7 Climatic hazards in the Himalayan region

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Introduction

Mountainous regions represent one of the most fragile and vulnerable regions on Earth owing to the intersection of steep gradients in topography, vegetation and climate. These regions thereby represent a key concern on the global climate change agenda (Beniston 2003; Kohler and Maselli 2009; Kohler et al. 2010). Mountainous regions occupy approximately 25 per cent of the global land surface and are home to ~26 per cent of the global population (Meybeck et al. 2001; Beniston 2003; Diaz et al. 2003). Hence, mountain regions are comprised of sensitive systems with great biogeophysical significance and that have gained recent attention owing to their vulnerability to climate change impacts (Beniston 2003; Messerli et al. 2004; Nolin 2012). The Hindu Kush-Himalayan (HKH) region and surrounding regions in South Asia epitomise such a mountain ecosystem at the forefront of global environmental change where cryospheric, hydrological and ecological processes are under threat owing to a warming climate. Although people have inhabited this region for centuries, coping with hazards and risks, there is growing scientific evidence that the HKH region has become increasingly hazardous and disaster-prone in recent decades, a process which could further intensify with climate change (Marty et al. 2009). In addressing climatic hazards in this region, we examine water-related hazards, extreme weather and climate, stress on water resources, agricultural production and food security, all of which amplify vulnerability of this region when they interact with societal and economical dimensions.

The HKH region sustains around 210 million people across eight countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan) with nearly 1.4 billion people depending on water across the major river basins such as the Indus, Ganges, Brahmaputra, Yangtze and Yellow River (Figure 7.1). The Indus, Ganges and Brahmaputra basins constitute one of the most agriculturally fertile regions globally, supporting the livelihoods of approximately 700 million people, 85 per cent of whom reside in lowlands (elevations less than 1000m) in India (79 per cent) and Bangladesh (18 per cent) (NRC 2012; Nepal and Shrestha 2015). Approximately 195 million people live within the Indus basin alone, which includes most of Pakistan. These basins provide ecosystems services such as drinking water, irrigation, hydropower and biodiversity, which are critical for the livelihoods of the growing population. It is further believed that the HKH region

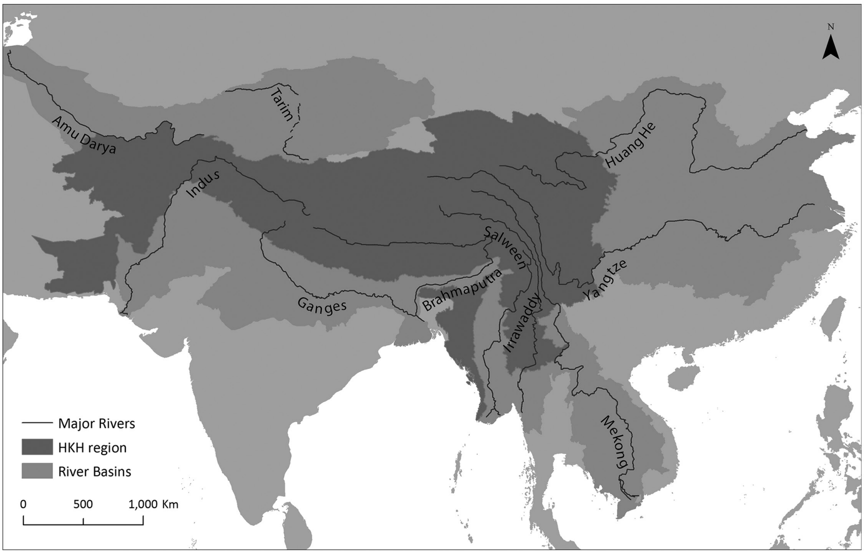

Figure 7.1 The Hindu Kush-Himalaya (HKH) region with the major river basins

will increasingly face challenges in meeting water, food and energy demands in the future due to rapid urbanisation, population growth and socio-economic development (Mukherji et al. 2015). Business-as-usual scenarios for the region project that water demands and energy requirements need to double in order to meet additional food and energy requirements within the next decade (Molden 2007; Mukherji et al. 2015). On the other hand, the vulnerability of the people living in the HKH to natural and climatic hazards is exacerbated by poverty, marginality, limited accessibility and social fragility (Gerlitz et al. 2014). Furthermore, a changing climate with rising temperatures and precipitation changes may further push the hydro-climatological regime over critical thresholds thereby exacerbating climate-related hazards as well as water, food and energy scarcity (Lutz et al. 2014; Nepal and Shrestha 2015).

The HKH region represents a critical high-elevation environment in central Asia where cryospheric (frozen water) changes along with large-scale atmospheric, hydrological and ecological changes are already observable as warming temperature trends, glacier shrinkage and retreat, permafrost degradation, decreasing length of seasonal snow cover at higher elevations, earlier snowmelt runoff, degradation of grassland in the Tibetan Plateau, changes in Indian monsoonal patterns and local perceptions of a changing climate. Climate change impacts over the last several decades have been observed through significant temperature changes and also through variable rates of retreat of glaciers across the region (Bolch et al. 2012; Gardelle et al. 2012; Yao et al. 2012). Recent research analysing tropospheric temperatures reveals widespread annual warming rates over the entire HKH region of 0.21 ± 0.08°C/decade from 1979 to 2007 (Gautam et al.

