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Climate change and its impacts on glaciers and water resource management in the Himalayan Region

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The greater Himalayan region sustains about 150 million people. Glacial melt provides important contributions to river flow. The region is highly vulnerable with respect to climate chance. The report describes the impact of climate change on glaciers and consequently on water resources of the region.

Introduction

Climate change is currently taking place at an unprecedented rate and will have potentially profound and widespread effects on the availability of and access to water resources. The mean global temperature rose by 0.74 °C over the past century. The rate of warming in the Himalayan region has been even greater than global average (Shrestha et al. 1999; Liu and Chen 2000).

Climate is an important determinant of water resources. Rising temperatures associated with changes in precipitation and evaporation are predicted to lead to changes in soil moisture, river flow, and groundwater. Melting glaciers are early indicators of climate change unlike the response of the forests which is slower and takes place over a long period of time. The Himalayan region provides an ideal environment for monitoring the response of regional hydrology to climate change because of steep climate gradients across elevation and latitude. Mountain glaciers are important environmental components of local, regional, and global hydrological cycles. As the climate warms, the water resource factors may also change, as evaporation may well increase and the quantities, timing, and reliability of supply may change.

The greater Himalayan region sustains approximately 150 million people. Additionally, changes in this vast region impact the lives of over 1.3 billion people living in the basins of rivers originating in the Himalayans, and on almost 3 billion people when downstream coastal zones are taken into account (Xu et al. 2007). The Himalayas are shared by Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan and are interwoven with nine major river basins – the Indus, Ganges, Brahmaputra (Yarlungtsanpo), Irrawaddy, Salween (Nu), Mekong (Lancang), Tarim, Yangtse (Jinsha), and Yellow River basins (Huanghe). Glacial melt provides important contributions to river flow, varying from the lowest rate of 1.3 % for the Yellow River to the highest rate of 40.2 % for the Tarim and 44.8 % for the Indus basin (Table 1). Mountain hydrology is extremely sensitive to climate change and many glaciers in the region have retreated considerably in the last two decades. The formation and growth of many glacial lakes, possibly due to the rapid retreat of glaciers, could lead to catastrophic outburst floods (Vuichard and Zimmermann 1986).

Landscapes in the Himalayas form a complex mosaic of rocks, glaciers, alpine meadows and wetlands at high altitude, human settlements, farmlands, home gardens, lakes and rangelands at middle altitudes, and paddy and wetlands at lower levels. As a result, the Himalayas offer a range of habitats for all life forms and a diversity of livelihoods. Glaciers, as a source of water, have immediate impacts on human societies in the mountains and surrounding lowlands as people rely on fresh water for domestic purposes, irrigation, hydropower, and industrial use, as well as environmental flow and other ecosystem functioning. Glaciers, together with high altitude wetlands and lakes, are

Table 1 Principal rivers of the Himalayan region – basic statistics

	River		River Basin			
	Mean discharge (m^3/s)	Glacial melt in river flow (%)	Area (km^2)	Population x 1000	Population density (km^2)	Water availability (m^3/person/year)
Indus	5,533	44.8	1,081,718	178,483	165	978
Ganges	18,691	9.1	1,016,124	407,466	401	1,447
Brahmaputra	19,824	12.3	651,335	118,543	182	5,274
Irrawaddy	13,565	Small	413,710	32,683	79	13,089
Salween	1,494	8.8	271,914	5,982	22	7,876
Mekong	11,048	6.6	805,604	57,198	71	6,091
Yangtze	34,000	18.5	1,722,193	368,549	214	2,909
Yellow	1,365	1.3	944,970	147,415	156	292
Tarim	146	40.2	1,152,448	8,067	7	571
Total				1,324,386		

Source: IUCN/ IWMI, Ramsar Convention and WRI 2003; Mi and Xie 2002; Chalise and Khanal 2001; Merz 2004
Note: Hydrological data may differ depending on the location of gauging stations. The contribution of glacial melt is based on limited data and should be taken as indicative only.

