Mountains and Climate Change

A Global Concern

Sustainable Mountain Development Series

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Cover photo: Mount Illimani, above La Paz, Bolivia (C. Devenish)

Contents

6 Food Security in Mountains

7 Mountain Economy

Mountains and Climate Change: A Global Concern

Foreword

Mountains are the world's water-towers: mountain regions provide freshwater to half of humankind. This water is critically needed for domestic use, lowland irrigation and hydropower production. Further, mountains are centres of biological diversity, key sources of raw materials and important tourist destinations. As providers of crucial ecosystem goods and services, mountains are essential for global sustainable development.

At the same time, mountains are highly sensitive to the forces of global change. They are especially vulnerable to climate change impacts. Some of the most visible signs of climate change are found in mountains, in particular glacier retreat, as was emphasized in the recent report by the Intergovernmental Panel on Climate Change (IPCC). This raises critical questions: How will vital mountain goods and services be affected by climate change? Will mountains continue to supply the same level of freshwater to humankind? What will be the relative magnitude and impact of climate change in mountains and adjacent lowlands? What needs to be done – practically and at the policy level – to address these issues?

Together with many other partners, the Swiss Agency for Development and Cooperation (SDC) and the United Nations Environment Programme (UNEP) have supported a wide array of initiatives to strengthen the position of mountains on international, regional and national agendas. Prominent examples include the creation of Chapter 13 on mountains in Agenda 21, adopted at the Rio Earth Summit in 1992, the establishment of the Mountain Partnership following the World Summit for Sustainable Development in Johannesburg 2002, and the mountain-related paragraphs in the Rio+20 outcome document. The current discussion on the post-2015 agenda and sustainable development goals (SDGs) provides another important opportunity to raise awareness of mountains vis-à-vis sustainable development.

The present publication, prepared on the occasion of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 20) in Lima 2014, underscores the commitment of SDC and UNEP to sustainable mountain development. It aims to provide a synthesis of current knowledge on mountains and climate change, while emphasizing mountains' relevance to global sustainable development and raising awareness of possible changes and challenges for mountain regions resulting from climate change.

We hope that this publication contributes to fostering a comprehensive understanding of the role and importance of mountain ecosystem goods and services for global sustainable development. Finally, we hope it triggers practical action in response to climate change and the challenges it poses to mountain regions in our rapidly changing world.

Manuel Sager
Ambassador

Jan Dusik
Director and Regional
Representative UNEP

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1

Climate and Mountains

Stellihorn, Switzerland (P. Noti)

Niesen, Switzerland (A. Stickler)

Climate Change and Mountains

Stefan Brönnimann
Marcos Andrade
Henry F. Diaz

The world's mountains are home to about 800 million people. They serve as water towers for billions and provide ecosystem services for the entire globe. Climate change will affect the world's mountain regions and may jeopardize the important services provided by mountains. This could include impacts on drinking water supplies, hydropower generation, agricultural suitability and risks of natural hazards. Climate change may produce intensified extreme weather events such as heat waves, drought, and heavy precipitation leading to flooding and landslides in mountains and to extensive flooding in surrounding lowlands.

Mountain regions display large climate gradients within small spatial scales, and host a diversity of microclimates and macroclimates. This is due to their altitudinal extent, topography, and their effects on atmospheric flow. For instance, differences in solar insolation between mountains and forelands produce characteristic wind systems. The overflow over topography can trigger convection and precipitation.

Mountain climates

Large mountain ranges often act as climatic barriers, with humid climates on their windward side and semi-deserts on their lee side. Due to their altitudinal extent, many mountain regions intersect important environmental boundaries such as timber lines, snow lines or the occurrence of glaciers or permafrost. Climatically induced changes in these boundaries could possibly trigger feedback processes (see Box on page 11) affecting the local climate. For instance, a rising snow line and thawing permafrost could increase the risk of natural hazards as well as accelerate warming trends due to lower reflectance. Changes in these boundaries can have sharp consequences for ecosystems (e.g. species habitats) and can influence natural hazards, economic potential and land use.

At an even larger scale, mountain regions such as the Himalayas and the Tibetan Plateau (see case studies) play a pivotal role in monsoonal circulations. The effects of climate change on mountain regions could alter monsoon flow and intensify monsoon precipitation, affecting agricultural conditions for a huge portion of the global population.

Observed changes

Over the past 100 years, the globe has warmed by about 1 °C [1]. However, this warming has not been spatially uniform. The continents have warmed faster than the oceans and higher latitudes have warmed faster than lower ones. The Arctic has warmed especially fast (Figure 1.1). Rates of temperature increase have also changed over time. The last 50 years have seen a higher rate of warming than the last 100 years.

Mountain areas worldwide – i.e. areas over 1 000 m – have not warmed any more or less than lower-lying land areas over the last 35 years. However, the vertical structure of the atmospheric warming depends on the latitude (shown in Figure 1.2 for the period since 1979). In the Arctic, recent warming has been strongest near the ground. On the one hand, this is because of surface-level feedback processes such as "sea ice–albedo feedback" (see Box on page 11) – a positive feedback process commonly associated with the Arctic that also applies to snow-covered mountain regions. On the other, it is because convection is rare in the Arctic, so the greenhouse gas-induced warming of the Earth's surface has little effect on the higher reaches of the atmosphere here. In the tropics, by contrast, recent warming has been greatest at higher altitudes. This is due to the additional evaporation near the ground. Tropical convection transports the additional moisture to the upper troposphere, where heat is released during condensation. Such high-altitude amplification of warming trends could increasingly affect mountain regions and impact water resources in the future. Whether or not tropical mountain peaks such as those in the South American Andes might experience particularly magnified warming in a hotter, wetter world demands further analysis. Mountain climates often exhibit spatially complex trend patterns within a given region.

Policy messages

- Mountain regions have warmed considerably over the last 100 years, at a rate comparable to that of lowland regions.
- Mountain regions intersect important environmental boundaries such as tree lines or snow lines – boundaries whose altitudes have increased in the past century and will advance further in the future.

Harmony Lake, Canada (P. Noti)

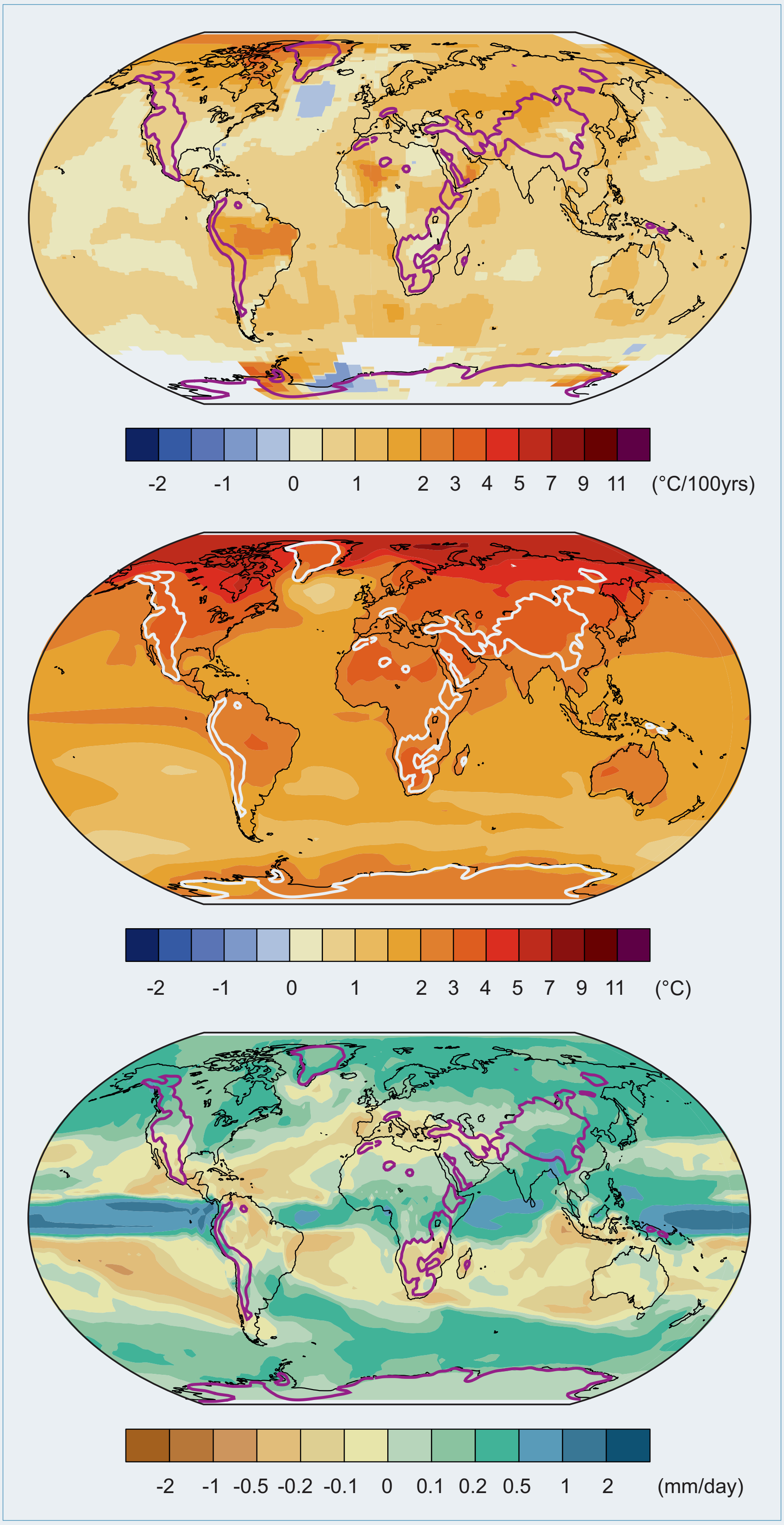


Figure 1.1. Linear trend in annual mean surface air temperature (top) from 1900 to 2013. Data source: NASA/GISS [2]. Modelled changes in temperature (middle) and precipitation (bottom) from 1985–2005 to 2081–2100 according to a moderate-to-high emissions scenario (RCP6.0, CMIP5 Atlas subset from KNMI Climate explorer; see [3]). Purple and white lines indicate topography over 1 000 m

Feedback and nonlinear behaviour of the climate system

The climate system – comprising the atmosphere, ocean, land, ice masses and the biosphere – is highly complex. It does not always react in a linear way to imposed disturbances. "Feedbacks" can either stabilize the system or amplify the response. The system may exhibit "tipping points", and changes may be "irreversible" or exhibit path-dependent behaviour ("hysteresis"). Below are definitions of these terms, closely following IPCC (2013):

Feedback

An interaction in which a perturbation in one climate quantity causes a change in a second, leading to an additional change in the first quantity. If that change weakens the initial perturbation, the feedback is said to be negative; if it strengthens the initial perturbation, the feedback is positive. Sea ice–albedo feedback is an example of positive feedback: a decrease in sea ice reduces the reflectance of shortwave radiation, leading to an increase in the energy absorbed by the ocean, which in turn causes a further decrease in sea ice. The same type of feedback mechanism affects the snow line in mountain regions.

Tipping point

A tipping point is a critical threshold after which a global or regional climate shifts from one stable state to another stable state (reversibly or irreversibly). For instance, if ocean salinity in a certain area of the North Atlantic falls below a certain – presently unknown – threshold, Atlantic overturning circulation may cease. Several tipping points have been posited that could affect the large-scale climate system. They involve, for example, the melting of Arctic sea ice, ice shields, Tibetan glaciers, and deforestation in the Amazon. Nevertheless, our knowledge in this field is still very limited.

Irreversibility

A change in the climate system is considered irreversible if the recovery is significantly slower than the time scale of the change. In addition, irreversibility is often considered in terms of politically relevant time scales, or based on feasible planning horizons of several decades. Considered this way, the melting of Alpine glaciers is seen as irreversible.

Hysteresis

A system that displays a sort of memory, such as the climate system, may exhibit path dependence in its reaction to perturbations, termed hysteresis. For example, the strength of the Atlantic overturning circulation depends on freshwater input into the North Atlantic, but for the same input it may exhibit two quasi-stable states – active or absent – and which state the system is in then depends on the previous state of the system.

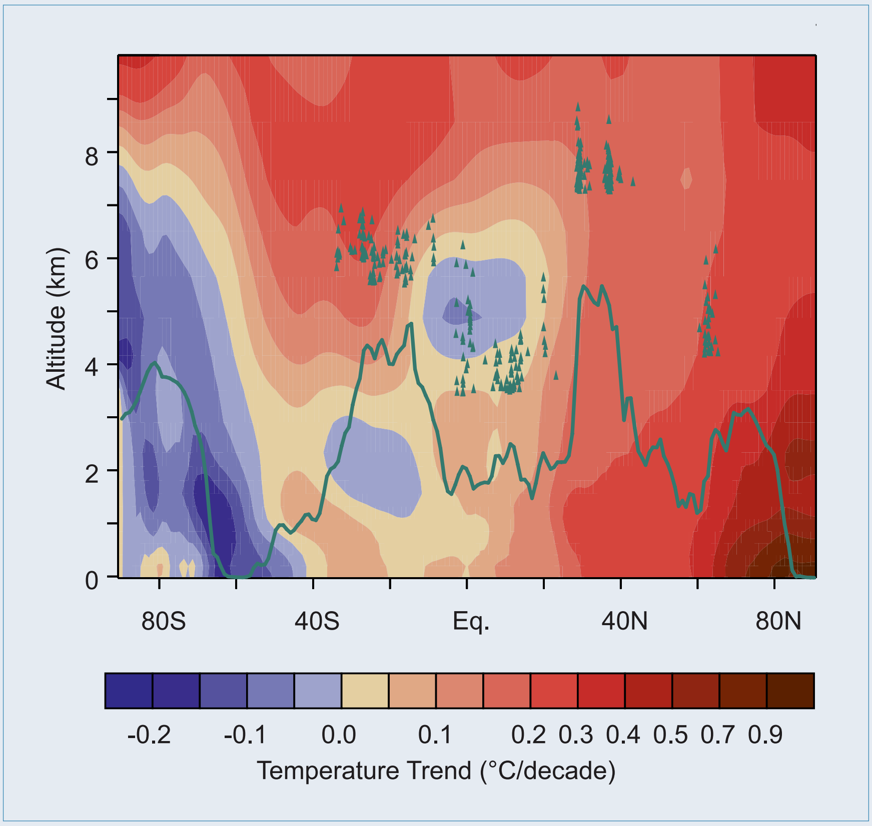


Figure 1.2. Linear trend in zonal annual mean temperature from 1979 to 2013. The green line denotes the heights of large mountain ranges (e.g. Andes ca. 4 000 m near 20° S, Tibetan Plateau ca. 5 000 m near 30° N); individual peaks are shown as green triangles. Data source: ERA-Interim reanalysis [4]

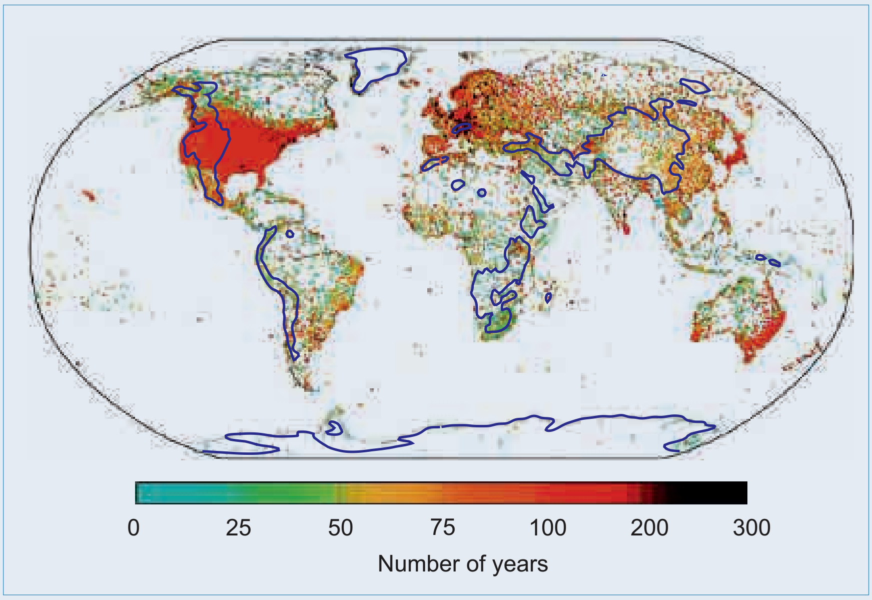


Figure 1.3. Location and length of record of 32 000 meteorological stations in the databank of the International Surface Temperature Initiative (ISTI, http://www.surfacetemperatures.org/). Blue lines indicate topography over 1 000 m

Changes in patterns of precipitation over the last century are even less well quantified. Clear trends have only emerged in certain specific regions. Mountain regions frequently appear to form a boundary between positive and negative precipitation trends [1].

Even though accounting for mountain regions' complex climatic processes is considered important for understanding broader climate trends, many mountain regions remain insufficiently monitored regarding climate parameters such as temperature and precipitation (Figure 1.3). Moreover, most of the meteorological stations in mountain regions are located in valleys, meaning that slopes and peaks are underrepresented in resulting data. At the same time, deriving climate data products for local users in mountain regions – by "downscaling" results from global climate models to the local scale – is difficult for providers of climate services. Yet there is a need for this type of local data because mountain regions host diverse economic activities such as agriculture, mining and tourism, as well as infrastructure that is susceptible to natural hazards (e.g. roads, hydropower stations).

Future changes

According to the IPCC Fifth Assessment Report [3], the globe will warm between 1.5 °C and 4.5 °C by the period of 2085–2100, depending on the prevailing emissions scenario (Figure 1.1). Similar to the previous century, future temperature increases are expected to be stronger over land than over the ocean, stronger at high latitudes than in the tropics and, in the tropics, stronger at high altitudes than near the ground [3]. The latter prediction of greater warming at high altitudes, supported by global models [5], demands further study in individual mountain regions. Nevertheless, it is clear that important environmental boundaries such as snow lines and freezing lines will move higher up in the future. For certain mountain regions, for instance the tropical Andes (see case study), this could accelerate the melting of glaciers and reduce water supplies in the long term. Precipitation is projected to increase in the inner tropics and at mid to high latitudes, but is expected to decrease in subtropical dry zones. However, seasonal differences are also predicted. Almost everywhere, heat waves will likely become more frequent and longer-lasting. Other extreme weather events such as heavy precipitation might increase in intensity, though not necessarily in frequency.

Climate Change in the European Alps

The European Alps are home to diverse ecosystems due to their complex orography and their position between the temperate European climate and the Mediterranean climate. At the same time, the Alps are densely populated and intensively used for tourism, transportation, hydropower, agricultural activities and industrial purposes. The famous glaciers of the Alps are not only a touristic asset, but also a water resource and a key part of Alpine countries' identity.

Stefan Brönnimann
Marcos Andrade
Henry F. Diaz

Sky over Grindelwald, Switzerland (S. Kummer)

Climate indicators are well monitored in the European Alps, and many data series reach back into the nineteenth century. Temperatures have increased by about 0.12–0.20 °C per decade over the last 100 years, with a particularly pronounced increase since the mid-1980s [1]. This recent Alpine warming occurred at about three times the rate of the global average. The regional warming trend exhibits little dependence on altitude. In fact, temperatures at altitudes above 4 000 m were found to increase at the same rate as in the lowlands [2]. In addition to mean temperatures, temperature extremes have also changed. In particular, the frequency of warm days has increased and the frequency of cold nights has decreased [3].

Regional precipitation changes were small over the last century, and the main factor affecting snowpack was temperature. At altitudes around 700 m, winter snow is particularly sensitive to temperature changes [4]. Studies show that Alpine snowpack has decreased since the mid-1980s – with high year-to-year variability – and that the snow season has shortened [5].

Summer temperatures are an important variable affecting the balance of glacier mass. The zero-degree level in summer has risen about 75 m per decade since 1959 [6]. Alpine glaciers have been receding since the 1980s. In terms of mass, the current loss rate for a sample of eight Alpine glaciers is estimated to be 2–3 percent per year

Mattmark reservoir and Allalin Glacier, Switzerland (P. Noti)

[7]. The temperature changes also affect vegetation. Shifts in vegetation distribution have already been observed in Switzerland, such as an increase in lowland forest species at mid-elevations and an upward shift in the occurrence of certain species [8].

Studies on future climate change scenarios in Switzerland point to acceleration in year-round warming and reductions in summer precipitation [9]; analyses produced for Austria suggest the same [10]. Climate change impacts in Alpine regions are expected to continue unabated or to intensify. Indeed, glaciers in Austria [11] and Switzerland will continue to retreat in the twenty-first century. A recent Climate Change Impact Assessment [12] for Switzerland projected a near-complete loss of glacial ice by the end of the century under a medium-to-high emissions scenario (A1B). Runoff regimes are projected to change from snow-controlled to rain-controlled. Tree species diversity and biomass in high-elevation forests are projected to increase, whereas forests in dry inner-Alpine valleys may deteriorate even under moderate warming [12].

Observed and Future Changes in the Tropical Andes

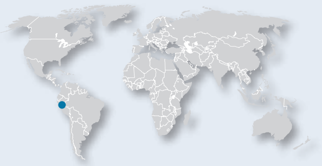
The retreat of glaciers in the region has been one of the most striking changes to take place in the tropical Andes in the last 50 years [1, 2], with smaller glaciers retreating more than larger ones. Precipitation in the region did not display any significant trend over the last century.

Stefan Brönnimann
Marcos Andrade
Henry F. Diaz

View from Mount Chacaltaya, Bolivia (M. Andrade)

Sixty years' worth of observations (1950–2010) from three surface stations in the Bolivian Altiplano indicate long, alternating periods of relative dryness or humidity [3]; no clear trends in annual precipitation or changes in the length of the rainy season were found. Based on a shorter period (1960–2009) and a greater number of surface observations, studies [4] have suggested that humid periods may be associated with warmer ocean temperatures off the Pacific Coast of South America – i.e. with positive phases of the Pacific Decadal Oscillation (PDO)[1] – while dry periods may be associated with colder ocean temperatures (i.e. with negative phases of the PDO). Two SDC-funded projects, CLIMANDES and DECADE, aim at improving climate services and at strengthening university education and research capabilites in climatology in Peru and in Bolivia.

Despite the complexity of the processes determining Andean glaciers' mass balance [5], there is a consensus that temperature increases are driving glacial retreat over the long term. However, surface observations do not always show a clear positive trend. Scarcity of surface data and issues of data quality have made it difficult to discern trends reliably in the tropical Andes. At the same time, there have been efforts to produce a consistent dataset of surface observations for the Andean region. These observations point to an increase in average temperature over the last 60 years. What is more, observations of air temperatures along the American Cordillera from Alaska to Tierra del Fuego indicate that temperatures have increased at high-altitude locations at rates generally exceeding those found



near sea level [6–8]. These indications of warming are consistent with other types of observations made throughout the American Cordillera [9–13]. For instance, a study using satellite imagery of Sajama Mountain (Bolivia, 6 542 m) in the Andes suggests that vegetation has shifted to higher elevations in the last 30 years [14]. A recent study of the Peruvian Andes using aerial photographs and satellite imagery shows a similar pattern [15]. Given the suggested relationship between PDO and temperatures in the tropical Andes, the regional effects of global warming could be exacerbated in the near future when the PDO shifts from a negative to a positive phase.

Looking further into the future, projections (Figure 1.4) suggest that the freezing level – an important threshold for maintenance of mountain glaciers – may rise several hundred metres by the end of this century. This phenomenon is expected to affect tropical regions more strongly than regions at mid and high latitudes. The magnitude of projected change highly depends on the level of radiative forcing, such that predicted changes under a strong emissions scenario (RCP8.5) are about 50 percent greater than under a weaker emissions scenario (RCP4.5) (Figure 1.4). The marked difference between possible scenarios underscores the need for implementation of effective policies that slow the growth of anthropogenic greenhouse gases in the atmosphere. Even in the absence of significant changes in precipitation, a warmer climate will likely lead to higher water stress in the Andean region, bearing consequences for the availability of water for both humans and ecosystems.

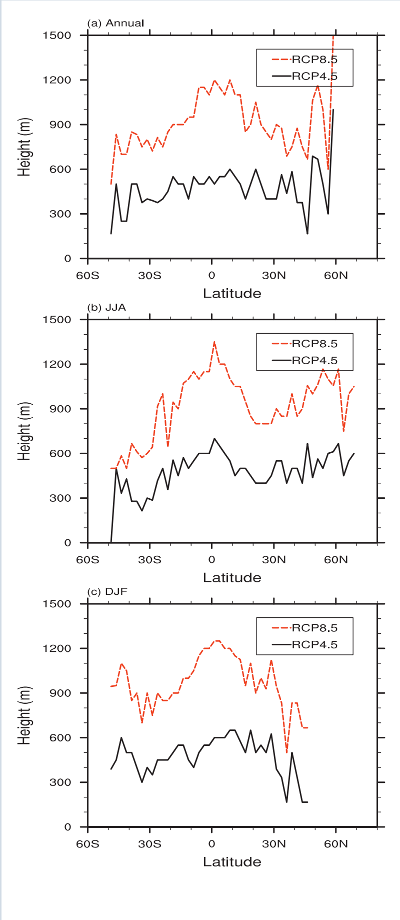


Figure 1.4. The projected rise of freezing levels along the American Cordillera in the current century (from 1981–2000 to 2081–2100) on an annual basis (a); for boreal summer (June, July, August) (b); and for boreal winter (December, January, February) (c); under low (RCP4.5, black) and high (RCP8.5, red) emissions scenarios. For example, under a high emissions scenario (red), the freezing level would rise by 1 200 m near the equator (0 latitude) for all three time periods concerned. Source: [8]

Huayna Potosí, Bolivia (M. Andrade)

[1]The PDO is a basin-wide change of sea-surface temperature in the Pacific best described as a long-lasting El Niño-like pattern of Pacific climate variability.

Climate Change and Black Carbon in the Himalayas

Among the world's mountain regions, the Himalayas play a particularly important role. About 1.5 billion people live in downstream river basins of the Himalayas. Melting snow and glaciers could severely impact ecosystems and human well-being in the region.

Stefan Brönnimann
Marcos Andrade
Henry F. Diaz

Atmospheric Brown Cloud over the Ganges Plain (NASA/MODIS)

Over the past century, air temperatures increased in the Himalayan-Tibetan region at a pace similar to the global average. Since 1979, however, a very rapid temperature increase has been identified in the middle troposphere during the pre-monsoon season. This temperature increase spans a region stretching from the Himalayas across Pakistan, Afghanistan and Iran, all the way to the Arabian Peninsula, with appreciable warming occurring over the Hindu Kush mountains [1, 2]. This strong increase has been partly attributed to the presence of black carbon or dust in the middle troposphere. These aerosols absorb solar radiation and heat the surrounding air. The cloud of aerosols that forms over the Indus Valley and northern Indian Ocean each year is called the "Asian Brown Cloud" – it is mainly caused by human-induced pollution from domestic or agricultural wood burning, industry, traffic, etc. It severely affects human health in the Indo-Gangetic Plain. In addition to increasing mid-tropospheric temperatures through absorption and decreasing surface temperatures by dimming the sun, aerosols affect the generation and dynamics of clouds and have been posited to affect atmospheric circulation. They may influence hurricanes over the Indian Ocean or play a role in the onset of monsoons; however, the nature of these impacts is not yet fully understood.

Air pollution over Kathmandu, Nepal (T. Kohler)

Aerosol deposition lowers the albedo of glaciers in the central Tibetan Plateau, with less solar radiation reflected back into the atmosphere. Thus, aerosols could be contributing to glacier melting. However, insufficient observation and the lack of a monitoring network in this critical region have hampered our understanding of the dynamics at play.

No long-term trend has been found in seasonal mean monsoon rainfall. In the future, the Asian monsoon circulation is expected to weaken and its moisture content is expected to increase. As a result, more intense monsoon rainfall events are predicted.