2009, 2010). Even greater rates have been observed for the Nepalese Himalayan region specifically, with warming at approximately 0.6°C per decade from 1977 to 2000 (Shrestha et al. 1999). As the evidence suggests, potential impacts of a warming climate are greatest on regional hydro-climatology that may severely impact water resources in this region. Water-related hazards such as flash floods, outburst floods, landslides, debris flows and hazardous weather are projected to increase in the uplands. Recent flooding in the northwestern Himalayan region in the Uttarakhand State of India and western parts of Nepal exposed the vulnerability of these mountain regions to catastrophic flood disasters. Floods and cyclones are likely to increase in frequency, intensity and extent, and are expected to impact the lowland areas such as Bangladesh. At a basin scale, water availability and food security are also threatened by climate change owing to dependence on large-scale irrigation systems. This study provides analysis of climate-related hazards along with the susceptibility of harm and ability to cope of this region.

Climatic hazards and extreme events

Potential changes in climate have spurred a growing interest in climatic hazards and extremes that may have profound ecological as well as societal impacts globally (Easterling et al. 2000). One of the few available datasets on occurrences of hazards and disasters is the Emergency Events Database (Guha-Sapir et al. 2015; http://www.emdat.be), an International Disaster Database on disasters provided by the Center for Research on the Epidemiology of Disasters (Guha-Sapir et al. 2004). Data collection efforts have improved over the recent decades owing to better communication (Elalem and Pal 2014). According to EM-DAT hazard classification, a climatological hazard is usually caused by long-lived meso- to macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability. Climate change impacts in mountainous regions can lead to hydrological hazards (flooding and landslides) and meteorological hazards (extreme weather events), all of which are most directly manifested through changes in extremes (Marengo et al. 2009; Huggel et al. 2010; Thibeault et al. 2010; Panday et al. 2014).

Hydrological hazards

Hydrological hazards in the Himalayan region are commonly related to hydro-meteorological conditions such as floods, landslides, avalanches, river-bank erosion and droughts (Pathak and Mool 2010). Extreme relief, enhanced orographic precipitation, thin soil over impervious bedrock and unstable mountain slopes contribute to the susceptibility of mountainous areas to hydrological hazards (Haritashya et al. 2006). Hazards such as flooding occur annually with the natural monsoonal cycle and are also positively correlated with the El Niño-Southern Oscillation phenomenon in the Indian subcontinent (Mirza et al. 2003). The frequency of reported annual occurrences of hydro-meteorological hazards across South Asian region indicates an increasing trend in the frequency of reported

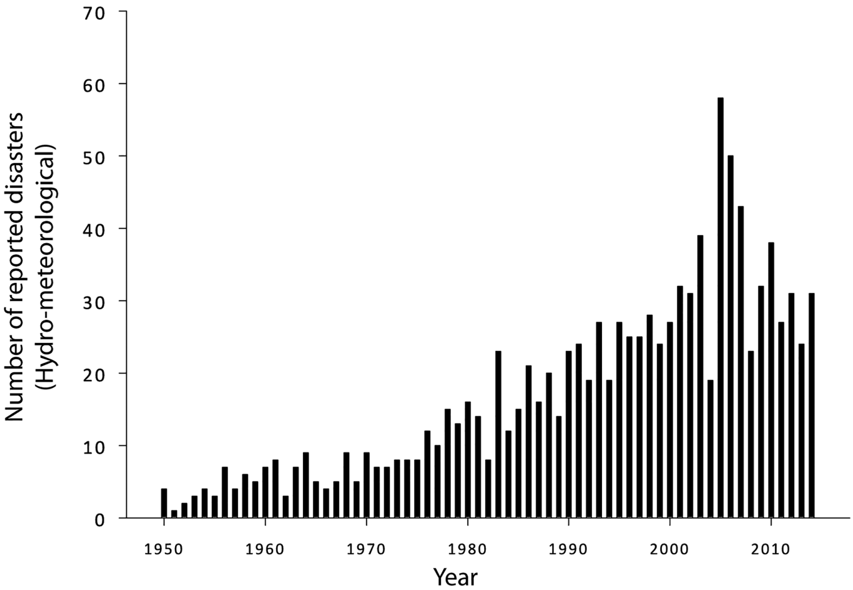

Figure 7.2 Number of hydro-meteorological disasters reported in the Emergency Events Database (EM-DAT) for South Asia (Afghanistan, Bangladesh, Bhutan, India, Nepal and Pakistan). Hydrological disasters include flood and landslides while meteorological disasters include extreme temperature and storms

Source: EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.be – Université Catholique de Louvain – Brussels – Belgium

disasters (Figure 7.2). Although better data reporting may result in bias of number of reported disasters for recent decades, there is a possibility of the impact of climatic and socio-economic changes on the frequency of such extreme weather events and resultant disasters (NRC 2012; Elalem and Pal 2014). Projections based on Coupled Model Intercomparison Projects Phase 5 (CMIP5) simulations also indicate increased hydrological hazards such as flooding in South Asia (Mirza 2011; Hirabayashi et al. 2013). Climate change is expected to increase extreme precipitation events, shift the onset and departure dates of the summer monsoon, and affect the magnitude and frequency of cyclones, all of which may increase the frequency of hydrological hazards in this region (Krishnamurthy et al. 2009; Sen Roy 2009; Christensen et al. 2013).