considered 'water towers', as well as indicators of climate change and have impacts on sea levels. (Meier 1984). It has been estimated that about 30 % of the water resources in the eastern Himalayas are derived from the melt of snow and ice; this proportion increases to about 50 % in the central and western Himalayas and becomes as high as 80 % in the Karakoram. As a result of global warming, significant quantities of water are being released from long-term storage as glacier ice. In the short term this may result in an increase in water supplies (higher water levels in high altitude lakes and increased stream flows), but in the long term, as glaciers disappear, water supplies from glacial melt will decline. Water is necessary for all life forms, but it also can be dangerous and destructive (Weingartner et al. 2003). Intense seasonal precipitation during the Himalayan monsoons can trigger hazard events at different elevations. While snow avalanches and glacial lake outburst floods (GLOFs) predominate at very high elevations (>3500 m), landslides, debris flows, and flash floods are common in the mid-elevation mountains (500 – 3500 m). Floods are the principal hazards in the lower valleys and plains.

Mountain ranges also have a great deal of influence on local and regional climates and are considered a critical element of the climate system (Beniston et al. 1997). The Himalayas play an important role in the global climate. At mid latitudes, the Himalayas are one of the trigger mechanisms of cyclogenesis through their perturbation of large-scale atmospheric flow patterns. Seasonal blocking episodes with associated anomalies in temperature and precipitation are also closely linked to the presence of mountains that act as orographic barriers to the flow of moisture- bearing winds and control precipitation in neighbouring regions. The Himalayas are of fundamental importance to the occurrence of the monsoon in northern India and the arid conditions in continental Central Asia. Therefore, any irregularity in hydrometeorological processes in the vast mountain region can, in return, also have impacts on climate change.

In 2001 in an effort to address issues of climate change and water resource management, UNESCO and ICIMOD, together with Himalayan regional member countries participating in the 'Flow Regimes from International Experimental and Network Data Programme' (HHK-FRIEND), organized a training workshop on Mass Balance Monitoring of Himalayan Glaciers for technology transfer and study of linkages between climate change and glacier retreat (Kaser et al. 2003). Regional member countries with ICIMOD support carried out research to establish a glacial inventory as a baseline for monitoring glaciers in selected sites in Bhutan, China, Nepal, and Pakistan.

Hydrometeorological conditions in the Himalayas

Mountains display a great variability in hydrometeorological conditions: the western Himalayas and north-facing slopes are generally arid while the eastern Himalayas and south-facing slopes are generally humid. The Himalayas act as a barrier to atmospheric circulation for both the summer monsoon and the winter westerlies. The summer monsoon dominates the climate but is longest in the Eastern Himalayas, lasting eight months (March-October) in Assam, four months (June-September) in the Central Himalayas, and two months (July-August) in the Western Himalayas (Chalise and Khanal 2001).

Precipitation in the Himalayas has an east-west and north-south variation on the macro-scale. The east-west variation is based on the dominance of different weather systems. Figures 1a, b, c, d, and e illustrate these variations. In the western Himalayas the westerlies bring peak precipitation during winter (Figure 1a). The eastern Himalayas are influenced by the southwest monsoon with a dominant summer maximum (Figure 1c and e). Maximum annual rainfall is measured in Cherapunjee (Figure 1d). Wyss (1993) determined the area of the India/Pakistan border as the transition zone from one to two peaks with Peshawar showing two peaks (Figure 1b). A substantial amount of winter precipitation occurs as snowfall in this region (Shamshad 1988), whereas the role of the summer monsoon is negligible.

The monsoon rainfall is mainly of an orographic nature, resulting in distinct variations of rainfall with elevation and distinct differences between the southern rim of the Himalayas and the rain shadow areas of the Tibetan Plateau behind the main mountain range (Mei'e 1985). Alford (1992) identified the lower and intermediate altitudes as the main source of precipitation, suggesting that there is an increasing trend with altitude up to about 3500 m after which precipitation again decreases.

On the meso-scale the impacts of climate are mainly due to local topographic characteristics (Chalise and Khanal 2001) with dry inner valleys and the luv-lee effect (i.e., more rain on the windward side than on the sheltered side of a mountain). Examples of this are Pokhara and Jomsom located in western Nepal: Pokhara receives about 3500 mm annually, whereas Jomsom, only 60 km north of Pokhara but located behind the Annapurna Massif, receives only 270 mm per annum (Domroes 1978). The valley bottoms of the deep inner valleys in the high mountains receive much less rainfall than the adjacent mountain slopes. This suggests that the currently published rainfall amounts, which are mainly based on measurements taken in the valley bottom, is not representative for the area and major underestimations may result from the use of these data.