Climate Change in the Carpathian Region

The Carpathian Mountains play an important role in Europe's overall climatic conditions and are home to unique ecosystems that are already being affected by climate change. Opportunities exist to steer the Carpathian region onto a sustainable, climate-proofed path, building on a strategic approach to climate change adaptation across different sectors and levels of governance.

Sandor Szalai
Matthias Jurek
Harald Egerer

High Tatras, Slovakia (© CarpathCC)

The Carpathians form an arc stretching about 1 500 km across Central and Eastern Europe, making them the second-longest mountain system in Europe. They strongly affect the surrounding climate, giving rise to very different weather patterns within the Carpathian region (Figure 1.5) in comparison with neighbouring areas. While the mountain range is quite long, it is not especially high – its highest peak reaches only 2 655 m. The climate of the Carpathian region is shaped by the combined effects of the Atlantic Ocean, the Mediterranean Sea and the large Asian continent.

Various climatic changes are evident in the region. Summer temperatures have exhibited the greatest change in recent decades, with temperatures having increased by as much as 2.4 °C in certain areas over the last 50 years. Winter temperatures have not warmed significantly – in certain places, even (non-significant) cooling has been detected. Changes in precipitation display a mosaic pattern. Overall, precipitation has increased in the summer and winter months, and decreased in the spring. These results do not fully match broader climate models. The drying that can be clearly observed in the western part of the region and other topographic effects have not been reproduced in modelling results [1].

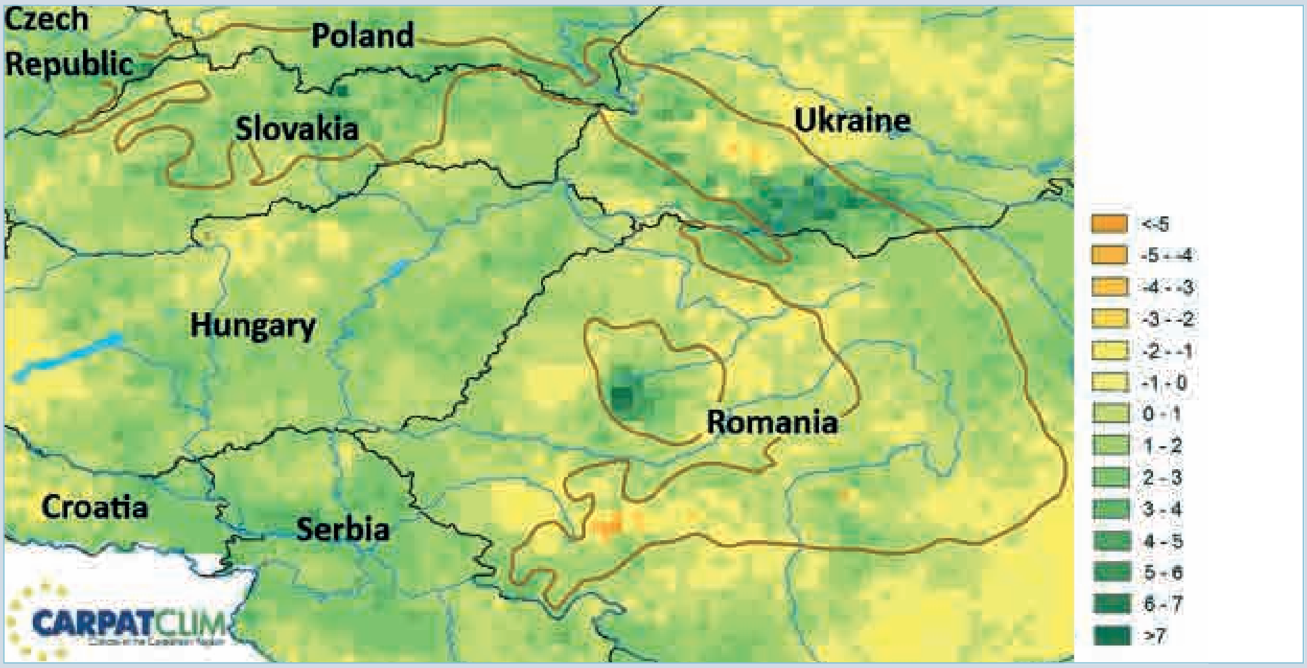


Figure 1.5. Climate change in the Carpathian region: Change in the number of days per year with over 20 mm of precipitation, between 1960 and 2010 [1]. The 500 m contour line (brown) serves as an approximate boundary of the mountain area.

According to reports by the Intergovernmental Panel on Climate Change (IPCC), intensification of precipitation can be expected. While precipitation totals do not appear to have changed significantly, intensification is indeed evident. Such intensification can be shown using various indices, but they all point in a similar direction. As seen in Figure 1.5, changes in the number of days with precipitation over 20 mm are almost uniformly positive [1]. But the simultaneous increase in precipitation intensity and decrease in total days with precipitation have negatively affected the surface water balance, resulting in diminished water availability and increased erosion. Water-management adaptation measures are needed to address the situation.

These changes are impacting nature, economy and health in the region [2]. The Carpathians encompass Eastern Europe's largest contiguous forest ecosystem, which provides habitat and refuge for many endangered species. Indeed, the mountain range is a hotspot of biodiversity, including Europe's largest remaining areas of virgin and old-growth forest outside of Russia [2]. A bridge between Europe's northern and southwestern forests, the Carpathian Mountains serve as a corridor for the dispersal of plants and animals throughout Europe [3, 4]. The area covered by certain tree species has already undergone change, and vulnerable protected ecosystems are in danger. Forests are exposed to many natural disasters that are partly attributable to climate change. Hundreds of climate change adaptation measures have already been identified [3], with the following showing the greatest promise:

- Maintenance of alluvial forests in wetlands
- Supporting and implementing high nature value farming in grasslands
- Compensation schemes for forest protection.

Lessons learned

- Field-based measurements and modelling results must be synthesized to establish appropriate adaptation measures and reduce methodological uncertainty.
- More investment and capacity building are needed to identify adaptation measures capable of protecting the unique ecosystems found in the Carpathian region.

Realizing the Strategic Agenda on Adaptation to Climate Change in the Carpathian Region

Following an initiative by the European Parliament and funded by the EU, a team of international experts has been studying climate change and adaptation measures in the Carpathians. The outcomes of three projects – Preparatory Action on Climate in the Carpathian Region (CARPATCLIM), Climate Change in the Carpathian Region (CarpathCC) and Carpathian Integrated Assessment of Vulnerability to Climate Change and Ecosystem-Based Adaptation Measures (CARPIVIA) – have produced a diversified portfolio of sustainable adaptation measures. At the intergovernmental level, facilitated by the Secretariat in Vienna, Austria, the Strategic Agenda on Adaptation to Climate Change in the Carpathian Region was adopted by ministers at the Fourth Meeting of the Conference of the Parties to the Carpathian Convention (COP4) in 2014. The agenda includes recommendations for policy, institutional change and potential priority adaptation actions. It calls upon contracting parties, local and regional authorities and other stakeholders involved in management and development of the Carpathian region to formulate policies and design strategies to adapt to climate change and to mitigate its adverse effects.

Towards a transnational approach to climate change adaptation

Linking different policies of nature conservation, river basin management and sustainable farming could significantly strengthen the Carpathian region and its resilience to climate change. Transnational cooperation – as facilitated by the Carpathian Convention – is crucial to adapting to climate change and increasing regional resilience. Indeed, the predicted impacts of climate change, such as seasonal changes in temperature and precipitation, will occur over vast geographical areas, affecting several countries at once. Approaches scaled to the "eco-region" rather than the nation-state are better suited to the challenges. At the same time, many individual countries lack the tools and capacities to adapt to climate change, such as the ability to designate and map future refuge habitats for wetlands and grasslands. The support provided by externally funded joint initiatives helps to fill the gaps and build cooperative capacity. Also key is the creation of flexible, equitable financial instruments that enable benefits and burdens to be shared. Overall, it is essential to build new partnerships between governments, civil society, research and education institutions, the private sector and international organizations.

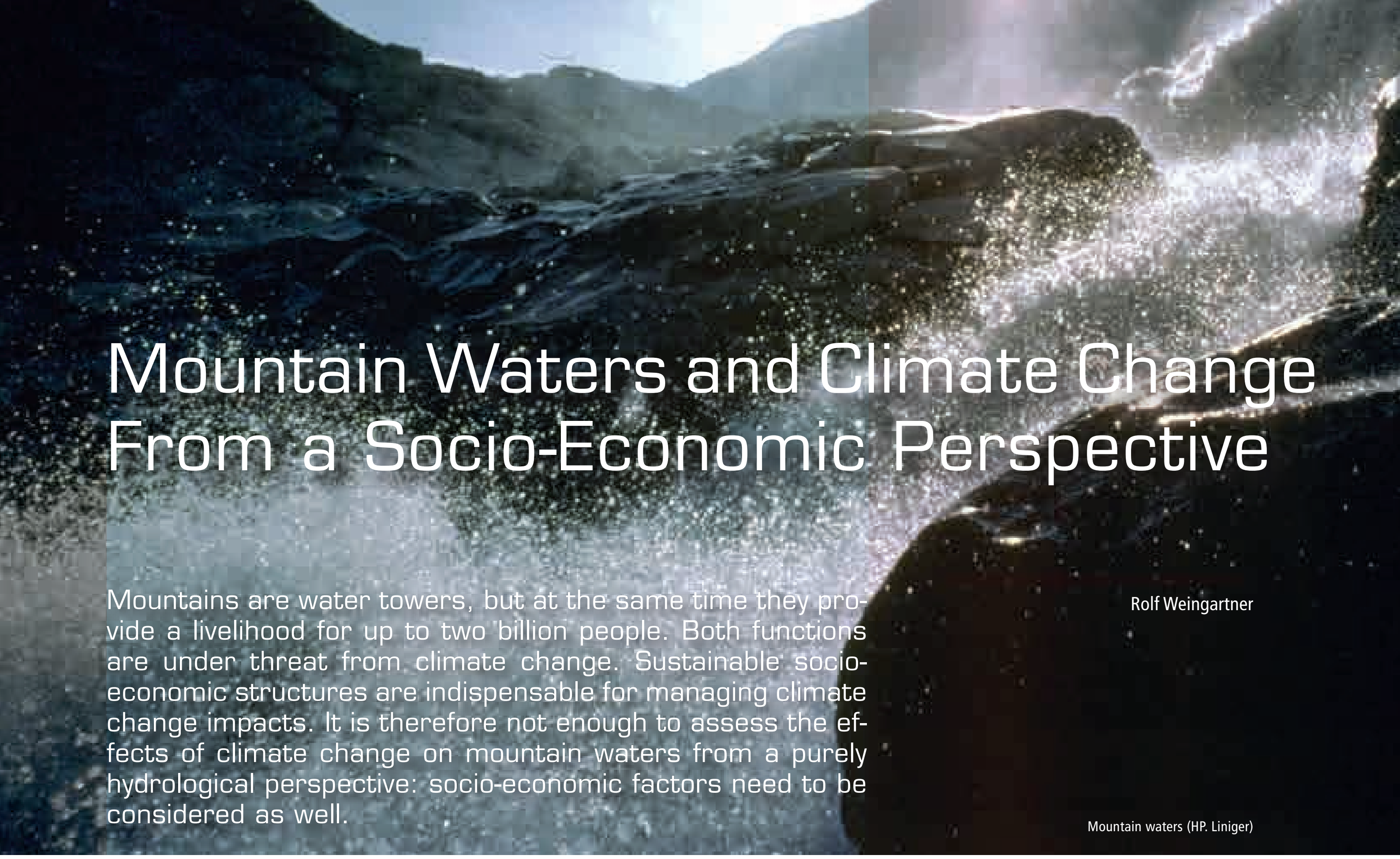
In the context of its interregional project "Climate change action in developing countries with fragile mountainous ecosystems from a sub-regional perspective" (financially supported by the Government of Austria), the United Nations Environment Programme (UNEP) aims to share knowledge gained in the European Alps and Carpathians with other mountain regions.

Participants at the Fourth Meeting of the Conference of the Parties to the Carpathian Convention, Mikulov, 2014 (© Lenka Burcinova)

A typical landscape in the Carpathian Mountains (© CarpathCC)

2 Mountain Waters

Water channel near Crans-Montana, Switzerland (F. Schneider)



Mountain Waters and Climate Change From a Socio-Economic Perspective

Mountains are water towers, but at the same time they provide a livelihood for up to two billion people. Both functions are under threat from climate change. Sustainable socio-economic structures are indispensable for managing climate change impacts. It is therefore not enough to assess the effects of climate change on mountain waters from a purely hydrological perspective: socio-economic factors need to be considered as well.

Rolf Weingartner

Mountain waters (HP. Liniger)

Mountains are often described as water towers because they serve as a significant source of water for the adjacent lowlands [1]. Indeed, average runoff is approximately twice as high in mountain areas as in lowlands, except in the humid tropics. Nevertheless, this observation only scratches the surface. The assumption that higher precipitation rates and lower evapotranspiration rates cause mountains to generate more runoff than lowlands is correct (Figure 2.1). But a comprehensive hydrological assessment requires consideration of additional factors that can be summarized as water availability and water use (Figure 2.2). Changes in the climate and in socio-economic structures will alter these two parameters. They may evolve quite differently from region to region, given that mountain regions are highly diverse in terms of their environmental, cultural, societal and economic development. There are commonalities, however, and these commonalities are the focus of the following considerations.

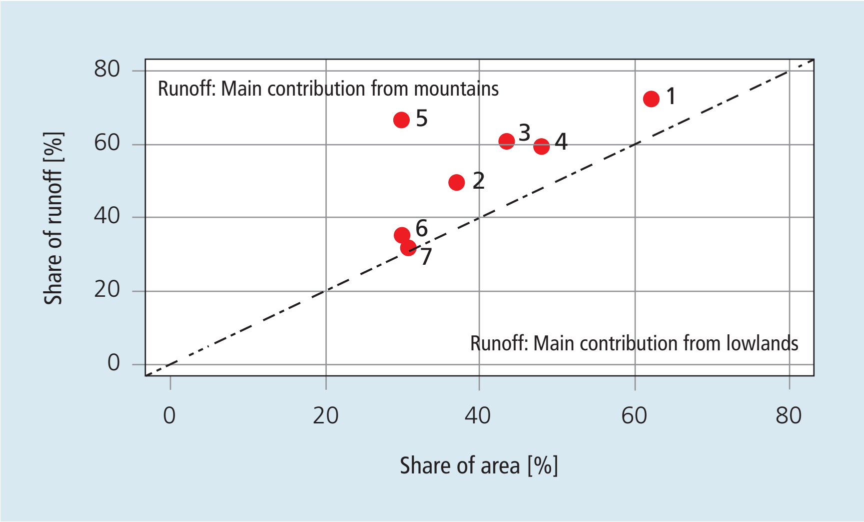


Figure 2.1. Mountains provide an above-average share of runoff in all zones except the humid tropics, as shown in this comparison between their shares of area and their shares of runoff in the different climatic zones. 1: polar, cold; 2: cool, 3: temperate; 4: semi-arid; 5: arid; 6: subtropical; 7: humid tropical. Data source: [2]

Water availability in transition

More than half of the world's drinking water originates from rivers and river-fed reservoirs. The shares of runoff that mountain regions contribute to these rivers are substantial: they range from 40 to 95 percent, depending on the region [2]. Runoff from mountainous watersheds is controlled mainly by precipitation and air temperature (Figure 2.2). While changes in precipitation amounts affect both annual and seasonal runoff volumes, temperature influences seasonal runoff behaviour by controlling snowfall and snowmelt. A rise in temperature usually leads to more runoff in winter, an earlier snowmelt in spring and, as a result, reduced runoff in summer (Figure 2.3). These changes are very likely to become a general trend, as climate models largely agree that temperatures will increase worldwide. The "only" remaining uncertainties concern the extent and the timing of the pre-

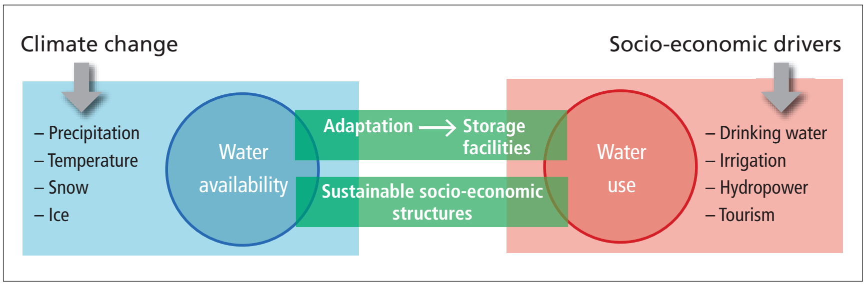


Figure 2.2. Interaction of mountain waters with water availability and water use (R. Weingartner)

Policy messages

- Sound planning of adaptation measures on regional, national and transboundary levels is key, as the direction of change in hydrological systems is widely known. Adaptive measures such as implementing storage facilities have already been identified. Planning must be based on sufficient and sound evidence; but data are still lacking in many mountain regions.
- Adaptive measures are part of an overall strategy which also includes mitigation. The latter is much more effective than adaptation. Creating sustainable socio-economic structures must be part of the overall strategy: Without such structures, most measures will fail.

Hydropower facility, Binntal, Switzerland (R. Weingartner)

"A total of 65 countries use over 75 percent of available water for food production, including China, Egypt and India, all of which rely heavily on mountain water." [6]

dicted temperature rise. By contrast, climate change effects on precipitation remain highly uncertain in terms of both the extent and the direction of change [3]. Figure 2.4 shows how annual precipitation might change in the world's mountain regions. It suggests that annual precipitation will increase in Asia, the northern Andes and the northern Rocky Mountains, whereas it will decrease in the Mediterranean basin, the southwestern United States of America, Central America and Southern Africa. Most climate models assume that the seasonal distribution of precipitation will not change much; but they predict a tendency towards drier dry seasons and wetter wet seasons. In conclusion, while snowmelt and glacier melt in the past mostly succeeded in compensating for summer dryness, we must now expect a strong reduction in summer runoff. This is one of the greater future challenges, especially because the demand for water is highest in summer.

Peak water in glaciers and the key role of snow

From a supraregional perspective, snow is a far more important source of water than glaciers are; this is due to its vast spatial extent. In Switzerland, for example, snowmelt contributes 40 percent of total runoff, whereas ice melt contributes only 2 percent. But in smaller and more glaciated catchments, a temperature-driven reduction in glacier mass is nevertheless hydrologically significant. It results in a temporary phase of increased summer runoff, a phenomenon referred to as "peak water". Its extent and duration depend primarily on the size of a glacier and the degree of glaciation in a catchment. A constantly retreating glacier will eventually shrink to a critical size where it can no longer deliver the same amount of water as before it began to retreat; this marks the end of the peak water phase with above-average runoff. Glaciated catchments in the tropics and several catchments in the European Alps have already reached or surpassed peak water, meaning that the glaciers in question will be unable to fulfil their important hydrological role in the near future [4].

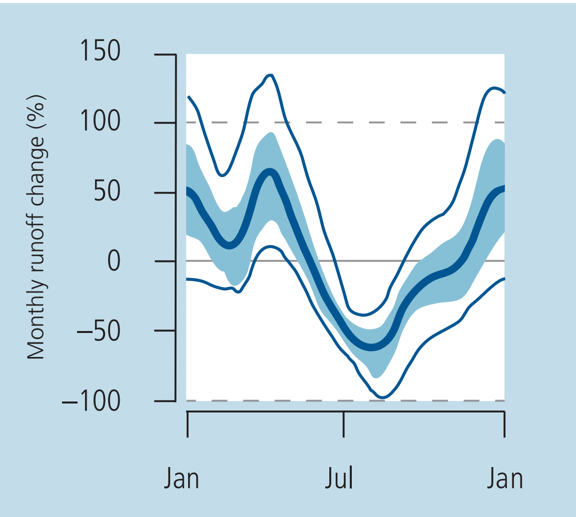


Figure 2.3. Mean relative monthly runoff change (in percent) of an Alpine basin in Switzerland between today and 2085 based on the medium emissions scenario A1B. Runoff is projected to increase in winter and decrease in summer. The mean over the uncertainty range (bold curve) is shown along with the standard deviation (shaded area) and the minima/maxima (thin curves). Source: [3]

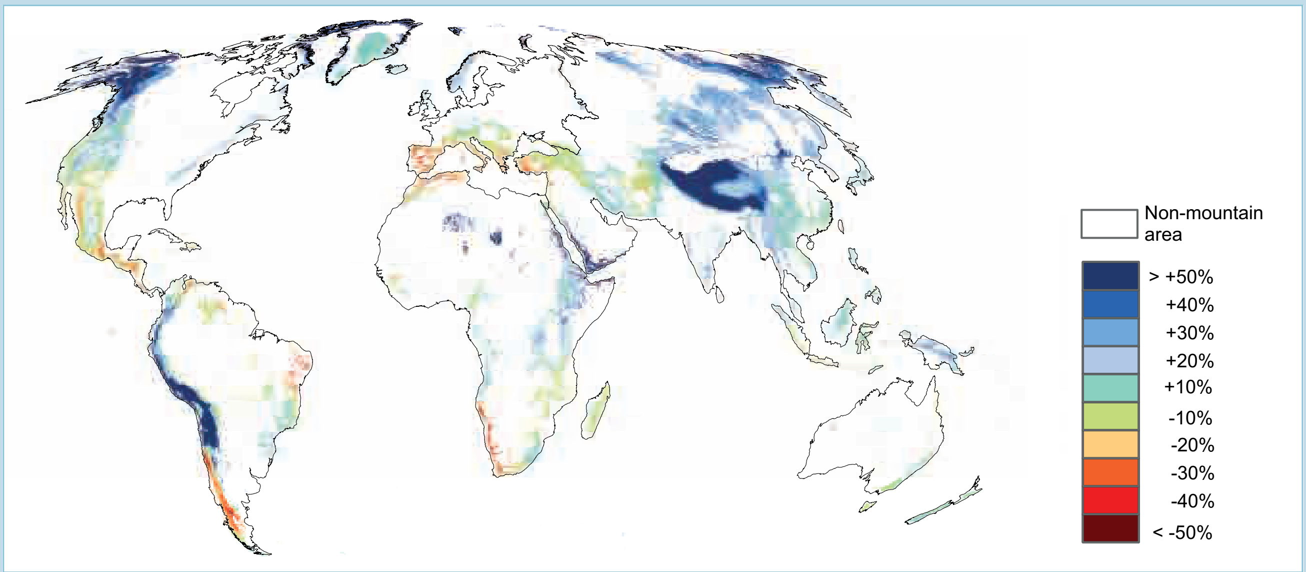


Figure 2.4. Percentage change of annual precipitation between 1950–2000 and 2070, based on the high emissions scenario RCP8.5. Precipitation data from IPCC (2014). Definition of mountain regions according to Kapos (modified). Courtesy of Andreas Heinimann and Lukas Wuersch (Centre for Development and Environment and Institute of Geography, University of Bern)

Demand for artificial storage facilities

We can say that climate change will lead to changes in snow and ice, and hence in seasonal runoff with lower flows particularly during summer seasons. At the same time, socio-economic pressure on mountain waters is constantly increasing, particularly in summer: More and more water is being needed for farming, energy production, industrial production, tourism and drinking. These opposing trends can be bridged by means of artificial multipurpose storage facilities. They can store the abundant winter runoff and thus compensate for reduced summer runoff while meeting the various users' water needs. In addition to building new storage facilities, existing single-purpose hydropower facilities can be transformed to multipurpose facilities for hydropower, irrigation, drinking water supply, flood control and other uses. Indeed, from today's perspective, this is one of the most important adaptation measures to be taken. It should be complemented by water-management schemes that regulate demand and set priorities for times of emergency.

Lake in the Andes (W. Buytaert)

The importance of looking at socio-economic factors

We estimate that over two billion people live in mountains and their surrounding lowlands [5], and this number will continue to increase. A case study in the Andes (Rio Santo, Cordillera Blanca) [4] reveals the consequences of this socio-economic pressure that is typical of many mountain regions: the demand for water in this region has drastically increased and will continue to increase. This is the result of population growth, combined with new irrigation systems that were installed in response to advantageous runoff conditions during the peak water phase. But once the peak dies down, supply constraints will be very likely (Figure 2.5). Situations like this are often significantly worsened by insufficient and badly maintained water infrastructure, increasing per capita water demand and urbanization.

A case study in the Swiss Alps (Crans-Montana, Valais) showed that the sustainability of a region's water supply depends on multiple factors: the manifestation of governance (can water infrastructure and management cover the population's needs?), ecological integrity (are the natural resources overused?), justice (do all have equal access to water?) and adaptive capacity (is society capable of reacting to change?). Most mountain regions are neglected border regions where poverty is widespread and a large majority of the population depends on subsistence agriculture; they do not fulfil these sustainability criteria. This is why an isolated focus on climate change is not enough. Ensuring sustainable socio-economic structures and good governance is the real key to managing the effects of climate change.

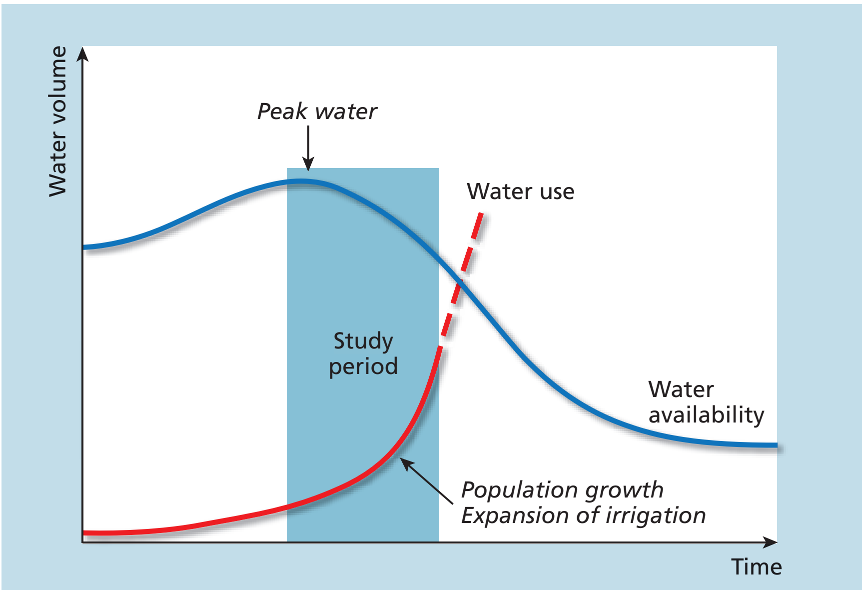


Figure 2.5. Water availability and water use in Rio Santo, Cordillera Blanca (Andes). Based on [4]

Mekong River, China (HP. Liniger)

Andean Water for Peru's Coastal Deserts

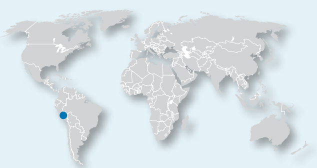
Andean water resources vary widely in time and space. This is most notable on the Pacific side of the Peruvian Andes, where Amazonian humidity reaches only the highest part of the basins, while the seaside gets virtually no rain. The water draining from the Andes to the Pacific represents only 1.8 percent of Peru's water resources [1]. But it is vital for the booming agro-export industry that depends on irrigation, and it provides domestic water for the 60 percent of Peru's population that are concentrated in desert cities such as Lima.

Bert De Bièvre
Luis Acosta

The *páramo* ecosystem's water-regulating capacity is under threat from climate change, Peru (CONDESAN)

The Quiroz river in northern Peru has its origin in the *páramo* grasslands at an altitude of 4 000 m. In the tropics, this is not high enough for a glacier cover. But Amazonian humidity and the water-regulating capacity of the *páramo*'s organic soils make the river an excellent year-round source of water for irrigating mangoes, lemon and even rice in the desert around the city of Piura. Thanks to its agro-export industry, Piura is one of the fastest-growing cities in Peru.

