ICIMOD Research Report 2016/3

ICIMOD

FOR MOUNTAINS AND PEOPLE

Impacts of Climate Change on the Cryosphere, Hydrological Regimes and Glacial Lakes of the Hindu Kush Himalayas:

a Review of Current Knowledge

Statkraft

FutureWater

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.

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Impacts of Climate Change on the Cryosphere, Hydrological Regimes and Glacial Lakes of the Hindu Kush Himalayas: a Review of Current Knowledge

Report prepared by

Arthur Lutz

Walter W Immerzeel

Samjwal Ratna Bajracharya

Maxime Litt

Arun Bhakta Shrestha

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A. Beatrice Murray (Consultant editor)
Amy Sellmyer (Editor)
Dharma R Maharjan (Layout and design)
Asha Kaji Thaku (Editorial assistant)

Photos: Arun B Shrestha and Sharad P Joshi

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Contents

Foreword

The climate and cryosphere of the Hindu Kush Himalayan (HKH) region have changed in the past and are very likely to change in the future. Warming of the climate system is unequivocal. The atmospheric concentration of greenhouse gases and short-lived climate pollutants has increased, the atmosphere and oceans have warmed, snow and ice have diminished, and the sea level has risen. The Himalayan region has the third largest amount of ice and snow in the world, after the Antarctic and Arctic, but these reserves are considered to be exceptionally vulnerable due to climate change. There is good agreement among global climate models (GCM) on future temperature trends in the region, but projections of future precipitation patterns differ widely. As a result, the demand for increased knowledge about likely future climate change is still high. Growing scientific knowledge and recent weather events show that extremes related to hydrological change can be substantial, although the geographical and temporal resolution of the projected changes is still low in many areas.

Energy is one of the major drivers of change in the region. The region has a high hydropower potential, but the changing climate and likely changes in the hydrological regime may pose a risk to future hydropower development. The changing probabilities and magnitudes of extreme events can place an additional risk on power generation infrastructure (dams and hydropower plants) as well as secondary infrastructure (roads and transmission lines). Further, hazards associated with shrinking glaciers, such as glacial lake outburst floods, can jeopardize large infrastructure investment. It has become imperative for hydropower developers to have a good understanding of the changes in the hydrological cycle and its uncertainty.

Statkraft, the largest generator of renewable energy in Europe and a leading company in hydropower internationally, and the International Centre for Integrated Mountain Development (ICIMOD), a regional intergovernmental learning and knowledge sharing centre with a rich experience of climate and water related issues in the HKH region, are working together to further understanding of the climate change impact on hydrological regimes in the region, and the implications for hydropower development. Statkraft is particularly interested because it has plans to develop hydropower in northern India (mainly Himachal Pradesh), Nepal, Bhutan, and possibly Myanmar, while ICIMOD is interested in developing climate and water availability scenarios to support future planning. ICIMOD and Statkraft, with technical support from FutureWater in The Netherlands, have conducted a detailed review on the state of knowledge regarding climate change in the HKH region and its connections to changes in the cryosphere and hydrology, with a specific focus on the implications for hydropower development. The present publication is based on this review and presents a summary of state-of-the-art understanding related to climate change, cryosphere dynamics, changes in the hydrological regime, and glacial lake outburst flood risk in the HKH. We hope that these findings and the recommendations drawn from them will help in developing future research plans for assessing the impacts of climate change on hydropower development in specific catchments and sub-basins in the region.

David J Molden, PhD
Director General

Acronyms and Abbreviations

ADC	advanced delta change
CORDEX	Coordinated Regional Climate Downscaling Experiment
DECM	downscaling and error correction method
DEM	digital elevation model
DGPS	Differential Global Positioning System
ESD	empirical statistical downscaling
GCM	general circulation model
GLOF	glacial lake outburst flood
GPCP	Global Precipitation Climatology Project
GPR	ground penetrating radar
HKH	Hindu Kush Himalayas
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Inter-governmental Panel on Climate Change
LES	large eddy simulation
MAGT	mean annual ground temperature
MOS	model output statistics
PP	perfect prognosis
RCM	regional climate model
RCP	representative concentration pathway
SAR	synthetic aperture radar
SCA	snow cover area
SRES	Special Report on Emissions Scenarios
SWE	snow water equivalent
WECS	Water and Energy Commission Secretariat
WG	weather generators
WGMS	World Glacier Monitoring Service
WWD	winter westerly disturbance

Summary

The climate, cryosphere, and hydrology of the Hindu Kush Himalayan (HKH) region have changed in the past and will change in the future. This literature review investigates the state of knowledge on climate change and its projected impact on the cryosphere and hydrology of the HKH, with a specific focus on the implications for hydropower development.

The air temperature has been increasing in the HKH region over the past decades, with different rates for daily mean, maximum, and minimum air temperature. The temperature has increased more at higher elevations than at lower elevations. There have been no clear trends in precipitation overall, but the trends vary locally.

Projections of future climate have been made using dynamically or statistically downscaled general circulation models and regional climate models. The current state of knowledge indicates that climate warming is likely to continue during the 21st century. The projections of precipitation change are uncertain as the climate models project a wide range of possible futures, including strong precipitation increases and precipitation decreases. An increase in precipitation is most likely for the upstream Ganges and Brahmaputra, but the magnitude is highly uncertain. Precipitation projections for the upstream Indus show increases, as well as decreases, with large uncertainties related to the projections. Extreme precipitation events are likely to be more severe and to occur with higher frequency. The Indian summer monsoon is likely to show increases in the precipitation totals, precipitation intensity, interannual variability in monsoon strength, and inter-daily variability. The current state-of-the-art climate models have significant difficulty in simulating the complex climate in the HKH region. Only a limited number of models can satisfactorily simulate the monsoon dynamics, and no single model is able to simulate all important features in the HKH precipitation regimes.

Over the past years, much knowledge has been gathered about the cryosphere in the HKH region. Glaciers in most of the region are losing mass in response to climate warming. Glaciers in the Karakoram region have been expanding in recent years – a phenomenon known as the 'Karakoram anomaly' – but the reason for this is not yet fully understood. Despite scientific progress, estimates of total ice volume vary considerably because of the difficulties of estimating ice volumes in situ or from remote sensing products. No strong trends in snow cover changes have been observed, although minor increases and decreases have been reported for different areas. Little is known about the distribution of permafrost in the HKH region, and its importance for the regional hydrology remains unclear. Estimates of future glacier volumes and areas are uncertain and are hampered because modelling of ice flow is restricted to catchment scale studies. However, strong decreases in glacier volume and area are projected for the HKH region as a whole.

As a result of glacier retreat, the number of proglacial lakes is increasing rapidly, and existing lakes are increasing in area and volume. The lakes are often dammed by moraines, which can be unstable. Dam failure can result in glacial lake outburst floods (GLOF), which can have devastating downstream effects. Glacial lakes are being monitored more extensively, but wide-scale mitigation of more than a very limited number of lakes remains challenging.

In summary, consistent trends can be recognized for climate change related impacts on hydrology in the HKH region, but detailed catchment scale analysis remains necessary to enable proper assessment of climate change induced hydrological risks for candidate hydropower development sites. These analyses should also consider other factors influencing suitability for hydropower development, such as health, safety and security, and environmental and social factors.

There is a considerable need for further research. A coordinated research programme is needed for the region that focuses more strongly on understanding the impacts of climate change at the catchment and sub-basin level, and specifically in those catchments/sub-basins that are candidates for hydropower development. ICIMOD and its partners should consider ways in which such a programme can be developed to cover the spectrum of research requirements that have become apparent.

Introduction

Background and regional context

The evidence for warming of the climate system is unequivocal. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and the sea level has risen. The Himalayan region has the third largest amount of ice and snow in the world (after the Antarctic and Arctic) and is exceptionally vulnerable to temperature rise. A range of general circulation models (GCMs) have been used to project future temperature and precipitation trends for the region, but while projections of future temperature are generally similar, projections of future precipitation patterns differ widely and the need for increased knowledge about future climate change remains high. GCMs have mainly focused on temperature change and potential changes to the hydrological cycle. The overall tendency identified is that wetter regions are likely to become wetter and drier regions drier. Increased scientific knowledge, coupled with recent weather events, shows that changes in hydrological extreme events can also be substantial, but the geographical and temporal resolution of predicted changes remains low.

For hydropower developers and investors, understanding future changes in the hydrological cycle and their uncertainty is crucial for effective business planning. Investment decisions for the next 50 years depend on accurate predictions of climate change impacts on inflow over that period. In addition, changes in the probability and magnitude of extreme events can increase the risk to critical infrastructure (critical dams and hydropower plants, roads, and transmission lines). For both governments and investors, it is important to assess the short-, medium-, and long-term impacts, risks, and opportunities resulting from climate change to ensure that water resources can be managed sustainably for all stakeholders.

Climate-related hydropower issues in the HKH region

Water and energy are interrelated. Every drop of water that has to be pumped, moved, or treated to meet domestic, industrial, or agricultural needs requires energy. However, water is also a source of energy. Hydropower has been used for centuries, from turning millstones to turning turbines. Hydropower is a form of renewable energy as the water is not actually consumed when energy is generated. It represents a significant share of the global energy supply: about 16% of electricity generation globally, and almost 100% in some countries, notably Norway and Brazil.

The hydropower sector is sensitive to changes in seasonal weather patterns and weather extremes, which can adversely affect the generation of energy as well as the integrity of transmission pipelines and power distribution. Thus climate change is likely to have considerable implications for hydropower generation, especially in the Brahmaputra, Ganges, and Indus basins with their complex hydrological regimes. Expected climate impacts range from increasing temperature to changes in precipitation and snow, and an increase in the incidence and magnitude of extreme weather events, including floods and droughts. In most parts of the HKH region, the streamflow regime is characterized by high flows during the monsoon and/or melting seasonal and low flows in other seasons. The level of these flows could alter with climate change, affecting the amount of water available for hydropower generation. Furthermore, most infrastructure has been built to design codes based on historic climate data and may require extensive maintenance, upgrading, or replacement in the coming years to meet these changes. Hydropower is also affected by other environmental constraints such as glacial lake outburst floods (GLOFs), landslides, and general erosion and reservoir sedimentation, all of which may be affected by climate change (Molden et al. 2014).

Power demand is expected to increase as a result of rapid industrialization, urbanization, and increase in demand for food for an ever-growing population. Ensuring the availability of an uninterrupted supply of power is a major challenge to sustainable development in the region. Energy is needed to sustain growth and improve socioeconomic conditions and human development. There is vast potential for development of the hydropower sector to support accelerating economic growth, reduce poverty, and enhance human development. But harnessing this potential requires, among others, more reliable information about the climate related changes that can be expected over the coming decades.

Hydropower potential in the HKH region

The total theoretical hydropower generating potential in the HKH is very high, but considerably more information is needed before the long-term viability of electricity production can be ascertained. Nepal has a hydropower potential of 83,290 MW, but to date has only installed 689 MW generating capacity. Lack of basic infrastructure like roads and transmission lines means that mega hydroelectricity generating projects will need to include significant investments in infrastructure (Surendra et al. 2011). Bhutan has a hydropower potential of 30,000 MW, of which 23,000 MW can readily be exploited, but the installed capacity is only about 1,490 MW and electricity demand only 105 MW (Uddin et al. 2007). Pakistan has an estimated hydropower potential of 42,000 MW. The installed capacity of 6,500 MW contributes nearly 33% of the total electricity supply mix, but this is down from 70% in 1960, while there is an energy shortage of 4,500 MW and the capacities of the three reservoir-based hydropower facilities (Tarbela, Mangla, and Chashma) are declining due to sedimentation (Asif 2009). Many areas in Pakistan have a high potential for small-scale facilities and already nearly 300 micro and mini hydropower plants are in operation. Large dams are of strategic importance in India's energy policy. The total hydropower potential is 148,000 MW, while installed or under construction capacity is 42,780 MW. The Government of India has initiated preparation of preliminary feasibility studies for 162 new hydroelectric schemes totalling more than 50,000 MW (Choudhury 2010). China also has a tremendous hydropower potential estimated at 694,000 MW, largely located in the HKH region, and installed capacity of 145,260 MW, with a number of plants under construction.

About this review

This publication presents the results of a joint initiative between ICIMOD and Statkraft AS – the largest generator of renewable energy in Europe and a leading company in hydropower internationally – to assess the projected impacts of climate change on hydrological regimes in the Himalayas. The overarching objective was to jointly improve understanding of the impacts of climate change on the cryosphere and water resources in the Himalayan region with a focus on changes relevant to hydropower production. We review the state of understanding related to climate change, cryosphere dynamics, changes in the hydrological regime, and glacial lake outburst flood hazard in the Indus, Ganges, and Brahmaputra basins, as a basis for a detailed analysis of the potential impact of climate change on the cryosphere, glacial hazards, and hydrological regime in catchments where hydropower development is most likely to happen, predominantly the upstream parts which have the largest hydropower potential.

The review is mainly confined to peer-reviewed literature after the year 2000 from journals registered at the Thomson Institute for Scientific Information, except for the chapter on glacial lake outburst floods for which only limited peer-reviewed literature is available. The review focuses on four topics:

Climate variability (both spatial and seasonal) is assessed and future projections by climate models are summarized and reviewed.

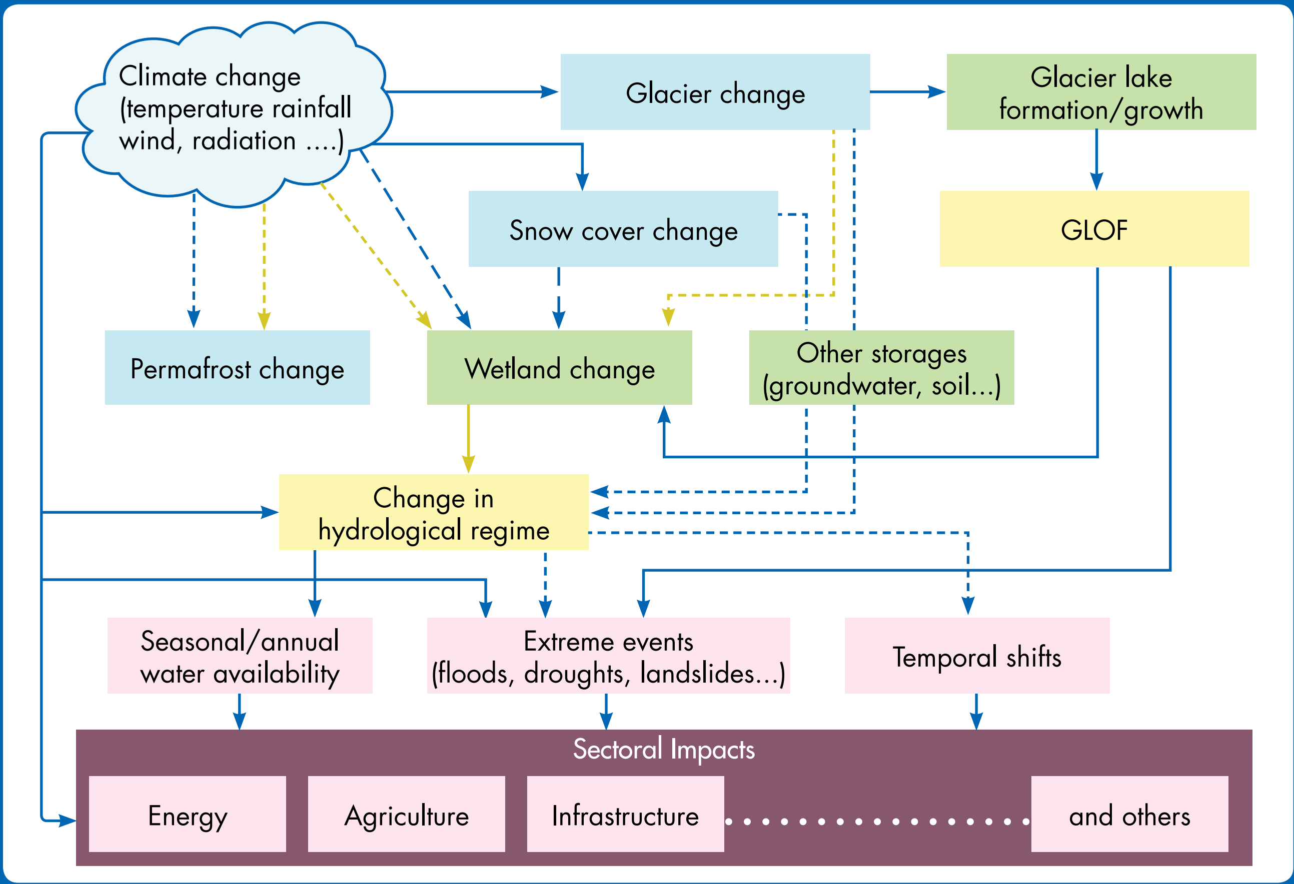
Observed changes in the cryosphere are reviewed, including an inventory of the snow and ice reserves compiled using different monitoring methods, and a review of future projections.

The impact of the projected change on cryosphere dynamics and hydrological regimes is analysed in terms of long-term changes in water availability, seasonal variability, the occurrence of extreme events, and changes in the components contributing to total river flow.

Climate change impacts on glacial lakes are analysed with a particular focus on the potential for glacial lake outbursts, as this could directly impact the selection of planned hydropower sites.

The topics are closely interlinked; changes in one component tend to influence other components as shown in Figure 1.

Figure 1: **The links between changes in climate, changes in hydrology, and the impact on different sectors**



Climate Change and Variability

Historical trends and variability

The climate in the eastern part of the Himalayas is characterized by the East-Asian and Indian monsoon systems (Figure 2) and the bulk of precipitation occurs between June and September (Figure 3), with a strong north-south gradient in precipitation intensity caused by orographic effects (Galewsky 2009). Precipitation patterns in the Hindu Kush and Karakoram ranges in the west are characterized by westerly and southwesterly flows, causing the precipitation to be more evenly distributed over the year (Bookhagen and Burbank 2010). In the Karakoram, up to two-thirds of the annual high-altitude precipitation occurs during the winter months (Winiger et al. 2005; Hewitt 2005, 2011) (Figure 3), about half of it brought by the Western Disturbances – such as westerly driven, eastward propagating cyclones (Barlow et al. 2005).

Precipitation has a high spatial variability in mountainous regions and can vary enormously over short distances due to orographic effects. In the Hindu Kush Himalayas, meteorological ground stations are relatively sparse because of the complexity of the terrain and difficult access, which means that the spatial variability is often poorly captured. Precipitation gauge networks are virtually non-existent, and where gauges do exist, they are mostly located in the valley bottoms where precipitation amounts are smaller than at higher altitudes. Furthermore, most gauges have difficulty capturing snowfall accurately. Snow accumulation measurements using snow pillows, snow courses, pits, and cores from accumulation zones are also scarce and usually confined to short observation periods. The precipitation projections for the HKH region tend to be based on ground observations, and as these are not able to capture the spatial variation the projections are not very accurate. Other approaches such as the use of remote

Figure 2: **The HKH region, Tibetan Plateau, and surroundings area showing the Indus, Ganges, and Brahmaputra basins and the dominant sources of precipitation**

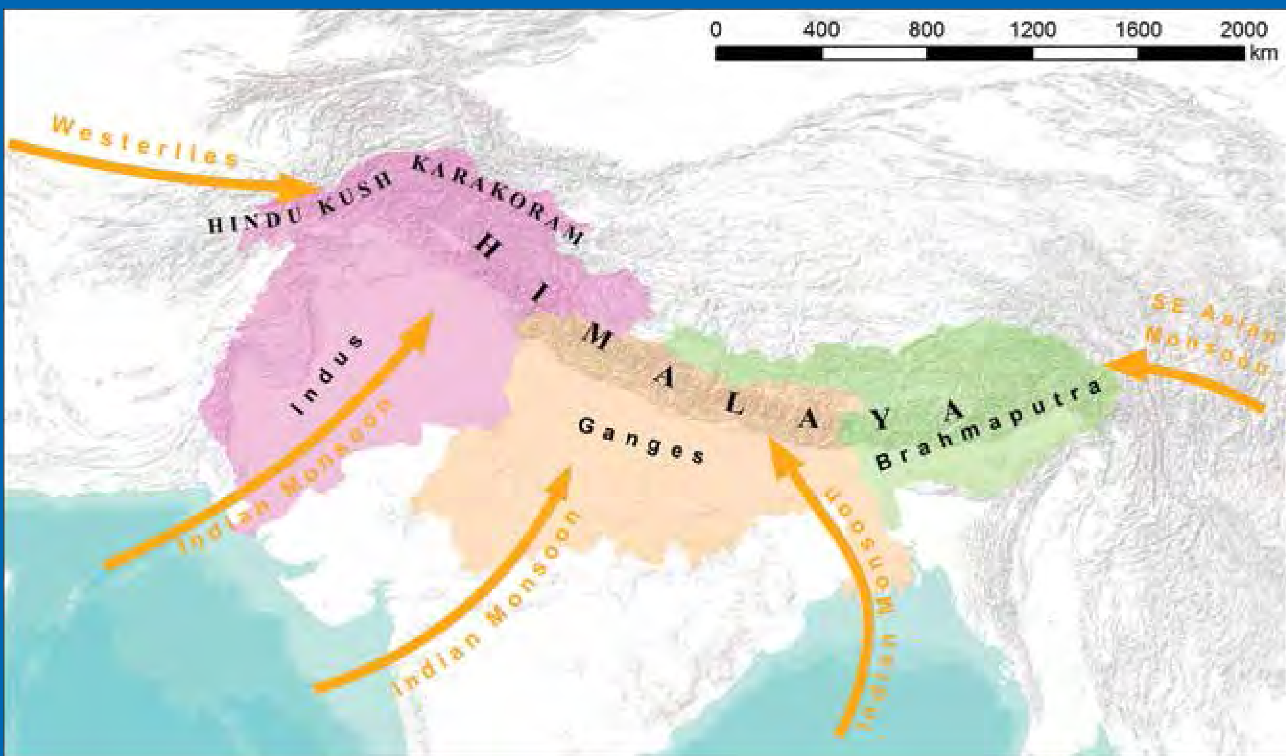
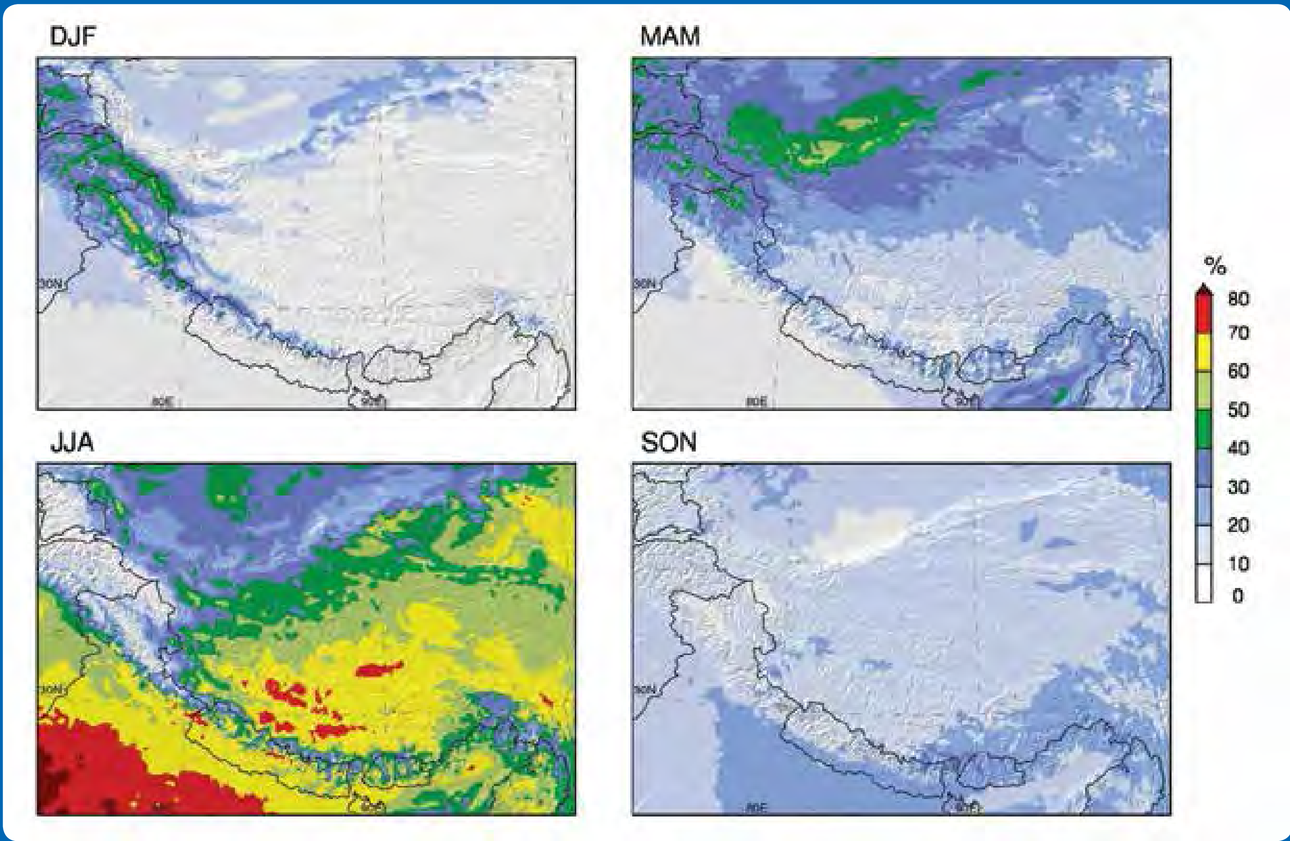


Figure 3: **Percentage of mean annual precipitation falling in December to February (DJF), March to May (MAM), June to August (JJA), and September to November (SON)**



Source: Maussion et al. 2014 © American Meteorological Society

sensing and reanalysis techniques are necessary to generate gridded climate products and obtain more accurate projections (Table 1).