Flooding

MONSOON FLOODING

The South Asian region is one of the most flood-vulnerable regions in the world. Flooding in the Himalayan region and the adjacent lowlands is commonly associated with heavy or extreme rainfall events particularly during the Indian summer monsoon season or with artificial or natural dam bursts (Sen Roy 2009; Bookhagen 2010). The summer monsoon dominates the climate of eastern Himalayan region from the months of June and September and accounts for a large part of the annual precipitation budget over the Indian subcontinent. Subsequently, this results in flood events in the rivers and tributaries particularly in the Eastern Himalayan region. Long-term disaster data indicates that flooding events of various severities have mostly occurred over the last 30–40 years that is also consistent with the increase in intensity of the global monsoon (Webster et al. 2011). This data also indicates a high spatial heterogeneity in the occurrence of flooding disasters with northern regions of Afghanistan, Pakistan, India and Nepal in the western and eastern HKH showing high vulnerability to flooding (Elalem and Pal 2014).

Although total summer rainfall is far less in the western Himalaya and Indus River Basin, the severity of the monsoonal precipitation can sometimes be strong in these regions. Large flooding was observed in the Indus valley in Pakistan in the monsoon of 2010 (July–August) affecting 20 million people with 2,000 deaths and total damages exceeding US$40 billion (Houze Jr. et al. 2011; Webster et al. 2011). What started as heavy rainfall over a short period of time, leading to flash flooding, magnified into one of the worst disasters in the history of the country. Similarly extreme rainfall and flash flooding in the north Indian state of Uttarakhand in June 2013 led to massive landslides in the Mandakani River catchment, resulting in the loss of thousands of human lives and damage to property and infrastructure (Rao et al. 2014). The floods in the Kedarnath region in Uttarakhand were due to an unprecedented amount of rainfall over several days, averaging 360mm from June 15–18, 2013. Radar imagery of the region before and after this event indicates extreme erosion, channelization and deposition of sediments (Figure 7.3).

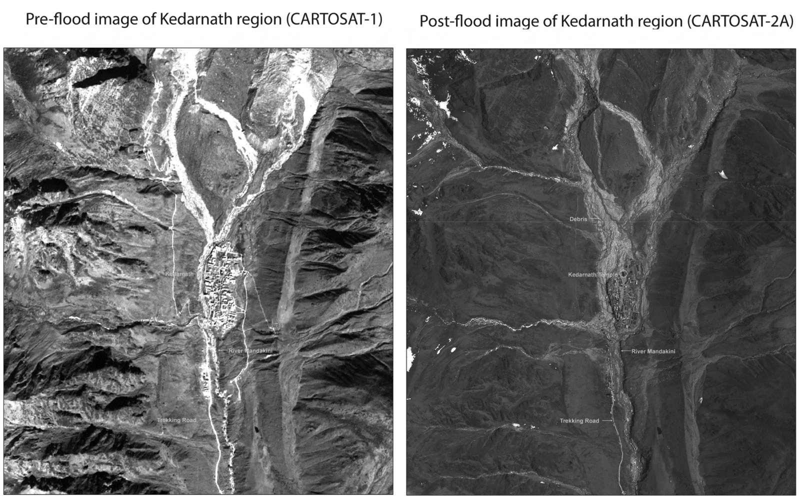

Figure 7.3 Radar imagery (CARTOSAT) of Kedarnath region taken before and after the flood event (NRSC 2015)

OUTBURST FLOODS

In upland areas on the high-mountain glacial environments, increased formation and expansion of ice- and moraine-dammed lakes has led to increased risks of glacial lake outburst floods (GLOFs, also jökulhlaup) in the HKH region (Richardson and Reynolds 2000; Mool et al. 2001; Bajracharya and Mool 2010). Greater warming at higher altitudes across the HKH region has led to the thinning and retreat of glaciers, accompanied by formation of new glacial lakes and expansion of preexisting ones. An inventory based on remotely sensed satellite data mapping has identified around 2,400 glacial lakes in this region, of which several hundred are identified as potentially hazardous (ICIMOD 2011). Several outburst floods have already occurred in the past in this region, causing the loss of lives and property, and damage to infrastructure such as hydroelectric plants. Nepal alone has experienced around 14 GLOF events in the past. Recognition of such lakes as potentially hazardous has led to the installation of early warning systems and measures to lower lake levels in the Nepalese Himalaya (Benn et al. 2012). Glacial lakes have been shown to purge its melt-water within days, which is indicative of rapid melting. Figure 7.4 shows an image of glacial lake on the moraine of the Ngozumpa glacier in the Everest region of Nepal taken a day apart on May 28, 2013 and May 29, 2013, showing the level of drainage that occurred within a day. Recent studies have shown that sustained melting and ice loss in the decades to come owing to increasing temperature across high-altitude regions such as the Everest (Shea et al. 2014) will only accelerate the rapid formation of such potentially hazardous lakes (Thompson et al. 2012).