Temperatures vary inversely with elevation at a rate of about 0.6 °C per 100 m; and wide ranges of temperatures are found over short distances.

Local temperatures also correspond to season, aspect, and slope (Zurick et al., 2006). Owing to the thin atmosphere above the Tibetan Plateau and ample and intense radiation, the surface temperature has a large diurnal variation but the annual temperature range is relatively small. Temperature ranges in the northern mountain regions of Pakistan and Afghanistan are wide.

The temperature regime varies from tropical – with average annual temperatures of more than 24 °C in the eastern part (Myanmar and Bangladesh) – to alpine in the areas of the Qinghai-Xizang plateau and high mountain peaks with annual average temperatures below 3 °C Wyss (1993). Most of the areas on the southern rim of the Himalayas are sub-tropical with annual average temperatures of 18 to 24 °C, followed by small bands of warm-temperate and cool-temperate climates.

Potential evapotranspiration (PET) in the region reaches a maximum in the border area between India and Pakistan and shows a general decreasing trend from West to East and from South to North with increasing altitude (Wyss 1993). PET on the lower slopes of the Himalayas is about 1250 mm per year.

Availability of water in the Himalayan region

The focus of this research is solely on fresh water. Estimates of water availability for different countries in the Himalayan region vary greatly: the figures from Seckler et al. (1998) are given in table 2. Kayastha (2001) estimated a seasonal difference of 6100 m^3/y per capita assuming 8800 m^3/y per capita in monsoon season and 2700 m^3/y per capita in dry season. Within Nepal the per capita availability drops to 1400 m^3/y per capita in the Kathmandu Valley.