All the gridded climate products currently available for the HKH region have a coarse spatial resolution (Table 2). They are mostly suitable for large-scale continental studies, but do not accurately depict climate variations at smaller scales or in orographically complex regions. There are also striking differences among the different precipitation estimates (Figure 4; Palazzi et al. 2013), both for the monsoon-dominated Himalayan arc and the westerly-influenced Hindu Kush and Karakoram. Using the observed glacier mass balance as a proxy to reconstruct the total precipitation for the upper Hunza basin of the Indus basin, Immerzeel et al. (2012a) indicated that total annual precipitation is likely to be more than double the precipitation derived from interpolated gauge data. The quality of the gridded datasets varies strongly over the HKH region, and the quality within the datasets also differs strongly in space. In general, products should be compared to station data for each region of interest to select the best performing dataset.

Past trends in climate in the upstream Indus, Ganges, and Brahmaputra basins have been analysed in many studies. Palazzi et al. (2013) analysed trends in precipitation for different products with records varying in length from 30 to 60 years and ending around 2010. They found no statistically significant long-term trends for winter precipitation averaged over the area. Two of nine products found slightly increasing but significant trends in precipitation during the monsoon season, but no significant trends were found in the other seven. The trends showed a very large spatial variability.

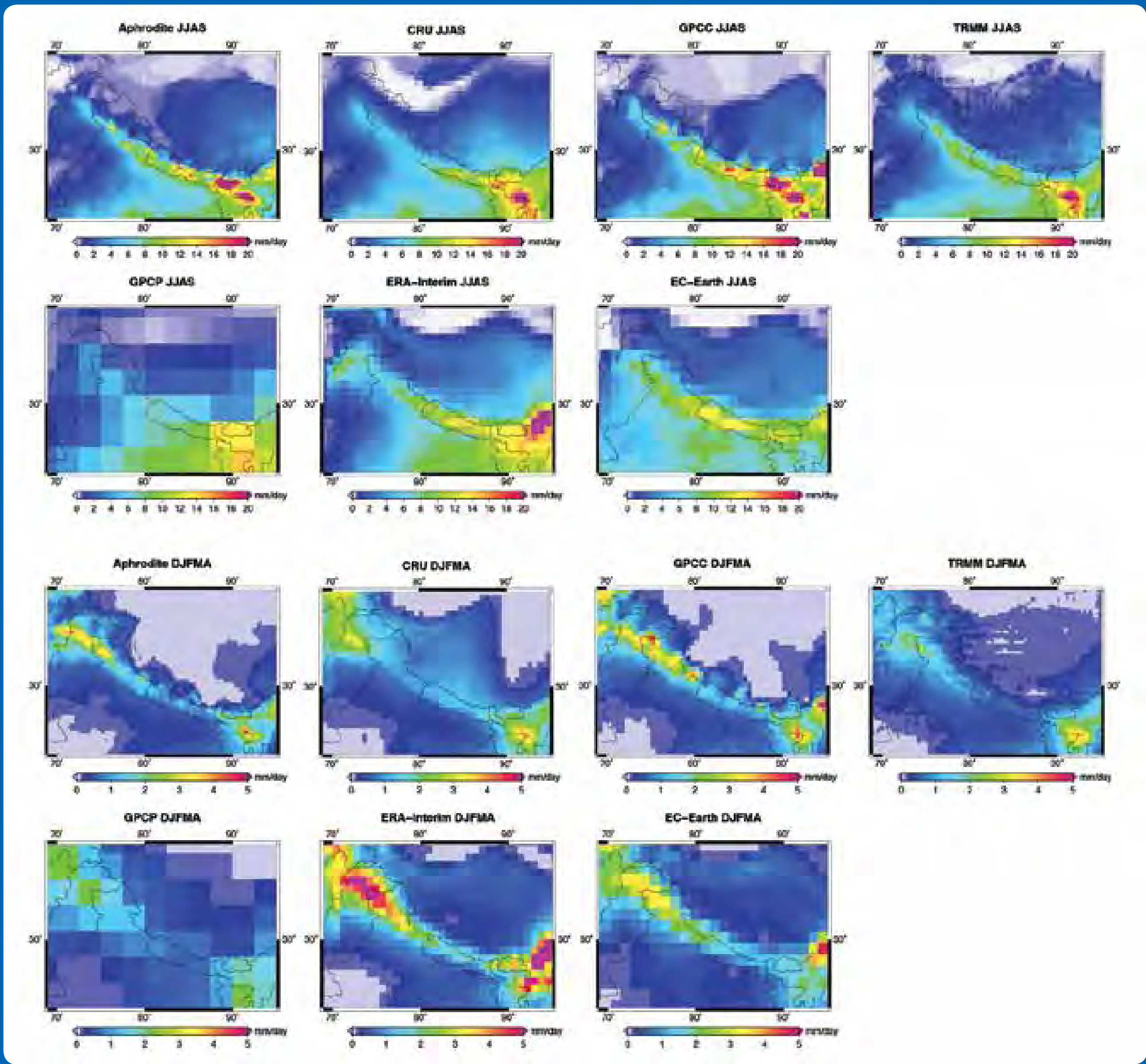
A number of studies have analysed trends in meteorological variables measured at ground stations. Fowler and Archer (2006) analysed temperature records in the upper Indus basin for the period 1961–2000: the winter mean and maximum temperatures increased significantly while summer mean and minimum temperatures consistently declined. The diurnal temperature range increased in all seasons. Analysis of precipitation records for the upper Indus basin showed significant increases in winter, summer, and annual precipitation for several stations over the

Table 1: **Overview of gridded meteorological products**

Dataset	Type	Coverage	Resolution	Frequency	Period	Parameters	Institute
NCEP/NCAR reanalysis data	reanalysis	global	~209 km (T62 grid)	6 hourly	1948 to present	pptn, Tmax, Tmin, Tavg (and many more)	NCEP/NCAR
CFSR	reanalysis	global	~50 km (0.5 degrees)	1 hourly, 6 hourly, monthly	1979–2010	pptn, Tmax, Tmin, Tavg (and many more)	NCEP
ERA 15 basic	reanalysis	global	basic: ~250 km (2.5 degrees)	monthly	1979–1994	pptn, Tmax, Tmin, Tavg (and many more)	ECMWF
ERA 15 advanced	reanalysis	global	~120 km (N80 grid)	monthly	1979–1994		ECMWF
ERA 40 basic	reanalysis	global	~250 km (2.5 degrees)	6 hourly	1957–2002	pptn, Tmax, Tmin, Tavg (and many more)	ECMWF
ERA 40 advanced	reanalysis	global	~120 km (N80 grid)	6 hourly	1957–2002	pptn, Tmax, Tmin, Tavg (and many more)	ECMWF
ERA Interim	reanalysis	global	~70 km (N128 grid)	6 hourly	1979–present	pptn, Tmax, Tmin, Tavg (and many more)	ECMWF
ERA 20 CM	climate model ensemble	global	~120 km (N80 grid)	3 hourly	1900-2009	pptn, Tavg	ECMWF
NASA MERRA	reanalysis	global	~70 km (0.5 x 0.67 degrees)	3 hourly	1979–present	pptn, Tmax, Tmin, Tavg (and many more)	NASA
Global Meteorological Forcing Dataset for land surface modeling	reanalysis + observations	global	~50 km (0.5 degrees)	3 hourly	1948–2008	pptn, Tmax, Tmin, Tavg (and many more)	Princeton University
APHRODITE	observations	Asia	~ 25 km (0.25 degree)	daily	1961–2007	pptn, Tavg	Meteorological Research Institute of Japan
CRU TS 3.10.01	observations	global	~ 50 km (0.5 degree)	monthly	1901-2009	pptn, Tmax, Tmin, Tavg (and many more)	Climate Research Unit at the University of East Anglia
GPCC	observations	global	~50 km (0.5 degree)	monthly	1901–2007	pptn	Global Precipitation Climatology Centre
GPCP	observations	global	~250 km (2.5 degrees)	monthly	1979–present	pptn	GEWEX
CPC-UGBAGDP	observations	global	~50 km (0.5 degree)	daily	1979 to present	pptn	CPC
DEL	observations	global	~50 km (0.5 degree)	monthly	1900-2008	pptn, Tair	CCR University of Delaware
WATCH (based on ERA-40)	reanalysis	global	~50 km (0.5 degree)	3 hourly	1901-2001	pptn, Tair (and many more)	Met Office Hadley Centre
WFDEI (based on ERA-Interim	reanalysis	global	~50 km (0.5 degree)	3 hourly	1979-2012	pptn, Tair (and many more)	Met Office
High Asia Reanalysis (HAR)	downscaled WRF	high Asia	30 km, 10 km	3 hourly	Oct 2000-Sept 2010	pptn, Tair, (and many more)	TU Berlin

pptn = precipitation; T = temperature; CPC = Climate Prediction Center; GEWEX = Global Energy and Water Cycle Exchanges Project; ECMWF = European Centre for Medium-Range Weather Forecasts; NASA = National Aeronautics and Space Administration; NCAR = National Center for Atmospheric Research; NCEP = National Center for Environmental Prediction

Figure 4: **Multi-annual mean (1998–2007) of monsoon (JJAS) and winter (DJFMA) precipitation over the HKH region as represented by different datasets**



Source: Palazzi et al. 2013

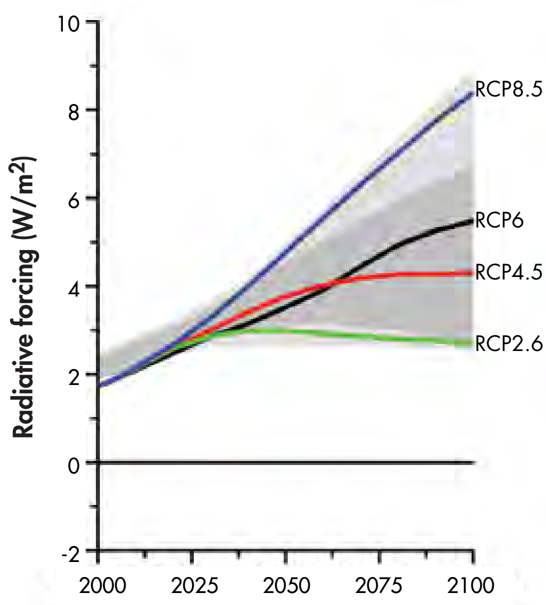
period 1961–1999 (Archer and Fowler 2004). Khattak et al. (2011) found stronger increasing trends in winter maximum temperature at higher elevations but no significant precipitation trends.

Studies worldwide show that recent increasing temperature trends are stronger for mountainous regions than for other land surfaces (Rangwala and Miller 2012; Pepin et al. 2015). Such trends have also been observed in the Himalayan region (Bhutiyani et al. 2007; Lu et al. 2010).

Cannon et al. (2015) found that the strength and frequency of winter westerly disturbance (WWD) activity and associated heavy precipitation events increased in the Karakoram and western Himalayas over the period 1971–2010, whereas WWD influence weakened in the central Himalayas, resulting in a decrease in heavy winter precipitation.

Table 2: **Description and visualization of the four RCPs**

RCP	Description	Development of radiative forcing
RCP8.5	Rising radiative forcing pathway leading to 8.5 Wm² (~1,370 ppm CO_2eq) by 2,100	
RCP6	Stabilization without overshoot pathway to 6 Wm² (~850 ppm CO_2eq) at stabilization after 2,100	
RCP4.5	Stabilization without overshoot pathway to 4.5 Wm² (~650 ppm CO_2eq) at stabilization after 2,100	
RCP2.6	Peak in radiative forcing at ~3 Wm² (~490 ppm CO_2eq) before 2,100 and then decline (the selected pathway declines to 2.6 Wm2 by 2100	



Climate change studies

Climate modelling and climate change scenarios

Climate is modelled at different spatial scales. General circulation models (GCMs) operate at spatial resolutions ranging from ~100 to ~250 km, while regional climate models (RCMs) run at a typical resolution of ~50 km. Climate change information is usually required at a higher spatial resolution and different downscaling techniques are used to bridge these scale differences.

The current state-of-the-art GCMs are organized in the CMIP5 archive (Taylor et al. 2012), which is used as a basis by the Intergovernmental Panel on Climate Change (IPCC) in the generation of its assessment reports. The CMIP3 archive (Meehl et al. 2007) was used prior to the release of CMIP5. The CORDEX framework (Giorgi et al. 2009) is a similar effort to organize the output from RCMs.

Since the release of the IPCC's Fifth Assessment Report in 2013, four representative concentration pathways (RCPs) have been used by the climate modelling community as a basis for long-term and near-term climate modelling experiments (van Vuuren et al. 2011). The four selected RCPs were considered to be representative of the literature, spanning the range of projected radiative forcing values for 2100 from 2.6 to 8.5 Wm-2. They include one mitigation scenario (RCP2.6), two medium stabilization scenarios (RCP4.5/RCP6) and one very high baseline emission scenario (RCP8.5) (Table 2; van Vuuren et al. 2011). Climate modellers use the time series of future radiative forcing from the four RCPs for their climate modelling experiments to produce climate scenarios. The development of the RCPs has allowed climate modellers to proceed with experiments in parallel with the development of emission and socioeconomic scenarios (Moss et al. 2010).

Since the four RCPs must represent the possible radiative forcing that can be expected by 2100, each should theoretically be included in climate change impact studies. However, there is usually a trade-off between how many RCPs and how many climate models can be included and the available time and resources.

Between 1996 and 2013, the IPCC used a different set of future scenarios that combined the main demographic, economic, and technological driving forces with future greenhouse gas emissions. Briefly, the A1 storyline and scenario family describes a future world of very rapid economic growth, a global population that peaks mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 storyline and scenario family describes a very heterogeneous world with an underlying theme of self-reliance and preservation of local identities. The B1 storyline and scenario family describes a convergent world with the same global population as in the A1 storyline but with rapid change in economic structures towards a service and information economy. Finally, the B2 storyline and scenario family describes a world in which the emphasis is on local solutions for economic, social, and environmental sustainability, with a continuously increasing global population but at a rate lower than in A2.

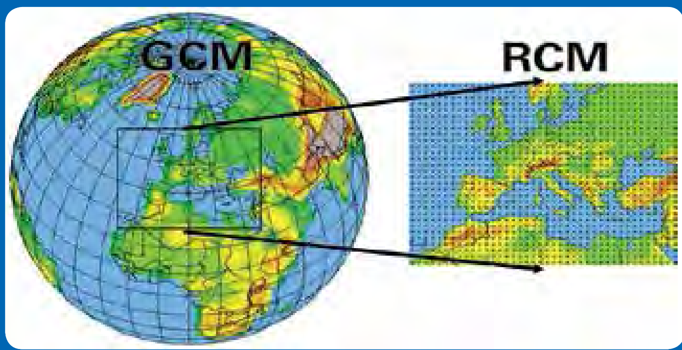
Downscaling techniques

The climate models have a low spatial resolution; thus downscaling techniques are used to force other models requiring input data at higher resolution, for example hydrological models.

Dynamic downscaling

Dynamic downscaling generally comprises a nesting of climate models of different spatial resolution. A GCM provides the boundary conditions for an RCM that has a nested domain within the GCM domain (Figure 5). Higher resolutions can be reached when a finer resolution RCM or weather model is nested within the RCM domain. The RCM then in turn provides the boundary conditions for the finer resolution RCM. On finer scales, large eddy simulation (LES) models can be deployed, which can include atmospheric turbulence. The high spatial resolution of RCMs means that computation resources limit the length of the simulated period and size of its area (spatial dimension).

Figure 5: **Schematic representation of the RCM nesting approach**



Source: World Meteorological Organization 2008

Empirical statistical downscaling

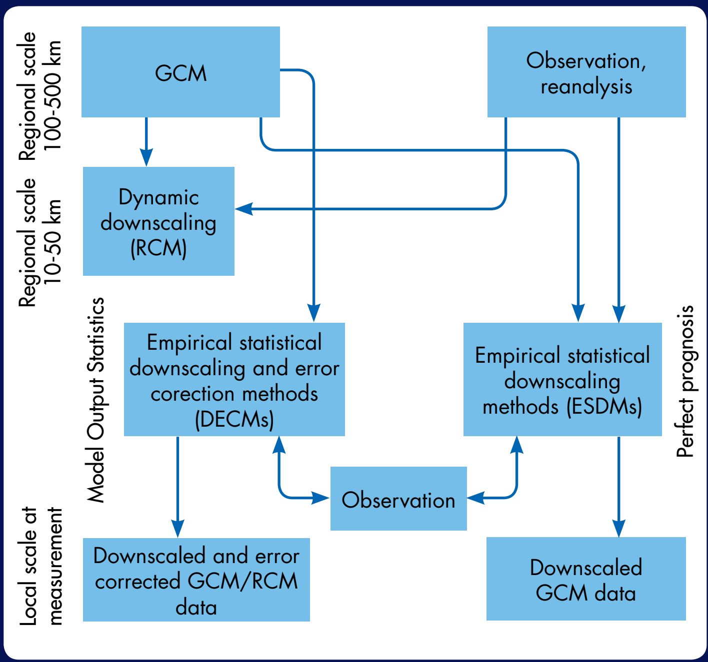
In areas where the climate has large spatial variations – as in mountainous regions – the RCM resolution is generally too low to simulate the climate satisfactorily and additional empirical statistical downscaling and error correction are usually required (Figure 6). Statistical downscaling also facilitates comparing the outputs of a range of GCMs, which helps to reduce the uncertainty caused by using the output from a limited number of models.

A range of statistical downscaling techniques have been developed to account for the scale differences between the global models and smaller scale hydrological models, and to interpolate regional scale atmospheric predictor variables to station-scale meteorological series. GCMs typically operate at ~1–3° (100–300 km) spatial resolution, but applications like hydrological models operate at resolutions down to several metres. Many processes, for example circulation patterns leading to hydrological extreme events, cannot be resolved by GCMs (Christensen and Christensen 2003).

Fowler et al. (2007) distinguished four approaches for downscaling, with the delta change or perturbation method as the simplest, and regression models, weather typing schemes, and weather generators being more sophisticated. Maraun et al. (2010) categorized statistical downscaling methods into weather generators (WG), perfect prognosis (PP), and model output statistics (MOS). The methods all have pros and cons, as indicated in the following brief summary, which focuses on applications in mountainous terrain.

Figure 6: **Scheme of different downscaling approaches:**

Traditional empirical statistical downscaling (right pathway) calibrates the statistical transfer function between large-scale observation/reanalysis data and local-scale observations using empirical-statistical relationships appropriate for use with any GCM; empirical statistical downscaling (ESD) with DECMs (left pathway) are calibrated using RCM (or GCM) data and local observations which account for both downscaling and model errors but can only be applied to the model they are calibrated for



Source: Themeßl et al. 2011

Perfect prognosis approaches (traditional empirical-statistical downscaling methods, Themeßl et al. 2012) establish links between observed large-scale (synoptic scale) predictors and observed local-scale projections and include the classical approaches such as regression models and weather pattern-based approaches (Maraun et al. 2010). In a standard linear regression model, the unexplained variability is assumed to be Gaussian distributed (Maraun et al. 2010); such models can be used for downscaling of mean precipitation and mean air temperature, but are not suitable for shorter timescales because daily precipitation is commonly modelled using a gamma distribution. The generalized linear model and linear dependency models project a vector of parameters of a distribution, including for example the mean and the variance, and are useful when studying the behaviour of extreme events and to estimate the dependence of the variance or the extreme tail on a set of predictors (Maraun et al. 2010). In weather type-based downscaling, a set of categorical weather types are used to project the mean of local precipitation and temperature. Other approaches include non-linear regressions, for example the use of an artificial neural network (Maraun et al. 2010). The analogue method is based on selecting the most similar large-scale weather situation in the past and selecting observations from corresponding local-scale situations and are thus limited to past events. The method can be extended by randomly choosing the analogue from a number of most similar historical conditions (e.g., Moron et al. 2008).

The most basic linear regression model is the simple delta change or perturbation method (Prudhomme et al. 2002; Kay et al. 2009), which downscales GCMs to the local scale using change factors. Differences between a future and a control GCM run are superimposed on a local-scale baseline observation dataset. Because of the simplicity of this method, a large number of GCMs can be downscaled, facilitating the use of a large ensemble of possible future climates in climate change impact studies. The shortcomings are the assumption that the bias between the GCM and the local-scale data remains constant in time, and the fact that only changes in the mean, minima, and maxima of climatic variables are considered (Fowler et al. 2007), making it less suitable for hydropower related assessments.

The advanced delta change (ADC) approach (van Pelt et al. 2012; building on Leander and Buishand 2007), has the advantage that changes in extremes are considered as well as changes in the mean, thus making a non-linear transformation of climate signals in GCMs; changes in multi-day precipitation events are also modelled. Although successfully applied in Europe (van Pelt et al. 2012), difficulties were experienced with the downscaling of precipitation when applied in the upper Indus basin (unpublished), probably as a result of the high spatial variability of precipitation in the high mountainous terrain. Additional corrections had to be applied to correct unrealistic changes in extreme precipitation events. Bordoy and Burlando (2013) tested the usefulness of the original nonlinear bias-correction approach developed by Leander and Buishand (2007) in complex, orographically influenced climate systems and found that the method dramatically reduced RCM errors for air temperature and precipitation, but generated extreme precipitation values that considerably exceeded the range of the observations.