Landslides

Landslides are another common hazard in mountainous environments usually triggered by monsoonal rains, tropical cyclones and flooding in the Himalayan region (Hewitt 1997; Petley et al. 2007). Landslides are also causally linked to climate change through changes in precipitation (Huggel et al. 2012). Case studies from mountains of Europe, the Americas and the Caucasus indicate several mechanisms that can alter landslide magnitude and frequency under warming conditions which include the triggering of mass movement processes, slope instability due to permafrost degradation, tipping points in geomorphic systems and storage of sediment and ice involving important lag-time effect (Evans and Clague 1994; Gruber and Haeberli 2007; Huggel et al. 2012). Debris flows are common occurrences in mountain areas such as the Himalayas, but there is no clear evidence of increase in such events in peri-glacial environments. However, extreme rainfall events have increased in many regions of the world that commonly activate debris flows (Jones et al. 2007; Huggel et al. 2012). Landslide database for Nepal from 1978–2005 also indicates an upward trend in landslide fatalities despite high level of interannual variability in the occurrence of landslides (Petley et al. 2007). However, this increase in fatalities has been linked to rural road construction and deforestation as there are no substantial changes in rainfall patterns during the time period.

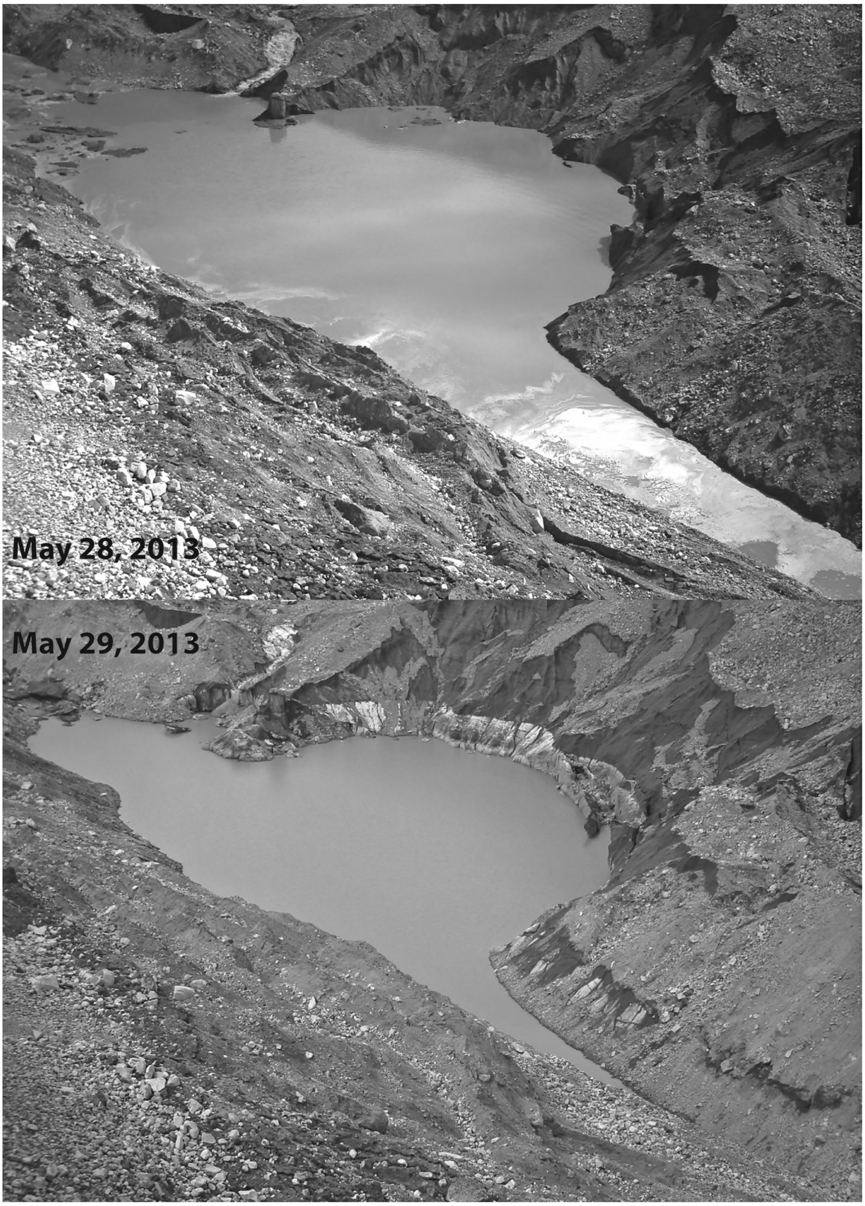

Figure 7.4 Rapid drainage of a glacial lake on the Ngozumpa glacier as shown by the drop in the water levels between May 28 and May 29, 2013 (Horodyskvj 2013)

