Climate Change in the Hindu Kush-Himalayas

The State of Current Knowledge

ICIMOD

FOR MOUNTAINS AND PEOPLE

Climate Change in the Hindu Kush-Himalayas

The State of Current Knowledge

Surender P. Singh
Isabella Bassignana-Khadka
Bhaskar Singh Karky
Eklabya Sharma

International Centre for Integrated Mountain Development, Kathmandu, Nepal, 2011

Published by

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

ISBN 978 92 9115 220 9 (printed)
978 92 9115 221 6 (electronic)
LCCN 2011-312015

Printed and bound in Nepal by

Hill Side Press (P) Ltd., Kathmandu, Nepal

Production team

Greta Pennington Rana (Consultant editor)
A Beatrice Murray (Consultant editor)
Andrea Perlis (Senior editor)
Punam Pradhan (Layout and design)
Asha Kaji Thaku (Editorial assistant)

Citation: Singh, SP; Bassignana-Khadka, I; Karky, BS; Sharma, E (2011) *Climate change in the Hindu Kush-Himalayas: The state of current knowledge*. Kathmandu: ICIMOD

Contents

Foreword iv
Preface vi
Acknowledgements vii
Acronyms and Abbreviations viii
Executive Summary ix

1 Introduction 1
Global Significance of the World's Mountain Areas 2
The Hindu Kush-Himalayan Region 3
The Mountain Agenda 6

2 Analysis of Change 8
Climate and Hydrology 8
Biodiversity and Ecosystems 23
Atmospheric Changes 32

3 Impacts 38
Impacts Related to Water 39
Impacts on Frequency and Intensity of Natural Hazards and Disasters 40
Impacts on Biodiversity 41
Impacts on Agriculture and Food Security 42
Impacts on Demography and Movement of Populations 43
Impacts on Human Health 46
Using Models to Predict Impact 48
Farmers' Knowledge 49

4 Strategies to Address Climate Change 51
The Link Between Livelihoods and Ecosystem Services 51
Rewarding Providers for Ecosystem Services 52
Prospects for Sustainable Greening of the Himalayas 54
Improved Water Storage can Enhance Resilience to Climate Change 58
Mitigating the Effects of Black Carbon 59
Managing Biodiversity in a Warming World 60
Regional Cooperation 61
Country-Level Plans for Adaptation 62

5 The Way Forward 63
Identifying Knowledge Gaps, Scientific Uncertainties, and Challenges 64
Strategies to Fill Data Gaps and to Augment Systematic Observations 68
Identifying Capacity Building Needs in the Region 70
Linking Global and Regional Frameworks on Climate Change with Appropriate Regional-Level Policy Making and National Governance 71
Challenges and Opportunities 72

References 73

Foreword

It is widely understood that the Hindu Kush-Himalayan (HKH) region is one of the most ecologically sensitive and fragile areas in the world. This mountain system is also geographically, geologically, and culturally unique. It features immense mountains and extraordinary landscapes which are the source of livelihoods for hundreds of millions of people. Their importance has local, regional, and global dimensions.

Over 200 million people live in the mountains, valleys, and hills of the Hind Kush-Himalayan region, and over 1 billion people live in the basins downstream. All told, an estimated 3 billion people benefit from the water and other goods and services that originate in the mountains above.

The HKH region is undergoing dramatic change that is triggered largely by the economic growth of India and China and in part also by the 'brown economy' dominated by the countries of the Middle East. Globalisation and increased mobility have exacerbated the marginality of the mountain valleys while creating new opportunities, mostly outside the region. This change is complicated by growing climatic variability, which has now reached such a dimension that it can be talked about as climate change.

In all likelihood, the effects of climate change will become evident here first and with the greatest intensity. The situation is compounded by the fact that the mountains in the region store vast quantities of water in the form of snow and ice, which is all part of the regional monsoon circulation patterns. The central role of the monsoon as the lifeline of regional agriculture may be changing.

At present, not much is known about how mountain ecosystems will respond to these changes. We have clear indications that variations in temperature lead to accelerated melting of ice and snow and have an impact on biodiversity, water supplies, agriculture, and hazards; and that these effects will in turn have an impact on general human wellbeing. The fragility and inaccessibility of the mountain landscape, with scattered settlements and poor infrastructure, imply that mountain areas will suffer most. No other mountain system and no other coherent ecological system in the world has as significant a role in the livelihoods of as many people as the Hindu Kush-Himalayas.

In recent years, the countries of the region have made efforts to undertake climate vulnerability assessments. These assessments have been useful in pointing out shortcomings and in indicating what measures need to be taken locally. Most of the countries have now developed national-level adaptation plans and strategies and are implementing them. Climate change transcends national boundaries, however, and plans on a national scale run the risk of being ineffective because they do not take regional-scale effects into consideration.

This report synthesises the present knowledge about the consequences that climate change can have for the Hindu Kush-Himalayan mountain system. It indicates gaps in knowledge and shows a way forward for the future. What is the relevance of this information? We think that it is necessary for people to be knowledgeable in order to adapt and be resilient to change. At present, many adaptation measures are being devised without proper analysis and without a complete understanding of the source of the problems. Development packages often echo the agenda for sustainable rural development conceived in the 1970s. For the moment, this is justified; however, going forward it will be important to decide whether a change course may be beneficial; and for this scientific evidence is essential.

This report captures the cutting-edge knowledge from the region with a specific focus on the mountain situation. It is intended to provide inputs to support the discussions that will take place at the United Nations Conference on Sustainable Development (Rio+20) in June 2012 as well as in the context of other multilateral environmental agreements. What is happening in the Himalayas is an excellent indicator of climate change globally. The information that forms the basis of this report should therefore not only be of interest to planners and policy makers in the region, but should also provide vital inputs into global climate change negotiations.

I would like to thank everyone involved in producing this synthesis report, including regional and international scientists who shared their expertise in an Authors' Workshop held at ICIMOD (18–19 August 2011) and the authors who compiled the material from the workshop and the existing literature. I would also like to acknowledge the role played by the publications team in putting together the final report.

Andreas Schild
Director General
ICIMOD

Preface

This synthesis report summarises the most up-to-date knowledge from scientific enquiries into the impacts of climate change in the Hindu Kush-Himalayan (HKH) region. When the Intergovernmental Panel on Climate Change (IPCC) released its fourth assessment report (AR4) in 2007, data for the whole HKH region were for the most part absent, and to date the situation for the entire region remains largely underreported. This year ICIMOD has undertaken the task of contacting scientists working in the HKH region to bring to light the progress that has been made in the intervening four years.

Are the data available today sufficient to evaluate climate change in the region? What do the available data tell us? On 18 and 19 August 2011, leading experts in the different fields of climate science (including climatology, hydrology, and environmental science) from across the region and abroad gathered at an Authors' Workshop in Kathmandu to help answer these questions. The intention in gathering these researchers together was to replace the data deficit 'white spot' of 2007 with state-of-the-art information on the region and to indicate what gaps in knowledge still need to be bridged. Since the AR4 was first published, a considerable amount of research has been initiated, and it is likely that the next report, the AR5, which is due out in 2013, will give a more comprehensive picture of the region.

The aim of the present report is to assist the countries of the HKH to bridge the knowledge gap by disseminating the most up-to-date science-based information available. The countries can use this information to participate more knowledgeably in the meetings of the United Nations Framework Convention on Climate Change (UNFCCC) and the IPCC. The content of this report should also provide important inputs to support the discussions that will be held in conjunction with the United Nations Conference on Sustainable Development (Rio+20) in June 2012 and in the contexts of other multilateral environmental agreements.

The authors assembled this synthesis report from presentations and discussions that took place at the Authors' Workshop. The authors, reviewers, and participating experts from the region and beyond all endeavoured to ensure that the report provides thorough, rigorous and relevant information on the region. It is our sincere intent that the summaries of experts' views and the insights in this synthesis report prove to be useful for policy makers and planners. This report is structured in five chapters. Chapter 1 gives background on the global significance of mountains with a focus on the mountain agenda. Chapter 2 summarises the latest scientific knowledge on climate change in the region. The third chapter describes the impacts of climate change across different sectors, presenting projections based on models as well as impacts witnessed by farmers. Chapter 4 then highlights some of the strategies for addressing the adverse impacts of climate change, while the final chapter draws conclusions for the way forward, identifying knowledge gaps, scientific uncertainties, and challenges, with a focus on the regional dimensions of addressing climate change.

It was not possible to do justice to all of the research that is being carried out throughout the region. The HKH region is vast, and in all likelihood excellent research is being carried out by individuals and groups whose results are not yet widely communicated. We admit our bias in preferring to highlight the work of scientists who are either from the region or work mainly in the region. Our intention was to draw attention to the work being done by regional institutes and researchers. This is yet another way in which ICIMOD can help to create and facilitate a regional platform.

Acknowledgements

It is difficult to acknowledge everyone who contributed in some way to the preparation of this report. ICIMOD wishes particularly to thank the contributors to the Authors' Workshop listed below. We also thank Mozaharul Alam, United Nations Environment Programme (UNEP), Bangkok, and Othmar Schwank, Schwank Earthpartner Ltd., Zurich, for reviewing the publication.

The following ICIMOD staff members have contributed to the Authors' Workshop or the preparation or review of the document: Farid Ahmad, Dyutiman Chaudhary, Nakul Chettri, Dhrupad Choudhury, Anil Kumar Jha, Narpat S Jodha, Laxman Joshi, Madhav Bahadur Karki, Seema Karki, Michael Kollmair, Rajan Kotru, Mirjam Macchi, Utsav Maden, David Molden, Pradeep Mool, Beatrice A Murray, Hari Krishna Nibanupudi, Andrea Perlis, Jagdish Poudel, Bidya Banmali Pradhan, Neera Shrestha Pradhan, Golam Rasul, Gopal Rawat, Andreas Schild, Arun Bhakta Shrestha, Basanta Shrestha, Mandira Shrestha, Ramesh Ananda Vaidya, and Shahriar M Wahid.

External Contributors to the Authors' Workshop, 18–19 August 2011

Marina Ahmad, Zuhair Munawar, and Shakeel A Rmay, Sustainable Development Policy Institute (SDPI), Pakistan

Richard Allen, Helvetas, Nepal

K Ashok, R Krishnan, Ashwini Kulkarni, and Savita Patwardhan, Indian Institute of Tropical Meteorology (IITM), India

Isabella Bassignana Khadka, Kathmandu, Nepal

Paolo Bonasoni, Paolo Cristofanelli, and Angela Marinoni, ISAC-CNR, Italy

Ngamindra Dahal, Asian Development Bank (ADB)/ Ministry of Environment, Nepal

Shobhakar Dhakal, National Institute of Environmental Studies, Japan

Ashok Priyadarshan Dimri, Jawaharlal Nehru University, India

Arif M Goheer, Moshin M Iqbal, and Arshad M Khan, Global Change Impact Studies Centre (GCISC), Quaid-i-Azam University, Pakistan

AK Gosain, Indian Institute of Technology (IIT Delhi), India

Nilabja Gosh, Institute of Economic Growth, India

Walter Immerzeel, Future Water, Utrecht University, Utrecht, The Netherlands

Xu Jian and Xiaoliu Yang, Peking University, China

Nanki Kaur, International Institute for Environment and Development (IIED), UK

Anil V Kulkarni, Centre for Atmospheric and Oceanic Science, Indian Institute of Science, India

Dheeraj Kumar, Nayan Sharma, and Pratibha Warwade, Indian Institute of Technology (IIT Roorkee), India

Pushpam Kumar, United Nations Environment Programme (UNEP), Kenya

James D Miller, Centre for Ecology and Hydrology, UK

Dev Niyogi, Purdue University, USA

Roger A Pielke, University of Colorado at Boulder, USA

Atiq Rahman, Bangladesh Centre for Advanced Studies (BCAS), Bangladesh

S Rao, INRM Consultants Pvt. Ltd., India

Pradeep K Rawat, Kumaon University, India

Gwyn Rees, Centre for Ecology and Hydrology, UK

Maheshwar Rupakheti, UNEP Regional Resource Center for Asia and the Pacific, Asian Institute of Technology (AIT), Thailand

Mohammad Ashraful Amin Shah, Bangladesh Centre for Advanced Studies (BCAS), Bangladesh

Rita Sharma, The Mountain Institute–Asia Regional Office, Nepal

Sudhirendar Sharma, The Ecological Foundation, India

Suresh Sharma, Institute of Economic Growth, India

Ram Manohar Shrestha, Asian Institute of Technology (AIT), Thailand

SP Singh, State Planning Commission, Government of Uttarkhand, India

E Vuillermoz, Ev-K2-CNR, Italy

Acronyms and Abbreviations

AR4	fourth assessment report of the Intergovernmental Panel on Climate Change
BC	black carbon
CBD	Convention on Biological Diversity
GHG	greenhouse gas
GMC	global climate model
HKH	Hindu Kush-Himalayas
IPCC	Intergovernmental Panel on Climate Change
masl	metres above sea level
PES	payment for ecosystem services
RCM	regional climate model
REDD	reducing emissions from deforestation and forest degradation
SCA	snow cover area

Executive Summary

The premise of climate 'change' assumes that the environmental situation today already is, and in the future will be, different from what it has been previously. An analysis of scientific measurements is needed to support this claim. Although in some parts of the world environmental information abounds, in other parts it is sorely lacking. The vast Hindu Kush-Himalayan region has, in the past, had few resources with which to develop the detailed scientific understanding needed to assess climatological, environmental, and other data; and this means that today there is very little historical information upon which to form a baseline for comparison with the present and from which to anticipate future impacts. Over the past decade, many changes have taken place and capacities in the region have improved. Data are now more easily sorted and shared, and in general more data are available than ever before. This report analyses what the available data tell us about climate change in the region, and identifies persisting insufficiencies in the data.

Scant evidence on climate trend, glacial melting and hydrology

The first step in analysing climate change is to assess historical time series' data on temperature and precipitation. Hydrometeorological data for the HKH region are scarce and the region overall has far too few weather stations because of the difficulties presented by extreme variations in altitude and aspect. The data that are available indicate that there is a moderate warming trend and that temperature increases are more pronounced at higher than at lower elevations. The data on precipitation are even scarcer and do not show any statistically significant trend. In view of the paucity of observational data, global climate models are downscaled to the region to help predict trends. Models for the region generally predict increasing temperatures and greater amounts of precipitation than at present to the middle of the century.

The study of glaciers can yield insights into temperatures and precipitation in high-altitude areas. Recent reconnaissance by remote sensing shows that the HKH region has more than 50,000 glaciers. The ruggedness and inaccessibility of the region renders the study of glaciers difficult and repeat measurements are rare; to date less than a few dozen glaciers have been observed and documented at close range. Published findings on glaciers show no consistent and corroborated pattern of increased rates of melting. In general, glaciers in the central and eastern Himalayas are shrinking, while changes in the western Himalayas and Karakoram are more uncertain. Glacial melting impacts river discharge and the availability of water in areas downstream. To date contributions to river flows have been poorly studied; there are few data on river hydrology that indicate either an increasing or decreasing trend in river flows; and models that predict river flows are also inconclusive.

Effects on biodiversity still uncertain

The HKH region is home to some of the richest and most varied ecosystems on the planet. Changes in climate and the consequent changes in the availability of water can be expected to be reflected in the biodiversity of these ecosystems. To date, however, it is still unclear how the biodiversity has been affected by climate change since the necessary baseline data are not available; the identification and recording of species is still in its early stages; and the constant monitoring needed to examine population dynamics as a function of changing climate impacts is sorely lacking.

Atmospheric pollutants (black carbon) an unequivocal actor

In the HKH region climate change is exacerbated by atmospheric pollution that originates in the plains and is transported to the high Himalayas as a 'black cloud'. These tiny particles of black carbon warm the ambient air, and when they are deposited on ice and snow they accelerate melting by lowering the albedo. The presence of these pollutants even at high altitudes is unequivocal; it has been confirmed by several groups of researchers using a variety of techniques. The extent to which these atmospheric pollutants are capable of altering circulation and precipitation patterns, however, and the extent to which they accelerate the melting of ice and snow remain unknown.

Livelihood impacts inferred

The degree of impact on the lives and livelihoods of the people in the HKH region from changes taking place in the supporting, provisioning, regulating, and cultural services of the region's ecosystems is at present deduced from the predicted changes in climate. Although it is certain that climate change will affect the availability of water and the richness of biodiversity – and food security, which depends on both of these – the manner in which these changes will occur can so far only be inferred. Since trends are still unclear, the extent to which changes can be attributed to climate variations alone (amid a matrix of other drivers of change) is difficult to determine.

Human health impacts both positive and negative

The rising temperatures and erratic weather patterns that are the hallmark of climate change will interfere with water supplies, facilitate the spread of infectious diseases, and increase the frequency of natural hazards and disasters. Predictions based on models show that the impacts on both human life and ecosystems can be both positive and negative. Similarly, anecdotal evidence collected from farmers can be contradictory. Although farmers in some areas are reporting warmer wintertime temperatures and erratic weather patterns, the limited number of interviews conducted with farmers throughout the region cannot be used as conclusive evidence of change.

Strategies in the face of uncertainty

The ecosystems of the HKH are extremely vulnerable to both growing anthropogenic changes and the consequences of climate change. The need for suitable strategies for climate resilient development has policy and governance implications. Policy options warranting discussion include payment for ecosystem services; mitigation measures such as reducing emissions from deforestation and forest degradation (which have an adaptation co-benefit); water storage measures; and regional cooperation policies for water resources.

The gaps and scientific uncertainties that surround climate change in the HKH region need to be prioritised and addressed strategically. Ecosystem resilience, green sector mitigation, and adaptation to climate change are areas that should be strengthened through policy advocacy supported by evidence from rigorous research and verified information. This report concludes by discussing how existing knowledge and data gaps need to be filled by systematic observations and enhanced capacities for research in the region. Research needs to be enhanced in the areas of biophysical observation and modelling as well as socioeconomic analysis and policy research, since these will be fundamental for developing climate change adaptation and mitigation programmes.

The last section concludes by discussing climate change frameworks for linking efforts both regionally and globally. It considers relevant policies for the region and for national governance, as well as the challenges and the opportunities that can arise from climate change.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) gave two pieces of information in its fourth assessment report (AR4) that immediately drew global attention to the Hindu Kush-Himalayan (HKH) region (IPCC 2007). First, the report showed clearly the lack of data to support assessments for the HKH region and, second, it claimed that all glaciers in the Himalayas could disappear by 2035 (Cruz et al. 2007) severely affecting water supplies in the region. Later, this unfortunate claim was traced back to an inaccurate citation of the grey literature (Schiermeier 2010) and the IPCC retracted its statement, but reiterated that the broader conclusions of the report remained unaffected. The controversy that ensued over the statement highlighted how little is known about the HKH region in general.

Whereas not much is known in detail about the Hindu Kush-Himalayan region, it is nonetheless widely believed to be one of the planet's hot spots of climate change (see the ranking of the HKH countries in Maplecroft [2011]). Rising temperatures will have a greater impact here than elsewhere since they can disturb the fine equilibrium that governs how the vast reserves of snow, ice, and water in the high mountains provide water to rivers downstream. Moreover, climate change can affect the role that the region plays as part of the monsoon circulation pattern in which any changes in temperature are likely to affect the cycle and have global implications. Equally important are changes that can alter how the ecosystems and biodiversity of the HKH provide essential services for the populations of the plains.

This synthesis summarises what is known about the HKH region as a starting point for highlighting the gaps in knowledge and information and indicating what needs to be investigated. Box 1 gives a quick idea of the problem of data gaps, using glaciers as an example. Scientists and experts from around the world can help by assisting the region to generate relevant data that can be converted into information, which can be used by decision makers and planners in the region to respond to the risks of climate change by devising options for mitigation and adaptation.

Box 1: **Where are the data gaps?**

Much of this document is concerned with identifying data gaps. A typical example illustrates the problem. Data related to glaciers are very important for assessing the existence and potential impacts of climate change. The only way to assess ice reserves with any confidence, however, is to carry out mass balance measurements in the field, at least for a range of representative glaciers. Long-term measurements made in the same place are needed in order to investigate whether climate change is having an impact. The HKH region has the largest glaciated areas in the world outside the polar regions, but mass balancing has only been carried out for 10 or so of the region's more than 50,000 glaciers, and there are no long-term data sets apart from a very few observations of terminus positions, mostly for the more accessible glaciers. Furthermore, meteorological stations with complete datasets of temperature and rainfall data, for at least the five decades from 1960–2010, are rare in the region and, even where they do exist, the data are not necessarily available in the public domain. This results in significant knowledge gaps for modelling, considering the variability of climatic conditions in mountain areas. Recently, satellite data have become more readily available. Remotely sensed data are ideal for investigating snow and ice cover, and even glacier mass balance and changes in ice depth, over the vast and largely inaccessible HKH region; however, the use of remotely sensed data raises a whole different set of gap issues around data protocols and interpretation, as well as the need for field verification.

Global Significance of the World's Mountain Areas

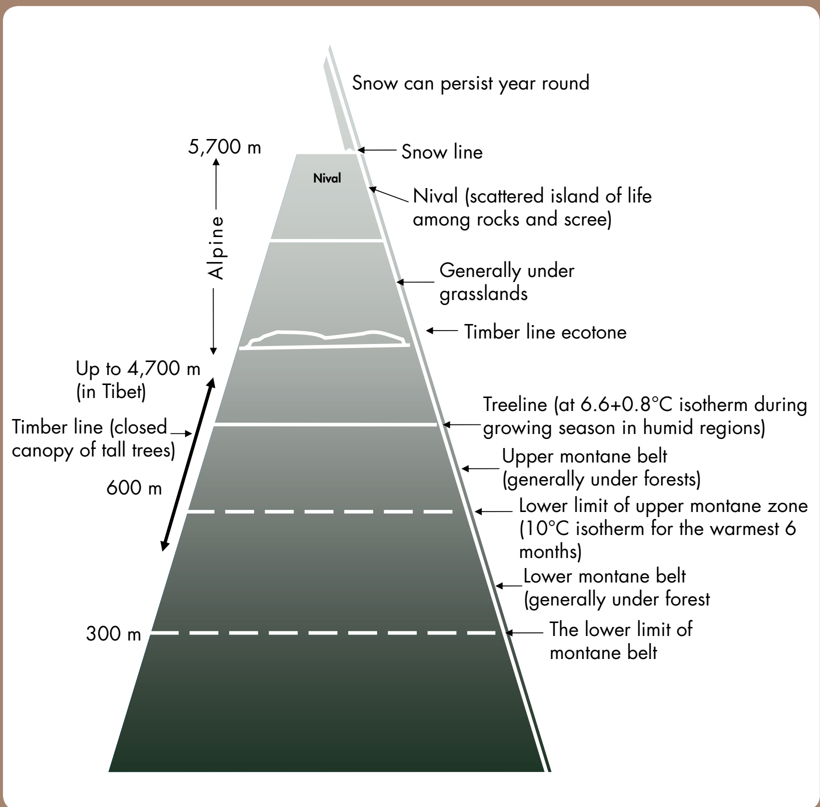
Mountains occupy 24% of the global land surface area (about 25 million km²) and are home to 12% of the world's population (GTOS 2008). They have ecological, aesthetic, and socioeconomic significance, not only for the people who derive their day-to-day subsistence from mountain resources but also for the estimated 40% of the global population depending indirectly on these resources for water, hydroelectricity, timber, biodiversity, and niche products (Schild 2008; Schild and Sharma 2011). More than half of the 34 global biodiversity hotspots are in mountain areas, and mountains harbour one-third of global terrestrial biodiversity (ICIMOD 2009a).

Mountains store water in the form of snow, glaciers, permafrost, wetlands, and rivers, and they supply watersheds by providing ground water recharge (Hua 2009). The communities who live in mountain areas benefit from these services, but the main beneficiaries of this huge water storage capacity are the multitudes who live in the vast basin areas downstream. Mountains also represent a unique opportunity to detect climatic change and to assess climate-related impacts (Nogués-Bravo et al. 2007, 2008).

Despite harbouring some of nature's richest natural resources, mountains are home to some of the world's poorest people, many of whom are marginalised subsistence farmers belonging to a diversity of ethnic groups and minorities. These mountain communities have benefited neither from the 'green revolution' nor from the fruits of recent global economic growth. They have remained on the fringes of modern advancements in spite of being the guardians of some of the world's most valuable water and biodiversity resources.

Mountains host diverse vegetation and varied microclimatic and ecological conditions, due in part to the extreme heterogeneity and rapid changes in soils and climates, to the rapid elevation changes that give rise to a variety of altitudinal vegetation belts (Figure 1), and to the variable directional orientation with rapid changes in aspect (Hamilton 2002; Körner 2004; Spehn et al. 2002; Viviroli and Weingartner 2004). As a result of the extreme variations in the environment, mountains have abundant high biodiversity, often with sharp transitions (ecotones) in vegetation sequences (Figure 2). Mountain ecosystems are often rich in endemics, i.e., species that are unique to the region (as much as 30–40% of species in different mountain ranges) since there is a high rate of speciation in isolated areas near mountain tops. The endemism increases with altitude, well above the height at which species' richness peaks. Thus, the majority of mountains can be seen as the last bastions of wild nature 'islands' in a sea of transformed lowlands and, as such, provide a number of very important ecological functions (Hamilton 2002). Mountains contain the headwaters of rivers which are vital for maintaining human life in the densely populated areas downstream, and natural and semi-natural vegetation cover on mountains help to stabilise these headwaters, prevent flooding, and help to maintain steady year-round flows by facilitating the seepage of rainwater into underwater aquifers.

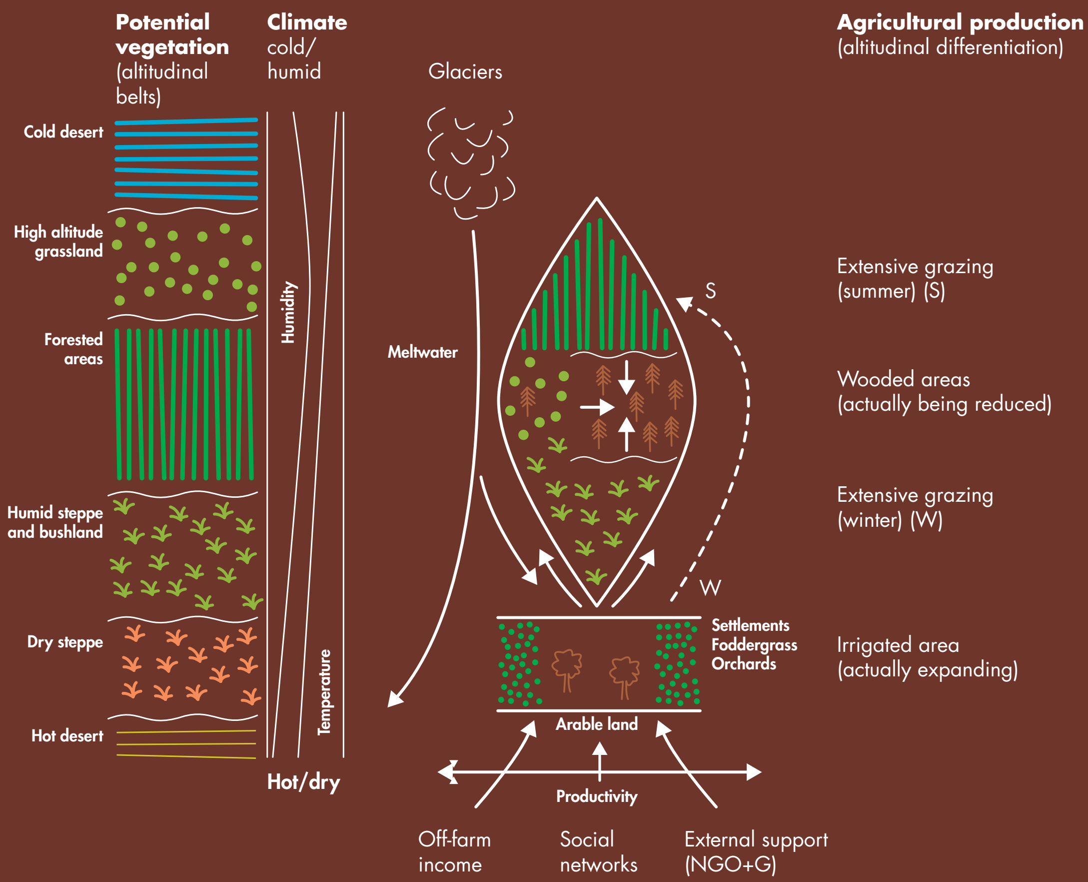
Figure 1: **A representation of mountain stratification with respect to altitude, temperature, and vegetation for mountains located in humid climates**



Note that the 'treeline' is the line connecting the uppermost patches of trees of at least three metres height and that the timber line 'ecotone' is the area between the timber line (the limit of closed, tall forest) and the tree species line (the line connecting the uppermost crippled trees)

Source: Adapted from Kõrner and Paulsen (2010) and Kõrner (2007)

Figure 2: **Vertical arrangement of natural vegetation and agricultural productivity**



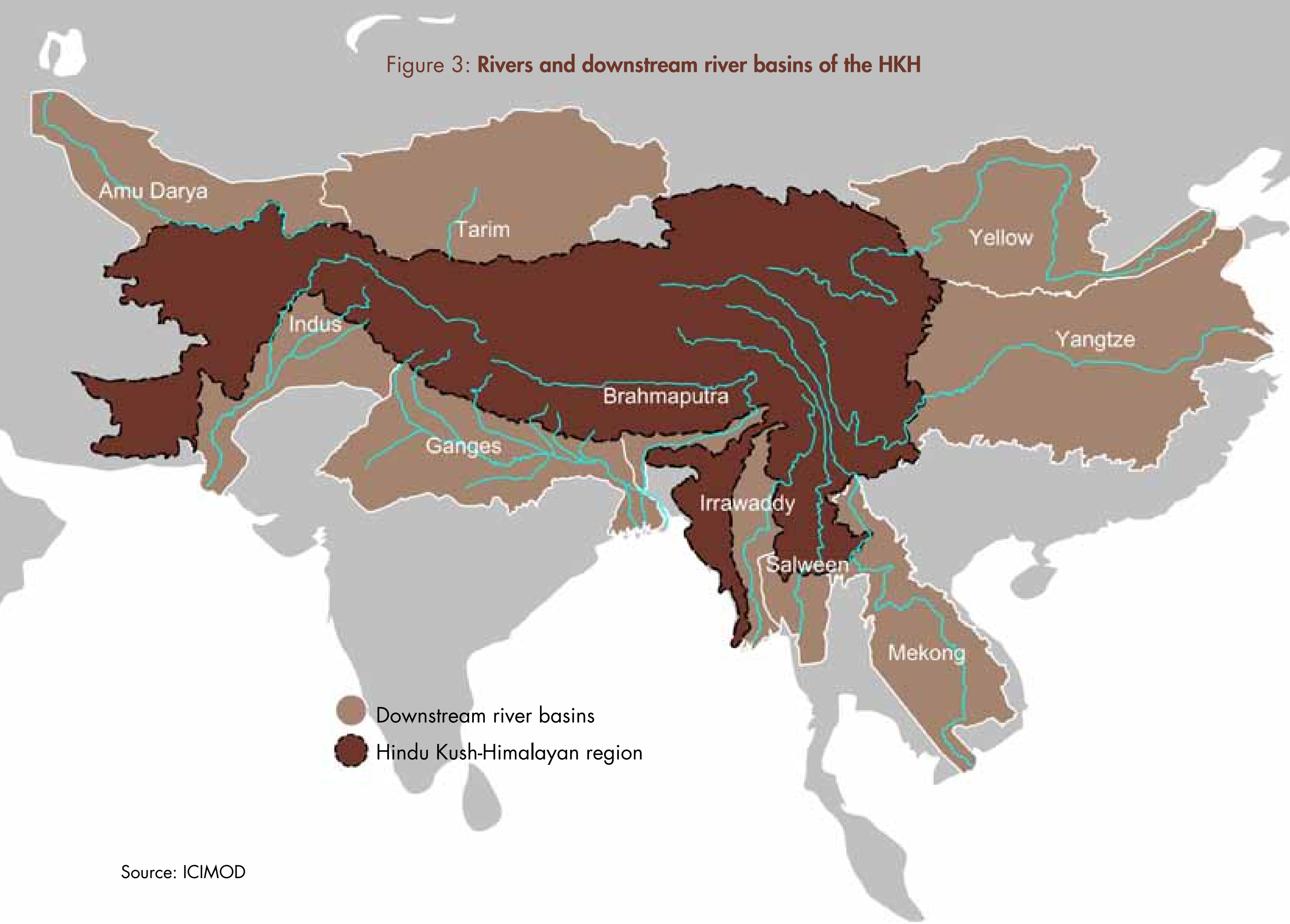
Source: ICIMOD (2009a)

The Hindu Kush-Himalayan Region

The Hindu Kush-Himalayan (HKH) region spans over 4 million km^2 (Gurung et al. in preparation), which is about 2.9% of the global land area and approximately 18% of the global mountain area. These massive mountain ranges contain the world's tallest peaks (Mount Everest, K2, Kangchenjunga, Lhotse, Makalu, Cho Oyu, Dhaulagiri, and Annapurna, to name a few) and the headwaters of ten major river systems: the Amu Darya, Brahmaputra, Ganges, Indus, Irrawaddy, Mekong, Salween, Tarim, Yangtze, and Yellow (Figure 3). The mountain regions of the HKH directly provide livelihoods to the 210 million people living there and indirectly provide goods and services to the 1.3 billion people living downstream. Overall, some 3 billion people benefit from food and energy produced in the river basins (Schild 2008).

The HKH region includes all of Nepal and Bhutan and the mountainous parts of Afghanistan, Bangladesh, China, India, Myanmar, and Pakistan. The HKH region is divisible into two sub-regions: one which is extremely rugged with altitudes changing rapidly and in which almost all the forest types known on earth occur; and the other, primarily a high plateau with less ruggedness and vast grasslands. The dominance of the second landform in the region is reflected in the overall distribution of land cover (Table 1): grasslands occupy nearly twice as much area as forests. The HKH region is endowed with a rich variety of gene pools and species which form ecosystems of global importance; it hosts all or part of four Global Biodiversity Hotspots – the Himalayas, Indo-Burma, Mountains of South-West China, and Mountains of Central Asia (Mittermeier et al. 2004) – and several endangered species and it is an important component of the global ecosystem (Chettri et al. 2008a). Approximately 39% of the area of the HKH region is managed as protected areas. Overall, the most recent estimates show that throughout the HKH region the land cover is as follows: 14% forest, 26% agriculture (including areas with a mixture of natural vegetation), 54%

Figure 3: **Rivers and downstream river basins of the HKH**



Source: ICIMOD

Table 1: **Land cover distribution in the HKH countries**

Country	Total area (km²)	Total area within the HKH region (km²)	(%)*	HKH population in 2007 (millions)	Protected area within the HKH (km²)	Agricultural area** within HKH (km²)	Forested area within HKH (km²)	Grassland, shrubland and other (km²)
Afghanistan	641,903	391,560	61	28.48	2,461	94,577	2,179	235,935
Bangladesh	137,878	15,543	11	1.33	632	2,723	4,920	7,912
Bhutan	39,837	39,837	100	0.71	12,681	2,897	28,739	3,994
China	9,369,194	239,5105	26	29.48	1,522,172	688,294	228,699	1,388,496
India	3,152,148	404,701	13	72.36	62,417	99,886	140,097	137,806
Myanmar	667,062	323,646	49	11.01	23,967	63,747	143,588	112,488
Nepal	147,163	147,163	100	27.80	24,972	68,777	41,942	26,929
Pakistan	876,534	479,039	55	39.36	18,721	84,644	5,541	354,044
Total area	15,031,719	~4,190,000		210.53	1,668,023	1,105,546	595,705	2,267,600
% of HKH					39%	26%	14%	54%

*% of total country area located in the HKH

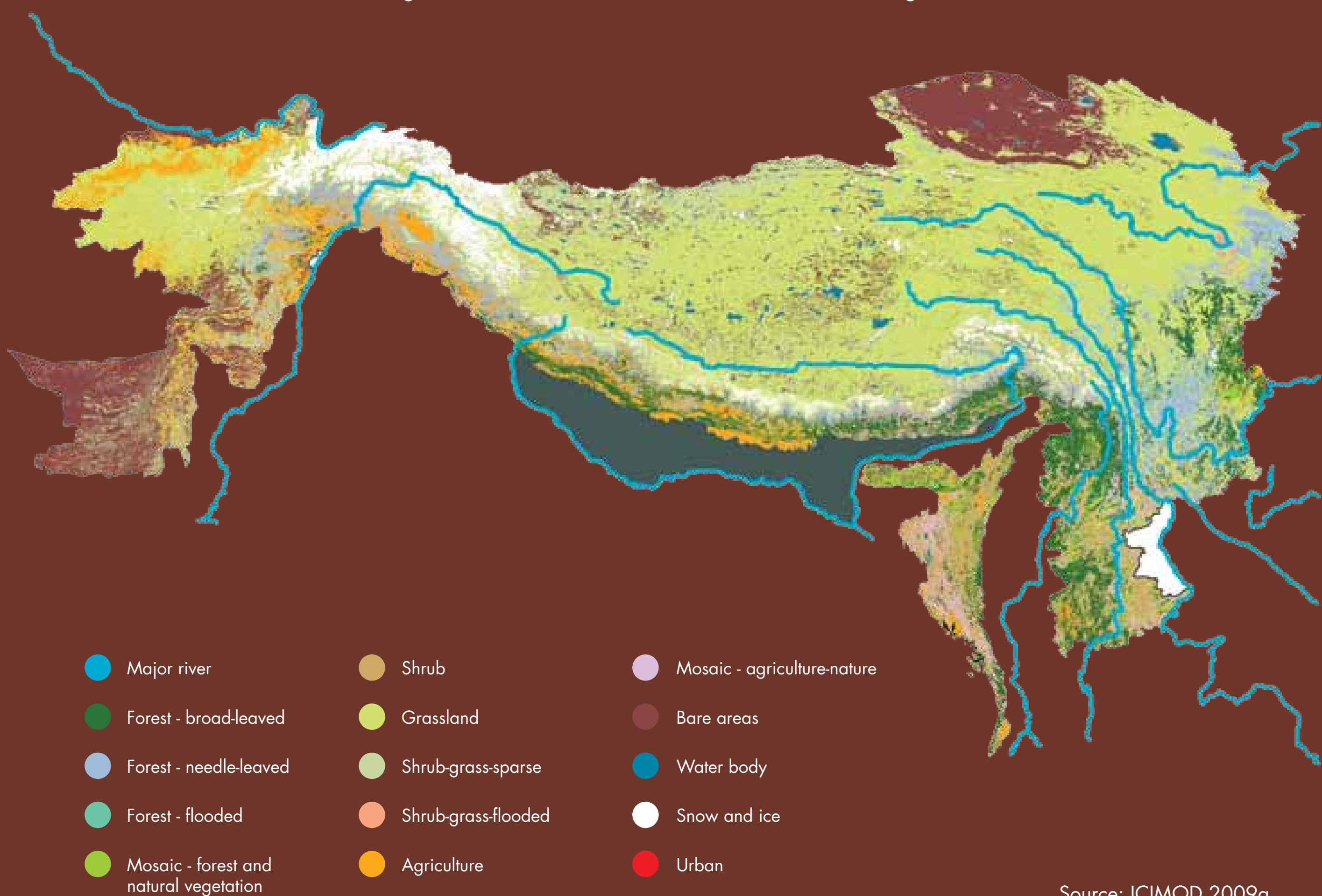
**Agricultural area includes irrigated cropland, rainfed cropland, mosaic cropland/vegetation, and mosaic vegetation/cropland

Sources: Globcover 2009 Version 2.3 from European Space Agency; Bajracharya and Shrestha (2011); Chettri et al. (2008a) rangeland and scrubland, 1% water bodies, and 5% permanent snow cover (Table 1 and Figure 4). Elevation zones across the HKH region extend from tropical areas (<500 masl) to alpine ice-snow (>6,000 masl), with a principal vertical vegetation regime comprised of tropical and subtropical rainforest, temperate broadleaf deciduous or mixed forest, and temperate coniferous forest, including high-altitude cold shrub or steppe and cold desert (Pei 1995; Guangwei 2002).

The ethnic diversity and cultural wealth of the HKH region is enriched by the Hindu Kush valleys in Afghanistan; the high mountains of India, Nepal, and Pakistan; the unspoilt beauty and heavily forested areas of Bhutan; the Tibetan Plateau of the Tibetan Autonomous Region of China; the Three Gorges in the far east of China, and the few diverse hill/mountain systems in eastern Bangladesh and Myanmar. The HKH region is home to many varied ethnic communities who speak about 600 different languages and dialects, and who have enormous socioeconomic and cultural diversity (Turin 2005). Downstream, the Gangetic Plain, the Indus Delta, and the Bangladesh floodplains are historically unique systems of global importance which have produced food and have been the backbone of cultural and economic development in the region for centuries. Recently, changes in the river systems and their basins have affected the wellbeing of hundreds of million people directly (Schild 2008).

Climate change, land use change, and population dynamics are the main drivers of environmental change in the HKH region. These drivers have changed the livelihoods of the mountain people of the HKH region and increased their economic and environmental vulnerability dramatically. The process of change and its associated constraints and opportunities have been summarised in Jodha (2011). The sources of these drivers are both internal and external to the region, and they mutually reinforce the effects that they have on human wellbeing and on natural resource availability and use. Although mountain people are particularly vulnerable to such changes, it is less apparent, but nonetheless true, that these changes impact entire river basins and that their impact is felt globally also (ICIMOD 2008a). Climate change has emerged as the most widely discussed driver of global change; however, it is embedded in a matrix

Figure 4: **Land use and land cover in the HKH region**



Source: ICIMOD 2009a

of drivers such as globalisation, population growth, and local land use change, all of which can have significant ramifications too. For instance, the fact that the HKH countries account for about 15% of the world's total migration will possibly impact land use, livelihoods, and even health outcomes. Overall, there are significant challenges in disaggregating the impacts of climate change and in unravelling the complexity of dealing with them.

Increasing demands on ecosystem goods and services from the mountains are putting pressure on the natural resources that they contain. These demands stemming from a burgeoning human population and haphazard infrastructural development, combined with unsustainable use, poor management, and limited investment in conservation, have led to habitat degradation, biodiversity loss, and decreased agricultural productivity (Chettri et al. 2008b; Xu et al. 2008b; GOI 2009; Sharma et al. 2009; Tse-ring et al. 2010). The extensive modification of vital ecosystems may affect their natural processes and reduce their capacity to provide services in future; however, with the exception of a few empirical studies (such as Maharana et al. 2000a, 2000b; Baral et al. 2007, 2008; Badola et al. 2010; Chen and Jim 2010) there have been no serious efforts to assess the value of the ecosystem services of the HKH region and there is an increasing urgency to develop sound methodologies for valuing them in order to ensure that their benefits are be realised (Rasul et al. 2011).

The Mountain Agenda

With the inclusion of Chapter 13, 'Managing Fragile Ecosystems: Sustainable Mountain Development', in Agenda 21 at the United Nations Conference on Environment and Development (UNCED), or 'Earth Summit', in 1992, the importance of mountain social-ecological systems was acknowledged for the first time on a global scale. Chapter 13 of Agenda 21 focuses on two programme areas: generating and strengthening knowledge about the ecology and sustainable development of mountain ecosystems; and promoting integrated watershed development and livelihood opportunities. A summarised version (UN 1992) of Chapter 13 reads:

> Mountains are important sources of water, energy, minerals, forest and agricultural products and areas of recreation. They are storehouses of biological diversity, home to endangered species and an essential part of the global ecosystem. From the Andes to the Himalayas, and from Southeast Asia to East and Central Africa, there is serious ecological deterioration. Most mountain areas are experiencing environmental degradation.

The Food and Agriculture Organization of the United Nations (FAO) was given the task of facilitating and reporting on the implementation of these two programme areas. Over the years, it became apparent that although Chapter 13 had been a good starting point, it could not address adequately on a continuing basis many of the key issues related to sustainable mountain development, such as water resources, biological diversity, cultural diversity and heritage, infrastructural development for mountain people (access to health services, markets, and so on), appropriate recognition and valuation of services and benefits derived from the mountains, the importance of mountains for people's livelihoods, and the recreational and spiritual significance of mountains (Sonesson and Messerli 2002).

Similarly, during 2002, the International Year of Mountains and the World Summit on Sustainable Development (WSSD) also discussed mountain ecosystems and advocated that mountains should be considered as special places in the global sustainable development agenda. Paragraph 42 of the Plan of Implementation of the WSSD focuses on mountains, stating:

> Mountain ecosystems support particular livelihoods, and include significant watershed resources, biological diversity and unique flora and fauna. Many are particularly fragile and vulnerable to the adverse effects of climate change and need specific protection.

The International Year of Mountains raised awareness about the importance of mountains on a global scale. With that year, the mountain agenda gained fresh momentum and many new initiatives materialised, including the Adelboden Group out of which the SARD-M (Sustainable Agriculture and Rural Development in Mountains) project emerged. Also in 2002, the Mountain Partnership was launched at the World Summit on Sustainable Development in Johannesburg to promote and facilitate closer collaboration between governments, civil society, intergovernmental organisations, and the private sector towards achieving sustainable mountain development. As a result, the Conference of the Parties (COP) to the Convention on Biological Diversity (CBD) adopted the 'Mountain Biodiversity Programme of Work' as Decision VII/27 at its 7th Meeting held in Kuala Lumpur in February 2004 (Sharma and Acharya 2004). Since the advent of this Programme of Work, significant progress has been made in networking, mobilising, and influencing programmes related to mountain biodiversity.