Model output statistics (MOS) approaches establish the statistical relationship between predictors and projected values by using simulated predictor values instead of observed values to make projections. In most applications, local-scale climate is projected, and a correction and a downscaling step are combined in MOS. MOS is mostly used for RCM downscaling (Eden et al. 2012; Eden and Widmann 2014).

Empirical-statistical downscaling and error correction methods (DECMs) (multiple post-processing) are also based on the MOS approach. Themeßl et al. (2011) tested seven DECMs for RCM-downscaling of climate in the mountainous terrain of Austria; point-wise methods improved the original RCM signals. Quantile mapping can also be used to downscale and bias-correct multiple climatic variables, and has been successfully applied to air temperature and precipitation – the main drivers for most hydrological models; improvement can also be expected in other variables derived from temperature and precipitation such as snow accumulation and melt water generation.

Multiple linear regression methods have significant shortcomings in modelling daily climate due to their linear nature. Linear regression is not realistic, for example, in the case of precipitation which shows high spatial variation in mountainous regions. Local intensity scaling applies a spatially varying scaling to climate model precipitation to account for the long-term bias at the location of the observation (e.g., Schmidli et al. 2006). Quantile mapping (e.g., Boé et al. 2007) corrects for errors in the shape of the distribution and can correct errors in both the variability and the mean. Themeßl et al. (2011) found that quantile mapping performed the best of seven DECMs compared for mountainous terrain. Adaptations in the quantile mapping method also allow for good simulation of future extremes (Themeßl et al. 2012). Immerzeel et al. (2013) successfully applied quantile mapping to downscale GCM data using observed data from two ground stations in the HKH region.

Weather generator models generate random sequences of weather variables with statistical properties resembling observed weather (Ferraris et al. 2003). They are mostly used to simulate weather at point locations. Attempts to generate continuous spatial precipitation fields have only recently been extended for downscaling (Maraun et al. 2010).

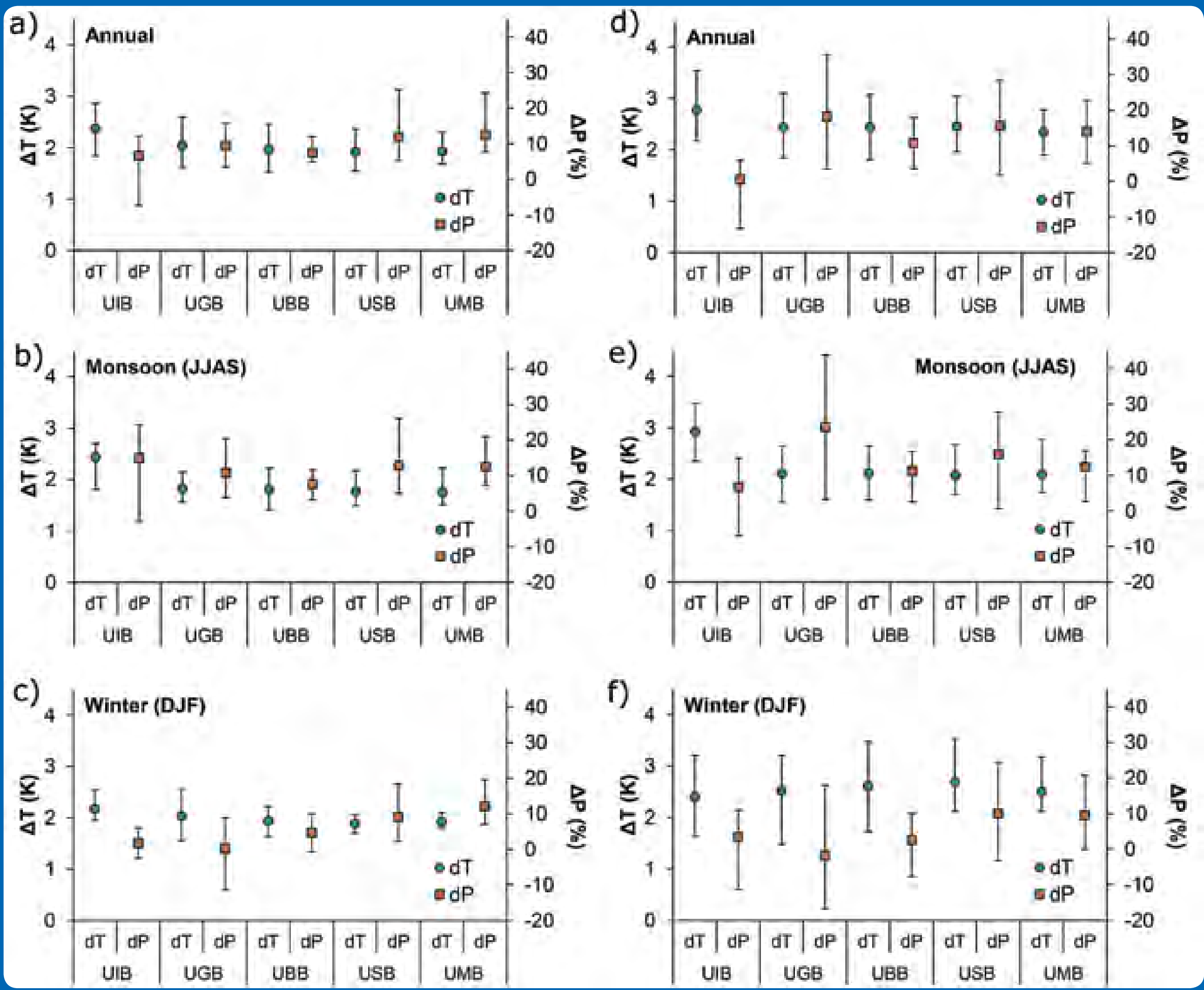
Forsythe et al. (2014) combined a stochastic rainfall model and a rainfall conditioned weather generator to assess climate change signals for three ground stations in a section of the Upper Indus basin. Validation against a time-series of observations at these three locations showed that the model simulated means of climatological variables well, despite the complex climate of the mountainous region at the boundary of monsoonal and westerly climate systems. Future climate was assessed using change factors derived from comparison of a future and control time slice of an RCM.

Bordoy and Burlando (2014) used a stochastic approach to downscale climate model outputs from several locations in the Swiss Alps to a sub-daily temporal resolution. Their approach was more effective than other downscaling techniques in addressing the internal variability of precipitation (Bordoy and Burlando 2014). Ragettli et al. (2013) successfully applied the same methodology to downscale GCM monthly data to a daily temporal resolution at three stations in the upper Indus basin.

Future climate change and variability in the Indus, Ganges, and Brahmaputra basins

Climate change in the upper Indus, Ganges, Brahmaputra, Salween, and Mekong basins was simulated up to 2050 in a study by ICIMOD's HICAP programme using the simple delta change method (Lutz et al. 2014). Four GCM runs were selected for RCP4.5 and RCP8.5 to cover the entire range of area-averaged projected changes in mean air temperature and total precipitation for the entire upper parts of the basins. The mean air temperature in the upper Indus, Ganges, and Brahmaputra basins was projected to increase by ~1.7 to 2.9°C (RCP4.5) or ~2.0 to 3.5°C (RCP8.5) between 1961–1990 and 2021–2050 (Figure 7). The projections for precipitation are more uncertain, with potential changes under RCP4.5 ranging from -10% to +10% for the upper Indus and +5% to +15% for the upper Ganges and Brahmaputra, and under RCP8.5 -15% to +10% for the upper Indus, +5% to +35% for the upper Ganges, and +5% to +15% for the upper Brahmaputra. The large differences in the projections for the winter and monsoon seasons are striking and indicate that GCM outputs for climate change

Figure 7: **Projected range of change in mean air temperature and total precipitation between 1961-1990 and 2021–2050 in the upper Indus (UIB), Ganges (UGB), Brahmaputra (UBB), Salween (USB), and Mekong (UMB) basins**



Source: Lutz et al. 2014

impact studies, including hydropower related studies, should be analysed at least at a seasonal level, and preferably on a monthly or even shorter period.

An analysis of PRECIS RCM data for the A1B scenario in the Indus basin up to the end of the century indicated a potential increase in winter precipitation in the upper Indus basin, and decrease in winter precipitation in the lower Indus basin (Rajbhandari et al. 2014). The projected change in monsoon precipitation was highly variable. Greater warming was projected for the upper basin than for the lower basin, indicating that the elevation-dependent warming observed at present is likely to continue in the future. A slightly greater increase in minimum air temperature compared to maximum air temperature was also projected, and a stronger warming of winter temperature than in the other seasons. Three simulations indicated that projected changes in precipitation are more uncertain than those in temperature.

The projections from 32 GCMs from the CMIP5 model ensemble were analysed for the Hindu Kush Karakoram and the Himalayas using RCP4.5 and RCP8.5 (Palazzi et al. 2015). The CMIP5 models projected wetter future conditions in the Himalayas during the monsoon season, with precipitation gradually increasing up to the end of the century. Wetter summer conditions were also projected for the Hindu Kush Karakoram under RCP8.5, no significant change in winter precipitation was projected for either region. The authors emphasized that no model performed significantly better than the others, and that the projections varied greatly.

Six statistically downscaled GCMs projected accelerated seasonal increases in temperature and precipitation in the Brahmaputra basin for the period 2000–2100, with the largest changes on the Tibetan Plateau and the smallest on the Brahmaputra floodplain (Immerzeel 2008).

RCM-based climate change projections were generated for the 21st century for India (Rupa Kumar et al. 2006). Projections were made for the IPCC Special Report on Emissions Scenarios (SRES). They indicated uniform widespread warming over the country with an increase in extremes of minimum and maximum temperatures. Change in annual precipitation was projected with substantial spatial variation and the maximum increase over west-central India. Precipitation extremes were projected to increase over a large area, with the strongest increases projected for the Indian west coast and west-central India.

Multiple studies have been conducted on climate change in smaller areas within the basins. A study using downscaled RCM output for the northern part of the upper Indus basin projected year-round increases in precipitation of +18% (annual mean) between 1961–1990 and 2071–2100, with increased intensity in the wettest months of February, March, and April (+27% seasonal mean), together with year-round increases in mean temperature of around +4.8°C (Forsythe et al. 2014). The authors emphasized that the year-round uniformity in temperature increase contrasted with the asymmetrical trend in recent observations. They also stressed that the study should be seen as exploratory because only one RCM was used; use of an ensemble of RCMs to force the model would provide more information about possible future climate change in the basin.

Downscaled climate change scenarios for the Langtang (upper Ganges) and Baltoro (upper Indus) catchments using the quantile mapping downscaling approach (Themeßl et al. 2012) showed a consistent temperature increase in both catchments up to the end of the 21st century (Immerzeel et al. 2013). A stronger increase in precipitation was projected for the Langtang than for the Baltoro catchment, with a larger uncertainty in the precipitation projections for Baltoro due to the large variability in GCM results over the Indus basin. Ragettli et al. (2013) also found a consistent temperature increase up to 2050 for the Hunza basin (upper Indus) based on three downscaled GCMs. Two GCMs indicated an increase in precipitation whereas the third indicated a decrease.

Sharmila et al. (2015) analysed future projections of Indian summer monsoon variability in CMIP5 GCMs for RCP8.5. The authors first filtered the CMIP5 ensemble for models simulating the monsoon satisfactorily over a historical period. Subsequently, changes in future monsoon dynamics were assessed for the five remaining models. The projections of these five models were consistent, in summary:

- The Indian summer monsoon is very sensitive to global warming
- Summer monsoon mean rainfall is likely to increase moderately
- Higher rainfall intensity is likely over the core monsoon zone
- The number of wet days is likely to decrease
- The monsoon season will lengthen due to later withdrawal
- Larger interannual variability in monsoon intensity is likely

Earlier projections for summer monsoon climate over India using an RCM and IPCC SRES scenarios indicated an expected increase in summer monsoon precipitation by 9–16% in the 2080s compared to the 1970s. The number of rainy days was also projected to decrease accompanied by increasing rainfall intensity on wet days (Krishna Kumar et al. 2011).

Performance of climate models

Mishra (2015) showed that in the Coordinated Regional Climate Downscaling Experiment (CORDEX) framework all RCM ensemble members fail to reproduce observed climatic trends in the Indus, Ganges, and Brahmaputra basins, and that the GCMs that provide the boundary conditions for the RCMs in general simulate winter climate in the region better than the CORDEX RCMs. The authors conclude that reliability of future climate projections and their impacts on water resources in the region will depend on improvements in the models and observations in coming years.

From their analysis of 32 CMIP5 GCMs, Palazzi et al. (2015) concluded that there is no particular model that is 'best' in simulating the climate in the HKH region. From their pool of models, only three were able to satisfactorily simulate the annual cycle of precipitation. However, even these three models failed to reproduce observed trends in precipitation. The authors conclude that since no single model can be chosen as best performing, it is important to use results from the whole range of models in climate change impact assessments.

Monsoon dynamics

The monsoon is a crucial climatic feature in the HKH region and it is important to know how well the regional monsoon dynamics are represented in climate models. A study by Sperber et al. (2013) compared the performance of CMIP3 and CMIP5 GCMs in representing the Asian summer monsoon using pattern correlation in spatial grids of model results compared to the observation-based Global Precipitation Climatology Project (GPCP) results. The models were very diverse in their ability to simulate the monsoon annual cycle but the CMIP5 GCMs were better able to simulate monsoon dynamics than the CMIP3 models. The ability to simulate the pattern of monsoon peak and monsoon withdrawal was typically better than that for simulating the onset, with the simulated onset of the monsoon over India typically too late in all models, but there was no statistical relationship in the ability to simulate peak or withdrawal relative to onset. The pattern of monsoon duration was better represented in models that simulated the onset pattern better. The simulation of intra-seasonal variability was also problematic, although several CMIP5 models showed an improved skill in representing the northward propagation of convection and the development of the tilted band of convection that extends from India to the equatorial west Pacific.

Using a different technique to assess monsoon representation in CMIP5 climate models, Sperber and Annamalai (2014) concluded that most model simulations show delayed onset of summer rainfall over India. They also observed that most models simulate the interannual variability in the date of monsoon onset quite well; the exceptions being models with the most pronounced dry biases.

Another study compared the CMIP3 ensemble to the CMIP5 ensemble in representing the continental Indian monsoon and concluded that no significant progress had been made (Ramesh and Goswami 2014). The authors observed a larger bias in CMIP5 model projections than in those from CMIP3 models, and that the interannual variability of the CMIP3 multi-model mean was better than that of the CMIP5 multi-model mean.

Sharmila et al. (2015) assessed the performance of 20 CMIP5 GCMs in simulating various precipitation parameters for the Indian summer monsoon – seasonal precipitation, interannual variability, latitudinal migration of daily precipitation, and intra-seasonal variance – and concluded that only five of 20 models represented the monsoon satisfactorily.

From these studies it is clear that satisfactory representation of monsoon dynamics in climate models remains problematic, which also makes projections of future climate more uncertain in the HKH region than in other regions. The spread in model outcomes also indicates that it is preferable to use an ensemble of climate models for simulation. Applying empirical-statistical downscaling and bias-correction techniques to the raw GCM data can help to overcome this poor representation to a large extent. These techniques introduce historical climatic information from observations that have a higher quality and higher resolution than the raw GCM data. This additional information is used to correct for biases between the GCM historical run and observations for the same period at the spatial resolution of the observations-based dataset. The corrections can then be applied to a GCM run in the future, assuming that the error characteristics stay constant over time. The improvement of raw GCM data using empirical-statistical downscaling and bias-correction techniques has been demonstrated in multiple studies (e.g., Piani et al. 2010; Terink et al. 2010; Themeßl et al. 2011, 2012; Wilcke et al. 2013; Maurer and Pierce 2014). Very recent research suggests that some empirical-statistical downscaling and bias-correction techniques even improve the climate change signal from the raw GCM data (Maurer and Pierce 2014; Gobiet et al. 2015). However, even though a part of the errors stemming from poor representation of monsoon dynamics in GCMs can be corrected using these techniques, uncertainty remains since the projected changes by a GCM with poor representation of the actual climate are less certain.

Summary

In summary, the analyses of historical climatic trends in the HKH region show the following:

- Air temperature has been increasing in the region over the past decades. The rates of increase are different for daily mean, maximum, and minimum air temperature. The temperature increase is elevation dependent, with a greater increase at higher elevations.
- Overall, precipitation shows no significant increasing or decreasing trends, but this varies locally.

The major findings of the analyses of future projections of climate change using dynamically or statistically downscaled global and regional climate models are as follows:

- Climate warming is likely to continue during the 21st century.
- The climate models project a wide range of possible futures for changes in precipitation including strong increases and decreases. Precipitation increase is most likely for the upstream Ganges and Brahmaputra basins, but the magnitude is highly uncertain. Projections point to both increases and decreases in the upstream Indus basin, but with large variability (uncertainty).
- The Indian summer monsoon is likely to show an increase in total precipitation, precipitation intensity, interannual variability in monsoon strength, and inter-daily variability.

The current state-of-the-art GCMs and RCMs have significant difficulty in simulating the complex climate in the HKH region. Only a limited number of models can satisfactory simulate the monsoon dynamics and no model is able to simulate all the important features in the HKH precipitation regimes.

Cryosphere Dynamics

Distribution of cryosphere components

Glaciers

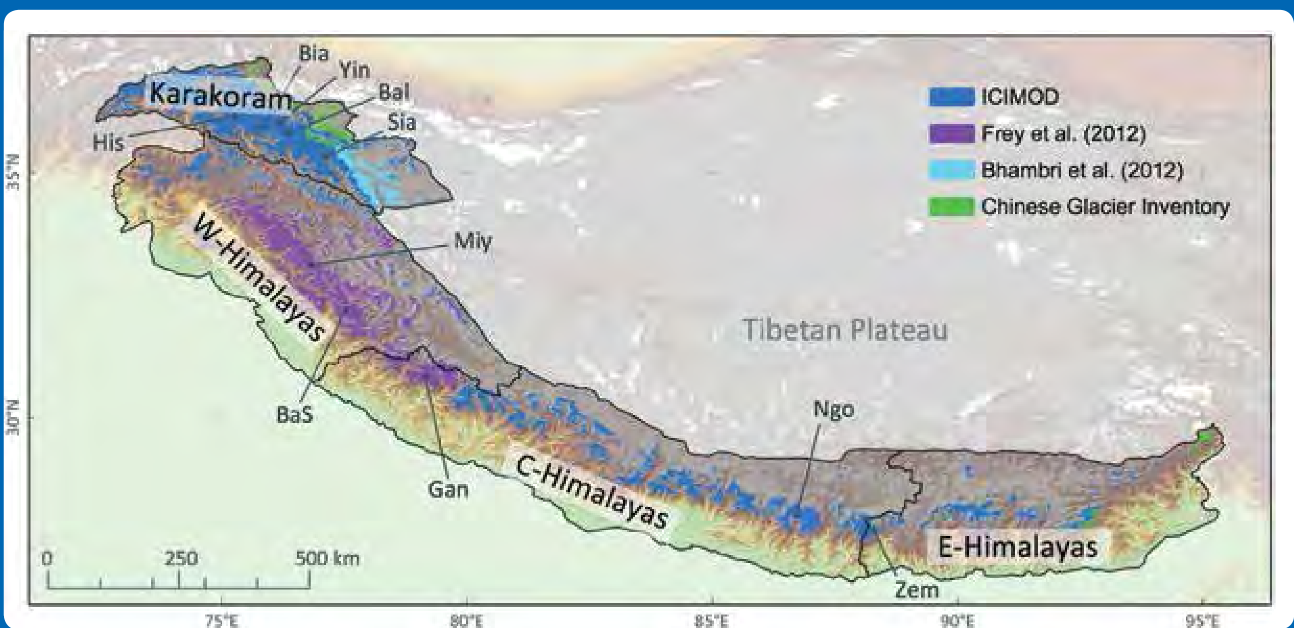
Frey et al. (2014) prepared a map of the distribution of glaciers across the HKH compiled from various sources (Figure 8). According to the ICIMOD glacier inventory (Bajracharya and Shrestha 2011) there are 37,955 glaciers in the Indus, Ganges, and Brahmaputra basins, covering 44,224 km^2 and with an estimated volume of about 4,793 km^3 (Table 3). The estimates of total glacier area vary among authors, but all studies indicate that the percentage of glacier area, total cover, and volume differ significantly among the different basins (Table 3).

The Indus basin includes large glaciers in northern Pakistan and northwestern India. The Ganges basin includes glaciers in India (Uttarakhand) and Nepal. And the Brahmaputra basin includes glaciers located along the border between China and Nepal in the southern part of the Tibetan Plateau, to the north-east of Lhasa in the Nyaingentanglha mountain range, to the southeast of the Tibetan Plateau in the Parlang Zangbo mountains near China's border with India (Arunachal Pradesh), in Sikkim and Arunachal Pradesh in India, and in Bhutan. The Indus basin probably has the largest volume of ice of all three basins, while the Ganges has the least glacier cover and volume (Bajracharya and Shrestha 2011; Frey et al. 2014) (Table 4).

The Indus basin in the western part of the HKH lies at the junction of the Hindu Kush, Karakoram, and Himalayan mountain ranges and is influenced by westerlies; most of the yearly precipitation comes from winter snowfall and the glaciers accumulate snow during winter. The Brahmaputra and Ganges basins lie in the central and eastern parts of

Figure 8: **Distribution of glaciers in the HKH based on outlines from ICIMOD's inventory**

(Bajracharya and Shrestha 2011), Frey et al. (2012), Bhambri et al. (2013), and the Chinese Glacier Inventory (Shi et al. 2010). The largest glaciers in each sub-region are indicated (Sia: Siachen, Bal: Baltoro, Bia: Biafo, Yin: Yinsugaiti, His: Hispar, BaS: Bara Shigri, Miy: Miyar, Gan: Gangotri, Ngo: Ngozumpa, Zem: Zemu)



Source: Frey et al. 2014

Table 3: **Glacier cover and volume estimates for the Indus, Ganges and Brahmaputra basins from different studies**

	Study	Indus	Ganges	Brahmaputra
Basin area (km^2)	ICIMOD (Bajracharya and Shrestha 2011)	1,116,086	1,001,019	528,079
Number of glaciers	ICIMOD (Bajracharya and Shrestha 2011)	18,495	7,963	11,497
Glacier area (km^2)	ICIMOD (Bajracharya and Shrestha 2011)	21,193 (1.9%)	9,012 (0.9%)	14,020 (2.7%)
	Nuimura et al. 2015	23,668	7,537	9,803
	Randolph Glacier Inventory (Pfeffer et al. 2014)	26,018 ± 1,750	10,621 ± 824	17,419 ± 1,373
Debris covered fraction	ICIMOD (Bajracharya and Shrestha 2011)	9.6%	12.6%	11.1%
Volume (km^3)	ICIMOD (Bajracharya and Shrestha 2011)	2,696	794	1,303

Table 4: **Glacier volume estimates for the whole HKH region from different studies (km^3)**

	Karakoram	Western Himalayas	Central Himalayas	Eastern Himalayas	Total
Frey et al. (2014)	2,965–1,537	759–394	723–345	283–147	4,731–2,453
Marzeion et al. (2012)	2,748	611	771	279	4,409
Grinsted (2013)	1,896	584	714	265	3,459
Radić et al. (2014)	2,953	657	828	300	4,738

the HKH; most of the yearly precipitation occurs during the monsoon and glaciers tend to accumulate snow during summer, so that the accumulation and melt seasons tend to overlap.

