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An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India and China

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Nepal
‘Nepalese Glaciers, Glacier Retreat and its Impact to the Broader Perspective of Nepal’
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India
‘Status review of possible Impacts of Climate Change on Himalayan Glaciers, Glaciers retreat and its subsequent impacts on fresh water regime’
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China
‘An Overview of Glaciers, Retreating Glaciers, and Their Impact in the Tibetan Plateau’
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FOREWORD

Climate change is real and happening now.

The planet is already experiencing its impacts on biodiversity, freshwater resources and local livelihoods. Using current climate change trends, by 2100, the average global temperature may rise by 1.4 – 5.8^{0}C according to the Third Assessment Report from the Intergovernmental Panel on Climate Change (IPCC, 2001). This is certain disaster for fragile ecosystems like glaciers.

Seventy percent of the worlds freshwater is frozen in glaciers. Glacier melt buffers other ecosystems against climate variability. Very often it provides the only source of water for humans and biodiversity during dry seasons. Freshwater is already a limited resource for much of the planet, and in the next three decades, the population growth is likely to far exceed any potential increase in available water.

The Himalayas have the largest concentration of glaciers outside the polar caps. With glacier coverage of 33,000 km^2, the region is aptly called the “Water Tower of Asia” as it provides around 8.6 X 10^6 m^3 of water annually (Dyurgerov and Maier, 1997). These Himalayan glaciers feed seven of Asia’s great rivers: the Ganga, Indus, Brahmaputra, Salween, Mekong, Yangtze and Huang Ho. It ensures a year round water supply to millions of people.

Climate change has impacted the glacial ecosystem tremendously. Sixty-seven percent of glaciers are retreating at a startling rate in the Himalayas and the major causal factor has been identified as climate change (Ageta and Kadota, 1992; Yamada et al., 1996; Fushinmi, 2000). Glacial melt will affect freshwater flows with dramatic adverse effects on biodiversity, and people and livelihoods, with a possible long-term implication on regional food security.

WWF sees the impacts of climate change on glaciers and its subsequent impact on freshwater as a major issue, not just in the national context but also at a regional, transboundary level. The WWF offices in Nepal, India and China are taking the initiative to develop a regional collaboration to tackle climate change impacts in the glacial ecosystem and address adaptation measures. This report is the outcome of a regional collaboration of the three countries, providing an overview of climate impacts on glaciers with a focus on key areas that needs future intervention.

We hope this will highlight the issue of climate change and galvanize policy makers to take action to ensure a living planet for future generations.

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ACRONYMS

AOGCMs	Atmosphere-Ocean General Circulation Model
ASTER	Advance Space borne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
DFID	Department of International Development
DHM	Department of Hydrology and Meteorology
ENSO	El Nino-Southern Oscillation
GCMs	General Circulation Models
GDP	Gross Domestic Product
GIS	Geographical Information System
GLOF	Glacial Lake Outburst Flood
GSI	Geological Survey of India
HMG/N	His Majesty's Government of Nepal
ICIMOD	International Centre for Integrated Mountain Development
ICSI	International Commission for Snow and Ice
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
LGM	Last Glacial Maximum
LIA	Little Ice Age
MOPE	Ministry of Population and Environment
OECD	Organization for Economic Co-operation and Development
SPOT	Satellite Pour Observation de la Terre
SRES	Special Report on Emission Scenario
TM	Thematic Mapper (Landset)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	United Stated Dollar
USGS	United State Geology Survey
WECS	Water and Energy Commission Secretariat.
WGHG	Working Group on Himalayan Glaciology
WGMS	World Glacier Monitoring Service

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Regional Overview
Executive Summary

Introduction

Climatic changes and its impacts on the fluctuation of glaciers are a natural phenomenon that has been occurring in the Earth's five billion-year-old history. In the past few decades, global climate change has had a significant impact on the high mountain environment: snow, glaciers and permafrost are especially sensitive to changes in atmospheric conditions because of their proximity to melting conditions. In fact, changes in ice occurrences and corresponding impacts on physical high-mountain systems could be among the most directly visible signals of global warming. This is also one of the primary reasons why glacier observations have been used for climate system monitoring for many years (Haeberli 1990; Wood 1990).

A historical overview

There have been at least 17 major glacial advances (glaciations) in the last 1.6 million years alone (Goudie 1983). The most recent, the Last Glacial, reached its peak some 20,000 to 18,000 years ago and came to an end about 10,000 years ago (Goudie 1983). Glaciations are followed by 'interglacial' periods, during which the glacier ice retreats as a result of global warming. The interglacial typically continues for about 10,000 years before the cooling or the next glaciation begins. This cyclical activity, which recurs at intervals of approximately 100,000 years, is generally accepted to be caused by gradual changes in the earth's rotation, tilt and orbit around the sun, which affects the amount of solar radiation the earth receives (Milankovitch 1941 in Bradley 1985).

Glacial cycles are punctuated by relatively short periods of localized cooling and warming, during which glaciers advance and retreat. The most recent cooling episode of the present interglacial commonly referred to as the 'Little Ice Age' (LIA), affected parts of North America (Curry 1969), Asia (Chu Ko-Chan 1973) and Europe from about 1300 AD through to the latter half of the 19th century. During the LIA (1550-1850 AD) glaciers were much longer than today (Yamada *et al.* 1998). It may have been the result of volcanic eruptions and the presence of volcanic ash in the atmosphere that caused cooling by reducing the amount of solar radiation reaching the earth's surface (Lamb 1970). Changes to ocean currents have also been suggested, as has tectonic activity, concentration of carbon dioxide in the atmosphere, and sunspot activity (Goudie 1983).

The present scenario

The 20th century has been a watershed vis-à-vis glacial fluctuations on a global scale. This has been a period of dramatic glacier retreat in almost all alpine regions of the globe, with accelerated glacier and ice-fields melt in the last two decades. The first phase of this glacier retreat was associated with emergence from the Little Ice Age that ended in the 19th century. It corresponded with a warming of 0.3ºC in the first half of the 20th century in the northern hemisphere (24° to 40°N). In the last 25 years, a second 0.3ºC warming pulse has caused northern hemisphere temperatures to rise to unprecedented levels compared to the last 1,000 years. The 1990s were the warmest decade of the millennium and 1998 the hottest year of the millennium. In all, there was a temperature rise of close to 1ºC across the continents.

Research shows that the glacier cover of mountain regions worldwide has decreased significantly in recent years as a result of warming trends. A recent comparison of historical glacier data with images from the ASTER (Advance Spaceborne Thermal Emission and Reflection Radiometer) instrument on NASA's TERRA satellite by the United States' Geological Survey revealed a significant shrinkage of mountain glaciers in the Andes, the Himalayas, the Alps and the Pyrenees over the past decade (Wessels *et al.* 2001). These observations are consistent with published results from many other glacier studies around the world that also recorded rapid glacier retreat in recent years. A study by Dyurgerov and Meier (1997), who considered the mass balance changes of over 200 mountain glaciers globally, concluded that the reduction in global glacier area amounted to between 6,000 and 8,000 km^2 over a 30 year period between 1961 and 1990.

According to Haeberli and Hoelzle (2001) of the World Glacier Monitoring Service (WGMS), the measurements taken over the last century "clearly reveal a general shrinkage of mountain glaciers on a global scale". They observed that the trend was most pronounced during the first half of the 20th century and that glaciers had started to grow again after about 1950. However, they claim that mountain glacier retreat has been accelerating again since the 1980s at a "rate beyond the range of pre-industrial variability". Based upon a number of scientific investigations (e.g. Kuhn 1993a, Oerlemans 1994) and the IPCC (1996b) there are forecasts that up to a quarter of the global mountain glacier mass could disappear by 2050 and up to half could be lost by 2100.

Closer to the present focus of our areas of study, Himalayan glaciers have also been found to be in a state of general retreat since 1850 (Mayewski & Jeschke 1979). The Himalayan glaciers feed seven of Asia's great rivers: Ganga, Indus, Brahmaputra, Salween, Mekong, Yangtze and Huang He, and ensure a year-round water supply to billions people.

The Khumbu Glacier, a popular climbing route to the summit of Mt Everest, has retreated over 5 km from where Sir Edmund Hillary and Tenzing Norgay set out to conquer the world's highest mountain in 1953. Since the mid-1970s the average air temperature measured at 49 stations of the Himalayan region rose by 1°C with high elevation sites warming the most (Hasnain 2000). This is twice as fast as the 0.6°C average warming for the mid-latitudinal northern hemisphere over the same time period (IPCC 2001b), and illustrates the high sensitivity of mountain regions to climate change (Oerlemanns *et al.* 2000). The Dokriani Barnak Glaicer in India retreated 20m in 1998, and the Gangotri Glacier some 30m.

Overview of the problem

The *New Scientist* magazine carried the article "Flooded Out – Retreating glaciers spell disaster for valley communities" in their 5 June 1999 issue. It quoted Professor Syed Hasnain, then Chairman of the International Commission for Snow and Ice's (ICSI) Working Group on Himalayan Glaciology, who said most of the glaciers in the Himalayan region "will vanish within 40 years as a result of global warming". The article also predicted that freshwater flow in rivers across South Asia will "eventually diminish, resulting in widespread water shortages".

As apocalyptic as it may sound, it needs to be underlined that glaciers need to be studied for a variety of purposes including hazard assessment, effects on hydrology, sea level rise and to track climatic variations. There are several problems associated with retreating glaciers that need to be understood in order to proceed to the next stage of quantifying research and mitigating disaster. In this context it would be imperative to understand the nature of problems that confront Nepal, India and China. While the following section deals with problems faced by all three countries, country-specific losses and details would be dealt with separately.

Risks and associated impacts of glacier retreat

Freshwater regime

More than half of humanity relies on the freshwater that accumulates in mountains (Mountain Agenda 1998). Glaciers 'mother' several rivers and streams with melt runoff. A significant portion of the low flow contribution of Himalayan rivers during the dry season is from snow and glaciers melt in the Himalayan region. The runoff supplies communities with water for drinking, irrigation and industry, and is also vital for maintaining river and riparian habitat. It is posited that the accelerated melting of glaciers will cause an increase in river levels over the next few decades, initially leading to higher incidence of flooding and land-slides (IPCC, 2001a). But, in the longer-term, as the volume of ice available for melting diminishes, a reduction in glacial runoff and river flows can be expected (IPCC 1996b, Wanchang *et al.* 2000). In the Ganga, the loss of glacier meltwater would reduce July-September flows by two thirds, causing water shortages for 500 million people and 37 percent of India's irrigated land (Jain 2001; Singh *et al.* 1994).

Glacial lake outburst floods (GLOFs)

Glacial lake outburst floods (GLOFs) are catastrophic discharges of water resulting primarily from melting glaciers. An accelerated retreat of the glaciers in recent times has led to an enlargement of several glacial lakes. As the glaciers retreat they leave a large void behind. The ponds occupy the depression earlier occupied by glacier ice. These dams are structurally weak and unstable and undergo constant changes due to slope failures, slumping, etc. and run the risk of causing GLOFs.

Principally, a moraine dam may break by the action of some external trigger or self-destruction. A huge displacement wave generated by rockslide or a snow/ice avalanche from the glacier terminus into the lake may cause the water to top the moraines and create a large breach that eventually causes dam failure (Ives 1986). Earthquakes may also be one of the factors triggering dam break depending upon magnitude, location and characteristics. Self-destruction is a result of the failure of the dam slope and seepage from the natural drainage network of the dam.

Characterized by sudden releases of huge amounts of lake water, which in turn would rush down along the stream channel downstream in the form of dangerous flood waves, GLOF waves comprise water mixed with morainic materials and cause devastation for downstream riparian communities, hydropower stations and other infrastructure. In South Asia, particularly in the Himalayan region, it has been observed that the frequency of the occurrence of GLOF events has increased in the second half of the 20th century. GLOFs have cost lives, property and infrastructure in India, Nepal and China.

Glacial Lake Out-burst Floods (GLOF) are the main natural hazards in the mountain areas of this region. A 1964 GLOF in China destroyed many kilometers of highway and washed 12 timber trucks 71 km from the scene. An outburst of Zhangzangbo Lake in 1981 killed four people and damaged the China-Nepal Friendship Bridge in the northern border, seven other bridges, a hydropower plant, Arniko highway and 51 houses. The damage was estimated to be USD 3 million. The 1985 GLOF at Dig Tsho was triggered by a large avalanche. A hydroelectricity project, 14 bridges, 30 houses and farmlands worth USD 4 million were destroyed. In 1998, the outburst of Tam Pokhari in Nepal killed two people, destroyed more than six bridges and washed away arable land. Losses worth over 150 million rupees have been estimated. A high water level was observed even after 19 hours in the Koshi barrage near the Indo-Nepal border. The river reverted to its original flow only after three days (Dwivedi 2000).

There are about 159 glacier lakes in Koshi basin (Sharma 1998). Nearly 229 glacier lakes were identified in Tibet's Arun basin, out of which 24 are potentially dangerous (Meon & Schwarz 1993). Since 1935 more than 16 GLOFs have been reported which either occurred or extended into Nepal.

National economic costs

For a landlocked country like Nepal, which relies on hydropower generation as a vital source of national income, the prospect of an eventual decrease in the discharge of rivers spells doom. For an energy-constrained economy like India, the prospect of diminishing river flows in the future and the possibility that energy potential from hydropower may not be achieved has serious economic implications. The implications for industry extend beyond the 'energy' argument: chemical, steel, paper and mining industries in the region that rely directly on river/stream water supply would be seriously affected. Reduced irrigation for agriculture would have ramifications not only on crop production but eventually on basic human indices like available food supplies for people and malnutrition.

While the impacts of deglaciation are briefly outlined in the aforementioned categories there are, as mentioned earlier, details specific to each of the countries that will be dealt within the country-specific case study. It would be useful to refer to each country analyses with the thematic support literature covered in the previous sections. The country case-studies are useful in understanding physical and climatological characteristics of the region and serve as useful bases of reference for further research.

Country Case Study 1

Nepal: Glaciers, glacier retreat and its impacts

Background

Shaped roughly like a rectangle, there are about 23.6 million people inhabiting Nepal. With China to the north and India on three other sides, the Nepali economy faces the uphill task of rectifying highly skewed development indices: access to electricity, drinking water and telecommunications are far outnumbered by people living on less than USD two per day.

Agriculture is the mainstay of the economy, providing livelihoods for over 80 percent of the population. Nepal also has one of the highest population densities in the world with respect to cultivable land (MOPE 2000). In the fiscal year 2001-02, the share of agriculture in GDP was 37.9 percent. The total land used for agricultural operation is 20.2 percent of the total area of Nepal. Industrial activity mainly involves the processing of agricultural products including sugarcane, tobacco, jute and grain.

The climate varies from sub-tropical to arctic in a span of less than 200 km. There is a wide range of natural resources, the most prominent among them being water and the Himalayas. In theory, the hydropower potential in Nepal is estimated at 83,000 MW (Shrestha 1985). While the practical potential might only be 50 percent of the theoretical, the total installed capacity of hydropower is only 494.9 MW on the ground—about 0.6 percent of the theoretical potential. Clearly, there is a lot to achieve in this field alone if hydropower is to be an indubitable anchor of Nepal's future development. Irrigation facilities and water supply also have to be enhanced.

Geography

Nepal is situated between latitudes of $26^0$22' to $30^0$27' north and between longitudes of $80^0$4' to $88^0$12' east. The east-west length of the country is about 800 km, roughly parallel to the Himalayan axis, and the average north-south width is 140 km. Within the 147,181 km^2 area of the country, physiographic regions range from tropical forests in the south to the snow and ice covered Himalayas in the north. Nepal has a very diverse environment resulting from its impressive topography. A cross-section of the country reveals that the topography generally progresses from altitudes of less than 100 m in the southern Terai plain, up to more than 8,000 m peaks in the north. Nepal can be divided into five ecological regions according to the Department of Survey (1978):

1. Terai: This is the northern part of Indo-Gangetic plain. The Terai extends nearly 800 km from east to west and about 30-40 km from north to south. The average elevation is below 750 m, including Terai region, Bhavar Terai and Inner Terai.

2. Siwalik: Commonly referred to as the Churia Hills, the elevation in the Siwalik ranges from 700 to 1,500 m. Due to its loose friable nature and extensive deforestation in past decades, this region experiences frequent landslides that contributes largely to the sediment load in many Nepali rivers.

3. Middle Mountain: Also known as the Mahabharat range, the elevation of this range is from 1,500 to 2,700 m. The Middle Mountain is cut in many places by antecedent rivers such as Kosi, Gandaki (Narayani), Karnali and Mahakali. They are the first great barrier to monsoon clouds and the highest precipitation occurs on the southern slope of this range.

4. High Mountains: High Mountains range from 2,200 to 4,000 m. This region consists of phyllite, schists and quartzite, and the soil is generally shallow and resistant to weathering. The climate is cool temperate.

5. High Himalaya: Ranges from 4,000 to above 8,000 m dominate the High Himalaya. Eight of the highest peaks in the world and the world's deepest gorge, 5,791 m in the Kali Gandaki valley, are located in this region. The climate is alpine and the snowline lies at 5,000 m in the east and at 4,000 m in the west. The area lying to the north of the main Himalayan range is the Trans-Himalayan region, which restricts the entry of monsoon moisture and therefore the region has a dry desert-like climate.

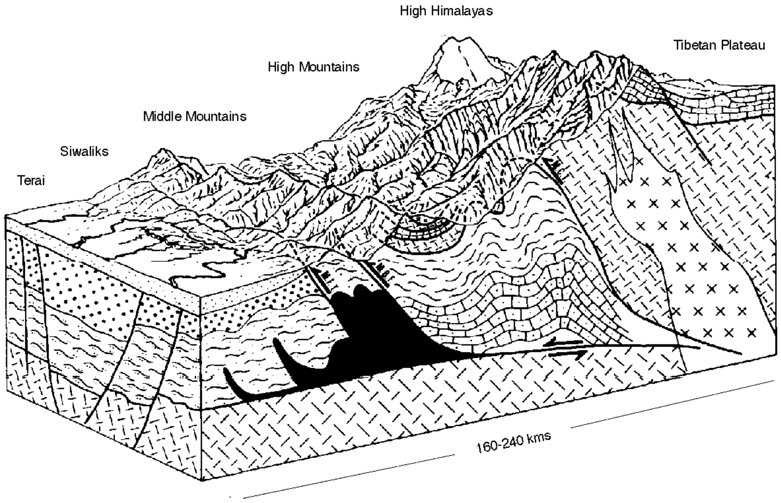


Figure 1: Cross-section of Nepal's topography

Climate and atmospheric circulation over Nepal

The remarkable climatic variability conditions in Nepal are primarily related to the impressive range of altitudes within a short north-south distance of the country. Precipitation is the most important climatic element for agricultural development and hydrology. Being located in the northern limit of the tropics, Nepal gets both summer and winter precipitation (Singh 1985). The thermal regime in the vast Eurasian region, the location of the Inter-Tropical Convergence Zone (ITCZ) and the resulting general atmospheric circulation dominate Nepal's precipitation regime.

The onset and retreat of the southeasterly summer monsoon is associated with the northward and southward movement of the ITCZ (Nayava 1980). During the monsoons, depressions form in the Bay of Bengal and move WNW causing heavy rain in its path. Nepal receives the first monsoon shower in the southeast before the rain moves slowly towards the northwest with diminishing intensity. The retreat of the monsoon begins from the northwest. The amount of monsoon precipitation shows a marked variation from south to north and east to west. Further, the contribution of the monsoon precipitation to the annual total is substantially greater in the southeastern part of the country compared to the northwest. In addition, there is also the altitudinal dependence of monsoon precipitation. Maximum precipitation occurs around 1,000 m in the Narayani basin, at around 1,500 m in the Sapta Kosi basin**,** whereas in the Karnali basin for the maximum precipitation, altitude is ambiguous (Alford 1992).

Winter precipitation is caused by the westerly disturbances originating in the Mediterranean. The lows formed here are steered and swept eastwards by the westerly aloft. Westerly disturbances affect the northern and western parts of Nepal (Singh 1985). Winter precipitation contributes significantly to the annual total precipitation in Nepal's northwest. It plays a major role in the mass balance of glaciers in western Nepal while playing a secondary role in the glaciers of eastern and central Nepal (Seko and Takahashi 1991). Although winter precipitation is not as impressive in volume or intensity as the summer monsoon, it is of vital importance in generating lean flow for agriculture. Most of the winter precipitation falls as snow and nourishes snowfields and glaciers and generates melt water in dry seasons between February and April. Lower temperatures mean less evaporation and rain of lesser intensity can have a higher rate of percolation that nourishes the root zone of the soil.

The summer monsoon is economically the most important season. The average precipitation in the country is 1,768 mm (Shrestha 2000), but it varies greatly from place to place owing to sharp topographical variation (Nayava 1980). As the rain bearing winds approach Nepal from the southeast in the summer monsoon season, heavier rainfall occurs in the foothills of the Churia range, increasing with altitude on the windward side and sharply decreasing in the leeward side. Monsoon precipitation occupies 70 to 85 percent of total precipitation depending on the location (Singh 1985; Ives & Messerli 1989). The precipitation occurs in a solid form in the high altitude and plays an important role in the nourishment of numerous Himalayan glaciers, most of which are of the summer accumulation type in central and eastern Nepal.

The maximum temperature of the year occurs in May or early June. Temperature starts decreasing from October and reaches the minimum in December or January. As temperature decreases with height, spatial variations are influenced by altitude. The hottest part of the country is the Terai belt where maximum temperatures cross 45ºC. The highest temperature ever recorded is 46.4 ºC in Dhangadhi, a town in far western Terai, in June 1995.