Global reports such as the Millennium Ecosystem Assessment (MA 2005) and the Intergovernmental Panel on Climate Change assessment reports, especially AR4 (IPCC 2007), have had implications for the HKH region. In 2008, ICIMOD organised the International Mountain Biodiversity Conference out of which the concepts of trans-Himalayan transects and transboundary landscape approaches evolved (ICIMOD 2009a, 2009b). Transboundary landscape management has been introduced in a number of landscapes to conserve enhanced ecosystem services – the prominent examples of this being the Kangchenjunga Landscape (Chettri et al. 2007 and Sharma et al. 2007) and the Kailash Sacred Landscape project (Zomer and Oli 2011).

In October 2011, participants from around the world gathered at the Lucerne World Mountain Conference and issued a Call for Action to include the issues of mountains at the upcoming Rio+20 conference since the impacts of global changes on the mountains are becoming increasingly apparent. The conference concluded that:

> Mountains are vital for sustainable development and human wellbeing. More than half of the earth's population depends on fresh water coming from mountains. Mountains also provide a number of important global goods and key services which are under increasing pressure from globalization and climate change.
> (MPS 2011)

The HKH countries have begun to take action on climate change by developing a regional understanding and frameworks for national action plans. India and China have prepared national action plans for climate change. India has taken a step further; among other things its National Mission for Sustaining the Himalayan Ecosystem puts forth objectives to evolve management measures for sustaining and safeguarding Himalayan glaciers, ecosystems, and water sources. Bhutan, Bangladesh, and Nepal have also prepared national adaptation programmes of action (NAPA), and other least developed HKH countries are in the process of doing so. Research capacities for monitoring the cryosphere and for glaciological studies are being supported more vigorously than before, especially in India and in Pakistan: China already has extensive expertise in this type of monitoring.

2 Analysis of Change

Analysis of possible changes related to climate change can be divided broadly into three areas: meteorology and ice and snow; biodiversity and ecosystems; and atmospheric changes. The approaches used to evaluate these, and the present status of knowledge, is summarised in the following passages.

Climate and Hydrology

Estimating meteorological change

The IPCC (2007) has estimated that during the last century the global mean surface air temperature increased on average by 0.74 °C but that increases varied from place to place. The extent to which global precipitation changed over the same time period is more variable and uncertain. In the HKH region, only scant temperature and precipitation data are available from observational measurements; the data which are available are summarised below. The challenge of collecting observational data over this vast mountainous terrain is outlined in Box 2.

Box 2: **The challenge of collecting meteorological data in the HKH**

The marked microclimatic variations with elevation and aspect in the HKH mean that a greater density of data sampling sites is needed to capture representative hydrometeorological data than in areas where the terrain is more uniform. In practice, however, the combination of poor accessibility and low population numbers means that the density of meteorological stations in the HKH is less than elsewhere, and that long-term data records are few even from the stations that do exist. Figure 5 shows the distribution of meteorological stations in the HKH in 2009 (a few stations have been added since but the total number has not changed substantially).Although at first glance it may seem as though there are many stations, this is misleading because data are not available from all stations, data from many stations are discontinuous, and there are extremely few stations located at the higher elevations (see inset to Figure 5). It is interesting to note that the mountainous country of Switzerland, which has a land area approximately 1% the size of the HKH, has about 500 weather stations.

Analysing the trends is also challenging. There are a few hill stations in India that have archival data going back a century or more but, for the most part, these data are either lost or have not been analysed. Most archival meteorological data in the region extend back for only 50 years or less. The changes that have been reported to date are based on the premise that this data should suffice to indicate climate change since most of the warming is assumed to have taken place during the past half century.

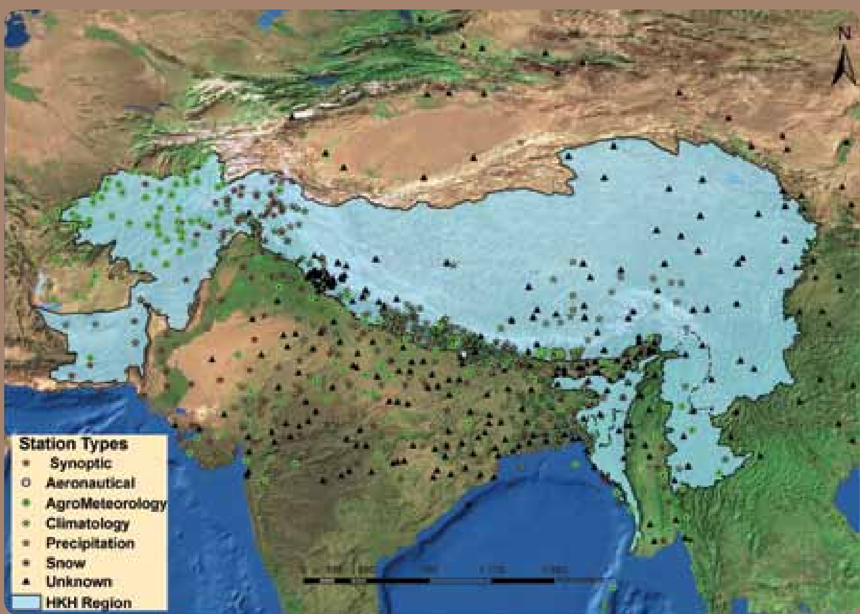
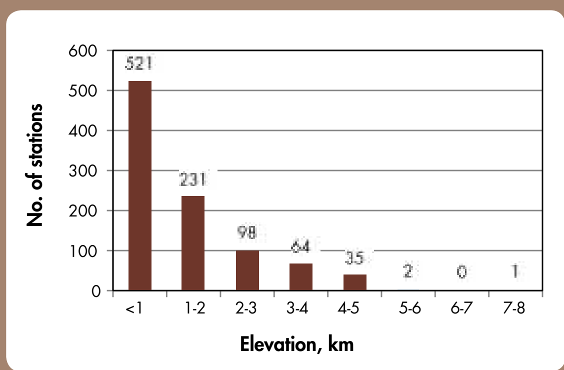


Figure 5: **Meteorological stations in the HKH region (in blue)**



Source: ICIMOD

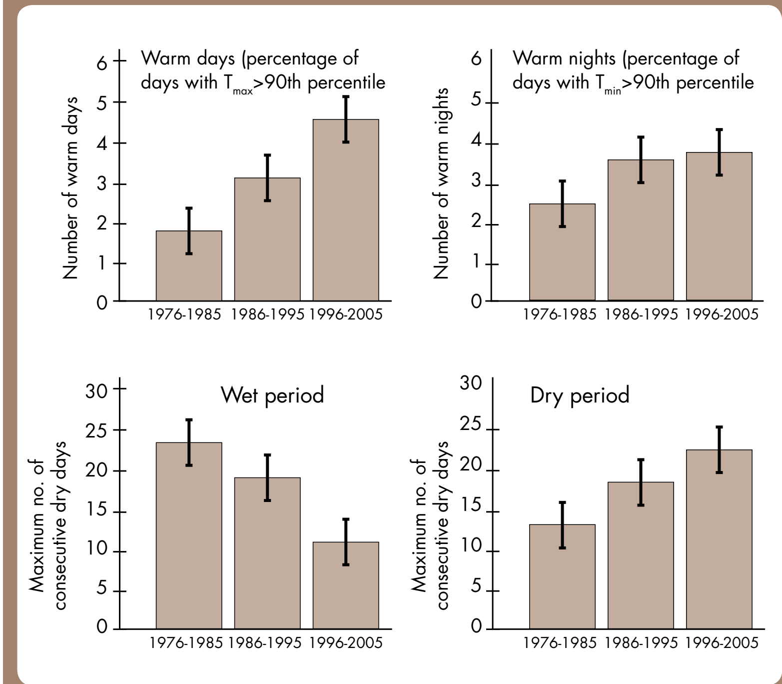
Changes in temperature

This section provides a summary of historical climate trends in the HKH region, with both an overview of change based on a few studies in specific locations and generalisations for the HKH region as a whole. The generalisations for the HKH region are based for the most part on records collected by Shrestha (2011). The findings are based on data from a limited number of stations, not necessarily representative of the different altitudes, aspects and other geographic factors, and often with only limited time series. Thus they provide an interesting snapshot of changes at specific locations, but the extent to which these can be generalised across the region is difficult to assess Western Himalayan region. The following major findings from an analysis of winter temperatures (December–February) and precipitation data in the western Himalayan region for the period from 1975–2006 based on data from 35 observation stations located between 2,192 masl and 3,250 masl (courtesy of the Snow and Avalanche Study Establishment, Chandigarh, India). Dimri and Dash (2011) show the following.

- During the period, average temperatures increased over most of the region, as indicated by lower and higher percentiles of the daily maximum, minimum, and average temperatures. The increases in average temperature ranged from 0.6 to 1.3 °C; the differences in the maximum temperatures across the stations ranged from 1.1 to 2.0 °C and the minimum from 0.2 to 0.5 °C .
- Decadal trends indicate a rapid increase in the number of warm days (days with T_{max} > 90th percentile) and warm nights (nights with T_{min} > 90th percentile) (Figure 6).
- The number of cold nights (percentage with T_{min} < 10th percentile) has decreased.
- Precipitation was more variable and trends less definite. The extremely complex topography makes it mandatory to survey a large number of meteorological stations in order to ascertain representative trends for the region.
- A distinct shift in precipitation from snow to rain was apparent.
- The longest number of consecutive dry days during winter increased and the longest period of consecutive wet days decreased.

Figure 6: **Decadal change in number of warm days and warm nights, and the length of the longest dry period** (maximum consecutive dry days) and longest wet period (maximum consecutive wet days) in winter

Data values are averages of 8 meteorological stations at altitudes close to 3,000 m in the western Himalayas (part of Himachal and Kashmir).



Source: Developed from Dimri and Dash (2011)

Nepal. Temperature data collected from the mid-1970s from 49 stations in Nepal (Shrestha et al. 1999 and Shrestha and Aryal 2011) indicate that:

- the average temperature between 1977 and 1994 increased at a rate of 0.06 °C per year;
- the rise in temperature was greater at the higher altitudes, in fact, the adjacent plains and foothill areas experienced only negligible warming; and
- increases in temperature were more pronounced during the cooler months (0.06–0.08 °C per year from October–February, for all of Nepal) than for the warmer months (0.02–0.05 °C per year for March–September for all of Nepal).

Nepal (high-altitude areas). Using the relationship between glacial retreats and climate warming, scientists have found greater temperature rises in some glaciated areas in Nepal. For example, Kadota et al. (1997) estimated a 1.4 °C temperature rise from 1989 to 1991 at the terminus of glacier AX010 in the Shorong Himal (at 4,958 masl) on the basis of rapid retreat of the glacier after 1989. Relatively smaller, but nevertheless considerable, temperature increases (average of 7 stations, 0.025 °C per year) were recorded at stations around glaciers in the Dhaulagiri region during the last decades of the twenty-first century (Shrestha and Aryal 2011).

Eastern Himalayas and China. Few long-term data exist on climate change for the Eastern Himalayas. The little data there are seem to indicate a moderate warming trend during the last decades of the twentieth century with the exception of one report which indicates a slight cooling (APN 2003). Table 2 gives a summary of temperature and precipitation changes reported for the northeast Himalayas and China.

In the Eastern Himalayas, the annual mean temperature (measured from 1975 to 2000) is increasing at a rate greater than 0.01°C per year or more; within this sub-region, the Yunnan Province of China, part of the Kachin State of Myanmar, and the northeastern states of India and Assam show a warming trend that is relatively less(≤ 0.02°C per year) and eastern Nepal and eastern Tibet show relatively greater warming trends (>0.02°C per year) (Shrestha and Devkota 2010). The warming trend was more evident during the winter months (December– February), when it was about 0.015°C per year higher than the annual rate, and at higher altitudes (Table 2).

Table 2: **Changes in temperature and precipitation observed in the northeast Himalayas and China**

Region or place	Changes in temperature	Precipitation	Source
Northeast Himalayas	+1.0 °C during winter and 1.1 °C during autumn over the last century	Small increase	Dash et al. 2007
Southeast Himalayas	+0.008 to -0.06 °C per year from 1960 to1990		APN 2003
West China	+0.01 to +0.04 °C per year (observed over 41 years)	-2.9 to -5.3 mm per year at one place (observed over 41 years)	Yunling and Yiping 2005; Yin 2006
Eastern Himalayas	Annual temperature changes from 1977 to 2000: +0.01 °C per year below 1,000 masl; +0.02 °C per year between 1,000 and 4,000 masl. +0.04 °C per year above 4,000 masl from 1975 to 2000		Shrestha and Devkota 2010
Bhutan	+0.5 °C between 1985 and 2002 (non-monsoon period)	Uncertain	Tse-ring 2003

Western Hindu Kush-Himalayan region. In the westernmost part of the HKH region, studies differ in their findings on temperature (Bhutiyani et al 2009). Whereas Fowler and Archer (2006) reported that mean and minimum summer temperatures show a cooling trend beginning in 1961, Chaudhry and Rasul (2007) reported a non-significant increasing trend in the annual mean temperature in the mountainous areas of the Upper Indus Basin in Pakistan. In contrast, for the 47-year period from 1960 to 2007, Baluchistan reported a +1.15°C increase, Punjab reported a +0.56°C increase, and Sindh reported a +0.44°C increase. The seasonal trend in the Upper Indus Basin takes the form of rising summer and falling winter temperatures. Long-term data sets, from as far back as the late nineteenth century, showed significant trends in increasing annual temperatures in all three stations studied by Bhutiyani et al. (2009) in the northwest Himalayan region. In the Karakoram region, Dimri and Dash (2010) found a decrease in winter temperatures in the accumulation zone and an increase in winter temperatures in the ablation zone of the Siachen glacier. This contrast within the same glacier gives rise to the hypothesis that, in sensitive ecoregions such as glacial regions, changes in temperature are more likely to be governed by local dynamics than by regional or global trends.

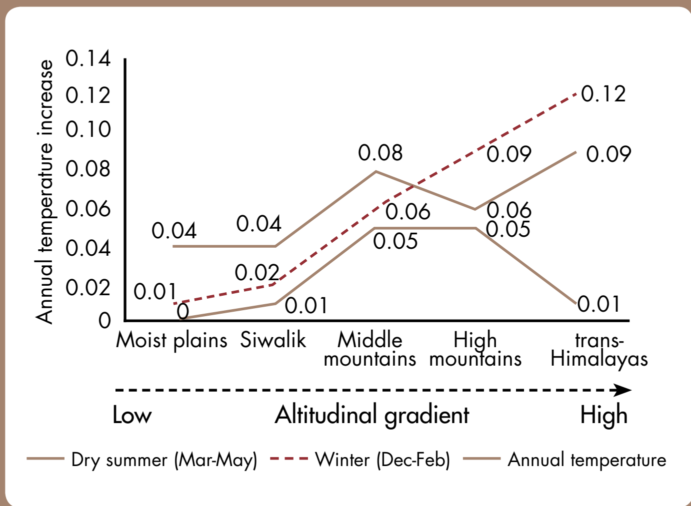
Central Himalayan region and the Tibetan Plateau. These areas have shown consistent trends of overall warming during the past several decades (Yao et al. 2006; Shrestha et al 1999; Xu et al. 2007; Eriksson et al. 2009). Various studies suggest that warming in this part of the HKH region has been much greater than the global average of 0.74 °C over the last 100 years (IPCC 2007; Du et al. 2004). Data are scarce but one study in Nepal estimated that the average warming in Nepal was 0.6 °C per decade between 1977 and 2000 (Shrestha et al. 1999). The mean increases in temperature over the Tibetan Plateau during the period from 1955 to 1996 were about 0.16°C per decade (annual mean) and 0.32°C per decade (mean for the winter months of December, January, and February), which exceeds the increases reported for the northern hemisphere in the same latitudinal zone during the same period. Warming in Nepal and Tibet is notably greater at the higher elevations (Shrestha et al. 1999 and Liu and Chen 2000).

The Tibetan Plateau has an annual mean temperature of from -2.90 °C to 1.60 °C (based on six weather stations in the northern area (88.6°–93.8°E; 30.7°–32.4° N; 4,024–4,674 masl, Environment and Development Desk 2009). The following changes in temperature have been observed for the Tibetan Plateau.

- Average temperature rises of 0.3°C per decade (Environment and Development Desk 2009) during the latter half of the twentieth century. The average temperature in Lhasa rose by 1.35°C between 1950 and 1980.
- An average annual warming rate of 0.016°C per year from 1955–1966 (based on 97 stations distributed over the entire Qinghai-Tibetan Plateau (Liu and Chen 2000).
- An average warming rate of 0.02°C per year in summer and 0.13°C per year in winter between 1978–1999 in Qinghai and Tibet (Du et al. 2004).
- The strongest winter warming trend was in the northern parts: more warming in winter season than in the growing season (Shen and Varis 2001).
- Summer and winter warming were observed in the extreme southeast (Baker and Moseley 2007).

Overall Hindu Kush-Himalayan region. Since the studies mentioned above are limited to isolated parts of the HKH region, they may not be representative of the region as a whole. Shrestha (2009a) attempted to analyse the temperature trend for the last two decades of the twentieth century for the whole HKH region based on a reanalysis of data from the Climate Research Unit, University of East Anglia (New et al. 2002). This study showed that a major part of the region is undergoing warming at rates higher than 0.01°C per year. Lower rates but still considerable warming (0.01–0.03°C per year) is observed in the western Himalayas, Eastern Himalayas, and the plains of the Ganges basin. Greater warming rates (0.03–0.07°C per year) are observed in the central Himalayas and the whole of the Tibetan Plateau. There are some pockets of very marked warming in the northeastern Tibetan Plateau, southern Pakistan, and Afghanistan. The central part of the Himalayas shows a south–north gradient in warming rates. This is clearly demonstrated by the area-averaged trends of three elevation zones (<1,000 masl, 1,000–4,000 masl and >4,000 masl) in the region. There were strong warming trends in all the three zones over the past one and a half decades, although the trend is greater at higher elevations (in the >4,000 masl zone) compared to the other two (see Figure 7). The warming trend in all three zones is significantly greater than the global average. In fact, the HKH region is one of the world's hotspots in terms of warming trends. In the global record, the warmest year up to the year 2000 was 1998; in the HKH region 1999 was the warmest year and 1998 the second warmest year.

Figure 7: **Changes in temperature noted for the HKH region between the 1970s and 2000 as a function of altitude**



Source: Developed from Shrestha and Aryal (2011)

Changes in precipitation

With respect to precipitation, the long-term pattern of precipitation in this region is not known due to a lack of long-term observations even on spatial scales of a few tens of kilometres. Box 2 shows the number of monitoring stations and how they are distributed with respect to elevation. Some information is available on a country basis. Chaudhry et al. (2009) suggests that overall the period from the 1960s to the mid-1970s was much drier than more recent decades in Pakistan; after which, a wetter period ensued until the El Niño event of 1998. Later, there seems to be a continued trend towards increased rainfall, but what was more notable was the increase in frequency of heavy downpour events. Equally, the study suggests that, although the stations in southern Pakistan were experiencing a slight increase in precipitation, most of the stations in the northern half of Pakistan were showing a significant decline in both the total annual precipitation and summer precipitation. Archer and Fowler (2005), however, observed different results based on data from the same sources: an increasing trend in winter precipitation at all stations studied and a high degree of correlation between different stations. In general, most of the studies of precipitation report a lack of any notable trends (Dimri and Dash 2011; Shrestha et al. 2000; Shrestha 2009a) with the exception that it is often reported that the frequency of heavy rainfall events has increased and the frequency of moderate rainfall events has decreased in the region. Regardless, insufficient data are available to support any of these claims.

The Tibetan Plateau has an annual mean precipitation of 299–708 mm (based on six weather stations in the northern area (88.6°–93.8° E; 30.7°–32.4° N; 4,024–4,674 masl, Environment and Development Desk 2009). Observed changes in precipitation on the Tibetan Plateau indicate the following.

- Data from 22 stations in the Gansu corridor indicate no significant change in precipitation between the early 1950s and 1999 (Chen et al 2002).
- Positive changes in precipitation were observed for all 670 weather stations of Qinghai and the Tibet Autonomous Region between 1982 and 1999 (Piao and Fang 2002).
- Decline in potential evapotranspiration throughout the plateau over the past four decades (Environment and Development Desk 2009).
- Positive precipitation trends and negative potential evapotranspiration were observed in 6 areas in the north of the plateau from 1981 to 2000 (Zhang et al. 2007).
- Tree ring-based data indicate no drying sites on the plateau for the last 400 years or so (Li et al. 2008).

Climate model projections for temperature and precipitation

The above analysis of available temperature trends suggests that the HKH region is warming and that, in general, warming is greater at the higher altitudes. Trends in data observed for precipitation are more difficult to summarise succinctly since precipitation is extremely variable, the spatial coherence is poor, and there is a lack of long-time series' records. In view of the fact that the observational data for the HKH region are scanty, climate model simulations can be used to assist planners and decision makers to look ahead and prepare for adaptation to and mitigation of climate change. The models also have a high degree of uncertainty, as they are based on large-scale observations with little possibility for verification and adjustment through ground-truthing.

Based on modelling studies, the IPCC AR4 (2007) states that the global rise in greenhouse gases (GHGs) is leading to a warming of the Earth's surface and lower atmosphere and that global temperatures will increase over the next century. While the IPCC provides projections on a global scale, projections at continental, regional, and sub-regional scales are scarce. Projections for precipitation in the HKH are generally not consistent (Immerzeel 2008) and range between predicting a 10–20% increase and a 10–20% decrease, although many models predict increased precipitation and an accelerated hydrological cycle. In general, temperatures are predicted to increase with altitude and are expected to be greater during winter than during summer. Box 3 discusses the challenges of using models.

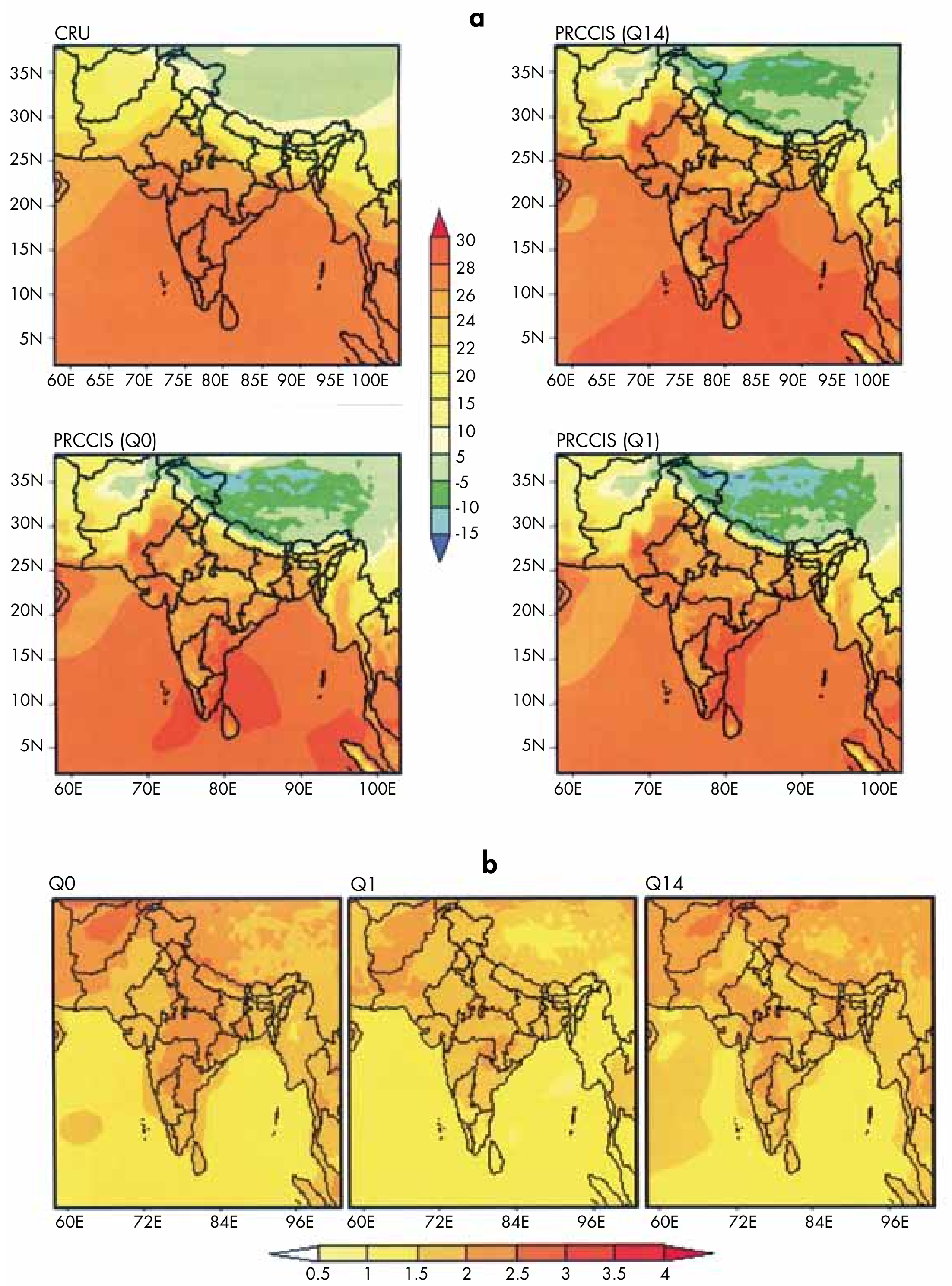
Box 3: **The challenges of using climate model projections for the HKH region**

While all global climate models to date provided a picture of significant climate warming in response to increasing greenhouse gases, it is important to remember that climate varies from place to place. This variation is driven by the uneven distribution of solar heating, the individual responses of the atmosphere and land surface, and the interactions between these and the physical characteristics of the region. Since confidence in the changes projected by global models decreases at smaller scales, other techniques, such as the use of regional climate models (RCMs) or downscaling methods, have been developed specifically for the study of regional- and local-scale climate change. These regional models depend on the use of reliable observational data sets and rely heavily on having good temporal and spatial baseline data which, as discussed above, are sorely lacking for the HKH region. To date, the most recent gridded data set for Asia is APHRODITE (Asian Precipitation—Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources, www.chikyu.ac.jp/precip/) which is a long-term (1951–2007) continental-scale daily product derived from thousands of stations throughout Asia. While this may seem like a large number, mountain areas require more accurate knowledge and an even greater density of hydrometeorological data on a finer temporal and spatial grid than other areas because the variable mountain terrain makes it prone to micro-climatic conditions over short distances.

Recent simulations by the Indian Network for Climate Change Assessment (2010) to the 2030s indicate an all-round warming over the Indian subcontinent associated with the increasing concentration of greenhouse gases. The annual mean surface air temperature is projected to rise by 1.7 to 2.0 °C in the 2030s (INCCA 2010), see Figure 8. The projections for precipitation are shown in Figure 9.

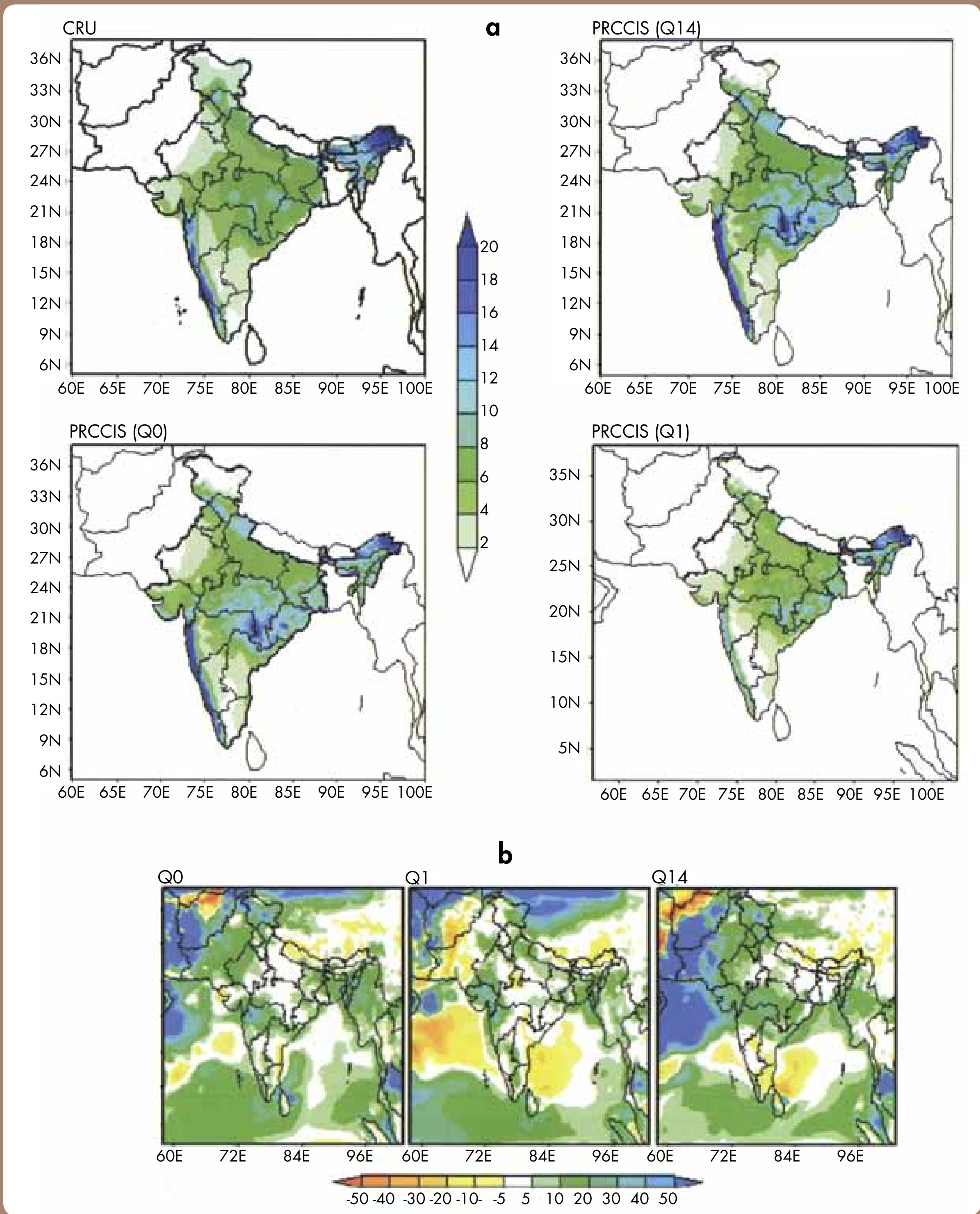
A few examples of the projections that are available are discussed below.

Figure 8: **(a) Mean annual surface air temperature climatology simulated by three PRECIS runs compared with the observed climatology (upper left panel) for the baseline period (1961–1990)**
(b) Projected changes in the annual surface air temperature in the 2030s with respect to the 1970s



Source: INCCA (2010)

Figure 9: **(a) Summer monsoon rainfall climatology simulated by the three PRECIS simulations compared with the observed climatology (upper left panel) for the baseline period (1961–1990)**
(b) Projected changes in summer monsoon precipitation in the 2030s with respect to the 1970s



Source: INCCA (2010)

Western Himalayas, Central Himalayas, and Eastern Himalayas. Kulkarni et al. (2011) recently examined the variability and change in seasonal precipitation and annual average temperature over three time slices – 2020s, 2050s, and 2080s – and found that the maximum warming (projected to the end of the century) will be in the Western Himalayan region. At the end of the century the annual average temperature is projected to be warmer by 4–5 °C for all three regions and rainfall may increase by 20–40% over the entire HKH region.

Eastern Himalayas. Three coupled general circulation models, HadCM3, CGCM2, and CSIRO Mk2, suggest the following for the Eastern Himalayas (Tse-ring et al. 2010).

- The rate of future winter warming up to the 2080s is projected to vary between 3.6 and 5.3°C, while the increase in summer temperature is projected to vary between 2.8 and 3.8 °C.
- Winter precipitation averaged across the Eastern Himalayas is likely to increase by 23 to 35%, and summer monsoon precipitation by 17 to 28%: at the local level some places may experience negative anomalies.
- In contrast to the small increase in summer rainfall, a much greater increase is expected in loss through evapotranspiration due to warmer temperatures; and this is projected to far exceed the increase in rainfall. In general, the model scenarios project drier and hotter summers and milder winters with enhanced precipitation.
- Projections of climate change and its impacts beyond 2050 have a substantial degree of uncertainty and depend strongly on the scenario and model chosen. Nonetheless, the scientific evidence is unequivocal on the emergence of climate change as an important stress in the Eastern Himalayas over the span of this century, despite considerable uncertainty about precise mechanisms and impacts, especially in precipitation.

Overall Hindu Kush-Himalayan region. Country-level and basin-level projections for the mountainous countries of the HKH region suggest the following: for Nepal, there are predictions of overall increases in annual temperatures which cover the summer monsoon (June–September) and winter months (December–March) for the three scenarios evaluated. The increase in temperatures is projected to be greater in the northern than in the central and southern parts of the country. Relatively greater temperature increases are predicted for the winters than for the summers for the rest of this century. Precipitation is expected to increase in summer and decrease in winter but, overall, the annual average is not expected to show any significant change. The projected increase in precipitation over the Eastern Himalayas is slightly greater than the projected increase over the South Asian region, but changes in precipitation are consistent with projected regional changes. The central part of the country will have the least increases in temperature. Precipitation changes will be greater in the eastern and southern parts of Nepal than in the northern parts (APN 2003). Projections for Bhutan indicate that surface air temperatures will increase most in the west and less towards the east. The projected surface warming will be more pronounced during the pre-monsoon season. Climate change maps show that the spatial pattern of temperature change has a marked seasonal dependency. The temperature increase will be more pronounced in the inner valleys than in the northern and southern parts of the country. The model predicts a peak warming of about 3.5°C by the 2050s in Bhutan. This pattern of change is predicted to be consistent for all months and all time slices. In general, Bhutan is expected to experience a significant overall increase in precipitation, but with an appreciable change in the spatial pattern of winter and summer monsoon precipitation, including a 20–30% decrease in winter precipitation over the northeast and southwest parts of Bhutan by the 2050s. A recent study by Gosain et al. (2011) investigated possible impacts of climate change on water resources and hydrology for the Brahmaputra basin and found that different scenarios predict an increase in precipitation to the end of the century.

Changes in snow cover and glaciers

The HKH region is often referred to as the Third Pole (see Dyhrenfurth 1955; Qui 2008; Edwards et al. 2010) because its vast stores of ice and snow are greater than in any other part of the world with the exception of the polar regions. Recent reports that the glaciers of the HKH region are shrinking, subsiding, and retreating have focused the world's attention on the need to develop glacier inventories for the HKH region. A better understanding of the Himalayan cryosphere can give insights into the future of freshwater resources and can be an indicator of the climate changes that are taking place globally. The loss of snow cover in the high mountains can be both an indicator and a cause of warming since, when snow cover is lost, the reduction in albedo can itself contribute to increasing temperatures.

Snow cover. Gurung et al. (2011a, 2011b) have recently estimated the snow cover area in the HKH region for the period from 2000–2010 at 0.76 million km^2 (by averaging snow cover area over the decade); and this accounts for approximately 18.2% of the total geographical area of the HKH region. The western HKH region has the most extensive snow-cover area on average because, in addition to having some of the highest elevations, it is at higher latitudes and is also more subject to the influence of winter westerlies (Bookhagen and Burbank 2010).

In contrast to the noted reduction in the length of glaciers (discussed below), the snow-cover area of the HKH region is estimated to have been more or less stable, or to have only decreased slightly during the decade 2000–2010. Linear regression analysis of snow- cover area indicates a negative trend in inter-annual variation for the years 2002–2010 which is prominent in the central HKH region (Gurung et al. in preparation). The trend for 2001–2010 is positive in the western and eastern HKH region. A similar study showed a 16% decrease in snow-cover area in the Himalayas from 1990 to 2001 (Menon et al. 2010). During the decade 2000–2010, snow-cover area and annual snowfall were significantly correlated, suggesting the influence of annual variation in circulation patterns. The snow- cover area during this period varied from both season to season and from area to area across the region. The snow-cover area in spring and summer time demonstrated a declining trend and in autumn an increasing trend. But the data are still insufficient to generate statistically significant results. Bohner and Lehmkuhl (2005) predict that the snow cover of the Himalayan regions will decrease by 43–81% in 2100 if the annual mean temperatures at higher elevations in Asia increase by 1–6 °C as predicted by the IPCC.

Glaciers. The HKH region stores freshwater in the form of glaciers and, for centuries, millions of people downstream have benefited from the glacial meltwaters that feed the rivers downstream. In addition to providing freshwater, glaciers are repositories of information about climate change as they are sensitive to changes in temperature and precipitation. See Box 4. Bajracharya and Shrestha (2011) recently prepared an inventory of all glaciers larger than 0.01 km^2 in the HKH region (except for China) based on Landsat7 ETM+ satellite images from 2005±3 and the SRTMZ DEM. (Data from China were integrated into the inventory through data exchange in collaboration with CARRERI/CAS). The results are summarised in Table 3 and show that the HKH region has over 50,000 glaciers with a total glacial area greater than 61,000 km^2 representing about 30% of the total glaciated mountain area of the world. This area is about double the previous estimate of 33,000–38,000 km^2 (Dyurgerov 2005), and this is probably because earlier reports did not include the entire HKH region. The present analysis is still continuing and this number may be revised. The area of an average HKH glacier is just above 1 km^2. Over most of the region, glaciers were found to be predominantly of the 'clean' type; debris-covered glaciers were mostly found in areas with a great deal of ruggedness. Most glaciers in the HKH region are found between 4,900 and 6,100 masl; and about half are on the Qinghai-Tibetan Plateau (Table 3).

Table 3: **Estimated number and dimension of glaciers in the HKH region**

Number of glaciers	>54,000
Total glaciated area	>61,000 km^2
Ice reserves	6,000 km^3
Percentage of the total glaciated area of the HKH	
Chinese Himalayan region (Qinghai-Tibetan Plateau)	48.9%
India	20.3%
Pakistan	18.2%
Nepal	7.0%
Afghanistan	4.4%
Bhutan	1.1%
Myanmar	0.04%

Source: Bajracharya and Shrestha (2011)

Box 4: **Glaciers**

A glacier is a perennial body of ice and snow, at least 30 metres thick, in which ice from a higher elevation is transported to a lower elevation. The movement of the ice is always from the upper part of the glacier towards the lower end (the terminus or snout), regardless of whether the glacier is advancing or retreating. Glaciers are divisible into an upper accumulation zone and a lower ablation zone. In the upper zone, more snow is deposited than melts in a year, while in the lower zone, annual snowmelt exceeds annual snow accumulation. The difference between the total annual accumulation of snow and ice and their loss (ablation) is called the mass balance of glaciers. When glaciers shrink, their mass balance is negative; and when they grow, their mass balance is positive.

Global warming can cause glaciers to shrink since warmer temperatures can increase the rate at which glaciers melt, and decreases in precipitation mean that glaciers accumulate less snow. The mass balance of glaciers is the key indicator of changes taking place within. Measurements based on the position of the glacier terminus give only a partial idea of the overall changes, although they help to indicate whether a glacier is retreating or advancing.

The meltwater of the HKH glaciers drains into the major river basins where it is an important source of discharge, especially in the dry seasons and particularly in the upper reaches and for the rivers of the arid western part of the HKH region.

Source: ICIMOD (2009c)

Studies of glaciers in the HKH region typically record only the position of the terminus. The data for glaciers which have been observed over a number of years are given in Table 4. Overall, a retreat of 15 m per year or less was recorded for about 70% of the glaciers studied. Many of the results of studies on termini positions in the Indian Himalayas are summarised in a paper for discussion prepared for the Indian Government (Raina 2009). Among others, although not highlighted, the paper also shows the limitations of such studies, which take no account of mass balance or changes in the depth of glaciers. Most studies in the Indian Himalayas have been in the form of intermittent expeditions, and there is a lack of continuous long-term data. The paper also notes that much of the data on glaciers collected by the Geological Survey of India are still unavailable as they have been classified.

Table 4: **Observed rates of glacial retreat in different parts of the Himalayas based on observations of glacier termini**

Glaciers and Region	Rate of retreat (m/yr)
Kashmir and Himachal (India)	
Barashigri, Chandan Basin of Eastern Lahul	44
Tajiwas Nar, Sindh basin of Kashmir	5
Stock, Ladakh	6
Fanfstang, Bhara basin of western Lahul	12
Garhwal (India)	
Trisul, Nanda Devi sanctuary	10
Betharti, Nanda Devi sanctuary	8
East Kamet	5
Gangotri, Bhagirathi Basin	15
Santopanth – Bhagirathi glaciers complex, Alaknanda	12
Kumaun (India)	
Milam, Gouri Ganga basin	13.5
Poting, Gouri Ganga basin	5
Shankalapa, Gouri Ganga basin	23
Sikkim (India)	
Tista Khangse, Tista Basin	8
Nepal	
Shorong region	2.7–2.3 (1978–1989)*
Khumbu region, 7 clean-type glaciers	30–60 (1998–2004)* 2.0–3.4 (1970s–1989)*
Exceptional rate in Nepal	71
Bhutan	
Luggye glacier**	160

* mean for the period
**this glacier is in contact with a large glacial lake

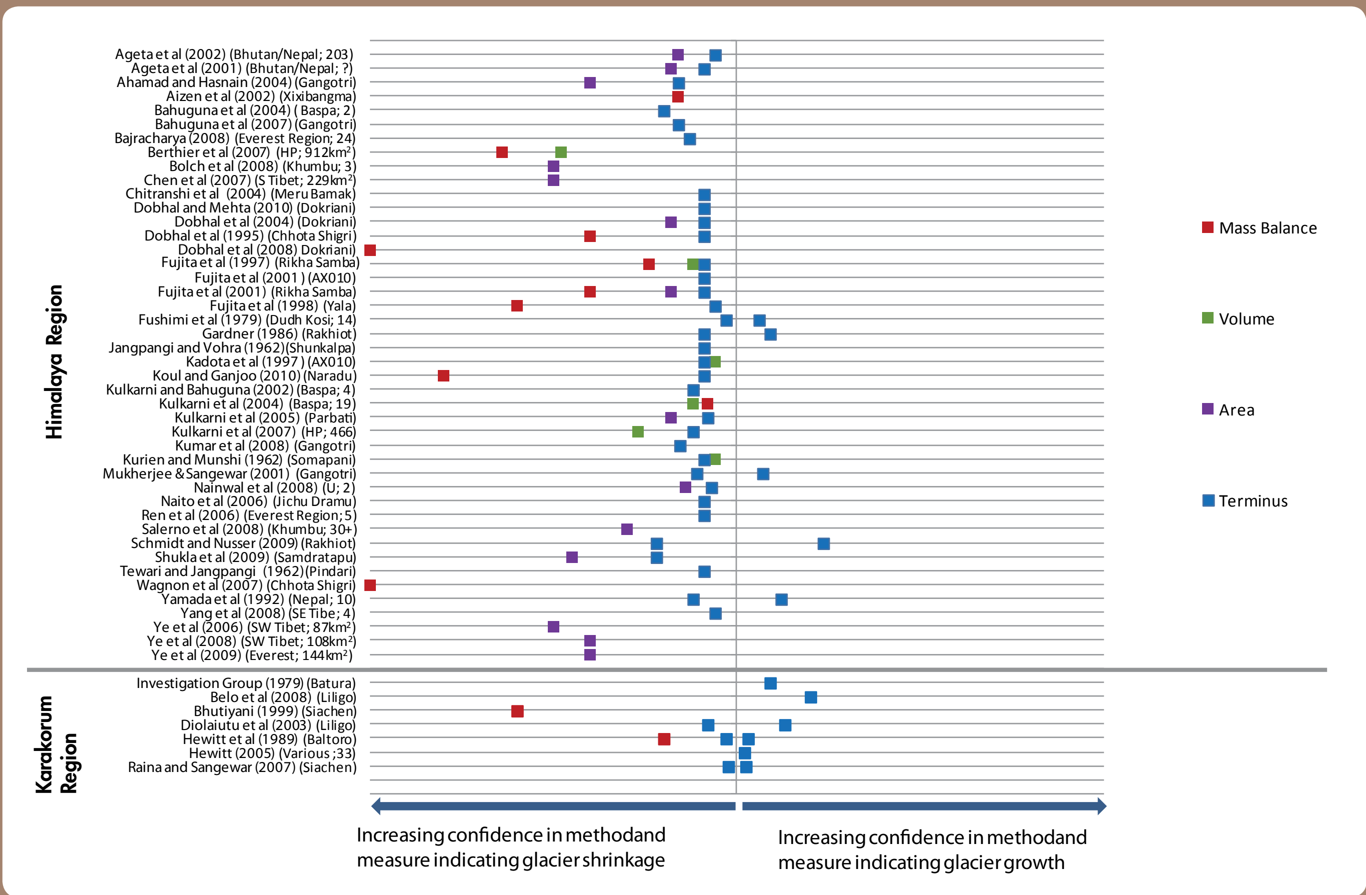
Source: Bajracharya et al. (2007); Fujita et al. (1998, 2001); Mukhopadhyay (2006); Shrestha and Ayal (2011)

Bajracharya et al. (2010a, 2010b, 2011) and Bajracharya and Shrestha (2011) indicate a substantial decrease in the total area of glaciers accompanied by an accelerated fragmentation of glaciers in Bhutan and Nepal. Comparisons were made of values obtained for a period of 40 years; the datasets are not strictly comparable and the results must be seen as indicative rather than exact. Glacial depletion in Bhutan was 27% (measured in 2006–7) and 21% in Nepal (measured in 2008). Other investigators have reported a similar range of glacial retreat from various areas in the HKH region (e.g., Kulkarni et al. 2010; Nie et al. 2010). These regional estimates are mostly based on measurements of glacier termini and area. In order to compare changes among glaciers, relative estimates are more useful than changes in absolute values which may be misleading. For example, a decrease in area at a rate of 50 m^2 per year in a 1 km^2 glacier is 2.5 times greater proportionally than a decrease of 200 m^2 per year in a 10 km^2 glacier. Reported area shrinkage has varied, on average, between 0.4 and 0.5% annually since the 1950s, while data on termini indicate rates of retreat that vary widely from 0.08% per year for large glaciers to 0.3% per year for smaller ones (Miller et al. 2011). Bajracharya et al. (2010a, 2010b) have analysed changes in glacial area from 1980 to 2010 in the Langtang Valley, Nepal, and in the Bhutan Himalayas from Landsat satellite images and have found decreases in area but not disappearance of glaciers. They also found that the perennial snow/ice on steep mountain slopes does disappear but not in the valleys.