The Chillón river in central Peru is one of three rivers that supply the country's capital city of Lima and its nine million inhabitants with water. Rainfall in the river catchment plays a significant role only at altitudes above 2 000 m (Figure 2.6). The dominant land use in the upper catchment is grazing – like in most of central Peru's highlands. The community of Huamantanga has ancient infrastructure in these uplands for storing water and regulating springs downslope that provide irrigation water for the fields around the village. The system consists of a complex combination of channels that take excess water in the rainy season to infiltration trenches and ponds, from where it can be made available at the right place during the dry season. Today, most of the system is abandoned.



Not only glaciers are driven uphill by climate change

Andean ecosystems are extremely diverse, but they all depend on a vertical niche or altitude range. Just like the well-described retreat of glaciers, where glaciers' lower limits move to higher altitudes, the limits of other biomes also move uphill. *Páramos* and glaciers play important roles in runoff generation and regulation. Much of the area they currently cover lies near their lower altitudinal limits, and accordingly they are prone to high relative losses due to warming: by 2039, the glacier cover will shrink to less than half of what it was in 2010, and *páramos* will shrink by one-third. By comparison, *puna* ecosystems cover less area near their lower altitudinal limit and are therefore less affected by warming (Figure 2.7).

Lima, capital of Peru and the world's second-largest desert city. Its 8.5 million inhabitants depend on mountain waters (E. Nitschke)

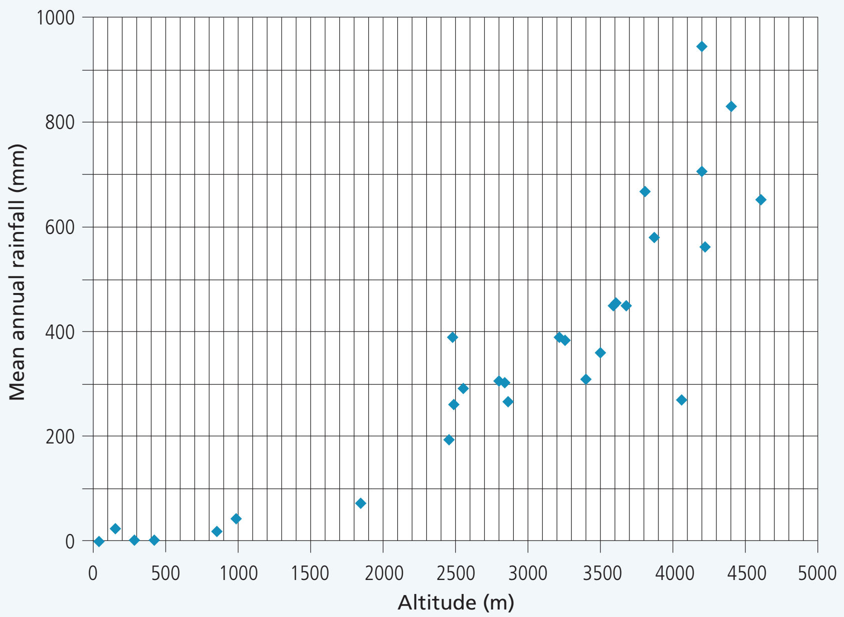
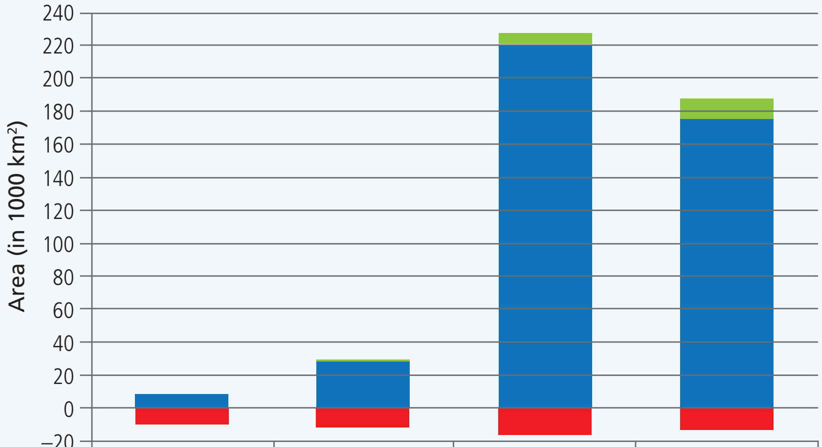


Figure 2.6. Mean annual rainfall by altitude in the Pacific catchments of central Peru. Source: [1]



	Glacier	*Páramo*	Humid *puna*	Dry *puna*
Loss	–10.9	–11.6	–16.5	–14.0
Gain	–	0.2	6.6	12.6
Stable	8.1	27.9	220.0	175.3

Figure 2.7. Area losses and gains (in 1 000 km²) of glaciers and ecosystems above the tree line in the tropical Andes for 2010–2039, under a medium emissions climate change scenario. Source: [4]

How exactly the climate in these areas might change is largely uncertain. But conservation of the *páramos* of Piura and rehabilitation of Huamantanga's precolonial infiltration systems are examples of useful investments in adaptation to climate change that benefit both upland communities and downstream water users.

These projects could be funded by downstream water users through rewards for ecosystem services mechanisms. Peru's government now explicitly aims to establish such mechanisms, after a law on their promotion was passed in June 2014.

In both cases, efforts to implement adaptation measures are driven by a growing demand for water and the prospect of potential future climate change impacts. Irrigation is expanding across widely available desert lands, and urbanization is creating highly localized demand for water. Lima's demand for water has doubled over the last 20 years and will keep growing – a development that will affect water supply in this catchment more severely than climate change [2].

Climate information and monitoring data are typically scarce for higher altitudes – a knowledge gap that seriously hampers research on climate change trends in mountains. Many climate change adaptation initiatives are responding by putting significant efforts in high-altitude and glacier monitoring sites. But another monitoring gap needs attention too: Most adaptation measures, such as re- or afforestation and different water conservation techniques, have not been evaluated for their hydrological benefits. In both the Piura *páramos* and the Chillón catchment, the initiative for Hydrological Monitoring of Andean Ecosystems (iMHEA in Spanish) is engaging in paired microcatchment monitoring to identify the hydrological impacts of land-use change. Established in 2009 [3], the initiative is currently working in 20 catchments in the tropical Andes, from Venezuela to Bolivia. While iMHEA data have the potential to enable the study of climate change effects in the long run, the initiative is primarily intended to increase the effectiveness of climate change adaptation measures in the short term.

Lessons learned

- Uncertainties are huge with regard to climate projections and their hydrological consequences in the Andes. But it can be said with certainty that adaptation efforts must focus on increasing water supply-regulating (or buffering) capacity, for example by means of natural and artificial storage, while keeping water use under control.
- Targeted monitoring of climate change adaptation efforts is urgently needed to improve the efficiency of investments in measures such as reforestation and restoration of ancient soil and water management practices.

Assessing Water Balance in the Upper Indus Basin

The Upper Indus Basin is the main feeder of one of the world's largest irrigation networks. It is key to energy production and to satisfying demand for water in the surrounding lowlands. Taken together, westerly and monsoonal rainfalls, meltwater from seasonal snow cover and long-term ice reservoirs serve to secure the local highland–lowland resource system. However, the exact shares of rainwater versus meltwater in regional water cycles are still uncertain.

Uwe Boerst
Matthias Winiger

Extensive irrigation with glacier meltwater in arid valleys below Mount Rakaposhi (7 788 m), Pakistan (U. Boerst)

Water flowing from the Upper Indus Basin – encompassing the high mountain ranges of the Hindu Kush, Karakoram and Western Himalaya – is vitally important to approximately 215 million people living in the lowlands. However, knowledge of the high-altitude water cycle remains weak. There is an urgent need for interdisciplinary analyses – including field surveys, remote sensing and modelling – to better understand the status and dynamics of this highland–lowland system and its diversity of regional characteristics (Figure 2.8). The few long-term hydro-meteorological observations available – mostly from valleys – do not provide enough reliable information on the system's dynamics and on the processes occurring at higher altitudes.

Recent studies are more accurate on vertical rainfall gradients, ranging from desert-like conditions of less than 100 mm annual rainfall in the valleys to more than 2 500 mm at altitudes of 5 000 m [1, 2]. Glaciers covering up to 50 percent of the area in catchments located above 2 500 m and seasonal snowfalls play important roles in the water cycle (Figure 2.9). Water stored as seasonal snow cover and long-term ice is gradually released during the hot summer months, satisfying the high local demand for irrigation water. Due to random or completely absent high-elevation records for the region, hydro-meteorological analyses have had to rely mainly on model-based approaches, resulting in rather divergent precipitation and water balance values, especially for individual subcatchments (Table 2.1). In addition, climate change may further alter these values in the future. While the western part of the region may receive increasing snowfall in the coming decades, the eastern part could experience the opposite.

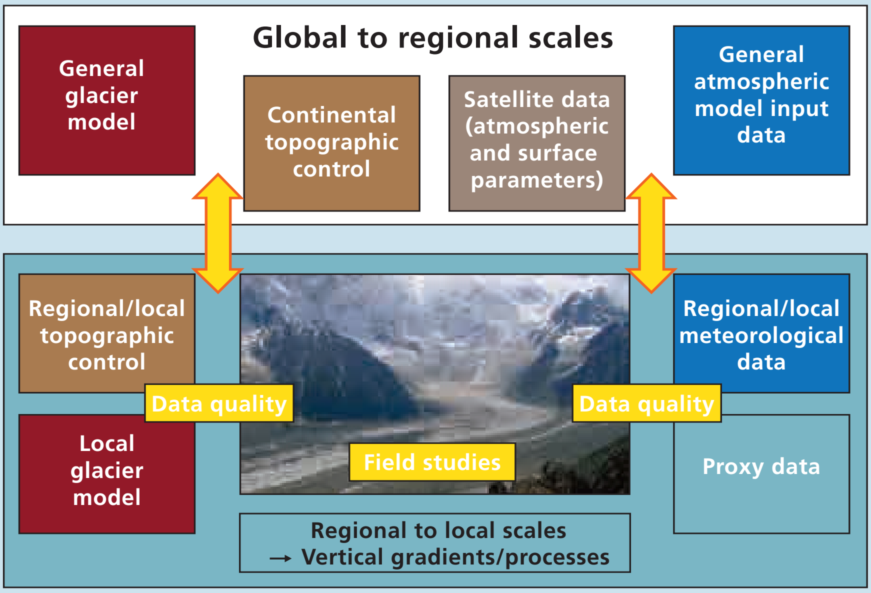
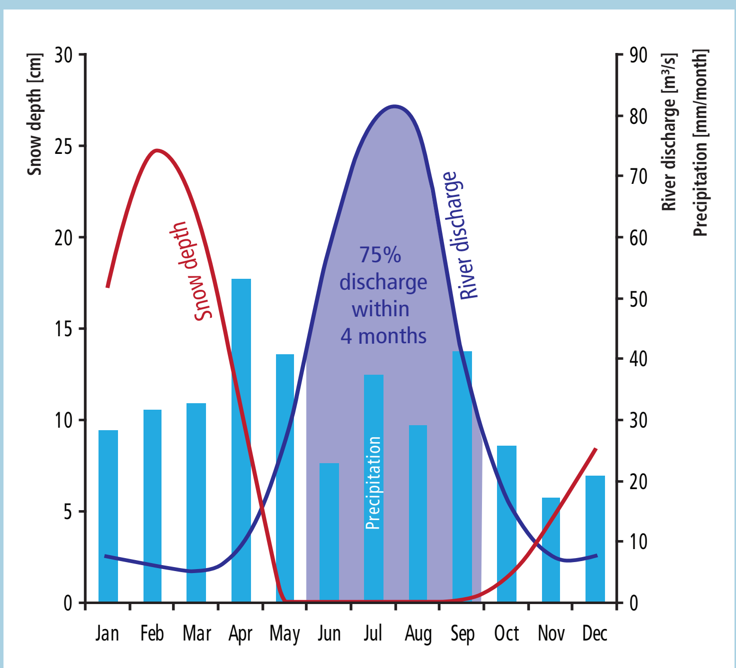


Figure 2.8. Achieving a systemic understanding of the cryosphere requires a combined approach of modelling and collecting data at different scales, including through detailed field studies and field verification (M. Winiger)



Scientific study	Approx. annual precipitation [mm]
Pak. Met. Dpt. 1985	440
Weiers, S. 1995	790
GPCC 2010	350
Reanalyse Data 2009 (Mid Troposphere)	235
Pak. Met. Dpt. 2010	367
Immerzeel, W. et al. 2012	530
WorldClim 2013	379

Table 2.1. Comparison of areal rainfall totals in the Karakoram Range. Source: [2, 4, 5]

Figure 2.9 Average discharge of Batura River, with distinct summer maximum. This is a good example of a large watershed in the Karakoram range; it covers 680 km² and extends from 2 500 to 7 800 m (M. Winiger, U. Boerst)

Automatic weather station on a lateral moraine of Batura Glacier (3 280 m) that collects data at hourly intervals, Pakistan (U. Boerst)

In contrast to global trends of glacier retreat, field evidence and remote-sensing data point to stable – or even positive – mass balances among a number of glaciers located in northwestern Karakoram [3]. This has been described as the "Karakoram anomaly" [1]: significant gains in mass balance are occurring at altitudes above 5 000 m – most probably due to increased precipitation caused by westerly disturbances. This compensates for glacier retreat at the terminus, giving rise to an overall stable or even positive mass balance. For the lower tongues, this so-called anomaly may produce "surges" with rapidly advancing glacier snouts. Elsewhere, pronounced loss of volume of lower glacier parts and retreating terminuses are evident. The latter gives rise to very challenging issues of irrigation management, affecting local farmers who must drain water from the melting glacier surfaces – it can even force inhabitants to abandon certain areas.

The Karakoram Range's exceptional vertical dimensions and vast spatial variety, including different types of glaciers (e.g. debris-free, debris-covered, avalanche-fed), demand robust long-term monitoring. The need for reliable data and system modelling is further accentuated by the region's constantly changing environmental conditions, including unstable riverbeds, floods, landslides and avalanches. Indeed, a coordinated interdisciplinary research approach is required to improve our knowledge of the status and dynamics of water-balance processes in the catchment and in the entire region.

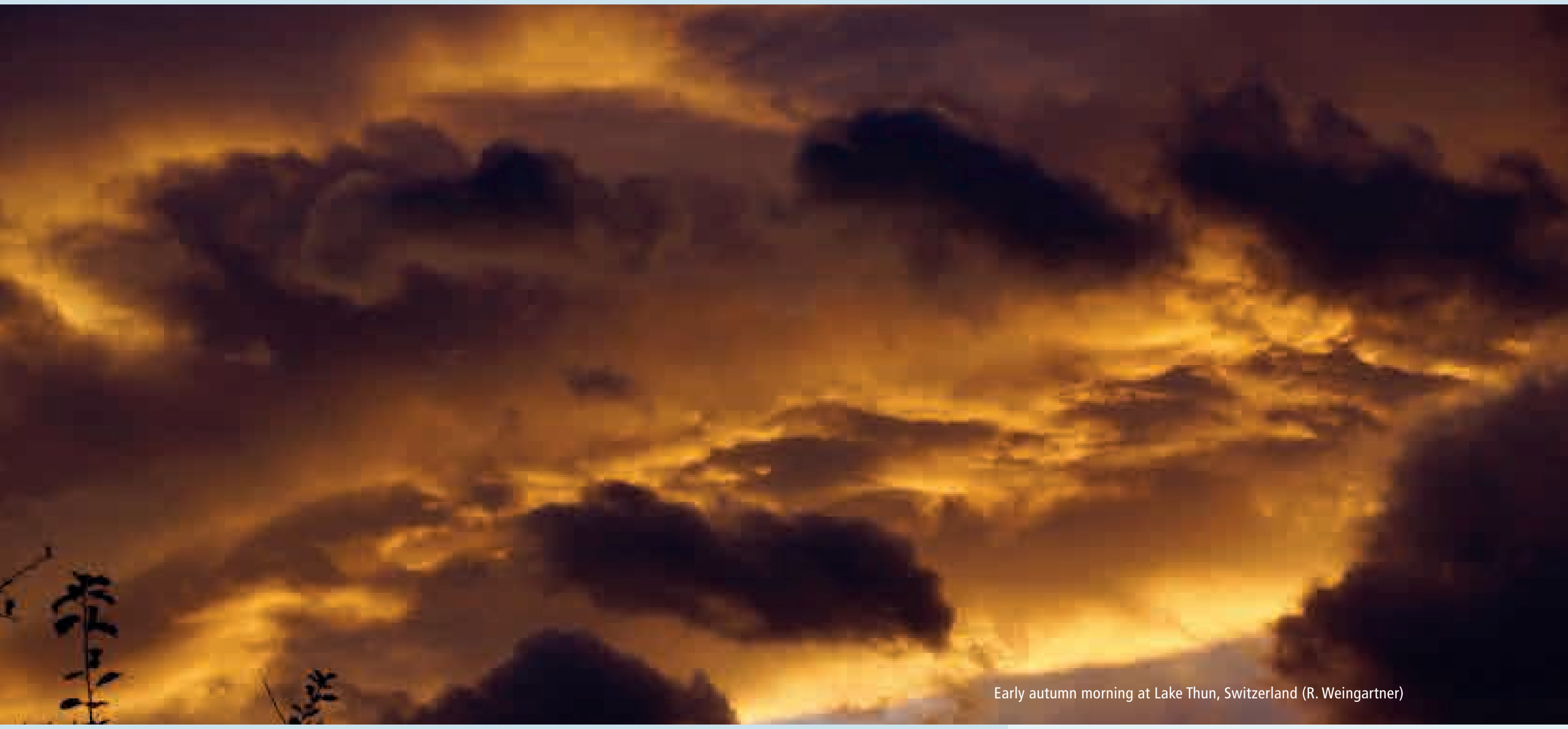
Lessons learned

- The complexity and importance of sound water management in the Upper Indus Basin demands a coordinated approach of data collection and system modelling.
- Interdisciplinary efforts must be launched or strengthened to establish a denser hydro-meteorological network in the region, including observation of snow cover and glacier dynamics at higher altitudes in addition to runoff gauges. To guarantee comparability and consistency, a mandatory standard has to be developed for installation and operation of monitoring stations, mainly at high altitudes.

Impacts of Global Warming on Mountain Runoff: Key Messages From the IPCC Report

Global warming is affecting snow and ice – i.e. the mountain cryosphere – altering seasonal runoff patterns. Hydrological cycles will gradually shift from being dominated by snow and ice to being determined by rain. These are two of the key messages from the 2013 IPCC Report relating to mountain waters [1, 2].

Rolf Weingartner
Martina Kauzlaric



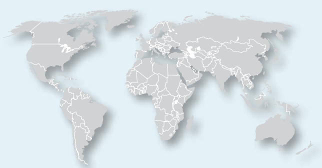
Early autumn morning at Lake Thun, Switzerland (R. Weingartner)

The main climatic drivers of runoff are precipitation and temperature, in addition to (net) radiation and – in mountainous environments – the cryosphere. Observed increases in the moisture content of Earth's atmosphere are likely to cause changes in precipitation patterns, leading to intensification of heavy rainfall over land regions. Increased precipitation is expected to occur around mountain ranges in the northern hemisphere at higher latitudes, in East Africa and New Zealand, whereas the Andes and mountains in West Asia and West Africa are expected to become drier. The largest precipitation changes over northern Eurasia and North America are projected to occur during the winter. Precipitation and precipitation extremes, however, are subject to large modelling uncertainties indicated by the large discrepancies between simulation models.

Increasing air temperatures are very likely. The remaining uncertainty is mostly due to divergent emissions scenarios. As a consequence of the diminishing significance of the cryosphere, net radiation is going to change in mountain areas – specifically, more energy will be available for latent (evapotranspiration) and sensible heat. Changes in temperature and precipitation are reflected in the cryosphere, which is composed of snow, glaciers and permafrost. The critical point is when air temperatures are close to freezing; it is here that changes in air temperatures have the greatest effect on the timing of snow accumulation and snowmelt as well as on the number of snowfall events. Overall, these changes result in a shorter period of snow cover – for example, a significant reduction in snow cover extent has already been

"Changes in the global water cycle in response to the warming over the twenty-first century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase."

IPCC, 2013 [1]



Blüemlisalp (3 660 m) seen from Kandersteg, Switzerland (R. Weingartner)

observed in the northern hemisphere for the period from 1967 to 2012 (Figure 2.10). Further, simulations indicate that March-to-April snow cover will likely decrease by 10–30 percent, on average, by the end of this century.

Runoff integrates climate-induced changes within a catchment. In terms of mountain rivers, a seasonal redistribution of runoff is expected, i.e. river regimes will change; however, total annual runoff volumes may or may not change, depending on annual precipitation levels. Greater variability of river flows is likely to be expected, as the damping effect of snow and ice storage will gradually diminish. Droughts and floods are expected to occur more frequently for the same reason.

In many mountain regions, the dry summer season can be bridged by using the abundant water from snow and ice melt. The challenge is to maintain this seasonal structure. This will likely require building new multi-purpose storage infrastructure and transforming existing infrastructure from single-purpose (e.g. hydropower generation) to multi-purpose (e.g. hydropower generation and drinking water supply).

"Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (high confidence)."

IPCC, 2014 [2]

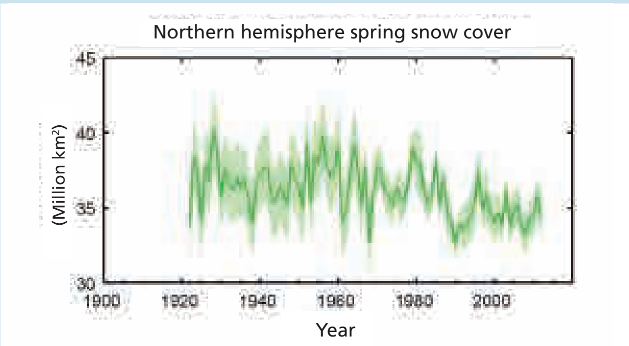


Figure 2.10. Extent of average snow cover in spring (March to April) in the northern hemisphere. Green line: annual values; green shading: uncertainties. Source: [1]

Water Management Options Under Climate Change in the Swiss Alps

The touristic region of Sierre–Crans-Montana–Plaine Morte is located in one of the driest valleys of Switzerland. In the MontanAqua project, researchers analysed how climate change and socio-economic changes are likely to affect water availability and water use in the region by 2050, based on four development scenarios. The analyses generated five key governance messages for sustainable water management.

Bruno Schädler
Olivier Graefe
Emmanuel Reynard
Stephan Rist
Rolf Weingartner

Tracer experiment, Plaine Morte Glacier, Switzerland (F. Schneider)

The MontanAqua study [1] sought to assess and compare the possible impacts of climate change and socio-economic change in the region by the middle of this century, as well as to propose governance options for policymakers involved in Sierre–Crans-Montana–Plaine Morte, located in the dry inner-Alpine region of Valais, Switzerland.

Annual water resources (Figure 2.11), available mainly in the upper part of the area, are currently plentiful (140 million m^3). They are expected to decrease slightly in the future, in terms of average annual availability. However, dry periods are expected to increase and temporary water shortages are anticipated, especially in the second part of summer (August to September). The Plaine Morte Glacier, towering above the region at 3 000 m and boasting a volume of 0.8 km^3, is expected to disappear completely by the year 2080 [2]. The contributions of the Plaine Morte catchment will remain sizeable (about 18 million m^3), but water flows, especially due to snowmelt, are expected to reduce sharply in the second half of summer [3].

Current total use (Figure 2.12) for drinking water, tourism (e.g. snow production, a golf resort) and agriculture ranges from 10.5 million m^3 to 13.5 million m^3 annually, amounting to less than 10 percent of the total available annual flow. Hydro-

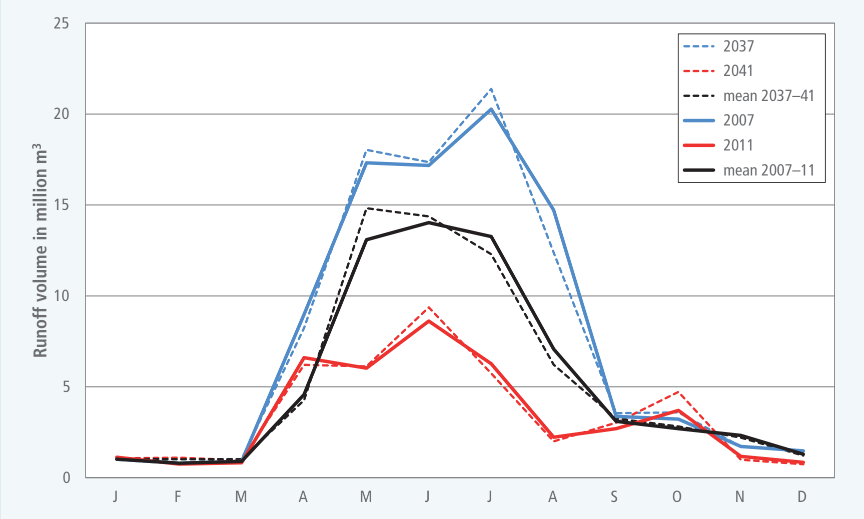


Figure 2.11. Annual water resource distribution for the "wet" year 2007, the "dry" year 2011 and mean annual values (2007–2011) in the eastern headwater region (Ertense to Tièche river) – the most important area in terms of water supplies to the Crans-Montana–Sierre region. The dotted lines represent projections for the near future (around 2040). Source: [1]

power production uses another 70–80 million m^3 water per year [4]. Depending on four different socio-economic scenarios (see Table 2.2), future water needs are expected to remain stable or decline slightly on average. However, the pressure on water resources is expected to increase in the second half of the summer (August to September).

Current water-management approaches are characterized by supply management over demand management, by technical management over political management and by a high degree of legal complexity, compounded by a multitude of conventions and informal rights held by communes and other users [5]. The price of water generally remains low when compared with the national and international situations.

Residential areas are increasingly replacing vineyards in Crans-Montana, Switzerland (F. Schneider)

Aerial view of Crans-Montana resort, Switzerland (E. Rey)

The region's current approach to water management may be described as moderately sustainable [6]. The different evolution scenarios analysed do not have the same impact in terms of sustainability. The "Growth" scenario is clearly characterized by a decrease in sustainability, while the other three scenarios would enhance sustainability (Table 2.2).

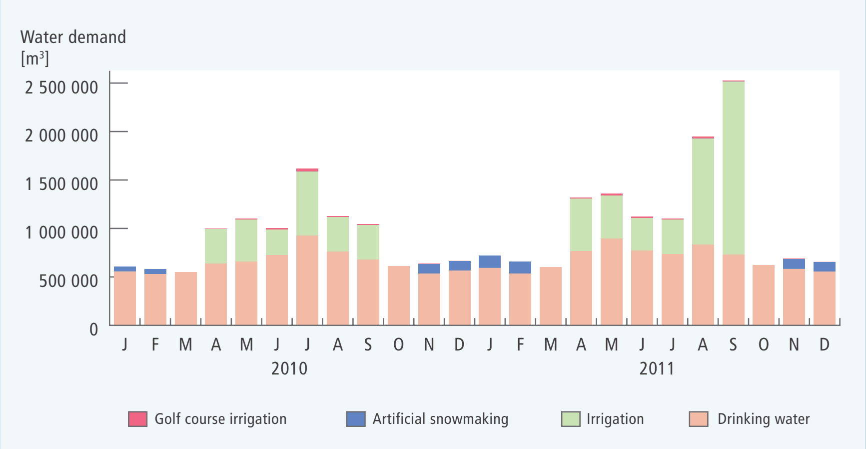


Figure 2.12. Water demand during a "normal" year (2010) and a "dry" year (2011), excluding hydropower production. Source: [1]

Final presentation of the research results to public authorities and stakeholders (HP. Liniger)

Table 2.2. Socio-economic scenarios of development in the Sierre–Crans-Montana region, Swiss Alps

Scenario	Main characteristics	Water management
1 Growth	Mass tourism, lucrative activities and second homes are emphasized; agriculture is less important; the population increases.	Water issues are easily managed by technical measures (supply management).
2 Stabilization	Water and the landscape are considered the region's most important resources; the skiing area is reduced; agriculture remains a core economic activity; irrigation increases; there is slight population growth.	Water issues are managed by optimizing water consumption (demand management).
3 Moderation	Improving the quality of life of residents and visitors is emphasized; soft tourism; agriculture is very important, serving nature conservation and landscape maintenance goals; the population decreases.	Water issues are managed based on collaboration between the communes, benefitting the well-being of all the region's inhabitants.
4 Shared stakeholders strategy	A mixture of scenarios 2 and 3; slight population growth; improved water distribution systems and water management.	Water issues are managed based on collaboration between the communes on behalf of the well-being of all the region's inhabitants.