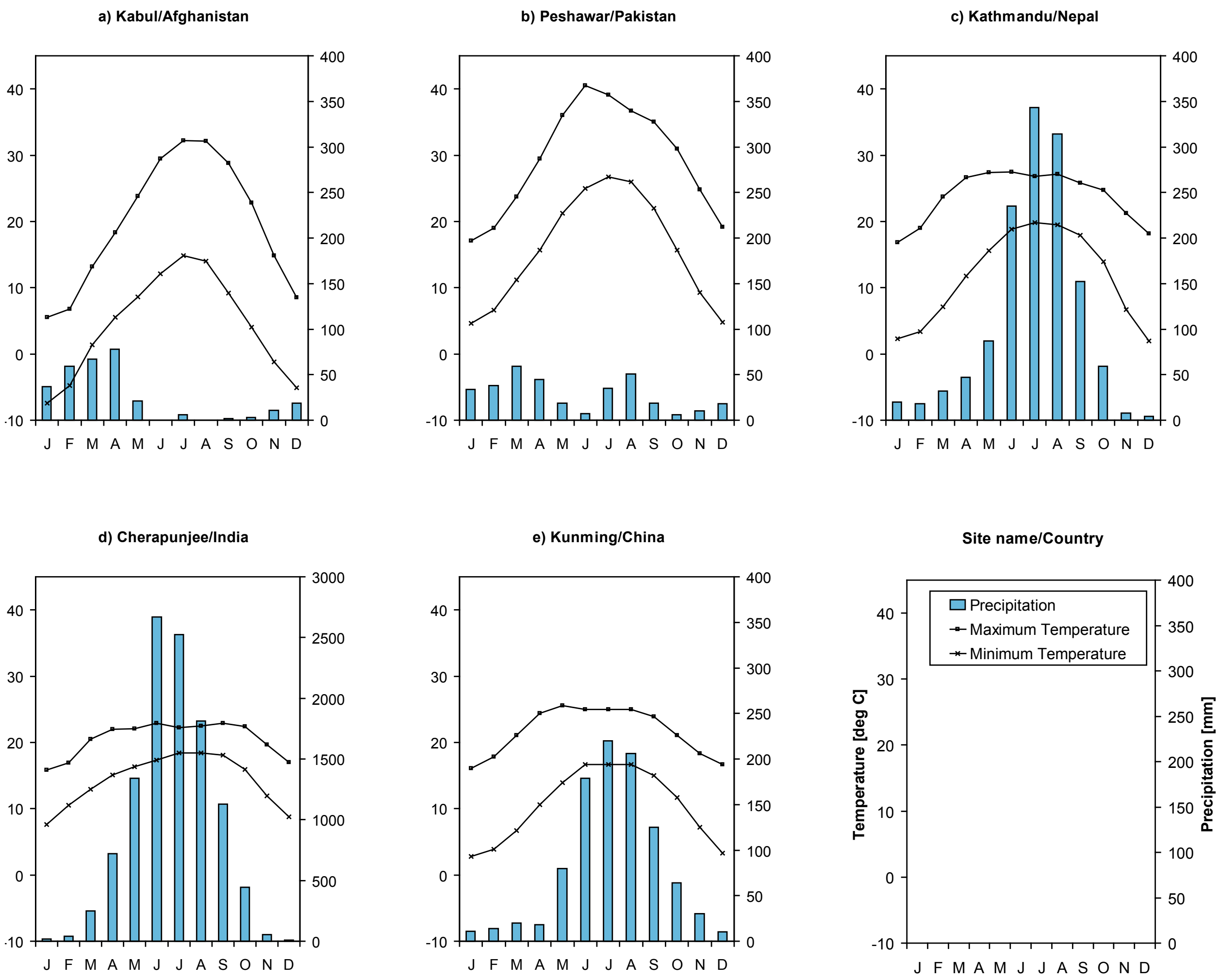

Figure 1 *Climatic diagram of five stations in a) the Hindu Kush, b) Western Himalayas, c) the Central Himalayas, d) the Eastern Himalayas, and e) Hengduan mountains (Data source: FAO, 2001; note: the precipitation axis in Cherapunjee is 8 times higher)*

Table 2 Water availability in Himalayan regional member countries (source for all countries: Seckler et al. 1998)

Country	Population (1990) Mio.	Annual water resources km³/y	Per capita water availability m³/y	Total withdrawals km³/y	Per capita withdrawals m³/y		
					Dom.	Ind.	Irr.
Afghanistan	15	65	4,333	256	102	34	1,566
Bangladesh	108	2,357	21,824	24	7	2	211
Bhutan	0.7		120,405				
China	1,155	2,800	2,424	533	28	32	401
India	851	2,085	2,450	518	18	24	569
Myanmar	42	1,082	25,762	4	7	3	91
Nepal	19	170	8,947	3	6	2	143
Pakistan	122	418	3,426	156	26	26	1,226

Key: Dom.: Domestic use, Ind.: Industrial use, Irr.: Irrigation use

Table 3 Criticality ratio for selected countries of the Himalayas (Seckler et al. 1998)

Country	Annual water resources km^3/y	Total with-drawals km^3/y	Criticality ratio CR %
Afghanistan	65	26	39
Bangladesh	2,357	24	1
China	2,800	533	19
India	2,085	518	25
Myanmar	1,082	4	1
Nepal	170	3	2
Pakistan	418	156	37

To define water scarcity Alcamo et al. (2000) used the criticality ratio (CR), i.e., the ratio of average annual water withdrawals to water availability. Summaries of water stress values are given in table 3 and show that Afghanistan and Pakistan are the most severely water-stressed countries in the region, followed by the two most populated countries in the world, India and China.

Climate change in the Himalayas

Observational records

The climate stations in the Himalayas are sparse and concentrated in proximity to settlements in valleys and might not adequately represent background conditions. Stations located in remote mountain areas often lack proper maintenance and inconsistencies in data collection due to poor accessibility render data of poor quality. The Himalayan region, including the Tibetan Plateau, however, has shown consistent trends in overall warming during the past 100 years (Yao et al. 2006). Various studies suggest that warming in the Himalayas has been much greater than the global average of 0.74 °C over the last 100 years (IPCC 2007; Du et al. 2004). Warming in the Himalayan region has also been progressively greater with elevation. For example, warming in Nepal was 0.6 °C per decade between 1977 and 2000 (Shrestha et al. 1999) (Table 4). There is also a tendency for the warming trend to increase with elevation on the Tibetan Plateau and in its surrounding areas (Liu and Chen 2000). Warming is furthermore greater particularly during autumn and winter.

