Introduction

The Region

The term 'greater Himalayan region' is used loosely to describe the area covering all the high mountain chains of Central, South and Inner Asia, including the Tien Shan, Kun Lun, Pamir, Hindu Kush, Karakoram, Himalayas, and Hengduan; the extensive middle mountain chains that surround them; and the high altitude Tibetan Plateau. Like other mountain areas, this region, sometimes called the 'Roof of the World', is demonstrating a number of noticeable impacts related to global climate change, the most widely reported being rapid reduction in many glaciers which has implications for water resources. The region plays an important role in global atmospheric circulation, biological and cultural diversity, water resources, and the hydrological cycle, apart from the beauty of its landscape and provision of other ecosystem amenities (Bandyopadhyay and Gyawali 1994). The region is the source of the nine largest rivers in Asia, the basins of which are home to over 1.3 billion people (Table 1). Environmental change in the greater Himalayas affects much of inland China, Central and South Asia, and the mainland of Southeast Asia. The Himalayan region is the most critical region in the world in which melting glaciers will have a negative affect on water supplies in the next few decades (Barnett et al. 2005). Moreover, the impacts of climate change are superimposed on a variety of other environmental and social stresses, many of them already recognised as severe (Ives and Messerli 1989), causing uncertainty (Thompson and Warburton 1985), and leading to contradictory perceptions (Ives 2004).

The Himalayas straddle some of the world's poorest regions and the plains below them are densely populated. Within these populations and communities, the impacts of climate change are not evenly distributed, either in intensity within the region, or among different sectors of society. The more fragile the ecosystem and the poorer and more marginalised the people, the earlier and greater the impact. This is inevitable unless concerted and effective action is taken to engage them and assist them to cope with the changes.

Mountains are part of the coupled ocean-atmosphere and terrestrial systems. Continuing climate change is predicted to lead to major changes in the strength and timing of the Asian monsoon, inner Asian high pressure systems, and winter Westerlies, the main systems affecting the climate of the Himalayan region. The impacts on river flows, natural hazards, and the ecosystem, as well as on people and their livelihoods, can be dramatic, although not the same in rate, intensity, or direction in all parts of the region. Given the current state of knowledge, determining the diversity of impacts is a challenge to researchers and risk assessment is needed to guide future actions.

Snow and ice

In the greater Himalayas, a substantial proportion of the annual precipitation falls as snow, particularly at high altitude (above 3000m). In the higher reaches, snowfall builds up from year to year to form glaciers that provide long-term reservoirs of water stored as ice. The high Himalayan and inner Asian ranges have the most highly glaciated areas outside the polar region, although accurate data are lacking (Dyurgerov and Meier 2005). Several of the largest concentrations of glaciers are found in the mid- and low latitudes, covering a total area of 112,767 sq.km (Table 2). The Himalayan range alone has a total area of 35,110 sq.km of glacier and ice cover, with a total ice reserve of 3,735 cu.km (Table 3).

Climate controls river flow and glacier mass balance in the Himalayan region, and these vary considerably from west to east. The monsoon from the Bay of Bengal, further developed in the Indian subcontinent, produces heavy precipitation – predominantly in the southeast

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 x1000	Population density	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: The hydrological data may differ depending on the location of the gauging stations. The contribution of glacial melt is based on limited data and should be taken as indicative only.

Table 2: Glacial resources in the greater Himalayan region

Mountain range	Area (km^2)
Tien Shan	15,417
Pamir	12,260
Qilian Shan	1,930
Kunlun Shan	12,260
Karakoram	16,600
Qiantang Plateau	3,360
Tanggulla	2,210
Gandishi	620
Nianqingtangla	7,540
Hengduan	1,620
Himalayas	33,050
Hindu Kush	3,200
Hinduradsh	2,700
Total	**112,767**

Source: Dyurgerov and Meier 2005

Table 3: Glacial resources in the Himalayan range

Drainage basin	No of glaciers	Total area (km^2)	Total ice reserve (km^3)
Mapam Yumco Lake	48	67	4.4
Ganges River	6,696	16,677	1971.5
Brahmaputra River	4,366	6,579	600.4
Indus River	5,057	8,926	850.4
Sutlej River	1,900	2,861	308.0
Total	**18,067**	**35,110**	**3,734.5**

Source: Qin 2002

Chapayev glacier: Tien Shan mountain range (David Melick)

of the Himalayan region. The monsoon weakens from east to west, penetrating northwards along the Brahmaputra River into the southeast Tibetan Plateau, rarely penetrating as far as the Karakoram (Hofer and Messerli 2006; Rees and Collins 2006). Water from both permanent snow and ice and seasonal snow-packs is released by melting, giving a distinct seasonal rhythm to annual streamflow regimes. Glaciers undergo winter accumulation and summer ablation in the west, but predominantly synchronous summer accumulation and summer melt in the east. The main melting occurs in high summer but, when this coincides with the monsoon, it may not be as critical for water supply as when the melting occurs in the shoulder seasons: spring and autumn. When the monsoon is weak, delayed, or fails, meltwater from snow and ice may limit or avert catastrophic drought.

The contribution of snow and glacial melt to the major rivers in the region ranges from less than 5% to more than 45% of the average flow (see Table 1). The Himalayan rivers of Nepal contribute about 40% of the average annual flow in the Ganges Basin. More importantly, they contribute about 70% of the flow in the dry season (Alford 1992). Snow and ice melt contribute about 70% of the summer flow of the main Ganges, Indus, and Kabul rivers in the 'shoulder seasons' before and after precipitation from the summer monsoon (Kattelmann 1987; Singh and Bengtsson 2004; Barnett et al. 2005). The contribution to inner Asian rivers, such as the Yarkand and Tarim, is even greater. The Indus Irrigation Scheme in Pakistan depends on approximately 50% of its runoff originating from snowmelt and glacial melt from the eastern Hindu Kush, Karakoram, and western Himalayas (Winiger et al. 2005). Glacial melt provides the principal water source in dry season water for 23% of the population living in western China (Gao et al. 1992).