Case study: Landslide in Sunkoshi, Nepal

In August 2014, heavy rainfall for several days caused a massive landslide in Jure village in Sindhupalchowk district of Nepal upstream of the Sunkoshi Hydropower project. The landslide led to the collapse of nearly 2km of hillside moving around 5.5 million cubic metres of debris that killed 156 people and displaced several hundreds. This landslide created a natural debris dam on the Sunkoshi River, forming a lake upstream which drained naturally without causing any fatalities. There have been three major flooding events in the Sunkoshi valley and its weak geological formation and steep topography combined with intense rainfall events, particularly during the monsoon, makes it vulnerable to hazards such as landslides. Figure 7.5 shows the extent of the landslide captured by Landsat 8, Operation Land Imager (OLI) images of the area on September 15, 2013 (pre-landslide) and September 2, 2014 (post-landslide).

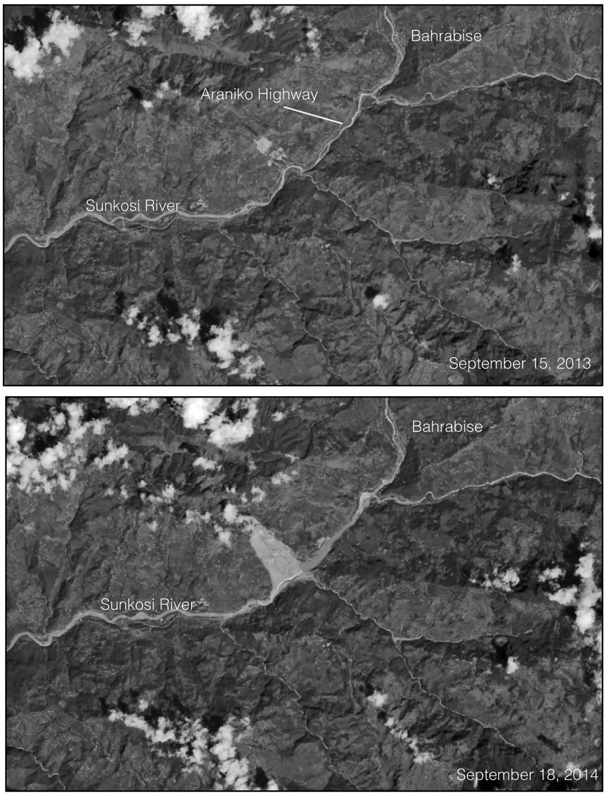

Figure 7.5 Landsat 8 images showing the Sunkoshi landslide area prior to the event in 2013 and post-landslide in September 2014 (NASA Earth Observatory 2014)

Extreme events

Observed historical trends of climate and future projections of climate change under different scenarios suggest that higher elevation regions will continue to experience the strongest warming across the planet (Beniston 2000; Beniston 2006; Déry 2011). This anomalous warming has prompted the attention to extreme weather and climate events due to the often large, catastrophic loss of human lives, the increasing economic costs and the disproportionately large part of climate-related damages associated with them (Easterling et al. 2000; Meehl et al. 2000). Such short-lived extreme weather events can strongly influence mass-transport processes and impact the rates of surface erosion processes (Bookhagen 2010). Klein Tank et al. (2006) and Panday et al. (2014) analysed station data for the late 20th century and show observed shifts towards climate extremes (fewer frost days and more warm nights) for the 1971–2010 across higher elevation areas in the Eastern Himalayan and South Asian region. At the same time, historical records of precipitation, streamflow and drought indices indicate increased drying over many land areas including South Asia since 1950 along with projections of severe drought over the coming decades (Dai 2011, 2013). Multi-model average projections from the Coupled Model Intercomparison Project (CMIP3 and CMIP5) indicate continued trends towards more extreme conditions consistent with a warmer, wetter climate in the Himalayan region, with more frequent temperature- and precipitation-related extremes, particularly for the Eastern Himalayan region (Panday et al. 2014).

The summer monsoon exerts a major influence on the regional hydro-climatology of South Asia. An understanding of its variability and underlying mechanisms of change is a fundamental challenge for climate science (Turner and Annamalai 2012). Long-term observations and climate models indicate a departure from normal monsoon years with a warming climate. Sen Roy (2009) analysed extreme hourly precipitation patterns in India from 1980 to 2002 and found rising trends in extreme heavy precipitation events, particularly in the high-elevation regions of the northwestern Himalaya as well as along the foothills of the Himalaya. The incidence of heavy monsoon rains has doubled from 1951–2000 as a result of significant rising trends in frequency and magnitude of extreme rain events (Goswami et al. 2006). Daily rainfall variability has ~~increases~~ with rain occurring less frequently but with more variability ~~intensity~~ leading to increased frequency of both light and heavy rainfall events (Singh et al. 2014).