Strong spatial and temporal variations exist in the rainfall distributions of Nepal (Shrestha et al. 2000). The seasonal mean rainfall is highest during summer monsoon and lowest during winter. Variability is highest during post-monsoon and lowest during monsoon seasons. Although the variability of the monsoon rainfall is small, the anomalies (too much or too little rain) on either side may have severe socioeconomic impacts. Precipitation data from Nepal do not reveal any significant trends.

In Pakistan mean temperatures exhibit mixed trends. Mean summer temperatures over all regions indicate an increase ranging from 0.03 to 2.17 °C. Mean maximum temperatures show higher increases than minimum temperatures. Summer monsoon rainfall has increased in all regions of Pakistan except for the Balochistan Plateau. Winter precipitation has decreased in the highland regions of Pakistan. The North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) have been found to have profound effects on winter precipitation in Pakistan (MoE 2003). Archer and Fowler (2004) found statistically significant increases in winter and summer precipitation and in annual precipitation in the Upper Indus basin. Temperature data from Skurdu and Gilgit indicate that

Table 4 Regional mean temperature trends in Nepal from 1977 – 2000 (°C per year)

Region	Seasonal				Annual
	Winter (Dec – Feb)	Pre-monsoon (Mar – May)	Monsoon (Jun – Sep)	Post-monsoon (Oct – Nov)	(Jan – Dec)
Trans-Himalayas	0.12	0.01	0.11	0.1	0.09
Himalayas	0.09	0.05	0.06	0.08	0.06
Middle Mountains	0.06	0.05	0.06	0.09	0.08
Siwaliks	0.02	0.01	0.02	0.08	0.04
Terai	0.01	0	0.01	0.07	0.04
All Nepal	0.06	0.03	0.051	0.08	0.06

Updated after Shrestha et al. 1999

there has been significant warming in these places in the past three decades. Mean daily maxima increased significantly more than mean daily minima. Winter temperatures increased more than annual temperatures.

In China, Liu and Chen (2000) analysed data from 97 stations distributed over the Tibetan Plateau. They found that significant warming ranging from 0.16 to 0.32 °C per decade had taken place. The greatest warming trend was observed in winter. The analyses of Liu et al. (2004) have clearly shown that warming is more significant in measurements from higher altitude stations than in those from lower stations. Gong (2006) studied the performance of 27 stations located within the upper Brahmaputra in Tibet and found temperature increases of 0.024 °C annually since 1959. In general, temperature increases accelerated during the two previous decades with greater changes in western Tibet than in eastern Tibet. Rainfall analyses from 27 stations in the Tibet Autonomous Region (TAR) of China in past decades (Gong 2006) show that there were increases in precipitation at 20 stations located in eastern and central Tibet and decreases in western Tibet.

The climate records for India are comparatively longer than others in the region and numerous studies on climate trends and variability have been carried out. Circulation of the Indian summer monsoon dominates rainfall over South Asia. All-India summer monsoon rainfall (AISMR) displays predominant inter-annual variability, marked by recurrent large-scale droughts and floods. Years of large-scale deficient and excess monsoon rainfall are usually identified with the criteria of the AISMR being below and above 10 % of the long-term mean, respectively. A remarkable feature of anomalous monsoon situations is the spatial coherence of seasonal rainfall anomalies over large parts of the country. The effect of drought are accentuated by the high coefficient of variability over regions of lower seasonal rainfall (Parthasarathy 1984) and their occurrence in two or three consecutive years on several occasions (Chowdhury et al. 1989).

An interesting new approach to monitoring surface ground temperatures is the borehole temperature profile, which represents high elevation mountainous sites and suggests a warming of ~0.9 °C over the past 150 years indicating that the warming began before the widespread changes in surface air temperatures. It is suggested that total warming for the 1980 baseline is 1.2 °C (Roy et al. 2002).