Intensified and complex responses

In the mountains, climatic conditions vary more sharply with elevation and over shorter distances than they do with latitude. Mean temperatures, for example, decline about 1ºC per 160m of elevation, compared with about 1ºC per 150 km by latitude (Hartman 1994). Hence, the effects of climate change are expected to intensify in mountain areas, and they are considered to be unique areas for detection of climate change and related impacts (Beniston 2003). The broad predictions of global climate change, especially the emphasis on shifts in mean temperature, do not take into account important regional complexities in the mountains related to the effects of topography and elevation. If climate change mainly involves vertical shifts in precipitation and thermal conditions, ruggedness, elevation, and orientation will also modify the significance of regional and local changes. The highest mountains, or those facing or funnelling the prevailing winds, may retain a substantial, if diminished, glacial cover, whereas lower or less favourably oriented watersheds may lose theirs. Furthermore, intensification of the Asian monsoon is predicted by most climate models. On a regional scale this could result in increase in precipitation, although local effects are poorly understood. Moreover, climate change means not only temperature warming, but also changes in precipitation, evapotranspiration, soil and air moisture, runoff, and river flow as well as groundwater through water cycles. Climate change is expected to accelerate water cycles and thereby increase the available, renewable freshwater resources (Oki and Kanae 2006). Temperature changes have a predominantly regional character, whereas precipitation changes are more locally determined and very difficult to analyse and to predict, especially in mountain areas and river basins (Jian et al. 2006).

Complexities arise, especially from interactions among different cold climate elements – freeze-thaw and periglacial processes, snowfall, valley wind systems, avalanches, glacial processes, and seasonal or spatial balance between frozen and liquid precipitation. Not only are they likely to change with general climate shifts, but also interactions among them can buffer, exaggerate, or redirect the impacts of change in any one element. The most rapid and varied interactions occur through the 'vertical cascade' between different topoclimates – zones stacked vertically and on slopes of differing orientation – notably transport of moisture, runoff, sediment, and dissolved solids downslope. The occurrence and impacts of major hazards, such as avalanches, debris flows, landslides, and flash floods, also have a bearing on downslope, down-glacier, and downstream cascades. Whereas snow avalanches and glacial lake outburst floods (GLOFs) predominate at very high elevations (>3500m), landslides, debris flows, and landslide dam outburst floods (LDOFs or 'bishyari') are more common in the middle mountains (500-3500m). Riverine floods are the principal hazards in the lower valleys and plains. The causes of these floods are related to climatic conditions (Chalise and Khanal 2001; Dixit 2003; Xu and Rana 2005).

Equally critical are issues related to the structure, processes, and resilience of ecosystems and human adaptations to them; bearing in mind that ecosystems and humans are possibly already stressed by adaptation to topoclimatic diversity. In general, local impacts of climate do not follow single or simple paths, whether in terms of plant ecology, stream hydrology, erosion and sedimentation, extreme events, or human activities.

Much of the mountain cryosphere system is sensitive to sustained changes in atmospheric temperature. Already many Himalayan glaciers are shrinking, some extremely rapidly in the global context. The widespread consensus is that climate change is the main factor in this. Apparently, conversely, in the high Karakoram-Himalayas, the rate of ice cover loss has been declining in the last half of the twentieth century, and evidence is emerging that some glaciers are expanding -- but this is also due to changing climatic patterns and unexpected regional consequences of 'warming' (Archer and Fowler 2004; Hewitt 2005). In the Tien Shan, predominantly summer-fed, continental-type glaciers are situated within 100km of predominantly winter-fed, more maritime ones. Although most glaciers in both classes are shrinking, there are significant differences in the rates and forms of response to warming (Bolch 2006). Although studies show marked variations in the local impacts of climate change,

Low flow in the Mechi River, a tributary of the Ganges affected by climate change (Xu Jianchu)

The Chhukha Hydropower Project in Bhutan depends on glacier melt low flow for power generation (David Melick)

such as orographic precipitation in different valleys and elevations within the same mountain range, most of the region remains unstudied in terms of a baseline for assessment or prediction of these complexities.

The constraints of limited or absent baseline investigations

The relationship between climate change and the Himalayan cryosphere, although confirmed by scientists generally, is not understood sufficiently to drive detailed policy responses. While in-depth studies of glaciers, snow pack, and permafrost have been carried out in some areas, they have been scattered widely in space and time. No detailed investigations of snow and ice processes or their relevance to climate have taken place in most areas of the Himalayan and other high ranges. Baseline studies are lacking for most areas, particularly for those higher than 4,000 masl, and there has been little long-term monitoring of climatic variables, perennial snow and ice, runoff, and hydrology in the extraordinary heterogeneity of mountain topography (Liu and Chen 2000; Rees and Collins 2006; Messerli et al. 2004). Most models and predictions for high-altitude areas (above 4,000 masl) are dependent upon extrapolation from climate and stream-gauging stations at comparatively low altitudes and upon assumptions based on other, better-studied parts of the world (Rees and Collins 2004). The importance of the most widespread cryogenic processes – avalanches, debris flows, rock glaciers, alpine permafrost, and surging glaciers – has been recognised and their incidence recorded for certain areas; and yet almost no basic scientific investigations of these cryogenic processes have taken place in the region, although they involve significant hazards, the patterns and intensities of which will be affected by climate fluctuations that may increase or decrease risk in given areas.