A significant proportion of the glaciers in the region are covered by a layer of rock debris in their frontal part. Melting of glacier surfaces below a layer of debris can be accelerated compared to debris-free surfaces if the debris layer is thin (a few centimetres), or slowed if the thickness is more than about 5 cm (Mihalcea et al. 2006; Brock et al. 2010; Nicholson and Benn 2006). Thus it is important to assess the distribution and percentage of debris-covered glaciers when studying changes in the cryosphere.

In 2011, ICIMOD developed a glacier inventory for the entire HKH region from satellite images (Bajracharya and Shrestha 2011). The debris-covered part of the HKH glaciers was mapped across all of the region except the section lying within China. Nuimura et al. (2015) have also developed a High Asian glacier inventory, and glacier data can also be obtained from the Randolph Glacier Inventory (Pfeffer et al. 2014). The glaciated area in the three basins as shown by the three inventories is shown in Table 3. There are considerable differences, which probably reflect differences in the methods used to define glacier boundaries, as well as different interpretations of debris-covered glaciers (Table 3). Glacier volumes are difficult to determine and are generally inferred from a knowledge of the area of a glacier and its slope using parameterizations (Frey et al. 2014). Table 4 shows examples of estimates of glacier volumes in different parts of the HKH from various studies.

Snow cover

Annual snow melt is an important contributor to river runoff in the higher altitude river basins in the HKH (Bookhagen and Burbank 2010). Recent studies have shown that snow cover extent in the Himalayas and on the Tibetan-Qinghai plateau can influence the strength of the monsoon: extensive winter snow cover on the Tibetan plateau generally leads to weaker monsoon intensity (Pu and Xu 2009). The variation in the snow-rain elevation transition line also impacts the reflectivity of glaciers (albedo) and plays a crucial role in the melt dynamics of the glaciers. Thus it is important to study the spatial and temporal variations of snow cover extent, snow accumulation, and melt dynamics.

Snow cover has a marked seasonal variation and is much more dynamic than glacier cover. It is important to understand both its spatial distribution and its seasonal variations. One of the most extensive studies on snow cover extent in the HKH is the ICIMOD study based on MODIS products (Gurung et al. 2011). This study investigated the snow cover area (SCA) in eight-day time steps, covering all of the Hindu Kush Himalayas from 2000 to 2010. A study by Immerzeel et al. (2009) also covered all of the HKH but with a stronger emphasis on the Indus basin. The ICIMOD study showed a mean SCA between 2000 and 2010 over the whole Indus basin of 167,992 km^2, 17% of the total area; while Immerzeel et al. (2009) found a mean SCA of 33% for the upper Indus basin taken separately. The mean SCA for the Ganges basin was 47,742 km^2 (5% of the total area), and for the Brahmaputra basin it was 107,121 km^2 (20% of the total area). The study didn't identify any significant trends in SCA between 2000 and 2010.

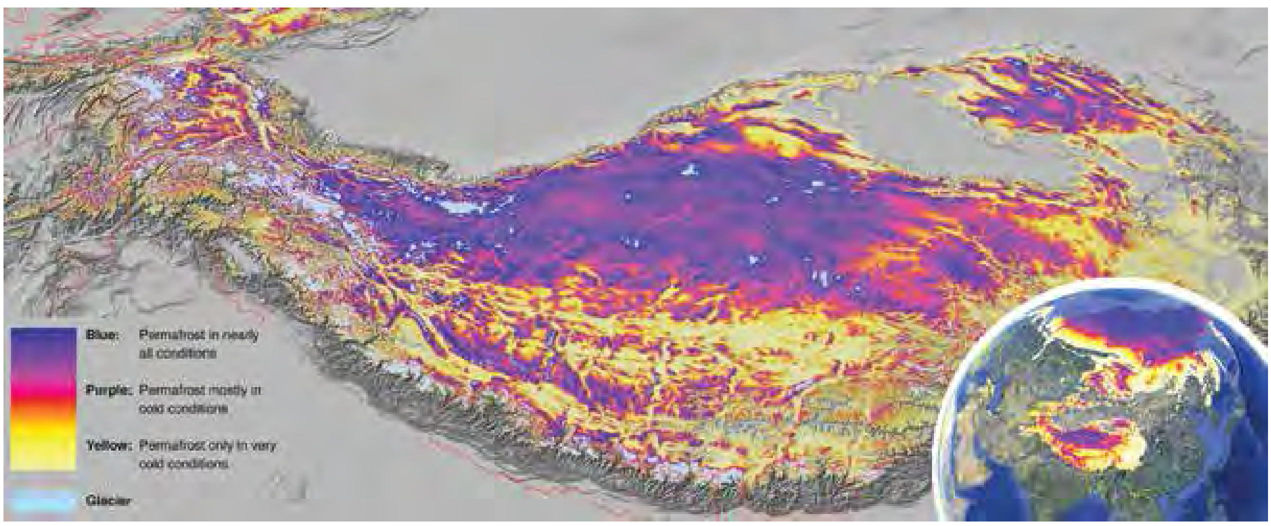
The maximum SCA over the Himalayas as a whole is at the beginning of spring (Bookhagen and Burbank 2010). The SCA in the Indus and Brahmaputra basins increases considerably over the winter, whereas the SCA over the Ganges basin increases only slightly. The snow line rises on average from 2,336 masl in winter to 4,109 masl in summer in the Indus basin and from 3,330 masl in winter to 4,573 masl in summer in the Ganges basin, while the values for the Brahmaputra basin lie in between (2,932 masl in winter, to 4,433 masl in summer) (Immerzeel et al. 2009).

Permafrost

There are very few studies of permafrost in the HKH region, and understanding is limited compared with other regions such as the European Alps or the Canadian tundra. Permafrost is defined as subsurface material (excluding glaciers) with a temperature of less than or equal to 0°C during at least two consecutive years. Both the mean annual ground temperature (MAGT) and occurrence and other properties of permafrost exhibit strong lateral variations over ranges of a few metres to a few kilometres as a result of topography, vegetation cover, ground material, water bodies, and/or snow distribution. This compounds the problem of identification in a poorly accessible area where ground observations are extremely limited. Although much more is known about permafrost and changes in permafrost in well monitored regions like the European Alps, it is not recommended to transfer findings from there to the HKH region because the regions differ strongly in climate, bedrock, elevation differences, and steepness of the terrain.

The global permafrost zonation map presented by Gruber (2012) is probably the best available indication of where permafrost is likely to occur in the HKH region. The map was generated using established links between air temperature and permafrost occurrence and parameterizations based on published estimates and is available at 1 km^2 resolution. The HKH portion of the map (Figure 9) indicates that the Brahmaputra river basin is likely to have

Figure 9: **Permafrost zonation index map of the HKH region and the Tibetan plateau**



Source: Gruber 2012

the most permafrost since a large part lies within the Tibetan plateau, where the conditions indicate a high likelihood of permafrost occurrence.

Approaches used to measure cryosphere components

A wide range of methods is used to measure or estimate glacier area and volume and snow cover, and it is important to have some understanding of their advantages and limitations as a basis for assessing the degree of certainty or uncertainty of published values and projections. The measurement methods fall into two main groups: in situ and remote sensing. Volume estimates are mostly carried out using different modelling approaches.

In situ

Glaciers

There are two basic types of in situ measurement of glaciers: identifying the position of the leading edge and estimating the mass balance. The front position is the easiest variable to measure and has been commonly monitored in past decades, especially in western India (Geological Survey of India 1998), but it is not a direct indicator of total glacier mass or of melting rate, as a range of factors may affect the glacier depth and volume. For example, significant areas of the Himalayan glaciers are covered with debris which can provide varying degrees of insulation and affect melt processes (Mihalcea et al. 2006). Some debris-covered glaciers with motionless fronts show a negative mass balance (Scherler et al. 2011), and surging glaciers can also show a negative balance. Thus, variations in the front position of glaciers are not thought to be suitable indicators of recent climate change (Scherler et al. 2011), and we do not expect such variations to be relevant indicators for hydrological change assessments in the HKH.

In situ glacier mass balance estimates are obtained by measuring the emergence and position of stakes inserted in the ice to determine the amount of ice melted at the surface, the depth, and thus the snow accumulation. In situ geodetic mass balances are obtained using differential GPS (DGPS) to measure the variation in surface elevation of the glacier, combined ideally with snow and ice density measurements (Zemp et al. 2013). The spatial density and distribution of stakes or of DGPS measurements can significantly influence the accuracy of the mass balance evaluation. The various monitoring programmes operating in the HKH do not use standardized methodologies and there are large variations in spatial coverage between sites, thus there is considerable variation in the accuracy of mass balance measurements (Zemp et al. 2013). Such measurements require thorough fieldwork, which is hampered by the poor accessibility and high altitude of glaciers in the HKH. Only a few sites can be monitored regularly and ideally these should be selected to ensure that they accurately represent the different climatic regions and provide the reliable data needed to validate the large scale assessments obtained using remote sensing.

Glacier surface velocity is inferred from measurement of the position of stakes or boulders on the glacier surface using DGPS and provides information about redistribution of mass from the upper to the lower parts of glaciers, which gives some insight into glacier response to climate change (Azam et al. 2012; Gardelle et al. 2012).

Glacier volume is an indicator of total water storage. It is usually inferred from a combination of glacier area and slope using parameterized relationships between area and volume which are validated by in situ measurements of ice depth. Depth is measured on site using ground penetrating radar (Frey et al. 2014), but this technique has only been used sporadically in the HKH (e.g., Azam et al. 2012).

Snow

Seasonal snow melt is an important contributor to river runoff in parts of the HKH (Bookhagen and Burbank 2010). In situ measurements are essential for validating remote sensing measurements of snow cover and depth and for assessing snow water equivalent precipitation, which is needed in hydrological models to assess the maximum amount of melt that can be expected from snow cover. Knowledge of the snow-rain transition elevation is also needed for modelling future snow cover evolution.

Snow water equivalent (SWE) is calculated from snow depth and density. The depth can be measured manually using stakes, or automatically using sensors such as sounding height rangers or lasers fitted on meteorological stations. The density is measured by weighing known volumes of snow manually. A classical rain gauge can provide measurements of snow equivalent if it is possible to distinguish between snow and rain events (Lejeune et al. 2003, 2007), but this remains a challenge and precipitation gauges often underestimate precipitation, especially during snow events (Lejeune et al. 2003, 2007). New generation, real-time, laser based precipitation sensors can help to distinguish snow and rain during precipitation events (Löffler-Mang and Joss 2000). When coupled with a properly calibrated and corrected pluviometer, they may enable the evaluation of snow water equivalent precipitation.

Field measurement data are needed to calibrate remote sensing measurements of snow over large areas. Negi et al. (2010) carried out spectrometry measurements of snow to gain some understanding of the influence on spectral reflectance of snow grain size, contamination, moisture, aging, snow depth, slope, and aspect, and determine the most appropriate wavelengths for snow mapping. In situ measurements of microwave penetration into snow have also been carried out to support calibration of satellite-based microwave measurements of snow depth (Singh et al. 2015).

Singh et al. (2011) tested the use of ground penetrating radar (GPR) to determine the depth of the snow pack in the Indian Himalayas; however, the GPR gives a signal for each layer where snow density changes abruptly and the method requires knowledge of the stratigraphy of the snow.

Remote sensing

Glaciers

Remote sensing techniques offer the most viable way of developing databases on glaciers covering large areas, although at least some field validation is required to ensure a degree of reliability. Satellite data have been available since the early seventies (Racoviteanu et al. 2008). Changes in mass balance can be derived from remotely sensed surface height variations using digital elevation model (DEM) differentiation (Racoviteanu et al. 2008). Remote sensing can also be used to infer glacier surface velocity and to determine spatial cover.

The sensors used to monitor elevation change can be classed as active or inactive. Active sensors use the reflection of a signal emitted by the sensor, and inactive sensors use natural signals emanating from the surface (reflection from the sun or emission). One of the most efficient active sensor techniques is LiDAR, which measures distance by illuminating a target with a laser light. Airborne LiDAR measurements provide high-resolution elevation maps with accuracies up to 20 cm in the vertical axis and 30 cm in the horizontal axis (Carter et al. 2012) but have not yet been used to measure glacier height in the HKH, probably at least in part due to the high costs involved for the extensive flights required to cover such large areas. LiDAR measurements are more frequently obtained from satellite-borne altimeters, for example ICESat's GLAS sensor (Carter et al. 2012; Bamber and Rivera 2007; Kääb et al. 2012). The vertical accuracy is still a few tens of centimetres but the spatial resolution is of the order of tens of metres. Satellite synthetic aperture radar (SAR) data have been used to estimate ice movement velocities in Arctic glaciers (Strozzi et al. 2008; Sund et al. 2014) and glacier surface velocities in the Himalayas (Kumar et al. 2011).

Space-borne photogrammetry, in which several photographs of the same area taken from different angles are combined to obtain a DEM, has been used in the HKH with satellites like Corona, ASTER, and SPOT5 (Hubbard et al. 2000; Berthier et al. 2007; Bolch 2007; Gardelle et al. 2012). The vertical resolution ranges from 10–20 m (Fujita et al. 2008; Nuimura et al. 2012) and the horizontal resolution from ~30–90 m. Airborne photogrammetry provides higher resolution elevation maps but has rarely been used in the HKH.

Glacier mass changes cause gravity field variations which can be measured by the GRACE twin satellites. This technique, called gravimetry, can be used to infer glacier mass change but it has marked limitations. The changes can also be due to changes in snow mass, isostatic response, and tectonic movements. Meltwater storage in the ground also influences gravimetric measurements leading to an underestimation of the glacier mass balance (Jacob et al. 2012; Matsuo and Heki 2010). Nevertheless, the gravimetry results published by Jacob et al. (2012) showed good agreement with results obtained by differentiating satellite-derived DEMs by Gardelle et al. (2013).

The presence of debris cover presents the greatest problem in using remote sensing to map glaciers. In general, glacier maps are obtained from spectral ratios combined with DEM information. Thermal emission data can also be useful since debris on glaciers is generally colder than usual rock surfaces. But spectral data alone are not sufficient to distinguish a debris-covered ice surface from a normal rock surface (Racoviteanu et al. 2008) and manual inspection of images is still necessary. Such kinds of analysis are time consuming and influenced by subjective errors.

Unmanned aerial vehicles were used recently above the debris-covered tongue of the Lirung glacier in Nepal (Immerzeel et al. 2014a) to picture the glacier front and reconstruct its surface velocities and volume change by stereo-photogrammetry. This technique permits quick sampling and can be used for glaciers that are difficult to access on foot. However, the spatial cover only ranges a few kilometres and the technique cannot be used to map high-altitude accumulation areas.

Snow

Although knowledge of the snow cover area does not provide information on snow depth or snow water-equivalent it is easier to monitor and remains useful for hydrological modelling. The snow cover extent can be monitored by differentiating spectral bands from satellite-based measurements. The methods rely on assumptions about emission or reflectivity from the snow surface as well as radiative properties of clouds which can influence the snow cover estimation. Links between elevation and snow line and snow persistence, and snow cover and slope orientation, can be obtained by combining snow cover maps with a digital elevation model. To date, only a few studies have validated remote-sensing snow cover results with field measurements.

Snow cover can theoretically be estimated using in situ or remotely sensed information about snow precipitation but the methods remain poorly developed (e.g., TRMM, APHRODITE) (Bookhagen and Burbank 2010; Ménégoz et al. 2013) and not yet reliable. Attempts have also been made to infer snow depth using data obtained from satellite based sensors and microwave technology. Shaman and Tziperman (2005) used the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) satellite data to estimate snow depth over the Tibetan plateau between 1978 and 1987.

Modelling

Glacier dynamics

The numerical methods used to model past or future evolution of glaciers range from simple statistical relationships linking a few climatic parameters to glacial change, to complex models including most physical processes such as ice rheology, fracturing, and assessment of energy transfer at the boundaries of the ice mass. Statistical and empirical approaches have also been used to project future glacier wastage by linking the mass balance to simple parameters such as temperature (e.g., Shi et al. 2010; Cogley 2011). However, in order to fully cover all the relevant processes governing glacier change, modelling approaches should include five aspects: accumulation (based on climate data or climate modelling); melt modelling; glacial flow; glacier water storage (refreezing, groundwater, lakes); and effects of glacial lakes on melt.

Melt processes can be assessed using simple approaches with information on measured mass balance gradients (Racoviteanu et al. 2013). More complex assessments use degree-day or improved degree-day approaches (Immerzeel et al. 2012a, 2013; Pellicciotti et al. 2012; Shea et al. 2015). Improvements in the degree-day approaches to incorporate relevant melt processes lead to fully distributed energy-balance models, but there are very few such studies on Himalayan glaciers (e.g., Shrestha et al. 2015) as they can only be applied over limited areas due to the high requirements for spatial resolution and calculation capacity.

Glacial flow must be incorporated into the models before they can be used to accurately project or reconstruct glacial evolution. Ice flow modelling can be done either with simplified parameterizations (Immerzeel et al. 2012a, 2013; Shea et al. 2015) or with complex models; from one-dimensional Stokes models (Zhang et al. 2013b) to fully resolved three-dimensional Stokes models. None of these have been applied so far at the basin scale for Himalayan glaciers. In large scale studies, where spatial resolution does not allow for the simulation of glacial flow, parameterizations are used (Huss et al. 2010; Lutz et al. 2013).

Snow and snow water equivalent

Modelling historical change and future evolution of snow cover is important for assessing the impact of climate change on the hydrological regime. For snow cover modelling to be accurate, it has to include modelling of snow precipitation and accumulation and modelling of snow depletion. Modelling of accumulation is done using precipitation estimates from climate models but there are large uncertainties. Improvements might be obtained by downscaling global scale climate models with regional climate models (RCM) which are able to provide precipitated snow water equivalent (e.g., MAR, WARF) (Collier and Immerzeel 2015). The models should be validated against precipitation measurements obtained from in situ and/or remote sensing methods. Model results could also be compared to re-analysis products like the European Centre for Medium-Range Weather Forecasts ERA-Interim or APHRODITE (e.g., Ménégoz et al. 2013). However, the magnitude of snowfall tends to be hugely underestimated by both remote sensing and surface rain gauges.

Snow pack depletion can be modelled by starting from the snow cover or snow water-equivalent accumulation (inferred from precipitation models or from measurements). Snow undergoes numerous complex processes such as melt, sublimation, condensation, compaction, metamorphosis, wind displacement, and avalanching. Whereas the commonly used degree-days approaches infer the snow melt from observed statistical relationships between melt and temperature, snow models should include all the relevant processes in order to accurately project snow pack evolution under changing climatic conditions. In situ measurements of snow pack evolution have to be compared with outputs from models in order to identify which processes are relevant, but up to now only a few studies in the HKH have done this (e.g., Shrestha et al. 2012; Nepal et al. 2014).

Glacier and snow status and projections

Glacier observations

Various studies have been carried out to gather information about the glaciers in the HKH. The World Glacier Monitoring Service (WGMS) collects and provides information gathered during field measurement campaigns, including stake measurements, geodetic mass balance, and front positions. Mass balance has been measured on several glaciers in the Indus, Ganges, and Brahmaputra basins but the time coverage of these monitoring programmes is poor and they are unevenly distributed.

Many glaciological studies have been carried out by the Geological Survey of India (GSI) in the Indus basin, mainly in the Indian part of the catchment. The front variations of several glaciers in Himachal Pradesh and Jammu and Kashmir were monitored by GSI in the 1970s and 1980s; mass balance measurements were carried out in the same period but less frequently and for fewer glaciers. The registered time series remain short (a few years). New measurement programmes were started around 2000 but they are still ongoing and focus on glaciers that were not monitored previously. In Nepal, some single measurements of yearly mass balance were recorded sporadically between 1978 and 1979; new glaciological programmes were started from 2007, some including previously measured glaciers. On the Tibetan plateau, mass balance programmes started in 2005 on glaciers that contribute to the Brahmaputra outflow.

The characteristics of the most important in situ glaciological mass balance measurement programmes in the Indus, Ganges, and Brahmaputra river basins are given in Table 5.

Many more studies have been carried out on glacial mass balance and change using remote sensing methods. The values given for different parts of the HKH by a number of more recent studies, and the methods used, are shown in Table 6.

Table 5: **In situ mass balance measurements of glaciers in the Indus, Ganges, and Brahmaputra river basins (source: WGMS)**

Indus (11 glaciers)	Stakes survey (period)	Geodetic survey (period)	Reference	Mean mass change rate[a] (mwe yr^{-1})
Siachen (Pakistan)	Hydrological method (1986–1991)		Bhutiyani (1999)	-0.51
Shisram (India – Jammu and Kashmir)	1983–1984		Dyurgerov and Meier (2005)	-0.29
Rulung (India – Jammu and Kashmir)	1980–1981		Geological Survey of India	-0.11
Kolahoi (India – Jammu and Kashmir)	1983–1984		Dyurgerov and Meier (2005)	-0.27
Neh Nar (India – Jammu and Kashmir)	1975–1984		Dyurgerov and Meier (2005)	-0.54
Hamtah (India – Himachal Pradesh)	2000–2009		Geological Survey of India	-1.60
Chhota Shigri (India – Himachal Pradesh)	2002–2010	1988 2002–2010	Wagnon et al. (2007); Azam et al. (2012, 2014b)	-0.67
Shaune Garang (India – Himachal Pradesh)	1981–1991		Dyurgerov and Meier (2005)	-0.36
Gara (India – Himachal Pradesh)	1974–1983		Raina (2009)	-0.37
Naradu (India – Himachal Pradesh)	2000–2003		Koul and Ganjoo (2010)	-0.40
Gor Garang (India – Himachal Pradesh)	1976–1985		Dyurgerov and Meier (2005)	-0.43
Ganges (9 glaciers)				
Tipra Bank (India – Uttarakhand)	1981–1988		Dyurgerov and Meier (2005)	-0.25
Dokriani (India – Uttarakhand)	1992–1006 1997–2000	1962→1995	Dobhal and Mehta (2010)	-0.32
Dunagiri (India – Uttarakhand)	1984–1990		Dyurgerov and Meier (2005)	-1.04
Chorabari (India – Uttarakhand)	2003–2009		Dobhal et al. (2013)	-0.74
Rikha Samba (Nepal – Daulaghiri)	1998–1998	1994 →1974 1999 → 2000	Fujita et al. (2001b)	-0.46
Yala (Nepal – Langtang)	1982–1984–1996	1982 → 1994 1982 → 1996 1996 → 2009	Fujita and Nuimura (2011)	-0.58
AX010 (Nepal – Khumbu)	1995–1999	1978 → 1991 1978 → 1999 1991 → 1996 1996 → 1999 1999 → 2008	Fujita et al. (2001a)	-0.61
Mera (Nepal – Khumbu)	2007–2012		Wagnon et al. (2013)	-0.10
Pokalde (Nepal – Khumbu)-	2009–2012		Wagnon et al. (2013)	-0.72
Brahmaputra (11 glaciers)				
Kangwure (China – Tibet)	1991–1993 2009–2010	1974 → 2008	Yao et al. (2012)	-0.66
Changmekhangpu (India – Sikkim)	1979–1986		Dyurgerov and Meier (2005)	-0.26
24K (China – Southeast Tibet)	2007–2008		Yang et al. (2008)	-1.22
Demula (China – Southeast Tibet)	2006–2010		Yang et al. (2008)	-1.02
Parlang Zangbo (China – Southeast Tibet) 4 glaciers included	2005–2010		Yao et al. (2012)	-0.78 -1.70 -0.92 -1.02
Zhadang (China – Tibet, Nyaingentanglha range)	2005–2010		Zhang et al. (2013a)	-0.57
Zhongxi (China – Tibet, Nyaingentanglha range)	2007–2010		Yao et al. (2012)	-0.52
Gurenhekou (China – Tibet, Nyaingentanglha range)	2005–2010		Yao et al. (2012)	-0.31

[a] mwe = metres water-equivalent

Table 6: **Changes in mass balance calculated using remote sensing methods from various studies in the HKH region during recent years**

Region	Study	Time range	Method	Surface height change (m yr[-1])	Clean-ice	Debris-covered	Mass balance (mwe yr[-1])
Hindu Kush and Karakoram (Indus)	Kääb et al. (2012)	2003–2009 3 methods, 3 results	DEM differentiation	Oct–Nov -0.26 ± 0.06 Feb–Mar -0.10 ± 0.06	-0.78 ±0.16	-0.76 ± 0.16	-0.23 ± 0.05 -0.19 ± 0.04 -0.21 ± 0.05
	Gardner et al. (2013)	2003–2008	DEM differentiation				-0.10 ± 0.18
Karakoram	Gardelle et al. (2012)	1999–2008	DEM differentiation				+0.11 ± 0.22
Himachal Pradesh (HP), Uttarakhand, and west Nepal (Indus and Ganges)	Kääb et al. (2012)	2003–2009 3 methods, 3 results	DEM differentiation	-0.38 ± 0.06 -0.38 ± 0.06	-1.20 ± 0.33	-1.02 ± 0.29	-0.34 ± 0.05 -0.30 ± 0.04 -0.32 ± 0.06
West Himalayan (Indus and Ganges)	Gardner et al. (2013)	2003–2008	DEM differentiation				-0.48 ± 0.17
East Nepal and Bhutan (NB) (Ganges and Brahmaputra)	Kääb et al. (2012)	2003–2009 3 methods, 3 results	DEM differentiation	-0.38 ± 0.06 -0.38 ± 0.06	-2.30 ±0.53	-1.53 ± 0.43	-0.34 ± 0.08 -0.26 ± 0.07 -0.30 ± 0.09
Central Himalayas (Ganges)	Gardner et al. (2013)	2003–2008	DEM differentiation				-0.40± 0.23
Eastern Himalayas	Gardner et al. (2013)	2003–2008	DEM differentiation				-0.80 ± 0.22
All Hindu Kush and Himalaya	Jacob et al. (2012)	2003–2010	Gravimetric				-5 ±6 Gt yr[1]

The evolution of glaciers in the Indus, Ganges, and Brahmaputra basins is not homogeneous. Overall, the results of in situ mass balance measurements (Table 4) and remote sensing studies (Table 7 and Bolch et al. 2012; Yao et al. 2012) indicate that glaciers are tending to retreat and lose mass in all three basins, but the rate varies.