Many of the inferences on glacial melting are based on measurements of termini fluctuation or changes in glacial area, neither of which provide precise information on changes in ice mass or volume. Measurements of glacial mass balance provide better and more direct and immediate evidence of increases or decreases in glacial volume with annual resolution. Only very few measurements of the mass balance of glaciers are available for the more than 50,000 glaciers in the HKH region, and none at the highest elevations: in general, those that are available indicate a loss in glacial mass. For the period from 1980–2000, they show an average change of 250 $kg/m^2/yr$ and for the period from 1996–2005 of 596 kg/m²/yr (Kaeser et al. 2006; Zemp et al. 2009). Using data from the gravitation satellite GRACE, Matsuo and Heki (2010) estimated the regional loss of ice at the rate of 490 kg/m²/yr for the period from 2003–2009. Relatively longer term data (1970–2007) on changes in specific mass balance are available for the Everest area (based on multi-temporal digital terrain models for ten glaciers with a total area 50 km²) (Bolch et al. 2011) indicating acceleration of negative mass balance during recent years (2002–2007). Despite thick debris cover, these glaciers have shown a significant loss of mass, the average specific mass balance for 1970–2007 being -0.32 ± 0.08 per metre water equivalent. Data for the period from 2002–2007 estimate -0.79 ± 0.52 per metre water equivalent; the entire 37-year period shows an acceleration in mass loss but this acceleration is not statistically significant because of a high degree of uncertainty. A tendency for mass loss has been noted by Cogley (2011a, 2011b) for other Himalayan glaciers. New studies of mass balance have recently been initiated by ICIMOD for the Rikha Samba glacier located in Kali Gandaki Hidden Valley and the Yala Glacier in Langtang Valley, both of which are located in Nepal.

As the discussion above shows, data and information on the glaciers in the Hindu Kush-Himalayan region are sparse and often contradictory. They lack consistency, multi-temporal recording, field validation, and peer review, and there is a particular lack of data for the glaciers at higher elevations. A recent review by Armstrong (2010) gives an extensive literature survey and references, as well as a comparative analysis and analytical discussion. Miller et al. (2011) have compared recent studies on glaciers together with the relative confidence levels for the measurements. Their summary, which is given in Figure 10, shows that across the HKH region there is an increase in data per se and in confidence in the quality of data which indicate that glaciers are shrinking than in data which indicate that glaciers are advancing. Interestingly, the data accepted with most confidence for the Karakoram indicate shrinkage, not growth. As an exception, about half of the glaciers in the Karakoram are thought to be either growing or stable (Hewitt 2005), possibly in some cases as a result of surging, but these estimates are based on measurements of

Figure 10: **Relative assessment of reviewer confidence in reported study outcomes according to method employed, clarity of reporting and measurement type**



Note: Brackets include name of glacier or region with associated number/area (km²) of glaciers studied if more than one single glacier; U=Uttarakhand, HP=Himachal Pradesh

Source: Miller et al. (2011)

glacier termini rather than glacial mass. Further, it is possible that debris-covered glaciers might be losing mass at high altitudes (Kulkarni 2007, 2011). The role of debris deposition in slowing down glacial melt is demonstrated by the fact that the 'clean' glaciers of the Tibetan Plateau are retreating at a faster rate than the debris-covered glaciers of the rugged central Himalayas (Immerzeel at al. 2011b). From measurements of the mass balance of three benchmark glaciers, Fujita and Nuimura (2011) found multi-decadal oscillations, trends of thinning and retreat, and, in two cases, indications of accelerated thinning. The paper underlines the complexity of individual glacial responses. The problems of glacial response times are highlighted in the discussion by Kargel et al. (2011), as is the fact that a stable terminus position may still be accompanied by considerable mass loss from thinning.

Glacial meltwater and river flows

The HKH region is often referred to as the 'water tower of Asia' as it stores large volumes of water in the form of ice and snow which release water gradually over a long period during the dry seasons (Messerli and Ives 1997; Chettri et al. 2011). Rivers collect water from melting snow and glaciers but there is a fear that this will cease as glaciers disappear (Collins 2008). The IPCC AR4 (2007) predicted that some Himalayan catchments would run out of water during the dry seasons if the present trend of glacial shrinkage continued but this has not been corroborated by subsequent studies: in part this is because the correlation between the availability of glacial meltwater and the abundance of river flows during the summer season is more complex than originally assumed. The contribution of snowmelt, as against glacial melt, is also poorly understood or recorded. As temperatures increase, less precipitation will fall as snow, and this may have as much if not more impact than changes in glacial melt. The extent to which rainfall contributes to river discharge in the HKH region diminishes considerably from east to west. Increased precipitation in the western region, probably due to climate change, may compensate for a decrease in the meltwater component of rivers such as the Indus that have arid downstream basins but may also lead to greater inter- and intra-annual variability. In the monsoon-dominated eastern region, the discharge of rivers such as the Ganges consists predominantly of rainwater; a decrease in glacial meltwater would be noticeable in its upper catchments but would be difficult to detect downstream.

Contribution of glacial meltwater to river discharge. With a predicted increase in global temperatures, glaciers are expected to melt faster leading to an initial increase in river flows; however, as glaciers disappear completely, the short-lived surge could be followed by the eventual disappearance of glacial meltwater altogether. Box 5 discusses why in general the contribution of glacial meltwater to river discharge is poorly understood. The concern is that some

Box 5: **Towards a better understanding of meltwater contribution to river flows**

The contribution of glacial meltwater to river discharge is poorly understood for the following reasons.

- Baseline data on glaciers are limited. Annual monitoring, which can give important insights into inter-annual changes is not conducted routinely, and the way in which debris-covered glaciers respond to climate change is poorly understood. Generally, few field-verified data are available.
- Simple measurements of the length of glaciers (by measuring the position of the terminus) can be misleading; relative assessments of glacial mass balance are more indicative of growth or shrinkage. Glacial mass balance, the most rigorous indicator of change in glacial mass and water storage, has only been assessed for less than 10 of the more than 50,000 glaciers in the region.
- Measurements made on various glaciers or by different investigators often vary in resolution and sampling procedures.
- Hydrological data are either sparse or not available.
- Long-term river discharge data are scarce and usually not available.

There is a need to develop better ways of incorporating information on precipitation and ice meltwaters into hydrological models and to emphasise the key factors that affect melt and forcing.

- Time series' precipitation data from high-altitude areas across the HKH region are needed to provide input to climate models.
- A better sampling of glacial and snowmelt at representative sites across the region will allow a better estimation of the contribution that each component makes to river flows in the region.
- A better sampling of precipitation and glacial meltwater can provide information on the spatial-temporal patterns of current and future stream flow composition.

Source: Based on Immerzeel (2011)

Himalayan catchments will eventually run out of water during the dry periods if the present trend in glacial recession continues. The following discusses the state of the understanding to date.

Several recent studies (e.g., Immerzeel 2008; Immerzeel et al. 2010; Bolch et al. 2011; Miller et al. 2011) indicate that, although glacial retreat in the HKH region is occurring, the rates of retreat are less than those originally suggested by the AR4 (Cogley et al. 2010; Miller et al. 2011). Clearly, more objective and transparent discussions of the evidence are needed (Miller and Rees 2011). As discussed above, many of the Himalayan glaciers which have been investigated in the eastern and central HKH region are receding, but it is still not clear how these attenuations in glacial mass will affect river discharges both upstream and downstream. Miller and Rees (2011) have summarised likely changes in the contributions of glaciers to river discharge as follows.

- The glacial melt that occurs in the monsoon-dominated eastern and central parts of the Himalayas does not contribute significantly to annual river discharge downstream. It is estimated that glacial melt accounts for, on average, only 10% of the river flow of the Ganges; estimates vary between 2–20% among basins. In the rivers of the eastern region, glacial melt coincides with monsoon precipitation, and by comparison, the large volume of rainwater dwarfs the contribution of meltwater (Table 5). Even in monsoon-dominated areas, however, glacial melt is still an important source of water for both agriculture and vegetation in the upper reaches, especially during dry periods.
- Glacial melt contributes significantly to the water discharge of the Indus (Table 5) because in this area the summer monsoon is weak and the contribution is more obvious in the arid areas downstream.
- A predicted increase in monsoon rainfall at the basin level in the Ganges would render the contribution by meltwater insignificant. In the long term, the predicted increase in rainfall might offset the reduction in the contribution of meltwater from glacial shrinkage, even in the Indus.
- From the various analyses available, the following issues are apparent.
  - The HKH region is likely to suffer significant changes in its cryosphere regime because of global climate change.
  - The predicted changes in climate will be manifested differently across the vast HKH region since the wide range in latitude and longitude and in topography will influence the amount of monsoon precipitation that it receives. The changes that will take place on the high, flatter, Tibetan plateau are likely to differ from the changes that will be experienced in the rugged mountain ranges to the south of it.
  - The lack of time series' observational data on glacial melt and river discharge in the upper reaches greatly limits the validation of models in these mountainous areas.

Table 5: **Contribution to meltwater from glaciers and snow expressed as Normalized Melt Index (NMI) for the present day climate (2000–2007)**

River	NMI* (%)	Contribution of glacial melt to total melt (%)
Indus	151	40
Brahmaputra	27	<20
Ganges	10	40
Yangtze	8	-
Yellow	8	-

*NMI = (runoff generated by snow + glacial melt) ÷ (runoff generated downstream)

Source: Adapted from Immerzeel et al (2011a)

Observed changes in river flows. A scarcity of long-time series' data still hampers the analysis of trends in river flow; moreover, the studies that are available (see for example Sharma 1993) are limited by factors that render either generalisations or model-based predictions difficult (see Box 5). Rivers that are fed heavily by glacial meltwater will respond differently to temperature rises than rivers which are mostly fed by rainwater during the monsoon. For example, long-term data on the Hunza basin in the Karakoram region (sampled at the Dainyur bridge) show a slight negative trend (3 mm per year) in runoff between 1980 and 2004, and this was attributed to an increase in the storage of snow and ice at higher altitudes (Khattak et al. 2011). The large rivers of Nepal exhibit no consistent trends; the Karnali and Saptakosi show a decreasing trend, whereas the Narayani shows an increasing trend, the southern rivers show no definite trend; and discharge in the snowfed rivers indicates a declining trend (Shrestha and Aryal 2011).

Using models to predict changes in river flows. Several modelling studies have been carried out in recent years to assess the impact of climate change on river discharge and water availability. These models differ greatly in how they approach the problem: they differ in structure and spatial resolution and, in the physical processes that they consider; they use different climate models and differ in the extent to which they downscale and calibrate these. Since these models differ so widely on so many fundamental inputs it is difficult to compare them or to generalise their findings. Box 6 summarises some of the challenges in using simulations to predict river flows.

Overall, studies indicate that the mean upstream water supply will decrease between the two time slices 2000–2007 and 2046–2065 as follows: -8.4% for the upper Indus, -17.6% for the Ganges, -19.6% for the Brahmaputra, and -5.6% for the Yangtze (Immerzeel et al. 2010). These decreases are less than the reduction in the release of meltwater would indicate, as they are compensated to varying extents by an increase in upstream rainfall of +25% for the Indus, +8% for the Ganges, +25% for the Brahmaputra, +5% for the Yangtze, and +14% for the Yellow River. In rivers where the contribution of snowmelt is negligible, an increase in upstream water yield is predicted (e.g., a 9.5% increase for the Yellow River). Immerzeel et al. (2010) emphasise that results should be treated with caution because of difficulties associated with monsoon simulation and inter-annual variations in precipitation.

In a study of intermediate spatial scale in the Hunza, Gilgit, and Astore river basins, Akhtar et al. (2008) considered three hypothetical glacial depletion scenarios: total disappearance of glaciers, 50% disappearance, and no disappearance. The time-scale slice was 2071–2100 at a spatial resolution of 25 km. This study found that both temperature and precipitation tended to increase towards the end of the twenty-first century. The models showed an increase in discharge with both a 100% and a 50% reduction in glaciers, whereas with 0% reduction in glaciers, less water was available.

In a study that compared the drier, western Himalayas with the monsoon-dominated, eastern part, Rees and Collins (2006) suggest that climate warming would not have a uniform effect on river flow in the region. In a study of the Sutlej River basin, Singh and Bengtsson (2004, 2005) showed that climate change is going to impact seasonal water supplies more than annual water supplies. Reduction of water supplies during the summer months is likely to affect agriculture and tourism adversely in many areas.

Box 6: **Factors that influence how well models can predict the effects of climate change on water resources**

Models predicting how climate change will impact the availability of water resources in the HKH region will need to take into consideration several factors that are difficult to quantify.

- Future climate warming, mainly due to greenhouse gases, will for the most part depend on emission scenarios for the global use of hydrocarbons (presently tied to economic growth) and the extent to which 'green' solutions can be developed and implemented as sustainable sources of alternative energy. For this reason, a range of downscaled climate models will need to be studied across different emission scenarios and these will need to be incorporated into hydrological impact models.
- Predicting precipitation is difficult; predictions can vary significantly between climate models. Precipitation is known to vary abruptly from the arid western HKH region to the monsoon-dominated eastern HKH region and is very different in dry areas in the plains than in monsoon-dominated areas with extreme relief.
- The Global Climate Models (GMC) and Regional Climate Models (RCM) require downscaling for impact analysis as the simulations have poor spatial resolution, and this adds additional uncertainty. Furthermore, simulations often show marked biases and predict extreme weather events inadequately.
- The availability of meltwater from glaciers will depend on the extent of glacial melt but this is difficult to predict because glaciers can vary considerably in the manner and the degree to which they respond to climate change.
- Since long-term observational data on river discharge are not available for the major Himalayan rivers (Indus, Ganges, and Brahmaputra), it is difficult to know what their water regimes were in the past in order to attribute differences.

Source: Adapted from Immerzeel (2011)

Recently, Immerzeel et al. (2011a) used fully distributed models forced by a full range of global climate models (GCMs) which paid particular attention to the parameterisation of future glacial extent. To deal with various uncertainties in climate change projections, they developed a high resolution combined cryosphere-hydrology model and used it to investigate how glaciers and runoff would respond to an ensemble of downscaled climate model data in the Langtang catchment in Nepal. These projections show both an increase in temperature and precipitation and a concomitant steady decline in glacial area which would lead to a significant increase in river flows.

A different study based on precipitation and stream flow models on a large-scale basin, the Niyang River basin in south east Qinghai (Tibetan Plateau, China), indicated significant increasing trends in stream flow, both annual and wet season, without any significant difference in precipitation (Zhang et al. 2011). The warming climate accelerated glacial melting, as evidenced by increased summer time stream flow and water cooling. These studies underscore the point that to achieve a reliable assessment of the impact of climate change on hydrology in the HKH region, there is a need to carry out this level of analysis in representative catchments covering the entire spatial range of the region.

Box 7: **Biodiversity in the HKH region**

- Most of the principal biome types of the world are represented in the HKH region, including arid steppe and cryptoptytic cushions, tropical rainforests, coniferous forests, and deciduous broadleaved forests. The wide range of altitudes supports more than 60 different ecoregions, including forests that occur at high altitudes (3,000–4,000 m range); and this diversity is even greater than that found in the forests of Amazonia. Overall, the ecoregions of the HKH region have not yet been well delineated; one exception is the Eastern Himalayan region, and Figure 11 shows the rich diversity of ecosystems found there.
- The biodiversity in the region varies widely in species' density (number of species per unit area). For example, parts of the Tibetan Plateau have less than 500 vascular plant species per 100 x 100 km^2, while mountain landscapes in the eastern Himalayas have species in excess of 5,000 per 100 x 100 km^2. Across the region, beta diversity, which indicates species' difference among samples, is also high Barthlott (2005).
- The number of species in the HKH region is estimated to exceed 25,000 and the high endemism (30–40% of species) makes the region particularly important. For example, northeastern India alone has more than 5,000 species out of the 8,000 species found in the Indian Himalayas, despite (and also because of) the fact that the 44,000 km^2 area is anthropogenically affected by shifting cultivation (IIRS 2002).
- In addition to the species that are permanently resident in the region, the HKH also provides asylum to a host of migrant species, which either traverse the region as part of their migratory patterns or which are taking refuge because of changes in global temperature.
- The isolation of mountain peaks promotes species' diversity as evinced by the fact that genetic diversity is particularly high and continues to increase well beyond the altitude where species' diversity peaks (Molau 2004). The remote Himalayan region facilitates speciation and is often the last sanctuary for many species and their populations. Mountains are often the bridge between continents because they help to facilitate species' dispersal.
- Though mountain forests often resemble temperate forests because they share many genera, the mountain forests of tropical regions, such as those found in the Himalayas, are not like the temperate forests of low-altitude areas. The forests found in the Himalayas at 2,000–2,400 masl are actually more like tropical rain forests, especially with regard to nutrient turnover; their nitrogen turnover time in litter is about two years, compared to about one year for tropical rainforests and 4–10 years for temperate forests (Zobel and Singh 1997).
- The forests in the HKH region, which extend up to considerable altitudes (>4,000 masl), influence the climate of the adjacent plains through biophysical processes such as evapotranspiration and reflectance.

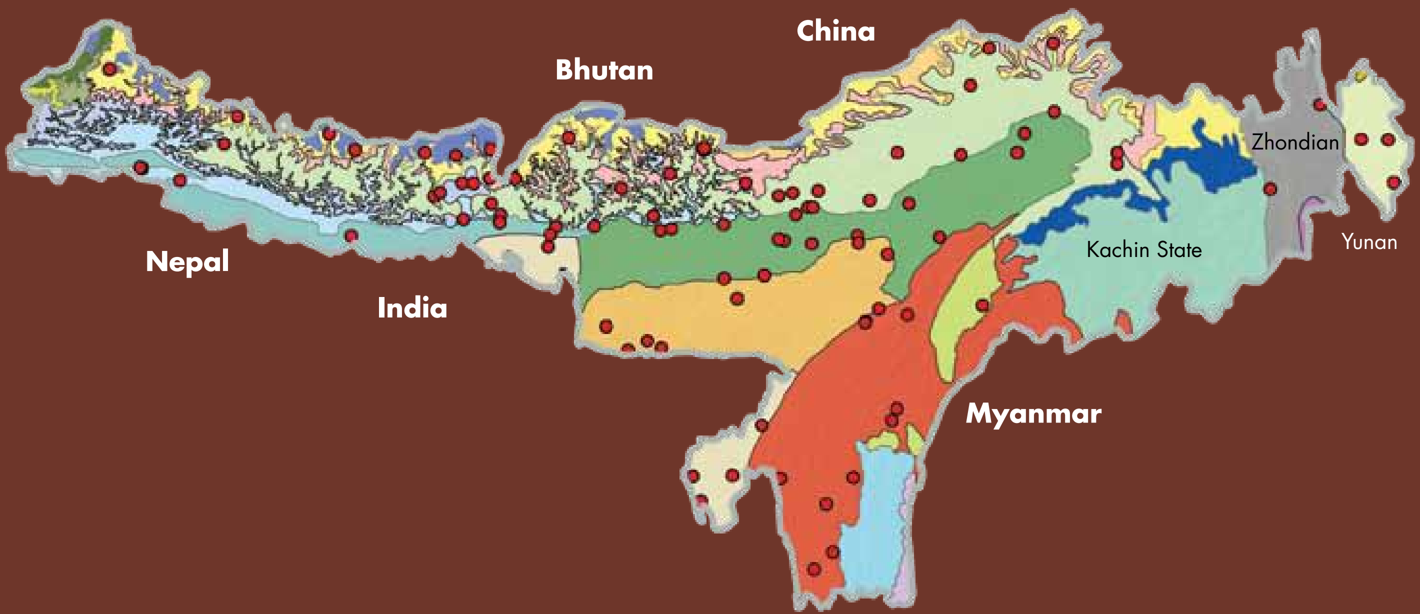
Biodiversity and Ecosystems

The HKH region is home to a wide variety of biomes and ecoregions; a summary of the rich biodiversity of the region is given in Box 7.

Vulnerable ecoregions and habitats

Ecoregions, such as the eastern Himalayan broadleaved forests and the semi-evergreen forests of the Brahmaputra Valley, are valuable conservation areas as they are rich in a variety of bird and plant species; but they are now vulnerable to climate change. Alluvial grasslands that stretch across the tropical forests in the Eastern Himalayas support some of the densest concentration of tigers in the world (Karanth and Nichols 1998). The greater one-horned rhinoceros is still found, but its habitat is restricted to several small, isolated populations within protected

Figure 11: **Ecoregions of the Eastern Himalayas**



- Protected area
- ICIMOD Eastern Himalayan boundary
- Meghalaya subtropical forests
- Mizoram-Manipur-Kachin rain forest
- Northeast India-Myanmar pine forest
- Northeastern Himalayan subalpine conifer forest
- Northern Indochina subtropical forest
- Northern Triangle subtropical forest
- Northern Triangle temperate forest
- Nujang Langcang Gorge alpine conifer and mixed forest
- Rock and ice
- Southeast Tibet shrubland and meadow
- Terai-Duar savanna and grassland
- Western Himalayan alpine shrub and meadow
- Western Himalayan broadleaf forest
- Western Himalayan subalpine conifer forest
- Yarlung Tsangpo arid steppe
- Brahmaputra Valley semi-evergreen forest
- Chin Hills-Araken-Yoma montane forest
- Eastern Himalayan alpine shrub and meadow
- Eastern Himalayan broadleaf forest
- Eastern Himalayan subalpine conifer forest
- Hengduan Mountains subalpine conifer forest
- Himalayan subtropical broadleaf forest
- Himalayan subtropical pine forest
- Irrawaddy moist deciduous forest
- Lower Gangetic Plains moist deciduous forest

Source: ICIMOD (2009a)

areas: the Eastern Himalayan region is the last mainstay for this charismatic mega herbivore. The Brahmaputra and Ganges rivers, which flow through the Himalayan foothills, support globally important endemic populations of the freshwater Gangetic dolphin (*Platanista gangetica*) with two endangered subspecies. The region is also well known for amphibians and reptiles, mostly found in moist forests and ephemeral freshwater habitats (Pawar et al. 2007; Allen et al. 2010). The central plain of the Irrawaddy in Myanmar has rich, moist deciduous forests that support a few persistent, high-level, endemic species which can easily be affected by changes in the patterns of the river system induced by climate variations (Sharma et al. 2009; Chettri et al. 2010; Tse-ring et al. 2010). This region is also one of the centres of crop plant evolution.

Impacts of climate change on biodiversity

Life in the high mountains is often perceived to be limited by low temperatures. Since global warming should increase temperatures in the high mountains, it is reasonable to ask why warming is considered a threat to biodiversity. What might seem harsh from a human stand point, however, is not harsh for species that have adapted to the environment through evolutionary processes (Körner 2004), see Box 8. Any change in the environment is a perturbation that can impinge upon biota. In mountains, temperatures change with altitude, so that mountain species have opportunities to migrate if 'new temperatures' do not suit them as long as other conditions, such as the availability of soil and water, are similar in the adjacent higher altitudes or more northerly aspect areas. In a way, mountain habitats provide asylum or refuge for species migrating away from a warming world (Figure 12). Since the Himalayas have witnessed several warm and cold climate cycles in the geological past, their biota should have experienced several migrations (Singh and Singh 1992), but it is difficult to assess whether the Himalayan biota have the genetic base suited to deal with this particular round of climate change. Recent research is available that covers the altitudinal distribution of species and beta diversity analysis across the Himalayas, see for example (Vetaas 2006) and Panigrahy et al. (2010).

The observed and projected impacts of climate change on biodiversity were studied in a detailed assessment in the Eastern Himalayas. The results provide an indication of potential changes across the region and are summarised in Table 6.

Using protected areas to study change The countries of the HKH region have set aside more than 39% of their most biologically rich terrain for protected area management; and, in total, the HKH region houses 488 protected areas (IUCN Category I-VI); 29 Ramsar Sites; 13 UNESCO Heritage Sites; 330 Important Bird Areas (Chettri et al. 2008a) and many of the world's major mountain protected areas and ecoregions: it also hosts a significant assembly of biological, social, and cultural diversity. Figure 13 shows the location of the protected areas and the inset shows that there is a growing trend for establishing these areas (Chettri 2011).

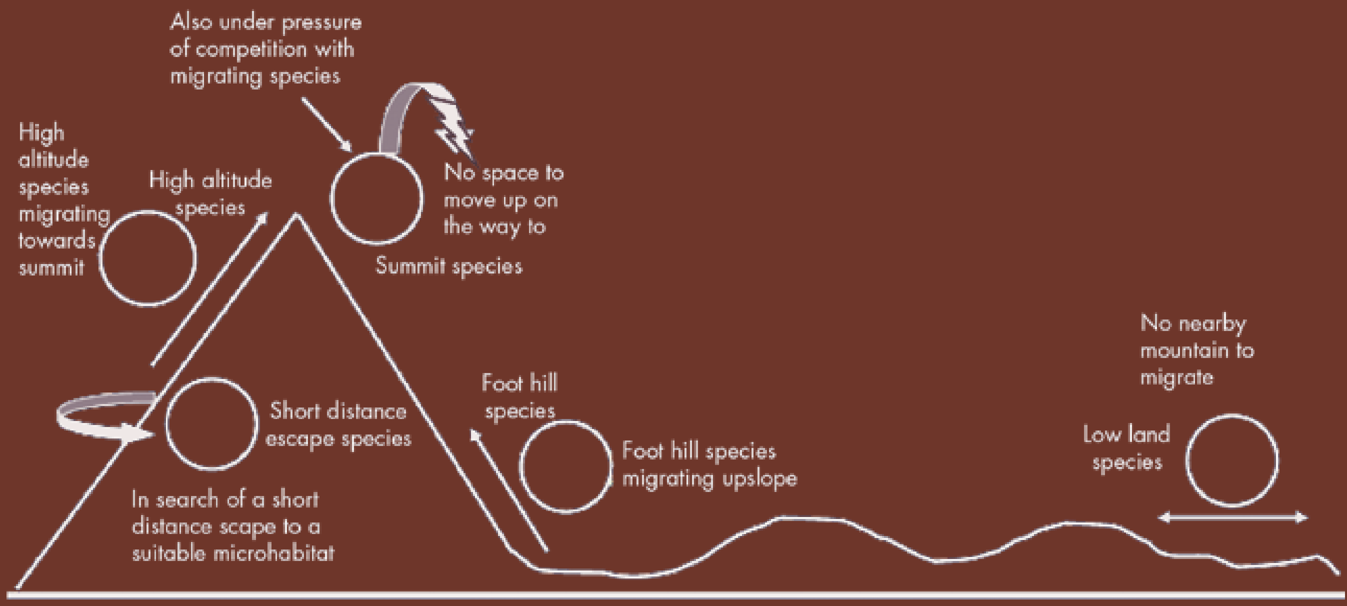
Box 8: **Adaptation**

In all organisms, adaptation involves physiological acclimatisation; in animals, it often entails changes in behaviour. This should not be confused with evolutionary adaptation which exerts selective forces on genotypes that lead to increased fitness of species and populations in a new environment. A large population, occupying a wide area with diverse environmental conditions, is likely to have genotypes that can be used to replace those that fail in a new environment. In the context of the present climate change time frame, evolution of new taxa is not possible. It is likely that an assemblage of new, adapted communities will result from the replacement of one species by another from the existing species' pools, and that novel species' combinations might be formed as a consequence of such changes.

Source: ICIMOD (2009a)

The growth in the number of protected areas is a noteworthy achievement on the part of the countries of the HKH region towards fulfilling their global commitment to conservation. Protected areas provide a unique opportunity not only to conserve but also to study the biodiversity of the region and to look for changes. Although protected areas have been established, the identification and recording of species is still in its early stages, and the constant monitoring to document changes in vegetation and identification and census of indicative species needed to monitor population dynamics as a function of changing climate impacts are still sorely lacking. Findings and conclusions from such research would give insight into the adaptive responses and resilience of natural systems and could become critical elements in evolving decision-support systems.

Figure 12: **Schematic representation of species' response to warming in mountains with assumed constant precipitation**



Source: Adapted from Kõrner (2009)

Table 6: **Observed and projected impacts of climate change on biodiversity in the Eastern Himalayas**

	System		Level			Range			
Description	Terrestrial	Freshwater	Ecosystem	Species	Genetic	Local	Widespread	Impact mechanism/ hypothesis	Climate change driver
Loss and fragmentation of habitat	●		●				●	Ecological shift, land use change, exploitation	Temperature change
Vertical species migration and extinction	○			○		○		Ecological shifts	Temperature change
Decrease in fish species (in Koshi river)		●		●		●		Less oxygen, siltation	Temperature change, extreme weather events
Reduced forest biodiversity	○●		○●				○●	Ecological shift, habitat alteration, forest fire, phenological changes	Temperature change, precipitation change, land use change, overexploitation
Change in ecotone and micro-environmental endemism	○		○	○		○		Ecological shifts, microclimate	Temperature change
Peculiar tendencies in phenophases, in terms of synchronisation and temporal variabilities	●			●		●		Phenological changes	Temperature change
Wetland degradation (Umiam Lake, Barapani in Meghalaya) (climate attribution is strongly contested)		●	●		●			Siltation	Precipitation change
Degradation of riverine island ecosystems (Majuli) and associated aquatic biodiversity (refuted, but not overlooked)		●	●		●			Flooding	Extreme weather events
Loss or degradation of natural scenic beauty	○	○	○				○	Drought, reduced snowfall	Less precipitation
Reduced agrobiodiversity	○●		○●				○●	Monoculture, inorganic chemicals, modern crop varieties, degeneration of crop wild relatives	Higher temperature and more precipitation

● Observed/documented response; ○ Projected/hypothesised response

Continues

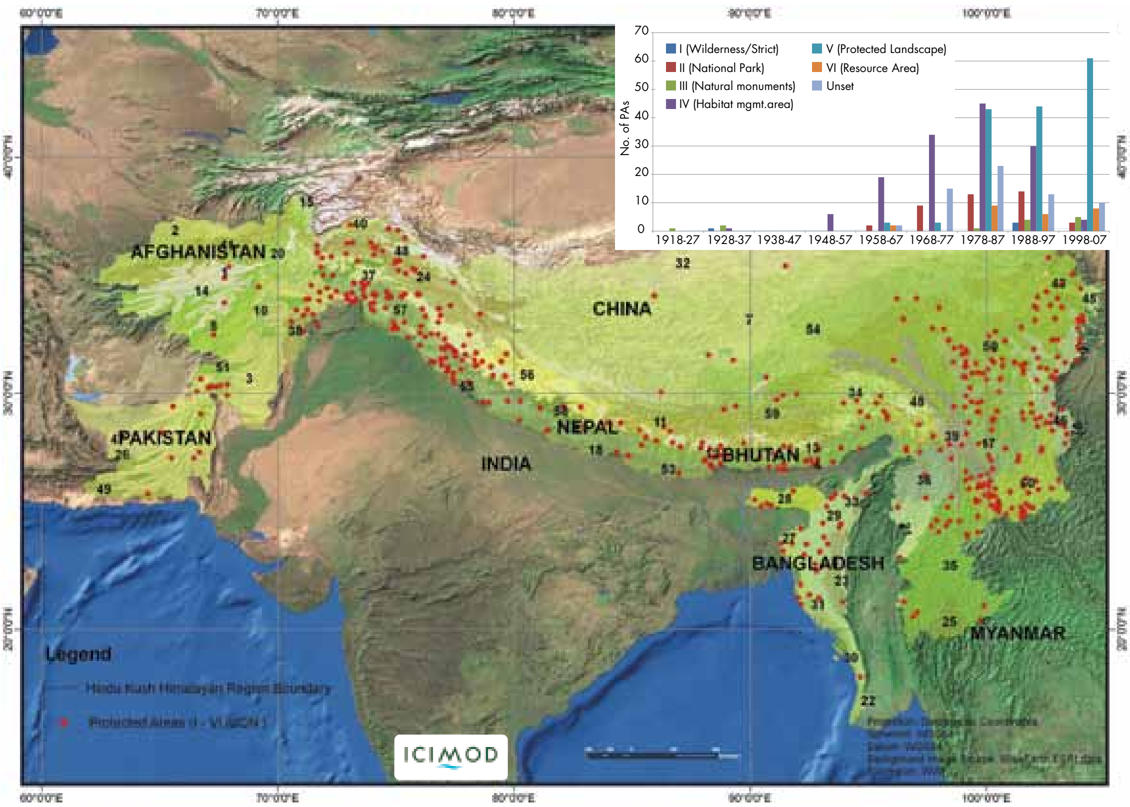
Table 6, continued

	System		Level			Range			
Description	Terrestrial	Freshwater	Ecosystem	Species	Genetic	Local	Widespread	Impact mechanism/ hypothesis	Climate change driver
Change in utility values of alpine and sub-alpine meadows	○		○			○		Biomass productivity, species displacement, phenological changes	Higher temperature and more precipitation
Loss of species	○	○		○			○	Deforestion, land use change, land degradation	Higher temperature and more precipitation
Increase in exotic, invasive, noxious weeds (mimosa in Kaziranga)	●			●		●		Species introduction and removal, land use change, tourism	Higher temperature and more precipitation
Decline in other resources (forage and fodder) leading to resource conflicts	●		●				●	Reduced net primary productivity	Higher temperature and less precipitation
Successional shift from wetlands to terrestrial ecosystems, and shrinkage of wetlands at low altitudes (Loktak Lake, Deepor Beel)	●○		●○			●○		Habitat alteration, drought, eutrophication	Higher temperature and less precipitation
Increase in forest fires (Bhutan)	●		●			●		Forest fire, land degradation	Higher temperature and extreme weather events like long dry spells
Invasion by alien or introduced species with declining competency of extant and dominance by xeric species (e.g., Mikania, Eupatorium, Lantana)	●○			●○			●○	Species introduction, land use change	Higher temperature and less precipitation
Increased crop diversity and cropping pattern	○			○		○		Demographic and socio-economic change	Variable temperature and variable precipitation
Drying and desertification of alpine zones			○				○	Drought, overgrazing	Higher temperature and less precipitation
Change in land use patterns	●		●				●	Development policy, socioeconomic change	Variable temperature and precipitation
Soil fertility degradation	●		●				●	External inputs, land use intensification, desertification	Higher temperature and less precipitation
High species mortality	○	○		○		○		Range shift, pollution, deforestion	Higher temperature and less precipitation, less days/hours of sunshine
More growth/biomass production in forests, variable productivity in agriculture (orange)	○●		○●			○●		Carbon enrichment, external input, reduced grazing	Increased CO_2 level, higher temperature
Net methane emission from wetlands (Thoubal, Vishnupur)		○●	○●			○●		Resource use, drainage, eutrophication, flow obstruction	Increased CO_2 level, higher temperature
Increased degradation and destruction of peatlands (bog, marshland, swamps, bayou)		○	○		○			Land conversion, drainage, removal of ground cover	Higher temperature and less precipitation
Land use change that increases soil degradation	●		●				●	Overpopulation, unsustainable agriculture	Variable temperature and variable precipitation

● Observed/documented response; ○ Projected/hypothesised response

Source: Tse-ring et al. (2010)

Figure 13: **Protected areas in the HKH region**

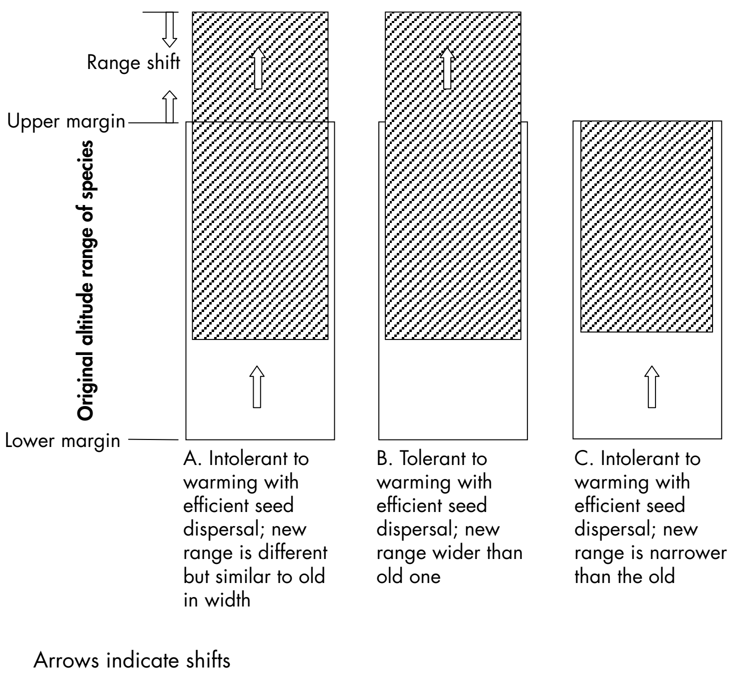


Which species are likely to be losers and which winners?

Certain characteristics enable one species to perform better than another in a rapidly changing climate. Small, highly mobile organisms are likely to fare better than large territorial animals. Ruderals (r-strategists) or early successionals with a high proportional allocation to reproduction, an efficient dispersal of propagules, and high light demand (in the case of plants) are particularly suited to survive in a diversity of conditions. Late successional species (k-strategists) with a lower proportional allocation to reproduction and slow propagule dispersal would find it harder to survive in such a situation. Species with extensive ranges and large populations are likely to be winners in a changing climate (Spehn and Körner 2011).

Species that are confined to summits live in island-like isolation and would be very vulnerable to increasing temperatures since they have no place to ascend further (Figure 14). These summit dwelling species are somewhat exceptional; species in general have a combination of characteristics attributed to both winners and losers. For example, since the Himalayan

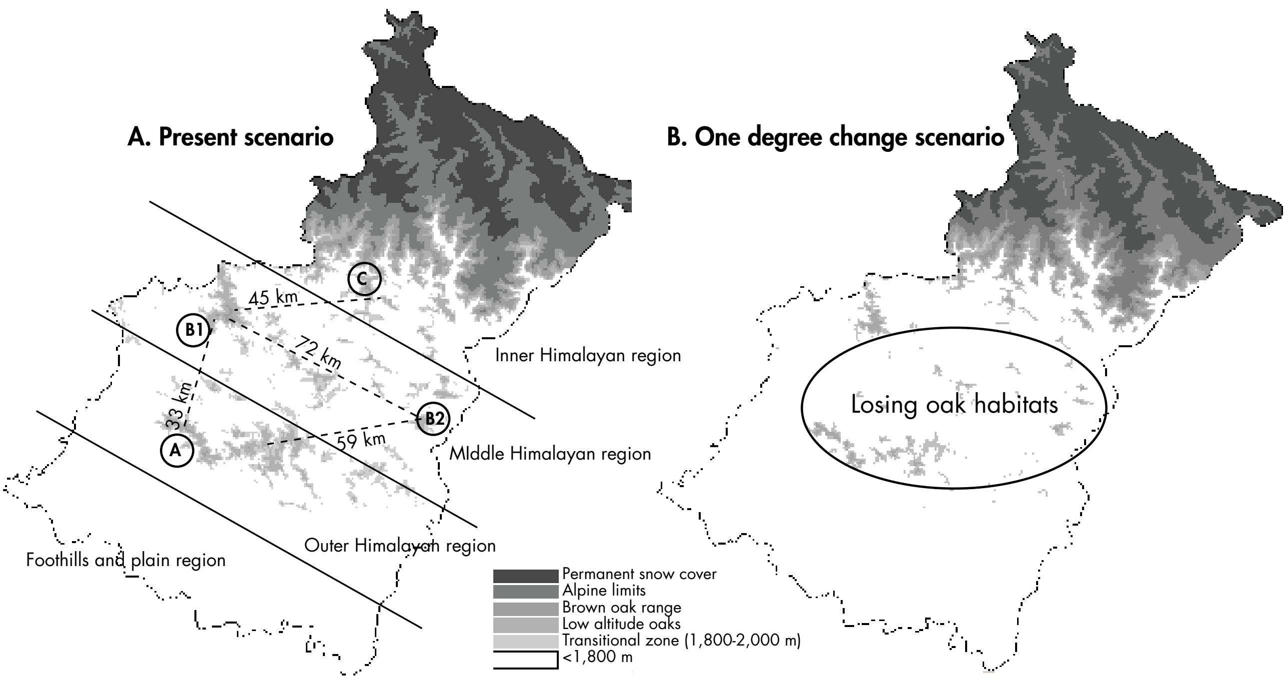
Figure 14: **Three categories of plant species with regard to toleranceto warm temperature and efficiency of seed dispersal as observed in Sikkim**



Source: Based on data from Telewala (2011) brown oak (*Quercus semecarpifolia*) is one of the most widely distributed tree species it should have genetic attributes capable of coping with severe climate change. But when it occurs in isolated islands (Figure 15) around mountain summits, it has little space to march upwards. Warming alone is projected to cause a marked depletion in the distribution of this oak (40% loss in area with a +1 °C increase and a 76% loss with a +2 °C increase). Anthropogenic pressures, which include grazing and other disturbances associated with the collection of lichens, fodder, and fuelwood, prevent this oak from regenerating over a large area of its distributional range (Singh et al. 1997; Sharma and Singh 2004). Warming may add to these disturbances to hasten its loss once the existing populations are gone. Its seeds are viviparous, i.e., they germinate while still on the tree, and cannot survive even for a few of days if they fall on an unfavourable micro-site. Since such seeds have very short seed viability, they cannot be dispersed to far-off places by acorn-eating birds and animals.

Several important Himalayan tree species have seeds that are viable for only 1–2 weeks, and their seed germination period coincides with the commencement of the monsoon. These include some important oaks, poplars (e.g., *Populus ciliata*), and dipterocarps (e.g., *Shorea robusta*). Vivipary adds to their vulnerability. Warming may directly cause early seed maturation and disturb the delicate synchrony between the arrival of monsoon rains and seed maturation/germination (Singh et al. 2010) which has been established over a long evolutionary period. Similarly, the uncertain weather which accompanies global climate change may induce rapid seed maturation through extreme droughts. Since seeds of these species are viviparous and only viable for a short time, they cannot wait for the favourable moisture conditions to be restored (Singh et al. 2010). Since the life cycle of some of these species takes more than a year to complete, their regeneration is likely to be more affected by climatic disturbances.

Figure 15: **Example of how warming temperatures can lead to the disappearance of certain species: The Kharsu oak (*Quercus semecarpifolia*) which occurs in isolated islands separated by 30–72 km (A) is likely to be a loser with rise in temperatures (B)**



Source: Sharma and Singh (2004)

Physionomic change

Evergreen broadleaved species with leaves having a lifespan of one year dominate in most of the Himalayas. They include species as diverse as *Shorea robusta* (a dipterocarp), *Pinus roxburghii* (a genus with leaves having a lifespan of several years), and *Quercus* spp. (generally deciduous in temperate forests). At lower latitudes in the Himalayas, the number of daylight hours does not differ substantially from season to season, and even winter days have long hours of intense sunlight for photosynthesis. Therefore species that can maintain photosynthesis throughout the year and which can produce leaves annually, as do deciduous species, can take full advantage of the favourable warm and moist monsoon conditions and are particularly successful in the Himalayas. Since winter temperatures are rising more than summer temperatures, the seasonal variation in temperature within the annual cycle is narrowing (Singh et al. 2010). These changes are likely to favour evergreen species with leaves having a one-year lifespan over the deciduous species, provided that the severity of droughts does not intensify markedly (Zobel and Singh 1997).

Shift in the altitudinal range of species. Shifts in the altitudinal range of species and communities are a common impact of climate change; however, evidence based on research is scanty. In a recent study on endemic species of the alpine belt in the Sikkim Himalayas (>4,000 masl), Telwala (2011) found that 87% of the 124 endemic plant species investigated demonstrated a pronounced upward shift over the past 150 years (from 1850 to 2007–10) with a mean species' shift in altitudinal range of 237.9±219.8 masl. During this period, the mean temperature increase was approximately 0.76 °C during the warmest months and approximately 3.65°C during the coldest months. The upward shift in species' range was between 100 and 400 m in 70% of the species but, in extreme cases, the range shift was 600–800 m. About half of the endemic species showed an upward shift in both the upper and lower margins. A sizeable portion of endemic species, however, only showed an upward shift on the upper side of their range, leading to an altitudinal expansion of the range. The distributional ranges increased in more than 50% of species. There were also a few species which showed an upward rise only at the lower end of their range and thus a reduction in range. Such species have a poor tolerance to warming as their ability to migrate appears to be limited and they are particularly vulnerable to warming. Species at relatively lower altitudinal bands (4,000–4,500 masl) showed more of a shift than species at higher altitudes (> 4,500 masl). The species' richness maxima showed a shift of 200 masl and, in general, species' richness increased, possibly because of accumulation of species in higher areas due to migration from the lower areas.

In a mountain belt, a 1 °C increase in mean annual temperature can cause an isotherm shift of 160 m. Since the lapse rate is relatively lower in the Himalayas (around 4.5 °C per 1,000 m increase in altitude, Singh and Singh 1992), the altitudinal shift in isotherm should be greater. The upward shift in species range in Sikkim might be partly due to the low temperature lapse rate. Himalayan species have the highest timberline (4,700 masl) and highest altitudinal limit of vascular plant species (6,400 masl) and plant communities (5,960 masl) of all alpine areas; species' migration in the forest zone would be difficult because of extensive fragmentation (IIRS 2003).

Based on a comparison of repeat photographs, Baker and Mosely (2007) estimated a 67 m rise in the tree line and a 45 m rise in the tree limit in northwest Yunnan. In another study, the tree line shift in the eastern Himalayas was estimated to be 110 m, with a considerable reduction in the area of *Abies georgei* forest (Xu et al. 2009). A smaller tree line species' shift was observed on the cooler north aspect than on the warmer south aspect in the western Himalayas (Dubey et al. 2003). Using the Holdridge life zone system, Xu et al. (2009) indicated a marked depletion of alpine vegetation and expansion of the tropical lowland forest in the Himalayas with a temperature rise of 5 °C.