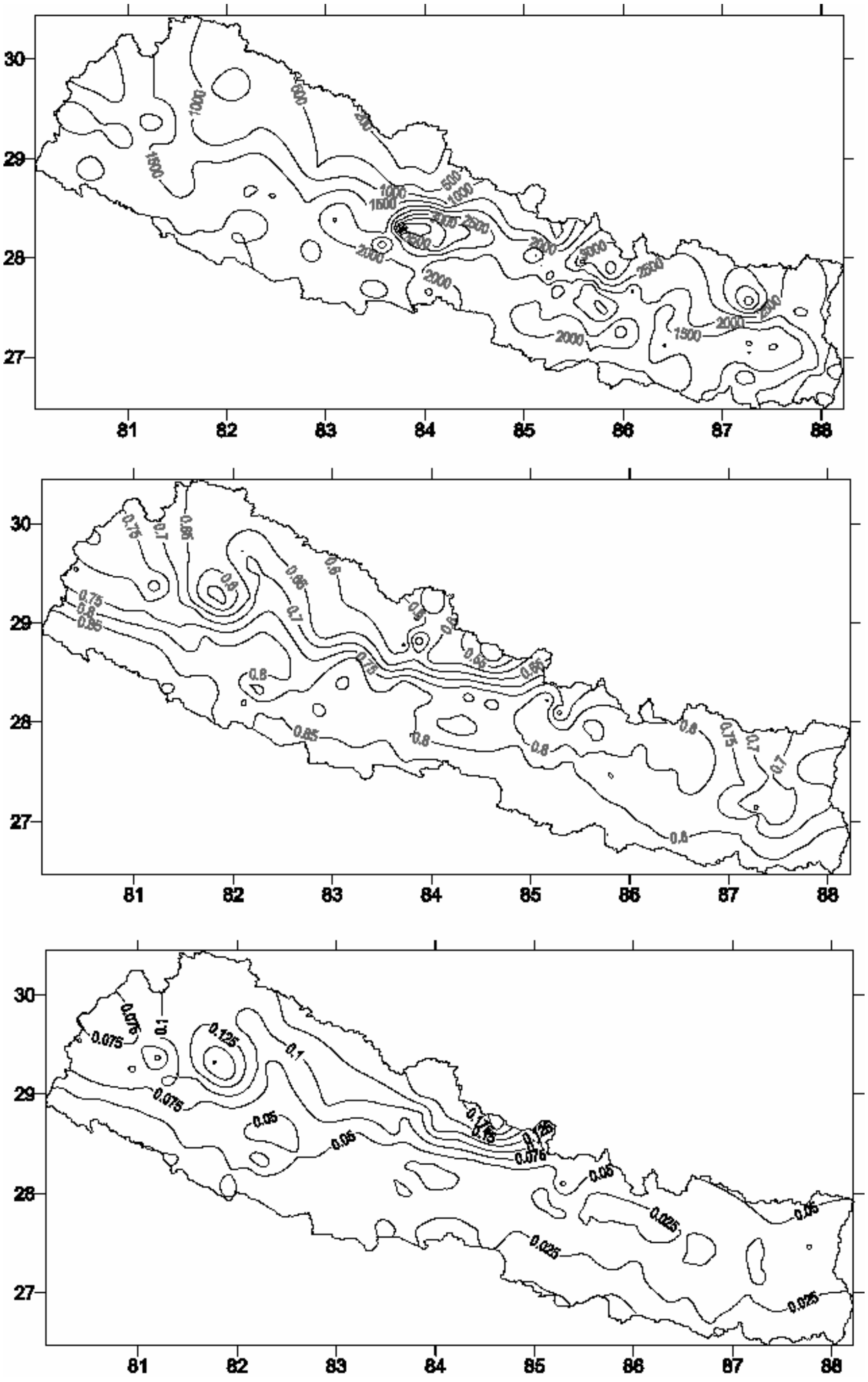


Figure 2: Precipitation in Nepal: Middle fractional contribution of monsoon to the annual total (top) and fractional contribution of winter precipitation to total annual (bottom)

Hydrology

Nepal's hydrology in one sentence can be described as rivers that originate in the Himalayas flow down-valley through the Gangetic plain to enter the Bay of Bengal. According to their origin, Sharma (1977) divides the rivers of Nepal into antecedent, subsequent and consequent rivers. The classification draws its significance from the development of the Himalayan system. The four major river basins that originate from the snow clad Himalayas are the Mahakali, the Karnali, the Gandaki, and the Kosi. The Babai, the West Rapti, the Bagmati, the Kamala, the Kanaka and Mechi are rivers originating from the middle Hills and meet with the four main rivers of Nepal (beyond the national territory or in the Ganges River). Of similar origin are several other rivers like Andhi Khola, Ridi, Rosi, Pikhuwa, East Rapti, Trijuga that meet the four main rivers within Nepal. Numerous rivers originate from the Siwalik and flow through the Terai. A large annual fluctuation is characteristic of these rivers that closely depict the annual precipitation.

Figure 3: Major drainage basins of Nepal

The timing of discharge coincides closely with the seasonal maxima and minima of precipitation at basin scales. Discharge maxima generally occur in August coinciding with the peak in monsoon. About 75 percent of the annual volume of water leaves the respective watershed during the monsoon season of June to September (Bhusal 1999). Minimum values occur during January through May (Alford 1992). Despite the general coincidence in the maxima and minima in precipitation and stream flow hydrograph (owing to great environmental diversity within the basin), the correlation between point-measured precipitation and discharge values is not found. Similarly, the general rule of linear relationship between discharge and basin area is not followed in Nepal.

Table 1. Discharge data of major rivers of Nepal.

River	Drainage Area (km^2)	Discharge (cumec)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mahakali[2]	12,600	99.5	86.9	85.0	104.6	155.8	379.3	1,097.0	1,507.1	1,097.0	395.7	182.5	123.0	442.8
Karnali at Chisa Pani	42,890	373.0	337.0	354.0	455.0	734.0	1,490.0	3,270.0	4,330.0	2,980.0	1,270.0	628.0	447.0	1,389.0
Narayani at Narayan Ghat	31,100	369.0	304.0	285.0	360.0	595.0	1,650.0	4,230.0	5,070.0	3,410.0	1,530.0	779.0	495.0	1,589.8
Sapta Kosi at Chatara	54,100	383.0	338.0	340.0	416.0	684.0	1,590.0	3,490.0	4,020.0	2,980.0	1,330.0	743.0	501.0	1,401.3
Babai at Bargadh	3,000	19.5	15.9	13.1	10.5	15.9	58.6	243.0	259.0	251.0	98.2	35.9	23.5	87.0
W. Rapti at Jalkundi	5,150	28.8	23.9	19.5	14.8	16.4	95.0	296.0	396.0	334.0	135.0	55.3	34.8	120.8
Bagmati at Karmaiya	2,720	18.0	16.9	15.4	16.7	31.5	214.0	539.0	513.0	338.0	137.0	51.0	26.9	159.8
Kamala[2]	1,786	12.0	11.0	10.0	13.0	22.0	98.0	245.0	240.0	168.0	69.0	30.0	17.0	77.9
Kankai at Mainachuli	1,148	12.9	10.0	9.3	11.7	22.5	67.4	182.0	180.0	123.0	56.6	27.2	17.9	60.0

[1] data taken from DHM, 1998

[2] data taken from Bhusal, 1999

The topography and geology of Nepal is favorable to soil erosion and mass wasting. Erosion rates vary largely and range between 800 to 57,000 T per km^2 (Bhusal 1998 and references therein). As a result, sediment loads in the rivers of Nepal are among the highest in the world. The monsoon is mainly responsible for surface erosion and sediment load closely follows the river discharge, peaking in August.

Relevance of climate change

Climate plays a large role in determining the feasibility of hydro-projects. Climate projections show that potential change in precipitation and temperature brought about by climate change could affect runoff. This in turn affects the potential water utilization and the benefits of establishing or continuing to operate a hydropower plant. It may also affect demand for electricity, although the influence of climate change on demand would probably be quite low. Extreme events such as glacial lake outburst floods (GLOFs) have the largest potential affect on water resources project because the force of a GLOF is often capable of destroying all hydropower infrastructure in a very short period. This happened in the Dig Tsho GLOF in 1985 that completely swept away the recently completed USD 1.5 Million Namche Hydropower Plant in the Khumbu region.

These climate concerns can span a variety of time scales, ranging from seasonal to interannual variability. In the coming years, hydropower planners may also need to incorporate measures to adapt to climate change, particularly in Nepal where GLOF events occur on a massive scale.

Observed climatic trends in Nepal

Temperature

Analyses of observed temperature and precipitation data in Nepal are limited. One of the reasons behind this is the relatively short length of records of about 30 years. From available studies, it has been found that temperatures in Nepal are increasing at a rather high rate. The warming seems to be consistent and continuous after the mid-1970s. The average warming in annual temperature between 1977 and 1994 was 0.06 ºC/yr (Shrestha *et al.* 1999). The warming is found to be more pronounced in the high altitude regions of Nepal such as the Middle Mountain and the High Himalaya, while the warming is significantly lower or even lacking in the Terai and Siwalik regions. Further, warming in the winter is more pronounced compared to other seasons. In this sense the trends in observed data are in agreement with projections made by climate models.

The temperature data for Kathmandu (the longest record from Nepal) was compared to the global data (mean over a ban of 24^o to $40\,^o$ N latitude around the globe; see Fig 5). It can be seen that there is a general resemblance between these two series: the generally decreasing trend from the 1940s to the 1970s and the continuous increasing trend thereafter. This suggests that the climatic variations in Nepal are closely connected to global climatic changes, probably being influenced by global greenhouse gas emissions.

Similar warming trends observed in Nepal are also observed in the Tibetan Plateau. Liu *et al.* (2002) show that warming is more pronounced in higher altitude stations than in lower ones in the Tibetan Plateau. In contrast, the widespread area of lowland India does not show significant warming. This suggests that the Himalayas and the Tibetan Plateau, being elevated regions of the globe, are sensitive to and affected by climate change.

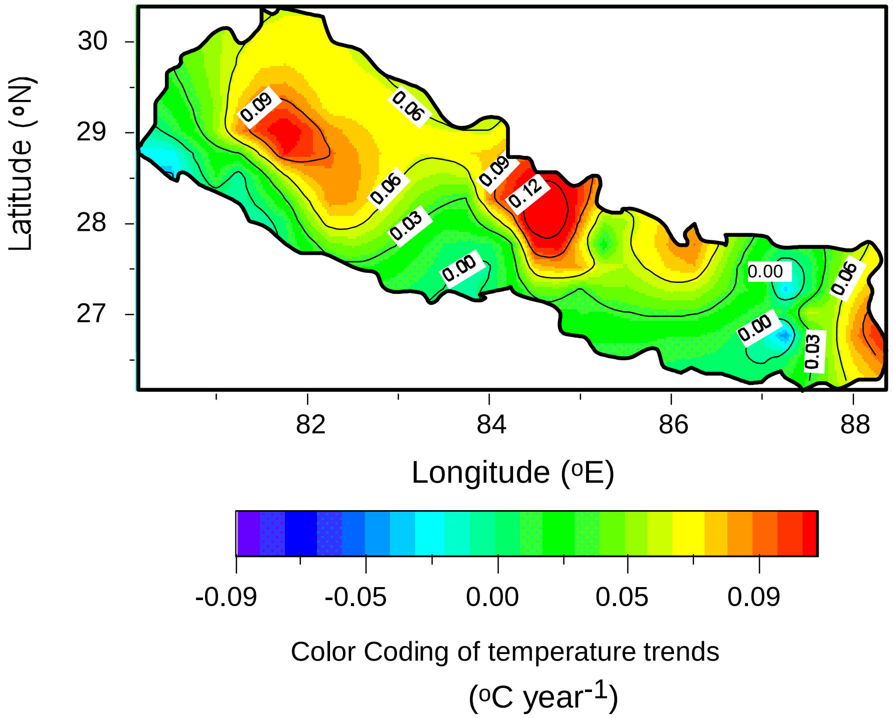


Figure 4: Spatial distribution of annual average maximum temperature trends in Nepal (1977 to 1994)

Table 2: Regional Annual Average Maximum Temperature Trends for the period 1977-94 (°C per year)

Regions	Seasonal				Annual
	Winter Dec-Feb	Pre-monsoon Mar-May	Monsoon Jun-Sep	Post-monsoon Oct-Nov	Jan-Dec
Trans-Himalaya	0.12[a]	0.01	0.11[b]	0.10[c]	0.09[b]
Himalaya	0.09[b]	0.05	0.06[b]	0.08[a]	0.06[b]
Middle Mountains	0.06[c]	0.05	0.06[b]	0.09[b]	0.08[b]
Siwalik	0.02	0.01	0.02	0.08[a]	0.04[a]
Terai	0.01	0.00	0.01	0.07[a]	0.04[a]
All-Nepal	0.06[a]	0.03	0.051[a]	0.08[b]	0.06[b]

[a] $p \geq 0.01$

[b] $p \geq 0.001$

[c] $p \geq 0.05$

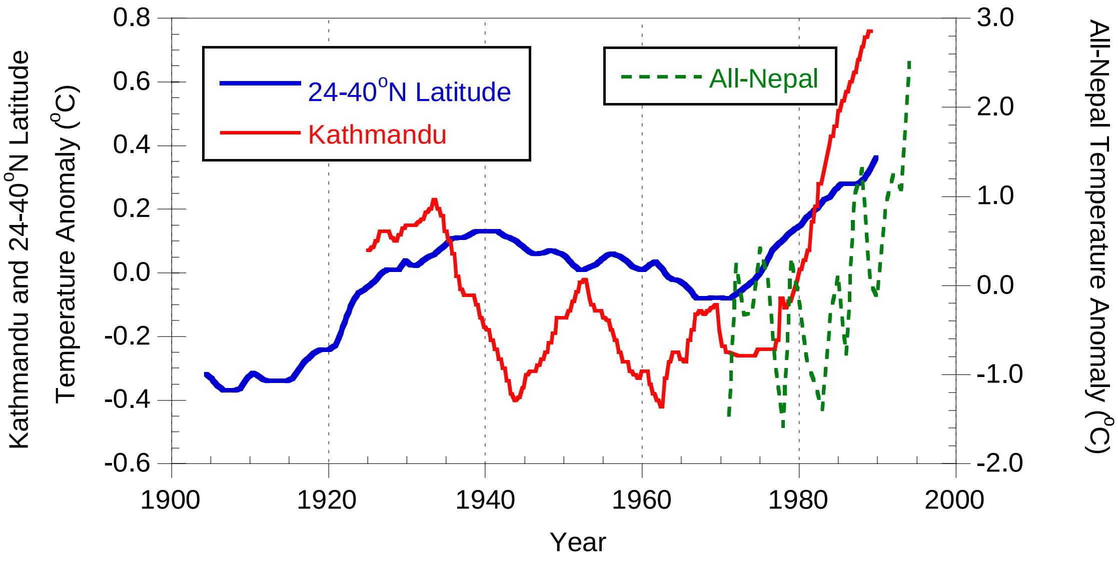


Figure 5: Comparison between temperature trends in Kathmandu, All-Nepal and globally. The Kathmandu data is a 5 year running mean of annual mean maximum temperature data from Kathmandu Indian Embassy station, which after 1976 was closed and the data after 1976 was extrapolated using data of four other station in Kathmandu Valley.The zonal mean temperature of 24 to 40°N latitude band developed by Hansen (1996) was used as a global temperature indicator. All-Nepal temperature was developed by Shrestha et al (1999) based on annual mean maximum temperature of 49 stations around Nepal.

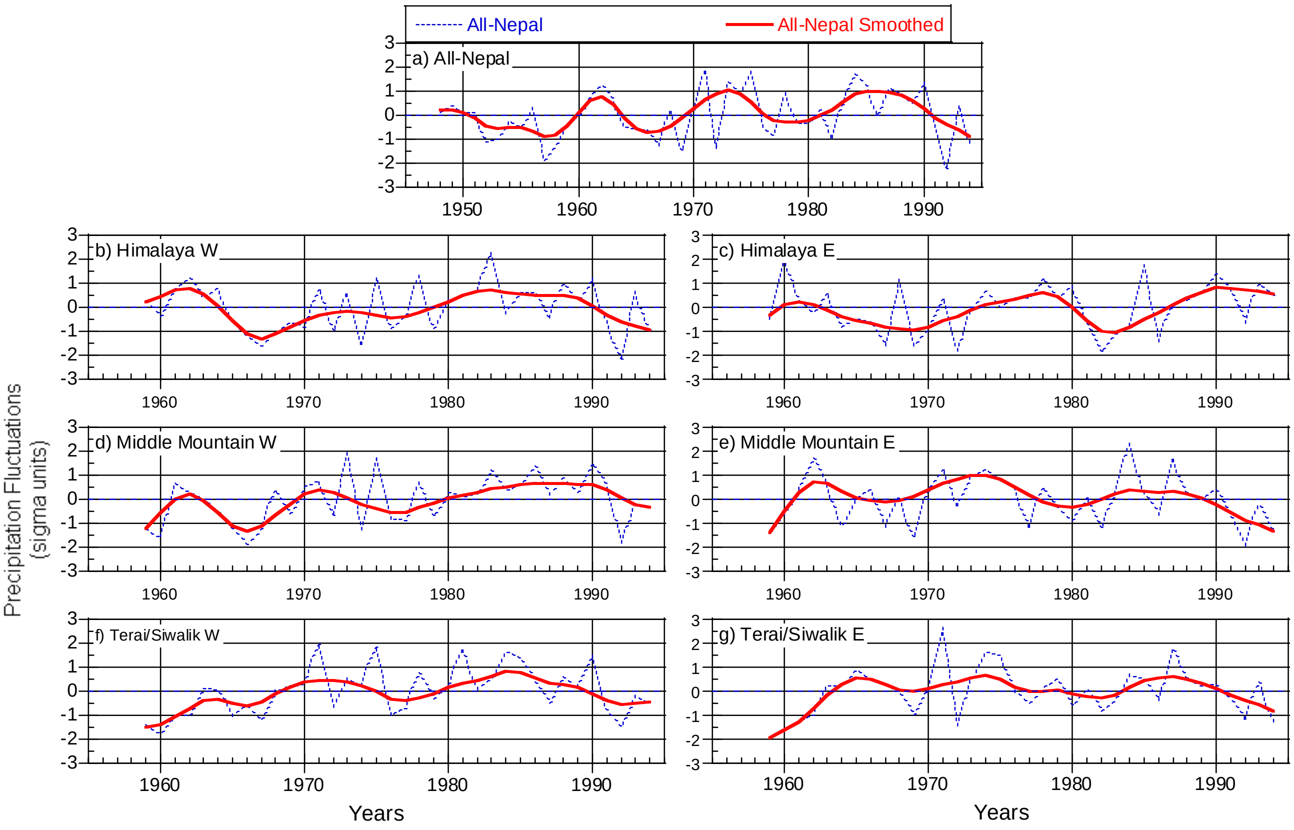


Figure 6: Time series of precipitation in Nepal: a. All-Nepal, b. Western Himalaya c. Eastern Himalaya d. Western Middle-Mountan, e. Eastern Middle-Mountain f. Western Terai and Siwalik g. Eastern terai and Siwalik.

Precipitation

Similar analysis on precipitation data, however, does not reveal any significant trends though oscillatory characteristics are present in the precipitation series (Shrestha *et al.* 2000). Similar to temperature, precipitation in Nepal is found to be influenced by or correlated to several large-scale climatological phenomena including El Niño/Southern Oscillation, regional scale land and sea-surface temperature changes and extreme events such as volcanic eruptions.

Climate change projections

The Intergovernmental Panel on Climate change (IPCC) provides a comprehensive review of climate models' results in terms of temperature and precipitation projections (IPCC 2001). The most complex climate models are called atmosphere-ocean general circulation models (AOGCMs) that couple atmospheric general circulation models with ocean general circulation models, sea-ice models and models of land-surface processes. These show greater than average warming in the South Asian region in summer. There is a general consistency among the models in their output for winter while the agreement is less for summer. The mean temperature increases for the period 2071 to 2100 relative to the period 1961 to 1990 is about 4ºC for the Special Report on Emission Scenario (SRES) A2 and about 3ºC for SRES B2 (see Fig 7, top). In contrast, the consistency among models in precipitation predictions, as well as the significance of projected changes is low both for the winter as well as the summer seasons (see Fig 7, bottom).

The Organization for Economic Co-operation and Development (OECD) performed an assessment of 12 recent General Circulation Models (GCMs) in 2003. The best seven GCM were run with the SRES B2 scenario. The results show significant and consistent increase in temperature projected for Nepal for the years 2030, 2050 and 2100 across various models. This analysis also shows somewhat larger warming in winter months than in summer. The projected change above the baseline average is 1.2ºC for 2030, 1.7ºC for 2050 and 3.0ºC for 2100. This analysis also agrees with the IPCC analysis on the projection of precipitation change i.e. less significant change and high standard deviation among the model results. A similar analysis done for Nepal under the First National Communication for United Nations Framework convention on Climate Change (UNFCCC) is also somewhat in agreement with the IPCC and OECD results (DHM 2004).

The effect of climate change on stream flow varies regionally and between climate scenarios, largely following projected changes in precipitation. In South Asia, HadCM3 shows increase in annual runoff ranging from 0 to150 mm/yr by the year 2050, relative to average runoff for the period 1961-1990, while the older version HadCM2 projects show a decrease of up to 250 mm/yr. These climate models are unable to highlight the details on seasonal variations in runoff, although it is generally suggested that due to higher evaporation and decrease in glacier mass, the low flows are likely to decrease (IPCC 2001).