Glacier melt and streamflow

Geographic areas where the water cycle is dominated by snowmelt hydrology are expected to be more susceptible to climate change as it affects the seasonality of runoff (Barnett et al. 2005; Adam et al. 2009). Regional climate projections by the Intergovernmental Panel on Climate Change (IPCC 2007) indicate Central Asia may warm by a median temperature of 3.7°C by the end of the 21st century, with the greatest warming over higher altitudes (particularly the Tibetan Plateau

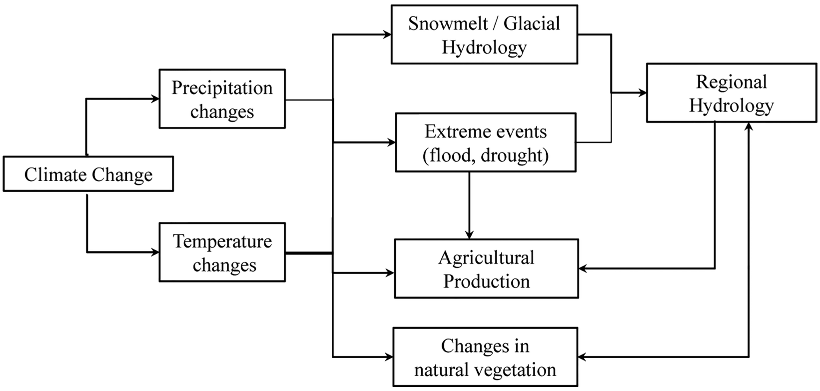

Figure 7.6 Flow diagram emphasising the connectivity and significance of regional hydro-climatology and climate change impacts to agricultural production for the HKH region (Panday 2013)

and the Himalayas). The HKH is one of the most glaciated regions outside of the polar regions occupying 60,054km^2 and an estimated ice reserve of 6,1247km^3 (Bajracharya et al. 2015). Glaciers across the Himalayas, except for the Karakoram Ranges, have retreated since the mid-19th century and mass loss has accelerated over the recent decades (Bolch et al. 2012; Bajracharya et al. 2015). There is an increasingly large body of evidence of a glacio-hydrological response along the east–west transect of the HKH corresponding to the these climatic changes, with glaciers in the eastern Himalaya exhibiting retreat and negative mass balance, and glaciers in the Karakoram and northwestern Himalaya exhibiting a positive mass balance over the last few decades (Panday et al. 2011; Bolch et al. 2012; Gardelle et al. 2012; Yao et al. 2012). Despite large variability in melt runoff regime, rising temperatures are projected to shift snow lines upward, shrink glacier coverage and reduce snow storage capacity thereby increasing melt runoff with greater hydrological extremes and shifts in seasonal peaks of total annual water availability (Lutz et al. 2014; Mukherji et al. 2015). These potential impacts of climate change, if realised fully, are greatest on the regional hydro-climatology which may severely impact water resources, irrigation, and hydropower generation (Figure 7.6).

Atmospheric hazards

Increasing concentrations of anthropogenic aerosols have negatively affected the air quality and climate over the Indo-Gangetic Plains (IGP) (Ramanathan and Ramana 2005; Gautam et al. 2010). Recent field experiments, in situ observations, and satellite monitoring have pointed out to the existence of atmospheric brown clouds (ABC) which are wide polluted tropospheric layers consisting of particles such as black carbon and sulphate aerosols from biomass combustion, power plants and vehicular pollutions (Bonasoni et al. 2010; Bonasoni et al. 2012;

Gautam 2014). These clouds can alter regional energy budget by reducing solar radiation at the surface by ~10 per cent, thereby reducing evapotranspiration and rainfall, while nearly doubling the atmospheric solar heating (Ramanathan et al. 2005). Previous studies have also found that adverse climate changes due to combined effects of ABCs and greenhouse gases have contributed to slowdown in rice harvest growth during the past two decades (Auffhammer et al. 2006).

During winter season, low temperatures, increased frequency of alternate low and high pressure systems, fine aerosols and valley-type topography of the IGP bounded by the Himalayas provide ideal conditions for fog and haze formation over this region (Gautam et al. 2007). The formation of fog starts in the latter half of December, extends over a stretch of ~1500 km in length and ~400 km in width and covers some parts of the region for more than a month (Ali et al. 2004). These annual occurrences of fog have been a recent phenomenon over India, and are responsible for trapping pollutants and poor visibility which disrupt transportation, leading to deaths from vehicular accidents (Hameed et al. 2000). Figure 7.7 shows the spatial distribution of the composite mean fog/low-cloud occurrences from 2000–2006 during winter season generated from Terra/MODIS data for aerosol and cloud properties (MOD04 and MOD06) (Gautam et al. 2007). The average number of foggy days over the six-year winter period is larger in the central IGP compared to the eastern and western regions. The clear demarcation along the foothills of the Himalayas is evident indicating the persistence of fog in the low topography/valley of the Ganges basin.