An assessment of the impact of projected climate change to 2085 on the forests of India indicates that between 68-77% of the forest grids will change in forest type (Ravindranath et al. 2006). Since the areas under Himalayan forests in India are projected to experience relatively greater increases in temperature, they should experience bigger changes in forest type. Widespread changes are expected for the khasi pine (*Pinus kesiya*) of the eastern Himalayas, the chir pine (*Pinus roxburghii*) of the western Himalayas, the fir (*Abies* spp.) and spruce forests (*Picea* spp.), the temperate broadleaved forests, the blue pine (Pinus *wallichiana*) forests, and the mixed conifer forests. The general forest dieback during the transient phase would be a serious problem. Clearly, the list includes almost all Indian forest types, particularly coniferous forests. Although the Himalayas are often associated with conifers, broadleaved evergreen forests are also significant in terms of ecological dominance. While almost all forest types are projected to experience marked increases in net primary productivity with a warming climate, Himalayan forests are expected to do so only at a relatively lower rate (<1.5 times the present values).

How climate change affects land use systems

Two of the major land use systems in the HKH region are the central Himalayan forests and the grasslands of the Tibetan Plateau. These vast areas of vegetation are both affected by, and influence, climate change. They can be a source of greenhouse gases as a result of degradation and, properly managed, can support carbon sequestration. Some of the changes and impacts are summarised in the following.

The Himalayan forests. This vast expanse of forest vegetation (2,500 km wide east to west) is expected to influence the humidity levels in much of northern India through evapotranspiration and this effect should be greater from west to east since the net primary productivity and carbon sequestration of the Himalayan forests increases from west to east. The primary productivity of the central Himalayan forests is typically 8–9 tonnes C/ha/yr, on the higher side of the range reported for most forests of the world (Singh and Singh 1987), and Table 7 shows that it remains high up to altitudes of 2,400–2,500 masl (Singh et al. 1994). The upper altitude range of productivity is likely to go up with global warming.

The Eastern Himalayan forests of the northeastern states of India have been studied over the past twenty years and a recent study by Chettri et al. (2010) (Table 8) shows that the forest cover has not changed significantly over the time period.

Table 7: **Carbon stock biomass, net primary productivity, and carbon sequestration potential of forests in the central Himalayas**

Forest type (altitude)	Carbon stock in biomass (tonnes/ha)	Carbon stock in NPP* (minus litter fall) (tonnes/ha/yr)	Carbon sequestration (tonnes/ha/yr)
Shorea robusta (above 300 masl)	154.3–355	7.7–9.9	3.33–6.1
Pinus roxburghii (1,200–1,700 masl)	56.5–141.5	8.7–9.9	3.8–5.4
Mixed *Quercus leucotrichophora* and *Pinus roxburghii* (1,500–1,800 masl)	19.6–213	7.5	3.6–4.35
Quercus leucotrichophora (1,700–2,000 masl)	193.8–287	5.6–6.6	2.24–5.1
Quercus floribunda (1,900–2,400 masl)	229.2–391	8.3–9.5	5.3–6.5
Quercus lanuginosa (1,900–2,100 masl)	142.6–278.5	5.1–7.8	3.9–2.4
Cedrus deodara (2,200 masl)	215.9–228.4	12.4	3.8
Quercus semecarpifolia (2,400–3,000 masl)	148.6	9	2.2

* Net primary productivity

Source: Singh and Singh (1992); Singh et al. (2006); Sah (2005); Singh (2009)

Table 8: **Total area and the forest cover trend during 1991-2005 in the northeastern states of India**

State	Total geographical area (km²)	Forest cover (km²)					
		1991	1995	1999	2001	2003	2005
Arunachal Pradesh	83,743	68,757	68,621	68,847	68,045	68,019	67,777
Assam	78,438	24,751	24,061	23,688	27,714	27,826	27,645
Manipur	22,327	17,685	17,558	17,384	16,926	17,219	17,086
Meghalaya	22,429	15,875	15,714	15,633	15,584	16,839	16,988
Mizoram	21,081	18,153	18,576	18,338	17,496	18,430	18,684
Nagaland	16,579	14,321	14,291	14,164	13,345	13,609	13,719
Sikkim	7,096	3,041	3,127	3,118	3,193	3,262	3,262
Tripura	10,486	5,535	5,538	5,745	7,065	8,093	8,155
Total	262,179	168,118	167,486	166,917	169,368	173,297	173,316

Source: Chettri et al. (2010)

The grasslands of the Tibetan Plateau. The Qinghai-Tibetan Plateau of China, situated at an average elevation of 4,500 masl, is one of the greatest wilderness areas on the planet. It is comprised of a geographical area of 2.5 million km², 1,000 km north to south and 2,500 km from east to west, and plays a significant role in thermal forcing of the atmospheric circulation in Asia. It is one of the largest grassland and wilderness areas in the world: it accounts for 1.7% of the earth's land surface and 2.5% of the global soil organic carbon storage pool. The permafrost area (subsurface earth material remaining below 0°C for two or more years) is 1.3–1.6 million km², storing about 12,300 million tonnes of carbon or 37% of the total carbon of the grasslands (Wang et al. 2008). Moreover, its grasslands (alpine cold steppe and alpine meadows) occupy 60% of the plateau and are the largest stretch of grasslands in the world (storing 7.4 Pg or 7,400 million tonnes of carbon). The alpine soil in swamps contains 14.4 kg/m² of organic carbons (Environment and Development Desk 2009).

Grasslands in the HKH region are most commonly found in alpine areas, occurring as islands of various sizes near mountain tops. They are extremely rich in species; and more than 1,900 species of vascular plants are found in the western alpine zone of the Himalayas alone (Tambe and Rawat 2010) where vascular plants dominate in ecological terms. This arid plateau has been used by pastoralists for centuries, but now the region is facing widespread land degradation. Although it is difficult to assess the impact of small temperature increases during the growing season and large increases during the non-growing season on grassland productivity; nevertheless, climate change and related factors are generally believed to lead to a desiccation trend due to reduced precipitation; reduced rangeland production because of warming; reduction in the depth and extent of permafrost; and glacial recession. The following factors have been observed.

- Based on remote-sensing data, Piao and Fang (2002) documented a roughly 1% annual increase in net primary productivity across the entire Qinghai and Tibet Autonomous Region from 1982–1989, and this was supported by an observed increase in the normalised difference vegetation index (NDVI), an indicator of biomass and productivity from 1985–1999 (Xu and Liu 2007).
- Other researchers, however, have shown an inconsistent relationship between temperature and normalised difference vegetation index (Zhang et al. 2007) or a negative relationship (Klein et al. 2004).
- The Tibetan Plateau has about 50% of the natural wetlands in the world (primarily salt marsh, peatland, and freshwater marsh): during recent decades the freshwater wetland area in the plateau decreased from 133,000 km² to 48,070 km² (Environment and Development Desk 2009).
- Harris (2010) argues that reduced precipitation and decrease in grasslands due to glacial recession are not scientifically proven, and that the effect of loss of permafrost on grasslands could only be seen in some areas. Precipitation data show either no change or a change towards a wetter climate (Harris 2007).
- The major cause of the widespread degradation of the Tibetan Plateau is thought to be global climate change, compounded by overstocking, unscientific livestock management, excessive numbers of herbivores,

and disturbance from small mammals such as pika (Harris 2010). Several controversial measures have been undertaken to combat the problems, including killing pikas and other small mammals by spreading toxins over 320,000 km^2 of the plateau and encouraging sedentarisation of pastoralists without ascertaining the long-term ecological and economic viability (Wu and Yan 2002; Yan et al. 2005; Davidson et al. 2008).

- A decrease in vegetation cover, including from human activities, might lead to a loss of permafrost (Wang et al. 2008). One study found a correlation between the depth of frozen soil and biomass of vegetation (Li et al. 2008). It is quite plausible that loss of permafrost or thinning of seasonally frozen soil caused by increased temperatures could be a substantial cause of grassland degradation (Harris 2010) since changes in the availability of water and nutrients when permafrost is lost might affect species' composition and productivity.

Changes in the carbon pool. Thawing of permafrost and loss of grasslands and wetlands for a variety of reasons are likely to lead to emission of greenhouse gases and changes in the carbon pool. Recent observations include the following.

- The permafrost temperature in the source areas of the Yangtze and Yellow rivers rose by 0.11–0.14°C between 1980 and 1998. Thawing permafrost is a large source of greenhouse gases as microbial decomposition of previously frozen organic carbon releases CO_2 and CH_4 (methane) into the atmosphere.
- Annual methane emissions from fresh wetlands are estimated to be 0.7–1.05 tonnes (average 0.8 million tonnes) during the period; the sum of CO_2, NO_2, and CH_4 is 68 million tonnes of CO_2 equivalent annually (equal to CO_2 emission in China of 10 million average automobiles for two months) (Environment and Development Desk 2009).
- The water level in the great lake Tso Ngonpo decreased by 3.62 m between 1959 and 2005, resulting in a 342 km^2 loss in area.
- Between 1980 and 2000 the Tibetan grasslands have lost 1.8 million tonnes of C from 30-cm deep soil largely because of degradation. The extent to which climate change is responsible is unclear, however (Wang et al. 2008).

Atmospheric Changes

How black carbon contributes to climate change

Until very recently, greenhouse gases were thought to be the main cause of global warming and the underlying reason for the melting of glaciers in the Himalayas. There is now, however, increasing evidence that indicates that air pollution originating in the rural areas and cities of South Asia is contributing significantly to the changes that are taking place in the ice and snow cover in the mountainous areas of the HKH region. Air pollution on the Indian sub-continent consists mainly of anthropogenic aerosols such as the dust, smoke, fly ash, and soot, which result from the incomplete combustion of fossil fuels, including the open burning of biomass used for cooking and heating. The key compounds include black carbon (BC) particulates and other gases such as those emitted by the combustion process. The O_3 in the troposphere is formed when methane, volatile organic compounds, carbon monoxide and oxides of nitrogen are exposed to sunlight and undergo photochemical reactions. Decesari, Facchini, Carbone et al. (2010) documented the effect of orographic transport of carbonaceous and sulphate particles upslope to the Himalayas and showed that the valley breeze

Box 9: **The atmospheric brown cloud**

- Atmospheric pollutants from adjacent areas in the plains accumulate in the troposphere where they cause a pollution accumulation commonly referred to as the 'atmospheric brown cloud'. They are transported from the lowlands to the high snow-clad regions of the HKH region both by up-valley winds and through long-range transport and are eventually deposited on the snow and ice fields there.
- Black carbon and other air pollutants induce radiative forcing that has consequences for the monsoon circulation patterns and rainfall; moreover, they are noxious to both human health and agricultural crops.
- There is evidence to suggest that atmospheric black carbon can cause melting by increasing tropospheric temperature and that when it is deposited in the high-altitude areas of the HKH region it can enhance glacial melting by reducing the albedo of ice and snow.
- Black carbon, the solid particulate component of the atmospheric brown cloud, has a residence time of only a few weeks in the atmosphere and even during the dry season it is relatively short lived: it is routinely and easily removed by rain.

circulation in the high Himalayas provides an efficient mechanism for the transport of anthropogenic aerosols into the Asian upper troposphere (>5,000 masl). When these particles and pollutant gases accumulate in the troposphere in sufficient concentration, they scatter and absorb solar radiation and become visible as an 'atmospheric brown cloud' (ABC) (Box 9).

Ozone and atmospheric black carbon are thought to be major contributors to radiative forcing (Table 9 and Figure 16). Black carbon is transported in the atmospheric brown cloud to locations far from its sources of origin (Ramanathan et al. 2007b), and high concentrations of black carbon have been observed in the air and in ice/snow core samples taken from high-altitude areas in the HKH region. It is thought that when black carbon is deposited on snow and ice surfaces it reduces the albedo and can cause snow and ice to melt (e.g Flanner et al. 2009).

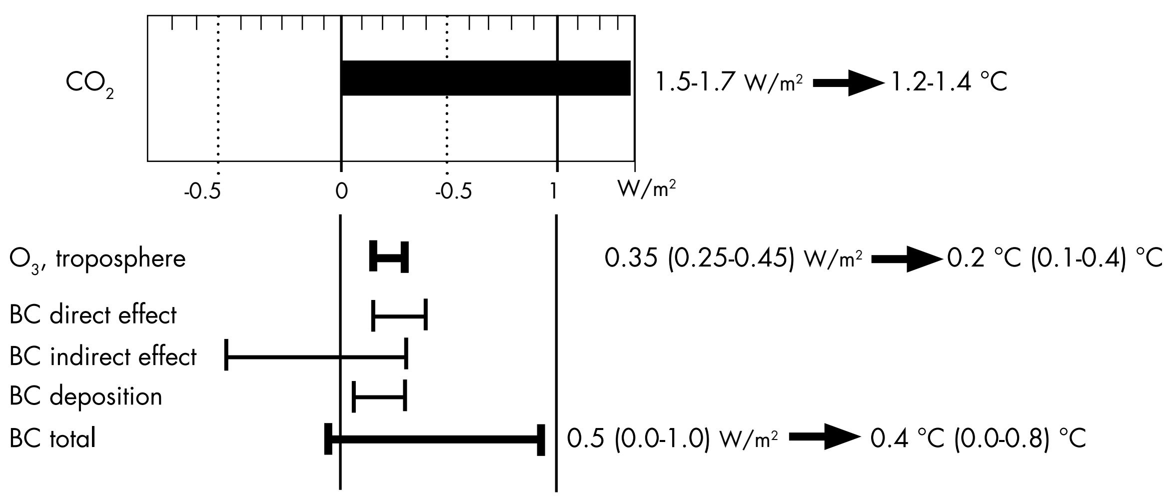
The current annual global black carbon emission is estimated to be 8 Tg (10^{12} g or 1 million tonnes), of which nearly 84% is from developing countries and 60% is anthropogenic (Ramanathan and Carmichael 2008). The major sources of black carbon in the atmosphere are from open burning (3.5 Tg/yr), from residential burning for cooking and heating (2 Tg/yr), and from the use of fossil fuels for transportation (1.5 Tg/yr). Man-made fires which are common during the dry season in agricultural areas of developing countries are also a source of black carbon

Table 9: **Estimated climate forcing (W/m²) of black carbon in comparison to CO_2 and other greenhouse gases**

Component	Estimated climate forcing (W/m²)*	Estimated climate forcing (W/m²)**
CO_2	1.66	1.50
BC**	0.05–0.55	0.8
CH_4	0.48	0.55
Tropospheric ozone	0.35	0.40
Halocarbons	0.34	0.30
N_2O	0.16	0.15

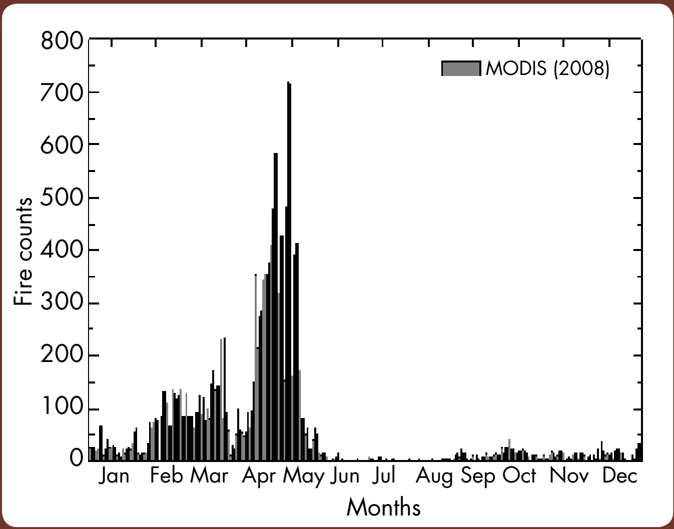
Source: * IPCC (2007); ** Hansen et al. (2004)

Figure 16: **Radiative forcing by black carbon (BC) and O_3 in comparison to CO_2**



Source: Derived from IPCC (2007)

Figure 17: **Seasonal changes in fire counts in India**



Source: Dumka et al. (2010 and 2011); Naja and Sagar (2011)

(Figure 17). Anthropogenic emissions of black carbon from the HKH region and the other Asian countries amount to 3.2 Tg/yr. The emission of black carbon in Asia, particularly from China, increased dramatically between 2000 and 2006 (Koch et al. 2009; Zhang et al. 2011) (Table 10). However, it should be considered that changes in emission estimates are due not only to actual growth or reduction of emissions, but also to emission inventory improvements. Based on the model study by Kopacz et al. (2011), the main contributors of atmospheric black carbon in the HKH region vary from season to season and location to location but are believed to originate from northern India, central China, Nepal, Pakistan, the Middle East, and Africa.

Table 10: **Percentage change in black carbon emissions in China and throughout Asia between 2000 and 2006**

	Power	Industry	Residential	Transport	Total
All Asia	41.3	406.9	902	103.0	46.9
China	424.9	546.8	28.4	231.9	93.5
Other Asia	-94.5	108.5	243.1	163.4	127.7
South East Asia	-28.0	6.3	15.4	63.8	20.0
South Asia	249.4	272.0	-34.7	6.4	-18.8

Source: Koch et al. (2009); Zhang et al. (2011)

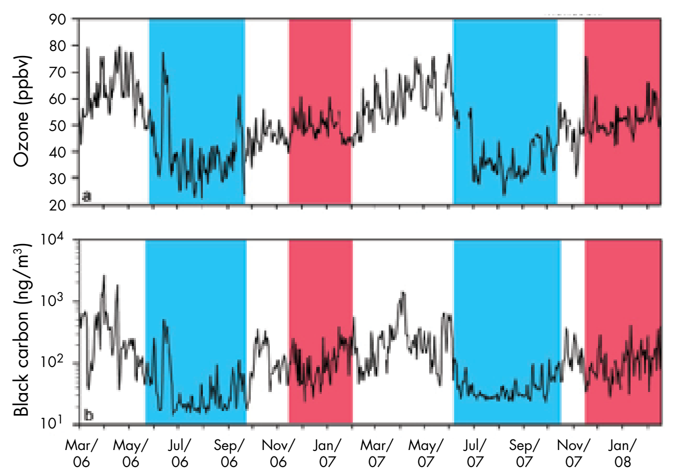
Optically active aerosols and ozone in the HKH region are of concern not only because they cause regional radiative forcing in the atmosphere, but also because surface O_3 can severely affect biodiversity and agricultural crops (Agarwal et al. 2008). Black carbon heats the atmosphere and disturbs the local heating profile and convection, thus being able to affect the precipitation patterns (Ramanathan et al. 2007a, 2007b; Ramanathan et al. 2008). Black carbon and other absorbing aerosols can affect monsoon circulation. The 'elevated heat pump' theory (Lau et al. 2006) suggests that together with mineral dust, the presence of large amounts of black carbon at higher altitudes of the Himalayan foothills can draw more moisture to this region during the pre-monsoon, intensifying the early monsoon. Observations show a widespread and sustained warming in the pre-monsoon season over the last three decades over the Himalayan-Gangetic region, with a 20% early monsoon rainfall increase; this suggests a close link between pre-monsoon tropospheric warming and the increased aerosol loading over this specific region (Gautam et al. 2009a, 2009b). Nigam and Bollasina (2010) suggested that the increased aerosol concentration in May can lead to cloud suppression and enhanced surface shortwave radiation reaching the region, thus indicating a further mechanism, in addition to tropospheric warming, that could strengthen the land-sea temperature gradient. All these factors can greatly affect the hydrological cycle and cryosphere in the Himalayas. Some estimates attribute more than 30% of the melting of ice and snow in the HKH region during the last century to the combination of the radiative forcing associated with black carbon and to deposited black carbon which lowers the albedo of snow and ice (Ming et al. 2009). It was estimated that black carbon causes a global radiative forcing of approximately 0.9 W/m^2, (range: 0.4–1.2 W/m^2), which is more than half of the forcing attributed to CO_2, and the second highest overall after CO_2 (Ramanathan and Carmichael 2008).

The atmospheric warming induced by atmospheric black carbon on the south slope of the Himalayas could be sufficient to account for the glacial recession that is being observed in the region (Ramanathan et al. 2007a). Moreover, elevated amounts of absorbing aerosols can affect the mountain cryosphere in several ways. Additionally, even small amounts of black carbon can significantly modify snow reflectance, thus altering snowmelt rate and snow spatial coverage, which influence the climate through the snow-albedo feedback. Flanner et al. (2009) showed that the absorption by BC impurities in snow exceeds the 'dimming' atmospheric effect and becomes significant for BC concentrations greater than 10 ng/g. These processes may lead not only to significant global snow/ice/climate feedback but also, at a regional scale, to critical changes in the local hydrology and water availability related to glacier and snow discharge. However, the impact of black carbon also depends on the ratio of organic carbon to black carbon since, if more carbon is present as organic carbon, less black carbon is available for radiative forcing.

Observations of black carbon

Anthropogenic pollutants such as black carbon and O_3 do not originate in large quantities from the HKH region, although large urban centres like the Kathmandu Valley, for example, do produce a visible pollutant load. During the pre- and post-monsoon dry seasons, pollutants are mainly transported to the highlands from lowland urban and rural areas, and circulated along valleys (Bonasoni et al. 2011) (Table 11 and Figure 18). The high pollution levels noted at several sites during the dry summer months of April and May are largely due to the strong far westerly circulation and regional-scale air mass transport from the Gangetic Plains and China.

Figure 18: **Average daily concentrations of surface ozone and black carbon measured at the Nepal Climate Observatory – Pyramid (5,079 masl, near Everest base camp in the Khumbu Valley)**



Note: June to September is the monsoon period; during this time the concentration of pollutants is low and the concentration of pollutants rises soon after the monsoon and peaks during the dry period from April to May.

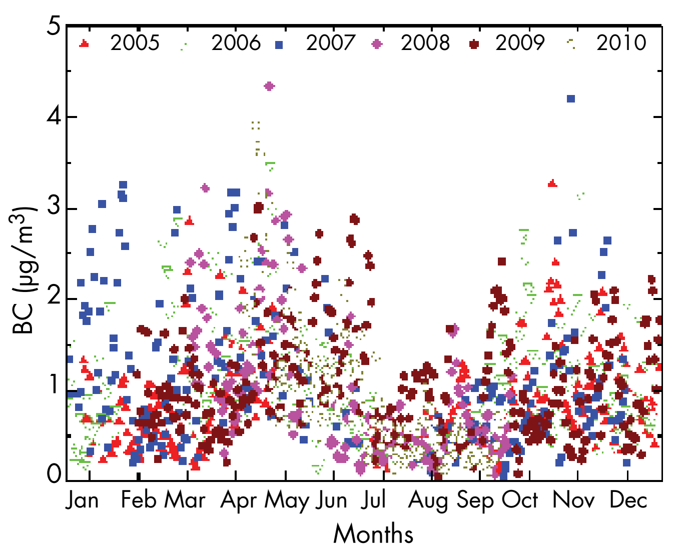
Source: Adapted from Bonasoni et al. (2011)

Table 11: **Concentration of particulate matter, black carbon, and other pollutants in the HKH region**

Site	Source	Concentrations
Langtang, Nepal; 3,920 masl 28.13°N, 85.60°E	Carrico et al. (2003) period: 1998–2000	Elemental carbon high from October to May (0.52±0.48 to 0.48±0.38 μg/m²) Elemental carbon low during the monsoon months of July to September (0.15±0.16 μg/m²)
Nagarkot, Kathmandu Valley, Nepal 2,150 masl	Carrico et al. (2003)	Aerosols high from February to May ($PM_{2.5}$ = 59 ± 61 μg/m³) and low June through September ($PM_{2.5}$ = 8 ± 7 μg/m³)
Manora Peak (Nainital, India) 1,950 masl 29:37°N, 79.45°E	Pant et al. (2006)	Total suspended particles:15–40 μg/m³ Mean total suspended particles: 27.1 ± 8.3 μg/m³ Black carbon: 1.36 ± 0.1 μg/m³ (about 5% of composite aerosol mass)
	Ram et al. (2010)	Elemental carbon monthly average: 1.7–1.9 μg/m³ Elemental carbon high: 8.8–12.3 μg/m³ (winter/spring)
	Dumka et al. (2010)	Black carbon concentration higher during spring, mean: 1.34±0.05 μg/m³
	Ram et al. (2010)	Average organic carbon/elemental carbon ratio 7.7–3.4 (based on 86 samples), highest single value: 27.2 The high ratio and other features of the composition indicate that the source was biomass burning in the Indo-Gangetic plains.
	Kumar et al. (2010) period: 2006–2008	O_3 maximum: 67.2 ± 14.2 ppbv (May) O_3 minimum 24.9 ± 8.4 ppbv (August)
Godavari observatory Nepal; 1,600 masl 27.59°N, 85.31°E	Stone et al. (2010)	Average $PM_{2.5}$ = 26 ± 19 μg/m³ Maximum $PM_{2.5}$ =120 ±10 μg/m³ (January) Minimum $PM_{2.5}$ < 8 μg/m³ (August) Average organic carbon = 4.8 ± 4.4 μg/m³ Average elemental carbon = 1.0 ± 0.8 μg/m³
Pyramid observatory, Khumbu, Nepal; 5,079 masl; 27.95°N,86.82°E	Decesari et al. (2010)	Average yearly PM_{10} = 6 μg/m³ Average yearly organic matter 2.0 μg/m³ Maximum O_3 = 60.9 pp bv and BC = 316.9 ng/m³ (pre-monsoon) Minimum O_3 = 38.9 ppbv and BC = 49.6 ng/m³

Source: Developed from Bonasoni et al. (2011)

Figure 19: **Black carbon (BC) concentration at a lower mountain site (Nainital), India**



Note: The black carbon concentration is lowest during the months of the summer monsoon.
Source: Dumka et al. (2010)

The effect that pollution from lowland areas has on the pristine mountain areas of the HKH region has been observed in locations, such as Central Tibet (Ming et al. 2010) and Nainital in the Kumaun Himalayas (at 2,000 masl), which are affected by pollutants transported from the foothills at Pant Nagar (Figure 19). Marinoni et al. (2010) monitored aerosol mass and black carbon concentration at the Nepal Climate Observatory-Pyramid research station located at 5,079 masl near the base of Mt. Everest. They show that both black carbon and other particulates have a typical diurnal cycle which peaks during the afternoon indicting the major role that thermal winds play in transporting atmospheric aerosols over the high Himalayas. The aerosol concentration shows great variability and frequently includes 'background' components which are added when particulates are carried up valley by thermal winds and long-range transport/synoptic circulation. Higher concentrations of particulate matter <1 µm size (PM_1) and BC are mostly associated with regional circulation and westerly air masses from the Middle East; while high concentrations of mineral dust arrive from the Middle East by regional circulation, there are also notable contributions from North Africa and the South-West Arabian Peninsula, particularly during the post-monsoon and winter seasons. The monsoon rains are very effective in removing pollutants: during the rainy season, the ambient black aerosol concentration is reduced by more than 80%.

During the pre-monsoon summer period of 2006–2008 several intense episodes of black carbon and O_3 transport were recorded in the Himalayan region (Bonasoni et al. 2010). These aerosols originated in the large reservoirs at the foothills and/or in the upwind regions (Bonasoni et al. 2011). Each episode resulted in significant enhancements in O_3 (up to 13.6% increase) and black carbon (up to 522.3% increase) (Bonasoni et al. 2010). The day-time up-valley winds often lead to afternoon maxima of pollutants (~550 ng/m^3 for BC and ~6 mg/m^3 for PM_1) (Marinoni et al. 2010). Occasionally, these winds cause acute pollution events, with high concentrations of black carbon (5 µg/m^3) and O_3 (90–95 ppbv) approaching urban levels. Forest fires, open stoves, and the combustion of fossil fuels at both regional and long-range scales are considered to be the main sources of black carbon and O_3 precursors (ICIMOD 2011).

Observations from ice cores

Snow and ice core samples testify that air pollution from the plains can be transported to remote high-altitude HKH areas (Xu et al. 2006; Xu et al. 2009b). Core samples showed that the black carbon content in three glaciers on the south rim of the Tibetan Plateau increased rapidly between the 1950s and 2000, and that the concentration has almost doubled since the 1980s. Xu et al. (2009a) suggest that black carbon should reach these glaciers from the south during summer via the summer monsoon circulation and from the west during the spring and winter months. Ming et al. (2008) measured 40 m ice cores from a glacier in the Everest area and showed that black carbon concentrations have increased on average by 20.3 ± 9.2 µg/kg since the 1990s. There are also indications that pollutants from South East Asia have been deposited in Tibetan Autonomous Region. In samples collected from the Tibetan Plateau, Kaspari et al. (2011) have shown that the concentration of black carbon increased three-fold over the period from 1860–1975 to 1975–2000 (0.2±0.3 µg/litre to 0.7±1.0 µg/litre). Studies by Bonasoni et al. (2010) and others stress the importance of the Himalayan valleys in acting as efficient chimneys and favouring the transport of large amounts of brown cloud pollutants from the plains and foothills up to the high Himalayas.

Modelling changes induced by black carbon

The deposition of black carbon reduces the extent to which the white surfaces of snow and ice can reflect sunlight and consequently accelerates their melting. It has been estimated that 10 μg/m^3 of black carbon can increase the absorption of solar visible radiation by fresh snow by as much as 10–100% (Xu et al. 2009a). Ming et al. (2007) estimated the amount of black carbon deposited in the ice cover of Mt. Everest in 2001 and found that it was large enough to cause a summer darkening effect of 4.5 W/m^2. A total black carbon deposition of 266 μg/m^3 was estimated for the Khumbu glacier during the pre-monsoon period of 2006. This corresponded to black carbon snow-concentration of 26.0–68.2 μg/kg (Yasunari and Yamazaki 2009), and could result in 2.0–5.2% reduction in the albedo, and a subsequent 70–204 mm increase in runoff (i.e. about 11.6–33.9% of the annual discharge of a typical Tibetan glacier). These effects attributed to black carbon deposition cannot to be taken lightly, despite uncertainties about the estimates.

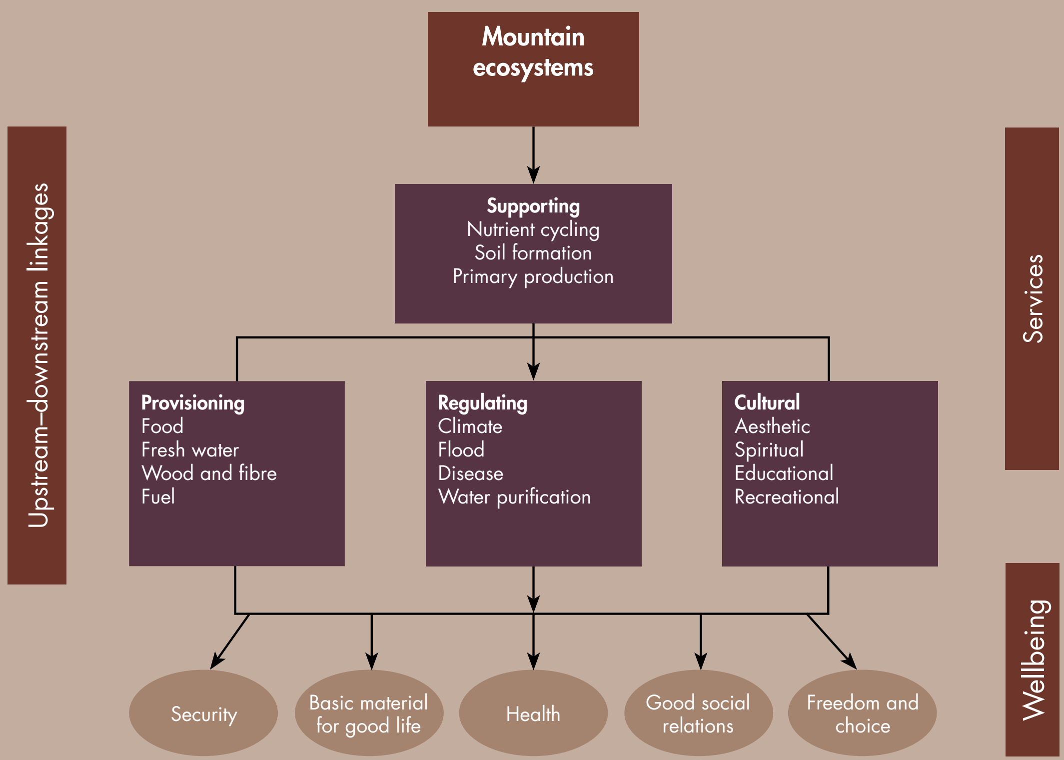
In a modelling study Qian et al. (2011) showed that a large amount of black carbon content (>150 μg/kg) in snow and high incident solar radiation in the subtropical latitudes and high altitudes can combine to bring about large surface radiative flux changes over the HKH region accounting for as much as a 2–4% reduction in surface albedo. Simulations by Kopacz et al. (2011) also showed that northern India, central China, and Nepal contributed over 90% of the black carbon in the atmospheric column in the Mt. Everest region. The study estimated that black carbon contributions by India, China, and Nepal to the air column over Mt. Everest were as much as 15, 12, and 10 tonnes per day, respectively. Significant contributions of black carbon were also shown to originate from as far off as Africa (burning of biomass) and the Middle East (from the combustion of fossil fuels). Based on data collected over Manora peak in Nainital, India, Pant et al. (2006) have estimated that atmospheric aerosols can have a forcing efficiency that could be as high as 88 W/m^2 over the western Himalayas.

Black carbon and other atmospheric pollutants are capable of modifying the atmospheric and surface energy balance, of altering atmospheric circulation and precipitation patterns, cloud coverage, rate of snow-melt, and snow coverage (Bonasoni et al. 2011). In addition, these pollutants are suspected to affect leaf structure, leaf physiology, plant growth, and productivity adversely. The models discussed above give some preliminary estimates of what can be expected but more work is needed in this important area to ascertain the extent to which atmospheric pollutants can modify climate in the HKH region especially since the results can have significant policy ramifications.

3 Impacts

Until recently ecosystem services have been available in sufficient abundance; however, climate change is now adding to other environmental pressures which are working to degrade and deplete them. It is important to consider the possible impacts of measured and predicted climate change on people and the environment, in order to assess the type and level of responses that may be needed and to evaluate present and future planning approaches. In the case of the HKH region, there is a strong relationship between upstream and downstream populations in the context of ecosystem services and human wellbeing. Predicting likely impacts, however, is a rather speculative undertaking. The systems in which people live are very complex, and any impacts of climate change on these will be equally complex. Human 'wellbeing' is a multifaceted quality that encompasses: good life, health, good social relations, security and freedom of choice and action – all of which ultimately depend on the availability of good ecosystem services and all of which contribute to political stability. At the same time, climate change is embedded in a wealth of other drivers of change that may influence the impacts in a variety of ways by amplifying, masking, or even compensating for them. The prediction of climate change effects is still open to a high degree of uncertainty also, as outlined in the previous chapter. Nevertheless, some of the possible impacts can be discussed based on past experience and current observations and understanding. The possible impacts can be grouped broadly into the categories of supporting, provisioning, regulating, and cultural services (Figure 20). In the case of the HKH region, there is a strong relationship between upstream and downstream populations in the context of ecosystem services and human wellbeing. In this section we consider impacts related to water, biodiversity, human health, disasters, and agriculture. In the second section we show how models can be used to predict impacts based on anticipated changes in temperature and precipitation. In the concluding section of this chapter we consider the observational data collected not by scientists but by farmers who are in close daily contact with the ecosystems and who should be among the first to notice changes in temperature and precipitation.

Figure 20: **How the mountain ecosystem provides services for the wellbeing of people in the mountains and those downstream**



Impacts Related to Water

Water, wetlands, and hazards

As the mountains are the source of the region's rivers, the impact of climate change on hydrology is likely to have significant repercussions, not only in the mountains, but also in populated, lowland regions that depend on mountain water resources for domestic, agricultural, and industrial purposes as well as hydropower generation. Significant shifts in climatic conditions may also have an effect on social and economic systems in the region through changes in demand, supply, and water quality.

Natural systems related to snow, ice, and frozen ground (including permafrost) are being affected through the enlargement and increased number of glacial lakes, increasing ground instability in permafrost regions, and rock avalanches in mountain regions. Widespread mass losses from glaciers and reductions in snow cover over recent decades are projected to accelerate throughout the twenty-first century, reducing water supplies and hydropower potential as well as changing the seasonality of flows in basins supplied by meltwater from snow and ice.

Increased temperatures will affect the physical, chemical, and biological properties of wetlands, freshwater lakes, and rivers with predominantly adverse impacts on their thermal structures, freshwater species, community composition, and water quality. Winter precipitation in the form of snowfall has declined over the years and the area under snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions. Drought-affected areas are projected to increase in extent, leading to substantial increases in the need for water for irrigation. The beneficial impact of increased annual runoff in some areas is likely to be tempered by the negative effects of increased variability in precipitation and seasonal shifts in runoff on water supply, water quality, and flood risk. Available research suggests that a significant increase in heavy rainfall events in future will result in an increased flood risk to society, physical infrastructure, and water quality. Increases in the frequency and severity of floods and droughts are projected to have an adverse affect on sustainable development. Shrestha et al. (2003) suggest that the number of flood days and consecutive days of flood events have been increasing in Nepal. Increases in glacial melting and likely increases in runoff will also heighten the risk of glacial lake outburst floods.

Surface water availability

Water availability, in terms of both temporal and spatial distribution, is expected to be extremely vulnerable to climate change. Some areas are expected to experience an increase in water supplies; other areas will have reduced water resources. The contribution of snow to the runoff of major rivers in the Eastern Himalayas is about 10%, but in the western Himalayas it is more than 60% (Vohra 1981). The greatest melting season for snow coincides with the summer monsoon, and any intensification of the monsoon is likely to contribute to flood disasters in the catchments of the Eastern Himalayas, although the impact will be less than in the Western Himalayas. The supply of water in the Eastern Himalayas is limited and governed by the renewal processes associated with the hydrological cycle. A warming climate will generally enhance the hydrological cycle resulting in higher rates of evaporation and a greater proportion of liquid precipitation (more rain and less snow). The potential changes in precipitation (amount and seasonality) will affect soil moisture, groundwater reserves, and the frequency of flood and drought episodes. Hydrological systems are controlled by soil moisture also, and this largely determines the distribution of ecosystems, groundwater recharge, and runoff: the latter two factors sustain river flow and can lead to floods. The impacts of these on freshwater biodiversity are uncertain, however. Given these possibilities, different impacts of these changes to the water cycle will have different consequences in different watersheds.

The seasonal character and amount of runoff are closely linked to the wetland ecosystems and the cryospheric processes of snow, ice, and glaciers. Glacial melt influences discharge rates and timing in the rivers that originate in the mountains. The timing of peak runoff, associated with the monsoon in many Eastern Himalayan river basins, may change in future. Shifts in the timing and intensity of the monsoon, and the manner in which the Himalayan range intercepts the available water content in the atmosphere, will have major impacts on the timing and amount of runoff in river basins such as the Ganges, the Brahmaputra, and the Irrawaddy.

When evapotranspiration is less than precipitation, water flow will increase. Increased glacial runoff and the thawing of permafrost due to warming will initially add to increases in flow in glacier-fed systems (for a period of decades, until this runoff eventually subsides). Increased water flow could change stream channel morphology by causing erosion along the banks and depositing sediments elsewhere. Such changes in channel morphology have direct links to the lifecycles and habitat requirements of freshwater species (e.g., fish spawning and rearing), which in turn can have direct impacts on population levels.

Freshwater ecosystems

There is growing concern that climate change may accelerate the damage to wetlands and freshwater ecosystems such as lakes, marshes, and rivers. The response of lakes and streams to climate change will involve complex interactions between the effects of climate on runoff, flow volume, hydrology, catchments, and in-lake processes. Climate change is expected to increase the temperature of lakes, streams, and other water bodies with unpredictable consequences for many aquatic species. In lakes and streams, warming will have the greatest biological effects at high altitudes. Altered precipitation and temperature patterns will affect the seasonal pattern and variability of water levels in wetlands, potentially affecting valued aspects of their functioning such as flood protection, carbon storage, water cleansing, and waterfowl/wildlife habitat (IPCC 1998). The geographical distribution of wetlands is likely to shift with changes in temperature and precipitation, with uncertain implications for net greenhouse gas emissions from wetlands. Changes in these ecosystems could have major negative effects on freshwater supplies, fisheries, biodiversity, and tourism. Inputs of nutrients and other pollutants into aquatic habitats will vary with rainfall and other characteristics of the watershed. One of the ways that climate change could affect freshwater biodiversity is by altering the carbon to nitrogen (C:N) ratio in riparian vegetation (Allan et al.2005). This change in nutrient quality could lead to corresponding changes in biological assemblages, enhancing organisms that use carbon efficiently, while suppressing those that depend on larger nitrogen inputs.

Water storage

Water in the HKH region is retained in the form of ice and snow in the high mountains, as well as being stored in natural lakes, wetlands, and groundwater aquifers and behind constructed dams (Vaidya 2011). Climate change is likely to result in an extensive decrease in this storage capacity which could have profound impacts on the hydrological regimes of the ten river basins originating in the HKH region. The Himalayas have a huge glaciated area which provides important short- and long-term water storage facilities in the form of glaciers, glacial lakes, and as permafrost. Glaciers were discussed at length in the preceding chapter, but the area covered by permafrost is even larger than that covered by glaciers or perennial snow, especially in the Tibetan Plateau, China, which has approximately 1,360,000 km^3 of perennial permafrost (Li and Cheng 1999). Recent studies show that the extent of permafrost is shrinking, that the thickness of the active layer (the upper portion of soil that thaws each summer) is increasing, and that this has altered the hydrological cycle, vegetation composition, and carbon dioxide and methane fluxes which appear to be linked to permafrost degradation. The Himalayas also have many lakes with an enormous capacity for water storage. High-altitude wetlands account for around 16% of the total area of the HKH region and play an important role in water storage and regulating water regimes (Trisal and Kumar 2008). They maintain water quality, regulate water flow (floods and droughts), and support biodiversity. The Himalayan wetlands are under pressure from drainage for agriculture, tourism related pollution, overgrazing, and climate changes. Groundwater aquifers are important for water storage in the Himalayan region, but there are few data available to enable assessment of the change and uses of groundwater on a regional scale.

Impacts on Frequency and Intensity of Natural Hazards and Disasters

The frequency and intensity of extreme weather events is one of the predicted consequences of climate change. The effect that this will have on the human population is likely to be more severe in the HKH region than elsewhere because the region consists of young mountains (250 million years) that are still growing and is thus already inherently vulnerable to earthquakes, landslips, and erosion. The physiographic and climatic characteristics of the region make it prone to a high incidence of both geological and hydrometeorological hazards (SAARC 2008).

Data analysis suggests that, of the total annual disasters in the HKH region, 14% are earthquakes and landslides; 48% are hydrological (36% flood, 9% mass movement, 3% drought); and 38% are other types such as storms (23%), wild fires (1%), extreme temperature events (6%), and epidemics (8%) (Guha-Sapir et al. 2011). Extreme weather events as a consequence of climate change will compound the HKH region's well-documented tendency for disasters with concomitant consequences for human health and wellbeing as well as for economic and human losses.

Impacts on Biodiversity

Warming is strongly linked to the changes observed in terrestrial biological systems such as those discussed in the previous chapter, including changes in the boundaries of forest types and areas, primary productivity, species populations and migration, the occurrence of pests and diseases, and forest regeneration. A recent study by Tse-ring et al. (2010) summarises the most important climate change threats to biodiversity in the Eastern Himalayas. Such studies will need to be repeated for the entire HKH region (Table 12).

The increase in GHGs also affects species' composition and the structure of ecosystems, which, in turn, affects ecosystem functions (Schutze and Mooney 1994). The interaction between elevated CO_2 and climate change plays

Table 12: **Summary of priority climate change threats to biodiversity in the Eastern Himalayas**

Species at risk	Although there could be some benefits for at risk species, in general, there is significant concern for species at risk that are already threatened by small population size, loss of unique habitats, and low reproduction/dispersal rates (among others). Any potential for climate change to further exacerbate these existing causes could greatly increase the risk of extinction.
Aquatic habitats	Extended summer low flow periods are expected in rainfed streams. This will further increase water temperature, favouring warm water species and altering community structure and functioning. Conversely, in snowmelt and glacier-fed streams, the magnitude and duration of summer floods is expected to increase. In either case, significant impacts on aquatic habitats are expected.
Wetlands	Wetlands are particularly vulnerable to climate change. As physiographically limited systems, they are unable to migrate and, hence, are vulnerable to changes in hydrology, nutrient inputs, and others.
Alpine ecosystems	Given their restricted geographic area and narrow elevation range, alpine ecosystems are particularly vulnerable to climate change. Climate and vegetation change rapidly with altitude over relatively short distances in mountainous terrain. As a result, alpine ecosystems are particularly vulnerable to encroachment by lower elevation ecosystems.
Forest and grassland ecosystems	The current pine bark beetle epidemic is a matter of serious concern. Ongoing concerns include the increased potential for major widespread wildfires and the subsequent potential for transformations in disturbed ecosystems, such as colonisation by invasive species and resultant new species assemblages. Grassland ecosystems may expand in range, yet face threats in terms of lost species diversity.
Invasive species	Climate change may expedite the colonisation of some areas by invasive species in both terrestrial and freshwater realms. Increased frequency and magnitude of forest disturbances will create openings vulnerable to colonisation by invasive plants.
Protected area ecosystems	Protected areas are widely acknowledged as one of the most important management instruments for biodiversity conservation. In the EH, protected area systems are some of the most intricate and complex, maintaining a delicate balance between conservation and sustainable use. The potential for major, long-term ecosystem shifts under a changing climate suggests a need to re-evaluate the protection of representative ecosystems with a stronger focus on the landscape approach as it is based on broad topographical features that do not shift with climate change.