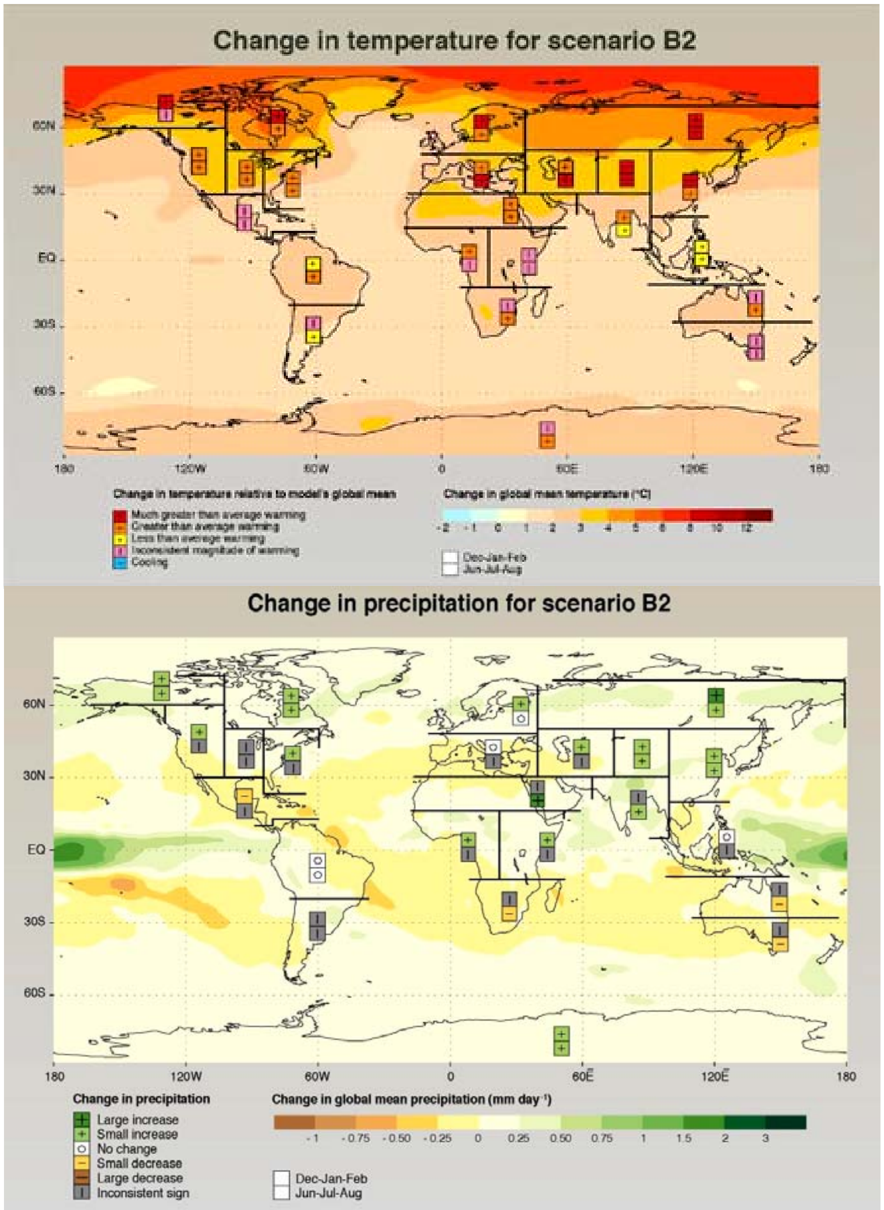


Figure 7: Changes in temperature (top) and precipitation (bottom) for SERES scenario B2. The background shows the annual mean changes and the boxes are inter-model consistency in regional temperature and precipitation changes.

Table 3: GCM Estimates for temperature and precipitation changes in Nepal

	Temperature change (°C) mean (standard deviation)			Precipitation change (%) mean (standard deviation)		
Year	Annual	DJF[4]	JJA[5]	Annual	DJF	JJA
Baseline average				*1433 mm*	*73 mm*	*894 mm*
2030	1.2 (0.27)	1.3 (0.40)	1.1 (0.20)	5.0 (3.85)	0.8 (9.95)	9.1 (7.11)
2050	1.7 (0.39)	1.8 (0.58)	1.6 (0.29)	7.3 (5.56)	1.2 (14.37)	13.1 (10.28)
2100	3.0 (0.67)	3.2 (1.00)	2.9 (0.51)	12.6 (9.67)	2.1 (25.02)	22.9 (17.89)

Physical and climatological characteristics

Glaciers of Nepal

The Nepal Himalaya revealed 3,252 glaciers and 2,323 lakes above 3,500 m above sea level They cover an area of 5,323 km^2 with an estimated ice reserve of 481 km^3. The Koshi River basin comprises 779 glaciers and 1,062 lakes. The glaciers in the basin cover an area of 1,409.84 km^2 with an estimated ice reserve of 152.06 km^3. The Gandaki River basin consists of 1,025 glaciers and 338 lakes. The glaciers in the basin cover an area of 2,030.15 km^2 with an estimated ice reserve of 191.39 km^3. The Karnali River basin consists of 1,361 glaciers and 907 lakes, with glaciers covering an area of 1,740.22 km^2 and an estimated ice reserve of 127.72 km^3. Only 35 percent of the Mahakali River basin lies within the territory of Nepal, comprising 87 glaciers and 16 lakes. The area covered by these glaciers is 143.23 km^2 with an estimated ice reserve of 10.06 km^3 (Bajracharya *et al.* 2002; Mool 2001a).

Since glaciers are excellent indicators of climate change (e.g. Oerlemans 1989, 1994), Nepali glaciers provide an excellent opportunity to study the impact of global climate change in this region. Regular glacier studies in Nepal began in the early 1970s. Since then, several glaciers in the Hidden Valley of Dhauligiri, Langtang, Khumbu and Kanchenjunga have been studied (see Fig 8). Some results of glacier fluctuation studies are presented below.

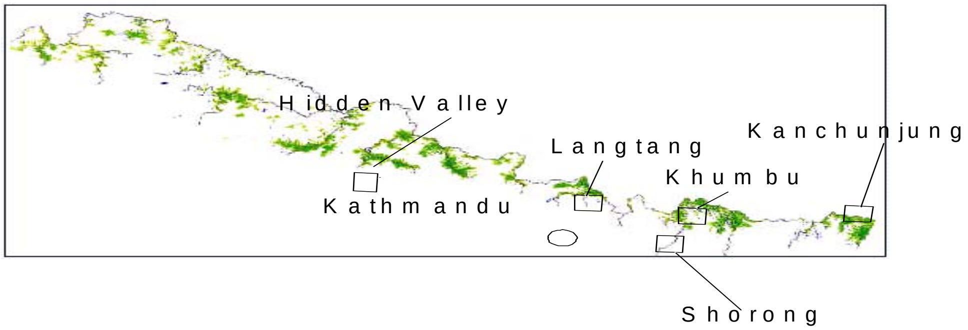


Figure 8: Different areas of glacier study

Shorong Himal

Glacier AX010 in the Shorong Himal (27^o 42’ N, 86^o 34’ E; Fig. 9) is one of the most studied glaciers in Nepal. Changes in glacier terminus area have been monitored intermittently between 1978 and 1995 and every year thereafter until 1999. The aerial extent of the glacier was measured intermittently in 1978, 1996 and 1999 by a topographical survey (Fujita 2001).

The retreat from 1978 to 1989 was 30 m, which is equivalent to 12 m thinning of the glacier surface. Ageta and Kadota (1992) used this to establish a relation between climate change and the retreat of the glacier. They applied a simple model using climate (temperature and precipitation) data from non-glacierized areas (Chialsa and Kathmandu). According to the analysis, the surface air temperature around the glacier terminus increased less (0.1ºC/yr) than in the non-glacierized area (0.2-0.4 ºC /yr); or that the higher effect of temperature increase was off-set by an underestimation of winter snowfall during the study period.

Kadota *et al.* (1997) re-applied the model with additional data and found that the retreat after 1989 had been much larger than for the period 1978-1989. They derived higher surface temperatures at the glacier terminus (4,958 m; +1.4ºC**).** The study predicts the shrinking tendency to continue and accelerate in the future even if climate conditions remain unchanged.

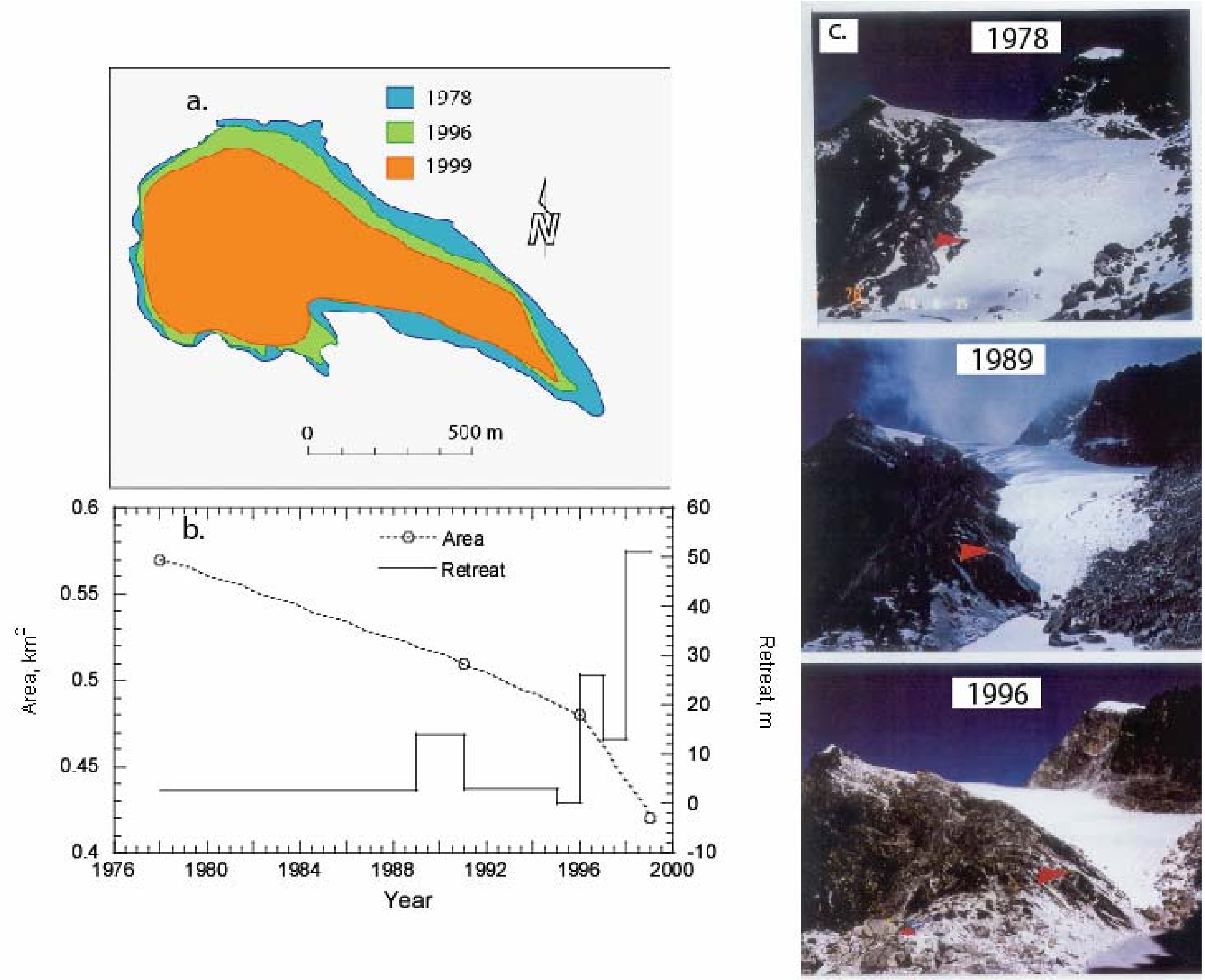


Figure 9: Retreat of AX010 glacier: a. Map showing the changes in the glacier area b. Changes in the glacier and the rate of terminus retreat c. Photographs of glacier terminus between 1978-1996

Khumbu Region

The Khumbu Glacier is a large debris-covered glacier in the Khumbu region. About 15 km long, it drains mainly from the West Cwm between Mt. Everest and Lohtse. Seko *et al.* (1998) studied the changing surface features of the Khumbu glacier using SPOT (Satellite Pour Observation de la Terre) high resolution visible images. They identified bare ice zones (ice pinnacles) in the glacier which was detected to be gradually shrinking. Kadota *et al.* (2000) conducted ground surveys of the Khumbu glacier in 1995 and compared the results with those of the 1978 survey. They found that the surface of the glacier lowered about 10 m throughout the debris-covered ablation area. Slowing down of the ice flow was also detected, which means shrinkage may accelerate even if ablation conditions remain unchanged.

Naito *et al.* (2000) developed a model coupling mass balance and flow dynamics of debris-covered glaciers and applied it to the Khumbu Glacier. The model predicts formation and enlargement of a depression in the lower ablation area about 5 km upstream of the terminus. This depression could transform into a glacier lake in future (see Fig 10).

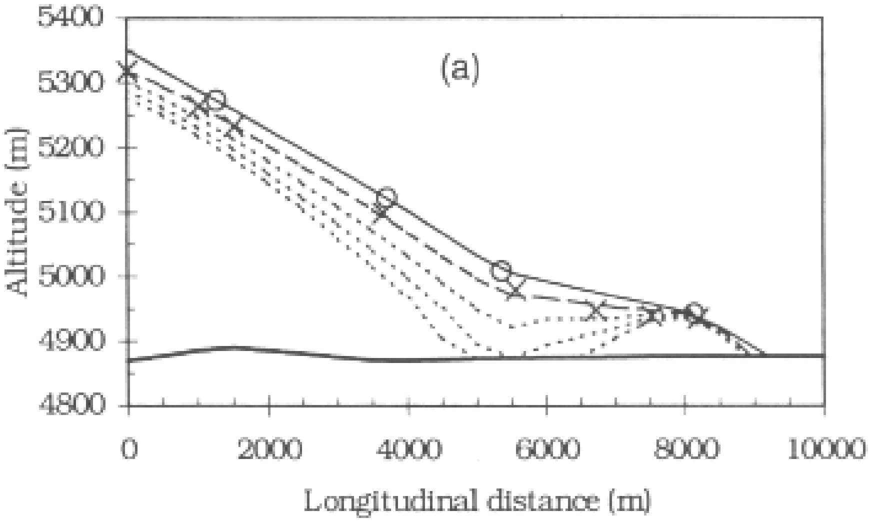


Figure 10. The longitudinal profile of Khumbu Glacier. The solid line represents the profile of 1978, the dashed line represents simulated result for 1999 and dotted lines are simulated results for 2020, 2040 and 2060. The circles and cross symbols represent survey positions in 1978 and 1999 respectively.

Yamada et el (1992) reviewed terminus fluctuations of seven clean-type glaciers in the Khumbu region for the 1970s to 1989 period. A majority of the glaciers were found to have retreated in the range of 30 to 60 m during the observed period.

Langtang Region

Yala Glacier is the most studied glacier in the Langtang region in terms of glacier fluctuations. The glacier terminus was surveyed in 1982 (Ageta *et al.* 1984) and glacier fluctuation was studied both by photogrametry and ground survey. Fujita *et al.* (1998) conducted a survey of the Yala Glacier terminus in September 1994, and in May and October of 1996. The retreat rate along an arbitrary line X on the glacier as shown in the figure below makes it clear that the retreat rate and surface lowering have accelerated in recent years.

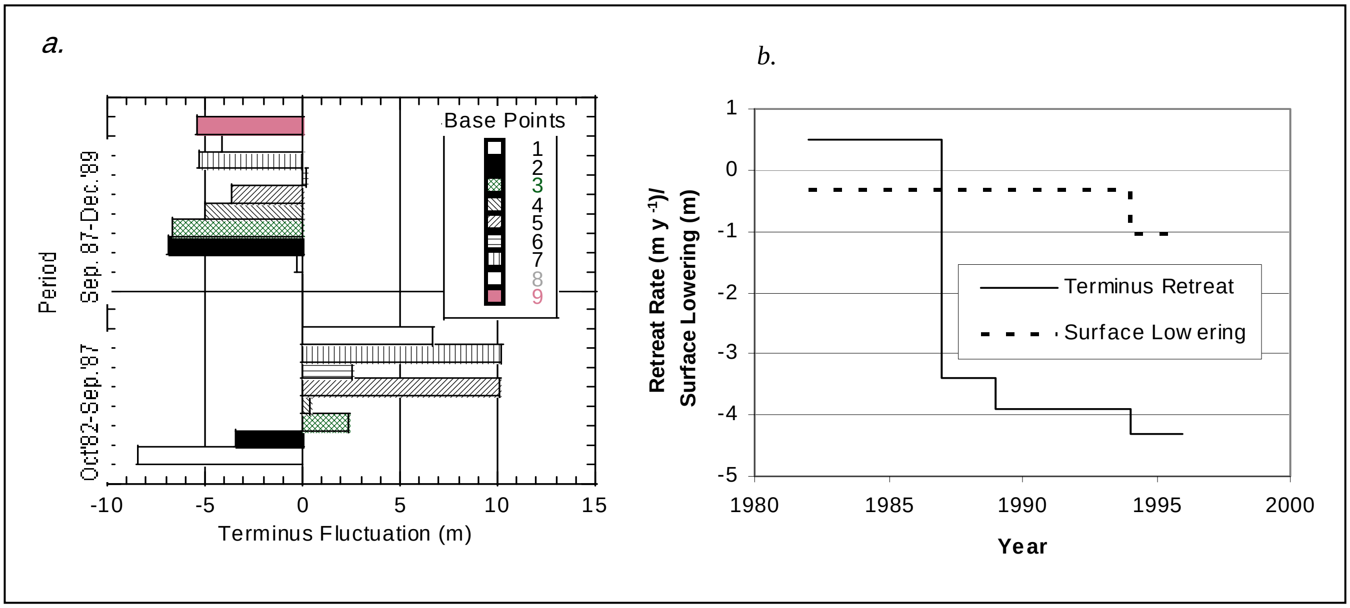


Figure 11: a: Fluctuation of nine different points on the terminus of Yala Glacier b: Terminus retreat and surface lowering of Yala Glacier during different periods.

Similarly, a transverse profile of the Lirung Glacier with debris-covered lower parts was surveyed in 1987 and in 1989. While there is no major change in the profile, photographs taken at different times show the glacier's retreat (see Fig 12). There is an indication that the upper steep part and the lower flatter part will separate in the near future. The Department of Hydrology and Meteorology (DHM) has been measuring different meteorological parameters including air temperature at Kyangjing, Langtang since 1987. There is a clear indication of an annual temperature rise at this region is at the rate of 0.27ºC/yr. However, this is quite a high rate and the relatively short record-length may not provide true judgment of the climatic trends prevailing in that region.

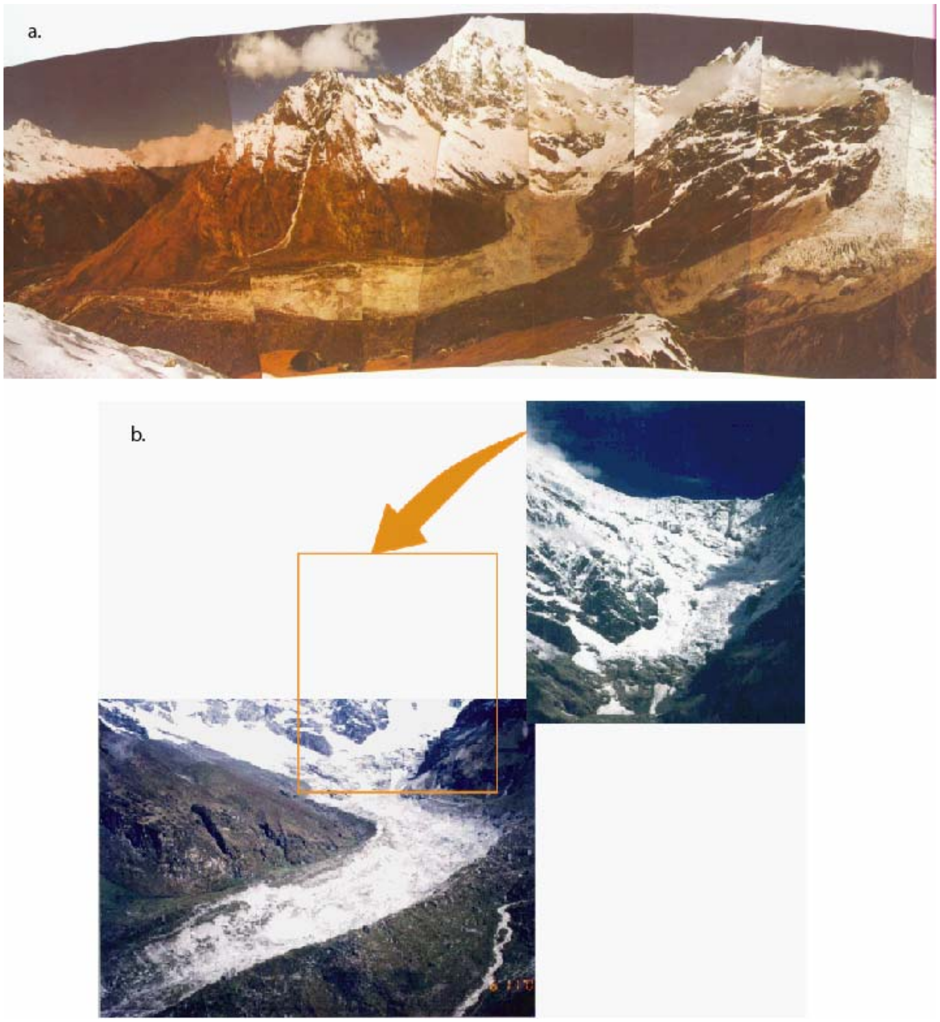


Figure12: Lirung Glacier in a. 1985 and b. 2002

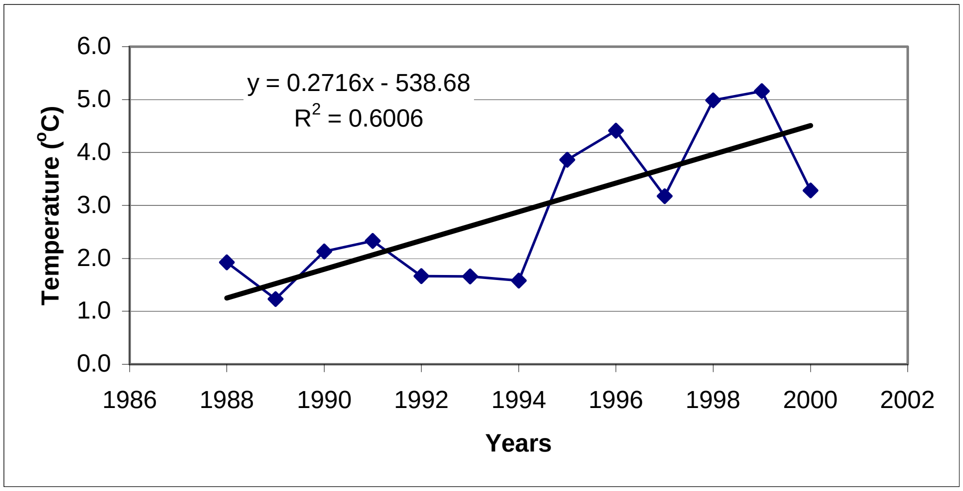


Figure 13: Annual mean temperature trend in Kyangjing, Langtang station (3,900 m)

Dhaulagiri Region

Rika Samba Glacier (28°50' N 83°30' E) is the most studied glacier in the Hidden Valley, Kali Gandaki basin. The terminus position was surveyed initially in 1974 (Nakawo *et al.* 1976) and thereafter intermittently in 1994 (Fujita *et al.* 1997), 1998 and 1999 (Fujita *et al.* 2001). The terminus retreat is illustrated in Figure 14. The rate increased dramatically in the period between 1994 and 1998. A study on temperature trends at seven stations in this basin showed warming in average 0.025 °C per year in last 30 years.