Thus, the immense diversity within the region should be recognised: diversity of climates and topoclimates, hydrology and ecology, and, above all, in human cultures and activities. Before effective responses can be made, much work has to be carried out to identify and predict the possible impacts of climate change filtered through such diverse contexts. In particular, there has been little engagement with local populations so far to learn from their knowledge and experience in adapting to unique and changeable environments and to address their concerns and needs (Xu and Rana 2005).

Warming, Glacier Loss, and Changing Environments

With rising temperatures, areas covered by permafrost and glaciers are decreasing in extent in much of the region. Moreover, in many areas a greater proportion of total precipitation appears to be falling as rain than heretofore. As a result, snowmelt begins earlier and winter is shorter: this affects river regimes, natural hazards, water supplies, and people's livelihoods and infrastructure, particularly in basins such as the Tarim that are dependent upon glacial melt: the highly glaciated Tarim Basin supplies about 138x108m^3 of glacial-melt freshwater to the downstream areas each summer (Yao et al. 2004). The extent and health of high altitude wetlands, green water flows from terrestrial ecosystems, reservoirs, and water flow and sediment transport along rivers and in lakes can also be affected.

Himalayan warming

The Himalayan region, including the Tibetan Plateau, 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). For example, warming in Nepal was 0.6°C per decade between 1977 and 2000 (Shrestha et al. 1999). Warming in Nepal and Tibet has been progressively greater with elevation (Table 4 and Figure 1). The increase in temperature over the Tibetan Plateau during the period from 1955–1996 is about 0.16°C per decade for the annual mean and 0.32°C per decade for the winter mean, and these exceed the increases in the northern hemisphere and for the same latitudinal zone in the same period. Furthermore, there is also a tendency for the warming trend to increase with elevation on the Tibetan Plateau and in its surrounding areas. This suggests that the Tibetan Plateau is one of the most sensitive areas in terms of response to global climate change (Liu and Chen 2000). Warming over parts of the Tibetan Plateau was in the range of 0.2-0.6ºC per decade between 1951 and 2001, particularly during autumn and winter. In the Karakoram and Hindu Kush mountains, winter mean and maximum temperatures show significant increases while mean and minimum summer temperatures show consistent decline (Fowler and Archer 2006) as well as in the Hengduan Mountains of southwest China (Hu et al. 2003). The length of the

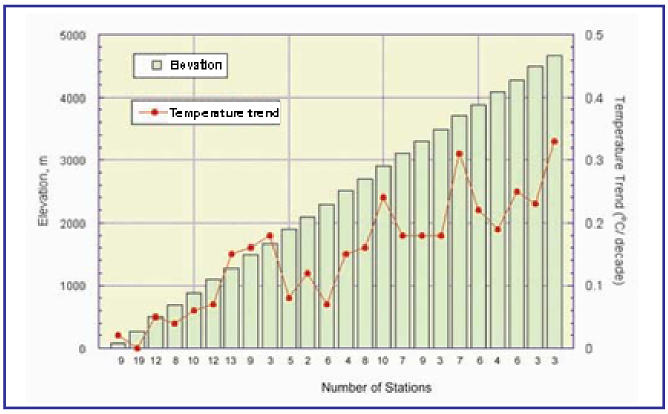


Figure 1: Dependence of warming on elevation on the Tibetan Plateau (Liu and Chen 2000)

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

Glacier-fed sacred lake in Sikkim, India (Nakul Chettri)

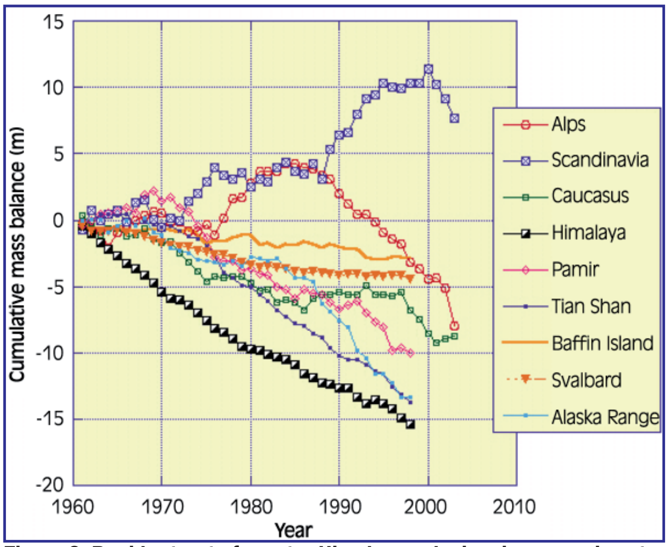


Figure 2: Rapid retreat of greater Himalayan glaciers in comparison to the global average (Dyurgerov and Meier 2005)

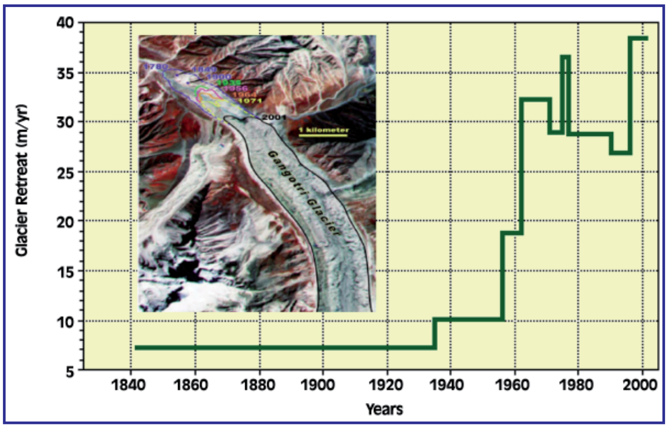


Figure 3: Increasing rate of retreat of the Gangotri Glacier in India (Source: Vohra 1993; Srivastava 2003; Jeff Kargel cited in WWF 2005. Inset: Satellite image showing the position of the terminus in different years)

growing season (daily temperature >10°C) on the Tibetan Plateau has increased by almost 15 days during the last three decades. This suggests that the elevated land masses of Asia are very sensitive to climate change.