Most glaciers in the Indus basin have been retreating from the 1980s to today, with those in Himachal Pradesh losing mass more strongly. However, glaciers in the Karakoram range have mostly been at equilibrium or gaining mass over the last decades as shown by remote sensing studies ($+0.11 \pm 0.22$ mwe yr^{-1}) (Gardelle et al. 2012; Jacob et al. 2012); this effect is known as the 'Karakoram anomaly'. Bolch et al. (2012) also reported that the front of 25% of glaciers in the Karakoram were advancing or stable between 1976 and 2007. This anomaly could be the result of increased winter accumulation in the region (Tahir et al. 2011), with the high altitude catchments less affected by climate change because temperatures remain below freezing. Some of the glaciers in the Karakoram have been seen to surge recently, which may result from a combination of increased accumulation in the upper part and a slight increase in ablation rate in the lower part.

The glaciers in the Ganges basin are losing mass at a moderate rate in Nepal and Himachal Pradesh (~ -0.3 mwe yr^{-1}, Kääb et al. 2012). This is confirmed by the many remote sensing studies conducted in the region. In the Khumbu region, for example, Gardelle et al. (2013) measured an annual rate of mass loss of -0.26 ± 0.13 mwe yr^{-1} between 2000 and 2011; Bolch et al. (2008) a rate of -0.33 mwe yr^{-1} for 1962 to 2002; and Nuimura et al. (2012) and Gardner et al. (2013) a slightly higher rate of -0.40 ± 0.25 mwe yr^{-1} from 1992 to 2008 and 2003 to 2009, respectively. The glaciers in the Ganges basin are expected to be more sensitive to climate change since they experience accumulation at roughly the same time as ablation during the summer monsoon. Any change in the snow line elevation as a result of temperature change will have a marked effect, with the elevation of the snow cover determining the percentage area of glaciers exposed to strong ablation induced by intense solar insulation. This could explain the more rapid recession rate observed in these regions (Bolch et al. 2012).

The glaciers in the Brahmaputra basin are losing mass strongly in the eastern Himalayas (Parlang Zangbo mountains ~ -1.1 mwe yr^{-1}) and moderately on the Tibetan Plateau (~ -0.4 to -0.55 mwe yr^{-1}) (Yao et al. 2012).

The in situ mass balance measurements of glaciers of the Parlang mountains showed the biggest negative trend in recent years (-1.02 mwe yr^{-1}) (Yao et al. 2012). Even though the glaciers in the central Himalayas are located on the leeward side of the range, in situ mass balance measurements suggest similar losses to those on the windward side in the Ganges basin.

A review of debris-covered glacier changes in the HKH region shows a similar pattern to that for clean ice glaciers, with mostly neutral mass balances in the Karakoram and negative mass balances in other regions, and the highest loss rates in the northern part of the Central Himalayas (Figure 10; Scherler et al. 2011).

Glacier simulations

Numerical modelling of glacier evolution has mainly focused on evaluating mass balance and evolution at a regional scale. Such studies usually rely on simplified parameterizations in order to be able to cover large areas. Table 7 shows the results obtained by various simulations of future glacier mass balance for the HKH region. All studies project a decline in glacier ice mass throughout the 21st century with an extensive retreat towards new equilibrium states with high-elevation frontal lines rather than complete disappearance. In most scenarios, the rate of ice loss decreases towards the end of the simulation period, which indicates a shift towards equilibrium conditions (Shea et al. 2015). The large differences between the results emphasizes the uncertainty of the projections, which mainly stems from the different scenarios assumed for greenhouse gas emissions, different model parameterization approaches, and poor knowledge of initial glacial volumes (generally parameterized) due to the sparse network of in situ measurements. In the Himalayas, glacier evolution will also be influenced by the changes in monsoon precipitation patterns, but as yet the climate scenarios cannot provide a clear estimate of the changes in precipitation amounts. In the Karakoram, especially, the poor understanding of observed glacier dynamics suggests large uncertainties remain in future projections of glacier change (Marzeion et al. 2012; Radić et al. 2014; Zhao et al. 2014).

Figure 10: **Regional distribution of debris-covered and stagnating glaciers**

a) Location of glaciers (circles) grouped by region. Histograms give relative frequencies (y-axis, 0–40%) of debris cover (x-axis, 0–100% in 5% bins). Number of studied glaciers is given in upper-right corner, measured frontal changes in parentheses. Globe depicts location of subset and atmospheric transport directions.
b) Regional distribution of mean annual frontal changes. Boxes give lower and upper quartiles and median (notches indicate 95%-confidence intervals). Whiskers extend 2.5 times the interquartile data range, crosses lie outside this range. Numbers left of boxes indicate percentage of advancing/stable (top) and retreating (bottom) glaciers.

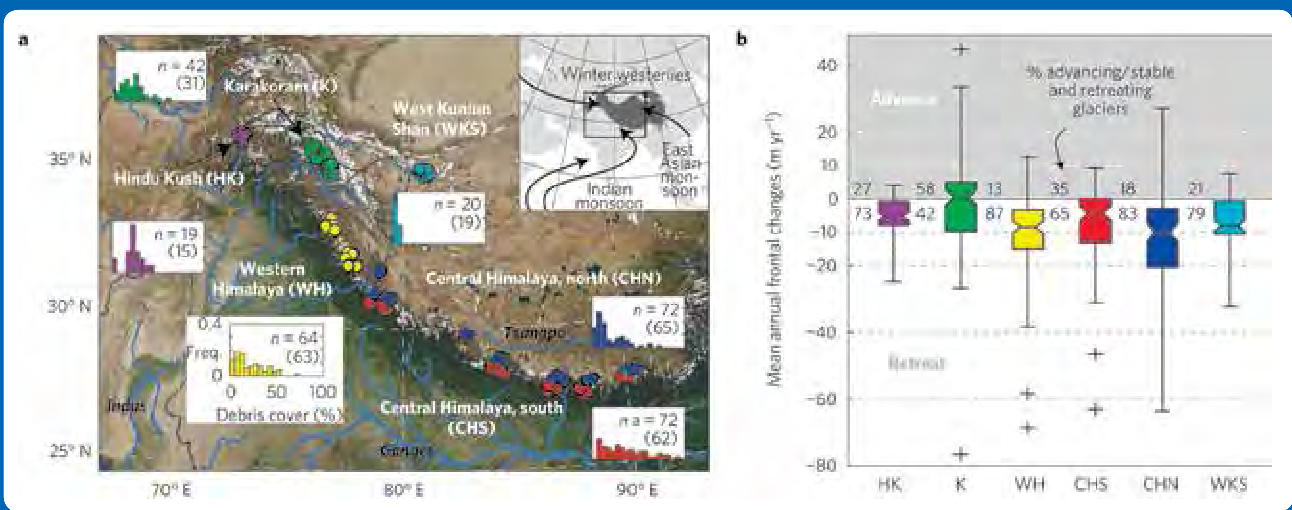


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Table 7: **Regional modelling studies of future glacier change in the HKH region**

Study	Region	Time period	Remarks	Method	Mass balance (mwe yr^{-1})	Volume change
Radić et al. (2014)	Southwest Asia	2003–2100	Initial volume 4,475 km^3	Degree-day; surface volume scaling	-0.68	+4 to -75% RCP4.5 -34 to -87% RCP8.5 (2006-2100)
	Southeast Asia		Initial volume 1,852 km^3		-0.64	-85 to -20% RCP4.5 -60 to -90% RCP8.5
Zhao et al. (2014)	Hindu Kush and Karakoram	2000–2050	RegCM3 climate projection scenario	ELA temperature-precipitation dependence; volume scaling		-0.47 to-0.26% yr^{-1} -23.5 to -13% (50 years)
	Western Himalayas					-0.79 to -0.47% yr^{-1} -39.5 to -23.5% (50 years)
	Central Himalayas					-1.18 to -0.53% yr^{-1} -59 to -26.5% (50 years)
	Eastern Himalayas					-0.96 to -0.69% yr^{-1} -48 to -34.5% (50 years)
	Hengduan Shan					-1.41 to -0.68% yr^{-1} -70% to -34% (50 years)
Marzeion et al. (2012)	Southeast Asia	2100				-60 to -70% RCP4.5, RCP8.5
Lutz et al. (2014)	Upper Indus	2008–2050	CMIP5 multi-model ensembles for RCP4.5 and RCP8.5	Basin-scale parameterization for glacier cover evolution, based on degree-day modelling and volume-area scaling (Lutz et al. 2013)		Surface area remaining in 2050 compared to 2007: 80–76% RCP4.5 72–77% RCP8.5
	Upper Ganges					Surface area remaining in 2050 compared to 2007: 55–64% RCP4.5 52–63% RCP8.5
	Upper Brahmaputra					Surface area remaining in 2050 compared to 2007: 58–69% RCP4.5 55–64% RCP8.5

Two detailed studies carried out projections of glacier evolution at a sub-basin scale. Immerzeel et al. (2013) compared the evolution of the Baltoro glaciers (upper Indus basin, India) up to 2100, and Langtang glaciers (Ganges basin, Nepal) under RCP4.5 and 8.5 emission scenarios from the CMIP-5 ensemble. Simulations showed a strong retreat, decline, and disintegration of glacier tributaries in both cases. There was a significant difference in projected glacier extent depending on the scenario and climate model used. In the extreme RCP8.5 scenario, the much smaller Langtang glaciers showed an area retreat of 54% in 2100 and the larger Baltoro glaciers 33%, with volume changes similar to the areal changes. In comparison, the glacier area shrank by 37% in the Langtang valley over the period 2071–2100 under the RCP4.5 scenario.

Shea et al. (2015) simulated the evolution of the Khumbu glaciers (Ganges basin, Nepal) using the CMIP5 ensemble scenarios RCP4.5 and RCP8.5 up to 2100. The projected mean total glacial volume loss was -83.7% for RCP4.5 and -94.7% for RCP8.5, with a range from -70 to -99%. Changes below 6,500 m were highly dependent on the chosen scenario; no changes were projected in glacier volume above 7,000 m. In the best case scenarios, the glaciated area near the current equilibrium-line altitude (ELA) of 5,500 masl was projected to decline by as much as 80%, with thinning below 5,750 m. Debris-covered termini may see area reductions of 40% by 2100. In RCP8.5, the most extreme scenario, glaciers below 6,500 m were essentially eliminated by 2100.

Lutz et al. (2014) projected basin-averaged glacier cover changes up to 2050 using a parameterization of future glacier changes. They projected decreases of 20 to 28% for the Indus basin, 36 to 48% for the Ganges basin, and 31 to 45% for the Brahmaputra basin.

Snow cover observations and projections

Very few studies have been carried out with in situ measurements of snow cover in the Indus, Ganges, and Brahmaputra basins. Brown (2000) used measurements on the Tibetan plateau since 1800 from the Chinese measurement network to reconstruct trends in snow cover area in the northern hemisphere. In two recent studies, automatic snow height sensors were installed on measurement sites in the HKH. Measurements on the Chhota Shigri glacier in India are briefly described by Azam et al. (2014a, b) and measurements in the Langtang catchment in Nepal by Immerzeel et al. (2014b). Sonic height measurements have also been made at the Pyramid station (EVK2CNR) in Khumbu, Nepal (Shrestha et al. 2012). The Snow and Avalanche Study Establishment of India is running a few dedicated snow meteorological stations in Jammu and Kashmir and Himachal Pradesh.

Numerous remote sensing studies have been carried out to monitor snow cover at a sub-basin scale in the HKH over different periods using different satellite products and methods; a selection of these is shown in Table 9. There are very few reports of long-term studies, or of large scale studies covering the entire Himalayan range.

Snow cover monitoring on a large regional scale started only recently when satellite data became available so it isn't possible to establish long-term trends; reported studies cover a maximum of ten years (Table 8). Two studies tentatively mapped snow cover over the HKH using MODIS satellite products: one by ICIMOD for 2002 to 2010 (Gurung et al. 2011) and one by Immerzeel et al. (2009) for 2000 to 2008. Neither showed any clear temporal change in snow cover area over the whole HKH region. A remote sensing study by Tahir et al. (2011) showed a slight increase in snow cover in the Hunza basin (upper Indus) between 2000 and 2009, which may be the result of an increase in winter precipitation caused by westerly circulation.

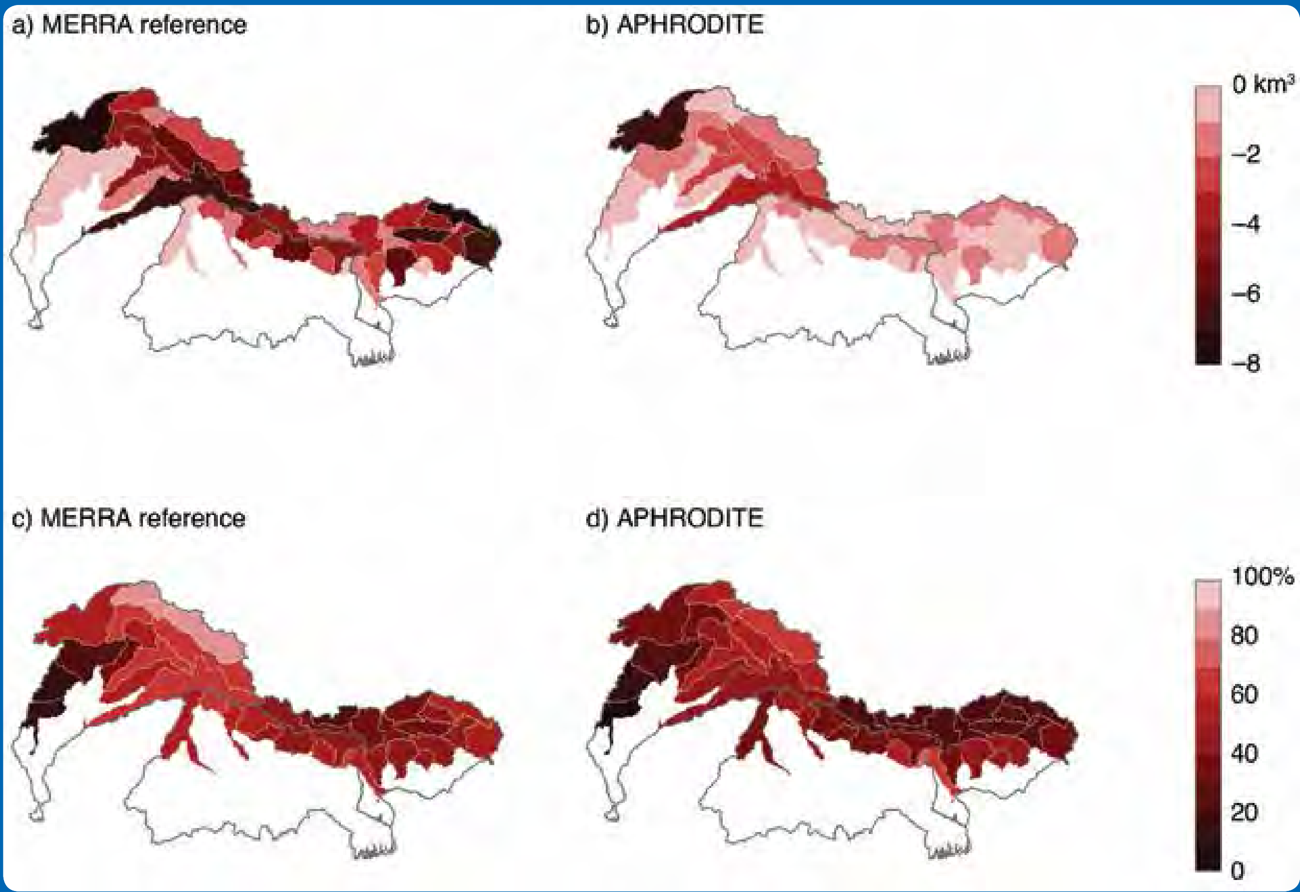
There is a possible negative feedback between winter snow cover on the Tibetan plateau and monsoon intensity. Increased snowfall produces a larger Tibetan plateau snowpack which persists through the spring and summer and weakens the intensity of the South Asian summer monsoon. However, Immerzeel et al. (2009) showed that this had recently changed to a positive relationship in the western Himalayas.

Few studies focus on future snow cover trends. Snow cover evolution is linked to precipitation, and climate model projections of future trends in precipitation are very uncertain. Furthermore, the presence of the negative feedback between monsoon and snow cover on the Tibetan plateau complicates the projection of future trends in snow cover; deeper insight into the precipitation patterns and processes in the Himalayas is needed. A few hydrological studies have estimated the future evolution of snow cover in the HKH using snow precipitation estimates prepared by downscaling outputs from GCMs (Immerzeel et al. 2012a). A study by Viste and Sorteberg (2015) used gridded products for historical precipitation and CMIP5 GCMs estimated changes in rainfall and snowfall to project snow cover in the Indus, Ganges, and Brahmaputra basins (Figure 11). The GCM runs for RCP8.5 projected reductions in annual snowfall of 30–50% (Indus), 50–60% (Ganges), and 50–70% (Brahmaputra) by the end of the 21st century. The snowline rose by 400–900 metres, depending on the region.

Table 8: **Selected sub-basin scale studies on snow cover in the HKH**

Study	Region	Mapping satellite	DEM method	Period	Slope/ aspect	Climate study
Kaur et al. (2009)	Baspa (upper Indus)	Resourcesat-I	SRTM	2004–2007	No	No
Jain et al. (2009)	Satluj, Chenab, Ravi, Beas (upper Indus)	MODIS	USGS	2003–2004	Yes	Yes
Kripalani et al. (2003)	Western Himalayas	INSAT	Not given	1986–2000	No	Yes (NCEP/NCAR) monsoon rainfall from the Institute of Tropical Meteorology
Krishna (2005)	Tista (Sikkim, Ganges basin)	Indian Remote Sensing Satellite	Not given	1992–1997	Not given	No
Negi et al. (2009)	Kashmir	AWiFS Resourcesat-I	Topographic maps	2004–2007	Not given	No
Pu andXu (2009)	Tibetan Plateau	MODIS	USGS	2000–2006	No	Pacific-East Asian Monsoon Index

Figure 11: **Projected future changes in snowfall in sub-basins of the Indus, Ganges, and Brahmaputra basins** (a) absolute change (km^3) with reference to MERRA reference snowfall; (b) absolute change (km^3) with reference to APHRODITE snowfall; (c, d) percentage relative change with reference to MERRA and APHRODITE. Multi-model means for 2071–2100 with respect to 1979–2008.



Source: Viste and Sorteberg 2015

Key limitations

A number of key limitations can be identified in the understanding of cryosphere dynamics in the HKH region.

Glacier change

In situ observations

- Not enough long-term observations and insufficient spatial coverage
- Insufficient representation of climatic conditions and glacier types
- No consensus on measuring methods
- Lack of in situ measurements of glacier volume to validate the widespread use of area-volume parameterizations
- Shortage of energy balance measurements in the region

Remote sensing observations

- IceSAT: uncertainty about penetration of radiation into the snow and reliance on assumptions of density to determine glacier losses
- Airborne sensing is efficient but poorly used (LiDar, photogrammetry)

Glacier models

- Lack of relevant input information, for example glacier thickness, climatic data
- Precipitation gradients and snow/rain transitions affect glacier dynamics and need more emphasis in studies
- Difficulties in assessing processes in debris-covered glaciers
- Few studies have focused on modelling future glacier change, especially in the HKH region
- Spatial distributions in debris thickness and thermal conductivity are nearly impossible to measure
- Many simplifications need to be applied due to a lack of data or knowledge, for example degree-day modelling/ volume-area scaling and simple parameterizations due to poor knowledge of processes (energy balance in debris covering of glaciers, complex ice melting processes in debris-covered glaciers)

Changes in snow cover

- Models generally unable to simulate snow processes; poor understanding of precipitation processes leads to unreliable projections
- Poor coverage of in situ measurements in the HKH
- Important phenomena such as the snow-rain transition line and precipitation gradients poorly understood and monitored
- No information on snow water equivalent
- Very sparse snow precipitation records at high elevations
- Role of ground sublimation and blowing snow sublimation in the HKH unknown

Summary

Scientific literature on the state of the cryosphere in the HKH has increased rapidly as has the state of knowledge, although it is still relatively weak. The current state of knowledge can be summarized as follows:

- Glaciers in most of the HKH region are losing mass in response to climate warming. Glaciers in the Karakoram region have been expanding in recent years, but the underlying reasons for this anomaly are not yet fully understood.
- Total ice volume measurements vary considerably because of the difficulties in measuring ice volumes in situ or from remote sensing products, and uncertainties in volume-area scaling relationships.
- No strong trends have been observed in snow cover; minor increases or decreases have been reported for different areas.
- Little is known about the distribution of permafrost in the HKH region and its importance for regional hydrology remains unclear.
- Estimates of future glacier volume and area are uncertain and hampered because thus far modelling of ice flow has been restricted to catchment scale studies. However, strong decreases in glacier volume and area are projected for the entire HKH region.