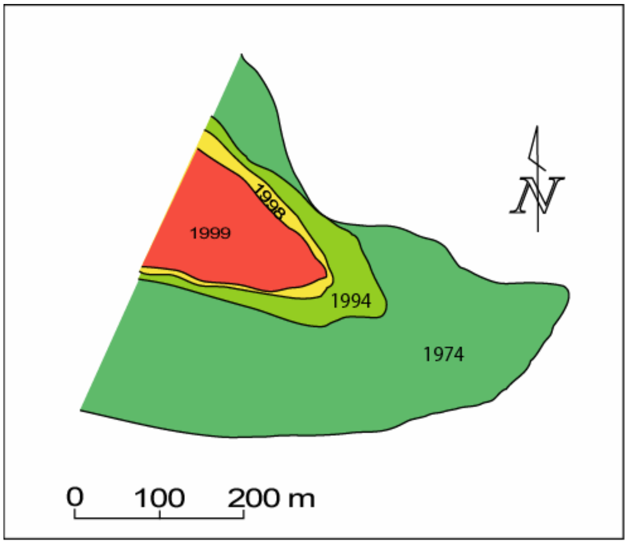


Figure 14: Terminus position changes of Rika Samba Glacier

Besides Rika Samba, termini altitudes of six other glaciers in the region were measured in 1994 using the altimeter and was compared with those found in 1974 (Fujita 1997). It confirmed that glacier retreat was a general trend in the Hidden Valley.

Kanchenjunga Region

Asahi *et al.* (2000) studied glacier fluctuations in the Ghunsa Khola basin, Kanchenjunga area. Based on aerial photo interpretation and field observations, clear morphological changes were indicated. These suggest glacier variation in the region during various stages in the past [Historical stage (around the early part of the 20th century), the Little Ice Age, the Holocene, and the late and early sub-stages of the Last Glaciation]. Further, a comparison of the 1992 glaciers with those of 1958 in the area revealed that out of 57 glaciers, 50 percent had retreated in the period from 1958 to 1992. In addition, 38 percent of the glaciers were under stationary conditions and 12 percent were advancing.

Impact of glacier retreat in Nepal

River discharge

More than 6,000 rivers and rivulets flow through Nepal. A comprehensive analysis of trends in river flow has not been performed yet. However, a preliminary analysis of river discharge i.e. trends in large outlet rivers, southern rivers and snow-fed rivers, has been carried out (Fig 15). Among the large rivers, Karnali and Sapta Koshi show decreasing trends although the records for Sapta Koshi are quite short. In contrast, the Narayani, another large river, displays an increasing trend. Southern rivers do not show any trend. All of the three snow-fed rivers examined showed declining trends in discharge. While these observations in river discharge are neither consistent nor significant in magnitude due to the short record-lengths and high inter-annual variability in discharge data, a separate study suggests that the number of flood days and consecutive days of flood events are increasing (Shrestha *et al.* 2003).

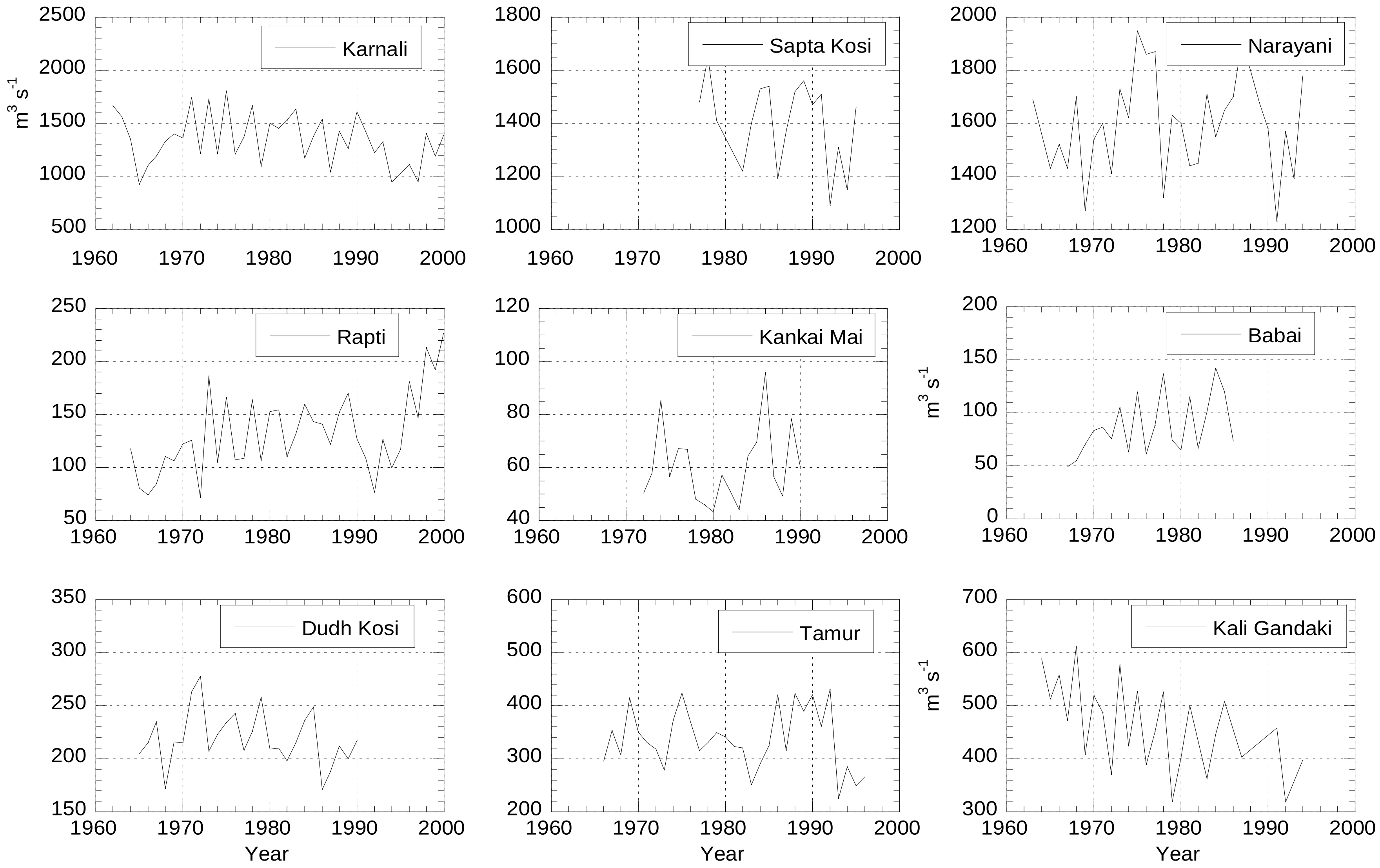


Figure 15: Discharge data of selected rivers: Large rivers (top); Southern rivers (middle) and Snowfed rivers (bottom)

Source: DHM (1996)

Glacier lakes and outburst floods

There are 2,315 glacier lakes of varies sizes, the total area of which is 75 km^2. (ICIMOD/UNEP 2001). The formation and growth of glacier lakes is a phenomenon closely related to deglaciation. Valley glaciers generally contain supra-glacial ponds. Due to warming climate, these ponds grow bigger and merge. This process is accelerated by rapid retreat of glaciers. As the glacier retreats it leaves a large void behind. The ponds occupy the depression earlier occupied by glacial ice. The moraine walls that act as dams are structurally weak and unstable and under go constant changes due to slope failures, slumping, etc. and are in danger of catastrophic failure, causing glacier lake outburst floods (GLOFs). Principally, a moraine dam may break by the action of some external trigger or self-destruction. A huge displacement wave generated by rockslide or snow/ ice avalanche from glacier 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 seepage from the natural drainage network of the dam.

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

The record of past disastrous GLOF event in Nepal is shown in Table 4 below. Although not new in Nepal, GLOFs attracted scientific and government attention only when Dig Tsho Glacier Lake flooded on 4 August 1985 in the Langmoche valley, Khumbu (Ives 1986; Yamada 1998). The lake, crescent in shape, was dammed by a 50 m high terminal moraine. The lake had a length of 0.605 km and width of up to 0.230 km in 1974 (ICIMOD/UNEP 2001). The GLOF was caused by detachment of a large ice mass from the upper portion of the Langmoche glacier after clear weather in July. The ice mass overran the glacier and splashed into the lake, which was full. The impact caused significant rise in the water level, overtopped the moraine dame cutting a V-shaped trench. The GLOF emptied the lake water within four to six hours. The flood water surged 10 to 15 m high in the valley and the effect was felt for more than 90 km downstream.

It had caused serious damage to the nearly completed Namche Hydropower Project, washed away cultivated land, bridges, houses, livestock and people. The flood waves that lasted for about four hours released about 6 to 10 million cubic meter of water (Ives 1986). Since then, His Majesty's Government of Nepal (HMG/N) has considered GLOFs as a threat to the development of water resources of the country and has focused on glacier flood studies.

Table 4: List of GLOF events recorded in Nepal

Date	River Basin	Name of Lake
450 Years ago	Seti Khola	Machhapuchhare
August, 1935	Sun Koshi	Taraco, Tibet
21 September, 1964	Arun	Gelaipco, Tibet
1964	Sun Koshi	Zhangzangbo, Tibet
1964	Trishuli	Longda, Tibet
1968	Arun	Ayaco, Tibet
1969	Arun	Ayaco, Tibet
1970	Arun	Ayaco, Tibet
3rd September, 1977	Dudh Koshi	Nare, Tibet
23rd June, 1980	Tamur	Nagmapokhri, Nepal
11th July, 1981	Sun Koshi	Zhangzagbo, Tibet
27th August, 1982	Arun	Jinco, Tibet
4th August, 1985	Dudh Koshi	Dig Tsho, Nepal
12th July, 1991	Tamo Koshi	Chubung, Nepal
3rd September, 1998	Dudh Koshi	Sabai Tsho, Nepal.

Figure 16: The Dig Tsho GLOF: The site of Namche Hydropower Project destroyed by the GLOF on 4 August 1985 (left) (Source: WECS). The lake in 2004 (bottom) (Source: WWF Nepal Program)

Imja Tsho is another potentially dangerous glacier lake in the Khumbu region. This lake is the headwater of the Imja River and is fed by Imja Glacier. Located at an altitude of 5,000 m, this lake did not exist before the 1950s. A few small ponds started forming as shown by a 1955-63 Schnider map. According to data from a survey in 1992, the length and width of the lake was 1.3 km and 0.5 km respectively, the average depth was 47 m and the maximum was 99 m. The lake occupied an area of 0.60 km^2. The accumulation of water was estimated at about 28 million m^3. The next survey of Imja in 2002 showed that the lake had expanded to an area of 0.86 km^2– 28 percent larger than the last survey.

Figure 17: Imja Tsho in 2004 (Source: WWF Nepal Program)

Tsho Rolpa is the largest glacier lake in Nepal occupying an area of 1.76 km^2. This lake began as a cluster of small supra-glacier ponds in the late 1950s that merged and grew to its present stage (see Fig 18). Studies suggest a high risk of GLOF based on the growth of the lake, rapid degradation of terminal and lateral moraines holding lake water, melting of fossil ice inside the moraine, seepage of lake water from end-moraines, and rapid ice calving from glacier terminus. This is the only lake in Nepal where some mitigation work and an early-warning scheme has been implemented (Rana 2000; Shrestha 2001). However, mitigation work is extremely expensive and it is not possible to set up at all dangerous lakes. Moreover, this does not completely exclude the possibility of GLOFs. The other glacier lakes listed as dangerous are Imja, Lower Barun and Thulagi. In a 2001 survey by ICIMOD and UNEP, 26 lakes in Nepal were identified as potentially dangerous lakes, although many of these need field verification.

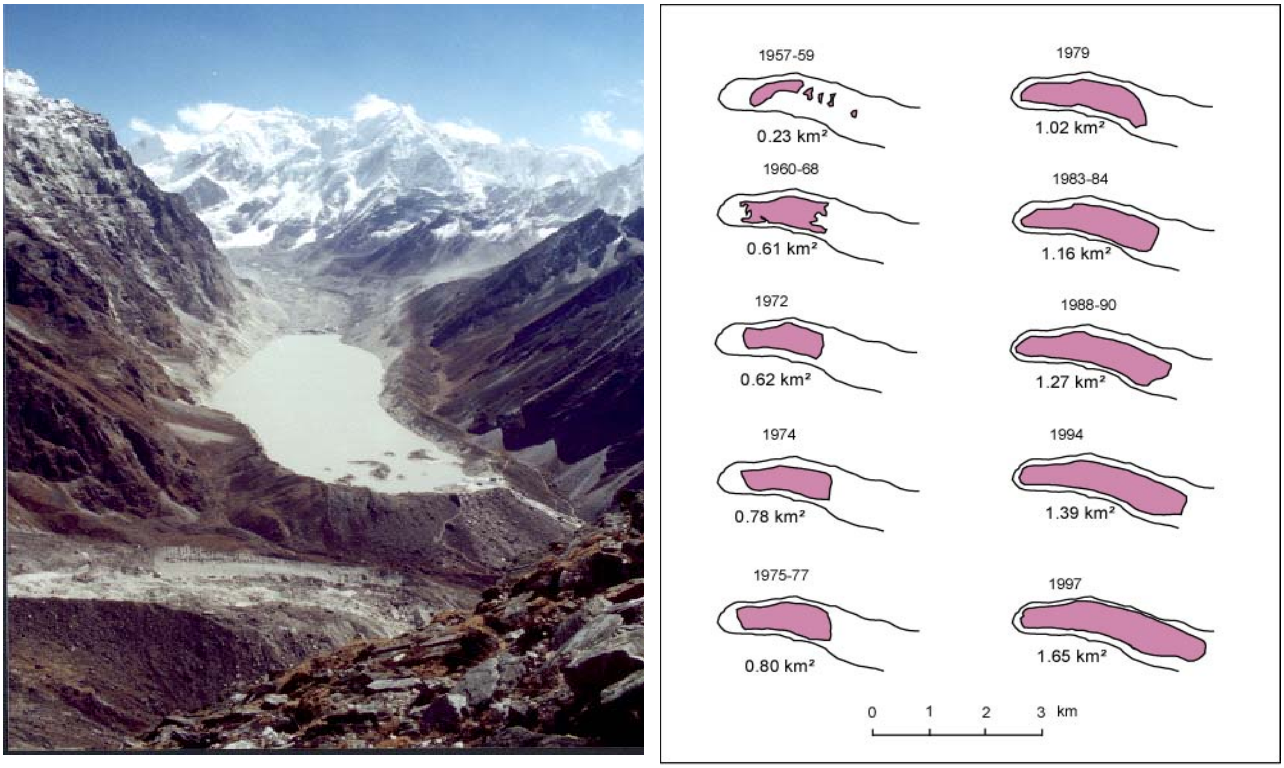


Figure 18: Growth of Tsho Rolpa from the late 1950s to 1997, Photo © P.K. Mool, 2000

Impact of Climate Change on other sectors

Freshwater flow

Glaciers are an important storage of freshwater in Nepal as they accumulate mass in monsoon and winter seasons at higher altitudes and provide melt-water at lower elevations. The latter is particularly important during dry seasons. The importance of glaciers is not limited to Nepal alone: all the rivers that flow through Nepal finally pours into the Ganga. It has been estimated that Nepali river discharge contributes upto 70 percent of water in the Ganga during dry seasons (e.g. Alford 1992). Any significant change in the glacier mass is certain to impact water resources on a regional level.

If the observed increasing trends in temperature are to continue in the future, several other sectors, apart from the water resources are also certain to be affected. Given below are some of the most important impacts presented in the initial National Communication of Nepal to United Nations' framework Convention on Climate Change (DHM 2004).

Agriculture

In an agrarian country like Nepal, with staggering increase in population and food demand, even a slight decline in annual food production is a matter of great concern. This sector is adversely affected by the loss of top fertile soil due to soil erosion, landslides and floods. Soil loss is a major cause of decline in agriculture production in Nepal and the negative effects of climate change may further aggravate this situation. It has been suggested that at 4ºC temperature and 20 percent precipitation rise, there could be marginal yield increase in rice; that yield will continue to decline between 0.09 to 7.5 percent and beyond. However, temperature rise has evoked mixed reactions in the case of wheat as the actual yield of wheat has increased in the western region with the rise in temperature while there has been a decline in other regions. Similarly, a rise in temperature has a negative effect on maize as yields decreased with warmer temperatures (the trend is almost similar to wheat).

Biodiversity and wildlife

A majority of the people in Nepal rely on forest products such as firewood, food, fodder, timber and medicines. Its extensive utilization and increasing demand has led to a decline both in area and quality. Global warming may cause forest damage through mitigation of forests towards the polar region, change in their composition and extinction of species. This could affect not only on Nepal’s biodiversity but the very livelihoods of people. Tropical wet forests and warm temperate rain forests would disappear, and cool temperate vegetation would turn to warm temperate vegetation. Vegetation patterns would be different under the incremental scenario (at 2ºC rise of temperature and 20 percent rise of rainfall) than the existing types. Thus climate change will have a direct impact on vegetation, biodiversity and even wildlife.

Health

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

While climate change model results are highly variable concerning South Asia, the projections for temperature change are more or less consistent and significant with projected mean temperature increase of 1.2 and 3ºC by 2050 and 2100 and 2.3 to 4.3ºC at 2 CO_2**.** Though an overall increase in precipitation is projected; the magnitude of change is low. The observed trends in temperature generally agree with climate model results and show warming in the last few decades. More warming is observed in high altitudes. No significant trend is found in precipitation. Both temperature and precipitation are found to be related to large-scale climatological phenomena.

Country Case Study 2

India: Glaciers, glacier retreat and its impact

Introduction

As discussed in the thematic introduction to this regional status review, there is particular concern at the alarming rate of retreat of Himalayan glaciers. In 1999, a report by the Working Group on Himalayan Glaciology (WGHG) of the International Commission for Snow and Ice (ICSI) stated: "glaciers in the Himalayas are receding faster than in any other part of the world and, if the present rate continues, the livelihood of them disappearing by the year 2035 is very high". Direct observation of a select few snout positions out of the thousands of Himalayan glaciers indicate that they have been in a general state of decline over, at least, the past 150 years.

The prediction that "glaciers in the region will vanish within 40 years as a result of global warming" and that the flow of Himalayan rivers will "eventually diminish, resulting in widespread water shortages" (*New Scientist* 1999; 1999, 2003) is equally disturbing. In the context of India this spells bigger trouble for the 500 million inhabitants of the Indus, Ganges and Brahmaputra river basins, who rely on the perennial supply of melt-water from the Himalayas (Sharma 2001). The problems of water stress are already prevalent in the region due to increasing demands of domestic, agriculture, industry and a growing population. Any reduction in the availability of freshwater could have serious consequences for the economy, the environment and the daily lives of many millions of people within the affected basins and beyond. The following sections describe the physical and climatological characteristics of the Himalayan region and assess the impacts of future deglaciation in the Himalayan region in context of freshwater resources.

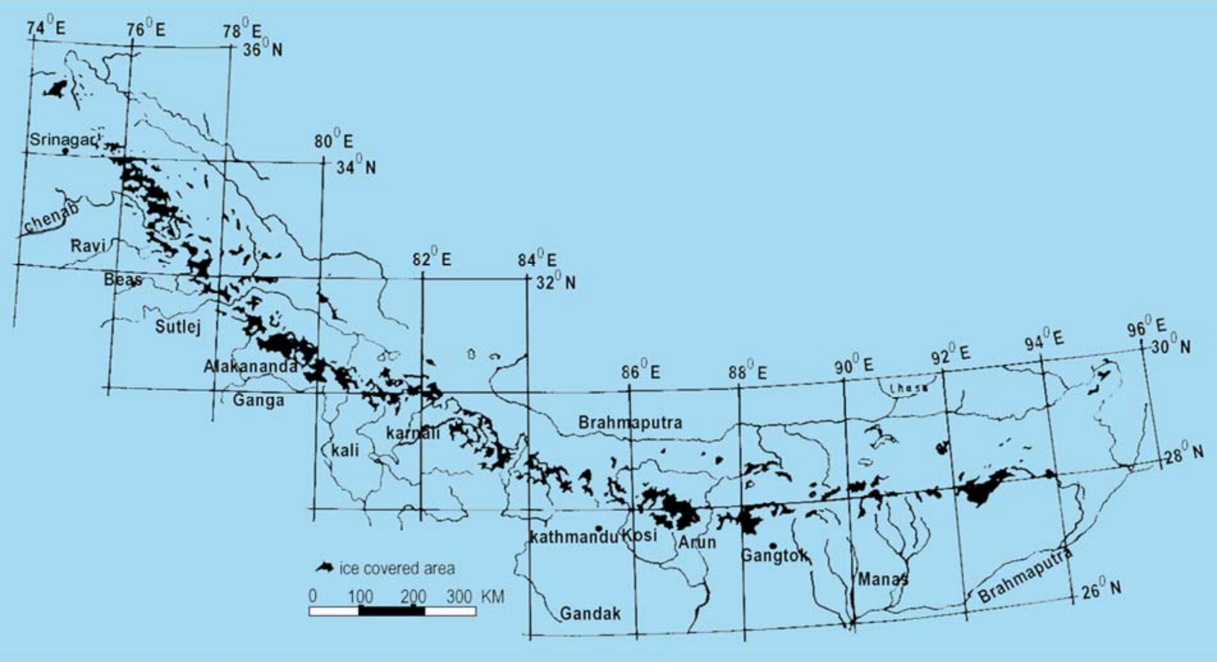


Figure 19: Glacier distribution along the Himalayan arc

Physical and climatological characteristics

The Indian Himalayan glaciers are broadly divided into the three-river basins of Indus, Ganga and Brahmaputra The Indus basin has the largest number of glaciers (3,538), followed by the Ganga basin (1,020) and Brahmaputra (662). Researchers have estimated that about 17 percent of the Himalayas and 37 percent of Karakorum is presently under permanent ice cover. The principal glaciers of this region are Siachen 72 km; Gangotri 26 km; Zemu 26 km; Milam 19 km and Kedarnath 14.5 km.