Moving a Whole Village as a Last Resort

Diminished snowfall – a prominent example of climate change impacts – can lead to altered hydrological regimes with serious consequences, particularly in catchments that strongly depend on runoff from snowmelt. For several villages in Upper Mustang, Nepal, this is a harsh reality. Rivers are running dry, and the villages may be forced to move as a result.

Daniel Bernet
Silvia Lafranchi Pittet
Fidel Devkota

Relocation site (lower left part of the picture). Since the plain lies 40–80 m above the main rivers and is delineated by steep slopes, water supplies cannot be accessed by the traditional means of open earthen channels (D. Bernet)

Upper Mustang is a high valley in Nepal, bordering the Tibet Autonomous Region, China, to the north, and shaped by the Kali Gandaki, a tributary of the Ganga River. In the south, the river has carved out the world's deepest gorge between the main Himalayan ranges, featuring mountains over 8 000 m high, such as Annapurna and Dhaulagiri. These ranges serve as a sort of moisture barrier, separating one of Nepal's wettest regions from one of its driest (Table 2.3 and Figure 2.13).

Nothing can be cultivated without irrigation in the desert-like conditions found in Upper Mustang. Aside from practising pastoralism, most of the valley's several thousand inhabitants carve out livelihoods through subsistence cultivation of grains [1]. The villagers depend directly on perennial rivers, which they use to irrigate their fields. While glacier-fed rivers may remain stable water sources, at least for the next few decades, the few villages that depend on snow-fed rivers are already struggling, and the future does not look bright.

Tucked away in a side valley lies Dheye, one of the affected villages. Water supplies in Dheye appear to depend on snowfall. However, the available data are sparse. Predictions rely on global climate change studies, which predict above-average warming in the region. Rising temperatures imply diminished snowfall as well as spatially and temporally reduced snow cover, which would lead to earlier, more erratic runoff [2].

Figure 2.13. Locations of the meteorological stations listed in Table 2.3, in addition to the current location of Dheye and the planned relocation site, Thangchung. The green and blue lines indicate the respective hydrological catchments. Source: Google Earth Pro (accessed on 25 August 2014)

A villager's view of climate change:

"In the past, there were heavy snowfalls and enough water. But things have changed – it now snows less and the precipitation has become erratic."

Pasang Gurung, farmer from Dheye

At present, local villagers try to divert every drop of river water onto their fields. Even so, many fields have already been abandoned. Ten of the 24 local households have already moved to different locations, one going as far as India. Lack of irrigation water is the main concern of the 14 remaining households (Figure 2.14). As a last resort, the remaining villagers of Dheye have decided to move the entire village to a small plain they own in the main valley, at a slight elevation, which overlooks the confluence of three glacier-fed rivers. The catchment area at the relocation site measures about 363 km^2, and 12 percent of it is still glaciated, promising a reliable water source for the next few decades at least [2].

Station	Station's altitude [m]	Mean annual precipitation [mm]	Incomplete/ complete annual records
(1) Lumle	1 740	5 534	0 / 26
(2) Lete	2 384	1 421	3 / 23
(3) Thakmarpha	2 566	403	3 / 23
(4) Jomsom	2 744	268	1 / 25
(5) Ghami	3 465	116	7 / 19
(6) Lo-Manthang	3 705	174	17 / 9

Table 2.3. Annual precipitation sums (average of complete annual records) of the meteorological stations south of Mustang District (1) and in Mustang District (2–6), based on data records from the Department of Hydrology and Meteorology, Nepal, from 1985 to 2010

Although the villagers abstract nearly all the water from the streamlet nearby, it is frequently insufficient to irrigate their fields (D. Bernet)

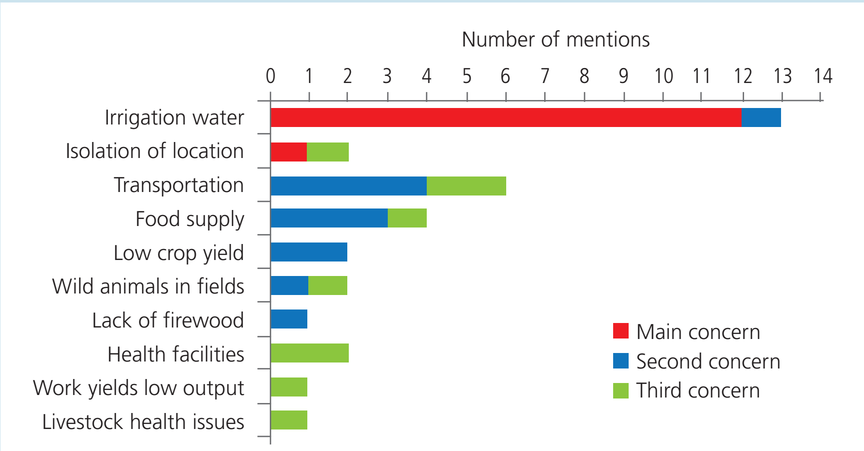


Figure 2.14. The main issues of concern identified by the 14 remaining households in Dheye, and ranked by importance. Note that one household abstained from choosing and three families identified fewer than three main issues

An interdisciplinary team led by the Swiss NGO Kam For Sud sought to assess whether Dheye's inhabitants could use certain measures to sustain their livelihoods at their current location, or if it was better to relocate. After analysing a wide range of factors, the team concluded it was better to move the village [2]. Low-tech external support measures were also proposed to solve irrigation and drinking-water supply issues (at the relocation site) that the villagers could not solve using traditional methods [3].

Lessons learned

- Diminished snowfall due to climate change can have major impacts on hydrological regimes, threatening the livelihoods of people who rely on affected bodies of water.
- The case of the village of Dheye illustrates how the world's poorest communities often suffer the most from the effects of climate change, though they have contributed the least to its causes.

Peak Water: An Unsustainable Increase in Water Availability From Melting Glaciers

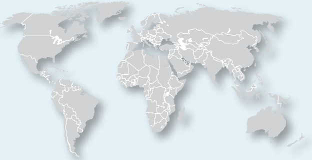
Melting glaciers are currently boosting freshwater availability in many large and densely populated mountain river basins. But this increase is not sustainable: Water supply from glaciers will start to decline as the glaciated area shrinks. This decline will start between now and the next turn of the century, depending on each individual basin's characteristics and on future climate change.

Ben Marzeion
Georg Kaser

Southern end of the Cordillera Blanca, Ancash, Peru (B. Marzeion)

Glaciers affect the input of freshwater into river basins in two principal ways. The first is seasonal: During the melting season, glaciers release water into the basin that fell as snow during the accumulation season [1]. The importance of this effect depends strongly on how glaciated a basin is and how precipitation varies across the seasons. In basins where there are only few glaciers or where the main precipitation season coincides with the melting season, glaciers play a minor role with regard to water availability [2]. But if there are many glaciers and the melting season coincides with scarce precipitation, glaciers may provide a substantial fraction of the total available water during several months every year (Figure 2.15). This seasonal effect of glaciers on water availability in basins is largely independent of longer-term glacier retreat or advance and can be understood as a sustainable contribution of glaciers to perennial water availability.

The second effect of glaciers is based on their ability to store water for many years. Retreating glaciers release more water during the melting season than they capture during the accumulation season, thus increasing water availability [1]. But glacier retreat also means that the glaciated area in the basin is shrinking, and although long-term glacier retreat first increases water availability, at some point this trend will reverse and water availability will begin to decrease. This means



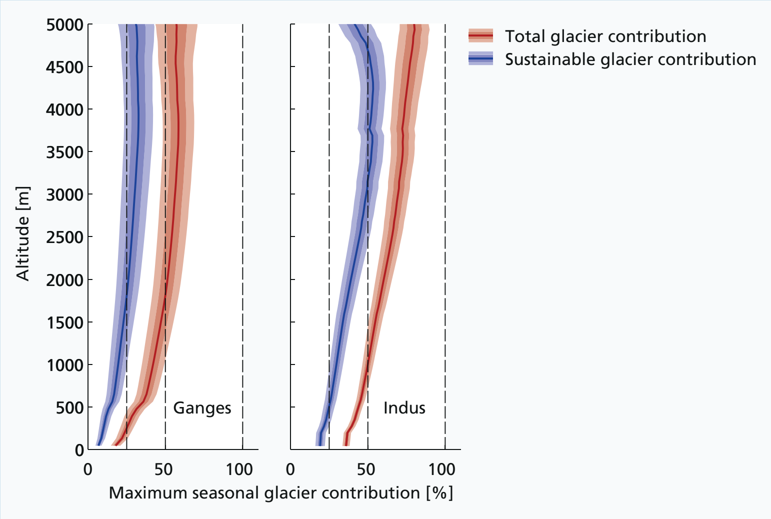


Figure 2.15. Maximum seasonal contribution of glaciers to water availability in the Ganges and Indus basins from 1981 to 2010, as a function of altitude. Shading indicates the effect of climate variability. Glaciers are less important for overall water availability in the Ganges basin, because precipitation and melting tend to coincide in monsoon climate (B. Marzeion)

that the increased release of water by retreating glaciers is unsustainable. The phenomenon is often referred to as "peak water". Figure 2.16 illustrates the net imbalance of glaciers worldwide as a function of time and future climate change scenarios (top) and for selected glaciated regions (bottom). Globally, the peak in unsustainable water contribution can be expected to occur between the middle and the end of the twenty-first century, but at the regional and local scales its timing depends strongly on the individual glaciers' characteristics. For example, the smaller the glaciers in a basin, the earlier the peak [3]. The red line in Figure 2.15 indicates the seasonal maximum of the total contribution of glaciers to water availability, whereas the blue line indicates the seasonal maximum of their sustainable contribution, which is not influenced by glacier retreat.

Kyanjin Gompa, Langtang, Nepal, on the way to Yala Glacier (G. Kaser)

Huaraz, Ancash, Peru, with a view of Huascarán (left) and Chopicalqui (right) (B. Marzeion)

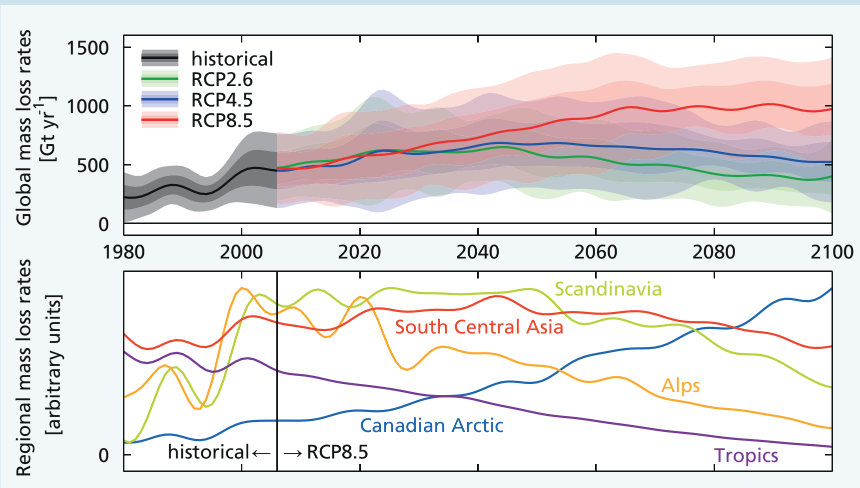


Figure 2.16. Reconstructions and projections of global net glacier mass loss rates. The upper panel shows global sums for different climate scenarios, with the solid line indicating the multimodel mean and shading indicating model uncertainty. The lower panel depicts mass loss rates for selected regions. Many regional rates will begin (or have begun) to decline long before the global rate will. Source: [4]

The global glacier retreat of the past decades coincided with a strong growth in water demand in many regions of the world, driven both by growing populations and by changes in economy and lifestyle. The growing demand has been met in part by glaciers' unsustainable contribution to water availability. This will no longer be possible once their contribution begins to decline. The key to avoiding future seasonal water scarcity in glaciated river basins is to identify the sources of the currently available water, to estimate the future development of these sources and to initiate adaptation early on.

Lessons learned

- Retreating glaciers contribute to seasonal water availability at unsustainably high rates. In many regions of the world, the glacier retreat witnessed over the past decades has coincided with rapid growth in water demand, and part of this demand has been met by glaciers' unsustainable contribution to water availability. This contribution will dwindle once glaciers shrink to a critical size.
- The key to avoiding future water scarcity is to prepare in advance.

3 Mountain Glaciers

Ellesmere Island (J. Noetzli)

Mountain Glaciers: On Thinning Ice

Mountain glaciers are key indicators of climate change. Glacier changes are the most visible evidence of global climate change we have. They affect the appearance of the landscape in high mountains and impact regional water supplies, local hazard conditions and global sea levels. Glaciers may be found in, and compared across, all latitudes – from the equator to the poles. Due to their sensitivity to climatic changes, glaciers are key indicators for use in global climate observation systems.

Michael Zemp
Wilfried Haeberli
Martin Hoelzle

Chopicalqui, Peru (E. Hegglin)

Glaciers have been observed in an internationally coordinated way for more than a century [1, 2]. The results from data collected around the world are not comforting – the outlook for the near future is even less so: evidence of accelerated glacier shrinkage at a global scale is mounting. The decadal average rate of thickness loss measured via 37 reference glaciers worldwide (Figure 3.1) has tripled since the 1980s (Figure 3.2). The record loss documented in the 1980–1999 time period (in 1998) has already been exceeded four times in the twenty-first century: in 2003, 2006, 2010 and 2011 [3]. Aerial and satellite data confirm the trend and point to even higher losses in certain regions such as southern Alaska. At the same time, decadal regional and individual exceptions have been found, showing intermittent glacier re-advance, for example, in the wetter parts of Norway, in New Zealand and in the western Himalayas. But assessed globally according to a centennial time scale, the dominant trend is one of rapid glacier melting.

Global glacier distribution and changes in mass and extent

According to recent global estimates, there are 170 000 glaciers worldwide covering an area of 730 000 km^2 [4]. More than 80 percent of that area is located in the Canadian Arctic, Alaska, High Mountain Asia and around the continental ice sheets of Antarctica and Greenland. If all the world's glaciers were to melt, it would result in a mean sea level rise of roughly half a metre [5, 6]. Much of the water locked in the world's glaciers may indeed reach the global ocean within the next few centuries [7].

Measurements of change in the length of glaciers were the main data collected during the initial phases of international glacier monitoring, which began in 1894. The data from these simple observations are extremely robust. They leave no doubt that mountain glaciers worldwide have been shrinking rapidly since the late twentieth century. Evidence suggests that this strikingly synchronous global retreat is exceptional; in many places, glaciers have now been reduced close to their minimum extent during the warmest periods of the Holocene – i.e. in the past 10 000 years [8] – and some have shrunk even smaller.

Observations based on mass balance – i.e. the difference between accumulation (snowfall) and ablation (melting) – indicate that ice loss is occurring at a considerably higher rate than greenhouse gas effects alone would predict. This means that feedback processes are probably playing an increasing role, in particular the mass balance altitude feedback and decreasing reflectivity (albedo) due to darkening glacier surfaces, retreating snow lines and enhanced dust deposition [9, 10].

New measurement techniques, new insights

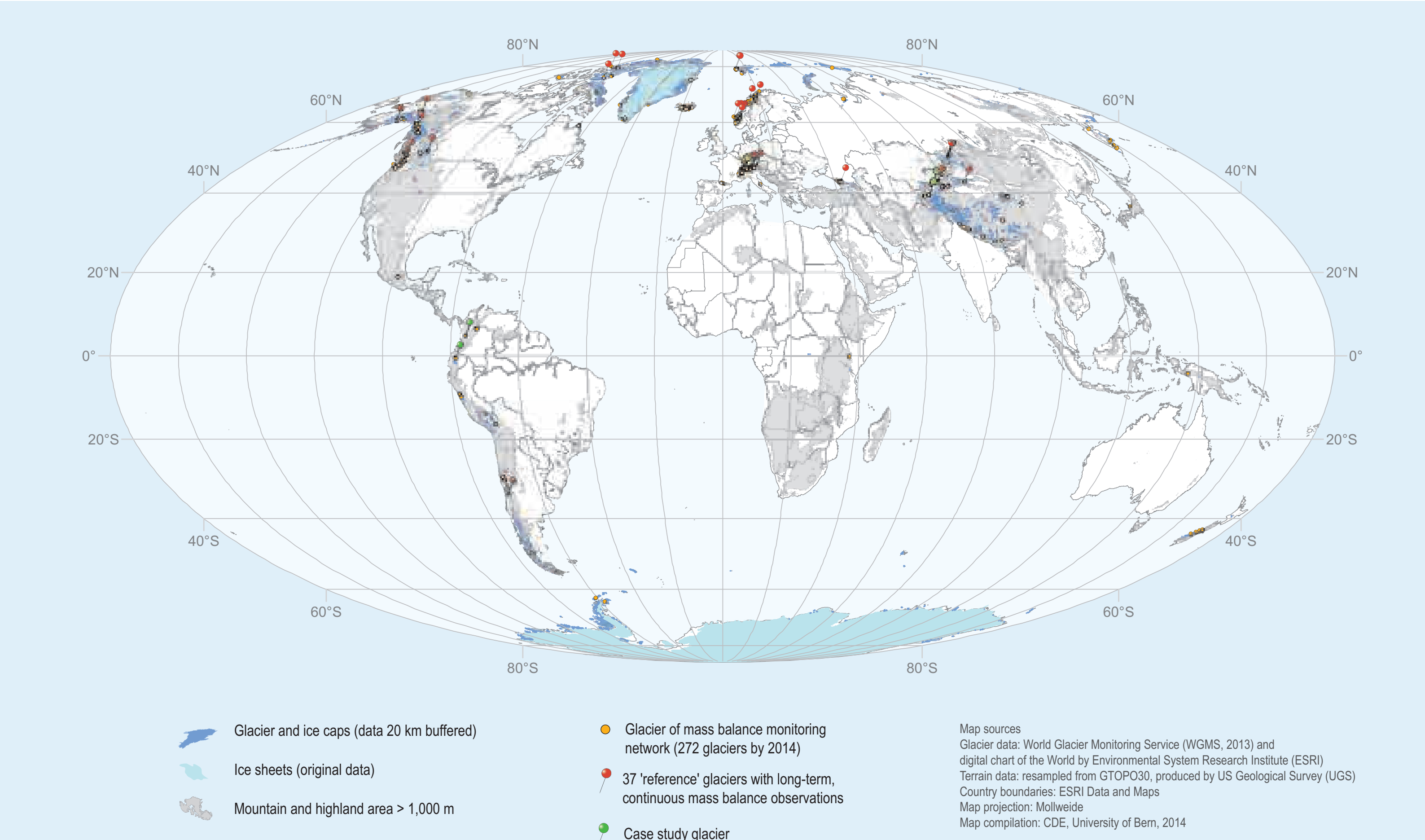
Recently, glacier inventories based on satellite imagery and digital terrain information have enabled new ways of documenting the distribution of glaciers and ice caps and changes affecting them. Computer models that combine data from observed time series with satellite information make it possible to examine changes across larger glacier ensembles, spanning entire mountain regions. The results show clearly that even if global warming is kept to 2 °C, many small- to medium-size glaciers in mountain areas are likely to disappear entirely in the coming decades, with serious consequences for hazard risks and water cycles [11]. Rather than gradually retreating, many large glaciers may develop extreme disequilibria, causing them to down-waste or collapse, as is being observed with increasing frequency.

Techniques have also been developed to model the topography that will be exposed by vanishing glaciers. This helps to anticipate the formation of new lakes in local depressions of glacier beds [12]. Some of these new lakes may bear potential

Policy messages

- Continue and expand the monitoring of glaciers via *in situ* and remotely sensed observations.
- Promote free, unrestricted international sharing of standardized data and information on glacier distribution and changes.
- Promote assessments of glacier change impacts on local hazard risks, on regional freshwater availability and on global sea level rise.

Figure 3.1. Global distribution of glaciers, ice caps and ice sheets as well as the locations of 37 reference glaciers with long-term continuous mass balance observations

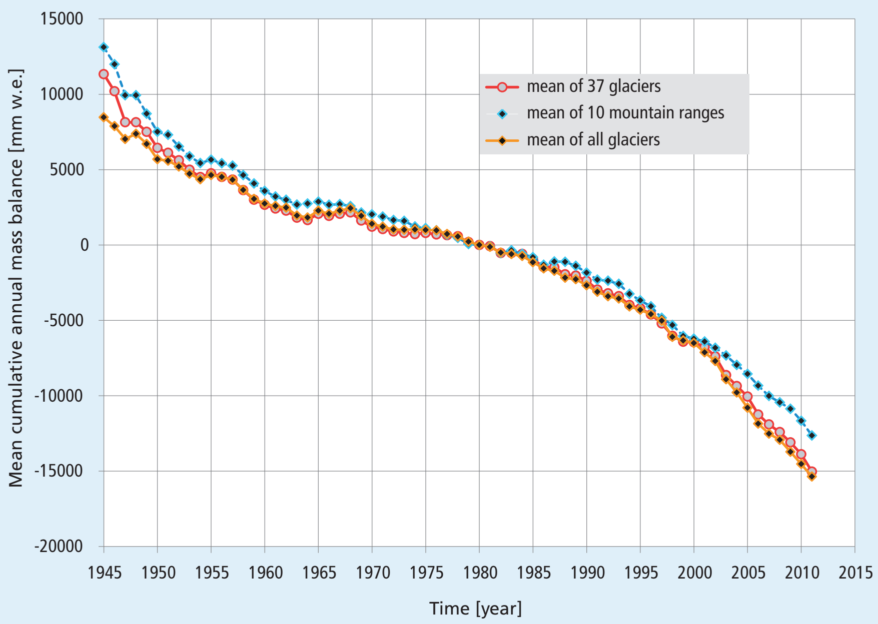


for generating hydropower or for preserving aesthetic appeal when the beauty of a glacier is lost. However, they also present a growing risk of flooding and far-reaching debris flows caused by moraine breaching or rock avalanches from de-glaciated slopes or slopes containing degrading permafrost [13].

Impacts of glacier retreat

The most serious impact of melting mountain glaciers concerns regional and global water cycles. Glacier melting will remain a major contributor to sea level rise in this century [11], and the seasonality of runoff will change dramatically in some regions due to the combined effects of diminished snow storage, earlier snowmelt and decreasing glacier melt. To assess the importance of glacier melt to water availability in a given place, one must consider the seasonal glacier contribution to water supplies vis-à-vis the catchment size and corresponding contributions from snowmelt and precipitation. Glaciers' importance to water supplies is minor in monsoonal climates, moderate in most mid-latitude basins and major in seasonally or perennially dry basins such as those in Central Asia or on the western slopes of the tropical Andes [14]. Currently, roughly one billion people – mainly in Asia, North and South America and Central and Southern Europe – depend on snow and glacier meltwater during the dry season and could be seriously affected by any changes [15]. In the future, water scarcity in long droughts exacerbated by changing snow and ice cover in high mountain ranges could seriously impact people's livelihoods and the economy. Problems that could arise during warm or dry seasons include diminished water supplies, longer-lasting discharge minima and low flow periods in rivers, lower lake and groundwater levels, higher water temperatures, disrupted aquatic systems and diminished hydropower generation. These effects could be compounded by increasing demand for water due to growing populations, urbanization, industrialization, irrigation, hydropower generation and firefighting. A combination of decreased supply and increased demand such as this could cause conflicts. Together with higher air temperatures, increased evaporation and changing snow conditions, the disappearance of mountain glaciers could dramatically heighten two fundamental questions: Who owns the water? And who decides how it is used in critical situations?

Figure 3.2. Mean global cumulative mass balance since 1945/1946. Positive and negative values indicate ice gain or loss, respectively, compared with the year 1980. The sample consists of observations from about 250 glaciers in total, with long-term observation series from 37 glaciers in ten mountain ranges. The mean balances of the first years are of limited value due to the very small sample size. w.e.: water equivalent
Source: WGMS (2013)



World Glacier Monitoring Service (WGMS)

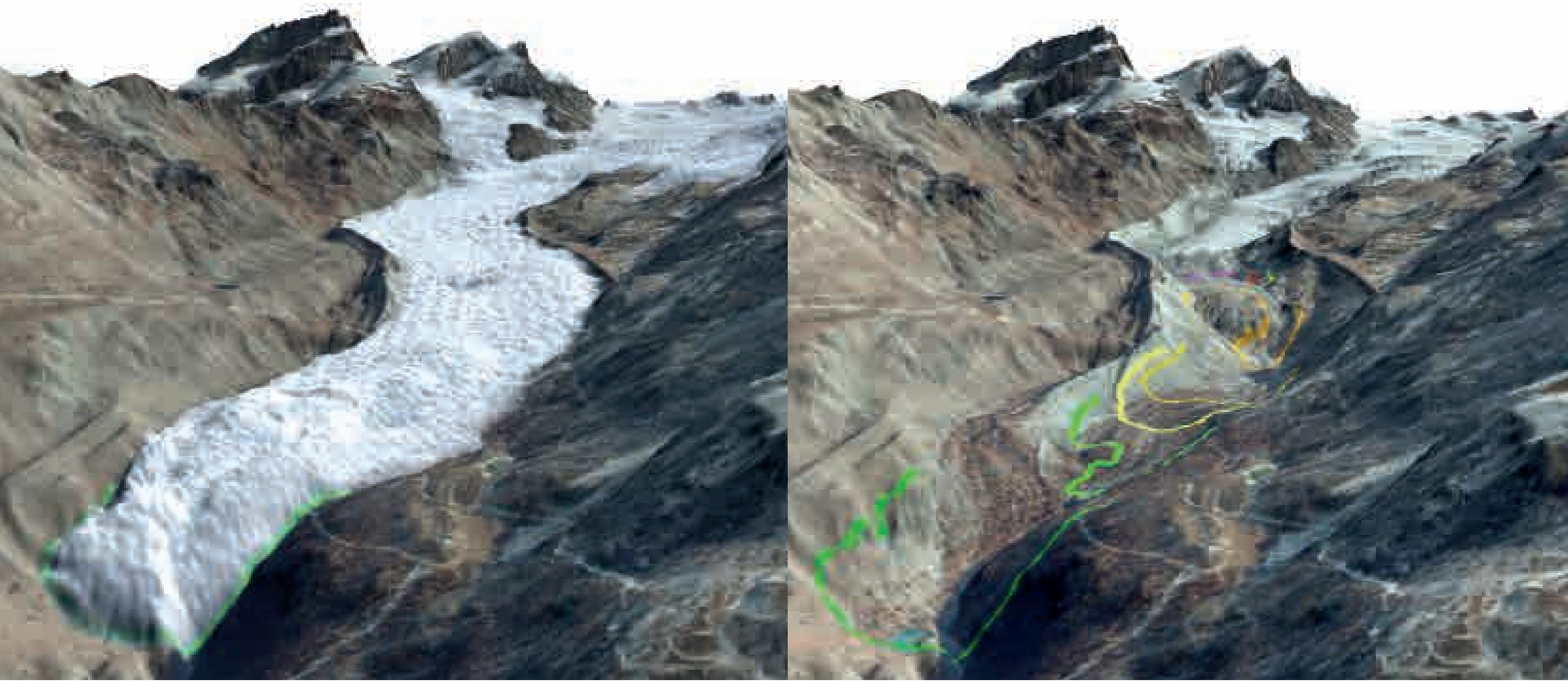
For over a century, the Swiss-led World Glacier Monitoring Service (WGMS) and its predecessor organizations have coordinated the worldwide compilation and free dissemination of glacier observations. Today, together with the US National Snow and Ice Data Center (NSIDC) and the Global Land Ice Measurements from Space (GLIMS) initiative, WGMS supervises the Global Terrestrial Network for Glaciers (GTN-G): the framework for internationally coordinated monitoring of glaciers within the Global Climate Observing System (GCOS), supporting the United Nations Framework Convention on Climate Change (UNFCCC). WGMS is financed by the Federal Office of Meteorology and Climatology MeteoSwiss in the framework of GCOS Switzerland.