Glacial retreat

Many Himalayan glaciers are retreating faster than the world average (Dyurgerov and Meier 2005) (Figure 2) and are thinning by 0.3-1 m/year. The rate of retreat for the Gangotri Glacier over the last three decades was more than three times the rate during the preceding 200 years (Figure 3). 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% 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 have been severely threatened by the diminishing 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 6,000m – 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.

Permafrost

Areas in the high mountains and on the high plateaux not covered in perennial snow and ice are underlain by permafrost. Recent studies show that the extent of permafrost is shrinking and that active layer thickness (the upper portion of soil that thaws each summer) is increasing, and this has altered the hydrological cycle, vegetation composition, and carbon dioxide and methane fluxes that appear linked to permafrost degradation (Lawrence and Slater 2005). The areas of permafrost are much larger than those covered by glaciers or perennial snow, especially in China (about 2.15×10^6 sq.km).This factor plays a critical role in terms of slope stability, ecology, erosion processes, and surface waters, and

Glacier melting and glacial lake in the Himalayas (Xu Jianchu)

such areas will be sensitive to degradation with climate warming. On the Tibetan Plateau, the recent warming trend has been associated with decreasing areas of permafrost and a rise in the elevation of its lower limits; and progressive thinning of what remains as geothermal heat thaws it from below. For example, in the past three decades, on the Central Tibetan Plateau in the Kekexeli Wildland area, the lower limit of permafrost has risen approximately 71m, while the sustained thickness has decreased by at least 20cm (Wu et al. 2001). Meanwhile the extent of seasonal thawing has intensified over large areas of permafrost causing increased ground instability and erosion (Zhao et al. 2004), with consequences such as activation of the soil carbon pool and northward expansion of shrubs and forests (Lawrence and Slater 2005). Disappearance of permafrost and expansion of non-permafrost would accelerate desertification on the plateau (Ni 2000). Notwithstanding, there is almost no information about the full extent and behaviour of high mountain permafrost areas in the region.

Extreme events

Climate change involves, perhaps most seriously, changes in the frequency and magnitude of extreme weather events. There is widespread agreement that global warming is associated with the most severe fluctuations, particularly in combination with intensified monsoon circulations. Global El Niño/Southern Oscillation (ENSO) events have directly affected the regional annual precipitation in the Yellow River Basin and resulted in an approximately 51% decrease in river discharge to the sea (Wang et al. 2006). Although many other factors are involved, the growing incidence and toll of related natural disasters, such as floods and drought, is of particular concern.

Each of the main features of the Himalayan cryosphere carries conditions that can pose threats to society. Large fluctuations in the melting of snow and ice can result in excessive or insufficient water supplies: heavy snowfalls can block roads or overload structures. Snowfall on steep slopes and associated conditions give rise to avalanches: advancing or retreating glaciers can interfere with communications or cause dangerous impoundments. The action of frost and melting of permafrost pose ecological and technological dangers. The most destructive hazards, and those that can have impacts far beyond their mountain sources, tend to be the direct consequences of changes in the cryosphere. These include ponding of water by or around glaciers and subsequent glacial lake outburst floods (GLOFs), and can involve much more water than the amount generated by climatic events alone (see below). Fluctuations in glaciers, especially retreat and thinning, destabilise surrounding slopes and may give rise to catastrophic landslides (Ballantyne and Benn 1994; Dadson and Church 2005) which can dam streams, and sometimes lead to outbreak floods. Excessive melt waters, often in combination with liquid precipitation, may trigger flash floods or debris flows. In the Karakoram, there is growing evidence that catastrophic rockslides have a substantial influence on glaciers and may have triggered glacial surges (Hewitt 2005). Glacial surges are a particular hazard in the Karakoram and Pamir mountains. Severe cold and high winds threaten wildlife, domestic animals, and humans.

In the eastern and central Himalayas, glacial melt associated with climate change has led to the formation of glacial lakes in open areas behind exposed end moraines, causing great concern. Many of these high-altitude lakes are potentially dangerous. The moraine dams are comparatively weak and can breach suddenly, leading to the sudden discharge of huge volumes of water and debris. The resulting GLOFs can cause catastrophic flooding downstream, with serious damage to life, property, forests, farms, and infrastructure. Twenty-five GLOFs have been recorded in the last 70 years in Nepal, including five in the sixties and four in the eighties (Mool 2001; NEA 2004; Yamada 1998).

Mountain ranges in the region have a history of disasters triggered by some or all of the cryogenic processes discussed. The main point is that climate change can alter their frequencies, distribution, mix, and magnitudes – both favourably and adversely. Because of limited investigation into these processes and their relationship to climate, our understanding of how climate change will affect them (and in different sub-regions) is also limited. Thus, we need to be cautious about making predictions, especially alarmist ones, while emphasising that there is cause for concern.

Biological indicators

Global climate change impacts can be tracked by biological indicators such as phenology (Menzel et al. 2006). There is an evident sign of advancing unfolding, blossoming, and ripening in the leaves and fruit of wild plants; and of hibernation, migration, and breeding of wildlife in mountain regions. Throughout China, the phenology of events has become two to four days earlier than in the 1980s (Zheng et al. 2002). Previous synchronous relationships between predators and prey, as well as those between insects and plants, are falling

apart, with negative consequences for both individual species and their ecosystems (Parmesan 2006).
Within a species there may be significant variations in climate tolerance among individuals. This can result in the evolution of new phenotypes, even the formation of novel species' associations and other ecological surprises. The disappearance of some extant climates increases the risk of extinction for species with narrow geographic or climatic distributions and disruption of existing communities. Most endemic plant species are unable to respond successfully as the rate of climate change increases (McCarty 2001) and resultant invasions of weedy and exotic species from lower elevations bring accompanying problems.