Source: Tse-ring et al. (2010)

an important role in the overall response of net primary productivity to climate change at elevated CO_2 (Xiao et al. 1998). Climate change will have a profound effect on the future distribution, productivity, and health of forests. Similarly, species may respond to changes in climatic variables by adapting, shifting their range, changing their abundance, or disappearing altogether. Species will shift their geographic ranges at different rates, and some may be unsuccessful in reaching or colonising new habitats.

Studies of satellite observations since the early 1980s indicate that there has been a trend towards the early 'greening' of vegetation in the spring, linked to longer thermal growing seasons due to recent warming (Dye and Tucker 2003; Shabanov et al. 2002). Changes in phenology are expected to be the primary short-term response to climate change (Root and Hughes 2005). Organisms will hatch, bud, or breed earlier in the year in response to warming trends. Migratory species are particularly vulnerable as a discrepancy could develop between the timing of migration and the availability of food. Pollination could also be affected when the timing of blooming is no longer synchronised with insect activity. Hence, both the structure and functioning of ecosystems could change. If climate change is more rapid than the capacity of species to migrate, the probability of species' extinction and disruption of ecosystems is great (Halpin 1994).

Changes in species' abundance, distribution, and phenology suggest changes in species' fitness in response to climate change. New community assemblages and interactions resulting from climate change will also exert evolutionary pressure on species. Subpopulations at the warmer edges of species' ranges are being extirpated, causing a loss in genetic diversity (Thomas 2005). Another mechanism is that dominant species are replaced by pioneer species from the same community that have enhanced capabilities for adaptation (Halpin 1994 and Pauli et al. 1998). Another possibility is that climate change may favour less dominant species, which then will replace dominant species through competition (Street and Semenov 1990). Jeong et al. (2011) have looked at phenological changes over an extended period and Chen et al. (2005) have looked at changes in eastern China. Recently, Yu et al. (2011) made an important contribution to phenology in which they have looked at the result of winter and spring warming in delaying spring phenology on the Tibetan Plateau.

Impacts on Agriculture and Food Security

As a result of their gradual integration into regional and global markets, mountain societies in the HKH region have been moving increasingly from subsistence farming to market-based agricultural production and cash crops, even though opportunities for intensive arable agriculture are limited by the biophysical conditions which are characterised by rugged mountains, steep slopes, high altitudes, harsh climates, and a fragile environment. A vast area of the HKH region consists of rangelands where 30 million people depend on livestock for their livelihoods. In parts of Afghanistan, Bhutan, China, India, Nepal, and Pakistan, livestock production, particularly for meat and wool, plays a major role in food security and income generation. All of these contribute to ensuring food security, and are likely to be affected by climate change.

Agriculture is very sensitive to climate change, but it is expected that the impacts across the region will be different, with some places projected to experience a decline in potentially good agricultural land, while others will benefit from substantial increases in suitable areas and production potentials (Fischer et al. 2002a). The main direct effects of climate change will be through changes in factors such as temperature, precipitation, length of growing season, and timing of extreme or critical threshold events relative to crop development, as well as through changes in atmospheric CO_2 concentrations (which may have a beneficial effect on the growth of many crop types). The positive effects of climate change – such as longer growing seasons, lower natural winter mortality, and faster growth rates at higher altitudes – may be offset by negative factors such as changes in established reproductive patterns, migration routes, and ecosystem relationships. Several studies in the past have shown that the production of rice, corn, and wheat has declined due to increasing water stress arising partly from increasing temperature, the increasing frequency of El Niño, and a reduction in the number of rainy days (Agarwal et al. 2000; Jin et al. 2001; Fischer et al. 2002b; Tao et al. 2004). According to a recently released Action Aid (2011) report, Bangladesh and India are among the world's ten countries most vulnerable to food crises and hunger induced by climate change, while Pakistan is one of the countries least prepared for future climatic changes.

The question arises of whether there are any specific factors related to climate change responsible for food insecurity in the HKH region (Iqbal et al. 2011). Recent instances of food inflation showed how vulnerable large sections of the population still remain to food insecurity and how food shortages can cause social instability and human injustice. Ghosh and Sharma (2011) have examined land use, agriculture, and food security for the Himalayan regions of India. It is difficult to segregate these from global and local drivers since local processes often are influenced by various mechanisms associated with globalisation and economic integration (ICIMOD 2008b). Chief among these economic driving forces are the following.

- Declining growth in grain production since the mid-1990s driven largely by intense competition in global markets from cheap food grain produced by developed countries with high subsidies. As a result, many farmers in the HKH region have substituted food crops with other crops (Chand et al. 2008) and some have even abandoned their land, as observed in Nepal, for example.
- Conversion of cropland to other uses mainly as a result of increased urbanisation, industrialisation, and population growth (see for example Lichtenberg and Ding 2008; Xu et al. 2006; Chen 2007; Deng et al. 2006). In addition to the conversion of cropland for other uses, there has been an increasing trend in almost all the HKH countries to substitute food crops with cash crops such as horticultural products, ginger, vegetables, and other high-value cash crops (Tulachan 2001).
- Abandonment of agricultural land, particularly in Nepal, as a result of the low returns, a shortage of labour caused by rural out-migration for additional earnings, and highly unequal distribution of land with lack of land ownership by the tenants (Khanal and Watanabe 2006).

Climate change will likely shorten the growing season and alter conditions; higher temperatures will enhance the transpiration of plants which will lead to increase in water demand; soil texture and the organic content of soil can change; and the incident of diseases and transboundary movement of species will introduce new challenges. Ravindranath et al. (2011) have recently developed a set of indicators for the key vulnerability sectors, such as agriculture, forest, and water, to calculate the future vulnerability to climate change in the northeastern region of India. Agriculture, particularly rainfed agriculture, is extremely sensitive to climate change and probably will be affected (Ramay 2011). Recently Kumar et al. (2011) investigated how climate change would affect crop productivity in the northeastern region of India and found that by 2030 the production of irrigated rice would increase by up to 5% but that the areas where rainfed rice could be cultivated would probably decrease by 10%. They went on to predict a 40% reduction in the production of irrigated maize and a reduction of 20% in the production of wheat but an increase of 5% in the potato crop. The current decline in apple yields in Himachal Pradesh is projected to continue (Sharma and Chuhan 2011).

Several other factors, such as loss of biodiversity and common property resources, growing water stress for irrigation, recurrent crop damage due to natural hazards (such as floods and droughts), poor infrastructure (especially transport systems), and inadequate institutional support, such as credit, crop insurance, and storage and processing facilities, have contributed to the undermining of agricultural production and food security in the HKH region (see Box 10). These have become more prominent with the enhanced links to and dependence on the plains. Many of the above trends are rooted in public interventions in mountain areas that have ignored the imperatives of mountain-specific attributes, such as inaccessibility, fragility, and diversity, while extending policies and programmes devised for the plains to these regions (Jodha 1997).

Impacts on Demography and Movement of Populations

The impact of climate change needs to be considered in conjunction with demographic and economic changes to assess human vulnerability. Data on this area are generally only just beginning to emerge, and they are still difficult to access for the HKH region. A recent study by Ghosh and Sharma (2011) looked at the Indian Himalayan region. Their study found that the share of the Indian Himalayan region in the country's population had remained stable; all states except Nagaland had witnessed population growth in the last decade and some districts were experiencing fast population growth, partly due to the ongoing public employment programme. Urbanisation, with a dwindling or stagnating rural population in the hill districts, is creating a serious challenge. Growth of small towns under restrained

Box 10: **Not all changes are related to climate: the case of apple cultivation in Himachal Pradesh**

The interaction between climate change and other factors is extremely complex, and it can be very difficult to ascertain the extent to which climate change or other factors are responsible for shifts in such areas as agricultural production. The following example illustrates the difficulty of attributing impacts.

The Indian Himalayan state of Himachal Pradesh is known for its success in establishing an apple-based economy worth INR 15 billion (about USD 300 million). The area under fruit crops (mainly apples) in Himachal Pradesh rose dramatically from 6,004 ha in 1960/61 to 88,560 ha in 2005/06, replacing the age-old subsistence agriculture and generating wealth and opportunities for education and development of the region. The fruit economy, however, has started to decline, at least in its traditional base. Apple production in Kullu Valley in 1995 was only 25% of that in the peak year of 1989/90 (Vedwan and Rhoades 2001). There is some indication that the changes are the result of climate change, as shown by a shift to cultivation at higher altitudes (Table 13). Although the apple area in Himachal Pradesh declined from 92,820 ha in 2001/02 to 86,202 ha in 2004/05, in Lahul-Spiti, it increased from 334 ha in 1995/96 to 5,516 ha in 2004/05 (Rana et al. 2009). The common problems associated with climate change include warmer and drier winters, shifts in snowfall from early winter to late winter, erratic weather conditions at the time of flowering, and early fruiting. Temperatures have increased more during the winter months than the summer months (Table 13). The early winter snow stays longer, while late winter snow is watery and short-lived. Overall snowfall (based on 21 sites) has declined at an average rate of 36.8 mm annually (Rana et al. 2008). These winter changes mean that, in Kullu Valley, apple trees don't have sufficient cold time (chilling 800–1,400 hr in a year).

People generally considered climate change as the principal cause of decline in apple production (Table 14). Although researchers agree that there has been an adverse impact of climate change on apple production, they also consider that part of the problem also is poor management. For example, an orchard requires at least 20% polliniser trees to maintain pollination but, because of commercial interests, farmers often do not maintain a sufficient number of them in their orchards (Vedwan 2006). Similarly, the overuse of pesticides affects apple yields adversely by killing pollinators.

Table 13: **Apple cultivation in three major valleys of Himachal Pradesh**

Valley	Altitude (masl)	Mean annual temperature (°C)	Annual orchard area cultivated (ha per household)		Income from fruit (% of total income)		Change in production over the last two decades (%)
			1995	2005	1995	2005	
Kullu	1,200–2,500	17	0.55	0.45	69.9	39.6	-18.2
Shimla	2,200–3,500	15.4	0.62	0.60	59.3	32.8	-3.0
Lahul-Spiti	average >4,000	<14	0.48	1.09	17.2	29.1	+27

Source: Developed from Rana et al. (2008)

mountain conditions, a changing sex ratio, and severe power crises are affecting several states in the northeast and are likely to impose pressure on urban amenities, infrastructure, and rural development programmes.

Population migration and livelihood transitions in the HKH region

Population growth interfaces with climate change in ways that intensify several other mechanisms that affect the availability of shelter, food, and water scarcity. There have been attempts to examine the ecosystem, health, and poverty nexus in fragile environments (Woodward et al. 2000). As the population increases, there is both increasing urbanisation and more competition for resources, such as food, water, and land, resulting in even greater environmental degradation. For example, recent changes in land cover and land use have occurred on the Tibetan

Table 14: **Apple cultivation in Himachal Pradesh: popular perceptions and research-based information**

Characteristic	Popular perception (% of people interviewed)	Research-based information
Temperature	Increasing (80–85%)	Over the last two decades, the mean annual temperature increased by 1.1–1.8 °C; and the mean winter temperature increased by 2.4 °C in the apple belt.
Uncertainty in climate with more extremes	Increasing	No investigation
Duration of winter	Shortened (88–94%)	Corroborates people's perceptions
Annual snowfall	Decreased (100%)	Decreased
Decline in early winter snowfall and shift from early winter to late winter	A clear shift	Early winter snowfall declined–based on an analysis of 21 stations
Requirement of chilling temperature	Not met	Required 800 to 1,500 hours of chilling.
Diseases	Increased	No analysis
Pollination: are there sufficient pollinisers and pollinators?	Pollinator population reduced	Insufficient number of polliniser trees were maintained in orchards
Total yield	Decreased	By 1995, reduced to 25% of the peak production year 1989–90 in Kullu Valley
Quality of fruit	Size reduced, unattractive	Not investigated
Shift to higher altitude areas	Such a shift has taken place	Some data in support of shift, shift to Lahul-Spiti documented
Main causes of decline in apple production and cultivation	Largely climate change	Climate change, inadequate pollinators in orchards, and cultural shift
Economics	Lower returns	In some areas costs exceeded or equalled returns
Use of pesticides	Increased	Norms were not followed
Response with regard to shift to other crops and time taken	Shift to off-season vegetables	Off-season vegetables grown; shifts take 2–8 years

Source: Vedwan and Rhoades (2001); Vedwan (2006); Rana et al. (2008)

Plateau at an unprecedented rate (Lambin et al. 2001; Du et al. 2004; Yan et al. 2005; Niyogi et al. 2011) and the Tibetan lifestyle of nomadic pastoralism has become sedentary (Xu et al. 2008c). Rising sea levels related to climate change will be a major contributing factor to population displacement, and this may have an impact on the HKH region as displaced populations from low-lying areas move to the hills and mountains. Haughton (2004) studied migration from the low-lying river deltas of Bangladesh to the Chittagong Hill Tracts. In the HKH region, large-scale population movement is likely to intensify as changing climate leads to the abandonment of flooded or arid and inhospitable environments. The resulting mass migration could lead to many serious health problems from the various stresses of the migration process; and population growth will increase the overall emissions, expand the number of vulnerable individuals (Lancet and University College 2009), and place additional stress on already weak health systems.

Impacts on Human Health

How human health can suffer from climate and land use changes in the HKH region
Much work is being done to examine how climate change can impact the biophysical resources of the HKH region (Sharma 2011) but, to date, little effort has focused on investigating how biophysical changes in the environment can affect human health and wellbeing (WHO 2006; Xu et al. 2008b; MA 2005). The major pathways are shown schematically in Figure 21. In general, climate change can have three types of impact on human health:

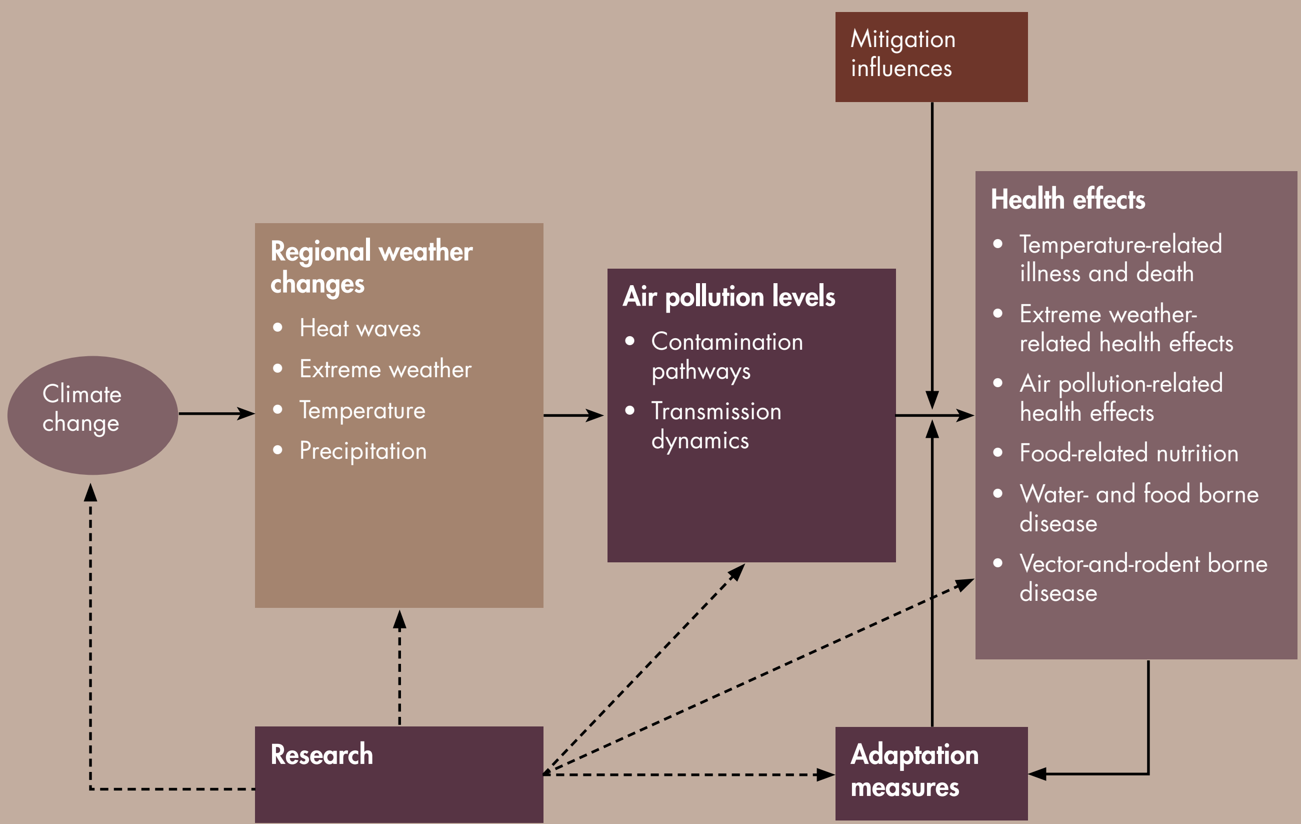
- those directly caused by weather extremes;
- the consequences of ecological disruption; and
- the diverse health consequences, such as trauma, infections, nutritional, psychological, and others, that occur in displaced populations in the wake of climate- induced economic dislocation (WHO 2003).

The IPCC in their second (1996) and third assessment reports (2001) provided some early evidence of actual health impacts related to changes in the frequency and intensity of extremes of heat and cold and of floods and droughts. The IPCC projected that increased threats to human health, would become manifest particularly in lower-income populations predominantly in tropical and subtropical countries. Table 15 summarises the main climate-sensitive health determinants and vulnerable populations (WHO 2006).

Health determinants particular to climate change in the HKH region

Table 16 shows the health determinants particular to climate change in the countries of the HKH region (WHO 2006); about half of these are contingent on water supply and half are related to the spread of infectious diseases. Water scarcity, either from a reduction in water availability as a result of reduced snowmelt or increased drought, is likely to increase water-related health hazards in the populations of arid basins downstream. Equally, erratic precipitation and increased glacial melting might exacerbate the flooding that is already common in mountain areas such as riverine floods, flash floods, glacial lake outburst floods, and breached landslide dams. The flood waters,

Figure 21: **Pathways showing how climate change can influence human health**



Source: Adapted from WHO (2003)

Table 15: **Populations vulnerable to climate-sensitive health determinants and outcomes in the HKH region**

Health determinant or outcome	Vulnerable populations
Heat wave mortality	Slum dwellers, the elderly, children, agricultural and outdoor labourers, people living in urban areas, workers in crowded and unventilated workplaces, and the homeless
Flash floods, including glacial lake outburst floods	Anyone living in a flood-prone area, especially the elderly, the poor, nomads, children, people who are either disabled or infirm, women, and ethnic groups in remote areas
Riverine (plains) floods	The elderly, the poor, the physically challenged, and the sick; children, women, and anyone living in poorly constructed housing; and people living in coastal areas, institutions, or isolated islands
Water scarcity and quality	Children, women, and poor people who do not have access to clean water and sanitation; those living in flood-prone areas; and people who lack awareness of proper hygiene
Drought-related food insecurity	Children, the elderly, pregnant women, and women in general
Malaria	Children, pregnant women, slum dwellers, the homeless, migrants, people with poor environmental hygiene, and isolated ethnic groups living in remote areas
Japanese encephalitis	Farm workers (especially those who work in paddy fields), children, and people living in close proximity to swine
Kala-azar	People living on the ground floor of buildings in endemic areas and the poor
Dengue	Populations in urban areas
Filariasis	Poor people living in the foothills or high humidity areas
Food-borne diseases	Not noted
Water-borne diseases	Children, women, the poor, those who lack access to clean water and adequate sanitation, people in flooded areas, and people who lack awareness of, or access to, proper hygiene

Source: WHO (2006)

Table 16: **Health determinants and health outcomes for the countries of the HKH region**[1]

Country	Afghanistan	Bangladesh	Bhutan	China	India	Nepal
Heat waves	+	+	-	+	+	+
Flash floods	M	+	M	M	M	M
Glacial lake outburst floods	M	-	M	M	M	M
Riverine (plains) floods	+	+	-	+	+	+
Water scarcity, quality	M	+	+	M	M	M
Drought-related food insecurity	M	+	-	M	M	-
Malaria	+	+	+	+	+	M
Japanese encephalitis	-	+	-	+	+	+
Kala-azar	+	-	-	-	+	+
Dengue	-	+	+	+	+	-
Water-borne diseases	M	+	M	M	M	M

M The health determinant or outcome is present throughout the country.

+ The health determinant or outcome is present in non-mountainous areas.

- The health determinant or outcome is not present.

[1]Data for Myanmar and Pakistan were not available.

Source: WHO (2006)

often accompanied by large amounts of debris, can lead to collateral damage and human catastrophe miles from the outburst source. Vulnerable groups, such as the poorest people, those from low castes, women, children, and the elderly, are often hit the hardest as are those that live in rural areas far from hospital services. Following a disaster, mountain village communities have to contend with severe damage to their property and livestock which entails an immediate threat to their livelihoods and food security but can also lead to protracted socioeconomic stress with related health implications, even if this aspect of extreme events is seldom highlighted (Eriksson et al. 2008). Table 16 shows that about half of the health determinants are related to the spread of infectious diseases. Ecological changes and economic inequities strongly influence the spread of diseases, and the warming and instability in the climate is playing an ever increasing role in driving the global emergence, resurgence, and redistribution of diseases (Leaf 1989 and McMichael et al. 1996). An altered distribution of vector species may be among the early signs of climate change, and pests, pathogens, and parasites are among the first to emerge during periods of transition. In addition, the distribution and seasonal transmission of vector-borne infections (such as malaria, dengue fever, and schistosomiasis) may be affected by climate change (Sutherst 1998; Sharma 1996; WHO 2000). Models predict the potential for malaria to spread as a consequence of global climate change (Martens et al. 1999; Rogers and Randolph 2000; Tanser et al. 2003; van Lieshout et al. 2004; Ebi et al. 2005) especially since climate affects the survival and reproduction rates of vector-borne diseases; the intensity and temporal pattern of vector activity; and the rates of development, survival, and reproduction of pathogens within vectors (Kovats et al. 2001). Recently, Dhiman et al. (2011) reported projections of malaria for 2030 (using the ABI scenario of the PRECIS model) for different Himalayan states of India. They determined the transmission window for malaria (TWM) using 18 and 32 °C as the lower and upper cut-off temperatures at a relative humidity above 55% and predicted a one-month increase in the transmission window for much of the region. For example, the period when malaria can be transmitted in the various districts of Uttarakhand and Kashmir is predicted to increase from the present 1–7 months to 3–8 months by 2030. In Sikkim it is predicted to extend from the present 3–4 months to 4–5 months. In Kashmir, the increase was attributed to earlier warming in May, while in Sikkim the longer transmission period was attributed to the warmer weather continuing through September.

In Nepal, outbreaks of Kala-azar and Japanese encephalitis have been linked to climate change, particularly in the subtropical and hot regions (Regmi et al. 2006). In India, there has been a growing concern about the changing pattern of most of these diseases as a result of climate change. Malaria is endemic in all parts of the country except for elevations above 1,800 masl and in some coastal areas (GOI 1986).

Land use change and infectious diseases

Climate change can precipitate land use change (Kalnay and Cai 2003 and Pielke 2005) and can impact food security (Parry et al. 2004) as well as socioeconomic systems (Winnett 1998). Most emerging human diseases are driven by human activities that modify the ecosystems or otherwise spread pathogens into new ecological niches (Taylor et al. 2001). The pace, magnitude, and spatial reach of land cover and land use changes have increased rapidly as a result of human activities, and now may be beyond the ecosystem's capacity for recovery (Lambin and Geist 2006). Such alterations in ecosystems lead to large-scale land degradation, changing the ecology of the diseases that influence human health and making people more vulnerable to infections (Collins 2001). Decisions about changes in land use, whether in response to climate change or otherwise, are thus human health decisions (Xu et al. 2008a). There are several examples of the direct effects of deforestation on human diseases. It is clear that habitat alteration can affect the prevalence and incidence of human malaria. The effects of deforestation on the vectors of human malaria are complex and can be influenced by the nature of agricultural development and specific local ecological characteristics (Yasuoka and Levins 2007). The southern foothills of the HKH region were, in the past, hotspots for malaria.

Using Models to Predict Impact

It is extremely difficult to predict future impacts of climate change with any degree of certainty but models can be used to predict temperatures and based on this it is possible to gain some idea of the type, distribution, and extent of impacts under various scenarios. One of the few examples available is the recent assessment carried out by the Government of India, and this is discussed below.

Projected impacts of climate change to the 2030s: an example from the Indian Himalayan region

The Indian Network of Climate Change Assessment (INCCA 2010) has recently completed an assessment of the impacts of climate change up to the 2030s on four key sectors of the economy that are known to be climate sensitive. Their predictions for the Himalayan region (including the northern states in the northeastern region and the states of Jammu and Kashmir, Himachal Pradesh, and Uttarakhand, in the northwestern Himalayas) are as follows.

- **Temperature** The mean annual temperature is projected to increase by 0.9±0.6 to 2.6±0.7 °C. The net increase in temperature ranges from 1.7–2.2 °C with respect to the 1970s. Rises in temperature should be noticeable throughout the year. Minimum temperatures are projected to rise by 1–4.5 °C and maximum temperatures by 0.5–2.5 °C.
- **Precipitation** The number of rainy days may increase on average by 5–10 days. The number of rainy days will increase by more than 15 days in the eastern part of Jammu and Kashmir. The average intensity of rainfall is likely to increase by 1–2 mm per day.
- **Agriculture** With increasing temperatures, it is anticipated that there may be an all-round decrease in apple production in the Himalayan region, and production may shift to higher elevations. Apple production in Himachal Pradesh decreased between 1982 and 2005 as the increase in maximum temperatures led to a reduction in total chilling hours in the region – a decline of more than 9.1 units per year over the last 23 years. This reduction was greater during the months of November and February.
- **Natural ecosystems and biodiversity** Approximately 56% of the region is projected to undergo a change, and the net primary productivity is projected to increase by about 57% on average.
- **Health** Projections of malaria transmission windows based on temperature show that new foci may be introduced in Jammu and Kashmir with a transmission window of 0–2 months. In addition, there may be an increase in the opening of more transmission months in districts of the Himalayan region and the northeastern states.
- **Water** The water yield in the Indian Himalayan region, mainly from the River Indus, is likely to increase by 5–20% in most areas compared to the 1970s, as a result of the combined effects of precipitation, distribution, evapotranspiration, and soil characteristics with some areas of Jammu and Kashmir and Uttarakhand showing an increase of up to 50%. The increase in precipitation should be paralleled by a similar increase in evapotranspiration. The increase in water yield will be greater in those areas that have less evapotranspiration.

Farmers' Knowledge

The extent to which impacts already exist is difficult to assess but insights can be gained through focused inquiry among those most directly affected – the farmers of the hills and mountains. Equally, lessons for the future can be learned from the ways in which farmers living in areas already affected by climate change stress have responded and adapted.

Listening to farmers' voices

Mountain communities that still use age-old methods of agriculture are the first to notice phenological changes, such the encroachment by invasive species, new pests, and other changes, and, over time, they develop their own indigenous know-how about how to tackle them. Some recent attempts have been made to approach mountain communities in the HKH region and to learn from them what they perceive to be the greatest changes taking place in their water supplies, weather, environment, and crop productivity and to inquire what means they are using for mitigation and adaptation to counter these.

A recent survey on 'too much too little water' conducted with different communities in four countries of the HKH region showed how remarkably resilient these mountain communities are to water stresses (ICIMOD 2009d and Pradhan 2011). In places where modern methods are still lacking, communities use indigenous knowledge of environmental clues to help forecast flash floods; use traditional methods to store and preserve food and avoid loss through floods; and use time-honoured adaptation strategies such as depending on horticultural crops when cereal crops fail due to floods and droughts. In the absence of government intervention, communities reported that they had organised themselves into user groups and had built water-harvesting and distribution structures. These communities are also eminently pragmatic and, when all other options are exhausted, they do not rule out migration as a survival strategy. The study also pointed out that, for the most part, government policies are either absent, or not well communicated to these communities, and that governments also do not routinely collect or use information from them to record the prevalence of water in their villages.

Anecdotal evidence collected from farmers can be very subjective, often farmers are uncertain of the timelines, their memories of past harvests may be more abundantly remembered; they may not be fully aware of land use changes upstream that affect their water supplies; and so on. Nevertheless, when many interviews with farmers from several districts (at different altitudes and latitudes) generally report the same conditions then these are noteworthy and can be a wakeup call indicating real changes in local weather patterns. At the very least, interviews with farmers are a valuable, documented baseline with which to compare future studies (See for example Chaudhary and Bawa 2011 and Chaudhary et al. 2011).

One study, carried out from November 2009 to January 2010 with a follow-up in July 2011, conducted representative interviews with farmers in the low-, mid- and high-hill districts of central, west, and far-western Nepal and compared the farmers' perceptions of recent weather patterns with data from Nepal's Department of Hydrology and Meteorology (Allen 2011). Overall, farmers reported that weather patterns had changed over the past 5 to10 years and that weather was becoming more extreme and erratic; and many (but not all) noted that the summer rains now seem to be delayed and that they lasted for a shorter period but were more intense than those they remember from previous times. Farmers also noted prolonged periods of drought, less snowfall at the higher altitudes, and a perceived warming in ambient temperatures. Whereas the interviewers found only a fair correlation between the weather changes reported by the farmers and data from the meteorological survey, the farmers themselves correlated weather changes with crop production. Farmers correlated weather events with the productivity of traditional crops (such as wheat, maize, and rice) that are not irrigated and reported a decrease in productivity. They noted that crops are failing due to drought during the growing stage and intense, heavy rainfall later in the season which flattens and floods crops when they are close to maturity. Farmers consistently reported a loss of agricultural production as a result of changing environmental conditions. In many areas, crop losses of up to 50% were attributed to problems of erratic rainfall and increased drought. Farmers in western and far-western Nepal correlated changing weather patterns with a trend in changing flowering times for tree species such as rhododendron, kaphal (*Myrica nagi*), gophi, and cotton tree (*Bombax ceiba*) which they observed flowering two months earlier than in previous years. They reported the same for fruit trees, such as apple, peach, mango, plum, orange, and wild pear, and linked this with the fact that the fruit was of poorer quality than in previous years. Another general observation by the inhabitants of these areas was that local drinking water sources seemed to be drying up; and on average, they reported a 50% decrease in drinking water sources. The farmers in these areas are countering persistent adverse annual weather conditions by adjusting sowing times; introducing mixed cropping to salvage at least some of their production; introducing new crop varieties; and learning as much as they can when partnering with NGOs who specialise in helping to introduce improved farming methods.

A different study interviewed farmers in the hill regions of western Nepal and northwestern India and also reported perceived reduced snowfall and warmer winters in recent years (Macchi and Choudhury 2011). Both in western Nepal and in the Meghalaya hills, farmers reported delayed and erratic rainfall during the rainy season followed by prolonged dry periods. Horticulturalists in northeastern India have observed fruit trees flowering out of season and sometimes even flowering twice in the same year. These farmers are not able to explain these observations that seem to fall beyond the extent of normal variation.

An assessment of ninety villages across fifteen districts in Bhutan, India, and Nepal to document community perceptions and response to climate change found that communities in the mountains realise that there is a critical need to address their vulnerability by diversifying their cash generation options. In the absence of non-farm income diversification, communities have started adopting crops that have a market demand. Thus, cereal crops are being replaced rapidly by crops that offer potential opportunities for cash returns. Seasonal vegetables and spices, such as ginger and turmeric, are rapidly becoming important crops in most parts of the Himalayas. Similarly, horticultural crops, particularly fruit crops, are an important cash generation option (Choudhury and Choudhary 2011).

4 Strategies to Address Climate Change

The preceding chapters summarised the data and analyses that are available to document climate change in the HKH region, and they have examined the impacts that climate change has had, or is projected to have, on the mountain communities of the region. This chapter looks at options and strategies that could help these communities to adapt to change or to mitigate the harmful effects. Mountain communities need to be helped to improve their current adaptation and coping strategies at both the autonomous or local level and at the community level, taking into full consideration the mountain perspective framework defined by fragility, marginality, multi-level vulnerability, and poor accessibility. For the most part, low- cost or no-regret options that are new to the region and which should help adaptation are suggested. The chapter elaborates on suitable strategies and opportunities for climate- resilient development that have policy and governance implications, and it includes a discussion of policy options such as payment for ecosystem services; mitigation measures such as reducing emission from deforestation and degradation (REDD) which have an adaptation co-benefit; water-storage measures; and regional cooperation policies for water resources.

The Link Between Livelihoods and Ecosystem Services

Development indicators, such as the Human Development Index (HDI) and the Millennium Development Goals (MDGs), have shown positive trends recently throughout Asia. This growth is not evenly distributed, however, and the rate of poverty reduction lags behind in the marginal mountainous areas because they are more exposed to the physical, social, and economic vulnerabilities created by processes of global change: for example, a recent ICIMOD study shows that poverty rates in the mountains are, on average, 5% higher than national-level averages (Hunzai et al. 2011).

Over the last 20 years the countries of the HKH have achieved high levels of economic growth, but also they have endured unprecedented demands and pressure on ecosystems and natural resources. India and China, in particular, have emerged as new global economic powerhouses in Asia. The mountain regions of the HKH have benefited only marginally from the economic growth in the region since national policies, even in countries with substantial mountain populations, have focused largely on growth based on natural resources. Nevertheless, with a growing awareness of the scarcity of resources (especially freshwater), and of the impending effects of climate change, the relevance of mountain ecosystem services has become a focus of attention. The wide range of services provided by the ecosystems of the HKH region are its greatest capital asset and it is becoming increasingly clear that sustainable approaches for livelihood improvement and poverty reduction in the mountains can only be achieved if they are linked appropriately with natural assets and ecosystem services.

Valuation of ecosystem services and payment by users for these services is emerging as essential for assessing benefits and designing policies (Rasul et al. 2011). Recently a growing awareness has emerged that mountain areas need to be differentiated and considered separately with regards to policy. Changes in mountain systems in the subtropical zones (in Asia, Africa, and Latin America) have a direct influence on the livelihoods and food security of millions of people. Mountain systems in subtropical zones brought new criteria for the relevance of mountains: increased vulnerabilities and reduced food security in areas downstream have impacts on the livelihoods of more than 1 billion people in the case of the HKH. Emerging areas of great importance are vulnerabilities, disaster risks, adaptation or sustainable mountain development, labour migration and remittances, how to build resilience in a changing social fabric, changing gender patterns and women's roles, and new opportunities and forms of livelihood (Schild and Sharma 2011).

Payment for environmental services (PES) is an incentive-based mechanism for addressing both environmental problems and poverty; this concept is gaining in popularity with natural resource managers and policy makers in the countries of the HKH region. The PES concept includes a range of institutional arrangements such as direct beneficiaries of environmental services paying the providers' communities; supporting other communities for watershed protection; state incentives for changing land use; and recent schemes for reducing emission from deforestation and degradation (REDD). The key ecosystem services in the HKH region provide benefits in the areas of water and watersheds and multiple ecosystem services from forests and rangelands such as carbon sequestration and biodiversity. Innovative emerging sustainable livelihood opportunities and poverty reduction in the context of the changing climate include the PES schemes; REDD mechanisms; and potential uses of water storage. This chapter deals specifically with these innovative livelihood opportunities as an approach to green sector mitigation and adaptation for sustainable development in the HKH region.

Rewarding Providers for Ecosystem Services

Payment for ecosystem services (PES) is an emerging global paradigm in the management of environmental resources. Instead of relying on regulatory instruments, such as prohibitions and standards, PES relies on adopting innovative mechanisms that are tied to incentives or compensations and are voluntary and contextualises the local socioeconomic reality. The criteria for a successful and self-supporting PES market are shown in Box 11. PES, or the incentive-based mechanism (IBM), as it is commonly known in India, basically realigns private and social costs and benefits by taking into account environmental externalities (Adhikari 2009). There is increasing recognition that PES can also contribute to broader economic development objectives, such as sustainable rural development, food security, and lasting poverty alleviation (Antle 2008), since incentives can help make the sustainable management option more attractive. Particular types of PES which focus on specific ecosystem services are commonly categorised as carbon sequestration, watershed protection, biodiversity protection, and landscape beauty (Wunder 2005).

Box 11: **Criteria for a successful and self-supporting PES market**

- Transactions must be voluntary
- The ecosystem services in question must be well-defined
- The ecosystem services must be bought by at least one buyer
- The ecosystem service must be sold by at least one supplier
- Payment is conditional upon receiving the ecosystem service

Several additional conditions such as sufficient awareness of stakeholders at every level, strong institutional set-up and governance mechanism, and so forth are also important

Source: George et al. 2009

In the context of the HKH region, PES-type schemes are not always strictly 'payment' based and may offer compensation or rewards in cash or in kind as incentives from the users downstream to the communities and land users upstream who are the custodians of the environmental services in the watersheds. PES schemes at the local level that are tailored to specific situations are likely to be more flexible and credible than government subsidy schemes for conserving landscapes and watersheds upstream. From a climate change perspective, PES can be regarded as an important policy instrument in the forestry and agricultural sectors in terms of mitigation and adaptation potentials. PES can help the land- use sector to reduce emissions and also to enhance its carbon sink capacity by making these actions attractive (e.g., through compensation schemes that reward specific types of land uses). In the HKH region, this type of mitigation is also an ecosystem-based adaptation strategy. PES as a policy instrument has a strong nexus with climate-change mitigation and adaptation. To date, the most significant discussions on PES have focused extensively on the potential of 'reducing emissions through deforestation and forest degradation (REDD)' which is designed to reward conservation in areas rich in biodiversity and advocates compensating countries for not cutting down trees.

A few examples of PES in the HKH region

Only a few examples of PES schemes in the HKH region are available; and these include the 'Grain for Green' programme in China (Chen 2010), watershed management programmes in India, and the new USD 200 million commitment to investment in ecosystem services in the Himalayas by the Indian Central Government. The existence of established forestry initiatives by local communities in many countries, as well as the development of landscape conservation programmes, may prove a strong base on which to develop additional economic payments.

Another example of PES as a policy instrument is demonstrated in the Kulekhani watershed in central Nepal. PES has played a role in enhancing the capacity of water storage of a hydropower plant reservoir by reducing siltation from the watershed through paying the local communities to maintain forest cover upstream (Karky and Joshi 2009).

Forest carbon projects are already being piloted in the HKH region and in Nepal, building on the country's history of community forestry (Skutsch 2011; Banskota et. al 2007; Chettri et al. 2007). ICIMOD and its partners in Nepal have started a demonstration REDD project that pays local communities for the carbon sequestered in their communities (www.communityredd.net).

At the local level, examples include drinking water schemes, and payments out of royalties from hydropower plants or irrigation schemes. PES schemes in watersheds have been developed by projects in Nepal (Khulekhani area) and in India (Himachal Pradesh). Others in the HKH region include targeting the way farmers use their own farmland and production to provide ecosystem services, such as conservation of agrobiodiversity through pollination services (Partap, 2010); in-kind incentives given to local communities to ensure protection of rare and endangered species and habitats (Wangchuk 2010); and tour operators paying higher prices for conditional environmental services provided by local communities (in Bhutan) (Ritsma 2010).

Challenges and opportunities

There is a growing general agreement that PES can be a promising area for simultaneously supporting development while securing the environment in mountain and hill areas. While economic incentives are not always a suitable way to manage all environmental problems; and while they may not be a sufficient guarantee for ecosystem service provision (Pagiola 2005; Perrot-Maitre 2006; Engel et al. 2008); nevertheless, where direct payments for marketed environmental services are appropriate, conservation can be a more competitive land use than conversion (Asquith et al. 2008).

Conservation in the HKH region needs to be proactive in terms of both mitigation and adaptation to the direct impacts of climate change. PES has the potential to minimise trade-offs between conservation and rural livelihoods, and the integration of valuation into the management of ecosystem services can inform policy by providing a bigger picture that helps weigh the trade-offs between conservation and conversion. PES presents both risks and opportunities for local livelihoods; nevertheless, it has the ability to increase the resilience to climatic change while maintaining ecosystem service provision and economic development by generating resources to support conservation, to encourage sustainable land use, and to deliver development objectives (Kumar 2011). Some of the main challenges are in the details of implementation, and they include the following.

- Translating the economic value of ecosystem services into real resource flows is still a challenge despite decades of work in this area. Marketable services must be clearly defined and valued. A scientific understanding of the ecosystem services on multiple scales is essential to map, model, and ultimately value ecosystem services effectively (Farley and Costanza 2010). Examples include the Central Himalaya (Negi and Semwal 2010) and Margalla Hills National Park, Pakistan (Khan, 2010). Outlining the full range of services from an ecosystem can also help to reduce the prevention of perverse incentives. Rasul et al. (2011) developed a framework for valuing ecosystem services in the HKH region which should help to address these issues.
- Past conservation efforts have focused in part on the development of protected areas. These projects are now experiencing a paradigm shift which recognises the transboundary nature of both the ecosystems and the issues facing their conservation (Sharma et al. 2010). The most significant obstacle to PES implementation in the region is the transboundary nature of the HKH region. Developing PES schemes is context specific (Tacconi et al 2001), and, although ecosystem services may flow between boundaries, different social, economic, and political settings may create difficulties in ensuring conditionality and low leakage.
- Ensuring the meaningful participation of mountain communities is paramount (e.g., Orange et al. 2010). Land users must be meaningfully engaged in order to understand what incentives will work and how. There are significant concerns around securing tenure rights for both equitable distribution of benefits and ecological conservation. Similarly, if stewards do not feel secure, either because of illegal resource usage or because of interference from regulatory or government bodies, they may not be willing to invest in long-term resource management techniques (e.g., Wendland et al. 2010; van Schoubroeck et al. 2010).

- Monitoring of effective implementation and compliance is necessary. It is suggested that indicators for both compliance and the degree to which the schemes succeed in alleviating poverty be built in at the beginning (e.g., Huang and Upadhyaya 2007; Keenan and Chaudhary 2010).
- Defining the links between land use and service provision must be carried out in a way that will ensure incentives target the right land use changes to support specific ecosystem services and ensure that payments do not become a flat subsidy (Wunder et al. 2008).

Prospects for Sustainable Greening of the Himalayas

Reducing emissions from deforestation and forest degradation (REDD)

Climate change is occurring at an alarming rate as a result of increased carbon dioxide in the atmosphere, and currently deforestation accounts for approximately 18–25% of the global greenhouse gas emissions. These emissions can be curbed by avoiding deforestation and forest degradation and by improving the management regimes of existing forests. A policy mechanism for 'Reduced emissions from deforestation in developing countries' (REDD) was first proposed by the UN Climate Conference of the Parties (COP 13) in Bali in 2007 and has been under consideration by the United Nations Framework Convention on Climate Change (UNFCCC). The REDD mechanism estimates a financial value for the carbon stored in forests and offers developing countries incentives to reduce emissions from forests. At UNFCCC COP 15 in Copenhagen in 2009, the REDD policy mechanism was expanded to REDD+ to include the role that conservation, the sustainable management of forests, and the enhancement of forest carbon stocks can add to reducing emissions. REDD+ allows for a wider range of forest-related activities than the previous proposal and provides opportunities for HKH regional approaches such as community forestry, joint forest management, social forestry, and collaborative forestry to derive benefit from international efforts to mitigate climate change (Dahal et al. 2011).

In addition to the ongoing discussions on REDD under the UNFCCC framework, the voluntary market for REDD is growing and there seem to be good prospects for future compliance. At the global level, REDD and REDD+ activities are viewed from the perspective of a cost-effective mitigation approach but, at the local level, such activities are regarded as an ecosystem-based adaptive measure by populations that depend on forest resources for their livelihoods and for whom biodiversity conservation and improved livelihoods can be co-benefits. Recognising this mitigation-adaptation interface is crucial for ensuring that international measures to promote mitigation of the impacts of climate change meet the needs of mountain communities and local forest resource users in terms of adapting to the rapidly changing environment of the HKH region.

REDD in the HKH region

Ecosystems in the HKH region are very vulnerable to both growing anthropogenic pressures and the consequences of climate change such as the increase in forest fires (mainly during long and severe droughts); outbreaks of diseases in tree species; and the rapid and frequent introduction of invasive alien species that have detrimental effects on endemic forest ecosystems (Chettri et.al. 2010). REDD financing can be used as an incentive to regain public support for mitigation and adaptation schemes that promote forest and biodiversity conservation, ecosystem services, and poverty reduction, and which also augment the capacity of natural sinks. At present, the HKH region is at the forefront in offering an innovative REDD framework which encompasses research and pilot financing, and in offering innovative designs for measuring, reporting, and verification (MRV) monitoring for REDD, sharing benefits, and empowering communities.

Recent estimates by ICIMOD and others (ICIMOD 2009e, 2010a) indicate that the forest ecosystems in the HKH region have a good biophysical potential for improved forest management activities as shown in Table 17 and Figure 22 The potential for avoiding forest degradation has been both over- and underestimated in some of the countries, but overall, there seems to be a definite potential throughout the whole region. In summary, the study found the following.

- Adaptation and mitigation are complementary and should not be perceived as mutually exclusive approaches. In the HKH region, adaptation and land-based mitigation are intimately linked and are not mutually exclusive;

mitigation activities can become an important complement to adaptation initiatives and, as such, should be supported by regional policy and enabling frameworks.

- The potential for biophysical mitigation in the region is substantial, but highly dispersed. The study identifies the biophysical potential for a series of land uses. Mitigation options exist throughout the HKH region but their nature varies from country to country. The mitigation potential for each of these land uses alone remains low if seen in isolation, in many cases too low to justify the high transaction costs for the formulation, implementation, and monitoring of carbon sequestration projects based on land use.
- Holistic approaches to mitigation at the landscape level, and not the promotion of individual land uses, are the appropriate mitigation strategy for the very diverse landscapes of the region. Approaches such as 'agricultural, forestry, and other land uses', which include a series of land uses, are more appropriate for the region than a narrow focus on REDD schemes or approaches focusing on a single form of land use.