This effort relies on a network of scientific collaboration comprising over 1 000 observers working in more than 30 countries. It has resulted in an unprecedented global database on glacier distribution and change. However, the resulting observations – especially from long-term programmes – are strongly biased towards the northern hemisphere and Europe. Regions with limited observational coverage include strongly glaciated areas in the Arctic and Antarctic as well as in the Andes and Asia (see Figure 3.1).

For more information see:

- World Glacier Monitoring Service: http://www.wgms.ch
- Website of the Global Terrestrial Network for Glaciers: http://www.gtn-g.org
- Report on global glacier changes (facts and figures): http://www.grid.unep.ch/glaciers/

Figure 3.3. Views of Findelengletscher, Switzerland, in 1862 (left) and 2010 (right), created based on historical maps and using modern laser scanning, respectively. The figures are provided by P. Rastner, University of Zurich, and were produced within the Glacier Laser Scanning Experiment Oberwallis project supported by the Swiss energy utility Axpo



Capacity Building and Twinning for Climate Observing Systems

Among the regions with limited glacier observations, the Andes and Central Asia are probably the most vulnerable to impacts of climate and glacier changes. In these regions, glaciers significantly contribute to water supplies during dry seasons, and people and infrastructure are especially vulnerable to glacier-related hazards such as glacier lake outburst floods. Both regions are currently the focus of international capacity-building and twinning programmes. But all related efforts to understand secondary climate change impacts and identify mitigation and adaptation measures are hampered by a lack of long-term, high-quality meteorological/glacier observation series. The Capacity Building and Twinning for Climate Observing Systems (CATCOS) project – coordinated by the Federal Office of Meteorology and Climatology MeteoSwiss and funded by the Swiss Agency for Development and Cooperation (SDC) – aims at improving the monitoring of greenhouse gases, aerosols and glacier mass balances in regions of the world where data are lacking. In close collaboration with regional partners, the glaciological work packages of the CATCOS project seek to continue *in situ* mass balance measurement programmes in Colombia and Ecuador in addition to carrying out new geodetic surveys of glaciers; and they seek to resume interrupted *in situ* mass balance measurements in Kyrgyzstan and Uzbekistan.

Note: This chapter is an updated version of W. Haeberli and M. Zemp's contribution to: Mountains and Climate Change (2009), pp. 22–25

Demonstration of snow density measurements during a summer school held in the framework of the CATCOS project in Zermatt, Switzerland (M. Zemp)

Resuming Glacier Monitoring in Kyrgyzstan

The mountain ranges of Central Asia are water towers for large populations. Glacier runoff represents an important freshwater resource in the extensive arid parts of the region. The mass balance of glaciers here is also an important indicator of climate change.

Ryskul Usubaliev
Erlan Azisov

Abramov Glacier, Kyrgyzstan (H. Machguth)

International guidelines for monitoring of mountain glaciers recommend combining *in situ* measurements (mass balance, front variations) with remote sensing (inventories) and numerical modelling. This helps to bridge the gap between detailed (process-oriented) local studies of glaciers and globally relevant datasets.

Certain glaciers in Central Asia – namely, Abramov and Golubin – have been listed as reference glaciers by the World Glacier Monitoring Service (see Box on page 55). They represent important mountain ranges, such as the Pamir-Alay and the Tien Shan mountains. Long-term mass balance series – i.e. series over 20 years old – are available for these glaciers. Following the collapse of the former Soviet Union, measurement efforts were largely abandoned. In late summer 2011, scientists from Kyrgyzstan, Uzbekistan, Switzerland and Germany resumed measurement activities for the Abramov glacier in the Pamir-Alay Mountains. This occurred within the Capacity Building and Twinning for Climate Observing Systems (CATCOS) project (see Box on page 56) and the Central Asian Water project (CAWa). Measurements were also resumed for Golubin Glacier, Suek Zapadniy and Glacier 354 in the Tien Shan Mountains in 2010. The resulting mass balance data were analysed together with snow line observations from terrestrial cameras and compared with measurements made earlier.

Efforts towards capacity building and twinning are intended to transfer leadership of the observation programme to regional partners and to generate information for regional stakeholders involved in water management, disaster risk reduction and the health sector.

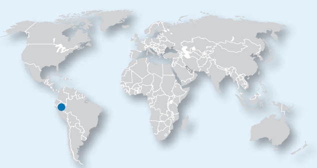
Strengthening Glacier Monitoring in the Tropical Andes

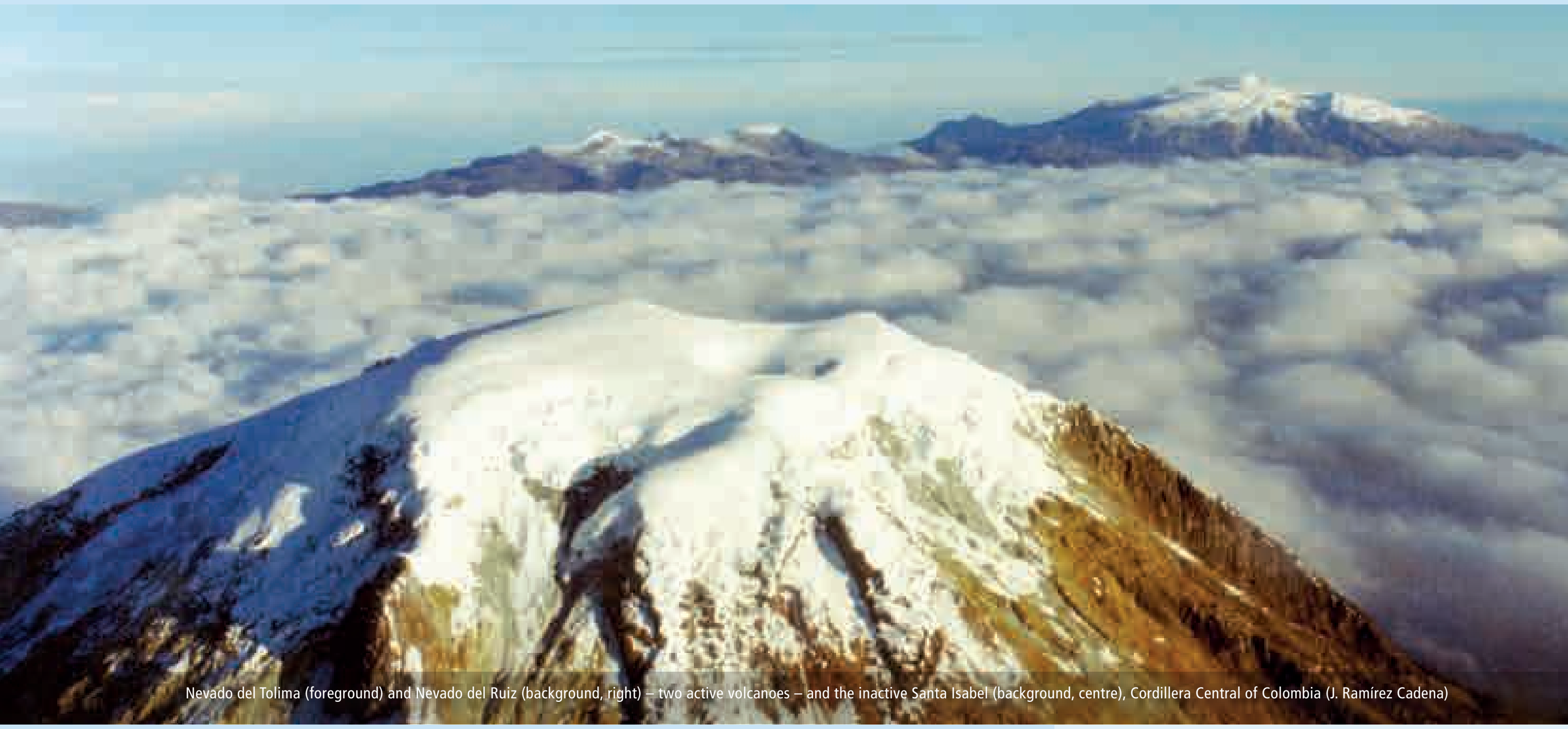
Glaciers in the tropical Andes are known to be especially sensitive to climate change. Due to the specific climate conditions in the tropical zone, ice melt occurs year-round on the lowest part of the glaciers. Thus, glacier termini display a short-term response to changes in mass balance and climate [1].

Bolivar Cáceres
Jorge Luis Ceballos

Antizana ice cap, Ecuador (M. Zemp)

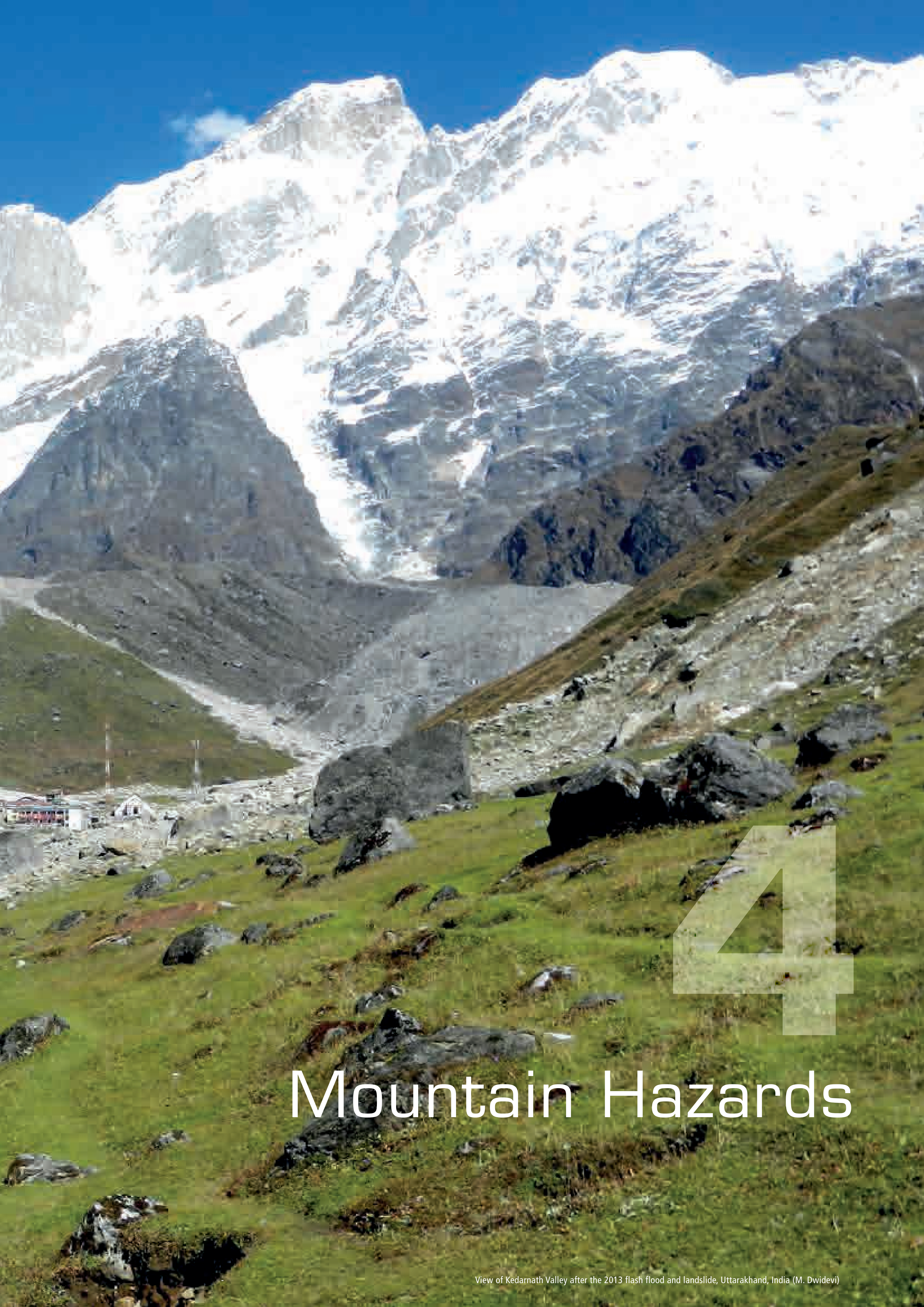
Tropical glaciers reached their "Little Ice Age" maximum extent between the late seventeenth and early nineteenth centuries. Since then these glaciers have exhibited a general retreat, marked by two periods of acceleration: one in the late nineteenth century, and another in the last 30 years – the latter being the more pronounced. These changes are best captured by monthly mass balance measurements performed in Bolivia, Ecuador and Colombia. The main drivers of recent glacier shrinkage are believed to be the increased frequency of El Niño events and changes in their spatial and temporal occurrence in combination with a warming troposphere over the tropics [2]. In the future, increasing air temperatures and minimal change in precipitation could greatly reduce glacial coverage and even eliminate small glaciers whose upper reaches are located close to the current equilibrium-line altitude [2]. This is a serious concern because large populations live in the arid regions to the west of the Andes and depend on water supplies from high-altitude glaciated mountain chains for agricultural, domestic consumption and hydropower [3].





Nevado del Tolima (foreground) and Nevado del Ruiz (background, right) – two active volcanoes – and the inactive Santa Isabel (background, centre), Cordillera Central of Colombia (J. Ramírez Cadena)

The Capacity Building and Twinning for Climate Observing Systems (CATCOS) project (see Box on page 56) aims at strengthening the glacier monitoring programmes in Colombia and Ecuador. It supports the continuation of mass balance measurements at the Antizana ice cap in Ecuador. In a joint effort with regional partners, participants are implementing a new geodetic survey based on aerial photography in order to validate *in situ* observations and assess the ice cap's overall decadal ice volume change. In Colombia, the project supports the continuation of the mass balance programme at Conejeras, an outlet glacier of the Nevado de Santa Isabel. The project further complements this effort with a terrestrial laser-scanning survey of the glacier surface as well as a ground-penetrating radar survey to determine remaining ice thickness. Together with the mass balance programme at Zongo Glacier in Bolivia, the two monthly observation series in Colombia and Ecuador are vital to improving our understanding of climate change in the mid-troposphere of the tropical Andes as well as its impacts on glaciers, runoff and the availability of freshwater for regional populations and ecosystems.



4 Mountain Hazards

View of Kedarnath Valley after the 2013 flash flood and landslide, Uttarakhand, India (M. Dwidevi)

Mountain Hazards and Climate Change

Oliver Korup

Mountain landscapes are home to a rich diversity of flora, fauna, terrain and climatic conditions, but also natural hazard risks. Many of the strongest earthquakes have occurred in mountainous areas whose unique topography is largely a result of active tectonics and volcanic eruptions. Three recent earthquakes alone – in the mountains of China (2008), Haiti (2010) and Japan (2011) – claimed more than 320 000 lives. Many of the deaths resulted from landslides, ground subsidence, natural dam breaks and a tsunami triggered by earthquakes. Climate change is likely to worsen the risks from non-seismic hazards such as floods, landslides or drought.

Forests serve a protective function in many mountain landscapes, particularly by reducing water erosion (O. Korup)

Mountain ranges often form distinct climatic barriers, fostering aridity in leeward regions, for instance, and accentuating the availability and variability of freshwater resources. Yet mountains can also promote drenching rain in some areas, such as parts of the eastern Himalaya region where annual rainfall totals can exceed 20 m. Topography stretching as high as nearly 9 km above sea level helps to build up rainwater and fuel major engines of erosion: glaciers and rivers that cut through highly varying terrain, undermining hillslopes and eventually inducing the collapse of mountain peaks. The resulting landslides can displace tens of cubic kilometres of rock and earth, defying even the most robust risk-management strategies.

Diverse forms of hazards

Mountains also host the world's largest dams – both natural and human-made. The tallest natural dam – almost 600 m high in parts – holds back Lake Sarez in Tajikistan, storing about 17 cubic kilometres of water. Failure of a dam of this size could unleash a lake outburst devastating downstream communities for as many as several thousand kilometres. Steep and narrow mountain rivers poorly attenuate discharge, which can lead to dangerous flash floods. Long-term mountain erosion continuously forms new landscapes, including patches of flat ground that may appear suitable for settlement, agricultural use and infrastructure construction. But viewed geologically, these new landscapes made of stored sediment are ephemeral and prone to sudden reworking; valley floors can be destroyed in an instant by rushing water, sediment, biomass and human-made litter in floods and debris flows. Even the highest recorded tsunami run-up stemmed from a mountain landscape: A massive rockslide that entered Lituya Bay in the Alaskan fjords in 1958 triggered a catastrophic displacement wave that swashed up the opposite fjord higher than 500 m. Put simply: The diversity of natural hazards in mountain regions is unparalleled (Figure 4.1).

Mountains are naturally active landscapes and often regarded as too steep or hazard-prone for settlement. However, with growing population pressure, human expansion into such terrain is increasingly common, putting ever more people at risk from natural hazards. This is not just a rural phenomenon. For instance, some 40 percent of those living in the world's largest cities are now considered at moderate risk from landslides – a significant number considering that more than half of humankind now lives in cities. Urban poor, in particular, are often pushed onto steeper terrain that is only marginally suitable for housing. Notably, from 1950 to 2010, the majority of urban population growth occurred in hilly or mountainous areas between 500 and 1 500 m [1].

Socio-economic factors including demographic changes influence vulnerability and exposure, whereas climate change influences the frequency and magnitude of hazards. Projected changes to temperature, wind and precipitation are likely to affect the water cycle and thus the distribution of snow, ice and water in mountain belts [2]. Dwindling glaciers expose steeply carved bedrock landscapes subject to large amounts of meltwater and sediment, causing intermittent landslides, floods and debris flows.

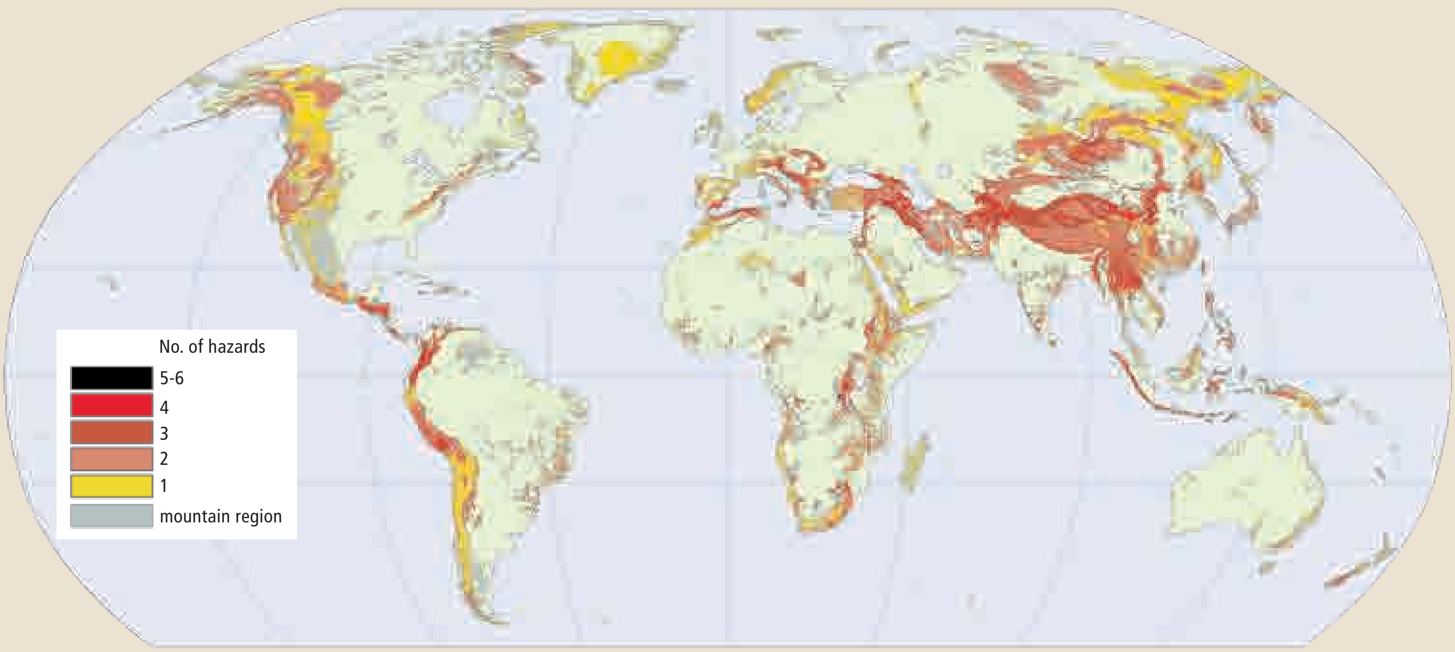
Policy messages

- Floods, debris flows, landslides and avalanches are among the mountain hazards most sensitive to climate change.
- The number of people affected by these hazards is most likely to increase in the future.
- Capacity building and integrated risk management can enhance community resilience and reduce the vulnerability of mountain populations.

Is climate change increasing hazards?

The early twenty-first century has already seen several of the warmest and wettest years since instrumental climate observations began [3]. The exceptionally hot summers of 2003 and 2010 saw an increase in rockfalls from peaks in the European Alps, spurring widespread concern about permafrost degradation as a possible cause of pervasive rock-slope failure. Abnormal monsoon rainstorms triggered devastating flash floods and debris flows in Pakistan, India and China, killing thousands and obliterating more than two million homes. Are these and other hazards rising in mountain regions because of climate change? Processes such as slope

Figure 4.1. Map of mountain regions affected by sets of hazard types



Most mountain areas are affected by multiple hazards, which magnifies overall negative impacts. The hazards considered are earthquakes, fire, human conflict, suitability for rain-fed crops (drought), the future impact of infrastructure and climate change (Courtesy of UNEP-World Conservation Monitoring Centre, Mountain Watch 2002)

Natural hazards, risks and disasters

Natural hazards occur where human activities intersect with geological, hydrological, biological or other natural processes. *Hazard* may be understood as the probability of a given adverse impact occurring within a given region and period. *Risk*, instead, may be understood as the average expected loss from a particular hazard, measured annually or otherwise. Risk is often calculated as the mathematical product of hazard, vulnerability (or damage potential) and the value of the elements at risk. Disaster and integrated risk management comprise bundles of strategic actions meant to reduce risk. Risk reduction can be achieved by curtailing hazards, vulnerability and exposure (the number of elements exposed to a hazard), or any combination thereof. Finally, *disaster* refers to the negative consequences of natural hazards, e.g. major structural damages or loss of life.

failure, flooding or avalanches are highly episodic – distinguishing a clear climate change signal from our observations is challenging. It requires robust statistical testing, which can be difficult to carry out when event inventories only encompass a few decades. Focussing on rare, highly destructive events can distort hazard assessments, but these events can lend themselves to detailed analysis when captured in sedimentary archives or by other "silent witnesses" in the landscape.

Scientists have long been interested in providing decision support for hazard mitigation in mountainous terrain. In particular, researchers have prioritized landslides, water- and sediment-related hazards for study (Figure 4.2). It appears likely that climate change is altering the magnitude and frequency of water-driven hazards

Damage from flood and debris flows, Leh, India (O. Korup)

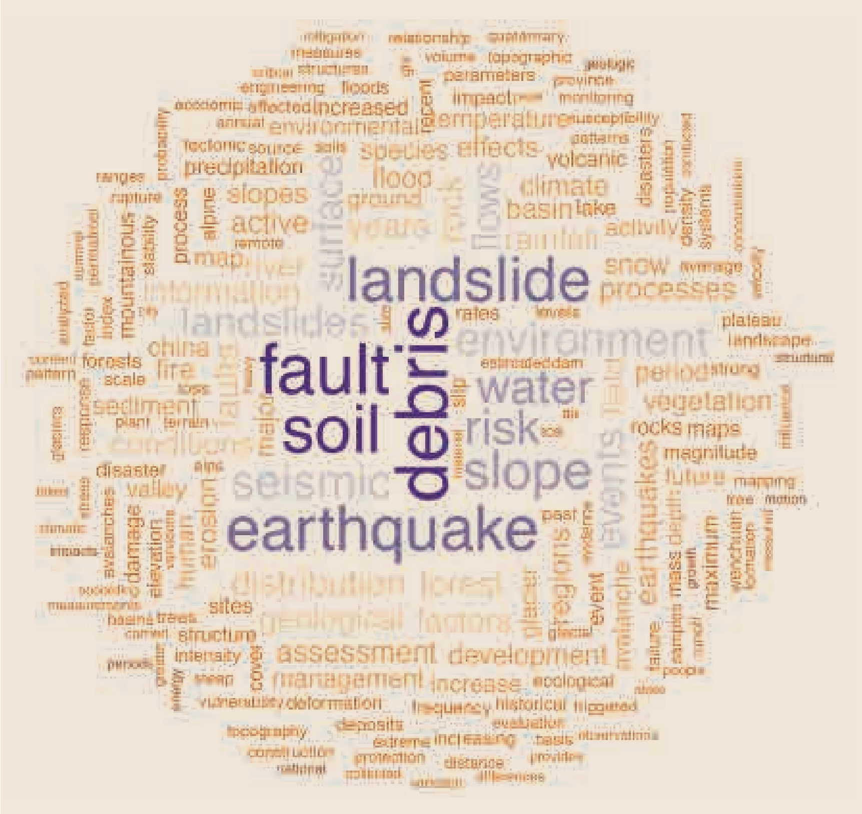


Figure 4.2. Word cloud based on 1 853 scientific articles in the earth and environmental sciences that contain the terms "mountain" and "hazard" in their title or abstract. The relative sizes of the words indicate how often they are mentioned. Analysis: Oliver Korup. Data source: Elsevier's Scopus database (accessed in August 2014)

Catastrophic deposits of debris flow, Ladakh, India (H. Munack)


Rockfall deposits, Alpenrhein, Switzerland (O. Korup)

such as permafrost rock-wall instability, ice avalanches and the failure of glacier dams. Still, the term "climate change" features in only about 10 percent of all recent publications on mountain hazards [4]. Mountain regions in China, Italy, Taiwan, Iran and India have taken centre stage in terms of research output. This points to the myriad problems resulting from high population densities in active mountain areas as well as the danger of overlooking poorly documented regions when dealing with natural hazards.

Trends and adaptation strategies

Certain trends are visible despite the patchy historical record of natural disasters in mountain areas, the diversity of impacts and possible underreporting in certain areas (Table 4.1). Geophysical processes such as earthquakes and volcanic eruptions (and their consequences) have been responsible for the lion's share of economic damage and loss of life in mountain areas since the beginning of the twentieth century. However, hydro-meteorological hazards – such as storms, floods and droughts – have affected the greatest number of people, mirroring the global trend. If the past record is any indication, then the impact of climate change in mountain areas will likely be most felt in terms of growing numbers of people affected. Adaptation strategies should take this into account and give equal attention to each component of the risk cycle – namely through efforts towards prevention, response and recovery vis-à-vis a given natural disaster. Prevention efforts need not solely entail costly engineering measures. Instead, the vulnerability of

Active earthquake fault, Bolnay Range, Mongolia (O. Korup)

mountain populations can be reduced through capacity building and by fostering community resilience. Finally, emergency preparedness training holds promise in mitigating the risks of natural hazards.