The possibility of alterations in overall albedo, water balance, and surface energy balance on high-altitude grasslands with increasing degradation and desertification in the arid areas is causing concern. Signs of the effects of climate change on the grasslands have been documented from the northeast Tibetan Plateau where Kobresia sedge and alpine turf communities are changing to semi-arid alpine steppe, known in Chinese as 'black bleaching' (Ma and Wang 1999; Miller 2000). Qinghai Province in China alone has more than 20,000 sq.km of degraded rangeland. Upward movement of the tree line and encroachment of woody vegetation on to alpine meadows are reported widely. In the eastern Himalayas, the tree line is rising at a rate of 5-10 m per decade (Baker and Moseley 2007). Although it is difficult to attribute this to climate change alone as human activities could also be a factor, rapid changes in alpine communities (both structure and species' composition) are expected as the climate changes. As temperatures rise and glaciers retreat, species shift their ranges to follow their principal habitats and climatic optima. However, the ability of species to respond to a changing climate varies. Shifts in species' ranges during past major global climate changes indicate that all species have climatic limitations beyond which they cannot survive.

Projected Future Trends and Impacts

Loss of glaciers, runoff, and river flow predictions

Based on regional climate models (RCMs), it is predicted that the temperatures in the Indian sub-continent will rise between 3.5 and 5.5ºC by 2100 (Rupa Kumar et al. 2006); and those of the Tibetan Plateau to rise 2.5ºC by 2050 and 5ºC by 2100. However, because of the extreme topography and complex reactions to the greenhouse effect, even high resolution climatic models cannot give reliable projections of climate change in the Himalayas.

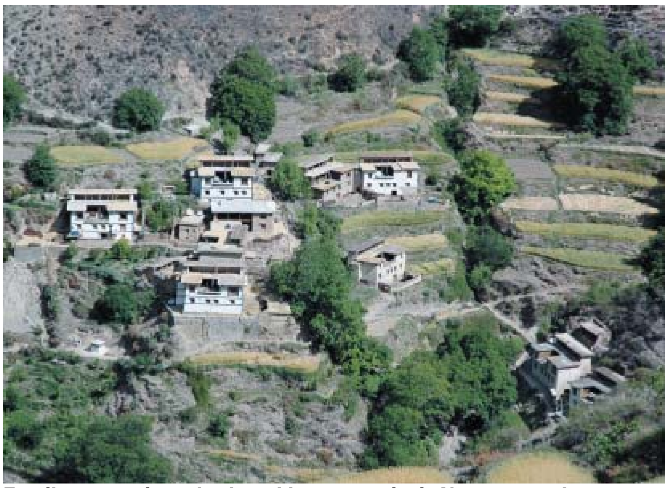
Various attempts to model changes in the ice cover and discharge of glacial melt have been made by assuming different climate change scenarios. One concludes that with a 2ºC increase by 2050, 35% of the present glaciers will disappear and runoff will increase, peaking between 2030 and 2050 (Qin 2002).

Under the uniform warming scenario of +0.06ºC per year, impacts of declining glacier area on river flow will be greater in small, more highly glaciated basins in both the western and eastern Himalayas. Flow for the most glaciated sub-catchments (glaciation ≥50%) will attain peaks of 150 and 170% of initial flow around 2050 and 2070 in the west and east respectively before declining until the respective glaciers disappear in 2086 and 2109 (Rees and Collins 2006).

Potential impacts

Drylands

There is significant uncertainty about the effects of global warming on vegetation and animal productivity of large dryland ecosystems. Although high altitude drylands might enjoy increases in net primary productivity (NPP) locally, the greatest confidence is in predicting implications for vegetation production, with lesser confidence in implications for vegetation composition, animal production, and adaptation options (Campbell and Stafford Smith 2000). Satellite observations suggest that some rangelands might be suffering from processes of degradation due to warmer and drier trends (Dirnbock et al. 2003). Degraded rangeland already accounts for over 40% of dryland on the Tibetan Plateau (Zhong et al. 2003; Gao et al. 2005); and it is expanding at a rate of three to five per cent each year (Ma and Wang 1999). The culprits are climate warming and overgrazing, as well as the mutual influence of human activities and climate change. Increase in evaporation, reduction in snow cover, and fluctuations in precipitation are key factors contributing to the degradation of dryland ecosystems. In addition degradation of grassland by overgrazing will increase the potential evapotranspiration level, thereby promoting climate warming and the degradation process (Du et al. 2004).



Fragile mountain and vulnerable community in Yunnan, southwest China, eastern Himalaya (Xu Jianchu)

Rangeland in Qinghai, Tibetan Plateau (Yang Xuefei)

Fresh water

Glacial melt provides the freshwater resources vital for certain ecosystems, particularly in arid areas of the Himalayas and during critical periods from the dry season to monsoon (Table 1). The supply of water resources, or the snow and ice meltwater component, in large river basins is projected to increase over the following decades as perennial snow and ice decrease. The glacial retreat caused glacial-melt runoff to increase by more than 5.5% in the 1990s in northwest China and by 13% in glaciated Tarim basins in the past decade (Yao et al. 2004). The impact of warmer climates on the melt from snow-fed basins has been converse to the impact on glacier-fed basins: snow-fed basins are more sensitive in terms of reduction in the availability of water due to a compound effect of increase in evaporation and decrease in melt (Singh and Bengtsson 2005). Most scenarios, however, suggest a water scarcity even of catastrophic proportions by the 2050s resulting from population growth, climatic change, and the increase of water consumption (Oki 2003).