Hydrological Regime

Approaches to quantifying the hydrological regime

Types of models

Hydrological models are commonly used to assess the hydrological properties of catchment areas, from small individual catchments to entire river basins. These models are simplified representations of the various components of the hydrological cycle. There is a wide range of models based on different concepts and with different levels of detail depending on the purpose. The simplest models are black box or empirical models that are based on observed relationships rather than simulated physical processes. They mainly emphasize correctly simulating the precipitation-discharge relationship. Deterministic or parametric models are based more on physical processes and represent hydrological systems as a collection of storages, and functions that transfer water between storages. They usually simulate the most important hydrological processes while keeping the number of model parameters limited. These models are more complex; they have detailed spatially distributed descriptions of physical parameters and need a large number of input variables. They can include both energy-balance modelling and water balance modelling. Because cryosphere processes are important in the Indus, Ganges, and Brahmaputra basins, the quality of results generated with the models largely depends on their representation of these processes.

Input data

Climate is the major driving force in the hydrological cycle, and climate data are the most important input for simulation models. The type of data used depends largely on the scale of the application. Catchment scale assessments often use station meteorological data (Bocchiola et al. 2011; Ragettli and Pellicciotti 2012; Ragettli et al. 2013; Soncini et al. 2015), whereas assessments on larger scales often use gridded regional or global climate datasets (Lutz et al. 2014). The large horizontal and vertical variability in climatic variables in mountain regions leads to challenges in extrapolating data from individual stations or downscaling to the required spatial resolution from coarser scale gridded datasets. The simplest models use air temperature and precipitation data from a single station, assuming the data measured there to be representative for the entire catchment. Distributed models use spatially interpolated data, corrected for elevation differences. Models that include simulation of the energy balance require data on more fluxes, including long-wave radiation, short-wave radiation, latent heat flux, and albedo.

Most approaches use a digital elevation model (DEM) to provide elevation and hillslope data. Depending on the approach, digitized glacier outlines are often used, sometimes with a distinction between debris-covered and debris-free glaciers. Models that include evapotranspiration require data on soil properties and vegetation type or land use. Often, there are no local data for vegetation type, soils, or land use and modellers rely on global datasets for these. Modelling of future scenarios requires downscaled GCM or RCM projections to force the model.

Process representation

Cryosphere processes can be simulated in different ways and a variety of hydrological modelling exercises have been conducted in the Indus, Ganges, and Brahmaputra basins using different approaches. Racoviteanu et al. (2013) used a simple ice ablation gradient model to estimate glacier melt in the Langtang catchment in the Ganges basin. Ablation gradient models assume a gradient of increasing glacier melt with lowering elevation starting at zero at the equilibrium line altitude (ELA) and based on field measurements. Different ablation gradients can be used for clean-ice glaciers and debris-covered glaciers. Another common approach used to simulate glacier and snow melt is the degree-day approach (Hock 2003), which is based on the relationship between air temperature and the amount of melt. A certain amount of melt water is assumed per positive degree. The advantage of this method is that it can be applied in many places because air temperature data is mostly available and relatively easy to interpolate to spatial fields. Enhanced degree-day models are also used to integrate more variables such as incoming radiation, aspect, or albedo in the model (Pellicciotti et al. 2005; Heynen et al. 2013). Glacier and snow melt can be simulated more accurately using models that include the energy balance. The amount of snow transported downslope through avalanching is often substantial and this is also simulated in some models (Bernhardt and Schulz 2010; Immerzeel et al. 2013; Ragettli et al. 2015). One of the components mostly disregarded in the models used in the HKH region is sublimation. This flux is difficult to measure and there are few if any observations available. At the same time, sublimation may constitute a significant component in the mountain water balance, especially in windy conditions (Wagnon et al. 2013). Similarly, the contribution of groundwater is difficult to observe and difficult to simulate, but this may also be an important component of the water balance (Andermann et al. 2012; Bookhagen 2012).

Historical and projected hydrological trends

Observed trends in streamflow

There are a number of studies that report analyses of observed discharge records and attempt to attribute the observed trends to observed meteorological trends. A study analysing streamflow trends from 19 stations in the upper Indus basin indicated that for highly glacierized catchments the discharge can be best correlated with temperature (Archer 2003). According to this analysis, summer flow in middle latitude catchments is predominantly influenced by the preceding winter precipitation, whereas runoff in catchments further downstream is controlled mainly by rainfall both in winter and the monsoon. Khattak et al. (2011) found that increasing trends in streamflow could be related to increases in mean and maximum temperature, in particular in the winter and spring seasons. Sharif et al. (2013) concluded that highly glaciated catchments in the upper Indus basin have decreasing trends in streamflow, whereas streamflow has increased in less glaciated catchments. They showed that flow is decreasing in early summer but increasing in winter.

Mukhopadhyay and Khan (2014b) showed that flows during the melting season in the central Karakoram increased between 1985 and 2010. The authors concluded that runoff can increase under neutral glacier mass balance conditions where both temperature and precipitation are increasing, i.e., the mass turnover of the glacier is increasing although the mass balance remains neutral.

Streamflow composition

Schaner et al. (2012) showed in a global study that the contribution of glacier melt to rivers in the HKH region is substantial. Lutz et al. (2014) estimated the contributions of glacier melt, snow melt, rainfall-runoff, and baseflow to total runoff for the entire upstream basins of the Indus, Ganges, and Brahmaputra using a distributed cryosphere-hydrological model. The results indicate that glacier and snow melt is more important in the upper Indus basin, and rainfall in the upper Ganges and upper Brahmaputra basins (Table 9).

A small number of published studies have estimated the composition of streamflow in different catchments or sub-basins in the Indus, Ganges, and Brahmaputra basins (Table 10). The results are difficult to compare due to the difference in concepts and approaches used and differences in application scales. Mukhopadhyay and Khan (2014b, 2015) estimated the contributions using hydrograph separation methods at locations with available streamflow records. Racoviteanu et al. (2013) estimated streamflow composition using a simple ice ablation model which was independently validated with stable water isotopes sampling. Their analysis showed that groundwater is already an important component close to the glacier outlets. Singh and Jain (2002) estimated streamflow composition using a basin scale water balance analysis with the inputs from glacier melt and snow melt estimated from remotely sensed snow cover imagery; Immerzeel et al. (2012b, 2013) used

Table 9: **Contribution to total runoff by different components averaged over the upstream basins**

Basin	Contribution to total runoff (%)			
	Glacier melt	Snow melt	Rainfall runoff	Base flow
Upper Indus	40.6	21.8	26.8	10.8
Upper Ganges	11.5	8.6	66.0	13.9
Upper Brahmaputra	15.9	9.0	58.9	16.2

Source: Lutz et al. 2014

Table 10: **Results of studies estimating streamflow composition at selected locations**

Site (river, location)	Reference	Period	Contribution (%)			
			Glacier melt	Snow melt	Rain runoff	Base flow
Satluj, Bhakra Dam	Singh and Jain 2002	1986–1996	59		41	-
	Lutz et al. 2014	1998–2007	27.6	20.8	38.6	13.0
Langtang Khola, Kyangjing	Immerzeel et al. 2012b	2001–2010	47.0	6.9	28.8	17.4
	Immerzeel et al. 2013	1961–1990	13.0	20.4	10.0	56.6
	Racoviteanu et al. 2013	1988–2006	58.3	41.7		
	Ragettli et al. 2015	2012–2013	26	40	34	-
	Lutz et al. 2014	1998–2007	52.5	12.8	25.0	9.7
Dudh Koshi, Rabuwa Bazar	Racoviteanu et al. 2013	1988–2006	7.4	92.6		
	Lutz et al. 2014	1998–2007	18.8	4.8	64.8	11.6
Lhasa basin	Prasch et al. 2013	1971–2000	3	41	56	-
Indus, Besham Qila	Mukhopadhyay and Khan 2014a	1969–2010	70	30		
	Lutz et al. 2014	1998–2007	67.3	17.6	7.1	8.0
	Mukhopadhyay and Khan 2015	1969–2010	25.8	44.1	-	30.2
Hunza, Dainyor bridge	Mukhopadhyay and Khan 2014a	1966–2010	74	26		
	Lutz et al. 2014	1998–2007	80.6	9.6	1.3	8.5
	Mukhopadhyay and Khan 2015	1966–2010	42.8	31.3	-	25.9
Baltoro watershed	Immerzeel et al. 2013	1961–1990	38.7	21.6	3.5	36.2
Shigar, Shigar	Soncini et al. 2015	1985–1997	32.9	39.5	27.6	

a distributed model including a simple ice flow model; Soncini et al. (2015) used a semi-distributed cryospheric-hydrological model fed and validated with in situ measurements; Ragettli et al. (2015) used a high-resolution process-oriented, distributed model; and Prasch et al. (2013) used a distributed process-oriented glaciohydrological model. The choice of model spatial resolution and amount of physical detail mostly depends on the scale of the application, i.e., the size of the catchment or basin in the simulation.

Long-term projections

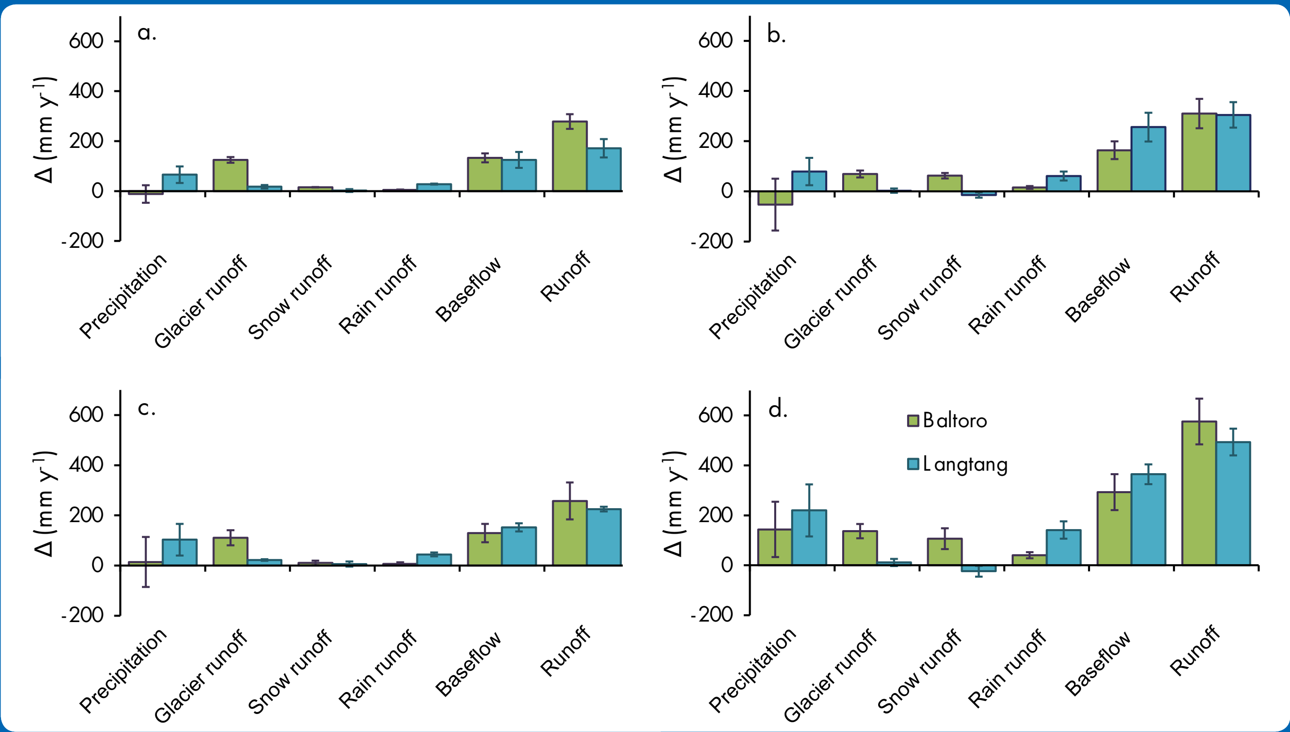
Total runoff

Immerzeel et al. (2013) projected runoff up to the end of the century in the Baltoro and Langtang catchments using different climate scenarios. The results indicated a consistent increase in total runoff in both catchments relative to 1961–1990 at least until 2100 under both RCP4.5 and RCP8.5 (Figure 12). The increase ranged from 172 mm yr—1 (Langtang, 31%) and 278 mm yr—1 (Baltoro, 46%) for RCP4.5 in 2021–2050, to 493 mm yr—1 (Langtang, 88%) and 576 mm yr—1 (Baltoro, 96%) for RCP8.5 in 2071–2100. Increase in glacier melt is the main cause of the strong increase in total runoff in the Baltoro catchment, where glacial melt is the largest component in total runoff, whereas increase in precipitation is the main cause of the increased total runoff in Langtang. Despite the differences in climate and hydrological regime, both catchments respond similarly to future climate change, especially for the first half of the 21^{st} century.

Soncini et al. (2015) found similar results for the Shigar watershed (which includes the Baltoro watershed) using results from three different GCMs under three different RCP scenarios (Figure 13). Increases in flow were projected until the end of the century under most scenarios; the authors speculated that there might be a potential slight decrease thereafter as ice volumes continue to decrease. In this catchment, changes in precipitation amount are unlikely to compensate for ice loss over the long run. The differences in streamflow changes under the three different RCPs are rather small.

Lutz et al. (2014) showed that a consistent increase in runoff is also expected at a large scale for the upstream Indus, Ganges, and Brahmaputra basins at least until 2050. For the upper Indus this is mainly due to increased

Figure 12: **Projected future changes in water balance components for the Baltoro and Langtang catchments.** All changes are relative to 1961–1990. Runoff is the sum of base flow, rain runoff, direct snow runoff, and direct glacier runoff. All values are expressed as a catchment average in mm yr−1. Changes are shown for RCP4.5 for the period 2021–2050 (a) and 2071–2100 (b) and for RCP8.5 for 2021–2050 (c) and 2071–2100 (d). The error bars show the standard deviation of four selected GCM runs



Source: Immerzeel et al. 2013

glacier melt, whereas for the Ganges and Brahmaputra the main driver is the projected increase in precipitation. The projections have a large uncertainty, especially for the upper Indus, because the projections for precipitation show contradicting patterns.

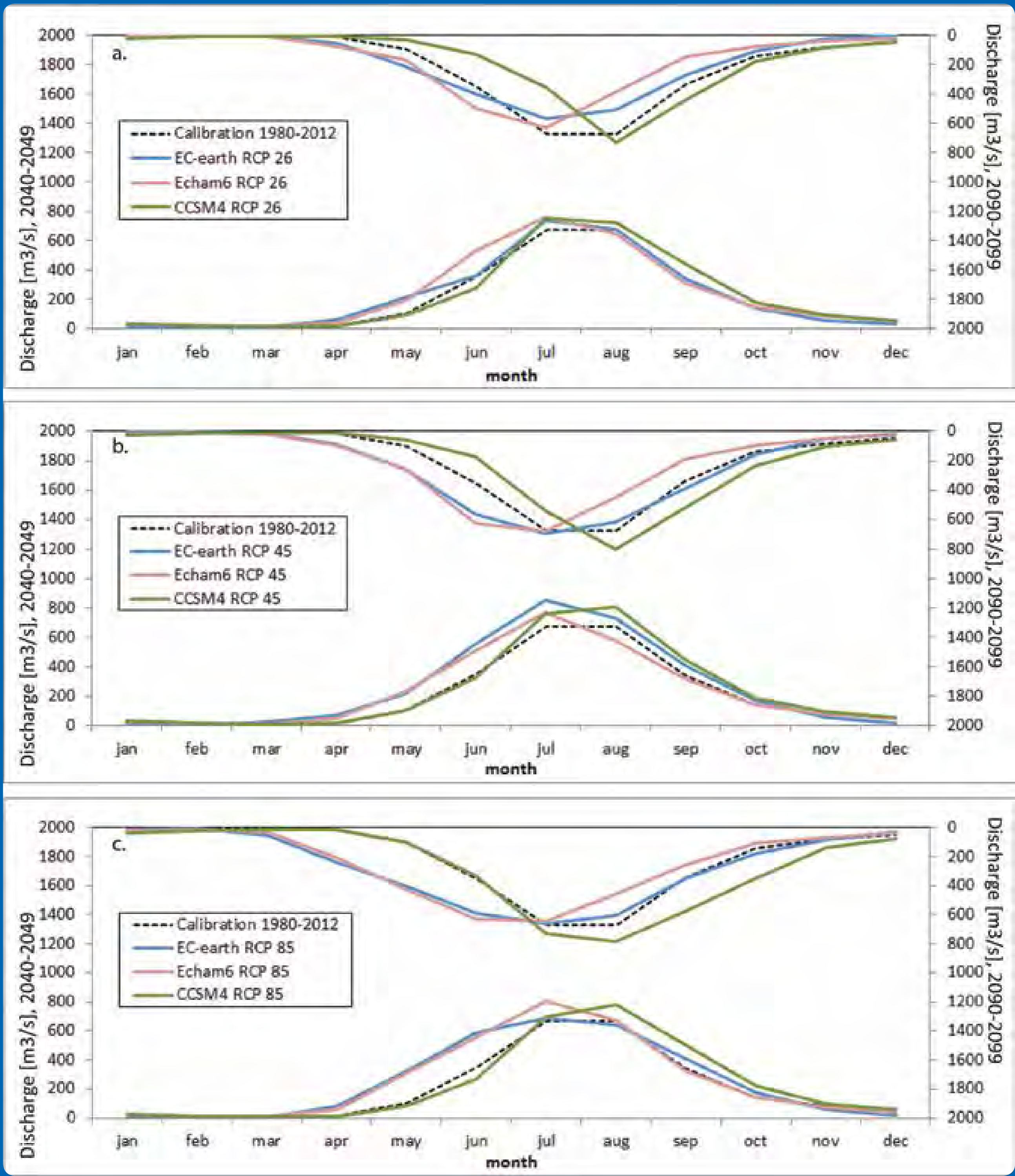
Simulated decadal mean runoff was relatively constant in projections until 2050 for the whole Hunza basin (Ragettli et al. 2013), but with strong contrasting changes in some of the sub-basins with flow volume in some decreasing by up to 50% due to the decrease in ice melt, and others increasing due to increasing snow melt related to increasing precipitation and temperatures.

Prasch et al. (2013) made hydrological projections until 2080 for the Lhasa basin by forcing a glaciohydrological model with the IPCC SRES scenarios. The contribution of ice melt to total runoff remains stable up to 2080, but with a slight increase during a short period in spring. In contrast, the contribution of snowmelt to river runoff generally decreases leading to a change in water availability. The increase in evapotranspiration with increasing air temperature will also reduce water availability.

Intra-annual changes in flow

The most important intra-annual changes in flow are related to earlier onset of melting and changes in precipitation patterns. Soncini et al. (2015) showed that in the Shigar catchment, the increased temperature and winter precipitation cause the increase in streamflow to begin earlier in the year due to earlier onset of glacier melt and snow melt (Figure 13). This is most dramatic for RCP8.5, where for two out of three GCMs the flow starts to increase significantly in April instead of June. Other RCPs also show this shift, and the shift becomes stronger towards the end of the century. However, one of the GCMs (CCSM4) showed a very different pattern, with decreasing flows in spring and a slight increase in flow for all other months.

Figure 13: **Projected discharges for three GCMs under the RCP2.6 (a), RCP4.5 (b), and RCP8.5 (c) scenarios**



Source: Soncini et al. 2015, © American Meteorological Society

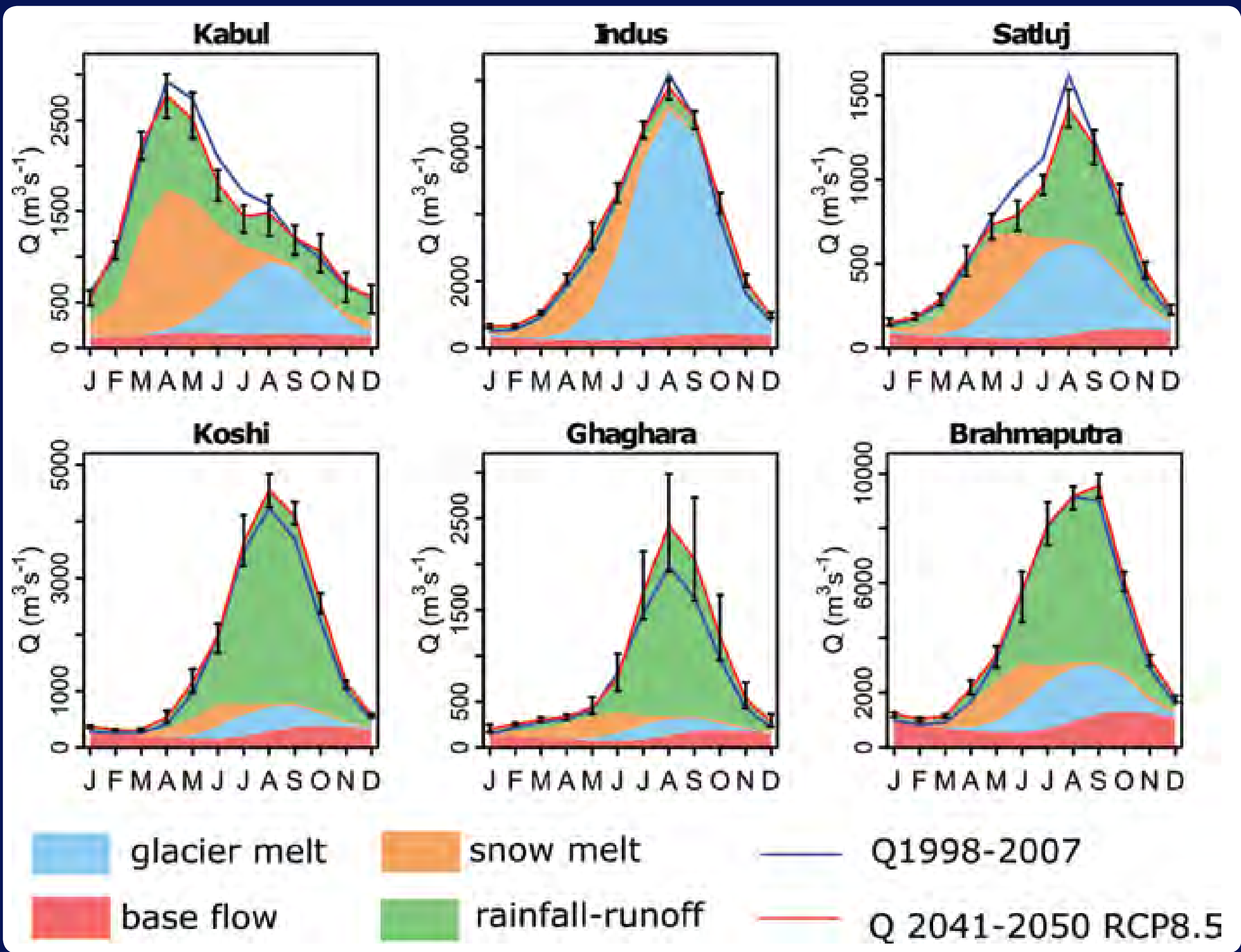
In their basin-scale study, Lutz et al. (2014) showed projected changes in the average annual hydrographs in 2041–2050 for some major rivers with sources in the HKH; the results show how different the responses to climate change are in rivers with different streamflow patterns (Figure 14). For example, the flow in the Indus river is dominated by temperature-driven glacier melt during the summer, and the uncertainty in future flow is relatively small as there is less uncertainty in future temperature change. On the other hand, the Kabul river has a much larger rainfall-runoff and snow component, leading to a larger uncertainty in future flow as a result of the large uncertainties in future precipitation. For the rivers in the Ganges basin (Koshi and Ghaghara in Figure 14) and the Brahmaputra, the absolute amounts of glacier melt and snowmelt do not change much, but their relative contributions decrease owing to the increased rainfall runoff. As a result, there is increased peak discharge in the monsoon season, with a large uncertainty in the magnitude of flow increase.