Country	Share of people killed	Share of people affected	Share of damage (US$)
Afghanistan	Earthquake (65%)	Drought (83%)	Flood (67%)
Bhutan	Flood (73%)	Storm (74%)	Wildfire (100%)
Colombia	Volcanic eruption (84%)	Flood (92%)	Flood (51%)
Japan	Earthquake (90%)	Flood (45%)	Earthquake (90%)
Kyrgyzstan	Landslide (58%)	Drought (89%)	Earthquake (79%)
Nepal	Earthquake (61%)	Drought (60%)	Flood (76%)
New Zealand	Earthquake (66%)	Earthquake (97%)	Earthquake (94%)
Papua New Guinea	Volcanic eruption (53%)	Drought (40%)	Volcanic eruption (53%)
Peru	Earthquake (78%)	Earthquake (36%)	Earthquake (48%)
Switzerland	Extreme temperatures (78%)	Flood (58%)	Storm (44%)
Tajikistan	Flood (77%)	Drought (58%)	Extreme temperatures (48%)

Table 4.1. The relative share (%) of the ten most damaging natural disasters since the beginning of the twentieth century for selected mountainous countries. In Afghanistan, for example, 65 percent of the people killed by one of the ten most damaging disasters were killed by earthquakes. Climate-related disasters are especially prominent overall. Source: [4]

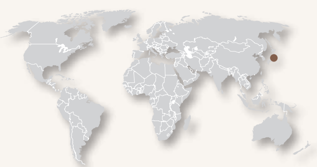
Erosion Control and Climate Change in Japan

Japan's mountain rivers are extensively regulated for hydropower and erosion control. More than 4 000 dams and a greater number of sediment retention dams (*sabo*) help to mitigate frequent floods and debris flows. Many hillslopes in Japan have been repeatedly stabilized using engineering measures to reduce incoming sediment loads to rivers. Future climate change scenarios suggest more extreme rainfall events in Japan, likely increasing floods and debris flows.

Yuichi S. Hayakawa
Norifumi Hotta

Heavily engineered flanks of Mount Nantai, Japan (Y. Hayakawa)

The frequency of heavy and prolonged rainfalls in Japan has increased 30 percent over the last 30 years (Figure 4.3). The annual frequency of landslide disasters has similarly increased. Measures to address this require a careful balance between maintaining river- management structures and safeguarding assets at risk. Central Japan's Nikko National Park is a very popular tourist destination known for its spectacular natural and cultural landscapes; its shrines and temples have been designated a UNESCO World Heritage Site. Towering above this cultural scenery is Mount Nantai, a 2 486 m high stratovolcano that has stood silently since its last major eruption 14 000 years ago. Numerous landslides and debris flows from its flanks have caused damage to downstream cities, home to some 60 000 inhabitants. Such events are likely to increase as rainfall extremes become more pronounced. To prevent future disasters, dozens of *sabo* have been put in place over the last century, requiring constant maintenance and upgrading. Landslides could still destroy these long-term efforts towards erosion control. Excess landslide sediment in river channels – an anticipated consequence of climate change – could increase the runoff ratio such that floods degrade river-channel beds and undermine check dams to the point where they fall like pearls from a string. Indeed, heavily engineered mountain rivers subject to extreme rainfall and flooding events are especially vulnerable to climate change. The climate change vulnerability of Japan's watershed-management efforts is heightened by broader trends such as the country's declining and aging population as well as recent financial crises.



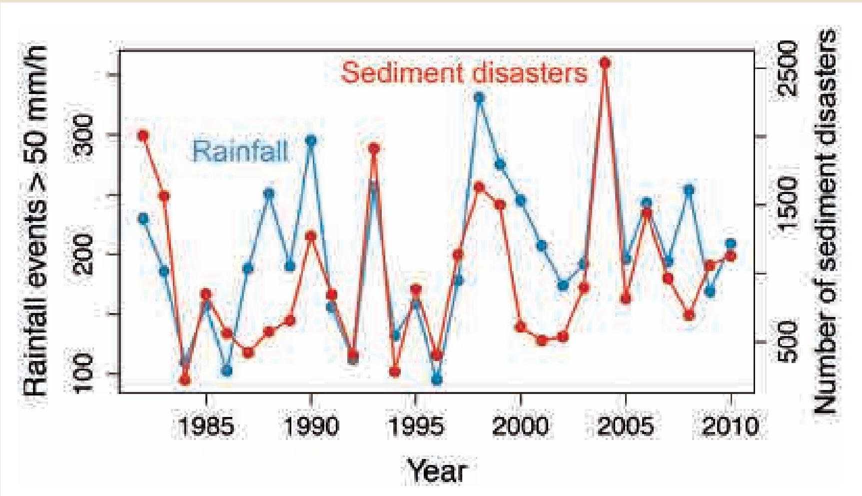


Figure 4.3. Heavy rainfall events and destructive mass movements of sediment appear to have increased slightly in Japan between 1982 and 2010. Source: [1]

Abnormal Monsoon Floods in the Indian Trans-Himalayas

People in the rugged high-mountain deserts of Ladakh and Zanskar ranges prefer living close to rivers. They supply the water necessary to sustain sophisticated irrigation, enabling lush oases in arid valleys that serve as centres of economic and agricultural activity. However, these river settlements may be vulnerable to hazards such as floods and mudflows – hazards that climate change could worsen.

Jan Blöthe
Henry Munack

Flash-flood damage in Ladakh's capital of Leh (A. Stolle)

Ladakh's population has more than doubled since the 1970s, pushing peripheral settlements into more geologically active terrain and endangering livelihoods and infrastructure. The disputed Trans-Himalayan borderlands of India, Pakistan and China have also seen massive growth in summer tourism in recent decades – receiving as many as 180 000 visitors per year – such that tourism has become the region's most important income source.

Summertime in the region is also monsoon time. Monsoons deliver the majority of the region's meagre annual precipitation (about 100 mm). However, global warming appears to be affecting the duration and intensity of summertime monsoons in South Asia. Over the last decade, the region experienced several years of extremely intense rainfall events. The most devastating rainfall events occurred during the nights of 4–6 August 2010, when monsoonal storm cells dumped more than half the region's mean annual rainfall in just a few hours. Torrential rains triggered floods and destructive debris flows, with peak discharge levels as high as 100 times the flood capacity of river channels. More than 250 people were killed, over 70 villages were severely damaged and major traffic routes were blocked for weeks, cutting off the lifelines of many small mountain communities.


One of many Trans-Himalayan oases in the Indus River valley (O. Korup)

The events were a wake-up call about the need for critical assessment of hazards arising from abnormal monsoonal rainfalls. Such events may occur with greater frequency in the future, making it critical that public focus is maintained on ways of mitigating or preparing for them.

Reducing Vulnerability to Climatic Risks in the Indian Himalayan Region

The Indian Himalayan Region is highly vulnerable to various hazards and risks caused by climatic extremes. Climate change and new settlements are factors that are altering the characteristics of such risks. Recent events such as monsoon flooding and related landslides in Kedarnath (2013) and Kashmir (2014) – which led to hundreds of fatalities and thousands gone missing – reveal the terrible toll that extreme weather events can take on mountain communities.

Nadine Salzmann
Janine Kuriger
Shirish Sinha
Kirtiman Awasthi
Mustafa Ali Khan

View of the valley with Kedarnath Temple in the background, following the 2013 flash flood and landslide (M. Dwidevi)

In order to reduce the vulnerability of those living in at-risk mountain areas, the Indian Government is conducting an integrated vulnerability and risks/hazards assessment encompassing the 12 Indian Himalayan states. The assessment will serve as an important basis for prioritizing, planning and implementing adaptation measures at the state and subnational levels (Figure 4.4).

The Indian Himalayas Climate Adaptation Programme (IHCAP) of the Swiss Agency for Development and Cooperation (SDC) is actively supporting these efforts by sharing longstanding Swiss expertise in climate-related mountain hazards and risks. As part of the Indo-Swiss collaborative efforts, involving the state of Himachal Pradesh and Indian and Swiss institutions, IHCAP is carrying out an integrated vulnerability and risk assessment for Kullu District. The knowledge and experience gained from pilot studies in Kullu will contribute to the development of a common framework for integrated vulnerability and risks/hazards assessment for the Indian Himalayan Region.

Kedarnath Temple in Uttarakhand, India, after it was hit by flash floods in 2013 (M. Dwidevi)

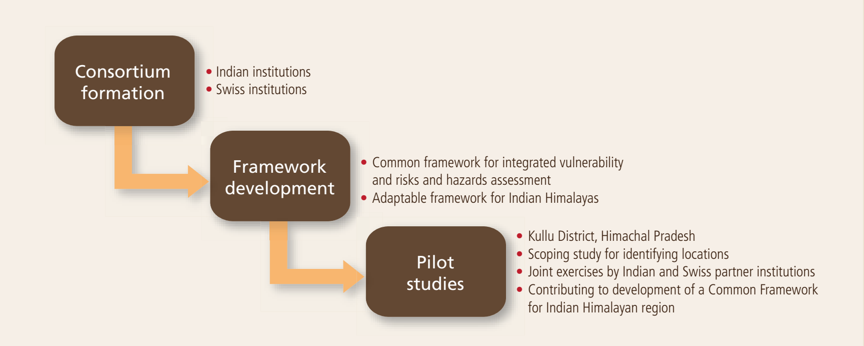


Figure 4.4. Process and expected outputs from Indo-Swiss collaborative studies in Kullu District, Himachal Pradesh

Pokhara's Elusive Past

Extreme geomorphological events are too rare to be reflected in our instrumental records. But examination of sediment in the Pokhara Valley provides indication of a massive landslide 800 years ago – likely one of the biggest ever in the Himalayas. Will climate change-related permafrost decay and glacier melt increase the likelihood of such disasters in the future?

Wolfgang Schwanghart
Anne Bernhardt
Amelie Stolle

Terraces made up of prehistoric debris-flow deposits, Seti Khola, Nepal (W. Schwanghart)

Nepal's second-largest city, Pokhara, home to more than 300 000 inhabitants and visited by some 800 000 tourists per year, is built on extensive sedimentary deposits that may have formed during a catastrophic debris-flow event about 800 years ago. If confirmed, the event would be one of the biggest, most recent landslides ever documented in the Himalayas. Flashing forward to our times – or in May 2012, specifically – Pokhara was hit by another type of disaster: a flash flood. It burst the banks of the Seti River, Pokhara's main water artery, wreaking havoc and killing more than 70 people. At the time, residents claimed that nothing like this had ever happened here.

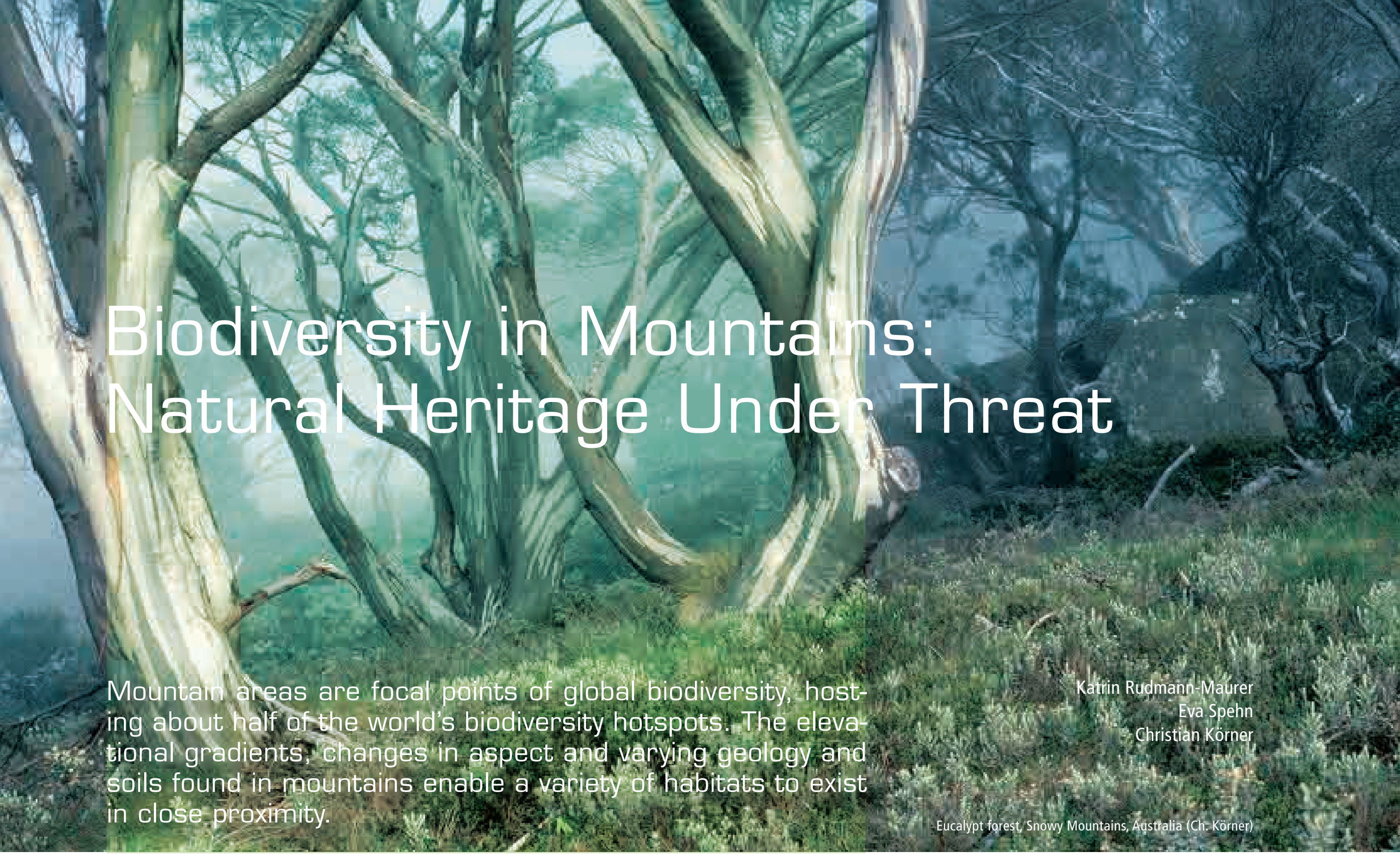
But, as researchers are discovering, the sediment beneath Pokhara tells a different story. Layers of gravel and boulders up to 100 m thick fill much of the Pokhara Valley. Peat beds preserved in these deposits appear to cluster around 800 years ago, suggesting a catastrophic landslide or debris flow around that time involving several cubic kilometres of sediment that dammed tributaries of the Seti River and formed lakes, seven of which still exist today. Strikingly, these deposits all share the same source: the Sabche Cirque, a large, debris-filled depression between the towering Himalayan peaks of Machapucharé and the Annapurnas II–IV. This cirque also spawned the 2012 Seti flood, which resulted from the sudden burst of a meltwater lake ponded behind

Pokhara with Machapucharé (6 993 m) in the background, Nepal (T. Kohler)

an ice avalanche. Climate change-related temperature increases, permafrost decay and glacier melt may make Himalayan peaks more unstable in the future, possibly causing further outburst floods from the Sabche Cirque. The evidence of catastrophic medieval debris flows from this cirque raises the prospect of future debris flows and flash floods hitting Pokhara that far exceed the 2012 event.

5 Mountain Biodiversity

Scorzonera paradoxa, Mount Shirkuh, 3 800 m, Iran (J. Noroozi)



Biodiversity in Mountains: Natural Heritage Under Threat

Mountain areas are focal points of global biodiversity, hosting about half of the world's biodiversity hotspots. The elevational gradients, changes in aspect and varying geology and soils found in mountains enable a variety of habitats to exist in close proximity.

Katrin Rudmann-Maurer
Eva Spehn
Christian Körner

Eucalypt forest, Snowy Mountains, Australia (Ch. Körner)

Mountains are home to many endemic plants and animals, i.e. species that occur nowhere else. Tropical and subtropical mountains are major centres of plant species diversity, including areas in Costa Rica and Panama, the tropical eastern Andes, the subtropical Andes, the Atlantic forests in Brazil, the eastern Himalaya–Yunnan region, northern Borneo, New Guinea and East Africa. The mountains of tropical and subtropical America, for example, harbour over 90 000 species of flowering plants (Figure 5.1). Epiphytes such as mosses and ferns are prominent examples of species richness in mountains: The diversity of mosses found in the five tropical Andean mountain countries is estimated to be seven times that of the entire Amazon basin.

Mountain forests and ecosystem services

Natural mountain forests are vital reservoirs of species. Evergreen tropical cloud forests, in particular, are very rich in endemic species – but they are also the most fragile and most diminished type of mountain forests. Mountain forests are also essential providers of key ecosystem services such as freshwater resources or protection against natural hazards. Many of the world's largest cities rely on freshwater resources supplied by mountain ecosystems. But ecosystem services interact in dynamic ways, and efforts to protect one type of service may result in losses of another service. For example, cutting down a mountain forest to exploit its value as timber can result in the loss of protection against landslides.

Agrobiodiversity – ensuring food security

Mountains are important centres of agrobiodiversity, hosting a wide variety of locally adapted crops and livestock. These varieties are a crucial genetic resource and help to ensure food security for the growing global population. Many mountain crops may be found in the gene banks of organizations such as the International Potato Center, which includes potatoes, sweet potatoes and Andean roots and tubers in its stores meant to preserve agrobiodiversity. Older crop cultivars or livestock breeds are frequently better adapted to the extreme climate and topography of mountain regions, and are better able to sustain mountain farmers' livelihoods under conditions of climate change.

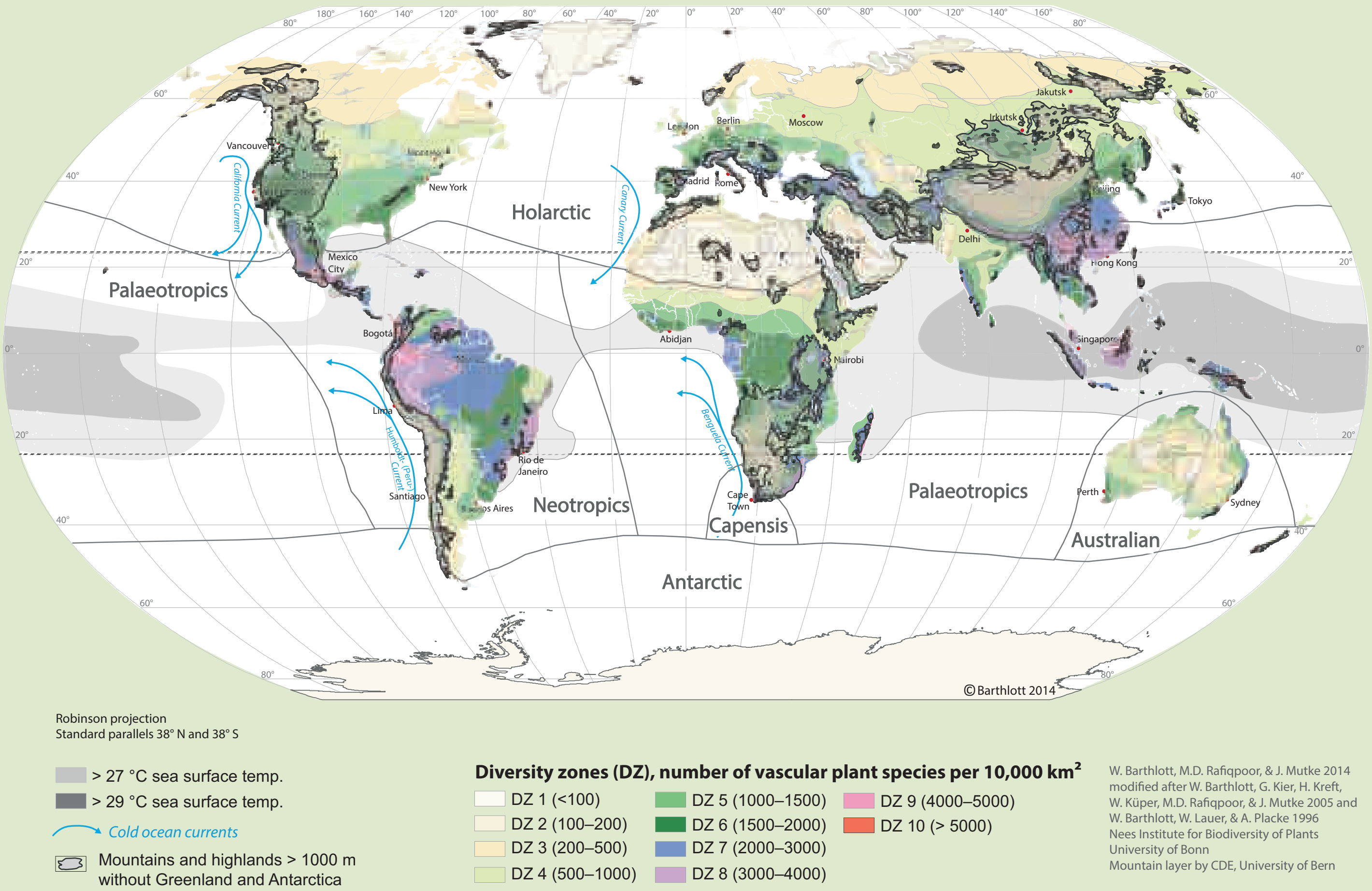
Climate change: a threat to mountain biodiversity?

Expansion and intensification of land use is a big source of biodiversity loss in mountain areas. In addition, climate change is increasingly seen as a major threat to mountain biodiversity. Air temperatures have been rising globally, with variations in magnitude at the regional level. Individual organisms must either escape or adapt to changing environmental conditions, lest they go extinct (Figure 5.2). For instance, certain butterfly species have been migrating north, or to higher altitudes, to escape rising temperatures. Plants, of course, cannot migrate as quickly as animals. Nevertheless, upward shifts have been found among certain plant species [1], while other plants have adapted to strong climatic changes. Many mountain plants exhibit a narrow habitat tolerance. This is often assumed to make them more vulnerable to changing conditions. However, above the tree line, the topographic richness of mountains also provides for a mosaic of microhabitat temperatures over short distances, with conditions varying more than the temperature change predicted by the Intergovernmental Panel on Climate Change (IPCC). This provides space for "climatic refuges" or stepping stones, and high-elevation organisms need not always migrate very far to find a suitable new habitat. When

Policy messages

- The many climatic zones along gradients and varying topography found in mountains enable them to host a high degree of biodiversity and many endemic species over short distances. Biodiversity conservation efforts must continue to emphasize mountain areas.
- Mountains' varying topography may enable certain cold-adapted species to find nearby refugia in a warming world.
- Mountain ecosystems provide essential services to humankind. Every effort should be made to preserve their biodiversity. However, the goals of biodiversity protection could clash with those of food production – climate change could heighten this dilemma.

Figure 5.1. Global biodiversity and mountain regions: Number of species of vascular plants from a regional perspective (100 x 100 km)



Mountain meadow at Furka Pass, Switzerland, 2 500 m (Ch. Körner)

global air temperatures increase by 2 °C, the number of cooler habitats will shrink, producing a crowding effect and increased competition among some species in the remaining cooler areas; at the same time, however, other habitat types will increase in abundance [2]. This will affect both plant species diversity and animal diversity. Alpine habitats could prove more attractive to plant species than lowlands because of their topography providing favourable microhabitats. However, certain rare species may lose out in the long-term competition for space, especially those favouring cooler climates.

The value of biodiversity

It is often easier to garner support for protection of things that possess an accepted monetary value. But biodiversity cannot easily be captured in economic terms. Of course, certain mountain crops – e.g. coffee or tea – do have a recognized economic value. But what is the precise worth of an Alpine plant or a butterfly? Most species are important constituents of ecosystems from which humankind profits directly or indirectly, for example via ecosystem services; attaching a specific economic value to individual species or ecosystem services is nearly impossible. For instance, maintaining diverse plant cover is practically the only way to sustainably prevent soil erosion under unpredictable conditions of environmental forcing. Forests in the European Alps require a high level of biodiversity to provide a long-term protective function against landslides, rockfall and avalanches. The protection afforded by a diverse mountain forest makes it possible to maintain settlements, transport routes and technical infrastructure.

The need to reconcile conservation and development goals

Managing mountain biodiversity is increasingly recognized as a global priority. Worldwide, protected areas have increased at least sevenfold in the last 40 years, largely in mountain areas. However, robust biodiversity conservation efforts must continue to achieve the 2020 target of reducing biodiversity loss. Climate change may create added pressure to conserve. But climate change could also increase demand for intensive resource use in mountains, since nearby lowland areas could be subject to flooding and hotter temperatures that erode the local conditions for habitation [3]. In this way, the goals of biodiversity conservation and food production often appear at odds in concrete settings. One way of reconciling biodiversity conservation goals and development goals is to engage local people in the stewardship of their natural heritage. Instead of increasing or expanding protected areas, many observers advocate the creation of conservation landscapes that both maintain biodiversity and support diversified, small-scale farming – particularly in Africa. Nevertheless, different strategies of land use and management are required to address the needs of highly developed mountain regions, such as the European Alps, versus those that appear to exist in a more pristine, natural state, such as the Patagonian Andes.

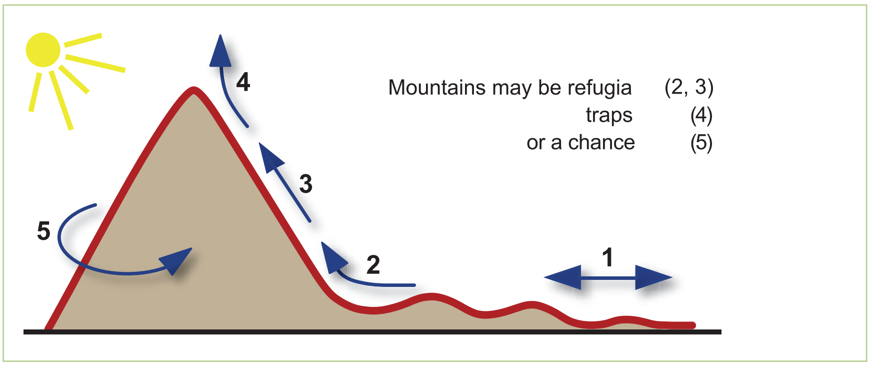


Figure 5.2. Species responses to global warming. Mountains may represent: refugia for species moving upwards (2, 3); traps leading to local extinction when no further upward movement is possible (4); or an opportunity to escape warming temperatures by exploiting topography (i.e. by "moving around the corner") (5). Lowland species often have to move across greater distances to find a suitable habitat in response to climate change (1). Figure modified from [4]

Espeletia sp., El Angel, 3 600 m, Ecuador (Ch. Körner)

Iran: Home to Unique Flora Threatened by Global Warming

Found at elevations above 3 600–3 900 m, Iran's subnival and nival zones are distributed in a highly fragmented manner across the Alborz mountains, the Zagross mountains and the northwest of Iran. Plant life in these zones is threatened by global warming.

Jalil Noroozi

Mount Damavand, 5 671 m, Iran (J. Noroozi)

Tiny areas scattered across the country's mountainous landscapes, Iran's subnival and nival zones (Figure 5.3) are home to 151 vascular plant species. Fifty-one of these can be considered true subnival–nival species. They only occur in these zones, and 68 percent of them are endemic to Iran (Figure 5.4). The proportion of endemic species decreases very sharply as one descends in altitude: Only 53 percent of the species occurring between Iran's subnival–nival and alpine zones are endemic; the proportion of endemic species decreases further to 20 percent of all species occurring between the subnival–nival and subalpine zones. Thus, species that have a narrow vertical distribution restricted to high altitudes are often also narrowly distributed geographically. Conversely, species featuring a broad elevational distribution are frequently also widely distributed geographically.

Overall, the level of endemism is very high in Iran's high-altitude areas, similar to mountain areas found around the Mediterranean Basin such as the central Apennines, Sierra Nevada or the Atlas Mountains. This mainly seems to be a result of fragmented cold areas and pronounced orographic isolation more recently, as well as a result of the absence of extensive glaciation during the Pleistocene.