Forest ecosystem

Impacts of climate change on forest ecosystems include shifts in forest boundaries by latitude and upward movement of tree lines to higher elevations; changes in species' composition and vegetation types; and an increase in net primary productivity (NPP) (Ramakrishna et al. 2003). In the eastern Himalayas, forest vegetation will expand significantly; forest productivity will increase from 1-10%; and it is expected that forest fires and pests such as the North American pinewood nematode (*Bursaphelenchus xylophilus*) will increase as dryness and warmth increase (Rebetez and Dobbertin 2004). The overall impact of climate change on the forest ecosystems can be negative (Siddiqui et al. 1999).

Biodiversity

Mountain ecosystems host a series of climatically different life zones over short distances and elevations and have a range of micro-habitats and 'niches', therefore mountains are hot spots of biodiversity and priority regions for conservation (Körner 2004). Mountain biodiversity is also most sensitive to global warming and is now showing signs of fragmentation and degradation caused by exogenous forces such as temperature increases and human activities (Xu and Wilkes 2003; Körner 2004). Species in high-elevation ecosystems are projected to shift higher. In the higher elevated areas, the rates of vegetation change are expected to be slow, and colonisation constrained by increased soil erosion. Alpine plant species on mountain ranges with restricted habitat availability above the tree line will experience severe fragmentation, habitat loss, or even extinction if they cannot move to higher elevations, particularly after an increase of 2ºC (Dirnbock et al. 2003). Climate warming will increase suitable habitats for the water hyacinth (Eichhornia crassipes), a noxious weed able to survive during winter.

Agriculture and food production

Increases in temperature and water stress are expected to lead to a 30% decrease in crop yields in Central and South Asia by the mid-21st century (UNDP 2006). However, at high altitudes and latitudes, crop yields should increase because there will be a decrease in frost and cold damage. It will be possible to grow rice and wheat at higher latitudes than is currently the case in China.

Human health

Warming has the potential to increase endemic morbidity and mortality because of diarrhoeal and vector-borne diseases, such as malaria, primarily associated with floods and droughts in the Himalayas. One study (Rodo et al. 2002) also found a relationship between El Niño/ Southern Oscillation (ENSO) and cholera prevalence in Bangladesh. Equally, an increase in temperatures at high altitude will reduce the risks from cold and the amount of fuelwood needed for heating and associated respiratory disease. Living in the mountains has advantages compared to the seasonally hot and humid lowland plains.

Mountain infrastructure

Valuable infrastructure, such as hydropower plants, roads, bridges, and communication systems, will be increasingly at risk from climate change. Entire hydropower generation systems established on many of the rivers will be in jeopardy if landslides and flash floods increase and if there is a decrease in the already low flows during the dry season. Mountain engineers have to consider how to respond to extreme events in the mountain context (OECD 2003). Permafrost melting was the main challenge for designing a railway connection to Lhasa.

Tourism

Although there will be benefits, trekking and mountaineering may be affected adversely by reduced snow and glacial cover and increases in natural hazards, endangering transportation on high-altitude routes.

Tourism could, however, become more profitable as post-monsoon dry periods increase and warm winters come to high elevations.

Conclusion

The Himalayas cover one of the most dynamic and complex mountain ranges in the world due to tectonic activity, and they are vulnerable to global warming and increasing human activities (Bandyopadhyay and Gyawali 1994). Uncertainties about the rate and magnitude of climate change and potential impacts prevail, but there is no question that it is gradually and powerfully changing the ecological and socioeconomic landscape in the Himalayan region, particularly in relation to water. Business as usual is not an option. It is imperative to revisit and redesign research agendas, development policies, management and conservation practices, and appropriate technologies. Given the level of uncertainty in science and research in the Himalayas, policies should be 'adaptation friendly'. Mitigation of carbon emissions should be a responsibility shared among citizens and the private sector in the mountains as elsewhere. Adaptation and mitigation measures intended to cope with climate change can create opportunities as well as offsetting the dangers of a warming planet; but they must be identified and adopted ahead of, rather than in reaction to, dangerous trends.

Himalayan uncertainty – We speak of uncertainty on a Himalayan scale in recognition that our science and information systems are no match for the complexity and diversity of regional contexts, quite apart from the lack of studies and basic data. In no context is this more relevant than in predicting what climate change will involve. The physical manifestations of climate change in the mountains include locally, possibly regionally, extreme increases in temperature and in the frequency and duration of extreme events. It seems certain there will be appreciable changes in the volumes and/or timing of river flows and other fresh water sources. There is, however, great uncertainty about the rates and even the direction of these changes, because so little is known about the dynamics of Himalayan topoclimates and hydrological processes and their response to changing climatic inputs. The global circulation models used to model climates capture global warming on a broad scale, but do not have adequate predictive power even for large Himalayan drainage basins. To reduce uncertainty we need well-equipped baseline stations, long-term monitoring, networking, open data exchange, and cooperation between all the Himalayan regional member countries. ICIMOD can play a role in facilitating knowledge generation, exchange, and cooperation with international mountain research programmes such as the Global Observation Research Initiative in Alpine Environments (GLORIA), Global Mountain Biodiversity Assessment (GMBA), UNESCO Biosphere Reserves, and the Mountain Research Initiative.