In the Hunza basin, June to September are the months most affected in the part where flow is expected to decrease (Ragettli et al. 2013). The annual peak runoff will occur earlier in the year than in the control period (in June/July instead of July/August). More water would also be available during the low flow season. As the amount of water discharged during the high flow season is reduced (July, August), less water is lost due to spilling.

Extreme events

There have been very few studies of changes in hydrological extreme events in the Indus, Ganges, and Brahmaputra basins. As an increase in precipitation is generally projected, it is reasonable to assume that precipitation extremes

Figure14: **Average annual hydrographs for the period 2041–2050 under RCP8.5 at the outlets of major rivers. The Kabul, Indus, and Satluj are in the Indus basin, the Koshi and Ghaghara in the Ganges basin, and the Brahmaputra in the Brahmaputra basin. Plots show the mean projected discharge when forced with a four GCM ensemble (red line) and the discharge for the reference period (1998–2007, blue line). Four streamflow components are shown for the future period: baseflow (red), glacier melt (blue), snow melt (orange), and rainfall runoff (green). The error bars indicate the variability in the projections.**



Source: Lutz et al. 2014

and associated extreme discharges may also increase. Soncini et al. (2015) used downscaled GCM data to force a semi-distributed model in order to carry out a basic analysis of changes in extreme discharges in the Shigar catchment. Most models indicated increased discharge for the flow return periods they analysed, indicating potentially heavier floods during the flood season from June to October.

Summary

The available hydrological knowledge in the HKH is based on historical streamflow measurements and hydrological modelling. Hydrological models are best suited to project future changes in the hydrology resulting from climate change. A variety of hydrological models are available that can use the range of data available on physical processes to model future changes at catchment to river basin scale. With climate warming, there is likely to be a shift towards more precipitation falling as rain instead of snow over the entire HKH region (except for the highest areas, where it will remain below freezing throughout the year). In rivers dominated by glacier and snow melt, it is likely that more water will become available in winter and especially spring due to the earlier onset of melting. However, where rainfall is an important contributor, the changes largely depend on the changes in precipitation in winter, which are uncertain. The main published findings on HKH hydrology show the following:

- The main uncertainties in hydrological modelling of historical periods in the HKH region stem from uncertainties in model input data, especially historical precipitation forcing.
- The large differences in future precipitation projected by different climate models makes future projections of hydrological changes very uncertain. The representation of the future extent in glacier cover is also a large source of uncertainty.
- Detailed modelling in the region is limited to the catchment scale.
- Increasing trends in streamflow in the most upstream glaciated regions seem to be related to increasing temperatures; streamflow trends at lower altitudes seem to be more controlled by trends in precipitation.
- The Indus river receives the largest proportion of its water from glacier and snow melt, whereas the Ganges receives most of its water from rainfall runoff.
- It seems likely that a consistent increase in streamflow will occur in the HKH river basins during the first half of the 21st century. Streamflow increases in the Indus river are mainly a result of increasing glacier melt, whereas increases in the other rivers are mainly a result of increasing precipitation.
- In the second half of the 21st century the contribution of glacier melt is likely to decrease, but the timing of the onset of the decrease is spatially highly variable. Changes in total water availability are uncertain due to uncertain precipitation projections.
- Increases in flows outside the monsoon and melting seasons are likely.
- Increases in extreme events (floods) are likely.

Glacial Lakes and GLOFs

Glacial lakes are lakes formed as a result of present or past glacier activity. Lakes can form on the surface of the glacier itself (supraglacial), within the glacier ice (englacial), below the glacier ice (subglacial), in front of a glacier (proglacial), inside or surrounding a glacier (periglacial), or in relict cirques (cirque) or other depressions formed by glacial erosion (see ICIMOD 2011 for a more detailed description of the different types of visible glacial lakes). The lakes of most concern are those that develop below a receding glacier terminus behind a loosely consolidated end moraine dam. Such lakes are potentially unstable and pose a risk of catastrophic drainage if the dam breaches leading to a glacial lake outburst flood (GLOF). GLOFs are a potential source of risk to hydropower infrastructure as well as to people and property in the valleys below. Glacier retreat and thinning as a result of climate change is resulting in the formation of new glacial lakes and the enlargement of existing lakes in the HKH. Recent studies show that glacier-fed lakes have expanded significantly, while non glacier-fed lakes have remained stable (Wang et al. 2015).

Historical GLOF events in the HKH

Thirty-five GLOF events have been documented in Bhutan, Tibet Autonomous Region (TAR) of China, and Nepal (34 described in Ives et al. 2010 and an additional GLOF in Bhutan in June 2015). Komori et al. (2012) identified 21 GLOF events along the Tibetan branches of the Kuri Chu, Chamkhar Chu, Pho Chu, and Mo Chu rivers (17 before 1970 and four between 1970 and 2010). Five GLOF events were reported during the first half of 2008 in the Gojal area of the Hunza valley, Pakistan. Reports, especially from earlier times, tend to be incidental and it is likely that other events have occurred. For example, there are indications that earlier reports of flash floods in the Ladakh Range in Jammu and Kashmir were actually from GLOFs far upstream (Gergan et al. 2009, cited in Ives et al. 2010)

A number of GLOFs are known to have caused substantial damage to people, property, and infrastructure (Ives et al. 2010). The damage is increased by the debris load that the GLOF generally carries with it. For example, the diversion weir at the Sunkoshi Hydroelectricity project in Nepal was struck by a large flood in July 1981, the result of a GLOF from the Zhangzangbo glacial lake in TAR, China. The flood also destroyed two bridges and large sections of the Arniko Highway. In August 1985, an outburst flood from Dig Tsho in Nepal totally destroyed the nearly completed Namche Small Hydel Project, while in October 1994 a GLOF from the Luggye Tsho in Bhutan caused extensive damage and some loss of life along the Pho Chhu river. As the number and size of glacial lakes increase, so too does the potential for GLOFs, and it is important to assess the risk, especially when selecting sites for infrastructure construction.

Inventories of glacial lakes in the HKH

By their nature, glacial lakes in the HKH region tend to be located in remote and poorly accessible areas, and studies, especially at the field level, are limited. Some effort has been made to develop inventories of lakes in certain areas, facilitated by the availability of satellite imagery which enables large areas to be scanned, but as yet there is no inventory for the entire HKH region (Bajracharya et al. 2007; Ives et al. 2010).

The Water and Energy Commission Secretariat (WECS) prepared a first glacial lake inventory for Nepal in 1987; the study also looked at possibilities for mitigation and early warning systems (WECS 1987; Mool 1995). In 1987, WECS in collaboration with the Nepal Electricity Authority (NEA) and the Lanzhou Institute of Glaciology and Geocryology (LIGG; now Cold and Arid Region Environmental and Engineering Research Institute, CAREERI) prepared an inventory for the Pumqu (Arun river) and Poiqu (Bhote Koshi/Sun Koshi) basins based on topographic maps, aerial photography, and some fieldwork (LIGG, WECS and NEA 1988).

Between 1999 and 2005, ICIMOD in collaboration with various national partners prepared inventories of glaciers and glacial lakes in selected parts of the HKH region: for Bhutan and Nepal, based mainly on topographic maps

Table 11: **Glacial lakes and potentially dangerous glacial lakes in selected parts of the HKH region**

Country	Region/ basin	Glacial lakes			Source
		Number	Area (km²)	Potentially dangerous (critical)	
Bhutan	Whole country	2,674	107	25	Mool et al. 2001b; RGOB 2008
China	Ganges sub-basins (Poiqu,	824	85	77	Mool 2005 Wu et al. 2005
India	Himachal Pradesh, Uttarakhand (Ganges), and Sikkim (Teesta)	549	408	30	Bhagat et al. 2004; Sah et al. 2005; Mool and Bajracharya 2003
Nepal	Whole country	2,323	76	20	Mool et al. 2001a
		1,466	65	21[a]	ICIMOD 2011
Pakistan	Whole country (Indus)	2,420	126	52	Roohi et al. 2005
Total		8,790	802	204	

[a] six lakes identified as high priority and requiring extensive field investigation and mapping

from 1963 to 1982 (Mool et al. 2001a, 2001b), and for selected basins in China, India, and Pakistan, based on analysis of satellite images (Table 12). Glacial lakes were taken to be all lakes above 3,500 masl and >0.001 km² (the limit of resolution). Details of the basins covered are provided in Ives et al. (2010). ICIMOD later updated the inventory of glacial lakes for Nepal using Landsat TM/ETM+ images from 2000/2001 (ICIMOD 2011); however, the low resolution of the satellite image meant that only lakes with an area >0.003 km² were captured. The total number of glacial lakes identified in these studies, and the number of potentially dangerous or critical lakes is summarized in Table 11.

The ICIMOD studies also attempted to identify lakes that were potentially dangerous, i.e., lakes whose attributes suggested that they might have a potential to burst out and which should be studied further. The criteria used were based on the condition of the lake (e.g., >0.02 km², growing), the dam (geomorphological indications of potential instability), the associated glacier (e.g., hanging, large, rapid retreat), and the surroundings (e.g., potential rockfalls, avalanche site) (Ives et al. 2010) and were evaluated using topographic maps published from 1963 to 1982 and aerial photographs from 1957 to 1958, with some field verification. Of the 8,790 glacial lakes, 203 were identified as potentially dangerous (originally 202, with Thorthormi lake in Bhutan added following a detailed field investigation (Karma et al. 2003).

Recently, Zhang et al. (2015) published an inventory of glacial lakes in the 'Third Pole' region – the Pamir, Hindu Kush, Karakoram, Himalayas, and Tibetan plateau – mapped using satellite imagery from 2010. They identified 5,701 lakes >0.003 km², 4,251 of them glacier fed, covering an area of 682 ± 110 km² – 39% in the Brahmaputra, 28% in the Indus, and 10% in the Amu Darya basin (Table 12). The number of lakes identified was smaller than in other studies. For example, only 364 glacial lakes were mapped in the Ganges basin, whereas ICIMOD mapped 1,266 glacial lakes in the Nepal Himalaya and Uttarakhand part of the Ganges basin alone.

Table 12: **Number and area of glacial lakes in the Third Pole**

Basin	Lake number		Lake area (km²)	
	Total[a]	Glacier fed	Total[a]	Glacier fed
Amu Darya	594	451	65.8 ± 10.9	50.3±8.3
Tarim	123	108	16.9±2.5	13.9±2.1
Indus	1,607	868	141.6±26.4	88.8±15.5
Inner Plateau	352	266	38.3±6.1	27.6±4.4
Qaidam	31	31	3.1±0.6	3.1±0.6
Hexi Corridor	11	11	2±0.3	2±0.3
Yellow	15	13	3±0.4	2.9±0.4
Yangtze	192	177	22.4±3.7	20.7±3.4
Mekong	34	31	3.8±0.7	2.3±0.5
Salween	131	114	22±3.1	17.8±2.6
Brahmaputra	2,247	1,883	317.3±48.7	285.6±42.8
Ganges	364	298	45.8±7.3	41.4±6.3
Total	5,701	4,251	682	556.4

[a] includes glacier derived erosion lakes and others (see ICIMOD 2011 for definitions)
Source: Zhang et al. 2015

A number of other studies have investigated glacial lakes in different parts of the region. Ukita et al. (2011) mapped 336 glacial lakes in four sub-basins of Bhutan (Mo Chu, Pho Chu, Mangde Chu and Dangme Chu), using high resolution satellite images from PRISM and AVNIR-2; small lakes (<0.05 km^2) accounted for 55% of the total number of lakes and 13% of the total lake area. The Geological Survey of India mapped some lakes while assessing glacier cover of the Indian Himalayas (Puri et al. 1999). More recently, Govindha Raj et al. (2013) mapped glacial lakes in Sikkim using a semi-automated method to analyse Resourcesat-1 LISS III satellite images. They found 320 glacial lakes; 85 of them formed after 2003. Basnett et al. (2013) also noted the formation of new, and expansion of previous, supraglacial lakes on many debris-covered glaciers in Sikkim. Bhambri et al. (2015) mapped glacial lakes in Uttarakhand using high resolution multispectral and panchromatic satellite imagery from LISS IV and Cartosat 1 and 2A. They identified 1,266 glacial lakes (>0.0005 km^2) with a total area of 7.6 ± 0.4 km^2, 809 of which were classified as supraglacial and 329 as moraine-dammed (51% total glacial lake area). Randhawa et al. (2005) identified 50 moraine-dammed lakes and five supraglacial lakes while mapping in the Chenab basin using satellite images.

Changes over time

The glaciers in the HKH region are shrinking and retreating as a result of climate change, and this is leading to increased formation and expansion of glacial lakes (Bajracharya et al. 2007), and especially of the potentially hazardous moraine-dammed lakes that form below the terminus of glaciers as they recede (Gardelle et al. 2011; Govindha Raj et al. 2013; Nie et al. 2013). The increased temperatures are also leading to the disappearance of smaller lakes that are not glacier-fed, while supraglacial ponds are growing and merging, which increases lake area but reduces lake number. In the longer term, the growing lakes may also reduce the stability of the end moraine dams and increase the risk of breaching in places where they are underlain by masses of dead ice and permafrost. Furthermore, as lakes increase in size and depth, they are more likely to come in direct contact with the glacier terminus, leading to increases in glacial retreat and thinning, which may also affect the end moraine stability (Bajracharya et al. 2015).

There have been a number of studies of changes in glacial lakes over time, as well as detailed studies of some individual lakes.

Trends in the Third Pole

Zhang et al. (2015) in their investigation of glacial lakes across the Third Pole region, investigated the variation over time for ~1990, 2000, and 2010 using Landsat TM/ETM+ data. They found that small lakes (≤0.2 km^2) were more sensitive to climate change; that lakes closer to glaciers and at higher elevations, particularly those connected to glacier termini, had undergone larger area changes, and that glacier-fed lakes showed faster expansion rates than non glacier-fed lakes.

Trends in the Bhutan Himalayas

The ICIMOD 2001 study based on topographic maps from the late 1960s mapped 2,674 glacial lakes larger than 0.001 km^2 in Bhutan, including 549 lakes in the Pho Chu basin covering an area of 23.5 km^2 (Mool et al. 2001b). Mapping was repeated for the Pho Chu basin using NaturalVue EarthSat images from 2000 and 2001 (Bajracharya et al. 2007); 456 lakes were identified (82 were newly formed while 175 of those previously mapped were no longer visible) covering an area of 25.5 km^2, a decrease of 17% in number and increase of 9% in area. Smaller lakes (<0.003 km^2) could not be mapped due to the low resolution of the satellite image, which accounts for some of the reduction in number. Most of the newly formed lakes had formed at the glacier termini; most of those that were no longer visible were erosional lakes, while some supraglacial ponds had merged to form single large lakes. Veettil et al. (2016) also observed an increase in the area of glacial lakes between 1990 and 2010 in the Mo Chu (23%), Pho Chu (21.5%), Mangde Chu (16.5%), and Chamkar Chu (22%) basins.

A more detailed analysis was made of the development of lakes Raphstreng, Thorthormi, and Luggye in the Lunana area of the Pho Chu basin between 1968 and 2001 (Figure 15) (Bajracharya et al. 2007). All three lakes increased in size, in all cases with a sudden increase in area at one point in their evolution. A fourth lake, Drukchung, breached in the early 1990s (Leber et al. 2002) and after this GLOF the lake area remained more or less constant. The development of large lakes in the Lunana region between 1980 and 2010 can also be seen in the satellite images used in a study of glaciers (Figure 16; Bajracharya et al. 2014).

Figure 15: **Development of selected glacial lakes in the Pho Chu basin**

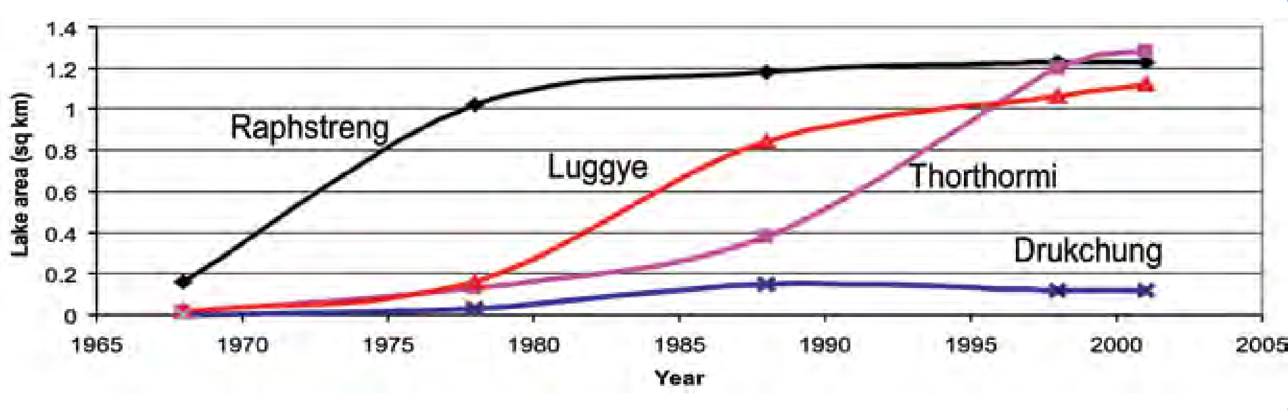
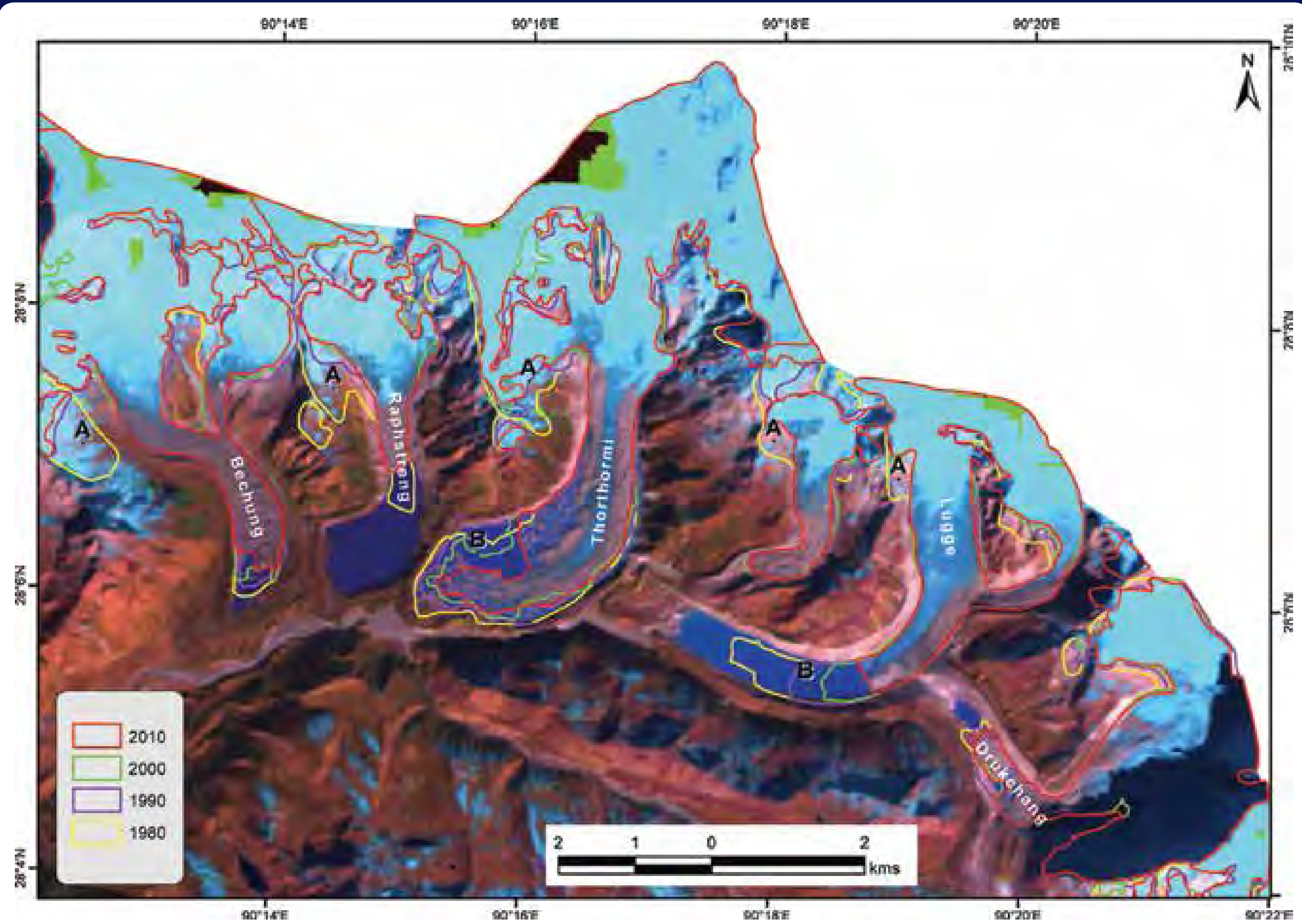


Figure 16: **Decadal development of glaciers and glacial lakes in the Lunana region from 1980 to 2010**



Trends in the Nepal Himalayas

The methodology used for the two ICIMOD inventories of glacial lakes in Nepal was somewhat different, nevertheless a comparison gives an indication of the changes that have taken place between the 1960s and 2010/11. Both the number and area of glacial lakes decreased (Table 12), part of which can be attributed to the lower resolution of the second study, and part to the merging of supraglacial lakes. A study of the Dudh Koshi sub-basin in 2000 identified only 296 lakes, 24 of them new, compared to 473 in the original survey, an overall loss of 177 or 37% (Bajracharya et al. 2007). The main reason was the disappearance of erosional lakes (and inability to identify the smallest) and the merging of supraglacial ponds. However, the glacial lake area increased by 21% despite the decrease in number; 34 lakes were identified as growing.

In 2010, more detailed analyses were made of Imja Tsho, Tsho Rolpa, and Lake Thulagi, as they were identified as potentially at risk of bursting out (ICIMOD 2011). Imja Tsho is one of the fastest growing lakes in the Himalayas (Bajracharya 2010). In the 1960s, it consisted of a group of supraglacial ponds, but by 1975, the glacier had retreated and the ponds had merged to form a moraine dammed lake (Bajracharya and Mool 2005). By 2000, the lake was approximately 2 km long and had an area of 0.95 km^2, with an average annual increase of 74 m in length and 0.02 km^2 in area between 1962 and 2000 (Bajracharya et al. 2007). The trend was even clearer in 2010 (Figures 17, 18; Bajracharya 2010).

Tsho Rolpa was mapped as a group of six small supraglacial ponds in 1959 with an area of about 0.23 km^2. The area increased at an average rate of 0.03 km^2/yr from 1959 to 1999, when it reached 1.55 km^2 (Bajracharya and Mool 2005), and decreased to 1.4 km^2 after mitigation work was carried out (Figures 19, 20). The mitigation project succeeded in reducing the lake level by approximately 3 m, and the volume by approximately 4.5 million cubic metres. Field studies in 2009 showed the lake to be 3.45 km long with an area of 1.54 km^2, average depth of 56 m, and storage volume of 86 million cubic metres (ICIMOD 2011).