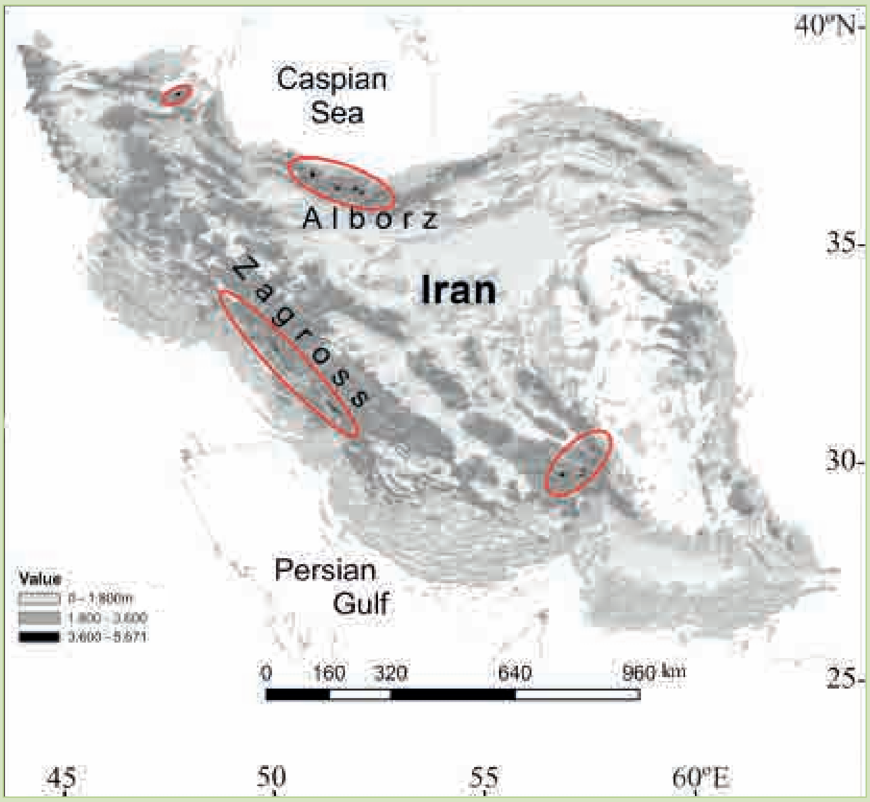


Figure 5.3. Iran's mountain areas (dark grey) and the distribution of its subnival–nival zone (individual black patches in red circles). Modified from [1]

The small size of Iran's cold habitats and the narrow distribution of its cold-adapted mountain flora mean that many of these plants are highly vulnerable to climate change – increasing temperatures could cause their extinction. There are very few protected areas in Iran that encompass subnival habitats. Safeguarding Iran's vulnerable mountain flora will require the expansion of high-altitude protected areas.

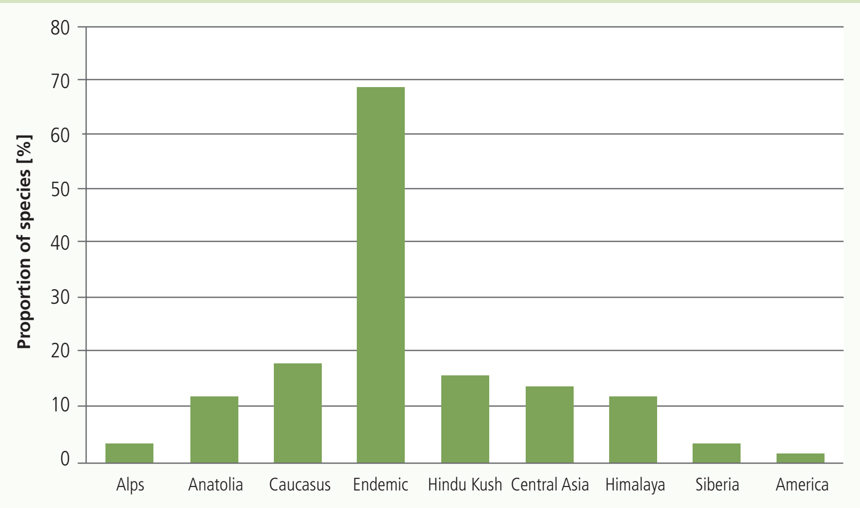


Figure 5.4. Global distribution of plant species which in Iran are found solely in its subnival–nival zone, showing the percentage of species endemic to Iran or also occurring in other mountain ranges and areas of the world: 68 percent of these species exist only in Iran, while 4 percent also occur in the European Alps, etc. Modified from [1]

Lessons learned

- Endemism is high in the upper reaches of Iran's mountains. Among the plant species occurring solely in the subnival–nival zones of Iranian mountains, 68% are endemic to Iran.
- These species are highly vulnerable to global warming, which could possibly cause their extinction.

Androsace villosa on Mt Alamkuh, 3 800 m, Iran (J. Noroozi)

Climate-Resilient Pasture Management in the Ethiopian Highlands

In the Ethiopian highlands, overgrazing accounts for 20 percent of the country's annual soil erosion [1], and vital plant species are disappearing from pastures mainly because of open-access grazing. Efforts to better manage access to communal pastures can support biodiversity conservation and increase communities' resilience to climate change.

Lemlem Aregu
Ika Darnhofer
Maria Wurzinger

Village in the Ethiopian highlands showing hay stocks at the bottom right (M. Wurzinger)

While many communities in the Ethiopian highlands permit open-access pasture grazing, the Kuwalla community in northern Ethiopia's Amhara region uses a rotational grazing system to manage its communal pastures. The community developed this system after recognizing the negative impacts of the open-access system, which they had practised until 1990. Soil erosion was severe and gully formation led to loss of grazing land. Pastures were seriously degraded and the shrinking number of plant species no longer provided adequate nutrition for oxen, a crucial asset needed for ploughing soils.

Three main factors enabled the community to reverse the negative trend. First, traditional leaders saw the need for change and mobilized the community, building on their skills, knowledge and authority as "fathers of the herders". Second, a local institution was created that allowed community members to discuss and revise the rules governing access to and use of communal pastures. The rules were adapted based on experimentation, with enclosures ensuring the regeneration of pastures. Third, the community collaborated with government agencies, securing their support to enforce rules – e.g. barring cattle from neighbouring villages – while safeguarding local autonomy. These measures helped to reduce grazing pressure and enabled the pastures to regenerate.

The case shows that effective community-based pasture management can enable valuable fodder species to regrow, ensuring adequate supplies of feed for oxen and cows (see Table 5.1) especially during critical times of the year. Proper rules can also help farming communities to cope with climate variability [2] and climate change, since pasture access is determined based on rainfall patterns. This enables targeted use of pastures depending on stages of regrowth or growth and levels of species mix.

Traditional threshing of harvested crops with cattle (M. Wurzinger)

Before enclosure		After enclosure	
Type of species	**Feed value**	**Type of species**	**Feed value**
Snowdenia polystachya (Muja)	Low	*Cynodon dactylon* (Serdo)	High
Sporobolus natalensis (Murgn)	Low	*Snowdenia polystachya* (Muja)	High
Trifolium spp. (Wajima)	Medium	*Andropogon abyssinicus* (Gaja)	High
		Medicago polymorpha (Mesobei)	High
		Sporobolus natalensis (Murgn)	High
		Trifolium spp. (Wajima)	High
		Eleusine floccifolia (Arma)	Medium
		NI (Armetmato)	Medium
		Pennisetum sp.	High
		Cyperus rigidifolius (Engecha)	High
		Hyparrhenia dregeana (Zeba)	Medium
		Lanceolata minor (Gorteb)	Medium
		Arthraxon prionodes (Yekok Sar)	Medium

NI: Scientific name of the species not identified. Local names in brackets. Source: [4]

Table 5.1. Plant species that regenerated thanks to introduction of a rotational grazing system, and the value of these species as fodder (according to the community)

Farmers' perception of climate change, Ethiopian highlands

"Lately we are experiencing rainfall variability. The *kiremt* rains, our main growing season, used to begin in early July and stop in early October; and it rained every day or every other day. These days, we never know. Some years, it comes early in June and stops in early September; other years, it comes in late July and continues to the end of October. Sometimes the rain ceases in the middle of the rainy season, for one or two weeks. So the rain has become unreliable."

Elderly man in focus group discussion, October 2012

Farmer visiting his fodder tree plantation, Ethiopia (M. Wurzinger)

While pasture management has improved, gender equity has not: Women are excluded from the institution governing pastures. So their preferences are not taken into consideration. They have also been banned from harvesting specific grass species used to craft traditional plates for serving or storing food. This clearly restricts women and also harms the species mix in pastures as certain species become too abundant and displace other species that animals prefer to graze [3].

Flexible pasture management

"When we have low production of crops due to less rain, we run out of crop residues which we use as fodder and must open the communal pasture for grazing a bit earlier than normal in order to feed our oxen and cows."

Member of pasture-management committee, October 2012

Lessons learned

- Empowering communities by encouraging leadership and use of local knowledge, and by promoting platforms that enable learning and collective action can ensure more sustainable use of common resources and increase resilience to climate change.
- Women are still neglected in pasture management. Including them in decision-making on this topic would strengthen communities' ability to adapt effectively in times of uncertainty, and would enhance social justice.

Mountain Forests for Biodiversity Conservation and Protection Against Natural Hazards

Mountain forests in the Alps and in other mountain regions provide effective protection against natural hazards such as rockfalls, avalanches and shallow landslides. Fostering biodiversity helps to maintain and increase protective functions in the long term, especially in the face of climate change.

Peter Bebi
Frank Krumm

A natural spruce forest in Germany's Harz national park, which displays high structural diversity of age classes and decomposition stages (F. Krumm)

Almost 50 percent of the forests in Switzerland provide protection against natural hazards. Without the natural protection supplied by forests, it would be necessary to build other protection measures in large areas of the Alps where important infrastructure (e.g. roads) is located [1]. Compared with other protection measures, the natural protection provided by forests is dynamic over time and hence susceptible to periodic or abrupt changes. Under the projected scenarios of global warming, we would expect an increase of protective functions around temperature-sensitive timber lines. However, forests' protective functions could also be drastically reduced as a result of large-scale disturbances such as forest fires or insect outbreaks – both of which are expected to increase as a result of climate change. Indeed, one of the biggest challenges in managing protection forests is that of understanding how they will respond to disturbances and how to maintain or enhance their capacity to recover after major disturbances.

Though very little research has been conducted focussing specifically on biodiversity in protection forests, the scientific evidence we do have strongly supports the conclusion that forest ecosystems' resilience depends on biodiversity at multiple levels [2]. For example, at the species level, it has been shown that pure spruce stands – common in montane and subalpine forests in the northern Alps – are more prone to spruce beetle outbreaks [3]; thus, stands featuring more species are more resilient to such outbreaks and maintain their protective function better.

Resilience

Resilience is the capacity of a forest ecosystem to sustain its fundamental structure, function and feedbacks when confronted with perturbations such as unprecedented warming or large-scale natural disturbances [2].

Large-scale disturbances in mountain forests, such as the forest fire shown here, can diminish the protection that forests provide against natural hazards (U. Wasem)

Similarly, forests displaying greater diversity of root types (reaching different soil layers and associated with different species of mycorrhizal fungi) are usually less prone to soil erosion and shallow landslides.

Overall, diversity within a forest stand – including different vertical layers and deadwood – provides a favourable habitat for a variety of other species of flora and fauna and provides greater resilience against insect damage or blowdown. Even natural mountain forests consisting of only one tree species (e.g. spruce) may include structurally diverse areas and habitats for rare species [4]. At the landscape level, protection forests spread across more heterogeneous landscapes are less susceptible to massive forest fires and other large-scale disturbances, since spatial variations in forest structure inhibit the spread of disturbances [5]. Synchronous forest succession in the Alps has led to widespread homogenous stages of development, which may currently provide good protection against natural hazards (e.g. rockfalls, avalanches) thanks to high stem counts, but could also compromise their resilience to certain threats. While the forest-management goals of maximizing biodiversity and minimizing risks to human infrastructure may not always converge in the short term, they increasingly converge when viewed from a long-term perspective, especially with respect to climate change. This is increasingly acknowledged in the management policies of forest authorities in charge of protection forests (e.g. [6]).

Lessons learned

- Fostering increased diversity at different levels will help to maintain or increase the resilience of protection forests to large-scale disturbances and to the effects of climate change.
- This, in turn, will increase the protection these forests provide against natural hazards in the long term.

6

Food Security in Mountains

Spring farming in Gasa, Bhutan (L. Hislop, GRID-Arendal)

Mountains, Climate Change and Food Security

Climate change is likely to worsen the living conditions of many mountain farmers who are already food-insecure. By building on indigenous practices and adaptation strategies, they can become more resilient to shocks and reduce their vulnerability to hunger.

Thomas Hofer
Sara Manuelli
Alessia Vita

Millet cultivation in Chilime Khola, Nepal (T. Hofer)

People living in mountains are among the world's poorest and hungriest: in developing countries, the vast majority of mountain people lives below the poverty line, and many are food-insecure (Table 6.1). Mountainous terrain, with its steep slopes and frequently harsh climate, presents farmers and herders with challenging conditions to live and work in. Crop growth is slower at high altitudes, so many mountain farmers have only one harvest per year. In addition, mountain soils are often degraded and do not provide enough nutrients for plants to grow well. The Food and Agriculture Organization (FAO) has estimated that around 45 percent of the world's mountain area is not or only marginally suitable for growing crops, raising livestock or carrying out forestry activities [1].

Traditional mountain diets tend to be limited to starchy foods and are often characterized by low dietary diversity. Nutritional studies have shown that mountain people are particularly likely to suffer from micronutrient deficiencies. Inhabitants of the Andes, the Himalayas and mountain ranges in China, for example, were found to have some of the highest rates of iodine deficiency.

Challenges of climate change

According to the 2014 Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), rising temperatures and an increased frequency of extreme weather events will have direct negative impacts on crops, livestock, forests, fisheries and aquaculture productivity in years to come [2]. Farming-dependent mountain populations in the developing world are particularly at risk.

Mountain ecosystems are extremely vulnerable to climate change. At the same time, impacts such as rapid glacial melting and reduced snow cover have implications far beyond the mountains. Changes in the volume of mountain glaciers and their seasonal melting patterns, increased temperature variability and extreme rainfall events will have an enormous impact on water resources in many parts of the world. Freshwater from mountains is fundamental for achieving global food security: many farmers in both highland and lowland regions depend on it for irrigating their crops. Climate-induced hazards such as storms, landslides, glacial lake outburst floods and avalanches affect mountain communities by disrupting access to basic infrastructures such as health services, schools, extension services, roads and markets. Isolation limits mountain people's opportunities not only to trade, but also to generate income, thereby additionally undermining their food security. Farming is the prevailing occupation and the main source of food in mountain areas. Mountain farming, which is largely family farming, is inherently "green": mountain agriculture has a low impact on the environment and helps to mitigate climate change by emitting only very small amounts of greenhouse gases while increasing carbon sequestration in plants and soils.

Policy messages

- Implement climate-smart agriculture policies tailored to national and regional contexts.
- Empower smallholders with equal rights, entitlements and opportunities to access credit, productive resources and secure land tenure.
- Ensure small farmers' access to markets and to a fair share of the value chain.

Can mountain farmers keep up with change?

People living in mountain areas are traditionally used to the fact that the climate varies considerably from year to year, from season to season and from day to day, as well as between different altitudes and even different slope exposures. They have adapted their traditional land-use systems to this variability, for example by growing sun-loving plants on the warmest slopes and moving livestock to high summer pastures after the snow has melted. With climate change, however, climate variability may eventually increase beyond the limits of past experience, and this will pose a great challenge to the adaptive capacity of land users and their communities.

Tending a farm near Gasa, Bhutan (L. Hislop, GRID-Arendal)

Teff fields in Ethiopia (G. Napolitano, FAO)

Many mountain farmers who are already vulnerable and food-insecure will likely see their living conditions worsened by climate change. Crop failures and loss of livestock are some of the risks they face. At the same time, the urgent need to deal with the challenges of climate change offers an opportunity to transform the way in which food systems use natural resources – an opportunity to make mountain agriculture more sustainable and promote new ways of reducing poverty and hunger. Supporting and promoting sustainable indigenous practices, solutions and adaptation options by means of adequate policies, capacity building and scientific research can help mountain people to build resilience to the adverse effects of climate change.

Climate change opportunities

Mountains might also benefit from certain positive effects. Higher temperatures could increase timber yields and enable crop growing at higher altitudes, at least in places where there is enough water and soils are adequate. An extended growing season and accelerated soil decomposition may lead to better nutrient uptake by trees and other plants, and to greater growth and productivity.

Climate-smart agriculture is increasingly being adopted worldwide as a way to ensure sustainable rural development for food security under climate change. It addresses the changes in farming that a warmer world requires, and identifies solutions based on local conditions and indigenous knowledge. Climate-smart farming can help mountain communities to become more resilient.

FAO's definition of climate-smart agriculture

Climate-smart agriculture is an approach to developing the technical, policy and investment conditions to achieve sustainable agricultural development for food security under climate change. It contributes to the achievement of national food security and development goals with three objectives:

1. Sustainably increase agricultural productivity and incomes
2. Adapt and build resilience to climate change
3. Reduce and/or remove greenhouse gas emissions where possible

Climate-smart agriculture ...

- addresses adaptation and builds resilience to shocks;
- considers climate change mitigation as a potential co-benefit;
- is a location-specific and knowledge-intensive approach;
- identifies integrated options that create synergies and reduce trade-offs;
- identifies barriers to adoption and provides appropriate solutions;
- strengthens livelihoods by improving access to services, knowledge and resources;
- integrates climate financing with traditional sources of agricultural investment.

Source: [3]

Table 6.1. Food security in mountainous developing countries. Prevalence of food inadequacy: proportion of the total population of a country in a condition of undernourishment, based on energy requirement for moderate physical activity. Source: [4]

Food Security	Indicators	
Developing countries with mountain areas covering more than 70% of national territory	**Number of people undernourished [millions]**	**Prevalence of food inadequacy [%]**
Armenia	NA	6.9
Bhutan	NA	NA
Burundi	5.9	76.7
Kyrgyzstan	0.3	11.2
Lao People's Democratic Republic	1.7	37.1
Lebanon	NA	6.5
Lesotho	0.3	23.9
Nepal	5.0	23.6
Rwanda	3.4	38.4
Tajikistan	2.1	38.5
World	**842.3**	**18.4**

Farming landscape, Kyrgyzstan (A. Karsymbek)

Raising awareness of climate change in mountains

A number of international and national activities and events have addressed the impact of climate change on mountain areas in recent years, highlighting their role as early warning systems and sharing scientific and traditional knowledge and lessons about adaptation measures:

- The World Bank's Strategic Initiative on Mountains and Climate Change: regional meetings in Chile, Tajikistan, Uganda and Morocco, 2011–2012

Under this World Bank initiative, the Mountain Partnership organized four regional meetings that brought together government delegates, policy-makers, scientists and climate change experts. Participants shared and strengthened knowledge about climate change impacts in mountain areas, discussed adaptation options in mountain ecosystems and improved alliances and cooperation among countries with mountain regions.

- Mountain Days at the Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC): Durban, South Africa, 2011 and Doha, Qatar, 2012

These events, held during the UNFCCC conferences of parties, called attention to the severe adverse impacts that climate change has on the life of mountain communities and how the role of mountains as the world's water towers is threatened by the melting of glaciers. They advocated the need for supporting mountain communities around the world through political action, capacity building and scientific research.

- International Conference of Mountain Countries on Climate Change: Kathmandu, Nepal, 2012

Hosted by the Government of Nepal in the context of the Mountain Partnership, this conference provided a forum for mountain countries to share knowledge and experiences concerning the impact of climate change on mountains. They deliberated common risks, discussed a common approach to dealing with specific concerns related to mountain ecosystems and livelihoods, and analysed the development prospects of mountain regions under climate change, including poverty alleviation.

- Global Landscapes Day: Warsaw, Poland, 2013

The session on "Building Climate Change Resilience in Mountains" was organized by the Mountain Partnership Secretariat to address glacial melting induced by climate change and its far-reaching impacts on the water cycle and the livelihoods of mountain and lowland communities. It highlighted how local community empowerment is essential to building climate change resilience in mountains.

- UNESCO's Man and the Biosphere (MAB) programme in mountain areas

Man and the Biosphere (MAB), a longstanding interdisciplinary environmental research programme, has a component dedicated to mountains. It assesses the impacts of global and climate change on fragile mountain ecosystems using mountain biosphere reserves as study and monitoring sites.

- The World Mountain Forum in Cusco, Peru, 2014

This event brought together around 200 mountain stakeholders from across the globe to promote concrete and collaborative action for sustainable mountain development and foster political dialogue. Activities were grouped around four thematic areas: climate change, family farming, mountain communities and urban communities.

Panchase watershed above Pokhara, Nepal (T. Kohler)

The way forward

Mountain farmers have many options for combatting the adverse effects of climate change and ensuring mountain households' food security. Among them are the following:

- Adopting an integrated landscape approach and better integrating agriculture, livestock, forestry and aquaculture in order to help diversify sources of income and make mountain food systems more resilient to climate change.

- Adopting sustainable and organic farming systems and diversifying food systems. Organic farming reduces the need for intensive irrigation while enhancing the soil's capacity to retain water and improve water quality.

- Maintaining and promoting the high agrobiodiversity of crops and livestock in mountains, which offers significant potential for adaptation to climate change, contributes to food security and can provide income.

- Promoting, integrating and sharing local and indigenous environmental knowledge, climate change adaptation practices and food security strategies, and enhancing them by means of policy measures and investments.

- Promoting community-based disaster risk management (CBDRM) and developing the technical capacity of local institutions and farmers' groups to manage disaster risks.

- Building the capacity of all stakeholders to recognize climate change processes and trends, negotiate and implement mitigation and adaptation measures, and raise awareness.

Preserving Agroforestry on Mount Kilimanjaro

Food and Agriculture Organization (FAO)

The *kihamba* agroforestry system covers 120 000 hectares of Mount Kilimanjaro's southern slopes. It is one of the most sustainable forms of upland farming and provides livelihoods for an estimated one million people. A project to restore coffee crops in the system has enhanced farmers' cash income while preserving the ecological and social functions of the system.

The multilayered *kihamba* system maximizes the use of limited land and provides for nutritionally diverse food all year around (D. Boerma, FAO)

The *kihamba* agroforestry system in Tanzania maximizes the use of limited land. Based on a multilayered vegetation structure similar to that of a tropical mountain forest, the system provides a large variety of foods and substantive environmental services beyond the areas where it is practised. With the large quantities of biomass it produces and its capacity to recycle organic matter on farms, the *kihamba* system also contributes significantly to carbon storage. Its trees and dense vegetation ensure that Mount Kilimanjaro can continue to function as a water-tower for the surrounding region.

Coffee as an ecologically compatible cash crop enabled the *kihamba* agroforestry system to adapt successfully to the emerging cash economy. But fluctuating coffee prices and the spread of pests and diseases eventually caused farmers to abandon about 20 percent of coffee crops in the area. A project under the Globally Important Agricultural Heritage Systems (GIAHS) initiative of the Food and Agriculture Organization (FAO) responded by piloting a series of climate-smart agriculture activities in 660 households. The focus was on conversion to certified organic coffee farming, adoption of vanilla as a high-value additional cash crop and introduction of trout aquaculture along irrigation channels. The project also rehabilitated the irrigation system to reduce water loss and expanded the capacity of storage ponds to help farmers cope with longer dry seasons resulting from climate change. Training in sustainable land management and coffee management is expected to increase farm cash income by 25 percent in three years.

The *kihamba* system on Mount Kilimanjaro (Tanzania) is one of the most sustainable forms of upland farming found worldwide (D. Boerma, FAO)

Adapting to Climate Change in the Peruvian Andes

The people of Quelcaya have been adapting to changes in the climate for centuries. But as climatic conditions continue to become harsher, people are increasingly hard-pressed to respond: combined socio-environmental threats risk to overwhelm the community's adaptive capacity. In this situation, Andean communities need policies that help to reduce their vulnerability and enhance their resilience to climate change.

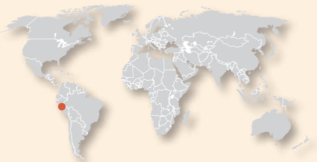
Julio C. Postigo

Nevado Huascaran, Peru (FAO, I. Camblor)

Quelcaya is a community of around 110 herding families in the southern part of the Peruvian Andes, in the district of Corani. It lies on a plateau between the eastern and western ranges of the Andes that is dominated by the world's largest tropical glacier: the Quelccaya Ice Cap. This huge glacier is melting at an increasing rate. Its largest tongue retreated around ten times faster (60 m/year) between 1991 and 2005 than between 1963 and 1978 (6 m/year) [1, 2].

The people of Quelcaya feel the impacts of climate change above all in this rapid glacier retreat, an increase in extreme temperatures and shifts in the rainy season [3] (Table 6.2). But not all of these changes have negative consequences. For example, some households have begun to grow potatoes at an altitude of 4 200 m in an area where the microclimate has become relatively favourable.

People in Quelcaya respond to climatic changes mainly by adapting the way they use their land and modifying their herds' movement patterns, depending on changes in land cover [4]. Farmers and herders have extensive experience with disturbances, including climate variability (see Box on page 101). By adapting their farming system, they regenerate their institutional capacity and create opportunities for transformation.



Alpacas grazing near stone corral (FAO)

Evidence shows that the community's institutions have responded to and been shaped by socio-economic and climatic disturbances over the past 150 years. But persisting socio-economic strains combined with increasingly harsh climatic conditions may overwhelm Quelcaya's institutional capacity and compromise its ability to respond to a broad range of threats. Policies are needed that can help to diminish the community's vulnerability, foster its adaptation and enhance its resilience to climate change.

Community responses to climate variability

Farmers and herders respond to drought by irrigating their land and moving their herds. By irrigating the land, they preserve, expand and create wetlands. Water for irrigation is diverted from springs, rivers and lakes through channels that are usually several kilometres long. They are built jointly by many households and over several years. This requires coordination and cooperation within and between households and communities. Growing precipitation variability has increased the importance of channel management in maintaining pastures and wetlands for seasonal grazing.

Livestock mobility and access to different grazing areas is a crucial response to extreme climatic events such as drought. As one herder puts it: *"What do we do when there is a drought? … we take the animals to another area where there is forage … we move them to the wetlands that have water."*

Precipitation	Temperature
Delayed onset of rainy season	Colder nights
Earlier end of rainy season	Warmer days
Irregular precipitation during wet season: few days of heavy rainfall followed by dry days	Glacier retreat

Table 6.2. Perceived effects of climate change in the Peruvian southern Andes. Source: [3]

Promoting Water Use Efficiency in Central Asia

Aida Jamangulova

In Kyrgyzstan, women farmers have adopted new irrigation techniques to deal with water scarcity resulting from drought. As a result, they are now harvesting crops earlier in the season and growing new varieties of vegetables that help to improve households' nutritional status and fetch premium market prices.


Women growing greenhouse vegetables in Kyrgyzstan (A. Karsymbek).

Kyrgyzstan, like many mountainous countries, is prone to extreme weather events and related hazards, such as floods, landslides, drought and cold spells. Experts say that climate-related events have become more frequent over the past 10 years and warn that climate change is likely to further increase hazards and reduce food security in the future. Rapid glacial melting and growing rainfall variability might affect crop yields, and, in the long term, lower annual rainfall might reduce the availability of water, exacerbate drought and accelerate soil degradation. In 2012 the Agency for Development Initiatives (ADI), a regional network of women's self-help groups, launched a project to promote efficient use of water resources by introducing water-saving irrigation techniques that also help to boost productivity and household income. Members of two groups in a village in Osh province in southern Kyrgyzstan started growing greenhouse vegetables in kitchen gardens using drip irrigation and water harvesting. The new techniques have helped them to mitigate the impact of weather fluctuations and adapt to increasing water scarcity: they can now harvest vegetables earlier and sell them on the markets. The project has not only increased the availability of nutritious vegetables, but also introduced crops that were new to the region, such as cauliflower, cherry tomato and mint. They are now being incorporated into the local diet. It is important to design climate change adaptation measures so that they address different target groups' specific needs and options (Table 6.3).