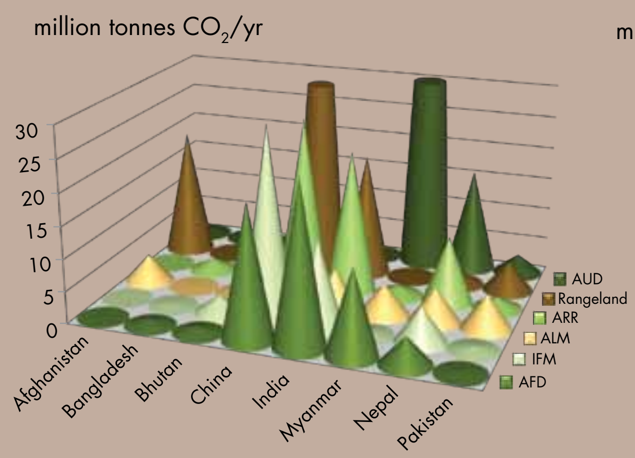
Table 17: **Biophysical potential of improved forest management activities in the HKH region**[a]

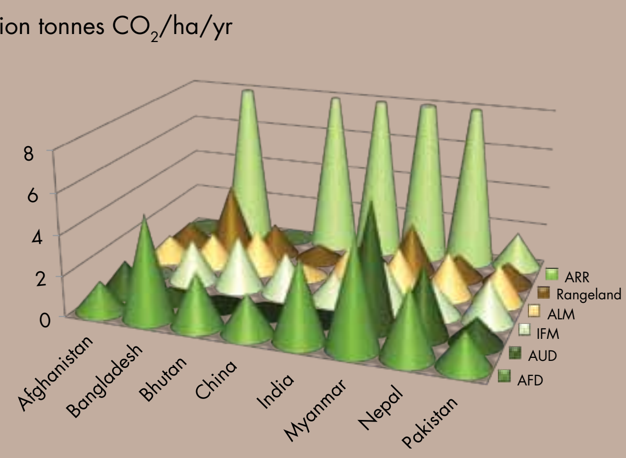
Country	Eligible forest area for IMF[b] activities ('000 ha) (% of total forest area)	Mitigation potential (tonnes CO_2/ha/yr)	Biophysical potential (million tonnes CO_2/yr)	Potential annual revenues[c] (million USD)
Afghanistan	0	n.a.	n.a.	n.a.
Bangladesh	191 (23%)	0.27–4	0.4	4
Bhutan	1,050 (45%)	0.27–4	2.7	28
China	13,995 (33%)	0.27–4	29.8	298
India	9,705 (48%)	0.26–1.5/0.27-4	13.4	133
Myanmar	310 (2.2%)	0.27–4.0	0.7	6.6
Nepal	3,711	0.26–1.5/0.27-4	5.6	55.8
Pakistan	387 (17.5%)	0.27–4	0–8	8.2

[a] Forest areas were estimated from FAOSTAT forest area statistics (FAO 2009)
[b] IFM = improved forest management
[c] Based on a carbon price of USD 10 per tonne of CO_2

Source: ICIMOD (2009e)

Figure 22: **Estimates of the annual carbon mitigation potential in the HKH region overall and per unit area**





ARR = afforestation, reforestation, revegetation; Rangeland = rangeland management;
ALM = agricultural land management; IFM = improved forest management;
AUD = avoided unplanned deforestation; AFD = avoided forest degradation

Note that these estimates are only for the HKH portions of these countries.

Source: ICIMOD (2009e)

- 'Good carbon governance' is as important as high potentials for biophysical mitigation: this issue will take on increasing importance within the region and needs to be addressed early. Carbon finance schemes involve a multitude of stakeholders, interests, and regulatory mechanisms. In addition to the biophysical potential of land use systems, it is important to assess how existing institutional frameworks support 'good carbon governance', i.e., facilitating mitigation projects that are workable, credible, and legitimate.

The concerns of communities that derive their livelihoods from forest resources

While REDD could provide some viable options, the areas of special concern in the HKH region include that the terrain is very heterogeneous and land use varies greatly; a rich diversity of forest types abound; the region has a diversity of land tenure systems and legal frameworks; and there are concerns about the rights of indigenous people and the communities who depend on forests since community forestry and communal ownership are widespread. The challenge will be to generate resources that would motivate the target communities to share benefits equitably and to blend the scheme with conservation and development processes. This needs to be approached with caution since many people still derive their primary livelihoods from forests. For example, a recent study estimated the economic returns to carbon abatement through biological sequestration in community-managed forests under different possible management scenarios and showed that if local communities are not permitted to use the forest resources, carbon trading will not be attractive to them since revenue from carbon cannot cover the cost foregone by not harvesting forest resources (Karky and Skutsch 2010). The critical questions which may distract potential investors include the establishment of baselines and reference levels; challenges to implementation associated with wide variations in ecosystem type; the capacity building needed to undertake responsibilities assigned in areas such as measuring, reporting and verification; monitoring for REDD costs; and so on.

Boxes 12, 13, and 14 provide some examples of how such schemes can work in practice in the HKH region.

Box 12: **The Forest Carbon Trust Fund: a REDD pilot project in Nepal**

The Forest Carbon Trust Fund is a REDD pilot project that is being implemented in community-managed forests in three watersheds in Nepal (Charnawati in Dolakha District, Kayar Khola in Chitwan District, and Ludi Khola in Gorkha District). Together the projects cover 105 community-managed forests in an area of over 10,000 ha and involve 18,000 households (with an outreach population of nearly 0.1 million).

The Forest Carbon Trust Fund uses a bottom-up approach for validating carbon stocks, for monitoring and regulating forest management activities, and for paying REDD+ claims. The community forest users' groups are responsible for using funds for activities that reduce deforestation and forest degradation and promote the conservation of forest carbon stocks: they also conduct carbon monitoring, help to raise awareness and to build capacity on REDD, and audit and verify carbon data at the community level. The project also aims to address equity issues by distributing payments according to social criteria. REDD payments are made as a function of six basic elements: how much forest carbon was in the pool, how much forest carbon was saved (above the baseline), the number of households of indigenous peoples, the number of Dalit (very low caste, generally poor and marginalised) households, the ratio men/women, and the number of poor people.

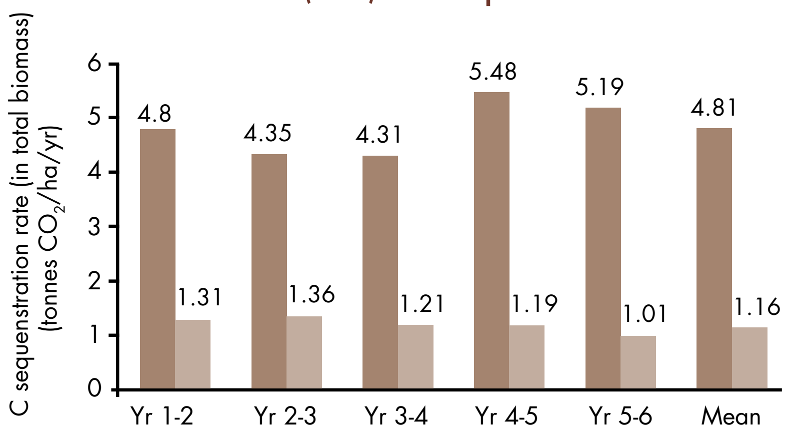
This pilot has been successful so far in demonstrating that REDD can be implemented at the local community level and that it both promotes mitigation and helps to enhance ecosystem-based adaptation in populations that depend on forest resources. The three communities learned how to monitor carbon in their forest areas and were able to claim the corresponding REDD payments. Together, they reported an increase of 100,528 tonnes of carbon dioxide over the baseline year (2010). Of the USD 100,000 allocated for the Forest Carbon Trust Fund in 2010/2011, the first payment (USD 95,000) was made in June 2011 to three communities who had demonstrated incremental carbon sequestration. One of the added benefits is that since these are naturally regenerated forests, biodiversity is also conserved.

Source: Dahal et al. (2011)

Box 13: **An example of carbon sequestration in the community forests of Uttarakhand (India)**

In order for forest conservation schemes to succeed, they need to have the active participation and involvement of local communities. A study in the Uttarakhand Himalayas (India) found that community forests can both sequester carbon and meet the day-to-day biomass needs of the communities for fuelwood, fodder, and litter, provided the forest areas are adequate (Singh et al. 2011) Typical management procedures instituted by the local communities included regulating how much fuelwood can be cut and how much tree-leaf fodder can be collected per household; limiting the grazing of cattle to only certain periods of the year to allow for natural regeneration; watching for fires and fire fighting; and making sure that the rules and regulations were enforced (Singh et al. 2011). The study was carried out over a seven-year period and compared a well-managed community forest and a degraded forest with little management. The study found that the total forest CO_2 biomass sequestration (both above and below ground) for the well-managed forest exceeded that of the degraded forest by 13.4 tonnes per ha per year (Singh et al. 2011). See Figure 23. Another study compared adjacent sites and found that the degraded forest site had been losing CO_2 at the rate of 7.7 tonnes of CO_2 per ha per year for the preceding 11 years (Singh et al. 2011). In these studies, the community was involved in sampling; and they measured tree diameters, and provided information on forest boundary and area with the help of GPS. The community was empowered to help with the carbon measurements which both saved the cost of otherwise measuring the carbon and proved that communities can be enthusiastic participants if they are given significant roles in REDD programmes.

Figure 23: **The rate of carbon sequestration in two adjacent forest areas in Uttarakhand (India) over the period from 2003–2010**



The dark bars show a well-managed community forest; the light bars are an unmanaged forest. The well-managed forest consists of banj oak (*Quercus leucotricophora*) and has a high sequestration rate; the degraded forest consists of mixed banj oak and pine (*Pinus roxburghii*) forest and has a poor sequestration rate. Community management saves an average of 13.4 tonnes CO_2/ha/yr in emissions.

Source: Singh et al. (2011)

Box 14: **Carbon dioxide and sink dynamics in the HKH region**

The current total CO_2 emission from all HKH countries has more than doubled over the past decade (from 4.7 Gt CO_2 in 2000* to 9.5 Gt CO_2 in 2009) (Dhakal 2011). China is at present the single largest emitter in the world and India is not far behind; together these two countries account for 97.5% of total emissions from HKH countries. The scenario is very different when only the HKH region is considered. One estimate (Singh personal communication 2011) calculates that the population of the HKH region only produces 0.1 Gt/yr of emissions but that the forests of the HKH region sequester CO_2 at three times that rate. Overall, the HKH region has 6.4 times more forest area for each unit of CO_2 emission than the global population. Moreover, this ratio can be improved by moving to clean cooking fuel and making hydropower more widely available.

*Includes emissions from the countries as a whole, not only the mountainous regions.

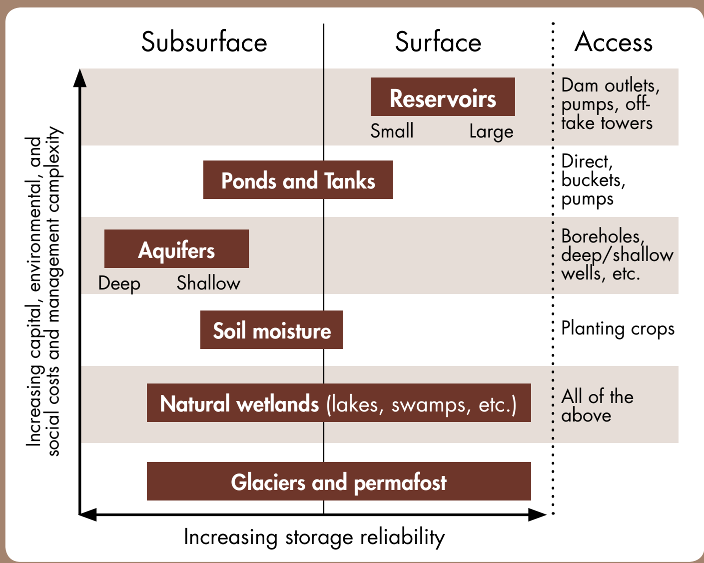
Improved Water Storage can Enhance Resilience to Climate Change

The Hindu Kush-Himalayan (HKH) region suffers from a high degree of intra-annual rainfall variability, marked by too much water in the wet season followed by too little water in the dry season. In the past, the mountain communities living in the ten river basins of this mountain region (and their counterparts downstream) have always found ways of storing enough water for their needs regardless of the extremes in water supplies. The recent changes in climate and consequent erratic weather patterns and reduced availability of glacial meltwater, however, warrant a rethinking of water storage strategies (Vaidya 2011). Projections by Vorosmarty et al. (2000) indicate that climate change in the region could cause the ratio of water demand to water supply to increase dramatically, bringing water scarcity to many areas in the region. The projections also suggest that when these changes are coupled with the effects of population growth and economic development, in the absence of deliberate attempts to conserve water, the results could create widespread scarcity. Recent indications show that there is already cause for concern: the annual water availability per capita in both India and Pakistan has been below critical stress levels (<1,700 m^3/person) for several years and supplies are continuing to decline; similarly, water supplies in China and Afghanistan are close to critical stress levels (WWAP 2006).

According to the Tyndall Centre for Climate Change Research, except for Afghanistan, the HKH countries have relatively high mean annual rainfall and low inter-annual rainfall variability. Thus one solution to the water scarcity problem can be found in innovative strategies for water storage. Water storage can take place in natural storage systems (in the cryosphere and the hydrosphere), in human-made storage structures (such as reservoirs), and in constructed systems designed to augment natural storage (e.g., groundwater recharge systems, bunds, and temporary runoff collection areas). Figure 24 summarises different types of natural and artificial storage systems (McCartney and Smakhtin 2010).

A comprehensive ecosystem framework is needed to explore holistically the potential and opportunities at the river basin level to make best use of the water stored in the form of ice and snow (Dyurgerov and Meier 2005); in high-altitude wetlands (Trisal and Kumar 2008); and in the more than 20,500 high altitude lakes (Schild 2010).

Figure 24: **Water storage options**



Source: Adapted from McCartney and Smakhtin (2010)

Traditional methods of water management

Water harvesting from glaciers is common in the Chitral and Hunza districts of Pakistan and in the Spiti Valley of Himachal Pradesh in India where the whole community is involved in repairing and maintaining the system kuls (diversion channels) used to tap distant glaciers for water (Agarwal and Narain 1997). In Nepal small surface water storage reservoirs (pokhari or aahal) are used for watering cattle and, in Rajasthan, India, long earthen bunds called johad are used to hold back surface flow during rainfall so that water soaks into the soil. India also has an extensive network of existing small and medium reservoirs called 'tanks', some dating back several centuries, that are used as a distributed water storage strategy for managing intra-annual rainfall variability (Palanisami et al. 2010). The zabo system of indigenous cultivation practiced in Kikruma village of Nagaland takes a holistic approach to watershed management in which \water harvested during the monsoon is stored in ponds with earthen embankments and is used for irrigation and livestock later (Agarwal and Narain 1997). Modern-day reservoirs associated with hydropower generation are an obvious solution to water storage and in fact, most of the storage projects in the Himalayan region of China, India, and Pakistan built over the past six decades are of the multipurpose type, providing both irrigation and hydroelectricity (World Commission on Dams 2000). Many of the smaller dams, however, do not have large storage reservoirs since the stations take advantage of the steep terrain to generate a 'head' rather than depend on large discharges as do stations in more level areas.

New initiatives for water storage

There are several ways that have been identified in which a portion of the monsoon flows could be stored underground in groundwater aquifers in the Ganges basin by increasing infiltration into the water table. These include schemes for spreading water, for the construction of bunds, for pumping out the underground aquifers during the dry season to provide space for groundwater storage, and for increasing seepage from irrigation canals during the monsoon season to harvest water to be used for irrigation later (Revelle and Laksminarayana 1975). Other new methods such as the artificial recharge of aquifers with excess water are also possible but much more research and development are needed before this technology can be widely used (Keller et al. 2000). A pilot project, the Kurnool irrigation system of Andhra Pradesh, showed that percolation ponds and check dams can increase the duration of spring flow from 75 to 207 days (Singh and Singh 2002). Small reservoirs can be effective as shown by a pilot project in Jagti village of Jammu, India, where a small reservoir, built at minimal cost, filled in a day with the heavy monsoon runoff and provided water throughout the dry season. In the Kandi region, which has many deep, narrow valleys, many more such reservoirs can be built (Agarwal and Narain 1997). Rainwater harvesting is another way of reversing the present trend of groundwater depletion near urban centres. One study estimates that if rainwater were harvested in the Kathmandu Valley it could supply about 12 times the present demand (Shrestha 2009b).

Water storage: challenges

There is a need to consider both natural and man-made storage options and to find ways to turn natural storage schemes from passive to planned, active schemes. In addressing the knowledge gaps, serious consideration should be paid to analysing the upstream and downstream impacts of projects since large storage schemes in particular may have high social and environmental costs upstream, but the substantial direct and indirect benefits are commonly mostly, or only, downstream.

Mitigating the Effects of Black Carbon

Many mountain communities depend on forest biomass for their subsistence living and most commonly use biomass as a fuel for cooking and heating. Providing clean alternatives to biomass for these communities is justified overall on the grounds that:

- clean alternatives can help to prevent atmospheric warming and glacial melting by not contributing to black carbon in the atmosphere;
- they can help to prevent the premature mortality of women from respiratory illnesses related to smoke inhalation;
- crop yield losses can be forestalled; and
- forests can be maintained and both their carbon sink value and their biodiversity can be preserved.

Governments could contribute to the affordability of viable clean energy alternatives for mountain communities, possibly by providing small subsidies that would promote the use of cleaner alternatives for cooking and heating. The cost of such schemes can be justified on the basis that they are likely to reduce black carbon in the atmosphere and result in all the benefits mentioned above. Other measures to reduce black carbon could include installing particle filters on diesel engines; substituting the use of biomass with the use of pellet stoves and boilers and the use of modern recovery ovens; promoting the use of biogas and clean-burning biomass stoves; and restricting the open field burning of agricultural waste and forest refuse.

Providing clean cooking and heating energy to people in the region can help to address many of the problems caused by atmospheric black carbon. Simple measures can bring about substantial benefits to the HKH region and South Asia as a whole, since black carbon and related pollutants impact not only climate change but also human health and food security. While mitigation measures will not be very difficult to implement, they will need to be implemented rapidly and widely to bring about the impact required. International and regional cooperation with regard to technology transfer, technical assistance, and multilateral funding will be the key to addressing this problem.

Managing Biodiversity in a Warming World

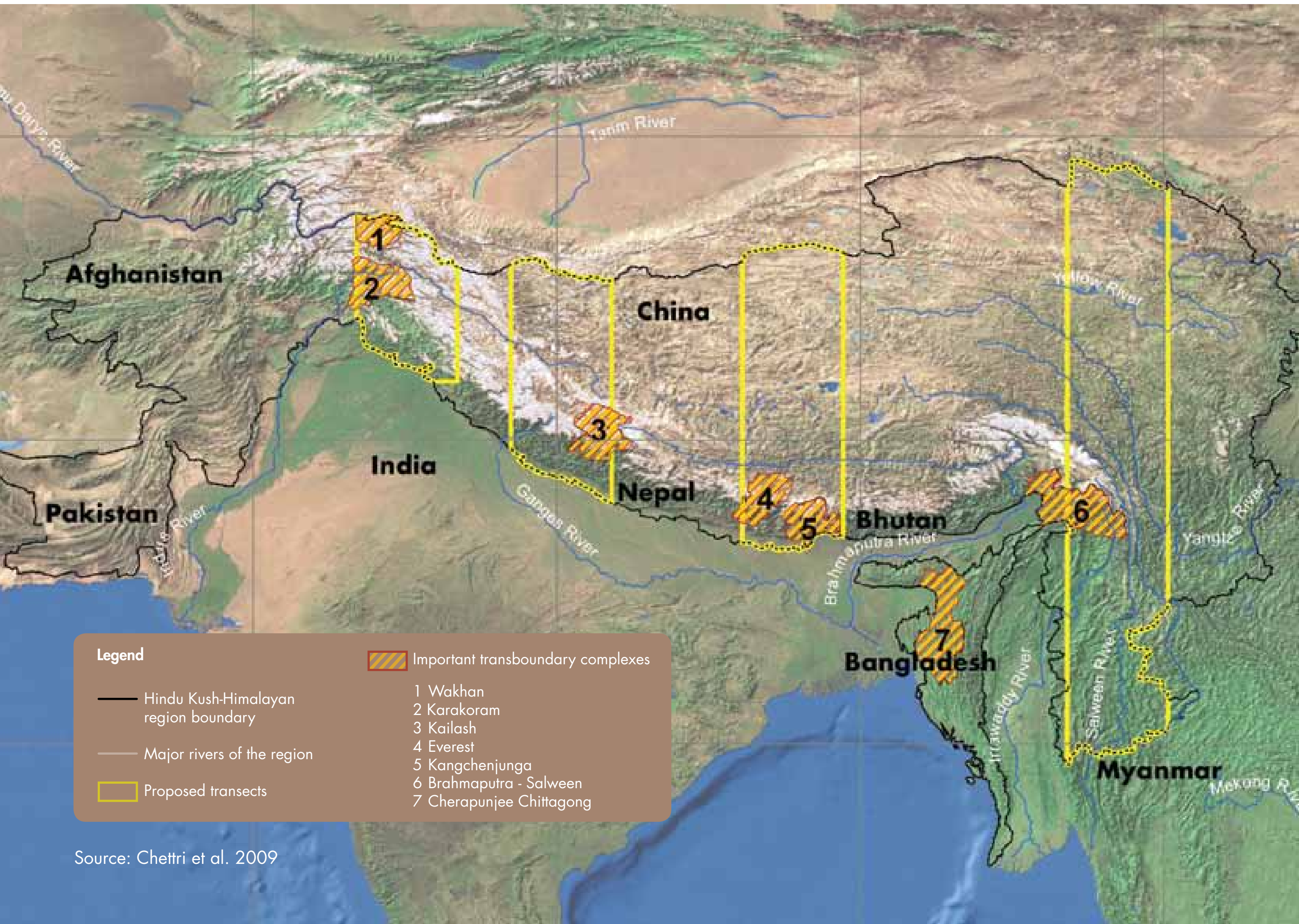
Transboundary landscapes

The Convention on Biological Diversity (CBD) advocates use of the landscape and ecosystem approach for managing biodiversity, in recognition of the need for increased regional cooperation and because of the extreme heterogeneity of the region, the inter-linkages between biomes and habitats, and the strong upstream-downstream linkages related to the provisioning of ecosystem services. In the HKH region, an approach to conservation based on the ecosystem has been developed and piloted in a number of transboundary landscapes since the late 1990s (e.g., Sherpa et al. 2003; Sharma and Chettri 2005; Chettri et al. 2007; Sharma et al. 2007). More recently, conservation corridors that enable climate-sensitive species to move and adapt to changing climate scenarios have been identified in the Kangchenjunga Landscape across an area including portions of eastern Nepal, Sikkim and Darjeeling of India, Western Bhutan (Chettri et al. 2007 and Chettri and Shakya 2010), and in the Brahmaputra-Salween Landscape in the far eastern Himalayas that covers adjacent protected areas in China, India, and Myanmar (Shakya et al. 2011). These corridors are shared by many species of global importance, and they provide an important habitat and refuge for them.

A trans-Himalayan transect approach

Climatic, environmental, and other change processes across the HKH region are of both regional and global concern (Messerli 2009). An improved understanding of these regional change processes is essential to provide the basis for informed decision making, risk and vulnerability mapping, adaptation and mitigation strategies, and

Figure 25: **The four north-south transects and seven major transboundary landscapes in the HKH region**



Source: Chettri et al. 2009

effective biodiversity conservation and management. The 'HKH trans-Himalayan transect' approach is designed to help address the information gaps across the region (Chettri et al. 2009). In place of uncoordinated scattered studies across the whole of the vast HKH region, four 'transects' have been proposed taking into account representation from west to east, dry to wet, and south to north of the HKH region (Figure 25), so that studies could be focused in a coordinated way to maximise representation of the region, the potential synergy, and usefulness of the findings. This conceptual framework promotes a participatory approach in regional cooperation for long-term standardised ecological research, capacity development, and the enhancement of a shared regional knowledge base. The geographically defined 'transects' allow for co-locating research, monitoring and sampling sites, in-depth studies, and action research projects across the region and for both comparative research and synergistic efficiencies

Regional Cooperation

Global commitments to conserve mountain ecosystems

The countries of the HKH region are aided by several global frameworks which show a worldwide commitment to sustainable development (Wahid et al. 2011). These include the following.

- Chapter 13 of Agenda 21 (UN 1992) makes a special commitment to sustainable development in mountain regions.
- The Conference of the Parties of the Convention on Biological Diversity at its Fifth Meeting endorsed the description of the ecosystem approach as a strategy for the integrated management of land, water, and living resources (CBD 2000) and at its Tenth Meeting exhorted the region to use existing, or to establish new, institutional arrangements at national and regional levels to enhance inter-sectoral coordination and collaboration for sustainable mountain development (Decision X/30) (CBD 2010).
- Article 4, paragraph 1(e) of the United Nations Framework Convention on Climate Change commits Parties to develop appropriate and integrated plans for water resource management for the protection and rehabilitation of areas affected by drought, desertification, and floods (UNFCC 2010).
- Paragraph 14a of the Cancun Agreement decided at UNFCCC COP 16 makes specific reference to water resources for 'Planning, prioritising and implementing adaptation actions, including projects and programmes' (UNFCCC 2011a, 2011b).
- The Johannesburg Plan of Implementation Para 26c (UN 2005) calls to: "Improve the efficient use of water resources and promote their allocation among competing uses in a way that gives priority to the satisfaction of basic human needs and balances the requirement of preserving or restoring ecosystems and their functions, in particular in fragile environments, with human domestic, industrial and agriculture needs, including safeguarding drinking water quality".

Regional commitments to conserve mountain ecosystems

While global mechanisms like the CBD and the Johannesburg Plan of Implementation provide an international framework for cooperation, the regional implementation of transboundary resource management requires extensive regional engagement. The search for a common appreciation of regional priorities and opportunities is aided by some regional initiatives as follows.

- The governments of Bangladesh, Bhutan, India, and Nepal convened the 'Bhutan Climate Summit for a Living Himalaya ' in November 2011 to scope out a 10-year road map for adaptation to climate change in the Eastern Himalayan sub-region that ensures food, water, and energy security while maintaining biodiversity and ecosystem services (Bhutan Summit 2011).
- The need to establish regional centres and networks to facilitate adaptation and enhanced actions in the short, medium, and long term at the sub-regional and regional levels for enhanced regional cooperation was also encouraged in the Cancun Agreement (UNFCCC 2011b).
- The South Asian Association for Regional Cooperation (SAARC), founded in 1985, is dedicated to the economic, technological, social, and cultural development of its member countries through collective self-reliance. SAARC also speaks for regional cooperation to preserve, protect, and manage the diverse and fragile ecosystems of South Asia. SAARC was recently accredited observer status at the United Nations Framework

Convention on Climate Change process at COP 16 (Cancun, Mexico, 2010). The SAARC Declaration on Climate Change adopted by the 29th Session of the Council of Ministers articulates that: "the best and most appropriate way to address the threats of climate change is to adopt an integrated approach to sustainable development" (UNFCC 2011b).

- The International Centre for Integrated Mountain Development (ICIMOD), founded in 1983, is a regional knowledge development and learning centre that supports regional transboundary cooperation through partnership with regional institutions and which facilitates networking among regional and global institutions. Over the past almost three decades, ICIMOD has worked to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream.
- Regional cooperation in transboundary landscapes can contribute to the joint management of transboundary biodiversity conservation efforts; scientific, technical, and monitoring cooperation; sharing and exchange of information; and the joint development and implementation of regional guidelines. Outside the HKH region, there are already a few models of binding agreements for the development of transboundary landscapes in the form of regional conventions, for example the Alpine and Carpathian Conventions. More recently, several bilateral agreements have emerged in the HKH region. Two recent agreements in the field of biodiversity conservation were discussed in 2010 between the governments of Nepal and China and between Nepal and India. ICIMOD facilitated this regional cooperation in conservation assessment efforts (Chettri et al. 2008a, 2008b; Desai et al. 2011). A recent example of a regional cooperation framework is that being developed by China, India, and Nepal for the conservation and management of the Kailash Sacred Landscape, spearheaded by ICIMOD (ICIMOD 2010b).

Country-Level Plans for Adaptation

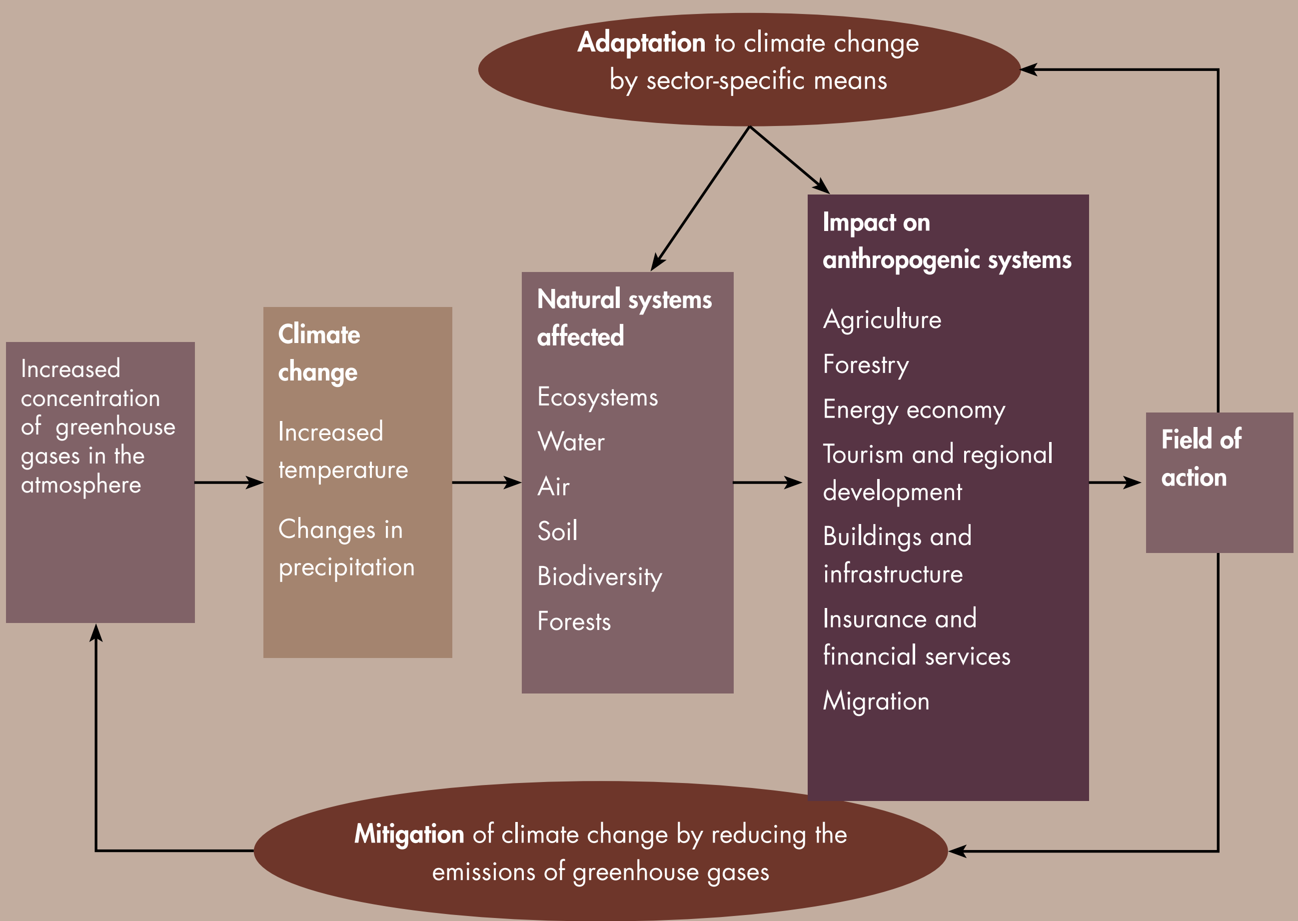
At present the policies and actions aimed at resilience to climate change in the HKH region are focused at the national level with specific time frames ranging from a few years to less than 10 years. At the national level, all HKH countries have identified climate-related vulnerabilities and prioritised adaptation measures (UNFCCC 2011b; Rahman and Amin 2011) through the National Adaptation Programme of Action (NAPA). Examples of NAPAs include Afghanistan's work in ten different activities in areas ranging from water resources through natural disaster preparedness; Bangladesh's Climate Change Strategy and Action Plan (BCCSAP) which includes six thematic areas and 44 programmes; Bhutan's NAPA that includes nine projects for immediate implementation including, among others, the aim to harvest rainwater for use during dry periods and to improve weather forecasting for agriculture (RGoB 2006); India's National Action Plan on Climate Change (NAPCC) which includes, among others, a National Mission for Sustaining the Himalayan Eco-system (GOI 2008); and Nepal's adaptation efforts which aim at an integrated ranking of priority activities (GON 2010). Some countries have also put in place water policies and strategies for improved water management which emphasise the upstream-downstream relationship of water resource management, and these include the Bhutan Water Policy, India Water Policy, and the Nepal Water Resources' Strategy. The need for a functional information system for water resource planning is also discussed in these policies (WECS 2002; GOI 2002; RGoB 2003).

5 The Way Forward

The HKH region provides many ecosystem services that benefit the wellbeing of the populations who make their homes in the mountains as well as those who live in the basins downstream and beyond. The preceding sections have shown how environmental change in general, and climate change in particular, are among the main drivers that influence the provisioning of ecosystem services and human wellbeing in the HKH region. These changes wrought by climate change pose practical challenges since they entail consequences for the delivery of the supporting, provisioning, regulating, and cultural services that ecosystems provide to the region and beyond (see Figure 20).

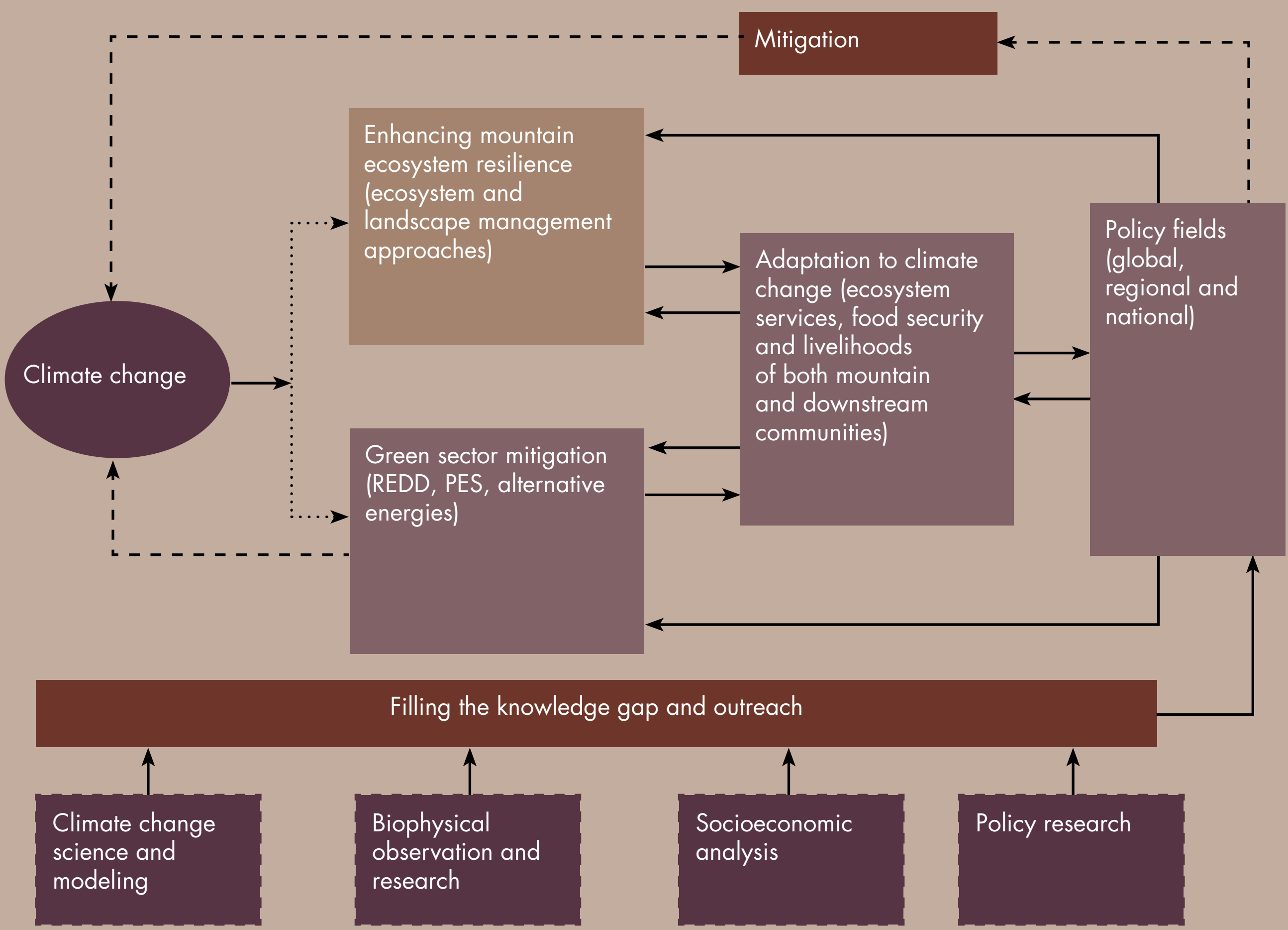
Chapter 3 discussed how climate change could impact a variety of both natural and anthropogenic systems but when climate change disturbs the equilibrium of natural systems it elicits human reactions in response. Figure 26 shows how climate change is linked to mitigation and adaptation and also shows where actions need to be taken. With changes in climate, all natural systems will be affected and the risk of disasters will increase as the climate becomes more erratic. The advent of an increased number of disasters will affect agriculture, forestry, and all buildings and infrastructure, including those used for tourism and regional development. While many of the impacts on anthropogenic systems have been discussed in the preceding chapters, it is also important here to draw attention

Figure 26: **Schematic linkages in the action fields of natural systems and anthropogenic areas related to mitigation and adaptation**



Source: Adapted from Bättig et al. (2011)

Figure 27: **Schematic diagram showing the link between the knowledge gap on climate change science, ecosystem resilience and green sector mitigation, and adaptation to climate change for policy outreach and interventions in relevant action fields**



to the importance of insurance and financial services because these have not been dealt with elsewhere.
This section begins by summarising the knowledge gaps and scientific uncertainties that surround climate change and which are challenges the region needs to overcome in order to be able to maintain the flow of ecosystem services as these need to be prioritised and addressed strategically. Ecosystem resilience, green sector mitigation, and adaptation to climate change are areas that should be strengthened through policy advocacy supported by information based on rigorous research. The section goes on to discuss how existing knowledge and data gaps need to be filled by systematic observation systems and enhanced capacities for research in the region. Figure 27 shows how the need to strengthen climate change research in the areas of modelling and biophysical observations, as well as socioeconomic analysis and policy research, are fundamental for developing adaptation and mitigation programmes. The section concludes by discussing climate change frameworks for linking efforts both regionally and globally. Relevant policies for the region and for national governance are considered as well as both the challenges and the opportunities that can arise from climate change.

Identifying Knowledge Gaps, Scientific Uncertainties, and Challenges

Defining the data deficit problem

Experts are unanimous that the data and knowledge at present available on the HKH region are grossly inadequate for developing either a regional or global understanding of climate change processes. It is essential to have an improved understanding of the biophysical processes taking place in the region to provide the basis for informed decision making, risk and vulnerability mapping, adaptation and mitigation strategies, and effective biodiversity conservation and management. Trend analysis and inputs for models that simulate climate, hydrology, glaciology, and the like require more data, of greater resolution, and over a longer-term than the data available at present. Reliable fine-grained observational data for the region would be a boon to the global study of climate change also since, at present, global models interpolate vast areas in the HKH region because of a lack of basic information.

Below is a summary of what researchers in various disciplines believe to be the most significant data gaps that need to be filled as a prerequisite for evidence-based action in the HKH region.

Biophysical data sets required

The following outlines the biophysical data sets needed for the region. The advent of remotely-sensed data will help to facilitate data acquisition especially in the most inaccessible areas, but ground truthing is equally important to help corroborate findings.

Meteorology. The time-series data for surface temperatures currently available for the HKH region do not provide a satisfactory sampling of the entire region, and there is an almost complete lack of reliable ground-truthed, time series', surface temperature data for high-altitude and remote areas.

Measurements of precipitation are even scarcer than temperature data and show less consistency, especially in the monsoon-dominated Eastern Himalayas. More observational data sets are needed for the region (daily, monthly, and seasonal). Observational data on a finer scale will be needed to test and refine models and to capture baselines.

Cryosphere. The extent to which glacial mass and seasonal snow cover have diminished in the glaciated areas of the HKH over the past few decades remains extremely uncertain as a result of the lack of substantiated time series' data for the region. There is a lack of observational data on ice stores, the extent to which snow and glacial melt contribute to stream-flow composition in high-altitude catchments, the spatial variation in glacial and snowmelt, measurements of snow depth, and estimations of snow to water equivalence.

Hydrosphere. The availability of water from rivers, lakes, and underground sources remains poorly understood, and more studies of river flow composition are needed. Studies on water storage have focused mainly on large water storage schemes in conjunction with hydro projects: but water storage, whether underground, in wetlands, or by communities and households in response to changes in the environment, is at present poorly understood and needs to be investigated. Similarly, the effects that climate variations have had on water quality in the region have not been investigated or documented.

Atmospheric pollutants. Long-term anthropogenic climate forcing as a result of increased production of aerosols and GHGs is underway in the HKH region. The data collected to date have been sufficient to generate awareness of the 'atmospheric brown cloud', but much more systematic, observational data are needed for the extensive modelling required to predict accurately the extent to which this mass of pollutant gases and particulates (mostly O3 and black carbon) are contributing to a changing climate in the HKH region and globally. Similarly, reliable information on GHG emissions and sinks are at present very limited and mostly not available for the HKH region.

Biodiversity. Whether and how biodiversity has responded to climate change remains largely anecdotal; the link between climate change and biodiversity is poorly understood. To date, there are few substantiated phenological studies of the timing of recurring biological events, such as leaf unfolding and bird migration, in the HKH region. At present, decisions on conservation are made without adequate survey since these are not available due to lack of expertise or even appropriate methodology. Similar considerations apply to data on carbon sequestration and to the impacts that climate change can have on the productivity of forests and other resources. Unless data are reliable, plans (such as access and benefit sharing and payment for ecosystem services) can neither be formulated nor implemented.

Attempts to understand and conserve biodiversity are hampered by a lack of biodiversity inventories and information on taxonomic groups, particularly those 'mega-diverse' groups such as insects that are rich in species but which are poorly understood. Claims about the effects of climate change on the regional flora and fauna need to be documented systematically and corroborating evidence is needed from measurements of temperature and precipitation. The monitoring activities should focus broadly on the following areas:

- making reliable lists of species to document species' loss;
- documenting historic coping mechanisms of relevant agrobiodiversity (evolutionary and adaptive mechanisms), together with an understanding of gender-based knowledge and knowhow pertaining to domestic crop management and crop genetic resource management;
- documenting current adaptive responses of species and/or biodiversity;
- documenting current local and/or indigenous practices and coping mechanisms of communities;
- studies to investigate the effects of atmospheric CO_2 enrichment on the productivity, species' composition, and carbon dynamics in different ecosystems and on ecosystem resistance and resilience; and
- studies to investigate anthropogenic obstructions or assistance to the spread of invasive alien species and migrating species.

Land use and land cover changes. Land use and land cover are of concern since they are the key anthropogenic source of CO_2 emissions and can have regional and global ramifications. Land use in mountain areas is being transformed rapidly by the demands of a changing climate, population growth and migration, increasing urbanisation, and the demands of the market. At present, information on land use is usually collected at the sub-basin level and is neither categorised nor generally available. In the region there is little understanding of the science of ecosystem services, and user-friendly valuation methods are still heard of for the most part in the context of the HKH countries.

Disasters and natural hazards. The physiographic setting and the climatic characteristics of the HKH region make it prone to a high incidence of both geological and hydrometeorological hazards (SAARC 2008). The countries in the HKH region have a history of devastating earthquakes, floods, landslides, droughts, and cyclones that have caused economic and human losses. People's livelihoods will depend largely on being able to withstand the financial burden that accompanies disasters. Improved databases would help with many aspects of disaster risk reduction and relief operations. Appropriate information from improved databases could also help financial market providers to price the risk adequately and provide services commensurate with this. Disasters will impact rural credit for agriculture, buildings, and other investments irrespective of whether insurance is made available or not but, when the risk is properly priced, stakeholders can weigh the options and decide for themselves whether insurance can help them or whether they had rather reduce their risk by adaptation measures. If they choose this second option, then they can choose to insure only the reduced, residual risk.

Agriculture. The Hindu Kush-Himalayan region has vast agrobiodiversity with land races of crops and livestock developed over centuries as an adaptation to local microclimates and conditions and farmers' needs (Partap and Sthapit 1998). These species, subspecies, and land races represent a huge pool of genetic resources which potentially could play an important role in identifying or developing crops suited to changing climatic and soil conditions. These resources are being lost at a rapid rate, however. Information, seeds, and other genetic material should be collected from as wide a range of this material as possible and made available across the region.

Human health and wellbeing. Information about how climate change is affecting human health in the HKH region is scanty. Comprehensive and systematic studies are needed in areas such as the relationship between climate change and health; human health sensitivity, vulnerability, and adaptation to climate change; extreme events and natural disasters and their impacts on human health; air pollution and black carbon-related impacts on both resources and human health; emergence of infectious diseases; water-related health hazards; food security, nutrition, and human health; health transition related to land use change and the eco-health approach; and highland-lowland linkages in a health perspective. Of immediate concern is that with increasing male migration (which is expected to grow with increasing climate impacts), there is an increasing feminisation of agricultural labour with as yet undocumented consequences for women's health.