Adaptive responses – the need for flexibility and resilience. Climate change is not new for Himalayan people. Tectonic uplift and Quaternary climate changes, including recovery from the last major glacial period and Little Ice Age mean that every aspect of life has been adapted to, or stressed by, changing temperature regimes, water availability, and extreme events. Himalayan farmers and herders have a long history of adapting to these uncertainties, other related and unrelated environmental changes, and ecological surprises, whether through mobility of people and land uses, or flexibility in livelihood strategies and institutional arrangements. Mountain people have lived with and survived great hazards such as flash floods, avalanches, and droughts for millennia. Building the capacity to adapt and strengthen the social-ecological system in the face of climate change is doubly important and is an important step in achieving sustainable livelihoods. Supporting and being resilient, and encouraging strategies to cope with surprises and long-term changes, are the new adaptive mantras, unlike earlier notions of improving people's adaptations to relatively stable and known habitats. Climate change, as a public and global issue, has evolved from a narrow interest in the hydro-meteorological sciences to a broad recognition that both the social consequences and policies in response have implications in all aspects of human development. Adaptive policies and major efforts to reverse the human drivers of climate change have to be incorporated into all sectors: land use, water management, disaster management, energy consumption, and human health. Hazard mapping would help both decision-makers and local communities to understand the current situation and through this it would be possible to anticipate or assess the flexibility to adapt to future changes through proper planning and technical designs.

Linking science and policy in climate change – Good science with credible, salient, legitimate knowledge can often lead to good policies in the context of climate change and mountain specificities or vice versa (Thompson and Gyawali 2007). By credible, we mean knowledge that has been derived from field observations and tested by local communities; salient information is immediately relevant

Mountain ecosystem and livelihood are vulnerable to climate change, southeast Tibet Autonomous Region of China (Xu Jianchu) and useful to policy-makers; legitimate information is unbiased in its origins and creation and both fair and reasonably comprehensive in its treatment of opposing views and interests. Policy is a formula for the use of power and application of knowledge. The question then is who has the power and who the knowledge, scientific knowledge or local knowledge, or a combination of both? Scientific knowledge is useful but limited and full of uncertainties on the complex Himalayan scale; so then 'Nobody Knows Best' becomes the model (Lebel et al. 2004). Alternative perspectives carry their own set of values and perceptions about who should be making the rules, where the best knowledge lies to guide decisions, and about what more knowledge is needed, and four contrasting perspectives – state, market, civil society and the greens, and locals–merge together in decision-making processes. In such processes, scientists have to generate new knowledge with reduced uncertainty and facilitate the dialogue with balanced perspectives. The role of different actors in contributing to resolving scientific uncertainty, adaptation, mitigation, and public engagement through this approach can be summarised in the form of a matrix (Table 5). In such processes, international cooperation is essential for transfer of technology from outsiders to locals, building regional cooperation into a global programme, and developing the capacity to downscale important results to the regional HKH scale.

Policy Recommendations

Reducing scientific uncertainty

1. **Developing civic, high, and school science programmes for climatic monitoring**
   Credible, up-to-date scientific knowledge is essential for the development of climate policy. The current review finds a lacuna in the context of field observation networks because of the vast geographical area and inaccessibility. It is essential to develop **high science** with government agencies and academia for application of standardised methodologies for year-round observation. Today remote sensing allows for regular and repeated monitoring of snow cover, which can be carried out by countries such as China and India to distribute to those without such technological infrastructure. It would facilitate analysis of the melting process and prediction of certain risks. Some areas of scientific focus are ground-based and satellite-based monitoring of weather and cryospheric processes, climate modelling, and impact modelling. For this, well equipped baseline stations and long-term monitoring, networking, and cooperation within and outside the region are essential. Along with scientific and technical criteria, participatory methods, or **civic science**, need to be developed to assess and monitor climate and environmental changes based on local perceptions, practices, and use. This would enable local communities to play key roles in determining adaptation practices to reinforce resilience based on local information and knowledge. Rainfall gauges or simple tipping baskets can be introduced into the schools in the region. A **school science programme** can be developed in local communities in the Himalayan mountain region.

2. **Application of regional climate models (RCMs)**
   Local climate change is influenced greatly by features of the Himalayas that are not well represented in global models because of their coarse resolution. Regional climate models, with a higher resolution

Table 5: Nobody knows best: policy matrix to cope with Himalayan uncertainty

	Scientific uncertainty	Adaptation	Mitigation	Public engagement
State	Regional cooperation, support long-term research, engaging in research processes	Inter-sectoral collaboration, support for poverty alleviation and environmental conservation	Commitment to international treaties, developing good policies	Transparency in information and support for public debates
Market	Partnership in research, new hardware and software for monitoring	New technology, support for community development and local education	Self-regulating and reducing greenhouse gas emissions	Green certification, support for civil society
Civil society	Participatory vulnerability analysis, linking local to global, facilitating knowledge learning	Community preparedness, facilitating local learning and adaptation	Social auditing, green watch and monitoring	Access to information, awareness campaign, social inclusion, inter-cultural dialogues
Local community	Local indicators and monitoring, local knowledge, innovations, and practices	Improved land/resource management, preparedness for surprises	Renewable energy, alternative livelihoods, and migration	Representation in dialogues and decision-making
ICIMOD's Role	Impact assessment, knowledge synthesis, regional database, forecasting, monitoring	Capacity building, support for mountain policies, pilot demonstration, optimising land-use patterns and livelihoods in mountain 'niche'	Facilitating the clean development mechanism (CDM) and carbon market place, designing payments for environmental services	Regional dialogue, debate at international forums, channelling funding support

than global ones, need to be constructed for different 'hotspots' and run for shorter periods (20 years or so). The inter-connectivities of Himalayan environmental change, the Asian monsoon, and local and global climate warming need careful study. Capacities at local, national, and regional levels should be improved through cooperation between ICIMOD and global environmental projects such as Monsoon Asia Integrated Regional Studies (MAIRS). The results of RCMs have to be downscaled and applied to impact assessments, in particular for watersheds or sub-catchments.