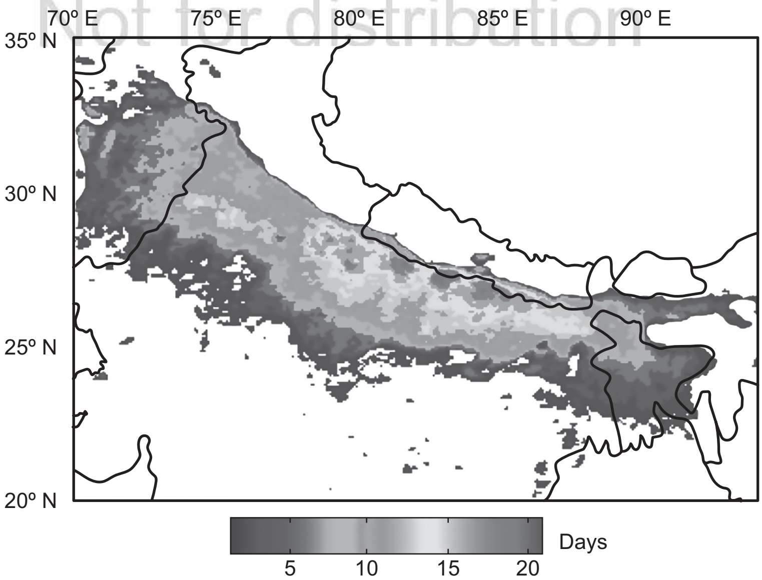

Figure 7.7 Composite mean fog/low-cloud occurrences for the six-year winter season (2000–2006) derived from MODIS cloud properties (Gautam et al. 2007)

Along with these events, the IGP is also exposed to high dust activity during pre-monsoon season from March to May when dust aerosols are transported from the Thar Desert in Northwestern India/Pakistan and the Arabian Peninsula (Gautam et al. 2009). Along with pollution implications, these dust storms can also have severe climatic effects. A mixing of this desert dust and soot aerosols over northern India and the Himalayan foothills may cause enhanced heating in the middle and upper troposphere over Tibetan Plateau, also known as the Elevated Heat Pump (EHP) effect, thereby strengthening the meridional tropospheric gradient and resulting in early advancement of the monsoon rainfall (Lau et al. 2006, 2008). Such potential interaction of aerosols and monsoon water cycle variability may have profound societal impacts of air pollutions and monsoon floods and droughts in South Asia (Lau et al. 2008).

Regional vulnerability

Impacts to agriculture and food security

One of the major potential impacts of climate change in this region is water availability and reduction of upstream discharges, which directly impact agricultural production and food security downstream (Immerzeel et al. 2010). Although very little land is irrigated in the upstream highlands of the HKH region, agriculture comprises the largest sector of water use in the lowlands in a majority of the countries within these larger basins. Irrigation is a major contributor to food security with 90 per cent of withdrawn freshwater used for irrigation in South Asia (Mukherji et al. 2015). By basins, the irrigated land areas are 149,900ha in the Indus, 156,300ha in the Ganges and 6000ha in the Brahmaputra (Nepal and Shrestha 2015). A large amount of irrigation is used for cotton production in the Indus basin, rice production in the Brahmaputra basin and primarily for wheat production in the Ganges basin (NRC 2012). As a result, the long-term sustainability of this region is dependent on water resource management, agricultural production and food security. Although South Asian countries increased food production during the early 1990s, production has slowed down since, leaving countries such as Afghanistan, Bhutan, Bangladesh, India and Nepal unable to cope with increasing population demands (Rasul 2010). Countries such as Afghanistan and Bangladesh are particularly vulnerable in terms of food security owing to increasing population, low productivity and lack of suitable land for arable agriculture. Datasets of hazards and disasters in this region have been dominated by occurrence of flood events in terms of the frequency of events and number of people affected; however, droughts and famine have accounted for more deaths in this region over the past century (NRC 2012). An analysis of climate risks for agriculture and crops in 12 food-insecure regions (based on statistical crop models and climate projections) identified South Asia as a region likely to suffer negative impacts on crops critical to large populations (Lobell et al. 2008). Given the poor food security conditions in this region and the surrounding countries, negative changes in water resources will certainly exacerbate these existing conditions.