Socioeconomic data required

More and more detailed socioeconomic data are available than biophysical data for the countries of the HKH region. Much of the data, however, are aggregated at a level that precludes their use in the study of mountain-specific change. There is a pressing need for data that are disaggregated geographically and in other ways related to impact; for example, by gender, economic groups, and so on from all countries; that can be used to develop a baseline overview of the mountain situation, to investigate climate-related changes and impacts, and as a base for predicting possible future scenarios.

Population growth and migration. South Asia is at present experiencing a hitherto unprecedented movement of its population. People in large numbers are either emigrating abroad or migrating within their own countries to leave behind a rural lifestyle for a more urban one. There is a growing recognition that such vast migrations and resettlement of people need to be better documented and understood since they have consequences for the environment, land use, energy requirements, water supply, air quality, and so on. Many regional experts now question whether the changes that accompany migration can have consequences that far outweigh those commonly attributed to the growing concentrations of GHGs. Disaggregated data are needed to help sort how each is contributing to climate change.

Food security. Estimates of present and future food security and potential climate change impacts in the HKH region are extremely uncertain as a result of a lack of knowledge about processes of land use and productivity in mountain areas and a lack of disaggregated socioeconomic information that can be applied to these areas. Studies are needed on agricultural productivity in different parts of the mountains together with relevant disaggregated socioeconomic data.

Documenting traditional knowledge. Indigenous people who still use time-honoured methods of farming (such as shifting cultivation and the Zabo indigenous techniques of water management) are attuned to even small changes in their environments. Over centuries they have developed adaptation strategies, such as drought and pest-resistant crop species, and other indigenous approaches to counter varying environmental conditions. To date only very few studies have captured the perceptions of these mountain communities on climactic variations and compared these vis-à-vis quantitative scientific measurements. Studies are needed to both capture perceptions of climate change archive approaches to adaptation, which may be useful for addressing future climate change impacts, before this knowledge is irrevocably lost.

The need for better climate models and interpretation of climate-related impacts

When global climate models (GCMs) and regional climate models (RCMs) are downscaled they can provide scenarios that are indicative of the expected range of rainfall and temperature changes, but the quantitative estimates still have a lot of uncertainties. Better models which can take the extreme topography and the specific atmospheric circulation patterns of the region into consideration are needed to improve climate forecasts. While improved data sets are a start, a better understanding of the underlying physical processes is also needed. Another challenge will be to develop a good understanding of how eventually changes in temperature and precipitation will impact hydrology, biodiversity, and the people living in the HKH region.

Focused research and policy formulation for protected areas

Research on institutional frameworks and their effectiveness in governance and assessments of good practices with examples of community-led conservation have to be central to formulation of an effective and responsive governance system for protected areas. Strong emphasis needs to be placed on indigenous knowledge systems, particularly in regard to natural resource management approaches and institutional frameworks, drawing upon traditional practices of management and governance, especially in regard to sacred landscapes.

An enabling policy environment is essential in order to support and strengthen community efforts to cope with change. Policy dialogues need to focus on areas in which adjustments in existing policies are required, particularly with regard to economic benefits, governance frameworks, and local-level policy adjustments. A clear concern is the multiplicity of policy actors governing natural resource management and livelihood support and the need for convergence of different (often conflicting) policies under one forum for ease of implementation. Dialogue needs to focus on this required convergence before moving on to sectoral details.

Strategies to Fill Data Gaps and to Augment Systematic Observations

Strategies to fill data gaps can be divided into two categories: the first set focuses on acquiring new, disaggregated data with an emphasis on obtaining long-term, permanent monitoring; the second set recognises that once data have been acquired they can only be used to their full potential when they are in a form that makes them easy to use and share. A number of suggestions for both are outlined in the following.

Strategies for data acquisition

The systematic acquisition of long-term disaggregated data from the mountainous areas of all the eight countries that share the HKH data is needed in all of the disciplines outlined above. Well-established, international monitoring efforts can share information and know-how. A good starting point might be to validate data sets such as those from the Global Precipitation Climate Centre, the Global Precipitation Climatology Project, and the Climate Research Unit. Other sources of data on climatology and biodiversity data include the SHARE network (EV-K2-CRN), Atmospheric Brown Cloud monitoring project, Global Climate Observing System (GCOS), Global Terrestrial Observing System (GTOS), Global Mountain Biodiversity Assessment (GMBA), Global Biodiversity Information Facility (GBIF), Global Observation Research Initiative in Alpine Environments (GLORIA), and the mountain research community (GLOCAMORE Mountain Research Strategy) among others.

The vastness and inaccessibility of most of the HKH region make the use of remote- sensing data a necessity, and some remote-sensing efforts are already underway. The extreme variability of the steep terrain in the HKH region, however, requires that data be sampled and ground-truthed periodically to validate the remote-sensing data. Biodiversity surveys on a regional scale are needed throughout the HKH region; and these should include inventories of forests and protected areas, documentation of changes in agricultural crops (and livestock) and cropping patterns, and monitoring of changes in the nutritive value of crops. Biodiversity surveys can take place in conjunction with the ongoing CBD programme of work on mountain biodiversity. The International Union for the Conservation of Nature (IUCN) has begun category mapping of protected areas in the region and this needs to be expedited since, as the global standard for defining and recording protected areas, it is being incorporated increasingly into the legislation of the regional national governments. Given that biodiversity inventories for many regions are sparse and that acquisition of new data is costly, surrogate-based approaches could be cost-effective. In the surrogate approach the diversity of well-known taxonomic groups are used as surrogates for overall biodiversity assessment. Examples of how the surrogate approach has been used in the region are given by Chettri (2010) and by Pawar et al. (2006). Mechanisms are needed to involve communities in collecting and documenting community perceptions and phenological information and to corroborate these with weather data collected by meteorological stations. An interesting emerging trend is to involve local people themselves in a form of 'citizen science' particularly through the use of new tools and technology such as the internet, social media, and crowdsourcing. Similarly, an inventory of traditional knowledge is needed to support future adaptation efforts; and this could be linked to inventories being developed in relation to protection of intellectual property rights and access and benefit sharing initiatives.

Strategies for sharing data

Data scarcity is an issue throughout the HKH region; however, even the data that are available are not used effectively owing to both a lack of regional sharing platforms and the fact that data are often in a form that is not easy to use. Box 15 gives an example of how relevant data can be overlooked. Sharing mechanisms are needed to ensure that existing data can be accessed and that new data are systematically collected and shared both regionally and globally.

Box 15: **How are data overlooked?**

While it is indisputable that very little primary observational data exist for the region, especially compared to the mountain areas of more developed regions, it is also the case that the data that do exist are often poorly shared, of limited accessibility, or simply overlooked. Forests provide a good example. Silviculture in the Indian Himalayas was thoroughly described about a century ago (Troup 1922). The Kumaun Himalayas in Uttarakhand is among the most investigated regions with regard to the structure and function of forest ecosystems (Singh and Singh 1992); moreover, there is a considerable amount of basic data available for the region on forest cover, species' diversity, and forest stock. Yet climate simulations rarely use these data; rather, they more commonly use data from forests at temperate latitudes (that are more widely available) to make future projections for Himalayan forests, even though the properties of Himalayan forest ecosystems are closer to those of tropical forest ecosystems than those of temperate forest ecosystems, even above 2,000 masl altitude

Source: Zobel and Singh (1997).

Countries often view data on hydrology and meteorology as proprietary and may not be inclined to share these; however, physical phenomena do not end at national boundaries and sharing data should be viewed as a mutual benefit and an opportunity for transboundary cooperation. Some examples of permanent structures for cooperation in the region include: the South Asian Association for Regional Cooperation (SAARC), the South Asia Water Initiative (SAWI), and ICIMOD itself. Topical conferences can also promote sharing: recent examples include Bhutan's upcoming 'Climate Summit for the Living Himalayas' to take place in November 2011 (RGoB 2011), the 'International Mountain Biodiversity Conference' held in late 2008, and the' International Symposium on Benefiting from Earth Observation: Bridging the Data Gap for Adaptation to Climate Change in the Hindu Kush-Himalayan Region' held in October 2010.

Data protocols need to be developed so that data can be shared and harmonised more easily in the long term; and the use of standardised formats in line with international standards would greatly help in this. Standard protocols are already used for some types of data and this is a good starting point. The use of standard protocols also extends to publishing findings in internationally recognised journals that are widely disseminated: often when findings are published in national journals in local languages their accessibility for those from elsewhere in the region or beyond is limited.

A central repository or data-sharing platform would help facilitate access to data throughout the region and beyond; one such facility is ICIMOD's Mountain Geoportal. ICIMOD partners with the Global Biodiversity Information Facility (GBIF) to provide a platform for biodiversity in the HKH region and also participates in the Global Earth Observation System of Systems (GEOSS), an international umbrella body that promotes open access to data, decision support tools, and imagery derived from remote sensing. Access to remotely-sensed data in the HKH region is also being facilitated by the SERVIR-Himalaya node located at ICIMOD which integrates satellite observations and predictive models with other geographic information (sensor and field-based) to monitor and forecast ecological changes and respond to extreme events.

Archival data may be available in universities and government meteorological stations, as well as other institutions throughout the HKH region; and these data need to be collected systematically and scrutinised since time series' data are essential for establishing baselines. Even within and among ministries in the same country, it will be necessary to develop systems for improved data sharing and archiving.

Many students and academics from developed countries carry out research projects in the Himalayan region which collect large amounts of detailed data, albeit often very localised. The synthesised outputs eventually become available in theses and scientific articles, but these often have limited accessibility in the region and do not include detailed data. A mechanism should be developed for compiling an inventory of research projects carried out in the region and compiling relevant data and data sources for regional use. Researchers should include the ethic of 'giving back' information collected to the communities and countries in which research is carried out in the research plans.

Information that has not been scrutinised or peer-reviewed, such as development-related reports, technical notes, and other documents, is often referred to as 'grey' literature. Although there is no general consensus about whether this literature is valid, it has been suggested that, considering the paucity of data on the region in general, it might be valuable to compile grey literature that is not in the public domain, with the proviso that it be used with caution. One such example is the metadata available from ICIMOD's HimalDoc (http://himaldoc.icimod.org/site/himaldoc).

Legal experts can help to sort out issues of intellectual property rights that may now be holding up the free exchange of data. Once data from the region have been collected and analysed, they should be scrutinised and published in peer-reviewed journals for the benefit of the global community. Thematic issues on different aspects of the HKH region can help to draw attention to the region.

Policy makers require authentic data inputs and, more often than not, these are not available or are not comprehensible. Scientific institutions need to bridge this gap so that policy making can be based on scientific findings. Institutions should focus on making data and information available to policy makers and planners by:

- developing policy reviews and policy briefs,
- facilitating dialogue among experts and policy makers,
- developing a framework for implementation, if necessary, and
- liaising with stakeholders at local, national, and regional levels for implementation.

Identifying Capacity Building Needs in the Region

The previous sections outline the monitoring needs and strategies for acquiring data, but these strategies all hinge on having adequate capacity in the region to both implement monitoring and to be able to customise and make the most of the monitoring resources and sharing platforms available globally. A framework of institutional support and skilled manpower is needed. The regional capacity building that needs to take place can roughly be categorised as the need to develop institutions that can address the various data deficit areas; the need to train environmental researchers and practitioners in the region; and the need to acquire the ability to communicate research findings to governments and the public at large effectively.

Building human capacity

Young researchers and policy makers in the region need to learn more about the different environmental disciplines and technologies for data acquisition and systematic documentation, and they also need know-how on converting this knowledge to make it useful for mitigation and adaptation. This exposure can take place in university courses, in short courses given by specialised agencies, by participating in thesis projects, and by 'learning by doing' while working in the different areas of environmental research.

Innovative strategies are needed for capacity building with mountain communities, such as community-led observations and participatory data collection, so that better use can be made of the stores of the traditional knowledge they harbour and the phenological observations they make. Similarly, mountain communities can benefit from modern day mitigation measures and adaptation options which are integrated holistically with local innovations. There are many possible venues for capacity building with communities such as print media, public radio, working with teachers and schoolchildren, and so on.

Building institutional capacity

Institutional capacity can be built by both establishing new institutions and refining the mandates of existing institutions such as universities, government institutes, and research centres. At present the region has an inadequate research and training infrastructure, but regional collaboration can make the most of limited resources by sharing and learning together about climate-adapted interventions specific to mountain regions. For example, specific technical aspects of monitoring can be concentrated in lead institutes that also take on the responsibility for coordinating and sharing data in that area and which provide training for researchers and practitioners in the region. The Himalayan University Consortium provides a potential platform for exchange among universities and the development of curricula on mountain-specific topics and climate-change impacts. Common platforms can also be created for enhanced interaction among scientists, policy makers, and decision makers in the region. In general, any approach that promotes interaction will help to reduce the isolation of researchers in the region and help to improve understanding and to augment the capacity needed to manage the region.

One aspect that has received little attention to date has been the economic plight of communities and individual farmers in the face of a changing environment and their need for information and capacity-building to help cope with the challenges.

The insurance and banking sectors need capacity building to devise measures that can help give those most affected by the day-to-day consequences of climate change the latitude to explore options for adaptation and mitigation.

Governments

Capacity building needs to extend to governments to assist them to put into play policies and laws that honour the commitments they have made to global climate-friendly international treaties and conventions such as the Kyoto Protocol, the Convention on Biodiversity, Convention on Desertification, the United Nations Framework Convention on Climate Change (UNFCCC), and so on. Governments also can benefit from capacity building in the area of integrated assessment frameworks; that is, capturing demands from different sectors (environment, agriculture, and so on) and integrating them both horizontally and vertically to help assess the food and agriculture situation and interaction between different systems such as water resources, market forces, and productivity.

Communicating information on environmental change

Research findings are most useful to end users when they are presented in a format that can be used to take action. As such, more capacity is needed in the region in terms of manpower and organisations that specialise in analysing and integrating primary observational data from different disciplines to make it useful for policy makers and others who implement mitigation and adaptation measures.

Linking Global and Regional Frameworks on Climate Change with Appropriate Regional-Level Policy Making and National Governance

Climate change transcends national boundaries; over the past decade there has been clear evidence that the consequences of anthropogenic activities in one area can have consequences regionally and globally. For this reason, there is a need to be more focused and pragmatic and to undertake an overall paradigm shift that views the sharing of resources in the context of overall benefit sharing. This sharing can begin by linking regional-level policy making and national-level governance in the HKH region with global frameworks to make the most of global know-how to inform policy – and to assist with planning for regional mitigation and adaptation to climate change. The sharing should also extend from the HKH region to the global community which can benefit from better data on the HKH region to bridge the substantial gap existing in information in order to refine global climate models and to inform global policies for countering climate change.

Global institutions have know-how in the many different aspects of climate change and the HKH region can benefit from collaborating with those that specialise in technical matters such as climate data acquisition and sharing protocols, downscaling of global models, biodiversity conservation, adaptive agriculture, seed banks, and so on. International agencies that can be accessed for these include, among many others, the Global Biodiversity Information Facility (GBIF) and the Intergovernmental Panel for Biodiversity and Ecosystem Services (IPBES). In addition to technical information and know-how, integrated information frameworks in the public domain can be engaged in different aspects of policy related to climate change; for example, the FAO on food security, the IUCN on managing land resources, the CGIAR centres for agriculture, and the ecosystem approaches of the CBD such as the Programme of Work on Mountain Biodiversity. Moreover, the CBD has agreed to form an IPCC-like body on biodiversity, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), which will be a platform to bring more scientific rigour to the science-policy platform.

Global implications extend beyond the exchange of knowledge and information. Recently people worldwide have begun to ponder how to level out the age-old inequalities between mountain dwellers (who are the custodians of the mountain ecosystem services such as forests and water) and the end users of these services downstream who typically enjoy the benefits without bearing much of the burden. A discussion of payment for ecosystem services has received academic attention for some time, but perhaps the moment has come for a serious discussion on what policies and institutional mechanisms will be required to balance the needs of the mountain communities with their continued stewardship of ecosystem services upstream and the ability of global benefactors downstream to contribute fairly for the services they enjoy.

Challenges and Opportunities

The regional dimension

ICIMOD has been mandated by its regional member countries to work on regional issues related to the HKH region. In the context of climate change and its global nature, which demand regional action, the role of an institution like ICIMOD is becoming ever more relevant. ICIMOD as a regional knowledge, capacity development, learning, and enabling centre has had almost 30 years of experience in bringing together the regional countries of the HKH region and linking them with global frameworks on issues of knowledge sharing and policy development for sustainable mountain development. A good starting point for data acquisition and sharing in the region can be the 'HKH trans-Himalayan transect and river basin' approach proposed by ICIMOD in collaboration with the regional countries of the HKH and international experts. This conceptualised approach identifies existing monitoring sites for hydrometeorological, cryosphere, and environmental monitoring across the HKH region and eventually can be expanded to include socio-ecological monitoring. Initial transect sites are located strategically to obtain representative data that cover the west to east, dry to wet, and south to north latitudinal and longitudinal expanse of the HKH region for long-term environmental monitoring. Ground-truthing of remotely-sensed sites can take place at the existing and planned monitoring stations identified by the transect project. Furthermore, ICIMOD uses an upstream-downstream approach in the work that it carries out in the ten major river basins that originate in the HKH region.

In addition to technical expertise on data acquisition and sharing, ICIMOD has been facilitating the regional countries of the HKH to adopt a problem analysis, design, and implementation model which is trans-disciplinary in order to translate concerns on mountain issues into operational action by supporting interdisciplinary team work; to institute programme monitoring and evaluation measures; and to optimise their use of financial, human, and institutional resources. ICIMOD remains committed to integrating crosscutting criteria of policy, governance, equity, and gender and to mainstreaming principles of information and knowledge management.

References

Action Aid (2011) *Who's best prepared for a climate and hunger crisis?* Johannesburg, South Africa: Action Aid

Adhikari, B (2009) *Market-based approaches to environmental management: A review of lessons from payment for environmental services in Asia,* ADBI Working Paper 134.Tokyo: Asian Development Bank Institute.

Agarwal, A; Narain, S (eds) (1997) *Dying wisdom: Rise, fall and potential of India's traditional water harvesting systems,* State of India's Environment, A Citizen's Report 4. New Delhi, India: Centre for Science and Environment

Agarwal, PK; Bandyopadhyay, SK; Pathak, H; Kalra, N; Chander, S; Kumar, S (2000) 'Analysis of yield trends of therice-wheat system in north-western India.' *Outlook on Agriculture* 29(4): 259–268

Agrawal, M; Auffhammer, M; Chopra, UK; Emberson, L; Iyngararasan, M; Kalra, N; Ramana, MV; Ramanathan, V; Singh, AK; Vincent, J (2008) *Impacts of atmospheric brown clouds on agriculture,* Part II of Atmospheric brown clouds: Regional assessment report with focus on Asia. Nairobi, Kenya: UNEP

Akhtar, M; Ahmad, N; Booij, MJ (2008) 'The impact of climate change on the water resources of Hindukush-Karakorum-Himalaya region under different glacier coverage scenarios.' *Journal of Hydrology* 355(1-4): 148–163

Allan, JD; Palmer, M; Poff, NL; (2005) 'Climate change and freshwater ecosystems.' In Lovejoy, TE; Hannah, L (eds), *Climate change and biodiversity,* pp 274–290. New Haven, USA: Yale University Press

Allen, DJ; Molur, S; Daniel, BA (comp) (2010) *The status and distribution of freshwater biodiversity in the Eastern Himalaya*. Cambridge, UK: IUCN; Coimbatore, India: Zoo Outreach Organisation

Allen, R (2011) *Climate change in the mid-hills of Nepal – fact or fiction¬ from a farmer's perspective*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Antle, J; Stoorvogel, J (2008) 'Agricultural carbon sequestration, poverty, and sustainability.' *Environment and Development Economics* 13(3): 353–373

APN (2003) *Global change impact assessment for Himalayan mountain regions: Resource management and sustainable development,* Final Report. Kathmandu: APM. www.apn.gr.jp/en/products/project_report/2003/finalreport/2003-03.pdf (accessed 15 September 2011)

Archer, DR; Fowler, HJ (2005) 'The use of exploratory data analysis with ground-based data to assess climate runoff links in the Upper Indus Basin.' In, *Landschaftsoekologie and Umweltforschung*, pp 75–82. Karlsruhe, Germany: Institut für Geographie und Geoökologie

Armstrong, RL (2010) *The glaciers of the Hindu Kush-Himalayan region: A summary of the science regarding glacier melt/retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain range.* Kathmandu, Nepal: ICIMOD

Asquith, NM; Vargas, MT; Wunder, S (2008) 'Selling two environmental services: In-kind payments for bird habitat and watershed protection in Los Negros, Bolivia.' *Ecological Economics* 65(4): 675–684

Badola, R; Hussain, SA; Mishra, BK; Konthoujam, B; Thapliyal, S; Dhakate, PM (2010) 'An assessment of ecosystem services of Corbett Tiger Reserve, India.' *The Environmentalists* 30(4): 320–329

Bättig, M; Rom, N; Dettli, R (2011) Anpassung an die Klimaänderung im Berggebiet Fallstudie Saastal. [Adaptation to climate change in the Swiss Alps, Saastal case study]. Zurich, Switzerland: Econcept

Bajracharya, SR; Maharjan, SB; Shrestha F (2010a) *Glaciers shrinking in Nepal Himalaya*. www.intechopen.com/articles/show/title/glaciers-shrinking-in-nepal-himalaya (accessed 20 October 2011)

Bajracharya, SR; Maharjan, SB; Shrestha, F (2011) 'Glaciers shrinking in Nepal Himalaya.' In Blanco, J; Kheradmand, H (eds), Climate change: *Geophysical foundations and ecological effects*, pp 445–458. Rijeka, Croatia: InTech

Bajracharya, SR; Maharjan, SB; Shrestha, F; Khattak, GA; Wanqin, G; Junfeng, W; Shiyin, L; Xiaojun, Y (2010b) *The status of glaciers in the Hindu Kush-Himalayas*. Unpublished internal report for ICIMOD, Kathmandu, Nepal

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

Bajracharya, SR; Shrestha, B (2011) *The status of glaciers in the Hindu Kush-Himalayan region.* Kathmandu, Nepal: ICIMOD

Baker, BB; Moseley, RK (2007) 'Advancing tree line and retreating glaciers: implications for conservation in Yunan, P. R. China.' *Arctic, Antarctic, and Alpine Research* 39(2): 200–209

Banskota, K; Karky, BS; Skutsch, M (eds) (2007) *Reducing carbon emissions through community-managed forests in the Himalaya*. Kathmandu, Nepal: ICIMOD

Baral, N; Gautam, R; Timilsina, N; Bhat, MG (2007) 'Conservation implications of contingent valuation of critically endangered white- rumped vulture Gyps bengalensis in South Asia.' *The International Journal of Biodiversity Science and Management* 3: 145–156

Baral, N; Stern, MJ; Bhattarai, R (2008) 'Contingent valuation of ecotourism in Annapurna conservation area, Nepal: Implications for sustainable park finance and local development.' *Ecological Economics* 66: 218–227

Barthlott, W; Kreft, G; Cooper, W; Rafiqpoor, D; Mutke, J (2005) *Global assessments of plant species richness and endemism: implications for conservation in a changing world*. Bonn, Germany: University of Bonn, Nees Institute of Biodiversity of Plants

Bernett, TP; Adam, JC; Lettenmaier, DP (2005) 'Potential impacts of a warming climate on water availability in snow-dominated regions.' *Nature* 438: 303–309

Bhutiyani, MR; Kale, VS; Pawarc, NJ (2009) 'Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006.' *International Journal of Climatology* 30(4): 535–548

Bohner J; Lehmkuhl, F (2005) 'Environmental changes modelling for Central and High Asia: Pleistocene, present and future scenarios.' *Boreas* 34(2): 220–231

Bolch, T; Pieczonka, T; Benn, DI (2011) 'Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery.' *The Cryosphere* 5: 349–358

Bonasoni, P; Cristofanelli, P; Marinoni, A; Vuillermoz, E (2011) *Atmospheric pollution in the HKH region: Evidences and implications to regional climate*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Bonasoni, P; Laj, P; Marinoni, A; Sprenger, M; Angelini, F; Arduini, J; Bonafe, U; Calzolari, F; Colombo, T; Decesari, S (2010) 'Atmospheric brown clouds in the Himalayas: First two years of continuous observations at the Nepal-climate observatory at pyramid(5079 M).' *Atmospheric Chemistry and Physics Discussions* 10(2): 4823–4885

Bookhagen, B; Burbank DW (2010) 'Toward a complete Himalayan Hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge.' *Journal of Geophysical Research* 115(F3): 1–25

Carrico, CM; Bergin, MH; Shrestha, AB; Dibb, JE; Gomes, L; Harris, JM (2003) 'The importance of carbon and mineral dust to seasonal aerosol properties in the Nepal Himalaya.' *Atmospheric Environment* 37(20): 2811–2824

CBD (2000) *Fifth ordinary meeting of the Conference of the Parties to the Convention on Biological Diversity,* 15–26 May 2000, Nairobi, Kenya. www.cbd.int/decisions/cop/?m=cop-05 (accessed 15 July 2011)

CBD (2010) *Tenth meeting of the Conference of the Parties to the Convention on Biological Diversity,* 18–29 October 2010, Nagoya, Aichi Prefecture, Japan. www.cbd.int/decision/cop/?id=12296 (accessed 15 July 2011)

Chand, R; Raju, SS; Pandey, LM (2008) *Progress and potential of horticulture in India*. Paper prepared for the 68th Annual Conference of the Indian Society of Agricultural Economics, 28–30 November 2008, Andhra University, Visakhapatnam, India

Chaudhary, P; Bawa, KS (2011) 'Local perceptions of climate change validated by scientific evidence in the Himalayas.' *Biological Letters:* doi: 10.1098/rsbl.2011.0269

Chaudhaury, P; Rai, S; Wangdi, S; Mao, A; Rehman, N; Chettri, S; Bawa, KS (2011) 'Consistency of local perceptions of climate change in the Kangchenjunga Himalayas' landscape.' *Current Science* 101(4): 504–513

Chaudhry, Q-u-Z; Mahmood, A; Rasul, G; Afzaal, M (2009) *Climate change indicators of Pakistan,* PMD Technical Report No 22/2009. Islamabad, Pakistan: Pakistan Meteorological Department

Chaudhry, Q-u-Z; Rasul, G (2007) 'Development of a mesoscale convective system over the foothills of Himalaya into a severe storm.' In Baudo, R; Tartari, G; Elisa, V (eds), *Mountains witnesses of global changes: Research in the Himalaya and Karakoram–Share-Asia Project,* Developments in Earth Surface Processes, Vol. 10, pp 301–311. Amsterdam, the Netherlands: Elsevier

Chen, C (2010) 'Using barren land for afforestation: Assessing the results of the first registered CDM Forestry Project.' *Mountain Forum Bulletin* January 2010: 40

Chen, J (2007) 'Rapid urbanization in China: A real challenge to soil protection and food security'. *Catena* 69: 1–15

Chen, RS; Kang, ES; Yang, JP; Lan, YC; Zhang, JS (2002) 'Variance tendency in the fifty-year annual meteorological and hydrological series of Hexi Region of Gansu Province.' *Journal of Lanzhou University* (Natural Sciences) 38: 163–170 (in Chinese)

Chen, WY; Jim, CY (2010) 'Resident motivations and willingness-to-pay for urban biodiversity conservation in Guangzhou (China).' *Environmental Management* 45: 1052–1064

Chen, X; Hu, B; Yu, R (2005) 'Spatial and temporal variation of phenological growing season and climate change impacts in temperate eastern China.' *Global Change Biology* 11: 1118–1130

Chettri, N (2010) 'Cross-taxon congruence in a trekking corridor of Sikkim Himalaya: Surrogate analysis for conservation planning.' *Journal for Nature Conservation* 18: 75–88

Chettri, N (2011) *Reconciling biodiversity conservation in a changing climate: A Hindu Kush-Himalayan perspective*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush-Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Chettri, N; Shakya, B (2010) 'Conservation connectivity in transboundary landscapes: an approach for climate change adaptation in the Hindu Kush-Himalayan region.' In, *Biodiversity and climate change: Achieving the 2020 targets, Abstracts of posters presented at the 14th Meeting of the SBSTTA of the CBD, 10-21 May 2010, Nairobi, Kenya,* CBD Technical Series No. 51, pp 42–44. Montreal, Canada: Secretariat of the Convention on Biological Diversity

Chettri, N; Shakya, B; Sharma, E (2008b) *Biodiversity conservation in the Kangchenjunga landscape*. Kathmandu, Nepal: ICIMOD

Chettri, N; Shakya, B; Thapa, R; Sharma, E (2008a) 'Status of protected area system in the Hindu Kush-Himalaya: an analysis of PA coverage.' *International Journal of Biodiversity Science and Management* 4(3): 164–178

Chettri, N; Sharma, E; Shakya, B; Bajracharya, B (2007) 'Developing forested conservation corridors in the Kangchenjunga landscape, Eastern Himalaya.' *Mountain Research and Development* 27(3): 211–214

Chettri, N; Sharma, E; Shakya, B; Thapa, R; Sharma, M; Bajracharya, B; Uddin, K; Oli, KP; Dasgupta, J; Chaudhury, D (2010) *Biodiversity in the Eastern Himalaya: Status, trends, and vulnerability to climate change; Climate change and vulnerability in the Eastern Himalayas,* Technical Paper 2. Kathmandu, Nepal: ICIMOD

Chettri, N; Sharma, E; Shrestha, AB; Zhoali, Y, Hua, Q; Bajracharya, B (2011) 'Real world protection for the 'third pole' and its people.' In Huettmann, F (ed), *Protection of three poles,* pp 113–133. Tokyo, Japan: Springer

Chettri, N; Sharma, E; Thapa, R (2009) *Long term monitoring using transect and landscape approaches within Hindu Kush-Himalayas*. Proceedings on 'International Mountain Biodiversity Conference', 16–18 November 2008, ICIMOD, Kathmandu, Nepal

Chettri, N; Thapa, R; Shakya, B (2007) 'Participatory conservation planning in Kangchenjunga transboundary biodiversity conservation landscape.' *Tropical Ecology* 48(2): 163–176

Choudhury, D; Choudhury, D (2011) *Diversification of livelihood strategies: moving from coping to adaptation*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Cogley, JG (2011a) 'Himalayan glaciers now and in 2035.' In Singh VP; Singh P; Haritashys, VK (eds) *Encyclopedia of snow, ice and glaciers*, pp 520–523. A. A. Dordretch, the Netherlands: Springer

Cogley, JG (2011b) 'Present and future states of Himalaya and Karakoram glaciers.' *Annals of Glaciology* 59(59): 69–73

Cogley, JG; Kargel, JS; Kaser, G; van der Veen, CJ (2010) 'Tracking the source of glacier misinformation.' *Science* 327(5965): 522

Collins, AE (2001) 'Health ecology, land degradation and development.' *Land Degradation and Development* 12: 237–50

Collins, DN (2008) 'Climate warming, glacial recession and runoff from Alpine basins after the little Ice Age maximum.' *Journal of Glaciology* 48:119–124

Costello, A; Ball, S; Patterson, C; Abbas, M; Patel, J; Allen, A; Levy, C; de Oliveira, JAP; Bell, S; Bellamy, R; Friel, S; Groce, N; Kett, M; Johnson, A; Lee, M; Scott, J; Maslin, M; McCoy, D; McGuire, B; Twigg, J; Montgomery, H; Napier, D; Redclift, N; Pagel, C; Rees, H; Rogger, D; Stephenson, J; Wolff, J (2009) 'Managing the health effects of climate change: Lancet and University College London Institute for Global Health Commission.' *The Lancet* 373(9676): 1693–1733 (http://download.thelancet.com/pdfs/journals/lancet/PIIS0140673609609351.pdf last accessed November 2011)

Cruz, RV; Harasawa, H; Lal, M; Wu, S (2007) 'Asia.' In Parry, ML; Canziani, OF; Palutikof, JP; Van Der Linden, PJ; Hanson, CE (eds), *Climate change 2007: Impacts, adaptation, and vulnerability*- Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp 470–506. Cambridge, UK: Cambridge University Press

Dahal, N; Karky, BS; Kotru, R (2011) *Prospects of REDD for sustainable greening of the Himalaya*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Damato, G; Cecchi, L (2008) 'Effects of climate change on environmental factors in respiratory allergic diseases.' *Clinical and Experimental Allergy* 38: 1264–1274

Dash, SK; Jenamani, RK; Kalsi, SR; Panda, SK (2007) 'Some evidence of climate change in the twentieth-century India.' *Climate Change* 85: 299–321

Davidson, G; Behnke, RH; Kerven, C (2008) 'Implications of rangeland enclosure policy on the Tibetan plateau.' *IHDP Update* 2.2008: 59–62

Decesari, S; Facchini, MC; Carbone, C; Giulianelli, L; Rinaldi, M; Finessi, E; Fuzzi, S; Marinoni, A; Cristofanelli, P; Duchi, R; Bonasoni, P; Vuillermoz, E; Cozic, J; Jaffrezo, JL; Laj, P (2010) 'Chemical composition of PM_{10} and PM_1 at the high-altitude Himalayan station Nepal Climate Observatory-Pyramid (NCO-P) (5079 m a.s.l.).' *Atmospheric Chemistry and Physics* 10(10): 4583–4596

Deng, X; Huang, J; Rozelle, S; Uchida, E (2006) 'Cultivated land conversion and potential agricultural productivity in China'. *Land Use Policy* 23: 372–384

Desai, BH; Oli, KP; Yongping, Y; Chettri, N; Sharma, E (2011) *Implementation of the convention on biological diversity: A retrospective analysis in the Hindu Kush-Himlayan countries*. Kathmandu, Nepal: ICIMOD

Dhakal, S (2011) *Global source and sink dynamics and Hindukush Himalayan region*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Dhiman, RC; Chavan L; Pant M; Sharmila, P (2011) National and regional impacts of climate change on malaria by 2030.' *Current Science* 101: 372–383

Dimri, AP; Dash, SK (2010) 'Winter temperature and precipitation changes in the Siachen Glacier.' *Current Science* 98(12): 1620–1625

Dimri, AP; Dash, SK (2011) 'Wintertime climate trends in the western Himalayas.' *Climate Change*: doi:10.1007/A10584-011-0201-y

Du, MY; Kawashima, S; Yonemura, S; Zhang, XZ; Chen, SB (2004) 'Mutual influence between human activities and climate change in the Tibetan Plateau during recent years.' *Global and Planetary Change* 41(3–4): 241–249

Dubey, B; Yadav, YR; Sing, J; Chaturvedi, R (2003) 'Upward shift of Himalayan pine in Western Himalaya, India.' *Current Science* 85(5): 1135–1136

Dumka, UC; Moorthy, KK; Satheesh, SK; Sagar, R; Pant, P (2008) 'Short-period modulations in aerosol optical depths over the central Himalayas: Role of Mesoscale processes.' *Journal of Climate and Applied Meteorology* 47: 1467–1475

Dumka, UC; Moorthy, KK; Kumar, R; Hegde, P; Sagar, R; Pant, P (2010) 'Characteristics of aerosol black carbon mass concentration black carbon mass concentration over a high altitude location in Central Himalayas from multi-year measurements.' *Atmospheric Research* 96: 510–212

Dumka, UC; Moorthy, KK; Tripathi, SN; Hegde, P; Sagar, R (2011) 'Altitude variation of aerosol properties over Himalayan range inferred from specie measurements.' *Journal of Atmospheric and Solar-Terrestrial Physics* 73: 1747–1761

Dye, DG; Tucker, CJ (2003) 'Seasonality and trends of snowcover, vegetation index, and temperature in northern Eurasia.' *Geophysical Research Letters* 30(7): 1405

Dyhrenfurth, GO (1955) *To the Third Pole: The history of the High Himalaya*, (1st ed.). London, UK: Ex Libris, Werner Laurie

Dyurgerov, MB (2005) *Mass balance of mountain and sub-polar glaciers outside the Green land Arctic ice sheets,* Supplement to Occasional Paper No 55. Boulder, USA: University of Colorado, Institute of Arctic and Alpine Research

Dyurgerov, MB; Meier, MF (2005) *Glaciers and changing Earth system: A 2004 snapshot,* INSTAAR Occasional Paper No 58. Boulder, Colorado: University of Colorado, Institute of Arctic and Alpine Research

Ebi, KL; Hartman, J; McConnell, JK; Chan, N; Weyant, J (2005) 'Climate suitability for stable malaria transmission in Zimbabwe under different climate change scenarios.' *Climatic Change* 73: 375–393

Edwards, SE; Lowe, C; Stanbrough, L; Walker, B; Kent, R; Oglesby, R; Morton, K (2010) *The waters of the Third Pole: Sources of threat, sources of survival*. London, UK: Aon Benfi eld UCL Hazard Research Centre, University College London www.chinadialogue.net/UserFiles/File/third_pole_full_report.pdf (accessed 11 October 2011)

Engel, S; Pagiola, S; Wunder, S (2008) 'Designing payments for environmental services in theory and practice: an overview of the issues.' *Ecological Economics* 65: 663–675

Environment and Development Desk (2009) *The impact of climate change on the Tibetan Plateau A synthesis of rent science and Tibetan research*. Dharmshala, India: Department of Information and International Relations (DIIR), Central Tibetan Administration

Eriksson, M; Fang, J; Dekens, J (2008) 'How does climate affect human health in the Hindu Kush- Himalaya region?' *Regional Health Forum* 12(1): 11–15

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

FAO (2009) FAOSTAT. Rome, Italy: FAO. http://faostat.fao.org/default.aspx (accessed 12 August 2011)

Farley, J; Costanza, R (2010) 'Payments for ecosystem services: From local to global.' *Ecological Economics* 69: 2060–2068

Fischer, G; Shah, M; van Velthuizen, H (2002b) *Climate change and agricultural vulnerability, special report to the UN World Summit on Sustainable Development, Johannesburg 2002*. Laxenburg, Austria: IIASA

Fischer, G; van Velthuizen, H; Shah, M; Nachtergaele, FO (2002a) *Global agro-ecological assessment for agriculture in the 21st Century: Methodology and results,* IIASA RR-02-02. Laxenburg, Austria: IIASA

Flanner, MG; Zender, CS; Hess, PG; Mahowald, NM; Painter, TH; Ramanathan, V; Rasch, PJ (2009) 'Springtime warming and reduced snow cover from carbonaceous particles.' *Atmospheric Chemistry and Physics* 9(7): 2481–2497

Fowler, HJ; Archer, DR (2006) 'Conflicting signals of climatic change in the Upper Indus Basin.' *Journal of Climate* 19(17): 4276–4293

Fujita, K; Nuimura, T (2011) 'Spatially heterogeneous wastage of Himalayan glaciers.' *Proceedings of the National Academy of Sciences* 108(34): 14011–14014

Fujita, K; Takeuchi, N; Seko, K (1998) 'Glaciological observations of Yala Glacier in Langtang Valley, Nepal Himalayas, 1994 and 1996.' *Bulletin of Glacier Research* 16: 75–81

Gautam, R; Hsu, NC; Lau, K-M; Kafatos, M (2009a) 'Aerosol and rainfall variability over the Indian monsoon region: distributions, trends and coupling.' *Annales Geophysicae* 27: 3691–3703

Gautam, R; Hsu, NC; Lau, K-M; Tsay, S-C; Kafatos, M (2009b) 'Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007.' *Geophysical Research Letters,* 36, L07704, doi: 10.1029/2009GL037641

George, A; Pierret, A; Boonsaner, A; Valentin, C; Orange, D; Planchon, O (2009) 'Potential and limitations of Payments for Environmental Services (PES) as a means to manage watershed services in mainland Southeast Asia.' *International Journal of the Commons* 3(1): 16–40

Ghosh, N; Sharma, S (2011) *Land use, agriculture and food security of the Himalayan regions of India*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

GoI (1986) *Malaria and its control in India,* Volume III. Government of India, Ministry of Health and Family Welfare, National Malaria Eradication Programme

GoI (2002) *National Water Policy*. New Delhi, India: Government of India, Ministry of Water Resources

GoI (2008) *National Adaptation Programme for Climate Change India*. New Delhi, India: Government of India

GoI (2009) *Governance for sustaining Himalayan ecosystem: Guideline and best practices*. New Delhi, India: Government of India, Ministry of Environment and Forests

GoI (2010) *Climate change and India: A 4x4 assessment a sectoral and regional analysis for 2030s,* Executive Summary. New Delhi, India: Government of India, Ministry of Environment and Forests. http://moef.nic.in/modules/others/?f=event (accessed 12 October 2011)

GoN (2010) *National Adaptation Programme of Action*. Kathmandu, Nepal: Government of Nepal, Ministry of Environment

Gosain, AK; Rao, S; Shrestha, AB (2011) *Climate change impact assessment on water resources of Brahmaputra river basin*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

GTOS (2008) *Why focus on mountain regions?* www.fao.org/gtos/tems/mod_mou.jsp accessed on 03.09.2009 (accessed 27 September 20110)

Guangwei, C (2002) *Biodiversity in the Eastern Himalayas: conservation through dialogue. Summary reports of the workshops on biodiversity conservation in the Hindu Kush-Himalayan Ecoregion*. ICIMOD, Kathmandu, Nepal

Guha-Sapir, D; Vos, F; Below, R; Ponserre, S (2011) *Annual disaster statistical review 2010: The numbers and trends*. Brussels, Belgium: CRED

Gurung, DR; Giriraj, A; Aung, KS; Shrestha, B; Kulkarni, AV (2011a) *Snow-cover mapping and monitoring in the Hindu Kush-Himalayas*. Kathmandu, Nepal: ICIMOD (in press)

Gurung, DR; Kulkarni AV; Giriraj A; Aung KS; Shrestha B; Srinivasan J (2011b) 'Change in seasonal snow cover in Hindu Kush–Himalayan Region.' *The Cryosphere Discuss* 5(2): *755–777*

Halpin, PN (1994) 'Latitudinal variation in the potential response of mountain ecosystems to climate change.' In Beniston, M (ed), *Mountain environments in changing climates,* pp 180–203. London, UK: Routledge

Hamilton, LS (2002) 'Why mountain matters?' *World Conservation: The IUCN Bulletin* 1/2002

Hansen, J; Nazarenko, L (2004) 'Soot climate forcing via snow and ice albedos.' *Proceedings of the National Academy of Sciences* 101(2): 423–428

Harris, RB (2007) *Wildlife conservation in China: Preserving the habitat of China's Wild West.* Armonk NY, USA: M.E. Sharpe

Harris, RB (2010) 'Rangeland degradation on Qinghai-Tibetan Plateau: review of evidence of its magnitude and causes.' *Journal of Arid Environments* 74: 1–12

Haughton, J (2004) *Global warming: the complete briefing* (3rd edn). Cambridge, UK: Cambridge University Press

Hewitt, K (2005) 'The Karakoram anomaly? Glacier explosion and the 'elevation effect', Karakoram Himalaya.' *Mountain Research and Development* 25(4): 332–340

Hua, O (2009) 'The Himalayas: Water storage under threat.' *ICIMOD Newsletter 56* (Winter 2009): 3–5

Huang, M; Upadhyaya, S (2007) 'Watershed based payment for environmental services in Asia.' *Mountain Forum Bulletin* August 2007

Hunzai, K; Gerlitz, JY; Hoermann, B (2011) Regional Poverty Report: Understanding Poverty in Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Pakistan. Kathmandu: ICIMOD (unpublished)

ICIMOD (2008a) *Strategic framework: Enhancing resilience and supporting adaptation of mountain communities.* Kathmandu, Nepal

ICIMOD (2008b) *ICIMOD position paper food security in the Hindu Kush-Himalayan region.* Kathmandu, Nepal

ICIMOD (2009a) *Mountain biodiversity and climate change*. Kathmandu, Nepal: ICIMOD http://books.icimod.org/index.php/search/publication/613 last accessed Oct 13 2011

ICIMOD (2009b) *Biodiversity and climate change in the Himalayas: Sustainable mountain development*, Newsletter No 55 Spring. Kathmandu, Nepal

ICIMOD (2009c) *Hindu Kush-Himalayan glaciers: Frequently asked questions*. Kathmandu, Nepall

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

ICIMOD (2009e) *Potential carbon finance in the land use sector of the Hindu Kush-Himalayas: A preliminary scoping study.* Kathmandu, Nepal

ICIMOD (2010a) *Global climate financing mechanisms and mountain systems.* Working paper prepared for the Mountain Initiative of the Government of Nepal. Kathmandu, Nepal

ICIMOD (2010b) *Kailash Sacred Landscape Conservation Initiative: Developing a transboundary cooperation framework for conservation and sustainable development in the greater Mt Kailash region of China, India, and Nepal*. Kathmandu, Nepal

ICIMOD (2011) *Black carbon in the Hindu Kush-Himalayan region*, Information Sheet 2/11. Kathmandu, Nepal

IIRS (2002) *Biodiversity characterization at landscape level in western Himalayas, India using satellite remote sensing and geographic information system*. Dehradun, India: Indian Institute of Remote Sensing, Department of Space, Government of India

IIRS (2003) *Biodiversity characterization at landscape level in North-East India using satellite remote sensing and geographic information system*. Dehradun, India: Indian Institute of Remote Sensing, Department of Space, Government of India

Immerzeel, W (2008) 'Historical trends in future predictions of climate variability in the Brahmputra basin.' *International Journal of Climatology* 28(2): 243–254

Immerzeel, W (2011) *Climate change impacts on the water resources of the Hindu Kush-Himalayas*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Immerzeel, WW; Pellicciotti, F; Gobiet, A; Ragettli S (2011b) 'The impact of uncertainty in climate change scenarios on projections of future water supply from the Asia water tower.' *Water Resources Research* (in preparation)

Immerzeel, WW; van Beek, LPH; Bierkens, MFP (2010) 'Climate change will affect the Asian water towers.' *Science* 328(5984): 1382–1385