A variety of climates are the beauty of the Himalayan region. The extreme relief of the Himalayas produces marked changes in air masses crossing the region and results in a complex mosaic of "topo-climates" determined by variations in slope, aspect and relative altitude (Flohn 1974; Alford 1992). These range from the sub-tropical climates in the southern plains, to the temperate climate of the middle hills and Alpine (or polar) climates in the high mountains. The main controls on climate are weather systems moving in from the south-east during the summer and from the west in winter.

The summer monsoon normally commences in mid-June and lasts until mid-September. The mountain ranges block the northward advancement of the monsoon causing widespread and intense rainfall on southern slopes, whereas on the lee of the mountain ridges, drier conditions prevail. Delayed onset of the monsoon decreases precipitation along the Himalayan arc from east to north-west. There is also a general decrease from south to north with each successively higher mountain range, featuring windward maxima and leeward rain-shadows, which culminate in the high-altitude aridity of the Tibetan plateau.

The western Himalayas get more precipitation from the westerly winds during November to April. There is a large variation in the annual average precipitation in the Himalayas. The southern slopes of the Eastern Himalayas experience some of the highest annual rainfall totals on Earth while other areas receive as low as 50 mm a year. Mean daily air temperature is low in January and rises during the pre-monsoon period (February to May) with maximum daily temperature in late May or early June while post-monsoon (October to January) mean daily air temperatures generally decline.

Glacial fluctuations in the Himalayan region

Himalayan glaciers have been in a state of general retreat since 1850 (Mayewski & Jeschke 1979) and recent publications confirm that, for many, the rate of retreat is accelerating. Jangpang and Vohra (1962), Kurien and Munshi (1972), Srikanta and Pandi (1972), Vohra (1981), and many others have made significant studies on the glacier snout fluctuation of the Himalayan glaciers. But a dramatic increase in the rate seems to have occurred in last three decades. In 1998, researchers LA Owen and MC Sharma showed, by studying the longitudinal profiles of the river, that between 1971 and 1996, the Gangotri Glacier had retreated by about 850 m. This would yield a post-1971 retreat rate of 34 m a year. For the post-1971 period, the 61-year (1935-1996) data of GSI too shows that the retreat rate is about 28 m/year, indicating a clear increase in the rate after 1971. The 1996-1999 data of Naithani and associates too matches this general trend of an increased rate.

Arial distribution of perennial ice and snow cover in the Indian Himalayan region was compiled from various maps and references by Fujii and Watanbe (1983) as shown in the table below. Kaul *et al.* (1999) produced the inventory of Himalayan glaciers for Jhelum and parts of Sutluj in the Indus basin and for Bhagirathi, Tista and Arunachal Pradesh in the Ganga-Brahmaputra basin. Retreats of the several glaciers based on the various literatures are also compiled for the quick referencing and are presented in the tables that follow.

Table 5: A status of the glacier inventory of Indus Basin

Basins	Numbers of glaciers	Glacierised area (Km^2)	Ice volume (km^3)
Jhelum	133	94.0	3.0
Satluj	224	420.0	23.0
Others	3398	33382.0	-
Total	**3755**	**33896.0**	**26.0**

Source: Kaul et al. 1999

Table 6: A status of the glacier inventory of Ganga-Brahmaputra basins

Basins	Numbers of glaciers	Glacierised area (Km^2)	Ice volume (km^3)
Bhagirathi	238	755.0	67.0
Tista	449	706.0	40.0
Brahmaputra	161	223.0	10.0
Others	640	2378.0	-
Total	**1488**	**4062.0**	**117.0**

Source : Kaul et a.,1999

Table7 Retreats of Important Glaciers in the Himalayas

Glacier	Location	Period	Avg. retreat (m/year)	Reference
Milam	Uttaranchal	1849-1957	12.5	Vohra (1981)
Pindari	Uttaranchal	1845-1966	23.0	Vohra (1981)
Gangotri	Uttaranchal	1935-1976	15.0	Vohra (1981)
Gangotri	Uttaranchal	1985-2001	23.0	Hasnain, *et al.* 2004
Bada Shigri	Himachal Predesh	1890-1906	20.0	Mayekwski & Jeschke (1979)
Kolhani	Jammu & Kashmir	1857-1909	15.0	Mayekwski & Jeschke (1979)
Kolhani	Jammu & Kashmir	1912-1961	16.0	Mayekwski & Jeschke (1979)
Machoi	Jammu & Kashmir	1906-1957	8.1	Tiwari (1972)
Chota-Shigri	Himachal Pradesh	1970-1989	7.5	Surender *et al.* (1994)

Impact of climate change on glacier recession

Precipitation levels are another component of climate change associated with the phenomenon of global warming. Himalayan glaciers are more likely to be affected by changes in the synoptic weather patterns that control the timing, the progression and intensity of moisture carried by the summer monsoon and the winter westerly than by changes in global temperatures alone.

An evaluation of the ability of General Circulation Models (GCMs) to model monsoon precipitation (Sperber & Palmer 1996) revealed that most provide realistic predictions. There are some areas though such as in East Asia (Lau & Yang 1996) where, due to their coarseness, climate models sometimes fails to provide satisfactory simulations (Lal *et al.* 1997). Several AOGCM applications have shown a strong relationship between the El Niño-Southern Oscillation (ENSO) phenomenon and the strength of the Indian summer monsoon (e.g. Meehl & Arblaster 1998).

According to the climatologists, alpine glaciers, such as those in the Himalaya, are particularly sensitive indicators of climate change and the trend is expected to continue this century (Ageta & Kadota 1992; Nakawo *et al.* 1997; Hasnain 1999; Naito *et al.* 2000). The particular vulnerability of Himalayan glaciers to climate warming is due to the facts that:

- They are “summer accumulation types” dependent on summer monsoonal precipitation and cool summer temperatures (Ageta & Higuchi 1984);

- Consequently, the summer mass balance of these glaciers nearly equals the annual mass balance (Kadota *et al.* 1993).

As global warming continues to increase the atmosphere temperature, it will lead to a continuous shift of zero temperature line (snow line) toward higher altitude. Thus glaciers will receive more liquid precipitation and less monsoonal solid precipitation. Shift in snowline will result in lesser input to glacier mass balance during summer periods. Therefore, higher atmosphere temperature and more liquid precipitation at higher altitude in the Himalayas will lead to rapid retreat of glaciers and downstream flooding in the coming future (Hasnain 2002, Kadota *et al.* 1993).

The impact of global warming is perhaps already upon the Himalayas. The 30.2 km-long Gangotri Glacier is receding rapidly: the rate of retreat in the last three decades has been found to be more than three times the rate during the earlier 200 years or so. The average rate of recession has been computed by comparing the snout position on 1985 toposheet map and the 2001 panchromatic satellite imagery and the result shows that average recession for this period is about 23 m/yr (Hasnain *et al.* 2004) The pictorial plot based on historical evidences and recent data on the Gangotri Glacier retreat in a research by Jeff Kargel, Geologist of USGS also supports the increased rate of retreat of the Gangotri (Fig 20). The enhanced rate of retreat is attributed to the increased anthropogenic contribution to the climate on account of greenhouse gas emissions contributing to global warming.

Figure 20: Retreat of the Gangotri Glacier (Garhwal Himalayas) snout during the last 220 years (Source: Jeff Kargel, USGS)

Dokriani glacier (30°49’to 30°52’N and 78°47’to 78°51’E) is one of the valley type glaciers of Gangotri group of glaciers in the Garhwal Himalaya, Uttranchal. The origin of this glacier is at an elevation of 6000 m asl from Draupadi ka Danda group of peaks and is formed by two cirque glaciers. The glacier follows NNW direction for about 2 km before it turns towards WSW and terminates at an altitude of 3886 m. The length of the glacier is 5.5 km with a width varying from 0.08 to 2.5 km. The total catchment’s area is 15.7 km^2 , with the glacier ice covering an area of 7 km^2 (Figure 21 & 22). The melt-water stream emerging from the glacier is known as Din Gad and joins river Bhagirathi at Bhukki. The thickness of the glacier ice varies from 25 to 120 m between snout and accumulation zone and its average thickness lies to 50 m (Gergan et al., 1999)

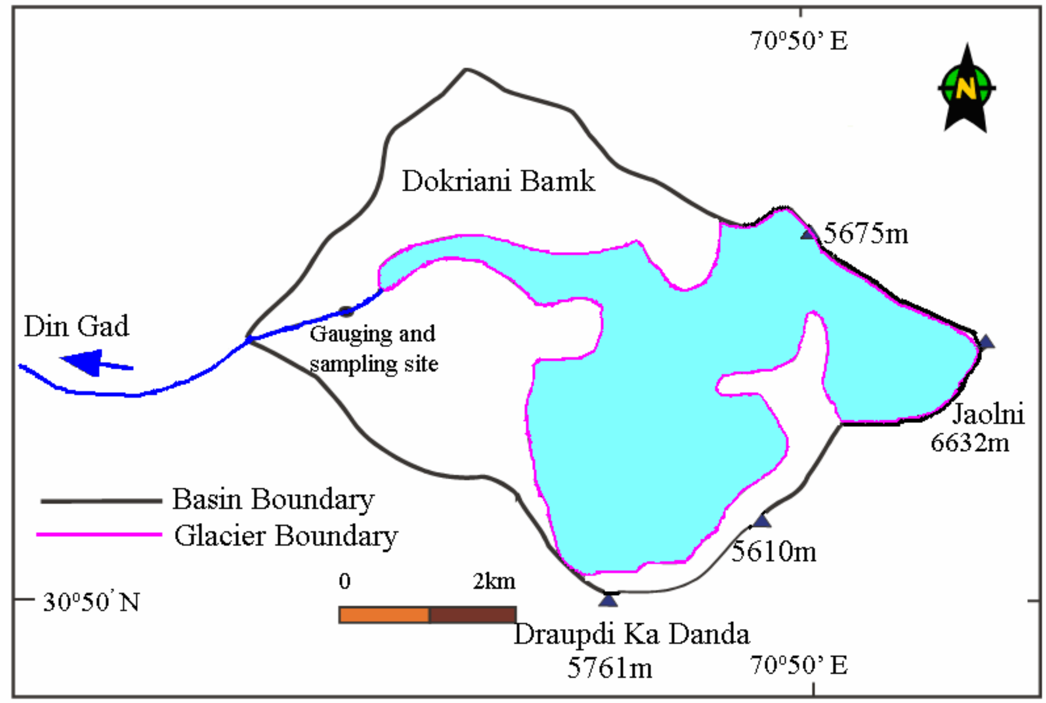


Figure 21: The drainage map of Dokriani basin

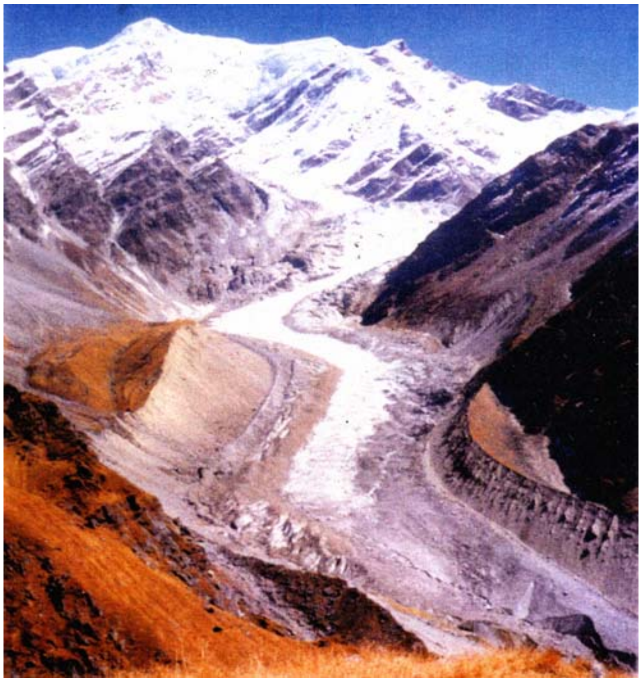


Figure 22: Synoptic view of the Dokriani glacier

The glacier shows rapid frontal recession, substantial thinning at the lower elevation and reduction of glacier area and volume. Between 1962 and 1995, glacier volume is estimated to have been reduced by about 20% and frontal area had vacated by 10%. During the period 1962–1995 the glacier has receded by 550 m with an average rate of 16.6 m/yr. However, the yearly monitoring of snout position of the glacier during 1991–1995 revealed an average rate of recession of 17.4 m/yr and has vacated an area of 3957 m^2 (Dobhal et al., 2004).

The calculated average ice thickness of Dokriani glacier was 55 m in 1962 and 50 m in 1995, and the corresponding glacier ice volume was 385.11 × 10^6 m^3 and 315.0 ×10^6 $m^3$of water equivalent respectively. The approximate reduction of the glacier ice volume between the period 1962 and 1995 is estimated as 70.11 × 10^6 m^3 (water equivalent). The annual mass balance study during 1992–1995 shows negative mass balance, which is 1.54 × $10^6 m^3$ (1992–93); 1.58 × 10^6 m^3 (1993–94) and 2.17 × 10^6 m^3 (1994–95) of water equivalent with an average rate of 0.28 ma^{-1} (Dobhal et al. 1996). The results show that the present trend of mass balance is moderately negative and increased from the previous years.

Chhota Shigri glaciers, located between $32^{0}11^{'}$-$32^{0}17$’N and $77^{0}30$’ – $77^{0}32$’E with varying altitude of 4,100 to more than 6,000 m, is a valley – type glaciers, debris covered in the lower ablation zone, lies on the Chandra-Bhaga river basin on the northern ridge of Pir Panjal range in the Lahaul-Spriti valley of Himalchal Pradesh. The snout in the year 2003 was located $32^{0}17$’N, $77^{0}32$’E. It falls in the monsoon-arid transition zone; therefore this glacier is considered to be a potential indicator of the northern limits of the intensity of the monsoon. The glacier is influenced by both the Asian monsoon in summer and westerlies in winter. From its snout to the accumulation zone near the Sara Umga Pass (4900 m), it extends up to a length of 9 km and its width varies from 0.5 to 1.5 in the ablation zone and about 4.5 km above the equilibrium line

(Surendra Kumar, 1988). Located above 4,000 – 6,000 m, it has an ice cover of 8.7 km^2 (Dobhal et al., 1995) with the equilibrium line varying between 4,800 to 5,100 masl. The fluctuations in the width of ablation zone are between 0.3 to 1.5 km and in accumulation zone 1.5 to 3 km (Hasnain et al., 1988).

The Chhota Shigri glacier drains into the river Chandra. The total drainage area of the glacier basin is about 45 km2 and the glacier occupies about 20% of the drainage area. Several supraglacial water streams are formed in the ablation zone, most of them terminates into moulins or crevasses.

Impact of glacier retreat in India

Uses of freshwater

Himalayan glaciers form a unique reservoir that supports mighty perennial rivers such as Indus, Ganga and Brahmaputra, which are the lifelines of millions of people. Recently the geologists of Geological Survey of India (GSI) counted 5,218 glaciers in the Himalayas (Puri 1994). It is estimated that 33,200 km^2 (Flint 1971) of the Himalaya is glaciated and glaciers occupy about 17 percent of the total mountainous area of the Himalaya (Vohra 1978) while an additional area ranging from 30-40 percent has seasonal snow cover. Meltwater draining from these ice and snowfields is important in regulating the hydrology of the Indian sub-continent. Though it contributes only to 5 percent of total runoff, it releases water in the dry season (Upadhyay 1995). Gradual shift of the snowline due to progressive increase in atmospheric air temperature and release of the water from snow and ice melting makes the water level constant in Himalayan rivers. A drainage map of the Bhagirathi River fed by Gangotri in the Garhwal Himalaya is presented in figure 21. About 75 percent of discharges in Himalayan rivers occur during May-September due to rise in atmospheric temperature and precipitation. The occurrences of monsoonal precipitation on the glacier surface increase albedo and reduce the ice and snow melting (Collins & Hasnain 1995). Monsoonal solid precipitation coming to the glacier in monsoon period constitutes the major input in glacier mass balance in tropic and sub-tropic glaciers (Ageta & Kadota 1992). Therefore, the onset of monsoon with its fresh snow protects ice from melting and the solid form of precipitation brought by monsoon trajectories on glacier surfaces is stored.

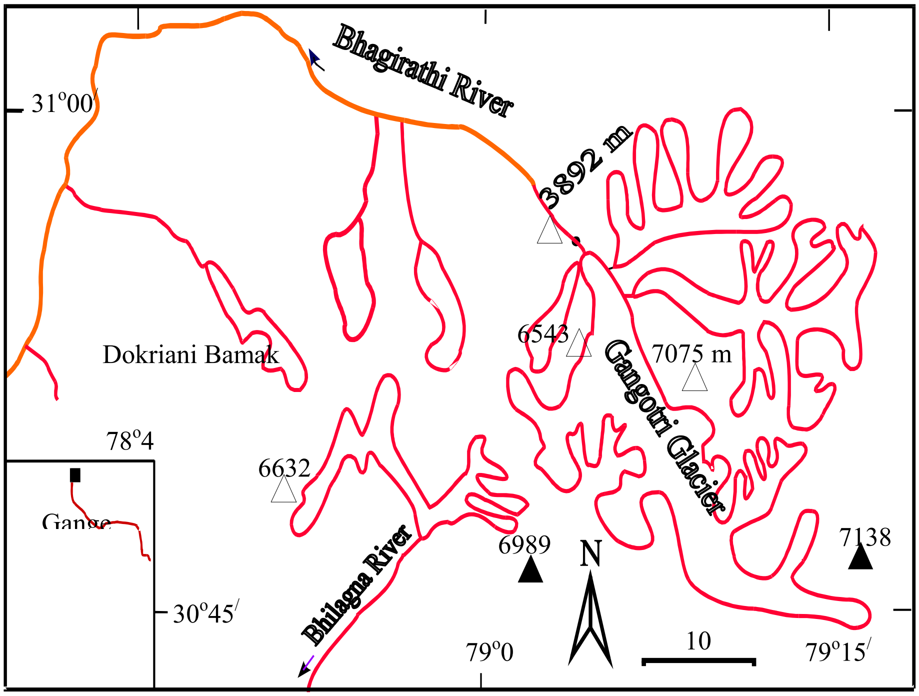


Fig 23: Drainage map of the Bagirathi River, Garhwal Himalayas

A reduction in water from the mountains would further affect the economy of the region by limiting the energy from hydropower plants and hampering industrial productivity (Johannesson 1997). Power shortages in India are already at about 10 percent of total electrical energy and 20 percent of peak capacity requirements (World Bank 2000). At a time when the Government of India is actively promoting the use of renewable energy sources as a clean and sustainable way of meeting the nation's growing energy requirements (MNES 2001), the possibility that the energy potential from hydropower may not be achieved has serious implications for the development plans of the whole country. Industries like food processing, mining, paper, chemical and steel production, which require a reliable supply of water, both as an input to the manufacturing process and as a medium for the dilution of effluent, would also be detrimentally affected.

A model has been developed in joint collaboration with the Centre for Ecology and Hydrology funded by the Department for International Development (DFID), UK under the SAGARMATHA project (2004). This model reveals that there will be an increase in river discharge at the beginning 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 permanent decreased level.

This model, when run for 100 years under different climatic scenarios, shows distinct differences in the potential impacts of deglaciation both regionally, in an E-W direction along the Himalayan arc, and within catchments. In the upper Indus, the study sites show initial increases of between +14 percent and +90 percent in mean flows (compared to baseline) over the first few decades of the 100 year incremental scenario runs, which are generally followed by flows decreasing between –30 percent and –90 percent of baseline by decade 10. For the Ganga, the response of the river, near the headwaters in Uttarkashi is significantly different from what is seen downstream at Allahabad. At Uttarkashi, flows peak at between +20 percent and +33 percent of baseline within the first two decades and then recede to around –50 percent of baseline by decade 6; further downstream the deglaciation impacts are barely noticeable. 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.

While deglaciation may hinder economic development nationally, the impacts are likely to be hardest felt at the local level by the most vulnerable in society, particularly the women and children of poor families. Pressures on rural livelihoods may force many landless and poor farmers to seek better employment opportunities in the region's cities, a response, which itself, has numerous social, economic and cultural implications for both the rural and urban areas (Pebley 1998). Yet, some 25-40 percent of the urban population in developing countries already live in impoverished slums, with little or no access to water and sanitation (Word Bank 1997, IPCC 2001b).

Country Case Study 3

China: Glaciers, retreating glaciers and its impact

Introduction

The Tibetan Plateau is the most concentrated glacier center in the middle and low latitudes of the Earth. The total area of glaciers is 104,850 km^2, including 40,000 km^2 in India and Pakistan and 49,873 km^2 in China. The largest glacier covers are on the Himalayas, amounting to 34,660 km^2. The largest distribution of glaciers is in the plateau margins of the Himalayas, Karakorum and West Kunlun mountains, which have both more and larger glacier cover; inland plateaus have less glacier cover. Consistent with the global climatic fluctuation of the 20th century and obviously rising temperatures since the 1980s, the air temperature has greatly changed on the Tibetan Plateau. The most significant warming periods have been the 1920s-1940s and from the mid-70s to the present. The last ten years have shown the greatest warming in the Tibetan Plateau.