Possible future climates in the Himalayas

Based on regional climate models (RCMs), it is predicted that the temperatures in the Indian sub-continent will rise between 3.5 and 5.5 °C by 2100 (Rupa Kumar et al. 2006), those of the Tibetan Plateau are expected to increase 2.5 °C by 2050 and 5 °C by 2100 (Shi 2000). In one analysis carried out by the Pakistan Meteorological Department, the temperature is projected to increase by 0.1 °C per decade. Climate projections indicate increases in both maximum as well as minimum temperatures by 2 – 4 °C during the 2050s in India (MoEF 2004). Because of the extreme topography and complex reactions to the greenhouse effect, however, even high resolution climate models cannot give reliable projections of climate change in the Himalayas.

Consequences of climate impacts

Impacts can be expressed as functions of climate change and `vulnerability'. Vulnerability is measured by a series of biophysical and socioeconomic indicators. Biophysical indictors include glaciers, flash floods, forest fires, pests and diseases, water resources, tree-rings, and agricultural production. Socioeconomic indicators include per capita income, infant and child mortality rates, nutritional status, vector-borne diseases, fatal cardiovascular and respiratory disorders, drinking water, economic structure, and social services. Impacts can be negative or positive depending on the time, place, and sector that is looked at. Overall, negative impacts tend to dominate in the fragile mountain ecosystem and in the poorer regions of the Himalayas.

Glacial retreat and Glacial lake outburst floods

Glacial retreat

Glaciers react to the climate and, with the general warming trends, glaciers in the Himalaya, almost without exception, have diminished in volume over the plast few decades. Many Himalayan glaciers are retreating faster than the world average (Dyurgerov and Meier 2005) (Figure 2) and are thinning at the rate of 0.3 – 1 m/year. For example, the rate of retreat for the Gangotri Glacier over the last three decades has been more than three times the rate during the preceding 200 years (Srivastava 2003). Most glaciers studied in Nepal are undergoing rapid deglaciation: the reported rate of glacial retreat ranges from several metres to 20 m/year (Fujita et al. 2001; Fujita et al. 1997; Kadota et al. 1997). In the last half century, 82.2% of the glaciers in western China have retreated (Liu et al. 2006). On the Tibetan Plateau, the glacial area has decreased by 4.5% over the last twenty years and by 7% over the last forty years (CNCCC 2007).

Such catastrophic reductions in ice cover have not been observed in the northwestern Himalayas, Karakoram, Hindu-Kush, or Pamirs. From the 1920s to the 1960s, the glaciers in these ranges exhibited the prevailing pattern of glacial retreat and ice mass reduction following the Little Ice Age. In the 1970s, however, many of these glaciers exhibited short-term thickening and expansion (Hewitt et al. 1989). Throughout the 1980s and most of the 1990s retreat and thinning again became the rule, but they were of a fairly gradual nature. In the Karakoram, there is widespread evidence of expansion, or downslope redistribution of ice, from the late 1990s onwards in more than thirty glaciers (Hewitt 2005). In addition, a large increase has been noted in the incidence of glacial surges compared to long-term records (Hewitt 2007). Moreover, since the 1960s, mean temperatures at valley weather stations have either remained unchanged or have declined, mainly as a result of cooler than average summers offsetting warmer than average winters (Archer and Fowler 2004). At the same time, since the 1950s various mountain communities