Immerzeel, WW; van Beek, LPH; Kong, M; Shrestha, AB; Bierkens, MFP (2011a) 'Hydrological response to climate change in a glacierised catchment in the Himalayas.' *Climate Change*: doi 10.1007/s10584-011-0143-4

IPCC (1996) *The second assessment report: Climate change 1995*, summary. Cambridge: Cambridge University

IPCC (2001) *The third assessment report: Climate change 2001*, Synthesis Report. Cambridge, UK: Cambridge University Press

IPCC (2007) *The fourth assessment report: Climate change 2007*, Synthesis Report. Cambridge, UK: Cambridge University Press

Iqbal, MM; Goheer, MA; Khan, AM (2011) *Impact of climate change on Agriculture and Food Security in HKH Region*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Jeong, S-J; Ho, C-H; Gim, H–J; Brown, ME (2011) 'Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008.' *Global Change Biology* 17: 2385–2399

Jin, ZQ; Shi, CL; Ge, DK; Gao, W (2001) 'Characteristic of climate change during wheat growing season and the orientation to develop wheat in the lower valley of the Yangtze River.' *Jiangsu Journal of Agricultural Science* 17(4): 193–199

Jodha, NS (1997) 'Mountain agriculture' in Messerli, B; Ives, JD (eds) *Mountains of the world: A global priority,* pp 313–335. New York, USA: The Panthenon Publishing Group

Jodha, NS (2011) *HKH mountain systems: Process of change constraints and opportunities*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Kadota, T; Fuita, K; Seko, K; Kayastha, RB, Ageta, Y (1996) 'Monitoring and prediction of shrinkage of a small glacier in the Nepal Himalaya.' *Annuals of Glaciology* 24: 90–94

Kaeser, G; Cogley JG; Dyurgerov, MB; Meier, MF; Ohmura, G (2006) 'Mass balance of glaciers and ice caps: consensus, estimates for 1961-2004.' *Geophysical Research Letter* 33: 1–5

Kalnay, E; Cai, M (2003) 'Impact of urbanization and land-use on climate.' *Nature* 423: 528–31

Karanth, KU; Nichols, JD (1998) 'Estimation of tiger densities in India using photographic captures and recaptures.' *Ecology* 79(8): 2852–2862

Kargel, JS; Cogley, JG; Leonard, GJ; Haritashya, U; Byers, A (2011) 'Himalayan glaciers: The big picture is a montage.' *Proceedings of the National Academy of Sciences* 108: 14709

Karky, BS; Joshi, L (2009) 'Payment for environmental services: An approach to enhancing water storage capacity.' *ICIMOD Newsletter* 56: 31–33

Karky, BS; Skutsch, M (2010) 'The cost of carbon abatement though community forest management in Nepal Himalaya.' *Ecological Economics* 69(3): 666–672

Kaspari, SD; Schwikowski, M; Gysel, M; Flanner, MG; Kang, S; Hou, S; Mayewski, PA (2011) 'Recent increase in black carbon concentrations from a Mt. Everest ice core spanning 1860–2000 AD.' *Geophysical Research Letters* 38: L04703

Keenan, L; Chaudhary, S (2010) 'Environmental services, equity and productivity: Interview with Dr. Meine van Noordwijk.' *Mountain Forum Bulletin* January 2010: 23

Keller, A; Sakthivadivel, R; Seckler, D (2000) *Water scarcity and the role of storage in development,* IWMI Research Report 39. Colombo, Sri Lanka: International Water Management Institute

Khan, H (2010) 'Valuing environmental services for recreation in the Margalla Hills National Park, Islamabad.' *Mountain Forum Bulletin* January 2010: 47

Khanal, NR; Watanabe, T (2006) 'Abandonment of agricultural land and its consequences: A case study in the Sikles area, Gandaki basin, Nepal Himalaya.' *Mountain Research and Development* 26(1): 32–40

Khattak, M; Babel, M; Sharif, M (2011) 'Hydro-meteorological trends in the upper Indus River basin in Pakistan.' *Climate Research* 46(2): 103¬–119

Klein, JA; Harte, J; Zhao, XQ (2004) 'Experimental warming causes large and rapid species loss, dampened by simulated grazing, on the Tibetan Plateau.' *Ecology Letters* 7: 1170–1179

Koch, D; Bauer, S; Perlwitz, J; Miller, R; Schulz, M; Balkanski, Y; Textor, C; Kinne, S; Feichter, J; Schuster, G; Bond, TC; Klimont, Z; Van Aardenne, JA; Spackman, JR; Fahey, DW; Schwarz, JP; McNaughton, C; Clarke, A; Freitag, S; Kondo, Y; Moteki, N; Sahu, L; Sakamoto, H; Takegawa, N; Krol, M; Berntsen, T; Iversen, T; Myhre, G; Boucher, O; Dubovik, O; Reddy, S; Chin, M; Dentener, F; Diehl, T; Easter, R; Ghan, S; Liu, X; Ginoux, P; Horowitz, L; Gong, S; Zhao, Y; Fillmore, D; Penner, JE; De Luca, N; Montanaro, V; Pitari, G; Stier, P; Takemura, T; Kirkevag, A; Seland, O (2009) 'Evaluation of black carbon estimations in global aerosol models.' *Atmospheric Chemistry and Physics* 9(22): 9001–9026

Kopacz, M; Mauzerall, DL; Wang, J; Leibensperger, EM; Henze, DK; Singh, K (2011) 'Origin and radiative forcing of black carbon transported to the himalayas and tibetan plateau.' *Atmospheric Chemistry and Physics* 11: 2837–2852

Körner, C (2004) 'Mountain biodiversity, its causes and function.' *Ambio Special Report* 13: 11–17

Körner, C (2007) 'Climatic tree lines: conventions, global patterns, causes.' *Erdkunde* 61: 316–324

Körner, C (2009) 'Conservation of mountain Biodiversity in the context of climate change.' In Sharma, E (ed), *Proceedings of International Mountain Biodiversity Conference, 16-18 November 2008, ICIMOD, Kathmandu, Nepal,* pp 21-33. Kathmandu, Nepal: ICIMOD

Körner, C; Paulsen, J (2004) 'A world-wide study of high altitude treeline temperatures.' *Journal of Biogeogr* 31: 713–732 Check http://pages.unibas.ch/botschoen/koerner/publications.shtml

Kulkarni, A; Patwardhan, S; Kumar, KK; Ashok, K; Krishnan, R (2011) *Projected climate change over Hindukush-Himalayan region using high Resolution Regional Climate Model PRECIS.* Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Kulkarni, AV (2011) *Observed changes in cryosphere of Hindukush Himalaya*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Kulkarni, AV; Bahuguna, IM; Rathore, BP; Singh, SK; Randhawa, SS; Sood, RK; Dhar, S (2007) 'Glacial retreat in Himalaya using Indian remote sensing satellite data.' *Current Science* 92(1): 69–74g

Kulkarni, AV; Rathore, BP; Singh, SK (2010) 'Distribution of seasonal snow cover in central and western Himalaya.' *Annals of Glaciology* 51(54): 123–128

Kumar, N; Agrawal, PK; Rani, S; Jain, S; Saxena, R; Chauhan, N (2011) 'Impact of climate change on crop productivity in Western Ghats, coastal and north-eastern regions of India.' *Current Science* 101: 332–341

Kumar, P (2011) *The potential for the application of payments for ecosystem services in Hindu Kush-Himalayas: Climate change and ecosystem services in South Asia.* Paper presented at 'Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Kumar, R; Naja, M; Venkataramani, S; Wild, O (2010) 'Variations in surface ozone at Nainital: A high-altitude site in the central Himalayas.' *Journal of Geophysical Research* 115 (D16): D16302

Lambin, EF; Giest, HJ (eds) (2006) *Land use and land cover change: Local processes, global impacts*. Dordrecht, The Netherlands: Springer

Lambin, EF; Turner, BL II; Geist, H; Agbola, S; Angelsen, A; Bruce, JW (2001) 'Our emerging understanding of the causes of land-use and -cover change.' *Global Environmental Change* 11: 261–269

Lancet and University College (2009) *Managing the health effects of climate change.* Lancet and University College London Institute for Global Health Commission. www.thelancet.com.

Lau, K-M; Kim, MK; Kim, K-M (2006) 'Aerosol induced anomalies in the Asian summer monsoon- the role of the Tibetan Plateau.' *Climate Dynamics* 26: 855–864, doi:10.1007/s00382-006-0114-z

Leaf, A (1989) 'Potential health effects of global climate and environmental changes.' *The New England Journal of Medicine* 321: 1577–1583

Li, X; Chen, G (1999) 'Responding model of multi annual permafrost to climate change in the high Altitude region.' *Science in China, Series* D 29(2):185–19

Li, XL; Yuan, QH; Wan, LQ; He, F (2008) 'Perspectives on livestock production systems in China.' *The Rangeland Journal* 30: 211–220

Lichtenberg, E; Ding, C (2008) Assessing farmland protection policy in China. *Land Use Policy* 25: 59–68

Liu, X; Chen, B (2000) 'Climatic warming in the Tibetan Plateau during recent decades.' *International Journal of Climatology* 20: 1729–1742

Macchi, M; Choudhury, D (2011) *Adapting to change: Community perceptions and responses to climate change in the Himalayas.* Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Maharana, I; Rai, SC; Sharma, E (2000a) 'Environmental economics of the Khangchendzonga National Park in the Sikkim Himalaya, India.' *GeoJournal* 50: 329–337

Maharana, I; Rai, SC; Sharma, E (2000b) 'Valuing ecotourism in a sacred lake of the Sikkim Himalaya, India.' *Environmental Conservation* 27: 269–277

Maplecroft (2011) Climate change risk atlas 2011. http://maplecroft.com/search/?q=climate+change+vulnerability+ranking (accessed 20 October 2011)

Marinoni, A; Cristofanelli, P; Laj, P; Duchi, R; Calzolari, F; Decesari, S; Sellegri, K; Vuillermoz, E; Verza, GP; Villani, P (2010) 'Aerosol mass and black carbon concentrations, a two year record at NCO-P(5079 M, Southern Himalayas).' *Atmospheric Chemistry and Physics* 10(17): 8551–8562

Martens, WJM; Kovats, RS; Nijhof, S; DeVries, P; Livermore, MJT; McMichael, AJ; Bradley, D; Cox, J (1999) 'Climate change and future populations at risk of malaria.' *Global Environmental Change* 9: S89–S107

Matsuo, K; Heki, K (2010) 'Time-variable ice loss in Asian high mountains from satellite gravimetry.' *Earth and Planetary Science Letters* 290(1-2): 30–36

McCartney, M; Smakhtin, V (2010) *Water storage in an era of climate change: Addressing the challenge of increasing rainfall variability,* IWMI Blue Paper. Colombo, Sri Lanka: International Water Management Institute

McMichael, AJ; Haines, A; Slooff, R; Kovats, S (eds) (1996) *Climate change and human health*. Geneva, Switzerland: World Health Organization

MA (2005) *Ecosystems and human well-being: Synthesis,* Millennium Ecosystem Assessment Report. Washington, DC, USA: World Resources Institute, Island Press

Menon, S; Koch, D; Beig, G; Sahu, S; Fasullo, J; Orlikowski, D (2010) 'Black carbon aerosols and the third polar ice cap.' *Atmospheric Chemistry and Physics* 10: 4559–4571

Messerli, B (2009) 'Biodiversity, environmental change and regional cooperation in the Hindu Kush-Himalayas.' In Sharma, E (ed), *Proceedings of the International Mountain Biodiversity Conference Kathmandu, 16-18 November 2008,* pp 13–20. Kathmandu, Nepal: ICIMOD

Messerli, B; Ives, JD (eds) (1997) *Mountains of the world: A global priority*. London, UK: The Parthenon Publ. Group

Miller, J; Rees, G (2011) *Water availability; River discharge and glacial hydrology.* Paper presented at Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Miller, JM; Warnaars, T; Rees, HG; Young, G; Shrestha AB, Collins, DC (2011) *What is the evidence about glacier shrinkage across the Himalayas?* (in press)

Ming, J; Cachier, H; Xiao, C; Qin, D; Kang, S; Hou, S; Xu, J (2008) 'Black carbon record based on a shallow Himalayan ice core and its climatic implications.' *Atmospheric Chemistry and Physics* 8(5): 1343–1352

Ming, J; Xiao, C; Cachier, H; Qin, D; Qin, X; Li, Z; Pu, J (2009) 'Black Carbon (BC) in the snow of glaciers in west China and its potential effects on albedos.' *Atmospheric Research* 92(1): 114–123

Ming, J; Xiao, C; Sun, J; Kang, S; Bonasoni, P (2010) 'Carbonaceous particles in the atmosphere and precipitation of the nam co region, central Tibet.' *Journal of Environmental Sciences* 22(11): 1748–1756

Ming, J; Zhang, D; Kang, S; Tian, W (2007) 'Aerosol and fresh snow chemistry in the east Rongbuk Glacier on the northern slope of Mt. Qomolangma (Everest).' *Journal of Geophysical Research* 112(D15): D15307

Mittermeier, RA; Gil, PR; Hoffman, M; Pilgrim, J; Brooks, T; Mittermeier, CG; Lamoreaux, J; da Fonseca, GAB (2004) *Hotspots revisited Earth's biologically richest and most endangered terrestrial ecoregions*. Mexico, USA: CEMEX

Molaur, U (2004) 'Mountain biodiversity patterns at low and high altitudes.' *Ambio* 13: 24

MPS (2011) *Press release launched upon conclusion of the Lucerne World Mountain Conference,* Mountian Partnership Secretarit (MPS), 14 October 2011, FAO, Rome

Mukhophadayay, SC (2006) 'Glaciers and water source appraisal of Himalaya with special reference to Central Himalaya, Uttaranchal.' In Rawat, V (ed), *Resource appraisal, technology application, and environmental challenges in central Himalaya,* pp 106–119. Srinagar, India: Transmedia

Naja, M; Sagar, R (2011) *Atmospheric pollution in Himalayas*. Presentation for seminar on "Climate change Scenarios in Himalayas CHEA", 21–22 May 2011, Naini Tal, India

Negi, GCS; Semwal, R (2010) 'Valuing the Services Provided by Forests and Agro-Ecosystems in the Central Himalaya.' *Mountain Forum Bulletin* January 2010: 44

New, M; Lister, D; Hulme, M; Makin, I (2002) 'A high-resolution data set of surface climate over global land areas.' *Climate Research* 21(1): 1–25

Nie, Y; Zhang Y; Liu, L; Zhang, J (2010) 'Glacial change in the vicinity of Mt. Qomolangmc (Everest), central high Himalayas since 1976.' *Journal of Geographical Sciences* 20(5): 667–686

Nigam, S; Bollasina, M (2010) '"Elevated heat pump" hypothesis for the aerosol–monsoon hydroclimate link: "Grounded" in observations?' *Journal of Geophysical Research* 115: D16201, doi:10.1029/2009JD013800

Niyogi, D; Dimri, AP; Pielke, R (2011) *Improving model projections and vulnerability assessments by adapting land surface feedback within regional climate studies over the Western Himalayas.* Paper presented at Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Nogués-Bravo, D; Araújo, MB, Lasanta, T; López-Moreno, JI (2008) 'Climate change in Mediterranean mountains during the XXIst century.' *Ambio* 37: 380–385

Nogués-Bravo, D; Araújo, MB; Martinez-Rica, JP; Errea, MP (2007) 'Exposure of global mountain systems to climate change during the 21st Century.' *Global Environmental Change* 17: 420–428

Orange, D; Dardenne, L; Geier, P; Duy Phuong, N; Jouquet, P; Duc Toan, T (2010) 'Using a biogas scheme to control soil erosion on sloping lands in North Vietnam.' *Mountain Forum Bulletin January* 2010: 52

Pagiola, S (2005) *Assessing the efficiency of payments for environmental services programs: A framework for analysis.* Washington, USA: World Bank

Palanisami, K; Meinzen-Dick, R; Giordano, M (2010) 'Climate change and water supplies: Options for sustaining tank irrigation potential in India'. *Economic and Political Weekly* 45(26/27): 183–190

Panigrahy, S; Singh, CP; Kimothi, MM; Soni, P; Parihar, JS (2010) 'The upward migration of alpine vegetation as an indicator of climate change: Observations from Indian Himalayan region using remote sensing data.' *National Natural Resources Management System NNRMS (B)* – 35: 73–80

Pant, P; Hegde, P; Dumka, UC; Sagar, R; Satheesh, SK; Moorthy, KK; Saha, A; Srivastava, MK (2006) 'Aerosol characteristics at a high altitude location in central Himalayas: Optical properties and radiative forcing.' *Journal of Geophysical Research* 111: D17206

Parry, ML; Rosenzweig, C; Iglesias, A; Livermore, M; Fischer, G (2004) 'Effects of climate change on global food production under SRES emissions and socio-economic scenarios.' *Global Environmental Change* 14: 53–67

Partap, T; Sthapit, B (1998) *Managing agrobiodiversity: Farmers' changing perspectives and institutional responses in the Hindu Kush-Himalayan region.* Kathmandu, Nepal: ICIMOD

Partap, U (2010) 'Honeybees as providers of pollination services.' *Mountain Forum Bulletin* January 2010: 42

Pauli, H; Gottfried, M; Grabherr, G (1998) 'Effects of climate change on mountain ecosystems. upward shifting of alpine plants.' *World Resources Review* 8: 382–390

Pawar, S; Koo, MS; Kelley, C; Ahmed, MF; Choudhury, S; Sarkar, S (2007) 'Conservation assessment and prioritization of areas in Northeast India: Priorities for amphibians and reptiles.' *Biological Conservation* 136: 346–361

Pawar, SP; Birand, AC; Ahmad, MF; Sengupta, S; Shankar-Raman, TR (2006) 'Conservation biogeography in North-east India: Hierarchical analysis of cross-taxon distributional congruence.' *Diversity and Distributions:* DOI: 10.1111/j.1472-4642.2006.00298.x

Pei, S (1995) *Banking on biodiversity: report on the regional consultations on biodiversity assessment in the Hindu Kush Himalaya.* Kathmandu, Nepal: ICIMOD

Perrot-Maitre, D (2006) *The vittel payments for ecosystem services: a 'Perfect' PES case?*, Project Paper No 3 London, UK: IIED

Piao, SL; Fang, JY (2002) 'Terrestrial net primary production and its spatio-temporal pattern in Qinghai-Xizang Plateau, China during 1982-1999.' *Journal of Natural Resources* 17: 373–380 (in Chinese)

Pielke, RA (2005) 'Land use and climate change.' *Science* 310(9): 1625–1626

PMD (2009): Qamar-uz-Zaman Chaudhry, Arif Mahmood, Ghulam Rasul, Muhammad Afzaal, Technical Report No. PMD 22/2009, Climate Change Indicators of Pakistan, Pakistan Meteorological Department, Islamabad.

Pradhan, NS (2011) *Farmers' response to too much too little water.* Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Qian, Y; Flanner, MG; Leung, LR; Wang, W (2011) 'Sensitivity studies on the impact of Tibetan Plateau snow peak pollution on the Asian hydrological cycle and monsoon climate.' *Atmospheric Chemistry and Physics* 11: 1929–1948

Qiu, J (2008) 'The Third Pole'. *Nature* 454: 393–396

Rahman, A; Amin, SMA (2011) *Climate change impact and adaptation assessment in the Hindu Kush-Himalaya, an up-scaling, implementing and capacity building initiative (HICIA-HKH).* Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Raina, VK (2009) *Himalayan glaciers: A state-of-art review of glacial studies, glacial retreat and climate change,* Discussion Paper. New Delhi, India: Government of India, Ministry of Forest and Environment; Dehradun, India: GP Pant Institute

Ram, K; Sarin, MM; Hegde, P (2010) 'Long-term record of aerosol optical properties and chemical composition from a high-altitude site (Manora Peak) in central Himalaya.' *Atmospheric Chemistry and Physics Discuss* 10: 7435–7467

Ramanathan, V; Carmichael, G (2008) 'Global and regional climate changes due to black carbon.' *Nature Geoscience* 1(4): 221–127

Ramanathan, V; Li, F; Ramana, M; Praveen, P; Kim, D; Corrigan, C; Nguyen, H; Stone, EA; Schauer, JJ; Carmichael, G (2007b) 'Atmospheric brown clouds: Hemispherical and regional variations in long-range transport, absorption, and radiative forcing.' *Journal of Geophysical Research* 112: D22S21

Ramanathan, V; Ramana, MV; Roberts, G; Kim, D; Corrigan, C; Chung, C; Winker, D (2007a) 'Warming trends in asia amplified by brown cloud solar absorption.' *Nature* 448(7153): 575–578

Ramanathan, V; Rodhe, H; Agrawal, M; Akimoto, H; Auffhammer, M; Chopra, UK; Emberson, L; Hasnain, SI; Iyngararasan, M; Jayaraman, A; Lawrence, M; Nakajima, T; Ruchirawat, M; Singh, AK; Vincent, JR; Zhang, Y (2008) *Atmospheric brown clouds: Regional assessment report with focus on Asia*. Nairobi, Kenya: UNEP

Ramay, S; Munawar, Z; Ahmad, M (2011) *Climate change and food security in the HKH region*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Rana, RS; Bhagat, RM; Kalia, V; Lal, H (2009) 'Impact of climate change on shift of apple belt in Himachal Pradesh.' In Panigrahy, S; Ray, SS; Parihar, JS (eds) *Proceedings of the workshop on Impact of Climate Change on Agriculture,* 17-18 December 2009, ISPRS Archives 38-8/3, pp 131–137. New Delhi, India: Excel India Publishers

Rasul, G; Chettri, N; Sharma, E (2011) *Framework for valuing ecosystem services in the Himalayas,* ICIMOD Technical Report. Kathmandu, Nepal: ICIMOD

Ravindranath, N; Rao, S; Sharma, N; Nair, M; Gopalakrishnan, R; Rao, AS; Malaviya, S; Tiwari, R; Sagadevan, A; Munsi, M (2011) 'Climate change vulnerability profiles for Nrth-East India.' *Current Science* 101: 384–404

Ravindranath, NH; Joshi, NV; Sukumar, R; Saxena, A (2006) 'Impact of climate change on forests in India.' *Current Science* 90(3): 354–61

Rees, HG; Collins, DN (2006) 'Regional differences in response of flow in glacier-fed Himalayan rivers to climatic warming.' *Hydrological Processes* 20: 2157–2169

Regmi, BR; Pandit, A; Pradhan, B; Kovats, S; Lama, P (2006) *Climate change and health country report- Nepal,* Capacity Strengthening in the least developed countries(LDC's) for Adaptation to climate change(CLACC) Working Paper. Pokhara, Nepal: Local Iniitatives for Biodiversity, Research and Development (LIBIRD)

Revelle, R; Laksminarayana, V (1975) 'The Ganges water machine.' *Science* 188: 611–616

RGoB (2003) *National water policy.* Thimphu, Bhutan: Royal Government of Bhutan, Bhutan Water Partnership

RGoB (2006) *National Adaptation Programme of Action*. Thimphu, Bhutan: Royal Government of Bhutan

RGoB (2011) *Bhutan Summit for a Living Himalaya*. Thimphu, Bhutan: Royal Government of Bhutan, Ministry of Agriculture and Forests, Bhutan Climate Summit Secretariat. last cited Nov. 2011 at www.bhutanclimatesummit.org.bt (accessed 11 October 2011)

Ritsma, N; Hummel, J; Gyeltshen, P (2010) 'Tourism and payments for environmental services: The outlook for a stronger business case to develop rural tourism in Bhutan.' *Mountain Forum Bulletin* January 2010: 34

Rogers, DJ; Randolph, SE (2000) 'The global spread of malaria in a future, warmer world.' *Science* 289:1763–1769

Root, TL; Hughes, L (2005) 'Present and future phenological changes in wild plants and animals.' In Lovejoy, TE; Hannah, L (eds), *Climate change and biodiversity.* New Haven, US: Yale University Press

SAARC (2008) *SAARC Workshop on Climate Change and Disasters: Emerging Trends and Future Strategies,* SAARC Disaster Management Center. www.saarc-sdmc.nic.in (accessed 20 August 2011)

Sah, M (2005) *Assessing carbon sequestration rate of medium and old growth Quercus floribubnda (Moru oak) forest in Uttaranchal Himalaya.* MSc thesis, Kumaun University, Nainital, India.

Schiermeir, Q (2010) 'Glacier estimate on thin ice.' *Geophysics Research Letters* 463: 276–277

Schild, A (2008) 'The case of the Hindu Kush-Himalayas: ICIMOD's position on climate change and mountain systems.' *Mountain Research and Development* 28(3/4): 328–331

Schild, A (2010) *Accessing available freshwater: Expanded capture and storage*. ICIMOD Presentation at Partners Conference 2010 on "Water Crisis and Choices" Asian Development Bank Headquarters, October 11–15, Manila, Philippines

Schild, A; Sharma, E (2011) 'Sustainable mountain development revisited.' *Mountain Research and Development* 31(3): 237–241

Schutze, ED; Mooney, HA (1994) *Biodiversity and ecosystem function*. Berlin, Germany: Springer Verlag

Shabanov, NV; Zhou, L; Knyazikhin, Y; Myneni, RB; Tucker, CJ (2002) 'Analysis of interannual changes in northern vegetation activity observed in AVHRR data from 1981 to 1994.' *IEEE Transactions on Geoscience and Remote Sensing* 40(1): 115–130

Shakya, B; Uddin, K; Chettri, N; Bajracharya, B; Sharma, E (2011) *Use of geo-spatial tools in the management of potential habitats outside the protected areas in the transboundary Brahmaputra-Salween landscape*. Extended abstract for 15th Meeting of the Subsidiary Body on Scientific, Technical and Technological Advice of the Convention on Biological Diversity

Sharma, E; Acharya, R (2004) 'Summary report on mountain biodiversity in the convention on biological diversity (CBD).' Mountain Research and Development 24(3): 63–65

Sharma, E; Chettri, N (2005) 'ICIMOD's transboundary biodiversity management initiative in the Hindu Kush-Himalayas.' *Mountain Research and Development* 25(3): 278–281

Sharma, E; Chettri, N; Gurung, J; Shakya, B (2007) *Landscape approach in biodiversity conservation: A regional cooperation framework for implementation of the Convention on Biological Diversity in Kangchenjunga Landscape*. Kathmandu, Nepal: ICIMOD

Sharma, E; Chettri, N; Oli, K (2010) 'Mountain biodiversity conservation and management: A paradigm shift in policies and practices in the Hindu Kush-Himalayas.' *Ecological Research* 25: 909–923

Sharma, E; Chettri, N; Tsering, K; Shrestha, AB; Jing, F; Mool, P; Eriksson, M (2009) *Climate change impacts and vulnerability in the eastern Himalayas*. Kathmandu, Nepal: ICIMOD

Sharma, KP (1993) 'Role of rainwater in major river systemsof Nepal.' In Young, GJ (ed) *International Symposium Snowand Glacier Hydrology,* pp113–122. Kathmandu, Nepal: International Association Scientific Hydrology

Sharma, R (2011) *Human health impacts from climate and land-use changes in the HKH region*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Sharma, S; Singh, SP (2004) 'Survival of brown oak forest in the Himalaya in the face of global climate change coupled with anthropogenic factors.' In *18th Annual Meeting of Society for Conservation Biology – Conservation in an Urbanized World,* pp 257–258. New York, USA: Columbia University

Sharma, SK; Chauhan, R (2011) 'Climate change research initiative: Indian network for chimate change assessment.' *Current Science* 101: 308–311

Sharma, VP (1996) 'Re-emergence of malaria in India.' *Indian Journal of Medical Research* 103: 26–45

Shen, DJ; Varis, O (2001) 'Climate change in China.' *Ambio* 30: 381–383

Sherpa, LN; Peniston, B; Lama, W; Richard, C (2003) *Hands around Everest: Transboundary cooperation for conservation and sustainable livelihoods*. Kathmandu, Nepal: ICIMOD

Shrestha, A; Aryal, R (2011) 'Climate change in Nepal and its impact on Himalayan glaciers.' *Regional Environmental Change* 11 (Supplement 1): 65–77

Shrestha, AB (2009a) 'Climate Change in the Hindu Kush-Himalayas and its impacts on water and hazards.' *APMN (Asia Pacific Mountain Network) Bulletin* 9: 1–5

Shrestha, AB (2011) *in preparation*

Shrestha, AB; Devkota, LP (2010) *Climate change in the eastern Himalayas: Observed trends and model projections*. Kathmandu, Nepal: ICIMOD

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

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

Shrestha, KL; Shrestha, ML; Shakya, NM; Ghimire, ML; Sapkota, BK (2003) 'Climate change and water resources of Nepal.' In Muhammed, A; Hansen, FJ (eds), *Climate Change and Water Resources in South Asia: Proceedings of year end workshop, Kathmandu, Nepal, 7–9 January 2003, Kathmandu, Nepal*. Islamabad, Pakistan : Asianics Agro Dev International

Shrestha, RR (2009b) 'Rainwater harvesting and groundwater recharge for water storage in the Kathmandu Valley.' *ICIMOD Newsletter* 56: 27–30

Singh, DK; Singh, AK (2002) 'Groundwater situation in India: Problems and perspective.' *International Journal of Water Resources Development* 18(4): 563–580

Singh, JS; Singh, SP (1987) 'Forest vegetation of Himalaya.' *Botanical Review* 52: 80–192

Singh, JS; Singh, SP (1992) *Forests of Himalaya, structure, functioning and impact of man*. Nainital, India: Gyanodaya Prakashan

Singh, P; Bengtsson, L (2004) 'Hydrological sensitivity of a large Himalayan basin to climate change', Journal of Hydrology 300, 140-154.

Singh, P; Bengtsson, L (2005) 'Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region.' *Journal of Hydrology* 300(1-4): 140–154

Singh, SP; Adhikari, BS; Zobel, DB (1994) 'Biomass, productivity, leaf longevity and forest structure along an altitudinal gradient in the central Himalaya.' *Ecological Monographs* 64: 401–421

Singh, SP; Rawat, YS; Garkoti, SC (1997) 'Failure of brown oak (Quercus semecarpifolia) to regenerate in central Himalaya: A case of environmental semisurprise.' *Current Science* 73: 371–374

Singh, SP; Singh, V; Skutsch, M (2010) 'Rapid warming in the Himalayas: Ecosystem responses and development options.' *Climate and Development* 2: 221–232

Singh, SP; Tewari, A; Phartiyal, P (2011) 'Community carbon forestry to counter forest degradation in the Indian Himalayas.' In Skutch, M (ed), *Community forest monitoring for carbon market, opportunities under REDD,* pp 118-133. London, UK: Eastscan

Singh, V (2009) 'Biomass stock and carbon sequestration rates.' In Oak, B, *Forests under different disturbance regimes in central Himalaya*. PhD thesis, Kumaun University, Nainital, India

Singh, V; Tewari, A; Gupta, M (2006) 'The pre logged stocks of carbon in Shorea robusta and Quercus semecarpifolia forests of Uttaranchal and their C sequestration rates –a tradable NTFP.' Int. *J. For. Usuf. Mngt.* 7(1): 1–5

Skutsch, M (ed) (2011) *Community forest monitoring for the carbon market: Opportunity under REDD*. London, UK: Earthscan

Sonesson, M; Messerli, B (eds) (2002) *The Abisko Agenda: Research for mountain area development,* Ambio Special Report 11. Stockholm, Sweden: Royal Swedish Academy of Sciences

Spehn, EM; Korner, C (2011) *Data mining for global trends in mountain biodiversity*. Boca Raton, USA: CRC Press

Spehn, EM; Messerli, B; Korner, C (2002) A global assessment of mountain biodiversity: synthesis. In Körner, C; Spehn, EM (eds), *Mountain biodiversity: A global assessment,* pp 365. Boca Raton, USA: Parthenon

Stone, EA; Schauer, JJ; Pradhan, BB; Dangol, PM; Habib, G; Venkataraman, C; Ramanathan, V (2010) 'Characterization of emissions from South Asian biofules and application to source apportionment of carbonaceous aerosol in the in the Himalayas.' *Journal of Geophysical Research* 115: D06301

Street, RB; Semenov, SM (1990) 'Natural terrestrial ecosystems.' In Tegart, WJKcG; Sheldon, GW; Griffiths, DC (eds), *Climate change: The first impacts assessment report*. Canberra, Australia: Australian Government Publishing Service

Sutherst, RW (1998) 'Implications of global change and climate variability for vectorborne disease: generic approaches to impact assessments.' *International Journal for Parasitology* 28: 935–45

Tacconi, L; Mahanty, S; Suich, H (2011) 'Forests, payments for environmental services and livelihoods.' In Tacconi, L; Mahanty, S; Suich, H (eds), *Payments for environmental services, forest conservation and climate change: Livelihoods in the REDD?*, pp 1-25. Gloucester, UK: Edward Elgar Publishing Limited

Talewala Y; Pandit MK a plant species range shifts during the twentieth century indicate Himalayan warming.

Tambe, S; Rawat, GS (2010) 'The alpine vegetation of Kangchendzonga landscape, Sikkim Himalaya.' *Mountain Research and Development* 30: 266–274

Tanser, FC; Sharp, B; leSueur, D (2003) 'Potential effect of climate change on malaria transmission in Africa.' *Lancet* 362:1792–1798

Tao, F; Yokozawa, M; Zhang, Z; Hayashi, Y; Grassl, H; Fu, C (2004) 'Variability in climatology and agricultural production in China in association with the East Asia summer monsoon and ElNiño South Oscillation.' *Climate Research* 28: 23–30

Taylor, LH; Latham, SM; Woolhouse, MEJ (2001) 'Risk factors for human disease emergence.' *Philos Trans R Soc Lond B* 356: 983–989

Telwala, Y (2011) *Biological response to climate change in Sikkim Himalaya*. PhD thesis, University of Delhi, New Delhi, India

Thomas, CD (2005) 'Recent evolutionary effects of climate change.' In Lovejoy, TE; Hannah L (eds), *Climate change and biodiversity*, pp 75–90. New Haven, USA: Yale University Press

Trisal, CL; Kumar, R (2008) *Integration of high altitude wetlands into river basin management in the Hindu Kush-Himalayas*. New Delhi, India: Wetlands International, South Asia

Troup, RS (1922) *Silviculture of Indian trees,* 3 Volumes (1915±1919). Dehradun, India: Forest Research Institute

Tse-ring, K (2003) 'Constructing future climate scenarios of Bhutan'. In *Project report on climate change vulnerability and adaptation study for rice production in Bhutan;* for Project: Climate change studies in Bhutan, Activity No www094505-But.2. Thimphu, Bhutan: Royal Government of Bhutan, Ministry of Agriculture

Tse-ring, K; Sharma, E; Chettri, N; Shrestha, A (eds) (2010) *Climate change vulnerability of mountain ecosystems in the eastern Himalayas* – Synthesis report. Kathmandu, Nepal: ICIMOD

Tulachan, PM (2001) 'Mountain agriculture in the Hindu Kush-Himalaya: A regional comparative analysis.' *Mountain Research and Development* 21(3): 260–267

Turin, M (2005) 'Language endangerment and linguistic rights in the Himalayas: a case study from Nepal.' *Mountain Research and Development* 25(1): 4–9

UN (1992) *Agenda 21*. United Nations Conference on Environment and Development, Rio de Janeiro, Brazil, 3–14 June 1992. New York, USA

UN (2005) *Johannesburg Plan of Implementation*. New York, USA: United Nations, Department of Economic and Social Affairs, Division for Sustainable Development www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/POIChapter4.htm (accessed 11 July 2011)

UNEP (1992) Convention on biological diversity. www.biodiv.org/convention/articles.asp (accessed on 13 August 2009)

UNFCCC (2010) *Synthesis report on efforts undertaken to monitor and evaluate the implementation of adaptation projects, policies and programmes and the costs and effectiveness of completed projects, policies and programmes, and views on lessons learned, good practices, gaps and needs*. Bonn, Germany: United Nations Framework Convention on Climate Change

UNFCCC (2011a) *NAPAs received by the secretariat.* Bonn, Germany: United Nations Framework Convention on Climate Change http://unfccc.int/cooperation_support/least_developed_countries_portal/submitted_napas/items/4585.php (accessed 15 July 2011)

UNFCCC (2011b) *Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November – 10 December 2010.* Bonn, Germany: United Nations Framework Convention on Climate Change http://unfccc.int/resource/docs/2010/cop16/eng/07a02.pdf#page=18 (accessed 15 July 2011)

Vaidya, R (2011) *The Role of Water Storage Capacity Development in Enhancing Climate Resilience in the Hindu Kush-Himalaya Region*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

van Lieshout, M; Kovats, RS; Livermore, MTJ; Martens, P (2004) 'Climate change and malaria: analysis of the SRES climate and socio-economic scenarios.' *Global Environmental Change* 14: 87–99

van Schoubroeck, F; Nasr, N; Maijer, M (2010) 'Can payments improve environmental services on farmland?' *Mountain Forum Bulletin* January 2010: 17

Vedwan, N (2006) 'Culture, climate and the environment: Local knowledge and precipitation of climate change among apple growers in Northwest India.' *Journal of Ecological Anthropology* 10: 4–18

Vedwan, N; Rhoades, RE (2001) 'Climate change in the western Himalayas of India: a study of local perception and response.' *Climate Research* 19: 109–117

Vetaas, OR (2006) 'Comparing species temperature response curves: population density versus second-hand data.' *Journal of Vegetation Science* 11: 659-666

Viviroli D, Weingartner R (2004) 'Hydrological significance of mountains: from regional to global scale.' *Hydrological Earth Systems Science* 8(6): 1016–1029

Vohra, CP (1981) 'Himalayan glaciers.' In Lal, JS; Moddie, AD (eds), *The Himalaya: Aspect of change*, pp 138–151. Delhi, India: Oxford University Press

Vorosmarty, CJ; Green, P; Salisbury, J; Lammers, RB (2000) 'Global water resources: Vulnerability from climate change and population growth.' *Science* 289: 284–288

Wahid, S; Shrestha, A; Karky, B; Shrestha, M (2011) *Regional cooperation on integrated water and ecosystems management for climate change adaptation*. Paper presented at the Authors' Workshop for the Regional Report on Climate Change in the Hindu Kush–Himalayas: The State of Current Knowledge, 18–19 August 2011, ICIMOD, Kathmandu, Nepal

Wang, GW; Li, YS; Hu, HC; Wang, YB (2008) 'Synergistic effect of vegetation and air temperature changes on soil water content in alpine frost meadow soil in the permafrost region of Qinghai-Tibet.' *Hydrological Processes* 22: 3310–3320

Wangchuk, R; Jackson, R; Lama, B (2010) 'Snow leopards and 'Himalayan Homestays': Catalysts for community-based conservation in Mountain areas.' *Mountain Forum Bulletin* January 2010: 25

WECS (2002) *Water resources strategy.* Kathmandu, Nepal: His Majesty's Government of Nepal, Water and Energy Commission (WECS)

Wendland, K; Naughton, L; Suárez, L; Suyanto (2010) 'Rewards for environmental services and collective land tenure: Lessons from Ecuador and Indonesia.' *Mountain Forum Bulletin* January 2010: 19

WHO (2000) *Climate change and human health: Impact and adaptation.* Geneva, Switzerland: World Health Organization

WHO (2003) *Climate change and human health: Risks and responses, Summary Report.* Geneva, Switzerland: World Health Organization

WHO (2006) *Human health impacts from climate variability and change in the Hindu Kush–Himalaya region.* Report of an Inter-regional Workshop, Mukteshwar, Regional Office for Southeast Asia, New Delhi, India

Winnett, SM (1998) 'Potential effects on climate change on U.S. forests: a review.' *Clim Res* 11: 39–49

Woodward, A; Hales, S; Litidamu, N; Phillips, D; Martin, J (2000) 'Protecting human health in a changing world: the role of social and economic development.' *Bulletin of the World Health Organization* 78: 1148–1155

World Commission on Dams (2000) *Dams and development.* Reports in the WCD Knowledge Base www.dams.org (accessed 12 August 2009)

Wu, N; Yan, ZL (2002) 'Climate variability and social vulnerability on the Tibetan Plateau: Dilemmas on the road to pastoral reform.' *Erdkunde* 56: 2–14

Wunder, S (2005) *Payments for environmental services: some nuts and bolts,* Occasional Paper No 42. Bogor, Indonesia: Center for International Forestry Research

Wunder, S; Alban, M (2008) 'Decentralised payments for environmental services: The cases of Pimampiro and PROFAFOR in Ecuador.' *Ecological Economics* 65(4): 685–698

WWAP (2006) *Water: A shared responsibility,* The United Nations World Water Development Report 2. Paris, France: World Water Assessment Programme

Xiao, XM; Melillo, JM; Kicklighter, DW; Pan, Y; McGuire, AD; Helirich, J (1998) 'Net primary production of terrestrial ecosystems in China and its equilibrium responses to changes in climate and atmospheric CO_2 concentration.' *Acta Phytoecologica Sinica* 22(2): 97–118

Xu, B; Cao, J; Hansen, J; Yao, T; Joswia, DR; Wang, N; Wu, G; Wang, M; Zhao, H; Yang, W (2009a) 'Black soot and the survival of tibetan glaciers.' *Proceedings of the National Academy of Sciences* 106(52): 22114–22118

Xu, B; Yao, T; Liu, X; Wang, N (2006) 'Elemental and organic carbon measurements with a two-step heatinggas chromatography system in snow samples from the Tibetan Plateau.' *Annals of Glaciology* 43(1): 257–262

Xu, B–Q; Wang, M; Joswiak, DR; Cao, J–J; Yao, T–D; Wu, G–J; Yang, W; Zhao, H–B (2009b) 'Deposition of anthropogenic aerosols in a southeastern Tibetan glacier.' *Journal of Geophysical Research* 114: D17209

Xu, J; Grumbine, RE; Shrestha, A; Eriksson, M; Yang, X; Wang, YUN; Wilkes, A (2009) 'The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods.' *Conservation Biodiversity* 23(3): 520–530

Xu, J; Sharma, R; Fang, J; Xu, Y (2008a) 'Critical linkages between land-use transition and human health in Himalayan Region.' *Environment Internationa*l 34: 239–247

Xu, J; Shrestha, A; Vaidya, R; Eriksson, M; Hewitt, K (2007) *The melting Himalayas: Regional challenges and local impacts of climate change on mountain ecosystems and livelihoods*, ICIMOD Technical Paper. Kathmandu: ICIMOD

Xu, J; Yang, Y; Li, Z; Tashi, N; Sharma, R; Fang, J (2008b) 'Understanding Land Use, Livelihoods, and Health Transitions among Tibetan Nomads: A Case from Gangga Township, Dingri County, Tibetan Autonomous Region of China.' EcoHealth 5(2): 104–114

Xu, JC; Sharma, R; Fang, J; Xu, YF (2008c) 'Critical linkages between land-use transition and human health in the Himalayan region.' *Environment International* 34: 239–247

Xu, WX; Liu, XD (2007) 'Response of vegetation in the Qinghai-Tibet Plateau to global warming.' *Chinese Geographical Science* 17: 151–159

Xu, Z; Xu, J; Deng, X; Huang, J; Uchida, E; Rozelle, S (2006) 'Grain for Green versus Grain: Conflict between Food Security and Conservation Set-Aside in China.' *World Development* 34(1): 130–148

Yan, ZL; Wu, N; Dorji, Y; Jia, R (2005) 'A review of rangeland privatization and its implications in the Tibetan Plateau, China.' *Nomadic People* 9: 31–51

Yao, TD; Guo, XJ; Lonnie, T; Duan, KQ; Wang, NL; Pu, JC; Xu, BQ; Yang, XX; Sun, WZ (2006) '$\delta^{18}O$ record and Temperature Change over the Past 100 years in Ice Cores on the Tibetan Plateau.' *Science in China Series D: Earth Sciences* 49(1): 1–9

Yasunari, TJ; Yamazaki, K (2009) 'Impacts of Asian dust storm associated with the stratosphere-to-troposphere transport in the spring of 2001 and 2002 on dust and tritium variations in Mount Wrangell ice core, Alaska.' *Atmospheric Environment* 43: 2582–2590

Yasuoka, J; Levins, R (2007) Impact of deforestation and agricultural development on anopheline ecology and malaria epidemiology. *American Journal of Tropical Medicine and Hygiene* 76: 450–460

Yin, YY (2006) *Vulnerability and adaptation to climate variability and change in western China*, AS25 Project Final Report to AIACC. Washington DC, USA: International START Secretariat

Yu, H; Luedeling, E; Xu, J (2010) 'Winter and spring warming result in delayed spring phenology on the Tibetan Plateau.' *Proceedings of the National Academy of Sciences* 107(51): 22151–22156

Yunling, H; Yiping, Z (2005) 'Climate change from 1960 to 2000 in the Lancang river valley, China.' *Mountain Research and Development* 25(4): 34–348

Zemp, M; Hoelzle, M; Haeberli, W (2009) 'Six decades of glacier mass-balance observations – a network review of worldwide mentoring network.' *Annals of Glaciology* 50: 101–111

Zhang, JH; Yao, FM; Zheng, LY; Yang, LM (2007) 'Evaluation of grasslands dynamics in the northern-Tibet Plateau of China using remote sensing and climate data.' *Sensors* 7: 3312–3328

Zhang, M; Ren, Q; Wei, X; Wang, J; Yang, X; Jing, Z (2011) 'Climate change, glacier melting and stream flow in the Niyang River Basin, South east Tibet, China.' *Ecohydrology* 4(2): 288–298

Zobel, DB; Singh, SP (1997) 'Forests of the Himalaya: Their contribution to ecological generalizations.' *Bio Science* 47: 735–745

Zomer; R; Oli, KP (2011) *Kailash sacred landscape conservation initiative – Feasibility assessment report.* Kathmandu, Nepal: ICIMOD

About ICIMOD

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

International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal
Tel +977-1-5003222 **Fax** +977-1-5003299
Email info@icimod.org **Web** www.icimod.org

ISBN 978 92 9115 220 9