In the past 40 years or more, glaciers have shrunk more than 6,606 km^2 in the entire Tibetan Plateau, with the greatest retreat occurring since the mid 1980s. With strong retreat since the 90s, all glaciers, except some large glaciers in the Tibetan Plateau, have begun shrinking. Alarming as the situation is, it is equally imperative to understand the physical and climatological features of various glaciers in China and study the morphosis that occurred over the years.

Background

The Qinghai-Tibetan Plateau with its high altitude, unique geographical features and rich wildlife, water and mineral resources, has been called the 'Roof of the World' and the 'Third Pole of the Earth'. Apart from being the 'source of rivers' and the 'ecological source' for South and Southeast Asia, it is also the 'starter' and 'regulating area' for the climate of China and indeed of the Eastern Hemisphere as a whole. The high mountain ranges and especially the Tibetan Plateau play a major role in the climatic system of Asia and the monsoon systems. This in turn affects even global climate and global climatic change. The Tibetan Plateau has an important influence on the regional and atmospheric circulation and splits the upper westerly winds in winter into northern and southern branches.

The Tibetan Plateau is the headwater of rivers that flow down to half of humanity. The Yellow River and the Yangtze start in northeastern Tibet and flow across China; the Mekong originates in eastern Tibet as do the Irrawady and Salween that traverse down to Burma. The Yarlung Tsang Po starts near Lake Manasarovar and travels eastwards for nearly 2,000 km before cutting through the Himalayas to become the Brahmaputra and emptying into the Bay of Bengal. Most of the major rivers in Nepal originate in the Tibetan plateau and cut deep gorges to flow down to the Ganga. Then there are the Indus and its tributaries that also start near Lake Manasarovar and flow westwards into Pakistan and empty in the Arabian Sea.

The Tibetan Plateau itself is located between the Karakorum and Himalayan ranges in the south and Altyn Tagh and Kunlun ranges in the north. It has a mean elevation between 4,500 m and 5,000 m with many isolated mountain massifs of more than 6,000m to 7,000 m heights.

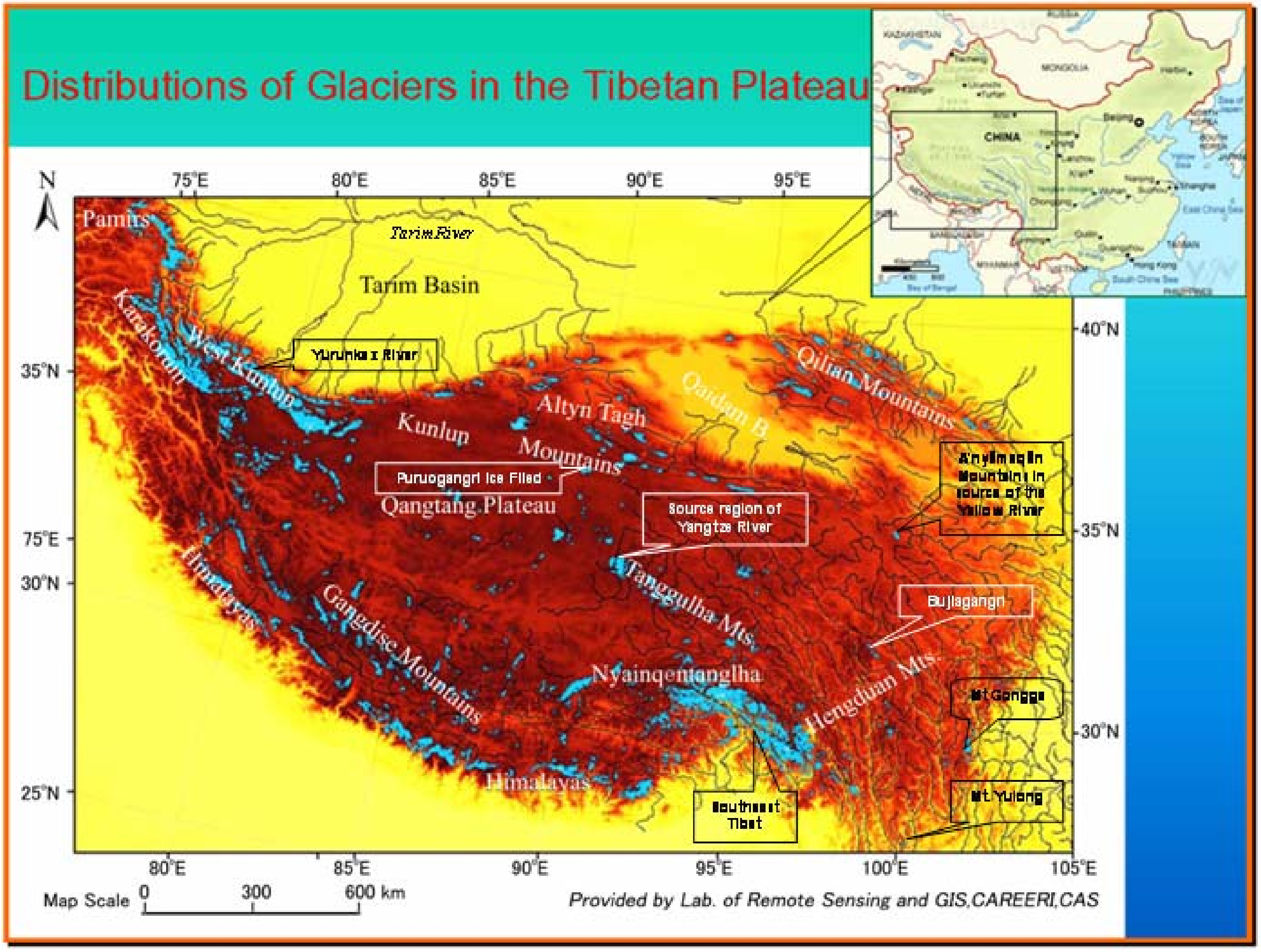


Figure 24: Distribution of glaciers in the Tibetan Plateau, and key sites in the report

Glacier resources and distribution

The inventory of glaciers in China has identified 36,793 glaciers with an area of 49,873.44 km^2 and ice volume of 4561.3857 km^3 in the Tibetan Plateau (Liu Chaohai *et al.* 2000). Glaciers are classified as maritime (temperate) type, sub-continental (sub-polar) type and extreme continental (polar) type (Huang Maohuan 1999; Shi Yafeng *et al.* 2000).

Maritime type or temperate type glaciers: These glaciers receive abundant summer monsoon precipitation. Annual precipitation at the equilibrium line varies from 1,000 to 3,000 mm, with summer temperatures of 1-5ºC, and ice temperatures of -1ºC - 0ºC. They are mainly distributed in southern Tibet, western Sichuan Province and western Yunnan Province, including the east Himalayas, the middle and east Nyainqêntanglha Range and the entire Hengduan Mountains. These glaciers cover an area of about 13,200 km^2 in China.

Sub-continental type or sub-polar type glaciers: For these glaciers annual precipitation at the equilibrium line varies from 500 to 1,000 mm. The annual mean temperature varies from -6° to -12ºC and summer temperature varies from 0° to 3ºC. Ice temperature at the lower bound of the active layer varies from above -1° to -10ºC. Sub-continental type glaciers are mainly distributed throughout most of the Qilian Mountains, the eastern Kunlun Mountains, the eastern Tanggulha Range, the western Nyainqêntanglha Range, part of the Gangdise Range, the northern slopes of the middle and western Himalayas and the northern slopes of the Karakorum Mountains. These glaciers cover an area about 27,200 km^2 of China's glacier area.

Extreme continental type or polar type glaciers: Annual precipitation at the equilibrium line varies from 200 to 500 mm for these glaciers. Annual mean temperature is below -10ºC and summer surface ice temperature is below -1ºC. Situated in extremely cold and dry conditions, heat loss from ice surface by evaporation is significant and ice melt is inhibited**.** These glaciers are distributed in the middle and western Kunlun Mountains, Qangtang Plateau, eastern Pamirs, western Tanggulha Range, western Gangdise Range and western Qilian Mountains. The extreme continental type glaciers cover an area of 19,000 km^2 in China (Shi & Liu 2000).

The annual distribution of glacier water resources is concentrated, especially for those inland glaciers developing under the dry and cold continental climate. The ablation season is generally from May to September, with runoff from June to August contributing 90 percent of that. As for maritime glaciers forming under the oceanic monsoon climate, the ablation season is relatively longer, generally from April to October, and the runoff process appears less concentrated with about 60 percent of ablation-seasonal runoff produced between June through August.

Meanwhile, in summer time when strong glacier ablation coincides with the rainy season, the glacier melt runoff enhances the amount of stream flow. The glacier melt runoff plays a role in regulating the variation in stream flow in a single year. This happens because the melt, being mainly controlled by temperature, would be less than normal during wet years with lower temperatures and a large amount of solid precipitation being stored in mountain glaciers, while in dry warmer years the opposite is true. Therefore, rivers with a larger portion of glacier melt water supply are characterized by runoff being not as insufficient in dry years and having smaller variability within a single year.

Physical and climatological characteristics

Fig 25: Pamirs Knot

The dimension and distribution of glaciers in the Tibet Plateau is quite uneven, with the mountain systems acting as centers of glacier covering. The following sections examine the features of glacier resources in the mountains of the Tibetan Plateau.

The Pamirs Plateau

The Pamirs Knot is the convergence area of several high ranges. These include the Hindukush from the south-west, the Karakorum from the south-east, Kunlun from the east and Tian Shan from the north-east. This high mountain complex between the Tarim and the Karakorum basins is inclined to the west and drained by the Amu Darya.

The altitude of snowline lies at 3,500-3,600 m in the west and rises as high as 5,800m in the east. Over a thousand glaciers are as long as 1.5 km, sixteen glaciers are over 16 km long, including those that are located in the area of Peak Revolution at the Yazgulem Ridge. The Ridges of the Academy of Sciences, Zaalai, Darvaz, Peter the First, Yazgulem, Rushan, and Northern Alichur are the largest centers of glaciation. The Northern-Western Pamirs from where the River Vakhsh flows out, and also the right affluent of the River Pianj - Bartang , Vanch and Yazgulem - are famous for its powerful glaciation.

There are 6,729 glaciers with a total area of 7,493.4 km^2 in the West Pamirs of Tajikistan, where precipitation is abundant and high mountain massifs are advantageous for catching water vapor and the consequent development of large glaciers. The eastern Pamirs lie in China, where there are 1,289 glaciers with a total area of 2,696.11 km^2. The Karayayilake Glacier with a length of 18.4 km and an area of 128.15 km^2 is the largest one of the Eastern Pamirs and originates from the northern slope of Kongur Jiubie Mt. Generally. More glaciers are developed in the Western Pamirs than in the Eastern Pamirs; the sum of both Pamirs being 8,018 glaciers with an area of 10, 189.51 km^2.

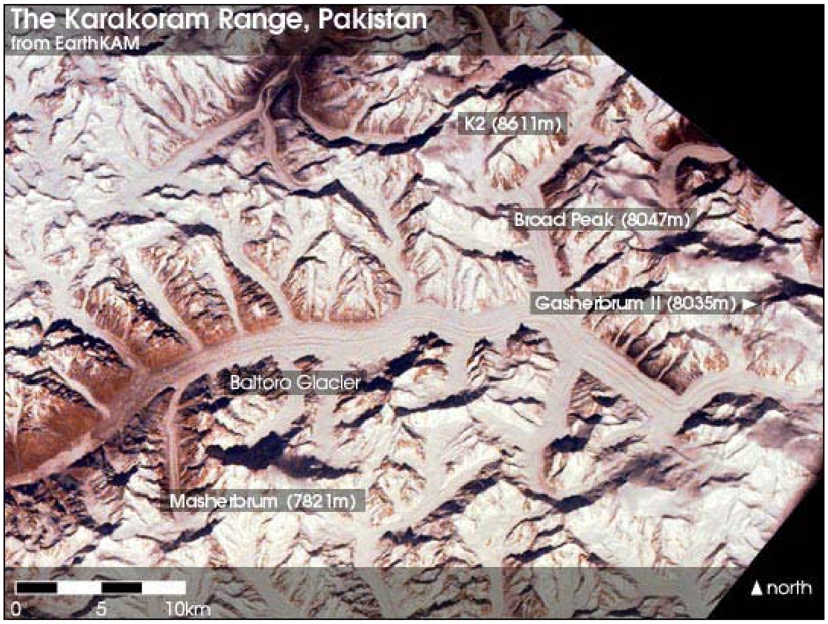


Figure 26: Glaciers and four peaks higher than 8,000 m in the Karakorum

The Karakorum

The Karakorum, lying immediately north of the western part of the greater Himalaya, is the highest of the southwest Central Asian mountain systems. It has the largest concentration of glaciers on mainland Asia and outside high latitudes, with eight glaciers over 50 km in length and more than 20 over 30 km long. The perennial snow and ice cover, exceeding 16,000 km^2, comprises a huge fresh water store in a generally arid, drought-prone region.

Glacial meltwaters make a major contribution to the flow of the Indus and Yarkant Rivers and to the livelihood of some 130 million people. The Karakorum Range is also regarded as the kingdom of the mountain glaciers. About 28 –37 percent of its mountain area is covered by glaciers. Of the eight glaciers that are more than 50 km long, six are located in the Karakorum Range. Siachen Glacier (also called Rose Glacier) on the southern slope of the Karakorum Range (Indian side) has a total area of about 1,180 km^2. With a length of 74 km and an area of almost 1,000 km^2 it is the largest glacier in the Karakorum. The main glacier and its largest side glacier, the Teram Sher branch, have a south-westerly and westerly aspect, respectively. Meltwater from Siachen Glacier forms the main source of the Nubra River which belongs to the drainage of the Ganges. The Insukati Glacier on the northern slope along the main ridge of the Karakorum Range is 41.5 km long and covers an area of 329 km^2 making it the largest glacier in China.

China's Karakorum Range has 3,454 glaciers, covering a total glacial area of 231 km^2 and storing as much as 686 km^3 of ice (based on air photos and map measured in 1968-1976). Of these 3,059 glaciers with an area of 5,925 km^2, and an ice volume of 684 km^3 are in the Yarkant River Basins. The glaciers on the north slope of the main ridge of the Karakorum Range cover an area of 2,234.81 km^2 and the Agile Range glaciers cover 1,450 km^2.

West Kunlun Mountains

Kunlun Mountains extend 2,500 km from the Pamirs Plateau in the west to the northwest of Sichuan Province. This range has an average elevation of 5,000 to 7,000 m. Its main peak, Muztag, is 7,723 m above sea level. The Western Kunlun Mountains lie in the northwestern part of the Tibetan Plateau. In this region there are 6,580 glaciers with a total area of 10,844 km^2, and an ice volume of 1,175 km^3. This corresponds to about three-fourths of the glaciered area in the whole of Kunlun Mountains (Liu Chaohai *et al.* 2000). The greatest glaciers among them, mostly 20-30 km long, are distributed in the high mountains between Tianshuihai and Keriya Pass, south of the Yurunkax River.

Alpine type glaciers are usually developed on the north slope of the Western Kunlun Mountains where the lands are severely cut and highly shadowed. Ice cap (flat-topped glaciers), slope glaciers and outlet valley glaciers are mainly developed on the south slope. This is due to the different topographical conditions from the North Slope.

Qilian Mountains

Qilian Mountains stretch along the northeastern fringe of the Qinghai-Tibet Plateau, with an average elevation of 4,000 m. Its main peak, Qilianshan, is 5,547 m above sea level. There are 2,815 glaciers with a total area of 1931 km^2, and total ice volume of 93 km^3 in all of the Qilian Mountains. There are 2,166 existing glaciers with a total area of 1,308 km^2 and an ice volume 60 km^3 in the Hexi inland basins on the north slope of Qilian mountains. Others belong to the Qaidam inland river basin and the Yellow River outflow river basins.

The Himalayas

The Himalayas lie to the north of the Indian subcontinent and to the south of the central Asian high plateau. They are bound by the Indus River on the west slope of Mt. Nanga Parbat (near Gilgit, Pakistan), and in the west, by the Jaizhug Qu River on the eastern slope of Mt. Namjabarwa (nearby Medog).

In the whole of the Himalayan Range, there are 18,065 glaciers with a total area of 34,659.62 km^2 and a total ice volume of 3,734.4796 km^3 (Qin Dahe 1999). This includes 6,475 glaciers with a total area of 8,412 km^2, and a total ice volume of 709 km^3 in China. The major clusters of glaciers occur in and around the following ten Himalayan peaks and massifs: Nanga Parbat, the Nanda Devi group, the Dhaulagiri massif, the Everest-Makalu group, the Kanchenjunga, the Kula Kangri area, and Namche Bazaar.

From west to east the Himalayas can be divided into three segments according to its topographic features: the Western Himalayas, the Central Himalayas and the Eastern Himalayas. There are 2,968 glaciers with a total area of 4,160.33 km^2 and a total ice volume of 414.9455 km^3 (Qin Dahe 1999). The glacier resources for each segment are captured in the table below.

Table 8: Glacier Resources in the Himalayas (after Dahe Qin et al. 1999)

	Numbers	Area/ km^2	Ice Volume/ km^3
Western Himalayas	5,648	10,284.75	980.7714
Central Himalayas	9,449	20,214.54	2,338.7627
Eastern Himalayas	2,968	4,160.33	414.9455
Total	18,065	34,659.62	3,734.4796

Nyaingentanglha Mountains

Figure 27: Midui Glacier in southeast Tibet is a monsoonal maritime glacier

Based on glaciers inventoried by air photos and large-scale maps, there are 7,080 glaciers with an area of 10,701 km^2 in the Nyaingentanglha Mountains. Most of the glaciers are located in the eastern parts of the mountains. The southeast part of the Tibetan Plateau experiences monsoon precipitation in excess of 1,000 mm/yr resulting in maritime temperate glaciers. This makes this one of the largest areas of monsoon maritime glaciers in the world. They make up two-thirds of the number of glaciers and five-sixth of the whole glacier area in the Nyaingentanglha Mountains. Glaciers fed by monsoon precipitation are mainly located on the eastern part of the mountains; simultaneous accumulation and ablation in summer season characterize these types of glaciers.

The Yarlung Zangbo Canyon cuts through the Himalayas, and has an average depth of 5,000 m with the maximum depth of 5,382 m. Special ‘surging glaciers’ like the Zhelonglong and the Midui Glaciers in the Great Canyon region have had periodical long distance and high speed jumping movements. During the jumping period, the glaciers move at a speeds of up to 1.5 km/day.

Mt. Gongga and Mt. Yulongxue in the Hengduan Mountains

The Hengduan Mountains constitute a series of ranges that descend east from the Tibetan plateau to form the highlands of Sichuan and Yunnan. Altitudes vary from 2,000-2,500m in the south to 7,000 m in the north. The highest peak, the Gongga Shan/Minya Konka (7,589 m), is in the Daxue Range. This range marks the transitional zone between the dry Tibetan plateau and the wet Sichuan basin.

Mount Gongga (Tibetan: Minya Gongkar, 7,556 m) is the highest peak in the east part of the Tibetan Plateau. Around the mount there are 74 glaciers, 255.10 km^2 in area with five of them being over 10 km in length. The Hailuogou Glacier on the east slope of the mount is 13.1 km in length and 25.7 km^2 in area, and rises to 2,980 m. It is the longest maritime glacier in the Hengduan Mountains. The Yanzigou Glacier, nearby the Hailuogou Glacier, is 10.5 km in length and 32.15 km^2 in area, and rises to 3,680 m.

The Jade Dragon Snow Mountain (Yulong Xueshan**,** 27°10′- 40′N, 100°9′-20′E**)** with its maritime temperate glaciers, represents the only one of its kind in the southern end of the Northern Hemisphere. There are 19 glaciers with an area of 11.6 km^2 in the mountains, of which Baishuihe Glacier No.1 is the largest one with an area of 1.53 km^2 and a length of 1.52 km.

Climate change and glacier retreat

Ice core records from the Dasuopu Glacier of the Himalayas, Tibet of China, indicate that the last decade and last 50 years have been the warmest in 1,000 years (Thompson *et al.* 2000). Meteorological records for the Tibetan Plateau show that annual temperatures increased 0.16°C per decade and winter temperatures increased 0.32°C per decade from 1955 to 1996.

In the source regions of the Yangtze and Yellow Rivers, climate change in the last 40 years show the trend of both temperature and precipitation rises. The decadal mean temperature in the 1980s was higher than that in the 1950s by 0.12 °C to 0.9 °C, and by 0.3 °C in most parts of the study area. Contrasting to the mean temperature increasing in the whole of China (0.2 °C), these regions have the highest temperature rise at an average of 0.44°C (Wang Genxu *et al.* 2002).

The climate in the Tibetan Plateau glaciered areas became warmer and more humid during the last few decades, especially since 1980s. Over the past 60 to 100 years, glaciers worldwide have been retreating. Mountain glaciers in the Tibetan Plateau, which are typically smaller and less stable to begin with, seem particularly susceptible to glacial retreat. The disappearance of mountain glaciers of the Tibetan Plateau is already affecting the supply of water to downstream natural and manmade systems (Yao Tandong *et al*. 2004).

Yurunkax River of the West Kunlun Mountains

The Yurunkax River Basin is located on the northern slope of West Kunlun Mountains and on the southern margin of the Tarim basin. There are 1,331 glaciers with an area of 2,958.31 km^2, and an ice volume of 410.3246 km^3. Shangguan Donghui et al (2004) investigated the changes of glaciers at the head of Yurunkax River (centered at 35°40′N, 81°E) by using aerial photos (1970), Landsat TM (1989) and ETM$^+$(2001) images. A comparative analysis performed for glacier length/area variations since 1970 shows that the prevailing characteristic of glacier variation is ice wastage, however, changes in glacier area is very small in this region.

Results indicate that a small enlargement of ice extent during 1970-1989 was followed by a reduction of over 0.5 percent during 1989-2002. The later shrinkage is attributed to the glacier response to the air temperature rise in region. It concludes that the decreases in air temperature and precipitation in the 1960s might have caused the enlargement of glaciers during 1970-1989.