3. **Establishment of earth science for integrated research in the Himalayas**
   Integrated research programmes in the Himalayan region have to consider the interlinkage of the six spheres (lithosphere, cryosphere, hydrosphere, atmosphere, biosphere, and anthrosphere). Mountain specificities (Jodha 2005) and vulnerability to environmental change are also important. The vulnerability of humans and ecosystems to the impacts of climate change should be identified through integrated research and partnership: the Brahmatwinn Project (www.brahmatwinn.uni-jena.de) is a good example of this.

4. **Disaster risk reduction and flood forecasting**
   Floods are the main natural disaster aggravating poverty in the Himalayas where half of the world's poor live. Technical advances in flood forecasting and management offer an opportunity for regional cooperation in disaster management. Regional cooperation in transboundary disaster risk management should become political agenda. Preparedness for disaster management is the best solution (www.disasterpreparedness.icimod.org).

Adaptation measures

5. **Supporting community-led adaptation**
   The best approach to vulnerability and uncertainty in regard to climate change is 'bottom-up' community-led adaptation built on local knowledge, innovation, and practices. The focus should be on empowering communities to monitor and take action to adapt to a changing climate and environment based on their own decision-making processes and participatory technology development with support from outsiders. For example, Tibetan nomads have already noticed the earlier spring and move yaks to alpine meadows much earlier than was the traditional practice. Farmers in the floodplains of Bangladesh build houses on stilts, and Nepali farmers store crop seeds for post-disaster recovery. Priority should be given to the most vulnerable groups such as women, the poor, and people living in fragile habitats such as along riversides and on steep slopes.

Glacier-capped Mt. Kawagebo ('White Snow Mountain'), part of the Hengduan Mountain Range, is one of the most sacred landscapes for Tibetan people (He Bin)

6. **National adaptation plans of action (NAPAs)**
   NAPAs are currently being prepared by regional countries under the initiative of the UN Framework Convention on Climate Change. They are expected (a) to identify sectors most vulnerable to climate change and (b) to prioritise activities for adaptation measures in those sectors. NAPAs need to pay more attention to certain sectors such as water, agriculture, health, disaster reduction, and forestry, as well as the most vulnerable groups such as children, women, and other disadvantaged groups.

7. **Integrated water resource management**
   Disaster preparedness and risk reduction should be seen as an integral part of water resource management: integrated water resource management (IWRM) should include further climate change scenarios and be scaled up from watersheds to river basins. IWRM is a political process and researchers should engage constructively with the relevant stakeholders in the public sector, private sector, and civil society. Water allocation for ecosystems and livelihoods deserves particular attention. Water storage, based on local practices should be developed in the mountain region to deal with the problem of too much water during the monsoon and too little during the dry season.

8. **Human ecosystem approach to human health**
   Human health systems will be challenged by climate change and its associated impacts. The ecosystem approach to human health can help alleviate the impacts of climate change through improved nutrition, vector and habitat management, and land-use practices.

Mitigation measures

9. **Land-use management for carbon sink and reduced emissions**
   Many regional member countries in the Himalayas have experienced forest recovery (or transition),

Tibetan nomads take their yaks to high altitudes in April and can shift one more time between summer and winter camps due to a lengthening growing season (Xu Jianchu)

through policy intervention and participation of local communities in forest management: examples are forest conservation in Bhutan, tree plantation in China, community forest user groups in Nepal, and joint forest management in India. The forests conserved have contributed significantly to carbon sequestration (Fang et al. 2001). Although planting trees at mid-latitude and high altitudes is still controversial (Bala et al. 2007), improved land-use management can contribute to changes in precipitation and temperature patterns through atmospheric circulation, greenhouse gas emission, and albedo change on a global scale (Gibband et al, 2005).

10. **Payment for environmental services (PES)**
    As natural habitats shrink and human demands increase, environmental services previously provided for free are threatened. This emerging scarcity makes environmental services potentially tradable. The idea of PES is that external beneficiaries of environmental services make direct contractual quid pro quo payments to local landowners and land users in return for their adopting land and resource uses that secure ecosystem services such as carbon sequestration.

11. **Towards the Kyoto protocol and beyond**
    With rapid regional economic growth, China and India, particularly, should accept equal, albeit differentiated, responsibilities from developed countries to control increasing carbon emissions. Himalayan regional member countries should jointly develop a regional action plan for control of emissions. Participation of all countries has to be achieved by allowing them to interpret the mandates of international agreements according to their national interests and priorities.

12. **Development of alternative technologies**
    Novel and affordable technologies and energy resources are needed that do not emit greenhouse gases. There are many opportunities to create 'win-win' situations all round in the attempt to prevent global warming. Notable examples in the region include the diffusion of hydropower in Bhutan, solar energy and biogas in China, bio-diesel and wind energy in India, and biogas and micro-hydropower in Nepal.

Public awareness and engagement

13. **Full disclosure, precaution, and prior information for grass-root societies**
    Indigenous and local communities should be fully informed about the impacts of climate change. They have the right to information and materials in their own languages and ways of communication.

14. **Engagement of the media and academia**
    Awareness and knowledge among stakeholders generally about the impacts of global warming and the threat to the ecosystem, communities, and infrastructure are inadequate. The media and academia together can play a significant role in public education, awareness building, and trend projection.

15. **Facilitation of international policy dialogue and cooperation**
    International communities – including donors, decision-makers, and the private and public sectors – should be informed in order to advance regional and international cooperation to address the ecological, socioeconomic, and cultural implications of climate change in the Himalayas.