 81(4):695-701

Nepal Red Cross Society (2006) *Disaster data of Nepal*. Kathmandu: Nepal Red Cross Society

Nigrini, C (1991) 'Composition and biostratigraphy of radiolarian assemblages from an area of upwelling (northwestern Arabian Sea, leg 117).' *Proceedings [of the] Ocean Drilling Program, Science Results* 117:89-126

Owen, LA; Derbyshire, E; Fort, M (1998) 'The Quaternary glacial history of the Himalaya.' *Journal of Quaternary Science* 13:91-120

Owen, LA; Mitchell, W; Bailey, RM; Coxon, P; Rhodes, E (1997) 'Style and timing of glaciations in the Lhul Himalaya, northern India: A framework for reconstructing late Quaternary paleoclimatic change in the western Himalayas.' *Journal of Quaternary Research* 12(2):83-109

Pant, SR; Reynolds, JM (19990 'Subsurface electrical imaging techniques for the investigation of Thulagi Glacier Lake dam.' *Journal of Nepal Geological Society* 20:80

Pratt, B; Burbank, DW; Heimsath, A; Ojha, T (2002) 'Impulsive alluviation during early Holocene strengthened monsoons, central Nepal Himalaya.' *Geology* 30(10): 911-914

Pratt-Sitaula, B; Burbank, DW; Heimsath, A; Ojha, T (2004) 'Landscape disequilibrium on 1,000-10,000 year scales Marsyandi River, Nepal, central Himalaya.' *Geomorphology* 58:223-241

Prell, WL; Kutzbach, JE (1992) 'Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution.' *Nature* 360(6405): 647-652

Price, M; Kohler, T; Wachs, T (eds) (2000) *Mountains of the world: Mountain forests and sustainable development.* Berne: University of Berne, Centre for Development and Environment

Quade, J; Cater, JML; Ojha, TP; Adam, J; Mark Harrison, T (1995) 'Late Miocene environmental change in Nepal and the northern Indian subcontinent: Stable isotopic evidence from paleosols.' *Geological Society of America Bulletin* 107(12):1381-1397

Ramstein, G; Fluteau, F; Besse, J; Joussaume, S (1997) 'Effect of orogeny, plate motion and land-sea distribution on Eurasian climate change over the past 30 million years.' *Nature* 386(6627):788-795

Reynolds, JM (1992) 'The identification and mitigation of glacier related hazards: Examples from the Cordillera Blanca, Peru.' In McCall, GJH; Laming, DJC; Scott, SC (eds) *Geohazards,* pp 143-157. London: Chapman and Hall

Reynolds, JM (1998) 'High-altitude glacial lake hazard assessment and mitigation: A Himalayan perspective.' In Maund, JG; Eddleston, M (eds) *Geohazards in Engineering Geology,* Engineering Geology special publications No 15, pp 25-34. London: Geological Society

Richardson, SD; Reynolds, JM (2000) 'An overview of glacial hazards in the Himalayas.' *Quaternary International* 65/66:31-47

Schelling, D; Arita, K (1991) 'Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal Himalaya.' *Tectonics* 10(5):851-862

Sharma, E (2007) 'Biodiversity resources of the eastern Himalaya: Challenges to climate change.' Paper presented at the Nepal stakeholder workshop on Climate Change and Vulnerability of Mountain Ecosystems in the Eastern Himalayan Region, 12-13 December 2007, Kathmandu, Nepal

Shrestha, AB; Wake, CP; Mayewski, PA; Dibb, JE (1999) 'Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971-94.' *Journal of Climate* 12(9):2775-2787

Shrestha, AB; Devkota, LP (2010) *Climate change in the Eastern Himalayas: Observed trends and model projections*; Climate change impact and vulnerability in the Eastern Himalayas – Technical report 1. Kathmandu: ICIMOD

Shrestha, AB; Wake, CP; Dibb, JE; Mayewski, PA (2000) 'Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large-scale climatological parameters.' *International Journal of Climatology* 20(3):317-327

Singh, P; Bengtsson, L (2004) 'Hydrological sensitivity of a large Himalayan basin to climate change.' *Hydrological Processes* 18(13):2363-2385

Stöcklin, J (1980) 'Geology of Nepal and its regional frame.' *Geological Society of London Journal* 137:1-34

Tapponnier, P; Molnar, P (1975) 'Major strike-slip faulting in China: Its significance for Asian tectonics.' *Seismological Society of America, Annual Meeting 7*: 425-426

Tsukamoto, S; Asahi, K; Watanabe, T; Rink, WJ (2002) 'Timing of past glaciations in Kanchenjunga Himal, Nepal, by optically stimulated luminescence dating of tills.' *Quaternary International 97*:57-67

Upreti, BN (1999) 'An overview of the stratigraphy and tectonics of the Nepal Himalaya.' *Journal of Asian Earth Sciences* 17(5-6):577-606

Valdiya, KS (1980) *Geology of Kumaun Lesser Himalaya.* Dehradun: Wadia Institute of Himalayan Geology