Socio-ecological vulnerability of HKH

The vulnerability of this mountainous region to potential impacts from climate will increase over the next few decades. Vulnerability as defined by Turner et al. (2003) refers not only to the exposure to hazards alone, but also to the sensitivity and resilience of the individuals, groups or systems. The exposure of household and communities to livelihood stresses caused by both climatic and non-climatic factors, and their capacity to cope or recover, makes certain groups in a population disproportionality more vulnerable to disasters. Poverty analysis of member countries of the HKH, using the national living standard surveys, indicates that one third of the population is living in absolute poverty and, on average, there is 5 per cent higher poverty in the mountains than the national average of the respective HKH countries (Hunzai et al. 2011; Gerlitz et al. 2012; Shrestha et al. 2015). A regional study from the Nepalese Himalaya finds erratic rainfall, snowfall and prolonged drought as major climatic hazards that pose greatest threat especially to low-income farmers who lack capacity for short or long-term adaptation (Bhatta et al. 2015). Similarly, others have shown that, despite high exposure and sensitivity to climate change within different regions in Nepal, much of vulnerability is indicative of persistence of constraints on adaptation to local environments (Pandey and Bardsley 2015). A basin-scale vulnerability assessment by Varis et al. (2012) found the Ganges-Brahmaputra-Meghna (GBM) and Indus River basins to be the most vulnerable than any other river basins investigated in the Asia-Pacific region. The GBM basins also had the highest vulnerability with regards to vulnerability related to environmental hazards (Varis et al. 2012). The assessment of socio-ecological vulnerability is therefore critical for identifying climate adaptation requirements, disaster and hazards risk reduction measures, and post-disaster recovery efforts.

Transboundary water issues

Increasing energy demands of the region are certain to spur infrastructure development, particularly in construction of river dams to expand current hydropower capacity. The hydropower potential of the HKH region is estimated to be around 500 GW (Vaidya 2013) with 25GW of electricity generation potential alone in the Ganges Basin through upstream storage of water in proposed 23 dams upstream (Sadoff et al. 2013). Construction of all proposed dams in India would transform the Indian Himalaya to a region with the highest average dam densities driving the displacement of people and massive biodiversity loss driven by land use changes (Grumbine and Pandit 2013). China has also stepped up its efforts to harness hydropower with 750 planned projects planned in Tibet alone and potential diversion of water from the Tsangpo-Bramaputra (Bawa et al. 2010; Pomeranz 2013). The proposed construction of dams and/or inter-basin water diversion projects will impose major stress on riverine ecosystems and carry impacts downstream to lower riparian regions in India and Bangladesh (Kattelus et al. 2015). Lessons have been learnt from nearby Mekong River Basin. Here, rapid hydropower development, with construction of a series of hydropower projects on the upper Mekong by China and 11 proposed dams in the lower Mekong, have already altered the ecological productivity of downstream ecosystems, such as the Tonle Sap, and may have further negative impacts to the downstream hydrological and floodplain regime (Grumbine and Xu 2011; Arias et al. 2014). The water resources are already overstretched in the South Asian region. Increasing interests in developing hydroelectric potential by both China and India will fuel the geopolitical tensions in the region associated with dams and transboundary water issues owing to unequal and unfair distribution of costs and benefits and governance issues (Kattelus et al. 2015).

Discussion and conclusion

The Himalayan region is under scrutiny in light of an increasingly large body of evidence of cryospheric, hydrologic and climatic changes. There is mounting warning signs that changes in regional hydro-climatology are inevitable and that the region is susceptible to increasing extreme climate and weather events and changing temperature and precipitation regimes in the coming decades. Although there is strong evidence that frequency of hazards across the Himalaya and surrounding lowlands has been increasing over the last decade, the linkage between climate change and hazards remains to be fully understood and investigated. Hazards and disasters in mountainous environments such as the Himalayas are also related to several other factors such as natural causes (e.g. seismic activity), environmental degradation and land use/land cover changes. Climate change is one of the many elements in this complex system that could amplify existing stress on resources, socio-economic, and political security.

A better understanding of the future trajectory of climate and the impacts of climate change on hazards, weather extremes and water resources is critical for adaptive and mitigation measures, and disaster preparedness and reduction. Current ability to predict future hazards and losses are particularly limited for this region mostly due to uncertainties associated with climate change projections. Despite the uncertainties, multi-model projections show agreement towards an overall increase in annual precipitation in the HKH river basins, reduction in snowmelt, increase in glacier melt and increase in climate extremes (Panday et al. 2014; Nepal and Shrestha 2015). Projections of demographic composition of specific regions are also limited for the region, but overall increased population and urbanisation translates to increased human exposure to climate-related hazards. We know that natural and hydro-climate hazards are not unique to this region and there is a high probability these may likely exacerbate given the inevitability of changes to the climate and hydrological system.

Recent hydrological disasters such as the Indus basin and Kedarnath flooding events have exposed the vulnerability of this region and also raised questions about its changing hydro-climatology, and the long-term implications for perennial and pervasive hazards in this region (NRC 2012). This gap in the knowledge of short and long-term implications of the impact of climate change on hazards in the Himalayas is also due to lack of adequate, long-term monitoring and data collection efforts. Such data is critical for monitoring and management of resources, forecasting and early warning systems, as well as disaster mitigation and response. For better anticipation of future hydro-climatic hazards and disasters in this region, there are several challenges which include (a) high uncertainty in measurement, modelling and forecasting; (b) high spatio-temporal variability in hazard losses across multiple scales and (c) better understanding of socio-economic vulnerability and resilience (NRC 2012). The environmental security of the HKH therefore rests on regional cooperation amongst HKH member countries; information sharing; capacity building; improved monitoring, forecasting and warning systems and measures for disaster risk reduction.

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