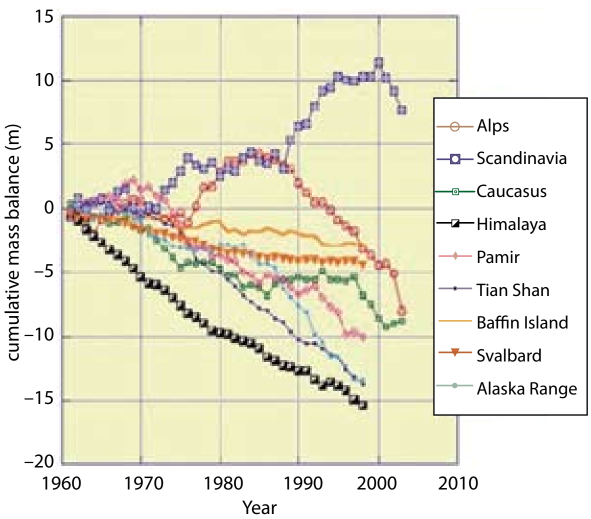

***Figure 2** Rapid retreat of Himalayan glaciers in comparison to the global average (Dyurgerov and Meier 2005)*

have been severely threatened by the diminishing of or disappearance of the small ice masses and snow fields on which they depend for water supplies. These are typically in watersheds situated at lower altitudes – not above 6,000 m – but there have been no studies to determine the scope and extent of changes in the many small ice masses in these ranges, or to determine changes in ice cover by elevation. These developments are certainly related to global climate changes, and they reinforce the need to recognise the diversity of responses in the greater Himalayan region.

Glacial lake outburst floods (GLOFs)

The formation and growth of glacier lakes is a phenomenon closely related to the deglaciation. As glaciers retreat they leave behind voids that fill with melt water to form glacial lakes. The loose moraine dams retaining glacial lakes are structurally weak and unstable and possess the danger of catastrophic failure, causing GLOFs. Principally, a moraine dam may break due to some external trigger or self-destruction. A huge displacement wave generated by rockslides or snow/ ice avalanches from the glacier's terminus into the lake may cause the water to overtop the moraines, create a large breach, and eventually cause the dam failure (Ives 1986). Earthquakes may also be one of the factors triggering dam break depending upon its magnitude, location, and characteristics. Self-destruction is caused by the failure of the dam slope and subsequent sudden drainage.

Inventories of glacier dammed lakes and occurrences of GLOFs have been undertaken (ICIMOD 2001a,b, 2003, 2004a,b,c, 2005b,c,d,e; Iturrizaga 1997; Che et al. 2004; Chan et al. 2005). The results for Pakistan indicate 728 lakes of which 45 are potentially dangerous: comparable figures for other regions are: Tibet, 441 lakes, 77 dangerous; Nepal 2315 lakes, 20 dangerous; Bhutan 2674 lakes, 26 dangerous; and India 356 lakes, 22 dangerous.

While the glaciers are in general in a condition of retreat, glaciers in Pakistan, especially in the Karakoram often experience surges thereby intercepting the flowing river and resulting in the formation of a glacial lake. There have been numerous outbreaks of such glacial lakes. Iturrizaga (1997 and 2005a) reports 20 such glacier-dammed lake outbreaks in Shimshal Valley, in the Karakoram Mountains. Similarly, there have been 19 glacial lake outburst floods in Karambar Valley in the Hindu Kush.

Impacts on water resources

Climate change is not just about averages, it is also a matter of extremes and is likely to affect minimum and maximum temperatures and trigger more extreme rainfall events. For the sub-continent, less rainfall in winter and increased precipitation in the summer monsoon are predicted. In high altitude areas, an increased annual average temperature will cause the thawing of perennial snow and ice. In the short term, this may lead to an increase in annual discharge in rivers since a great proportion of river water comes from snow and ice.

However, in the long run the annual discharge may decrease and the discharge in dry season decline, further limiting water supplies for communities downstream.

Besides causing catastrophic events including GLOFs and landslides, glacial shrinkage will have serious impacts on the hydrological regime of the region. For some rivers, e.g., the Indus and Brahamaputra in the upper reaches, glacial melt is important throughout the year, whereas for other rivers, such as the Ganges, it is important during the non-monsoon (lean) seasons. Climate change and its impacts on deglaciation will likely have serious implications for hydrology including agriculture and hydropower generation in Pakistan (MoE 2003), Nepal (Agrawala et al. 2003), and India (Johannesson 1997).

All of the three mainly snowfed rivers, the Karnali, Sapta Koshi, and Narayani, in Nepal show a declining trend in discharge. It has been estimated that 70 % of the flow in the Ganges during the lean period is contributed by Nepalese rivers mainly from snow and glacial melt sources. Disruption of the hydrological regime of Nepalese rivers is bound to have impacts on the flow of the Ganges as well. A separate study suggests that the number of flood days and consecutive days of flood events will increase (Shrestha et al. 2003).