The glacier shrinkage during 1989-2001 might be glacier reaction to increases in air temperature and precipitation. The results suggest that the rate of retreat has been increasing since 1989.

Qilian Mountains

Various measurement data obtained in the east, middle and west parts of the Qilian Mountains in the 1970s and mid-1980s showed that the glaciers retreated slower in mid-1980s than in the mid-1970s, while the glaciers in the east part of the Qilian Mountains were still in retreat (table 9) (Liu Chaohai *et al.* 1999) .

Table 9: Recent variations in the Qilian Mountains (After Liu Chaohai et al. 1999)

Glacier	Length/ km	Area/ km^2	Duration	Terminal retreating/ m
Shuiguanhe Glacier No.4	2.1	1.86	1956-1976	-320.0
			1976-1984	-69.7
July First Glacier	3.8	3.04	1956-1975	-40.0
			1975-1984	-10.0
Laohugou Glacier No.12	10.0	21.91	1962-1976	-71.08
			1976-1985	-11.7

Liu Shiyin *et al.* (2002) performed a comparative analysis for glacier area variations since the maximum of the LIA (Little Ice Age) in the western Qilian Mountains, northwest China. The glacial extent in the LIA maximum and also in 1956 was derived from air photos and relevant photogrammetric maps. In the 1990s this data was extracted from Landsat TM image and geometrically corrected by co-registering with the above-mentioned maps. The results indicate that total glacier area in four larger river basins was on average 16.9 percent bigger than that in 1956.

The satellite image of 1990 in the north part range (Daxueshan Mountains) of the western Qilian Mountains demonstrated a glacial area decrease by 4.8 percent compared with the glacial area in 1956. They found that glacial area has a close relationship with ice volume, or the length of individual glaciers. With these relations, they calculated the volume and length changes during the LIA and 1956, and 1956 and 1990. It shows that ice volume and glacier length changes are about 14.1 percent and 11.5 percent of their amounts in 1956 during LIA (Little Ice Age) and 1956. The result of Daxueshan Mountains during 1956 and 1990 was extended to the western part of Qilian Mountains by using the derived relations. The results show that glacier area and volume have all decreased by 10.3 percent and 9.3 percent during this period. The period from 1956 to 1990 saw a much stronger recession of glaciers, and rivers in the region received an extra glacial runoff of about 50×10^8 cubic meters.

Table 10: Glacier variations in the western Qilian Mountains during 1956-1990 (Liu Shiyin et al. 2002)

Rivers	Glaciers	Area / km^2	Variation in area / km^2	Variation in percent /%	Ice Volume / km^3	Variation in volume / km^3	Variation in percent / %
Beidahe	650	290.8	41.6	14.3	10.4	1.5	14.0
Sulehe	639	589.6	49.6	8.4	33.3	2.4	7.1
Danghe	336	259.7	25.0	9.6	12.4	1.1	8.9
Hara Lake	106	89.3	8.0	8.9	5.0	0.4	7.3
Sum	1731	1229.4	124.2	10.3	61.1	5.4	9.3

Pu Jianchen *et al.* (2004) offered new information on glacier mass balance in the Qilian Mountains in July 2004. Mass balances of the glaciers were -810mm and -316mm in 2001/2002 and 2002/2003 balance year, respectively. The results show heavy melting and dramatic thinning during 2001-2003 in comparison with the last 40 years. The glacier experienced a strong positive mass balance of about 360 mm per year in the 1970s and 4 mm per year in the 1980s. This change depicts how glaciers are very sensitive to global warming.

Ice Caps in the Qangtang Inland

The Qangtang is situated in the area between the Kunlun, Tanggulha, Gangdise and Nyainqêntanglha mountains; it covers two-thirds of the total area of Tibet. It is more than 4,500 meters above sea level on average. In the Mt. Xin Qingfeng region, the middle Kunlun Mountains of the Northern Qangtang, there are 46 glaciers around the main peak, an ice cape, distributed with a total area of 420 square kilometres. Li Zhen *et al.* (1999) carried out the glacier change analysis for this region with the support of GIS software by making the glacier distribution maps of five images from 1974,1976,1979,1987 and 1994.

Comparative analysis for the data show that the Xinqingfeng Glacier have retreated a total length of 918 m in 1976-1987, whereas another glacier, West Xinqingfeng Glacier advanced 640 m in the period. In the period of 1987-1994, the Xinqingfeng Glacier was retreating up to 347 m; at the same time West Xinqingfeng Glacier advanced a distance of 733 m, a rate of 105 m/year. However, a retreating tendency has been seen since 1994 in West Xinqingfeng Glacier (Liu Shiyin *et al.* 2004). The Xinqingfeng Ice Cap has shown a retreating trend since 1979, with accelerated glacier and ice-field melt since 1994 in the region (Liu Shiyin *et al.* 2004).

Malan Glacier is a large extreme continental glacier, with a total area of 195 km^2 in Hoh Xil region at the center of the Tibetan Plateau. The altitude of snowline varies from 5,430 to 5,540m. The three LIA (Little Ice Age) moraines can be found in most glacier tongues. The moraine indicates the retreating of glacier from the LIA. The glacier tongues are 20 m lower in the southern slope and 20-40 m lower in the northern slope in the LIA than at present. The lost glacial area since LIA accounts for 4.6 percent of the present glacial area, and nearly 8 percent of the total lost glacial area in Qangtang region since the LIA. The glacier has retreated 45-60 m over the past 100 years. In the past 30 years from 1970, the Malan Glacier retreated 30-50 m, with a rate of 1-1.7 m/year. Though the retreating is less pronounced compared to the surrounding area of the plateau, the retreat rate is increasing, which might have a significant effect on the weak ecosystem in the plateau (Pu Jianchen *et al.* 2003).

Puruogangri Ice Field in the Middle Tibetan Plateau

Figure 28: The Puruogangri Ice Field in the Northern Tibetan Plateau.

Puruogangri Ice Field composed of several ice caps with an area of about 422.58 km^{2}and a volume of 52.5153 km^3, ranging from 5,620 to 5,860 m, is the largest in the Northern Tibet Plateau (Yao Tandong 2000).

More than 50 ice tongues with different lengths extend around to wide and shallow valleys, of which the longest has a wide terminus reaching the foothill. In the area with lower tongues, there are many ice pyramids, mainly in an initial stage and with connected bases. Since the LIA, the ice field has tended to retreat. There are three moraines around the tongues in the north and southeast. They belong to three cold periods when glaciers advanced. At those times, fewer advances presented in the west.

From the LIA to the present, glacier area decreases run up to 24.20 km^2 - 5.7 percent of the original area, equivalent to 3.6583 km^3 of ice loss. In the west, the glacier retreated by 20 m from post-LIA to the 1970s, and 40-50 m from the 1970s to the end of the 1990s, an average of 1.5-1.9 m/year. It retreated 4-5 m from September 1999 to October 2000, showing intensified retreating (Pu Jianchen *et al.* 2002). However, the Puruogangri Ice Field is relatively stable as compared to other glaciers.

Lu Anxin (2003) analyzed glacier variations of the Puruogangri Ice Field during the Little Ice Age maximum, 1974 and 2000, supported by GIS, aerial photos, satellite images, topographical maps and the digital elevation model (DEM). The dynamic monitoring results show that the areas of the glacier had decreased remarkably, which in fact matches with the increasing air temperature.

Bujiagangri in the East Tanggulha Mountains

The Bujiagangri, with the highest peak of 6,328 m, is located in the East Tanggulha Mountains. There are 124 existing glaciers, covering area of 184.28 km^2 and an ice volume of 16.6697 km^3. Wang Ninglian *et al*. (2004) analyzed the new data of the variations of the glaciers in Bujiagangri in the East Tanggulha Mountains since the Little Ice Age and found that the area and volume of the glaciers during the maximum of the LIA, the 15th century were 241.46 km^2 and 19.6282 km^3, respectively in this region. This indicates that the glacier area and volume decreased by 23.7 percent and 15.1 percent respectively Since the LIA, 184 glaciers with a length of about 0.6 km have melted.

The absolute variations in area and volume of each glacier since the LIA increased with its size, while the relative variations decreased. The mean area shrinkage, the mean retreat amount and the mean terminus height-rise amount of the glaciers on the south slope were larger than that of the glaciers on the north slope. This implied that the glaciers on the south slope were more sensitive to climatic change than that on the north slope. Since the LIA, the snow line in this region has risen about 90 m, equivalent to temperature rise about 0.6 ºC.

Source Region of the Yangtze River

Wang Genxu *et al.* (2004), based on land ecological classification of the source regions of the Yangtze and Yellow Rivers and field investigation, compared two phases of TM remote sensing data obtained in 1986 and 2000. From spatial variations and type transformation trends, the spatial changes and evolution patterns of land ecosystem in the source regions of the two rivers were analyzed using the analytical method of landscape ecological spatial patterns.

Results show glaciers and firns in the headwaters region used to cover an area of 1369.86 km^2. They mainly occur in the source region of the Yangtze River, accounting for 92.46 percent of all cover. Comparative analysis of the remotely sensed satellite data obtained in 1986 and 2000 showed that glaciers and firns in the headwaters region are retreating. In the Yangtze River source region, the glaciated area has decreased from 899.13 km^2 in 1986 to 884.4 km^{2}in 2000 or 14.91 km^2 in 15 years.

From these figures it can be seen that glaciers in the Yangtze River source region have a relatively small recession rate, approximately 1.7 percent. Lu Anxin *et al.* (2002) surveyed glacier change of the Mt. Geladandong, the source of Yangtze River, supported by remote sensing techniques and GIS, and by applying aerial photos, satellite imagery, topographical and the derived digital elevation model (DEM) in the area. Glacier variations during the LIA maximum, 1969 and 2000 were analyzed. The results indicate that the glaciers' area had decreased about 5.2 percent from the time of LIA maximum to 1969 and the glaciers' area had decreased about 1.7 percent from the time of 1969 to 2000 (see tables below). The number of glacier change shows the glaciers were almost steady in the area. The number of retreating glaciers is more than the advancing ones, and there are an increasing number of retreating glaciers since 1994, resulting from the rising temperatures.

Table11: Glacier area change in the source of the Yangtze River (after Anxin Lu et al. 2002)

Period	Area / km^2	Variation in area/ km^2	Variation in percent / percent
Max LIA	948.58	-49.27 -14.91	-5.2 percent -1.7 percent
1969	899.31		
2000	884.4		

Table 12: Glacier length change in the source of the Yangtze River (after Anxin Lu et al. 2002)

Glacier	Length / m	Variation in 1969-2000 / m	Annual variation (m/a)	Variation in percent
South JiangdiguruGL	12400	-1288	-41.5 m/a	-10.39
5K451F12GL	5400	+680	+21.9m/a	+12.59

Northern Slope of the Tanggula Mountains

A sub-polar glacier, the Tanggula Glacier, has been studied since 1989. A lot of push moraines in front of the terminus were found in 1989. These moraines were separating or had already separated from the glacial terminus. A push moraine is an indicator of glacial advancing and its presence in front of the terminus implies that the Tanggula Glacier had indeed advanced for some time but the separation of the push moraines from the terminus indicates that the glacier had retreated now. It was found that 10 years before the retreat many glaciers on the Tibetan Plateau were advancing due to an impact of a short cooling from the late 1960s to the early 1970s. The separation of the push moraines from the terminus is a consequence of climate warming since 1970s (Yao Tandong *et al.* 1996). Most glaciers in the northern slope of the Tanggula Mountains have retreated since 1994 (Pu Jianchen *et al.* 2002).

Monsoonal temperate glacier region

The monsoonal temperate-glaciers in China are located in the region of the southeastern Tibet Plateau, including the Hengduan Mountains, the eastern part of the Himalayan Mountains, and the middle and eastern segments of the Nianqingtanggula Range, in the provinces of Tibet, Yunnan and Sichuan, southwestern China.

According to the Chinese glacier inventory, there are 8,607 monsoonal temperate-glaciers in China, covering an area of 13,203 km^2. This is equal to 18.6 percent of the total glaciers and 22.2 percent of the total glacier area. Since the Little Ice Age, the total glacier area in the region has reduced on average by 30 percent, about 3,921 km^2. The rates of decrease (of glaciers of different sizes) differ: the smaller the glaciers, the larger their rate of decrease, the larger the glaciers, the lower their rate of decrease (Shu and Shi 2000).

There are regional differences of glacier change (He *et al.* 2000; Zheng *et al.* 1999). For instance, the Baishui Glacier No.1 on Mount Yulong, the southernmost glacier of Eurasia, with a small area, is most sensitive to climate, and its area has decreased by 60 percent from the LIA to the present. However, the mean rate of decrease of some large valley glaciers on Mount Gongga between the Little Ice Age and the present has been only 27 percent. It is clear that the time and amplitude of the variations of these glaciers differed because of their different geographical locations, scales and sensitivities to climate.

Thus, the Baishui Glacier No.1 retreated about 1,250 m during the many decades of the Little Ice Age, and it has retreated again since the 1980s (see Table 10), with an accelerated speed of retreat within the last few years (He Yuanqing *et al.* 2003). The glacier retreated about 40 m from 1998 to 2002, reflecting rapid climatic warming. The Hailuogou Glacier and the Azha Glacier, with locations to the north and west, also have retreated very quickly since the 1980s. Although the Melang Glacier on Mt. Mainri is advancing, its velocity has been gradually decreasing since 1990s (Zheng 1999), indicating that the glacier has responded to post-1980s climatic warming.

Table 13: Variation of some typical glaciers in the Chinese monsoonal temperate glacier region since the Little Ice Age (He Yuanqing et al. 2003)

Glacier Baishui No.1, Mount. Yulong (area: 1.7 km^2, length: 2.5 km)

Period	End Altitude/m	Change/m
17th-19th century (LIA)	3,800	advance
19th century -1957	4,353 (1957)	-1 250
1957 – 1982	4,100 (1982)	+ 800
1982 – 2002	4,250 (2001)	- 150

Glacier Melang, Mount Mainri (area: 13 km^2, length: 11.7 km)

Period	End Altitude/m	Change/m
1932 – 1959	2,100	-2 000
1959 – 1971	2,740 (1971)	+800
1971 – 1982	2,700 (1982)	+70
1982 – 1998	2,660 (1998)	+30

Glacier Hailuogou, Mount Gongga (area: 23.7 km^2, length: 13.6 km)

Period	End Altitude/m	Change/m
Early 20th century - 1930	2,850 (1930)	+ or -
1930 – 1966	2,880 - 2,900 (1996)	-1150
1966 – 1981	2,920 (1982)	-177.8
1981 – 1989	2,940 (1989)	-170
1990 – 1998	2,980 (1994)	-200

Glacier Azha, Southeastern Tibet (area: 29.5 km^2, length: 20 km)

Period	End Altitude/m	Change (m)
1920 – 1930	2,000	Advance
1933 – 1973	2,400 (1973)	-700
1973 -1976	2,600 (1976)	-200
1976 -1980	2,700 (1980)	-100
1980 – 1998	2,950 (1998)	-420

The Nyaingentanglha Mountains of the Southeast Tibet

The Zepu Glacier located in the Nyaingentanglha Mountains of the Southeast Tibet is a typical maritime temperate glacier. The glacier was covered with very thin debris at the terminus in the 1970s, but there was no vegetation on the debris. In 1989, Yao Tandong and others found that the debris at the terminus had become thicker and its surface was covered with vegetation. The appearance of vegetation implies that the debris had become thicker and more stable in the terminus, resulting from glacial retreat. This phenomenon, therefore, indicates a retreating trend in the Zepu Glacier since the 1970s (Yao Tandong *et al.* 1996).

The Himalayas

Jin Rui *et al.* (2004) studied glacier change responding to climate warming. The Pumqu basin located in Tibet was selected as the test area. The general trend of glacier change in the recent 20 years was analyzed and computed, supported by GIS. The results show that the total glacier area in Pumqu basin has decreased by 9 percent and the ice reserve has reduced by 8.4 percent, which also confirms that small glaciers are more sensitive to climate change.

Shi Changan and Liu Jiyuan (1992) studied the changes of the Karila Glacier and Qiangyong Glacier in central and southern Tibet, at the northern foot of the Himalayas, to the southwest side of Yangzhouyong Lake. The glacier change analysis for this region was carried out with GIS software by making glacier distribution maps of two maps edited from ground close-shot photogrammetery data of the Karila glacier in 1979 and Karila Landsat TM images in 1989. Comparative analysis for the data revealed that the major glacial bodies in the study area had no marked advance and recession coverage changes were quite unbalanced—it had disappeared in some place and grown in others—but receded ice-snow coverage is more than advanced. For instance, in the Karila Glacier in the northern region, the western ice-snow cover has made great recession while the eastern cover is marked with advances. The middle part of Qiang Yong Glacier located in south of the region has been prolonged greatly.

It must be noticed that these changes did not take place on the major body of Karila and Qiang Yong glaciers. The final comparison of the glacial coverage is that they are in a receded state. From 1979 to 1988, total ice-snow area of the region shrank by 11.1 percent.

Gangrigabu Mountains

Liu Shiyin *et al.* (2005) studied temperate glaciers in the Gangrigabu Mountains (28°30'-30°00'N and 96°00'-97°00'E), Southeast Tibetan Plateau, mainly influenced by the Indian Monsoon, to examine the present status of glaciers under this warming background. It was concluded that the measured 102 glaciers in the region have all in retreat from 1920s to 1980 with a total area and ice volumetric decreases of 47.9km^2 and 6.95km^3. It is estimated that all glaciers in the research area might have lost 13.8% of their total area and 9.8% of the total ice volume during the same period. After 1980, glaciers in the region have also experienced in general the ice mass wasting processes, based on data of 88 glaciers with a total area of 797.78 km^2. About 60% of these glaciers were losing their ice mass and other glaciers were in the advance state. Analysis indicates that glacier retreat has exerted significant influence on glacial meltwater runoff, which might accounted for 50% runoff decrease during 1915 and 1980. Glacier wastage and climatic warming trend during the last the century, esp. during the past two decade, lead us conclude that mass wasting of glaciers in the region will be possibly in an accelerating state in the coming future.

The A'nyêmaqên Mountains in sources of the Yellow River

The A'nyêmaqên Mountains, the eastern part of the Kunlun Mountains, are situated in the northeastern part of the Tibetan Plateau within the block of 34°20′-35°N and 99°10′-100°E. The highest peak in the range is 6,282 m above sea level, where glaciers are mostly concentrated among the mountain ranges in the eastern Kunlun Mountains. There are 57 glaciers with a total area of about 125 km^2, with three larger glaciers over 10 km^2 in area and about 7-10 km in length. The glacial meltwater flows into the Yellow River. Glacier variations are of particular significance considering meltwater influence on the river discharge and extracting characteristics of glacier fluctuations in the east of the Tibetan Plateau (Liu Shiyin *et al.* 2003).

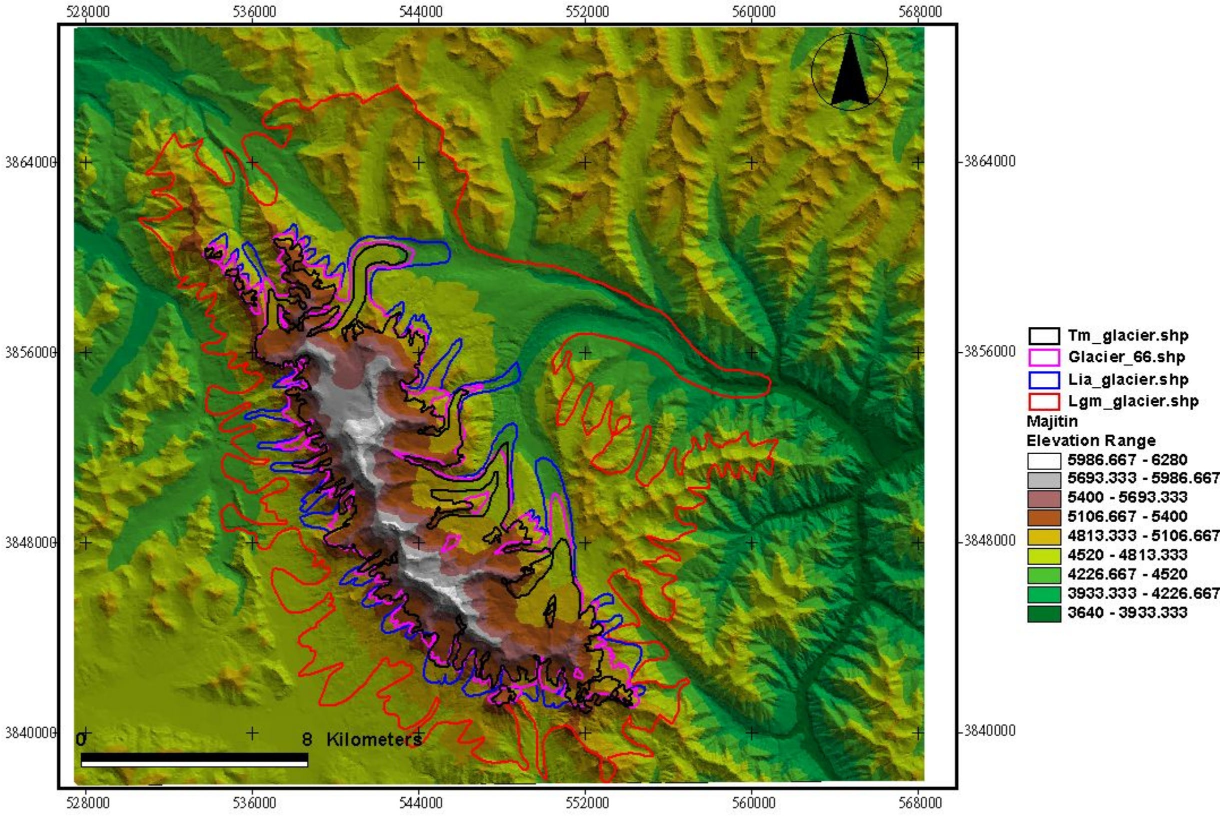


Figure 29: Boundaries of glaciers change in the A'nyêmaqên Mountains

Wang Wenying (1987) measured the change of glaciers in the A'nyêmaqên Mountains in 1981 through the Sino-German Joint Expedition to the Tibetan Plateau. His research covered 38 glaciers in the area. The results show that there are 16 advancing glaciers with advancing distances of 50-70m, 22 stable glaciers and only two retreating glaciers with retreating distance of 150-220 m during 1966-1981. Liu Shiyin *et al.* (2003) analyzed glacier variations during the

Last Glacial Maximum (LGM), the LIA maximum, and between 1966 and 2000 by applying aerial photos, satellite imagery, topographical maps and the derived digital elevation model (DEM) in the A'nyêmaqên Mountains, the source region of the Yellow River. Glacier area decreased during the past decades in the A'nyêmaqên Mountains shows much stronger trend than that found on other modern glaciers in northwestern China.