Vuichard, D; Zimmermann, M (1986) 'The Langmoche flash-flood, Khumbu Himal, Nepal.' *Mountain Research and Development* 6 (1):90-93

Vuichard, D; Zimmermann, M (1987) 'The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: Cause and consequences.' *Mountain Research and Development* 7(2): 91-110

Watanabe, T; Rothacher, D (1996) 'The 1994 Lugge Tso glacial lake outburst flood, Bhutan Himalaya.' *Mountain Research and Development* 16(1): 77-81

WECS (1987) *Study of glacier lake outburst floods in the Nepal Himalaya: Phase 1,* Interim report, May 1987, Report No 4/1/200587/1/1, Seq. No 251. Kathmandu: WECS

Whiteman, D (2000) *Mountain meteorology.* Oxford: Oxford University Press

World Bank (2006) *Managing climate risk: Integrating adaptation into World Bank Group Operations.* Washington DC: World Bank

Xu Daoming (1988) 'Characteristics of debris flow caused by outburst of glacial lake in Boqu River, Xizang, China, 1981.' *GeoJournal* 17(4): 569-580

Yamada, T (1998) *Glacier Lake and its outburst flood in the Nepal Himalaya,* Monograph No 1. Tokyo: Japanese Society of Snow and Ice, Data Center for Glacier Research

Zech, W; Glaser, B; Abramowski, U; Dittmar, C; Kubik, PW (2003) 'Reconstruction of the Late Quaternary glaciation of the Macha Khola valley (Gorkha Himal, Nepal) using relative and absolute (^{14}C, ^{10}Be, dendrochronology) dating techniques.' *Quaternary Science Reviews* 22: 2253-2265

Acronyms and Abbreviations

cal ka BP	thousand calendar years before present
CO_2	carbon dioxide
GLOF	glacial lake outburst flood
HKH	Hindu Kush-Himalayas/n
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
RMC	regional member country
Tibet AR	Tibet Autonomous Region of China

Acknowledgements

ICIMOD expresses its sincere thanks and gratitude to its regional member countries for their extended support during this study. ICIMOD acknowledges the MacArthur Foundation for supporting the initiative by funding the project, and GTZ for co-financing through ECES programme funding. The Centre especially acknowledges the support of all the experts and researchers who have contributed to the technical papers and helped to strengthen understanding of the potential impact of climate change on biodiversity and other natural resources in the Eastern Himalayas. ICIMOD is also grateful for the assistance provided by various government agencies, partners from the RMCs, NGOs, and INGOs, all of whom contributed to developing this valuable information about the Eastern Himalayas.

The assessment team comprised Birendra Bajracharya, Nakul Chettri, Mats Eriksson, Fang Jing, Brigitte Leduc, Pradeep Mool, Bandana Shakya, Eklabya Sharma, Rita Sharma, Rajendra Shilpakar, Arun Shrestha, Rajesh Thapa, and Karma Tsering.

Technical contributions were received from Dhrupad Choudhury, Joy Dasgupta, Anupa Lamichhane, Krishna P. Oli, Manisha Sharma, Kabir Uddin (all ICIMOD); SK Barik (North Eastern Hill University, Shillong, India); LP Devkota (Tribhuvan University, Nepal); Karpo Dukpa (Ministry of Agriculture, Policy and Planning Division, Bhutan); AP Gajurel (Tribhuvan University, Nepal); Brij Gopal (National Institute of Ecology, New Delhi, India); AK Gosain (Indian Institute of Technology, New Delhi, India); Sandhya Rao (Integrated Natural Resource Management Consultants, New Delhi, India); Janita Gurung (Nepal); D Pathak (Tribhuvan University, Nepal); Kamal Raj Rai (Namsaling Community Development Center, Ilam, Nepal); and Nitesh Shrestha (Nepal)

The authors are thankful to Madhav Karki, Deputy Director General, ICIMOD. Samjwal R Bajracharya, MENRIS, ICIMOD, is thanked for his constructive suggestions on the manuscript. The authors are grateful to SM Rai for allowing them to use his photograph.

Series editor
Eklabya Sharma

Production team
Greta Rana (Consultant editor)
A Beatrice Murray (Senior editor)
Dharma R. Maharjan (Layout and design)
Asha Kaji Thaku (Editorial assistant)

Publication details

Published by International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal

ISBN 978 92 9115 164 6 (electronic)

LCCN 2010-319009

Citation: Pathak, D; Gajurel, AP; Mool, PK (2010) *Climate change impacts on hazards in the Eastern Himalayas;* Climate change impact and vulnerability in the Eastern Himalayas – Technical report 5. Kathmandu: ICIMOD

About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

About MacArthur Foundation

The MacArthur Foundation supports creative people and effective institutions committed to building a more just, verdant, and peaceful world. In addition to selecting the MacArthur Fellows, the Foundation works to defend human rights, advance global conservation and security, make cities better places, and understand how technology is affecting children and society.

International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Khumaltar, Lalitpur, Nepal
Tel +977-1-5003222 **email** info@icimod.org www.icimod.org