Trends in the Poiqu and Pumqu basins, China

The reduction in glacier area in the Poiqu basin in TAR, China, has been well documented (Xiang et al. 2014) and also accompanied by an increase in the number of glacial lakes. Mool et al. (2005), using topographic maps for the earlier period and a variety of satellite images for later years, found an increase in glacial lake number from 119 to 139 between the 1970s and 2003 (Mool et al. 2005); two moraine-dammed lakes, Lumu Chimi and Gangxi Co, were seen to be growing rapidly – by 0.08 km^2/yr and 0.07 km^2/yr, respectively (Figures 21, 22). Che et al. (2014) found an increase in lake number from 199 in the 1970s to 254 in 2013, with all the increase after 2001.

Figure 17: **Decadal development of Imja Tsho from 1979 to 2009**

Figure 18: **Increase in length and area of Imja Tsho from 1962 to 2009**

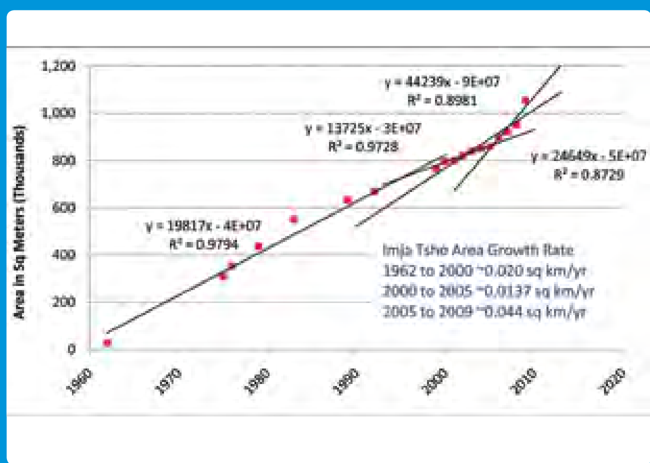


Figure 19: **Aerial view of Tsho Rolpa in 2000**

Photo: Sharad Joshi

Figure 20: **Change in area of Tsho Rolpa from 1959 to 2009**

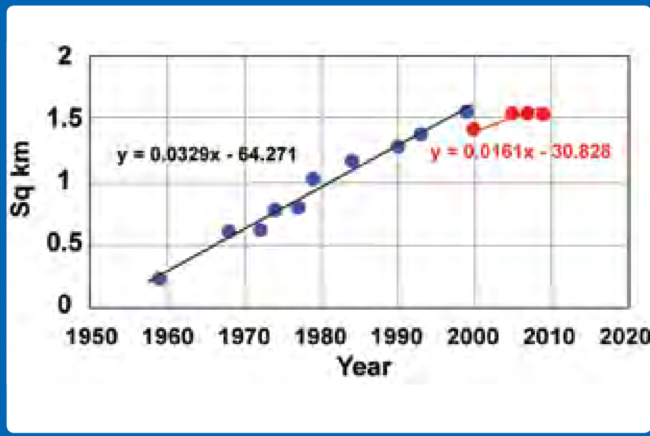


Figure 21: **Development of Lumu Chimi and Ganxi Co lakes**

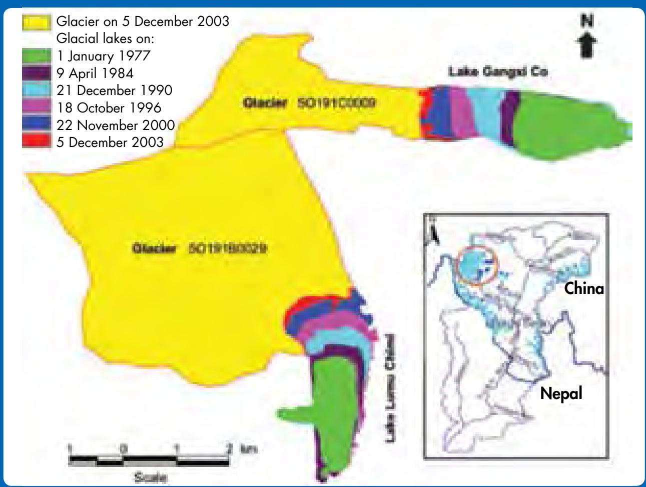
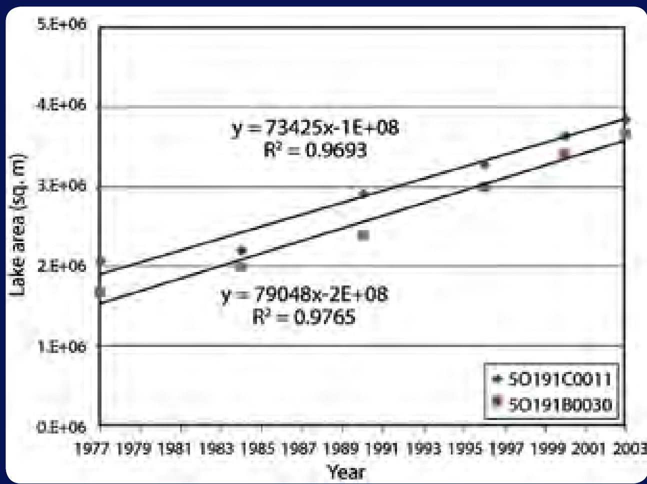


Figure 22: **Change in area of Lumu Chimi and Ganxi Co lakes from 1977 to 2003**



GLOF risk assessment

Assessing the risk from GLOFs is a complex issue; it entails assessing the probability that a GLOF will occur – the hazard – and the vulnerability of people, property, and infrastructure downstream. Clearly not all glacial lakes, and not all moraine dammed lakes, pose a risk of a GLOF. A multilevel approach is used to identify those lakes most likely to pose a risk and then carry out detailed studies to assess the actual level of this risk (ICIMOD 2011). Lakes are first identified at a regional scale, then very small lakes are excluded and the remaining lakes evaluated on the basis of geomorphological and physical criteria using high resolution satellite images to identify those warranting further investigation (critical or potentially dangerous lakes) (Ives et al. 2010). The potential for a 'cascade effect' from a series of interlinked small lakes that don't meet the criteria of concern individually should also be taken into account. The lakes are further ranked on the basis of physical and socioeconomic parameters to give a list of high priority lakes requiring detailed field investigation and mapping. Field investigation involves topographical and bathymetric mapping, hydrometeorological observations, and engineering geological, geophysical and glaciological research. Potential downstream impacts can then be estimated using flood outburst modelling including mapping settlements, infrastructure, land use, and so on. In this way, it is possible to overcome some of the difficulties posed by the extremely challenging terrain and poor accessibility, as well as very large numbers of glacial lakes, and limit the difficult, time consuming, and expensive field investigations to those lakes that have the highest potential for risk.

Assessment of vulnerability

GLOFs can affect people and infrastructure in two ways: the direct affect associated with the flash flood and characterized by erosion, inundation, and sedimentation; and secondary effects that can arise from slope failure triggered by the flood. Detailed case studies were carried out to assess the vulnerability for three lakes in Nepal – Imja Tsho, Tsho Rolpa, and Thulagi. The assessment included a review of past records, flood modelling, and interaction with key local stakeholders in order to quantify the elements exposed to risk (ICIMOD 2011). Two scenarios were used, one based on a flood level derived from a dam break and hydrological model; the second based on a maximum flood height of past GLOF events. The number of people at risk to a GLOF under the maximum scenario was 7,762 for Imja Tsho; 5,183 for Tsho Rolpa; and 3,808 for Thulagi, while considerably more could be indirectly affected through infrastructural damage and loss of goods and services. The monetary value of the elements exposed was also substantial, ranging from USD 8,781,000 under the maximum scenario for Tsho Rolpa to USD 415,351,000 for Thulagi. The greatest cost for Thulagi was the loss of hydropower infrastructure and electricity revenue. The potential impacts were compared with the calculated impact of the 1981 GLOF along the Bhote Koshi/Sun Koshi. In terms of lives and property, the potential impact for Imja was comparable to that in the Sun Koshi, and relatively higher than for Tsho Rolpa and Thulagi, mainly because the Imja Tsho area lies within one of the top ten tourist destinations in Nepal. However, in terms of monetary value, the risk from Thulagi was considerably higher than for the 1981 GLOF.

These figures provide some indication of the levels of risk, but risk is increasing because development is taking place along the river valleys, and the number of people and amount of property and infrastructure which could be affected is growing. This is particularly true for hydropower facilities, which by their nature are sited along rivers and likely to be directly impacted by any GLOF event.

Mitigation and early warning systems

Risk can be reduced or mitigated both by lowering the level of the hazard and by reducing vulnerability. GLOF mitigation measures can be structural and non-structural. They include monitoring to provide an early indication of change, early warning systems to provide downstream residents and owners of infrastructure time to take avoidance action, and measures to physically change the situation, for example reducing the lake level (ICIMOD 2011). Ives et al. (2010) summarize the experience with a number of these measures in different parts of the HKH, indicating both the potential and the limitations of different approaches.

Early warning systems

In order to be effective, early warning systems must integrate four elements: (i) knowledge of the risk; (ii) a monitoring and warning service; (iii) dissemination and communication; and (iv) response capability. In addition, in order to be capable of providing accurate and timely warning, the warning systems should be technically sound, simple to operate, easy to maintain or replace, and reliable. The systems put in place in the past have met with mixed success.

Tsho Rolpa was recognized as posing a potential risk as early as 1993. A fully functional automatic early warning system was put in place in 1998. However, by 2002, the system was no longer operational. Lack of participation by local communities and disruption during the insurgency, coupled with the problem of false alarms, led to the system being ignored and then destroyed as components were removed to use for other purposes (ICIMOD 2011). An early warning system, was installed in the upper Bhote Koshi valley near the Friendship Bridge on the Nepal-China border in eastern Nepal in 2001 with the aim of protecting the Bhote Koshi Hydroelectric Project. The system was still functional in 2016 – most probably because of the hydropower project involved – but because the stations are all within the Nepal part of the catchment, it only has a lead time of six minutes (Ives et al. 2010). To be truly effective it should be extended further upstream into China. Monitoring and telemetry stations were installed by the Snow and Hydrology Division of the Central Water Commission at three points in the Sutlej river basin of India to provide early warning of flash floods, which also act as early warning for GLOFs. This was done in response to a gap that was felt following floods in 2000, as well as for the protection of hydropower projects. Finally, a manually operated early warning system was put in place in the Lunana region of Bhutan by the Flood Warning Section (FWS) of Bhutan's Department of Energy (DOE). The area has been of concern since the Luggye Tsho GLOF in October 1994, which caused heavy damage to the Dzong at Punakha as well as 23 deaths (Richardson and Reynolds 2000). Two FWS staff members report lake water levels and issue warnings to downstream inhabitants (Bajracharya et al. 2007).

Structural mitigation measures

The aim of structural mitigation measures is to reduce the risk of a flood from the lake, generally by reducing the volume of water in the lake, which reduces both the potential peak surge discharge and the hydrostatic pressure exerted on the moraine dam. There are four main approaches: controlled breaching of the moraine dam; construction of an outlet control structure; pumping or siphoning the water from the lake; and tunnelling through the moraine barrier or under an ice dam.

The Tsho Rolpa Mitigation and Early Warning Program in Nepal was the first GLOF operation to include civil engineering structures in the entire HKH region. Siphons were installed over part of the terminal moraine in May 1995 but the outflow achieved was far less than the flow required. In 2000, an open channel was cut through the moraine dam and a four-metre deep artificial spillway succeeded in lowering the lake level by three metres. Mitigation processes are now proceeding for Imja Tsho in the Khumbu region with the major design studies completed in December 2014.

Mitigation measures have also been carried out for Raphstreng Tsho in the Lunana region of Bhutan. The outlet channel was widened manually using crowbars, pickaxes, and spades. By October 1995 the water level in the main lake had been lowered by 0.95 m, and in the two subsidiary lakes by 0.94 m and 1.5 m (Häusler and Leber 1998 ; Mool et al. 2001b). Lowering of the lake level continued until, by 1998, the lake level was reduced by 4 m. Detailed field studies for risk assessment in 1999 indicated that the risk of an outburst from Raphstreng Tsho was low following mitigation, but the risk from Thorthormi Tsho was still high (Häusler et al. 2000; Mool et al. 2001b). Risk reduction measures were carried out for Thorthormi Tsho in 2008–2012 and successfully reduced the water level by 3 m.

In Pakistan's Gilgit-Baltistan (formerly Northern Areas), the predominant glacial lakes are ice-dammed lakes resulting from local glaciers that have thickened and advanced in recent decades (Hewitt 2005). A number of GLOF events were reported in the Gojal area in 2008 (Ives et al. 2010). The risk reduction measures carried out included excavation, channelling, and spillway development. A local village community used a siphoning technique to drain the lake associated with the Ghulkin glacier and reduce the threat posed by a potential outburst flood (Roohi et al. 2005).

Impact of climate on GLOF risk

GLOFs are sudden, unpredictable, catastrophic events. Although it is possible to assess conditions as making a GLOF more or less likely, it is impossible to predict when a dam or ice barrier will actually fail, and whether the failure will be complete or partial. However, it is possible to assess the volume of water contained in a lake, and the potential impact downstream of catastrophic release. Historical events indicate that failure is most likely to occur when a lake reaches a certain volume and the dam is unable to hold back the weight of water, or when there is a sudden surge, for example from an ice fall, rock fall, or release of water from a supraglacial lake.

The great majority of glacial lakes are not thought to pose any risk as they are too small, have a natural outflow, are at low elevation, have a low gradient at the outlet, are in a hollow, and so on. The lakes that potentially pose a risk are those that form behind an unstable moraine dam and have or are likely to reach an area of more than 0.02 km^2, especially if they have unstable surroundings (Bajracharya et al. 2007; ICIMOD 2011). With climate change, glaciers are receding and the number and size of moraine dammed lakes is increasing. Lakes in contact with a glacier are likely to grow particularly fast, as this accelerates glacier retreat (Bajracharya et al. 2015). Rapid glacier retreat is also more likely to give rise to large calving events, which can destabilize an existing lake. The growth of existing lakes and development of new lakes means that the number of lakes that might pose a risk of a GLOF will also increase, especially as many of the new lakes are formed below the retreating termini. Bajracharya et al. (2007) found that 15 of 24 – more than 60% – of newly formed lakes identified in the Dudh Koshi sub-basin were end moraine-dammed, whereas only 16% of glacial lakes in Nepal overall are of this type (ICIMOD 2011). But as yet it is not possible to quantify this increase, and no research has been carried out into the potential retreat of individual glaciers and likelihood of lakes developing under different climate change scenarios.

Thirty-five GLOF events are known to have occurred in the HKH region, and it is likely that additional events occurred but remained unidentified either because they took place in remote regions and had little impact or because they were wrongly attributed, as in the Ladakh Range in Jammu and Kashmir (Ives et al. 2010). In the ICIMOD study, 204 out of 8,790 lakes were identified as critical and warranting further investigation to determine whether they actually posed a risk. Detailed investigation of three of the six high priority lakes in Nepal (Imja Tsho, Tsho Rolpa, and Thulagi lake) showed that none was in immediate danger of bursting out as they all drained through their end-moraine dams along relatively stable channels, although in one case this was because mitigation measures had been successful (ICIMOD 2011). This could indicate that the number at imminent risk is relatively low, but the risk could increase as the lakes enlarge.

Summary

The risk of GLOFs is real and is very likely to be increasing. In the past years, knowledge about the distribution of glacial lakes and trends in lake numbers and lake dynamics has greatly improved. Nevertheless, assessment of the actual risk for a GLOF from a particular glacial lake remains difficult. Hydropower planning should include mapping of all glacial lakes upstream, identification of those that could be critical using a standardized screening process, and direct investigation of the most critical. The results may affect site selection for hydropower infrastructure, or determine a need for mitigation measures and/or an early warning system. Regular screening should be done of glacial lakes above existing hydropower facilities to determine whether changes are taking place and whether these affect GLOF risk.

Conclusions

Changes in the cryosphere, hydrological regimes, and glacial lakes in the HKH region

The climate, cryosphere, and hydrology of the HKH region have changed in the past and will continue to change in the future. The historical climate trends show clearly that the air temperature has increased over the past decades although the rates of increase are different for daily mean, maximum, and minimum air temperature. The temperature at higher elevations has increased more than at lower elevations. No clear trends can be identified in precipitation, although there are some local effects.

Projections of future climate have been made using dynamically or statistically downscaled general circulation models and regional climate models. The current state of knowledge indicates that climate warming is likely to continue during the 21st century. The projections of precipitation change are uncertain as the climate models project a wide range of possible futures, including strong precipitation increases and decreases. An increase in precipitation is most likely for the upstream Ganges and Brahmaputra, but the magnitude is highly uncertain. Precipitation projections for the upstream Indus show both increases and decreases with large uncertainties. Extreme precipitation events are likely to become more severe and occur with higher frequency. The Indian summer monsoon is likely to show increases in precipitation totals, precipitation intensity, interannual variability in monsoon strength, and inter-daily variability. The current state-of-the-art climate models have significant difficulty in simulating the complex climate in the HKH region. Only a limited number of models can satisfactory simulate monsoon dynamics and no single model is able to simulate all the important features in the HKH precipitation regimes. However, empirical-statistical downscaling and bias-correction techniques can reduce climate model errors to a large extent.

In the past years, much knowledge has been gathered about the cryosphere in the HKH region. Glaciers in most of the region are losing mass in response to climate warming. Glaciers in the Karakoram region have been expanding in recent years, but the reason for the so-called Karakoram anomaly is not yet fully understood. Despite scientific progress, estimates of total ice volume vary considerably because of the difficulties of estimating ice volumes in situ or from remote sensing products. No strong trends in snow cover changes have been observed, although minor increases and decreases have been reported for different areas. Little is known about the distribution of permafrost in the HKH region and its importance for the regional hydrology remains unclear. Estimates of future glacier volumes and areas are uncertain and are hampered because modelling of ice flow is restricted to catchment scale studies. However, strong decreases in glacier volume and area are projected for the HKH region as a whole.

As a result of glacier retreat, the number of glacial lakes is increasing rapidly and existing lakes are increasing in area and volume. The lakes are often dammed by moraines, which can be unstable. Dam failure can result in glacial lake outburst floods (GLOF) which can have devastating downstream effects. Glacial lakes are being monitored more extensively, but mitigation on the scale required remains challenging.

Implications for hydropower

The aim of this report is to establish a state-of-the art understanding of future climatological and hydrological changes as a basis for future planning of hydropower development in the HKH. Although general statements can be made about the effects of climate change at the river basin scale based on this literature review, it is very important to note that the effects of climate change on hydrology in the larger HKH region are highly variable in space and time. Thus it is strongly recommended that this first phase assessment be expanded and intensified to include detailed studies of catchments that are candidates for hydropower development.

Continued warming and projected changes in monsoon patterns are likely to cause increases in flow during low flow periods of the year. This is due to earlier onset and longer continuation of the snow and glacier melting processes.

Increases in low flows and more evenly distributed flows will be beneficial for the generation of hydropower throughout the year.

Precipitation intensity increases are likely for most parts of the Indus, Ganges, and Brahmaputra basins. Increases in peak flows are very likely and pose a risk to hydropower plants, which can be damaged by floods and may also have reduced lifespans as a result of increased sedimentation. However, it is important to note that projections of precipitation intensity changes show large spatial variation, and catchment scale analysis is indispensable.

The total water availability in the Indus, Ganges, and Brahmaputra basins is expected to increase as a result of increased flows during the first half of the 21st century. This will stimulate hydropower development. But climate change projections become more uncertain in the long term and so do the hydrological projections. Increases in meltwater are projected for the first half of the 21st century in the HKH region. However, during the second half of the 21st century decreasing glacier melt is expected, with further decreases in ice volume and area. The projected timing of such a turnaround is highly variable and dependent on the specific climate change scenario and location in the HKH. Climate models project a large range of possible futures, especially for the amount of precipitation. A continued increase in precipitation can be expected for the upstream Ganges and Brahmaputra basins. The range in projections however is very large and very uncertain. Spatial variation in the projections is also very large. Climate models project partly increasing precipitation and partly decreasing precipitation for the upper Indus basin. With the contribution of glacier melt expected to decrease by the end of the 21st century, the hydrological future in the Indus is highly uncertain. These large uncertainties may be a risk for hydropower development. Thorough climate change impact analysis for hydrology at catchment scale may narrow down these basin-wide uncertainties. The large range in projections stresses the importance of using an ensemble of climate models covering the range of projections when performing a climate change impact study in the HKH region.

Glacial lake outburst floods (GLOF) have proven to be a serious risk for hydropower sites and cannot be disregarded. As inventories of glacial lakes are improving, more and more information becomes available on the risks of GLOFs. It is recommendable to do extensive risk analyses of glacial lakes before selection of possible hydropower development sites.

In summary, consistent trends can be recognized for climate change related impacts on hydrology in the HKH region, but detailed analysis at the catchment scale remains necessary for proper assessment of climate change induced hydrological risks for candidate hydropower development sites. These analyses should also consider other factors influencing suitability for hydropower development, such as health, safety and security, and environmental and social factors.

Limitations in our understanding

Lack of knowledge is a major limitation in reducing the large uncertainty pertaining to the present climatic and hydrological conditions in the HKH region and to future projections.

Quantification and prediction of precipitation, in particular high altitude precipitation and its spatial distribution, is problematic. Meteorological ground stations are sparse, and existing gridded meteorological products yield inconsistent simulations of past climate. Combining ground station data with weather model data may increase the accuracy of precipitation estimates.

The components of the water balance and hydrological processes in the HKH are also not yet satisfactorily quantified. Examples include water losses through sublimation of snow and ice and losses to deep groundwater. Although huge progress has been made in recent years to gain knowledge about the state of the cryosphere in the HKH region, large knowledge gaps remain. The distribution of permafrost and its role in the hydrological cycle remains unclear. Similarly, estimates of the ice volume are uncertain. The distribution of snow can be mapped well using remote sensing, but snow depth and snow water equivalent is difficult to assess. The amount of water stored in seasonal snow, which is important for assessing hydropower potential, is also difficult to assess.

Prediction of change in the climate of the HKH is very poor or non-existent, but forms an important basis for future projections of the cryosphere and hydrology of the region. Present climate models indicate different trajectories for future climate change, with especially large uncertainty in future precipitation. It is expected that climate modelling and the accuracy of projections will improve, but this will take time.

Even if climate projections are improved, the response of the cryosphere to climate change is not fully understood, making future projections of the cryosphere uncertain. It is, for example, very difficult to determine how fast glaciers, which have long delays in responding to changes in climate, will respond in the long run.

The way ahead

This review provides a comprehensive overview of the present state of knowledge on climate change impacts on the cryosphere, hydrological regime, and glacial lakes of the Hindu Kush Himalayas at regional and basin scales, with a focus on the implications for hydropower development. It provides an insight into the limits in present understanding of the relevant natural processes, as well as the shortcomings in models, in situ measurements, and technologies in general.

It is clear that there is a considerable need for further research. The research questions vary from the general (e.g., how to improve broad scale climate modelling for the region) to the specific (e.g., future sedimentation and its role in hydropower plant longevity). The marked large spatial variation in the findings indicates the need to follow up at smaller scales. The research needs also vary in degree of importance of their role in improving effectiveness in hydropower development.

Many reports have discussed the potential for hydropower to transform the economies of the Himalayan region. But in order to develop this potential, it is essential to have good information on the likely scenarios for water availability and water related risks over many decades. A coordinated research programme is needed for the region that focuses more strongly on understanding the impacts of climate change at catchment and sub-basin levels, and specifically in those catchments/sub-basins which are candidates for hydropower development. ICIMOD and its partners should consider ways in which such a programme can be developed to cover the spectrum of research requirements that have become apparent in this review.

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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

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