The results indicate that glaciers in the Last Glacial Maximum covered 3.1 times of the present glacier area in this region. Since the LIA maximum, glaciers in this region have experienced obvious shrinkage with accelerated reduction in area and length occurring in 1966 to 2000. The largest length retreat occurred on the Yehelong Glacier. It had a length reduction of 1,950 m between 1966-2000 accounting for 23.2 percent of its length in 1966. The second largest length reduction was seen on Glacier 5J352E20, which reduced 43 percent of the length recorded in 1966. Although the absolute length reductions of small glaciers are smaller than larger glaciers in the region, their proportions of length reduction are commonly higher than larger glaciers. For example, the length of Glacier 5J352E13 decreased by 76.6 percent from its original length of 900 m in 1966. Taking consideration of each basin in the area, it shows that glacier length in the basin 5J351D had decreased by 20 percent on average and in 5J352E the average was 27 percent from the 1966 values, respectively.

Taking the midpoint of 1622-1740 as the date of LIA maximum, Liu Shiyin *et al.* (2003) found that glaciers in this region had seen much accelerated retreat during the past 34 years. The yearly rate of glacier length reduction was found to be more than nine times of relevant rate during the LIA maximum and 1966. This implies that glaciers will continuously shrink under a rapid warming trend as predicted by miscellaneous research results and the summarization of IPCC (2001).

Yao Tandong *et al.* (2004) summed up systemically the research results of glacier change in China. Yao's research revealed a trend of glaciers retreating from global warming since the beginning of the 20th century (see Table 14). The glacier change can be divided into the following stages for the past century:

(1)The first half period of the 20th century is an advancing or advancing turning to retreating stage;
(2) A large scale retreating took place in the 1950s-1960s;
(3) In the end of 1960s to 1970s, glaciers were advancing or slowing down the retreating process. Many glaciers were advancing and showing advancing signs, such as positive mass balance and snowline altitude downing. However, advancing glaciers are more fractions than the retreating ones;
(4) Since the 1980s, glacier shrinking is more serious with strong retreating since 1990s. All glaciers turned to shrinking status except for some large glaciers in the Tibetan Plateau.

The overall trend of the glaciers in this area is retreating. Before the 20th century, the only scientific method to indicate the state of glaciers was through observation. Although not perfect and exact, it is still a reliable method. Observation showed that glaciers have shrunk significantly since the end of the Little Ice Age.

Table 14. Advancing or retreating of glaciers in the High Asia for varying periods (After Yao Tandong et al, 2004)

Period	Total statistical glaciers	Retreating glaciers /percent	Advancing glaciers /percent	Stationary glaciers /percent
1950-1970	116	53.44	30.17	16.37
1970-1980	224	44.2	26.3	29.5
1980-1990	612	90	10	0
1990 to Present	612	95	5	0

Loss in glacier volume on a global scale started in the middle of the 19th century and continued in several stages of ever-increasing rates, interrupted by short intervals of stagnation or growth. The acceleration of glacier wastage is not inherited from previous epochs. Also, glacier changes show much spatial variability. The stronger shrunk of the glaciers reveal in the Karakorum and southeast Tibet. Though there is weaker and lesser shrinking in the central Tibetan Plateau and surrounding mountains, amplitude of glacier retreating have an increasing trend from the inland of the Tibetan Plateau to the margin mountains. Thus, glacier retreating demonstrates different trends of volume change in different geographical locations resulting from global warming in different location in the Tibetan Plateau. In China, glaciers have shrunk an average of 6.3 percent over the past 40 years (Yao Tandong *et al.* 2004). In the entire Tibetan Plateau, over the past 40 years, glaciers have shrunk more than 6,606 km^2, with the greatest retreat occurring since the mid 1980s.

Impacts of glacier retreat on the Tibetan Plateau

Effect on water resources

In certain parts of the Tibetan Plateau, glaciers play a key role in supplying communities with water for irrigation, drinking, and hydro-electric power. The runoff they provide 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 riverhead regions. In the Baspa Glacier basin, the winter stream flow increased 75 percent since 1966, and local winter temperatures have warmed, which suggests that glaciers will continue to melt in future winters (Kulkarn *et al* 2004).

Shi Yafeng (2001) predicts that by year 2050 the temperature of the Qinghai-Tibet Plateau will rise by 2.5^0C. Perhaps more likely is that by 2050 the summer temperature, which causes intense ablation of glaciers, will rise by 1.4^0C. As a result, the altitude of equilibrium will rise by over 100 m; the ice ablation in the tongue zone will exceed the ice amount moved from the accumulation zone; and glaciers will become thinner and retreat. In the early stages glacial thinning prevails and meltwater increases. In the later stages glacial area largely shrinks, meltwater decreases and glaciers disappear.

The effects of glacier shrinkage on water resources before 2050 were examined for several regions, using the statistical data of China's glacier inventory. In some regions, such as Hexi at the north piedmont of the Qilian Mountains, most of the single glaciers have an area less than 2 km^2 making them the most sensitive to climate warming, and hence the most likely to melt rapidly. The volume of meltwater will peak at the beginning of this century. The impact of meltwater runoff on different rivers is estimated to be 10^6 to10^7 cubic meters^3 per year. 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 km^2 will increase by 10^8 cubic meters per year, peaking at mid-century. For example, glacial meltwater currently occupies 50 to 80 percent of the total discharge of the Yarkant River and Yurunkax River. It is predicted that glacier meltwater volume will increase by 25 to 50 percent by 2050, and the annual discharge of seven major rivers of the Tarim Basin will increase to 10^8 cubic meters per year.

Inland watersheds in the Qaidam Basin and the Qinghai-Tibet Plateau are dominated by extreme continental-type glaciers that have lower temperatures and retreat slowly. Temperature rises and increases in meltwater during the first half of this century are favorable to the development of animal husbandry and economic growth. However, in the maritime type glacier regions of southeast Qinghai-Tibet Plateau and the Hengduan Mountains, precipitation is heavy and ice temperatures are high. A temperature rise here will exacerbate the ablation of retreat of glaciers, perhaps causing frequent flooding and debris flow disasters.

Xie Zichu *et al.* (2001) studied glaciers in the basins of the rivers Ganga, Yarlung Zangbo and Indus, which together occupy one-third of the total glacier area in China, and cover an area of 19,500 square kilometers. Functional models of the variable glacial systems were established, and applied to the response of glacial runoff to climatic changes. The models simultaneously considered the effect of decreasing air temperatures, caused by rising ELA, and the reduction of a glacier's area. Under climatic conditions of increasing rates of 0.01, 0.03 and 0.05 km annually, the modeling results indicate that the glacial runoff fed by the marine-type glaciers with high levels of mass balance are sensitive to climatic change, and take 10 - 30 years to reach a climax. The glaciers then go back to an initial state in less than 100 years. However, the discharge-increasing rate of glacial runoff is small. During a peak period, the discharge-increasing 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 life-spans and lower levels of mass balance, respond slowly to climatic variations. They take over 100 years to climax, and hundreds of years to return to their initial state. At the similar levels of mass balance, smaller glaciers respond more quickly to climate change and retreat more quickly than large glaciers. Glacial systems with very large elevation differences have the longest life span. The age of the Rongbuk Glacier on the northern side of the Himalayas, at a temperature-increasing rate of 0.01 km / year, can reach over 1,800 years.

Glacier lake outburst floods

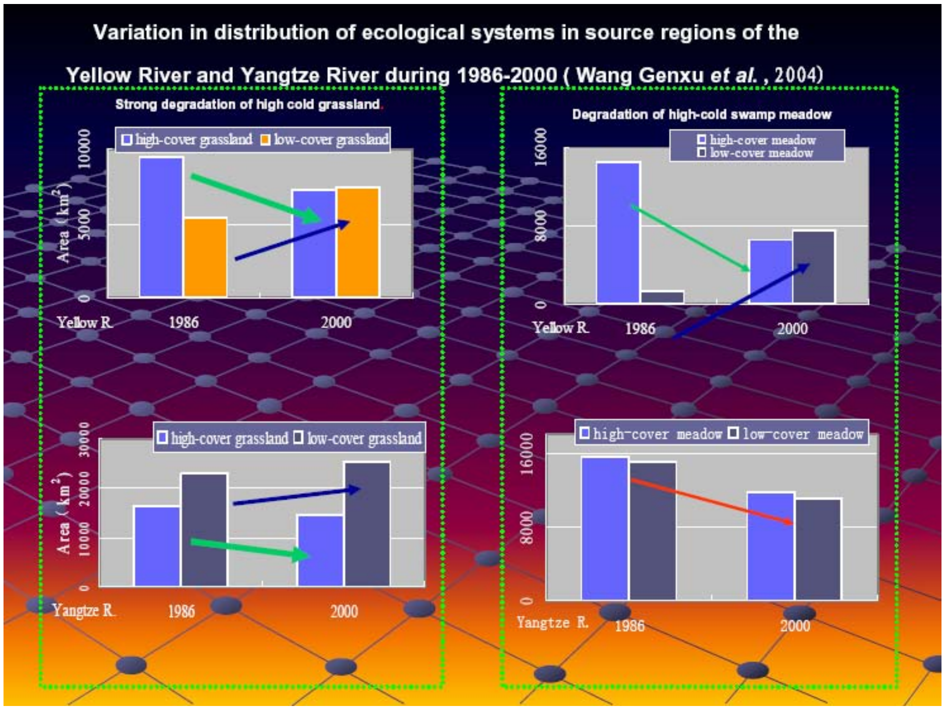
Glacial lake outburst floods (GLOF) are a common hazard in the high mountains of China. Glacial lakes that pose this type of danger are formed when water from the ice melt of a retreating glacier is retained by the glacier's terminal moraine. Eventually, either the volume of water becomes too great for the moraine to support or an event such as a large ice block detachment occurs and the moraine is breached. The resulting flood can cause devastating damage to property and infrastructure and frequently results in loss of life. A GLOF in China in

1964 destroyed crucial sections of a major highway and washed away 12 timber trucks 71 km from the scene.

In Tibet, the floods that struck one of the major barley producing areas of the Tibetan Plateau in August 2000 were the worst in living memory in the region. Financial losses were estimated at USD 75 million with more than 10,000 homes, 98 bridges and dykes destroyed. The loss of grain and livestock too had a great impact on the farming communities who faced food shortages that year.

Glacial debris flow hazards

During the night of 29 July 1983, the glacier thawing water in Peilong stream, a tributary in the upstream of Parlung Zangbo River, combined with ceaseless rains, resulted in large-scale glacier mud-rock flow in Peilong. Mingling with ice blocks, giant rocks and clay, it flew down and formed a giant piled fan. The quantity of the mud-rock flow was as much as 1 million m^3. A 32 m concrete bridge and the Sichuan-Tibet highway was damaged. The economic loss was estimated at over half a million Yuan. It has occurred several times since then causing loss of lives and property.



Degradation of wetlands

In the last decade, wetlands in the Qinghai Plateau have seen a visible decline in the lake water level, along with problems of the lake shrinking, the absence of flow of the river or the stream, the degradation of the swamp wetland, and so on. The percent of wetland area is 7.7 percent of the total area in Qinghai Province (Chen Guichen *et al.* 2002). According to statistics, there are 428 species of spermatophytes and 151 species of animals including 73 species of birds, 55 species of fishes, 14 species of mammals and nine species of amphibians in the wetlands. The wetlands comprise aquatic vegetation, swamp vegetation and swamp meadows. It is important to strengthen the conservation of the wetlands in the Qinghai Plateau according to its function.

Over the past 15 years (1986-2000), several changes in the source regions of the Yangtze and Yellow Rivers have manifested:

1) Areas of middle and high-cover high-cold grassland and high-cover high-cold meadow have decreased by 15.82 percent and 5.15 percent, respectively. The degradation degree of high-cover grassland is significantly higher in the Yellow River source region than in Yangtze River. The area of high-cold swamp meadow decreased sharply by 24.36 percent, mainly occurring in the Yangtze River source region (the largest degraded ecological type).

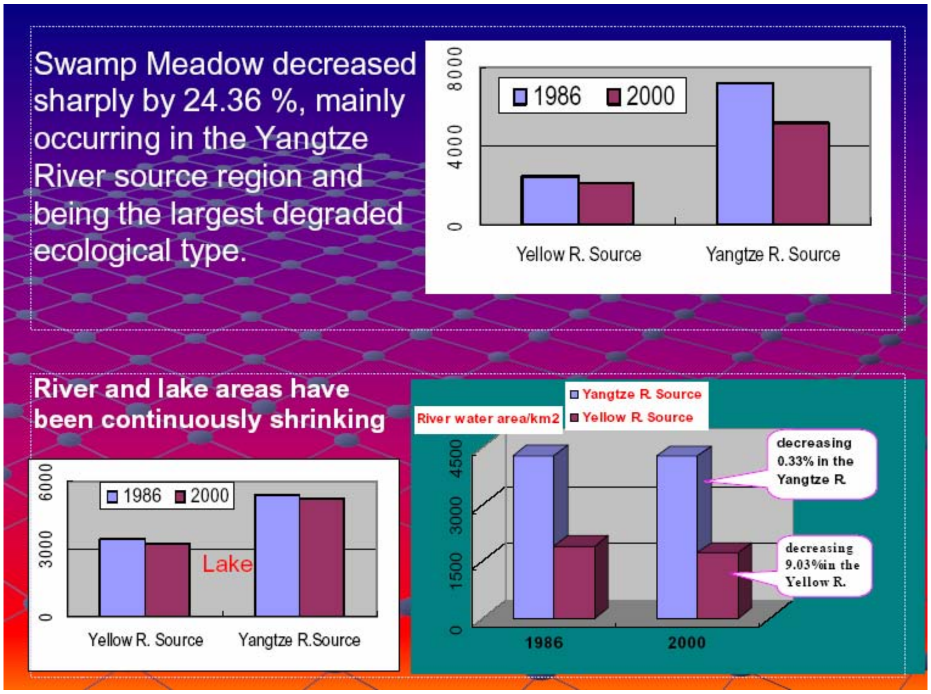
2) Lake water body area shrank by 7.5 percent, mainly occurring in the Yangtze River source region. Lake shrinkage in the Yangtze River source region was dominated by interior lakes and occupied 60 percent of the total shrinkage area of lakes. In the Yellow River source region the decreased area of exterior lakes occupied 71.15 percent of the total shrinkage area of lakes, and thus led to the inflow of many exterior lakes. River water body also decreased significantly, by 3.23 percent. Unlike lakes, 92 percent of the decrease in river water body area occurred in the Yellow River source region, a fact related to the inflow of exterior lakes and the formation of several wadis.

3) Land desertification, salinization and bare land developed at an average rate of 0.5 percent or faster. Desertified land expanded by 17.11 percent. In the Yellow River source region it increased by 25.65 percent, corresponding to an annual expansion rate of 1.83 percent, putting it in the severely desertified region category. Grassland degradation intensity is significantly higher in the Yellow River source region than in the Yangtze River source region due mainly to human activities.

Viewed from the features of eco-environmental change, and reflected by the spatial patterns of ecological land types in the headwaters region and by grazing activity in the Yellow River source region, climate change is a main factor affecting the eco-environmental changes in the headwaters region.

Lake area and river stream flow

The lakes of the headwaters region mainly occur in the Yellow River source region, accounting for 60.3 percent of the total area of the lakes in the headwaters region. However, river area is larger in the Yangtze River's source region than in the Yellow River's source region. Over the past 15 years, river and lake areas have been shrinking. The lake area shrank by 196.54 km^2, accounting for 7.5 percent of total lake area. Lake shrinkage mainly occurred in the Yangtze River source region, a total decrease of 114.81 km^2, accounting for 10.64 percent of the total lake area in the Yangtze River source region and for 58.4 percent of the total decreased area in the combined headwaters region. In the Yellow River's source region lake area decreased by 5.28 percent. Of the decreased lake area, the shrinkage of interior lakes occupied 66.38 percent, of which 91.62 percent occurred in the Yangtze River source region.



Swamp Meadow decreased sharply by 24.36 %, mainly occurring in the Yangtze River source region and being the largest degraded ecological type.

River and lake areas have been continuously shrinking

The shrinkage of exterior lakes in the Yellow River's source region occupied 71.15 percent of the total decrease in area; this is significantly higher than the interior lakes thus leading to the inflow of many exterior lakes. The river area decreased by 9.03 percent of the total area mainly in the Yellow River source region, leading to the formation of many wadis. This is also reflected in the changes of river runoff, as shown in the figure above. Since the early 1980s, the runoff measured at representative hydrological stations in the Yellow River source region has decreased. From 1995 onwards, a low discharge has been showing: a decrease of 19.3 percent compared to the discharge in the early 1980s. The Yellow River has run dry each year with the dry period becoming progressively longer. In 1996 it was dry for 133 days and in 1997, a year exacerbated by drought, it failed to reach the sea for 226 days and its 1998 annual dry period was 137 days.

As described above, the glaciers in the headwaters region have been retreating continuously since the 1980s, the recession rate of those in the Yellow River source region being larger than those of the Tianshan and Qilian Mountain regions. The glaciers in the Yangtze River source region, in comparison, are retreating at a relatively slow rate (Liu *et al.* 2002). Then again, the distribution changes of hard-to-use land types directly reflect on the eco-environmental regime and evolutional trend implying serious land degradation. All the hard-to-use land types in the headwaters region increased in various degrees over the past 15 years especially land desertification that expanded at an annual expansion rate of 1.22 percent, significantly higher than that in the Hexi corridor (Wang *et al.* 2000).

Saline-alkali soils mainly occurred in the Yangtze River source region occupying 91.14 percent of its total area in the headwaters region though its increase rate was much higher in the Yellow River source region. In total, saline-alkali land area increased by 10 km^2 in the headwaters region, an increase of 6.85 percent. The bare rock, bare soil and shoal land with a cover less than 5 percent is second only to the high-cold grassland and the high-cold meadow. Over the past 15 years, their area increased by 7.46 percent, and even in the Yangtze River source region this type increased by 9.2 percent. Thus, over the last 15 years, hard-to-use land types in the headwaters region have developed rapidly. On an average, the expansion rate of desertification, salinization and bare land has reached 0.5 percent or more. Serious desertification and salinization mainly occurred in the Yellow River source region, while bare land expansion mainly occurred in the Yangtze River source region.

It is true that there are still many problems in Tibet's ecological improvement and environmental protection efforts. As the whole global ecosystem is deteriorating, the fragile ecology in Tibet is particularly affected. Mud-rock flows, landslides, soil erosion, snowstorms and other natural calamities occur frequently in Tibet and desertification is threatening the region's eco-environment, compounded by man-made damage to the ecological environment as Tibet's economy develops.

In order to ensure the permanent stability of the ecological environment and natural resources and to guard against possible new threats to them, since 2001 the regional government of Tibet, supported by the government, has set up and put into practice a mammoth plan for ecological improvement and environmental protection. From now until the mid-21st century, more than 22 billion Yuan would be invested in over 160 eco-environmental protection projects aimed at steadily improving the ecosystem in Tibet.

Conclusion

As humans continue to alter the radiation balance of the earth through the burning of fossil fuels and other human activities, understanding past climate variability as a means to predicting future change becomes ever more important, and represents one of the great challenges for modern science. Glaciers around the world, including those in the Himalaya, provide a unique medium to study in-depth our complex climate system. It becomes clear from such a regional overview that deglaciation is a widespread problem with serious consequences for water resources around the world. As runoff variation is directly related to glacier condition, continued deglaciation is certain to have impact on runoff in the future.

Problems of water stress are already prevalent in the region, due to the increasing demands of domestic, agriculture, industry and the growing population. Rapid urbanization, population explosion and haphazard development are the main cause for the increasing pressure on our vulnerable fresh water resources. The demand for these limited resources is rapidly increasing for agricultural, industrial, domestic and environmental uses. Thus, any reduction in the availability of freshwater could have serious consequences in matter of food security, people's livelihoods, industrial growth and environmental sustainability the world over. It has been reported that the world used 3,906 km^3 of freshwater in 1995 and that, by 2025, this volume is projected to increase by at least 50 percent (Global Water Outlook to 2025, IWMI Food Policy Report, September 2002). Asia alone withdrew around 2,200 km^3 of freshwater in 1995, which is projected to increase to 2,900 km^3 by 2025.

For India alone, the prospect the entire agriculture of the northern region of being highly vulnerable to any change of stream flow has serious implications for the country's economy. In China the effects have included, among other impacts, degradation of a large area of high-cold swamp meadow, the water surface shrinkage of lakes and rivers, the retreat of glaciers and coverage reduction of high-cold grassland and high-cold meadow. Again, for both Nepal and India the entire system of the hydropower generation situated on these river systems would also be jeopardized—the potential water utilization and the benefits of establishing or continuing to operate a hydropower plant would be affected by changes in runoff. Then there are extreme events such as GLOFs that could spell danger for all three countries in terms of destruction of life, property and infrastructure.

From all three case studies one can gather the enormity of the predictions of retreating glaciers and associated impacts for the many millions of people whose very survival depends directly or indirectly on fresh water from these sources. While it is not yet clear which stage of deglaciation we are currently in, it is only wise to prepare for the worst. It is imperative to make vulnerability assessments of different development sectors and devise adaptation plans. Climate change impacts and responses are transboundary issues. Therefore, in addition to national discourses on linkage between climate change, mitigation and adaptation measures and development efforts, regional collaboration is necessary to formulate co-coordinated strategies.

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