The power sector of India, which is already facing a 10 % shortage, is suggested to be the hardest hit by climate change. A reduction in water from the mountains would affect the economy of the region by limiting hydropower production and hampering industrial productivity (Johannesson 1997).

A modelling-based study on the impact of deglaciation on river flow in India and Nepal suggests that that there will be an increase in river discharge in the near future causing widespread flooding in the adjacent areas. But, after a few decades, this situation will reverse and water levels in these rivers will start declining to a permanently decreased level. For the headwaters of the Ganges, flow volumes are projected to peak at between +20 and +33 % of the baseline within the first two decades and then recede to around –50 % of the baseline. In the headwaters of the Brahmaputra, there is a general decrease in decadal mean flows for all temperature scenarios: glaciers are few in this area and flows recede as the permanent snow cover reduces with increasing temperatures.

In certain parts of the Tibetan Plateau, glaciers play a key role in supplying communities with water for irrigation, drinking, and hydroelectricity. The runoff from glaciers is also essential for maintaining river and riparian habitats. There is growing concern about the impact that changes in glaciers may have on water resources in the headwater regions.

The effects of shrinking glaciers on water resources before 2050 were examined for several regions using the statistical data from China's glacier inventory. The volume of meltwater will peak at the beginning of this century. In some river basins, such as the Shule River in the Qilian Mountains, glacial meltwater can account for one-third or more of total river runoff. It is predicted that the meltwater volume of several medium-sized glaciers of 5 – 30 km² will increase, peaking around the mid century. For example, glacial meltwater currently represents 50 to 80 % of the total discharge from the Yarkant and Yurunkax rivers. It is predicted that glacial meltwater volume will increase by 25 to 50 % by 2050, and the annual discharge of seven major rivers of the Tarim Basin will increase. Inland watersheds in the Qaidam Basin and on the Qinghai-Tibetan Plateau are dominated by extreme continental-type glaciers that have low temperatures and retreat slowly. Temperature rises and increases in meltwater during the first half of this century are favourable to the development of animal husbandry and economic growth. In the maritime-type glacial regions of the southeast Tibetan Plateau and the Hengduan Mountains, however, precipitation is heavy and ice temperatures are high. A temperature rise here will exacerbate the glacial retreat perhaps causing frequent flooding and disasters from debris flow. Xie et al. (2001) studied glaciers in the basins of the rivers Ganges, Yarlung Zangbo, and the Indus, which together occupy one-third of the total glacial area in China and cover an area of 19,500 km².

Functional models of the variable glacial systems were established and applied to study the response of glacial runoff to climatic changes. The model simultaneously considered the effect of decreasing air temperatures, caused by rising equilibrium line altitude (ELA) and reduction in glacial area. The modelling results indicate that the glacial runoff fed by the marine-type glaciers with high levels of mass balance are sensitive to climate change, and take 10 – 30 years to reach a climax. The glaciers are then forecast to go back to an initial state in less than 100 years. The projected rate of increase in discharge of glacial runoff is small. During peak periods, the increase in discharge rate ranged between 1.02 and 1.15. In contrast, the glacial streams of continental-type glaciers, which have more rapidly decreasing rates of glacial area and storage, longer lifespans, and lower levels of mass balance, respond slowly to climate variations. They take over 100 years to climax, and hundreds of years to return to their initial state. At similar levels of mass balance, small glaciers respond more quickly to climate change and retreat more quickly than large glaciers. Glacial systems with very large elevation differences have the longest lifespan.

Conclusion

There is now adequate evidence that the climate in the Himalaya region is changing in a significant manner. This region is perhaps one of the most vulnerable regions in the world with respect to climate change. Ongoing climate change is most obvious in the widespread deglaciation in the region. Continued deglaciation is certainly a threat to the livelihoods of several hundred million people in the region who rely on glacial meltwater. Further threats could come from sudden glacial lake outburst floods or from slow changes in the hydrological regime of river basins. There are uncertainties related to the extent and timeframe of climate change and its impact on water resources. Clearly the predicted changes in hydrological regimes will not only have profound impacts on human lives and livelihoods through human health, agricultural production, industry and energy, but will also affect ecosystems in both the mountains and on the plains below. Societies will have to face the challenges of adapting to these changing situations.

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