Table 6.3. Managing climate risks for greater household food security

Main livelihood	Options for managing climate risks
Subsistence and smallholder farming	Reduce post-harvest losses Improve efficiency of water use to address increasing rainfall variability Ensure access to extension services for climate change adaptation (drought-tolerant seeds etc.)
Medium- to large-scale farming	Strengthen early warning system for floods, drought, heat waves and cold spells
Unskilled labour (rural)	Establish national social safety nets for coping with climate-related shocks by improving effective delivery of post-disaster assistance Support home gardening to enhance access to diverse food
Unskilled labour (urban)	Stabilize food prices (early price warning etc.) Support home gardening to enhance access to diverse food
Remittances	Ensure women's access to agricultural services for climate change adaptation (drought-tolerant seeds etc.)
Social allowances	Build resilience to climate-related risks and shocks through public works and social safety nets

Food Security in the Hindu Kush Himalayas and the Added Burden of Climate Change

Some regions of the world are more vulnerable to food insecurity than others. For many people in the Hindu Kush Himalayas, food insecurity is already a fact of life. Half of the world's undernourished people live in Bangladesh, China, India, Nepal and Pakistan, and in all of these countries, mountain areas have the highest levels of food deficiency.

Tiina Kurvits
Lawrence Hislop

Mountain farming in Bhutan (L. Hislop, GRID-Arendal)

Climate change and rising global food prices are challenging our ability to feed a growing world population. The latest contributions to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report identify food insecurity as one of the key risks of climate change [1]. Climate-related disasters such as floods, droughts and storms are among the main drivers of food insecurity. At the same time, markets have been highly sensitive to recent climate extremes.

Food insecurity is already a fact of life in the Hindu Kush Himalayas. The region's harsh climate, rough terrain, poor soils and short growing seasons limit agricultural productivity, often leading to food deficits. The impacts of climate change and extreme weather events on food security are projected to be particularly severe in mountain regions, and the Hindu Kush Himalayas, a so-called "climate change hotspot", are no exception. The adverse effects of climate change in this region are compounded by already high levels of poverty and undernourishment, high dependence on locally grown food and depleted natural resources, as well as poor infrastructure.

The semi-subsistence farmers of the Hindu Kush Himalayas rely on a great diversity of agricultural practices and have traditionally been well adapted to the local microclimate. But the diversity and resourcefulness which served farmers well in the

Irrigated terraces, Nepal (T. Hofer)

past is now being seriously tested by climate change. Recent vulnerability assessments show that over 40 percent of households in the Hindu Kush Himalayas face decreasing yields in their five most important crops as a result of floods, drought, frost, hail and disease [2].

Farmers in this region have always been very adept at using the inherent flexibility of mountain food systems. Today, they are responding to the new challenges by changing their practices. This includes delayed sowing and harvesting, resowing, changing crop varieties and abandoning staple crops and livestock varieties. More and more farmers grow cash crops, which opens up new opportunities for generating income, but also exposes producers to swings in the markets.

The level of food security varies greatly across the Hindu Kush Himalayan region (Figures 6.1 and 6.2). Compared to the global decrease in undernourishment over the last two decades, the number of undernourished people in the countries of the Hindu Kush Himalayas has been diminishing more slowly, and undernourishment remains high. Mountain areas have the highest levels of food insufficiency in these countries [1], and persistent undernourishment, especially among children, remains an urgent concern.

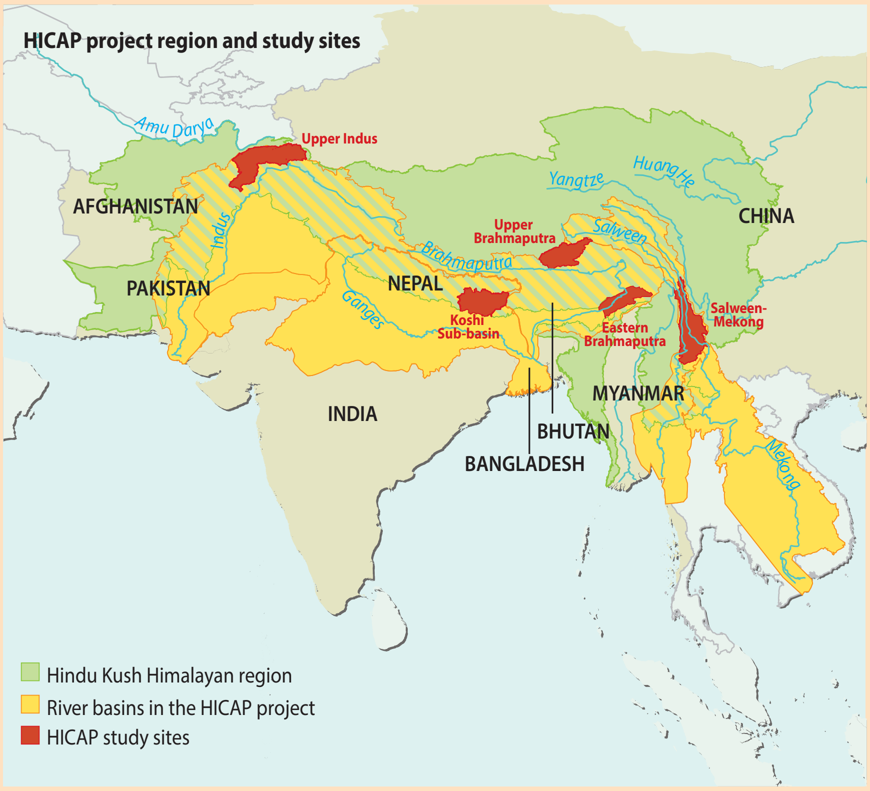
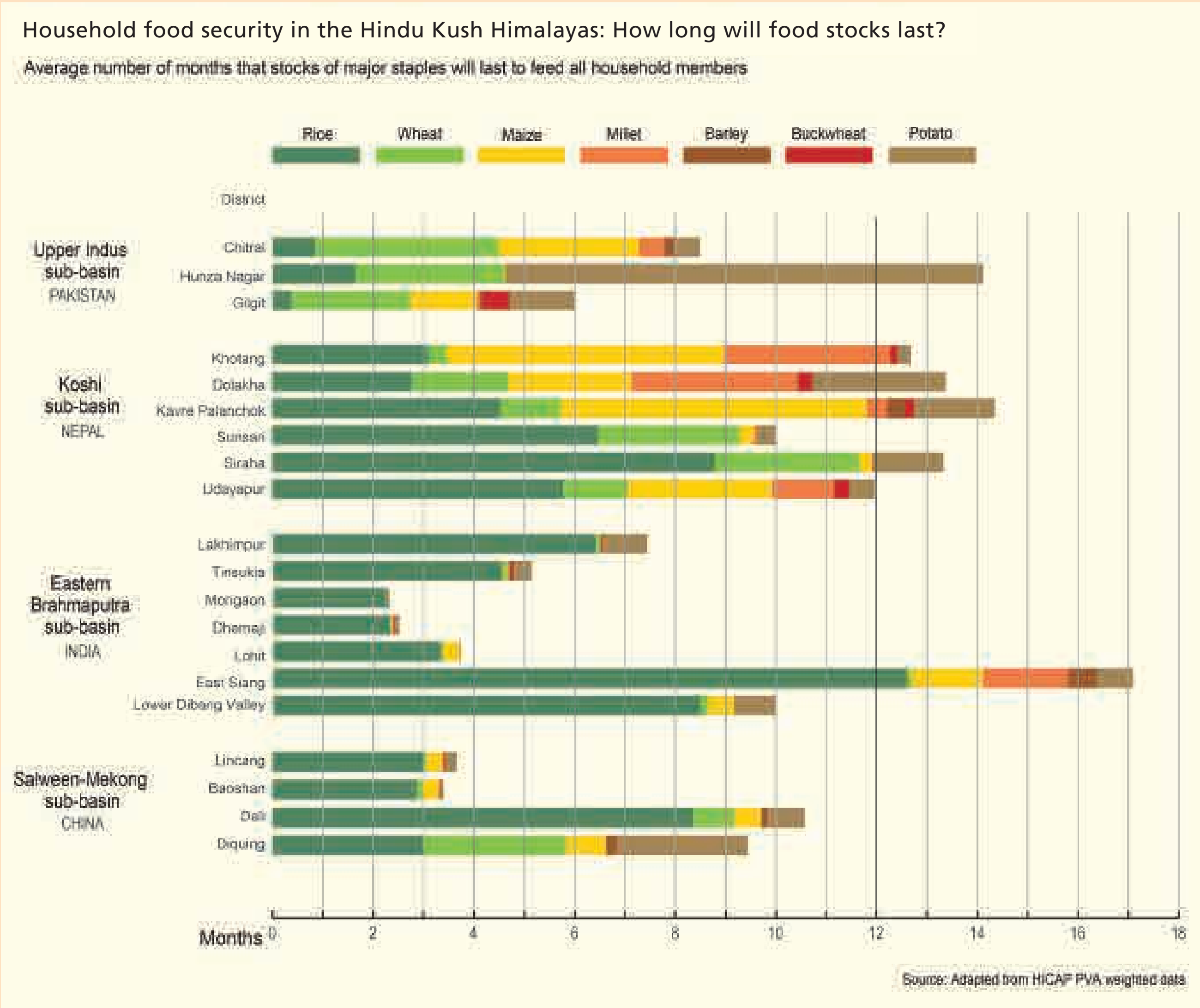


Figure 6.1. Himalayan Climate Change Adaptation Programme (HICAP): Project region and study sites

Figure 6.2. Household food security in the Hindu Kush Himalayas



Abandoned terraces due to migration, Nepal (T. Kohler)

Outmigration is one of the greatest social challenges to farming in the Hindu Kush Himalayas. The share of households engaged in off-farm employment ranges from 13 percent in Pakistan to 57 percent in Nepal [2]. While off-farm work is a source of social and financial remittances, it also results in labour shortages on farms. Women and elderly people are increasingly left to run the farms on their own. Women tend to be affected by climate change and disasters more severely than men because they are limited in their mobility and have less access to information, resources and decision-making.

Climate change is expected to affect food security in a number of ways. Scenarios indicate that Himalayan glaciers will release more water in the coming one or two decades, followed by a gradual decrease in most major river basins. At the same time, precipitation is becoming more variable [3]. Overall, water availability will vary significantly across the region and future water supply will be less predictable. Most projections suggest that more frequent extreme weather events and increasing rainfall variability will lower agricultural productivity.

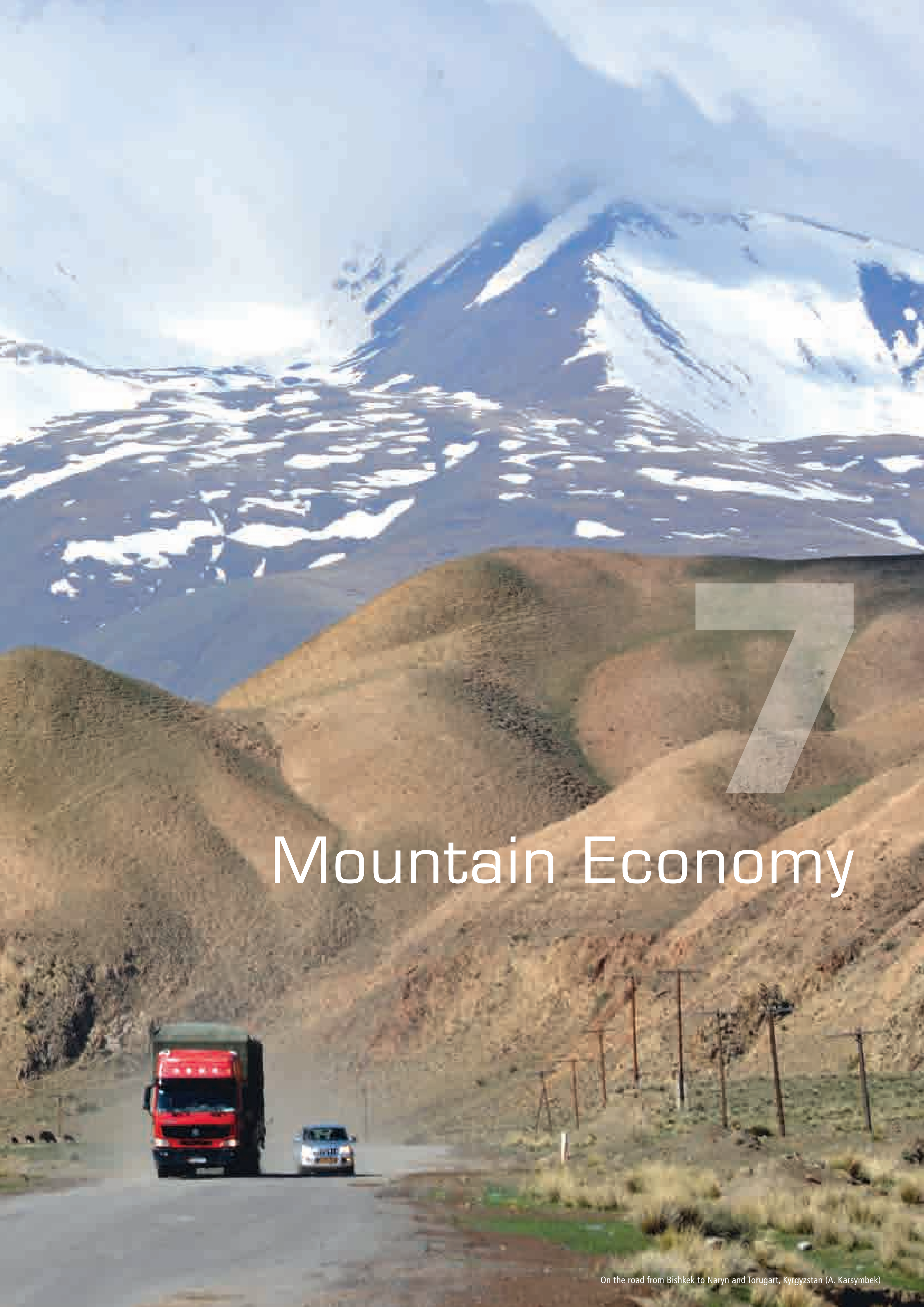
Climate change impacts on food security will vary across the Hindu Kush Himalayas. Pronounced trends indicate warming and increased proneness to drought in China and the Koshi Basin in Nepal, growing winter water stress in South Asia, high monsoon variability and more frequent flood-related disasters in the Upper Indus Basin and the plains of other basins, and warming at higher altitudes across all basins. All these trends pose a high risk to agriculture.

Lessons learned

- Develop policies and mechanisms to support small-scale farmers in expanding the flexibility inherent in their farming systems. Promote systems that provide ecosystem services critical for food production (water regulation, genetic diversity, pest control, soil management).
- Promote indigenous crop varieties that might be more resilient to climate change.
- Re-evaluate climate-smart technologies through a gender lens. Restructure and adapt farming systems to changing opportunities resulting from migration and climate change.

7

Mountain Economy



On the road from Bishkek to Naryn and Torugart, Kyrgyzstan (A. Karsymbek)

Mountain Economies, Sustainable Development and Climate Change

Golam Rasul
Eklabya Sharma

Mountains cover 24 percent of Earth's land surface area and host 12 percent of the human population. They supply 40 percent of global goods and services, including water, hydropower, timber, biodiversity, minerals, recreation and flood protection [1]. Despite their major contribution, mountains are still neglected in development agendas. And climate change has brought new challenges, since mountain economies are generally agrarian and depend on climate-sensitive sectors such as agriculture, forestry and livestock.

Livelihoods in the shadow of the Himalaya (Courtesy of ICIMOD)

The importance of ecosystem services provided by mountains is increasingly acknowledged. But the mountain people who help to sustain these services are seldom adequately compensated. Recently, rapid population growth, urbanization, outmigration, globalization, economic development and climate change have presented new challenges to mountain populations' traditional livelihood strategies and coping mechanisms. Once self-sufficient peoples now face dire economic poverty. In many countries, mountain populations are poorer than lowland populations. There is an urgent need to develop adaptation mechanisms for mountain communities that enable them to manage change and sustainably benefit from their environment and the economy.

Key characteristics of mountain economies

Mountain regions worldwide share common features including rugged terrain, marked topographic variation, remoteness and poor accessibility. While mountain economies vary considerably, they commonly lag behind the rest of the country or region in which they are situated. Rural economies in the developing world are generally weak, and mountain communities tend to suffer disproportionately. Mountainous terrain is associated with small and scattered production, high transport costs, restrictions on economies of scale, poor physical and economic infrastructure and poorly developed industrial and service sectors. Primary sector activities typically dominate, with mountain communities supplying raw materials and natural resource products to lowland populations. Many mountain populations in developing countries depend on agriculture, forest, pasture, livestock and collection of non-timber forest products (NTFPs) for their livelihoods. Their land is usually unsuitable for intensive cultivation, few specialized markets exist and farming is mainly rainfed, low-input and low-intensity.

Mountain areas generally lie far from seaports and other economic centres, further contributing to their economic marginalization. While mountain areas may be rich in resources, local investment tends to be low and resource activities seldom ensure adequate employment or even decent living conditions, with communities often lacking basic social and economic services. Industries, where established, are mainly extractive, such as mining, hydropower and timber. Upland–lowland production linkages and trade terms are generally asymmetrical and favour lowland areas.

Globalization and mountain economies

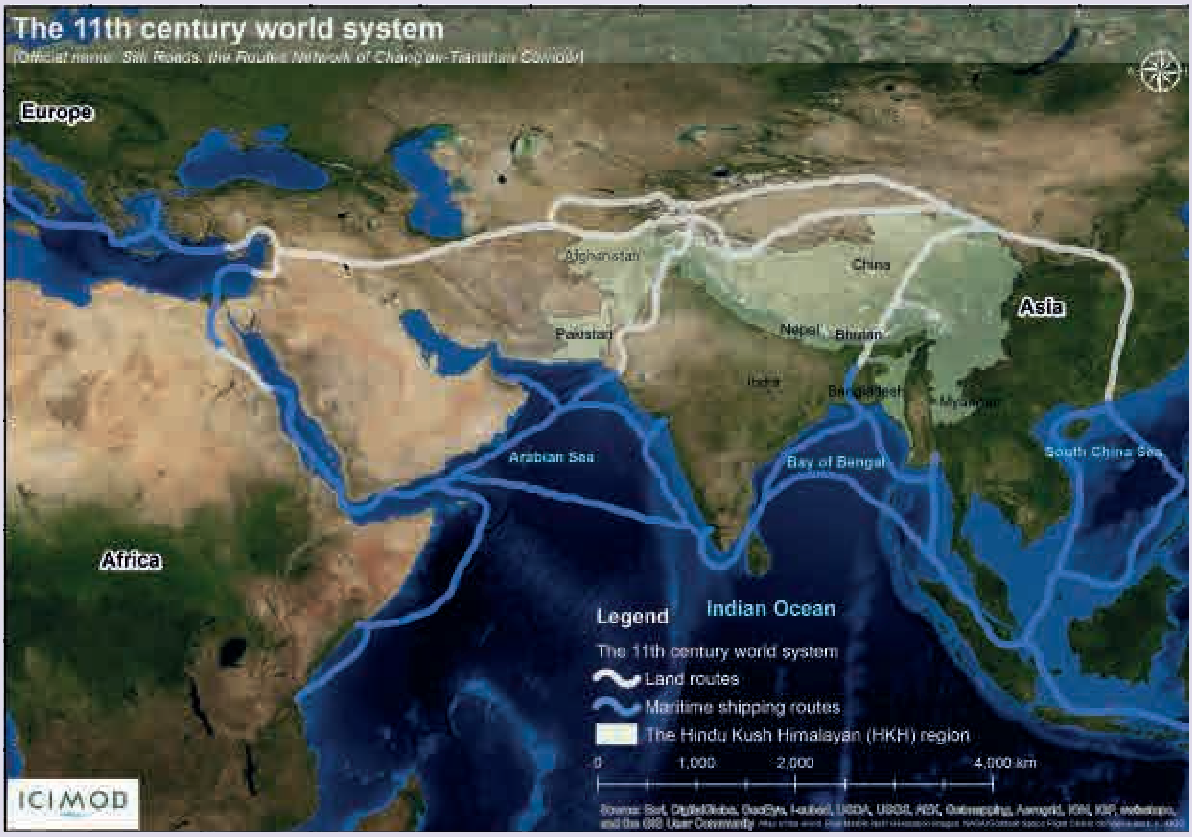
The global community has witnessed dramatic changes over the past century. The human population has quadrupled, the urban population has grown by a factor of 13, cropland has doubled, water withdrawals have increased seven times, irrigated land five times, energy use 13 times, industrial output 40 times and CO_2 emissions 17 times [2]. There have been rapid global changes in demography, economic growth, urbanization, globalization and economic liberalization, accompanied by advances in telecommunications and technologies.

Against this backdrop, demand for mountain resources – whether key commodities (e.g. timber) or niche products (e.g. medicinal plants) – is higher than ever before and various changes are underway. Efforts towards trade expansion and improvements in road and transport networks are connecting numerous mountain communities to national, regional and global markets. In many places, mountain farming is shifting from subsistence to commercial agriculture including production of cash crops, horticulture and sale of NTFPs. Tourism to mountains is also growing. At the same time, rural youth are migrating to urban areas and abroad, leaving women and old people behind; this has led to a "feminization" of the workforce in some mountain areas, and even depopulation in some cases. Yet such labour migration can also provide much-needed remittances that raise living standards and in some cases transform opportunities in mountains.

Policy messages

- Mountain regions face particular challenges including unequal exchange, poverty and climate change. These challenges call for mountain-specific policies in national development plans and programmes.
- Investment in mountain regions needs to be encouraged by creating a conducive environment. Investments will generate employment and unlock mountain regions' potential for a green economy and sustainable development in areas such as nature-based and organic products, water, hydropower and tourism.
- Policies must promote fair sharing of benefits from the development of mountain resources.
- The capacities of mountain institutions need to be strengthened to improve their access to markets, enhance livelihood security and advance transboundary cooperation.

Figure 7.1. The Silk Road Economic Belt: mainland routes in white; maritime routes in blue. Source: [9]



Llamas in Cerro de Pasco, Peru (M. Wurzinger)

Mountains and the global “green economy”

Mountains are crucial to many of the most pressing issues facing the global community today – water, energy, food security, adaptation to climate change and protection of biodiversity [3]. Mountains provide diverse habitats with a range of rare and endemic species, are home to indigenous peoples with distinct cultures and are a source of cultural, spiritual and recreational resources for urban populations. They have an enormous impact on inhabitants across the world and are critical for the global “green economy” and sustainable development.

Mountains are a vital source of ecosystem services and play a significant role in overall economic development, environmental protection, ecological sustainability and human well-being. Most notably, mountain-supplied water is critically important on every continent, contributing 40 to 90 percent of river flows in many places. The Hindu Kush Himalayan mountain system supplies water to about 1.3 billion people. Similarly, the Rocky Mountains, Andes, Atlas Mountains and mountains of the Middle East, around the Mediterranean and in eastern and southern Africa all play key roles in regional and lowland water supplies [4]. Featuring 6 000 km^3 of ice reserves – the largest outside of the Arctic and Antarctic – the Himalayan region is truly Earth’s “Third Pole”. It is estimated that the freshwater resources stored in the region’s ice and snow are enough to irrigate the entire world for two years, all of Asia for three years or South Asia for five to six years [5].

While greenhouse gas emissions continue to increase globally, mountain economies and communities still generally display a low-carbon footprint. Farming in mountains largely operates with low external inputs, often by necessity rather than choice. Further, mountain production systems – including soil conservation, watershed protection and conservation of indigenous seed varieties – produce positive externalities for the global community and can help in addressing climate change impacts.

Mountain woman carrying fodder for livestock (Courtesy of ICIMOD)

Half of the global biodiversity hotspots and one-third of all protected areas are in mountains. They are pivotal in conserving and harnessing biological diversity for a green economy. Mountain areas have furnished the genetic resources for many major food crops, and harbour genetic diversity that may prove essential in increasing the resilience of the world's food crops to climate change and other changes. Mountains also play an important role in regional and global climate regulation, through orographic rainfall, evapotranspiration, the influence of extended areas of ice and snow, and forests that sequester carbon and mitigate climate change.

Key issues and challenges faced by mountain economies

Mountain regions face particular economic, social and environmental challenges due to their inherent biophysical characteristics and broader socio-economic policies. The main challenges facing mountain economies in the developing world are unequal exchange, poverty, inequality and climate change.

Economic policies and development patterns are often biased against mountain regions. National economic policies generally focus on extracting mountain resources to benefit lowland areas, often causing conflict and social tension (Box 1). For example, mining is the main focus of investments in Andean and Central Asian mountains, while hydropower is the primary focus in the Himalayan region. Raw materials, capital and human resources flow from the mountains to the plains, where investment opportunities are better and returns are higher due to the better physical and economic infrastructure and market opportunities.

Farmers with mixed herd of alpacas and llamas, Peru (M. Radolf)

Box 1 Peru's mining sector: few benefits to local communities

Mining investment has grown exponentially in Latin America since 2000. In Peru, investment increased from US$ 109 million in 2003 to US$ 3.5 billion in 2013. In Colombia, the share of public revenue generated by mining doubled from 12 percent to 25 percent from 2009 to 2012. Though mining has economic benefits, it also poses major challenges. Mining's dramatic increase has been accompanied by a rise in conflict and violence around the large-scale mining operations in Peru's remote and overwhelmingly poor Andean highlands. Local communities generally oppose the mining, fearing that it will contaminate local land and water sources while bringing them few direct benefits. And, in fact, despite laws requiring that half of mining revenues be returned to mining areas, and despite the tremendous profits realized by mining companies, the lives of local people have not improved significantly. On average, 40 percent of Peruvians live in poverty; in the Andes, poverty rates exceed 70 percent. Mining appears to have exacerbated economic inequalities and conflicts. More responsible mining practices and equitable sharing of benefits are needed to reduce poverty among the affected mountain communities [8].

Mountain areas generally have higher levels of poverty and vulnerability than lowland areas. In both high- and low-income countries, poverty rates tend to be higher in mountain areas and per capita income tends to be lower (Table 7.1). Similarly, food, water and energy security are usually lower in mountain regions. For example, in Tajikistan, a mountainous state in Central Asia, stunting rates among children reach as high as 39 percent [6]. Economic inequality between mountain and lowland areas is also growing overall, likely contributing to the increasing number of conflicts in mountain areas in different parts of the world, such as Afghanistan, Kashmir, the Philippines, Colombia and the Horn of Africa. In many regions, conservation areas are established in places of abject poverty, further compromising the livelihoods of mountain people unless carefully arranged.

Climate change is an overarching concern that complicates and exacerbates poverty and livelihood insecurity among mountain communities. It may accentuate the food, water and energy crises through changing weather patterns and water regimes, increased floods, droughts and other extreme events.

Policies and strategies for sustainable mountain economies

Building sustainable mountain economies requires improving local economies and reducing inequality vis-à-vis lowland areas, while ensuring that ecosystem services are maintained for the benefit of all. Efforts to improve mountain economies can also alleviate pressure on nearby lowland areas by reducing migration and growing demands on social services, among other things. New policies must ensure that mountain resources are not overexploited for economic gain, as degradation of mountain ecosystems harms mountain communities as well as whole regions and ultimately the entire globe. In this way, the new initiatives to connect Asian and European economies through the Silk Road could pose environmental challenges (Box 2).

Table 7.1. Human development and per capita income

	Human Development Index		Per capita gross national income	
	High-income countries	**Low-income countries**	**High-income countries in US$**	**Low-income countries in US$**
All regions	0.890	0.493	40 046	2 904
Mountains	0.872	0.462	35 621	2 227

Source: Calculated from data in [7]

Degraded mountain – a potential threat to downstream livelihoods (Courtesy of ICIMOD)

Box 2 Development of the Silk Road Economic Belt – connecting Asia with Europe

China's President Xi Jinping announced the traditional Silk Road Economic Belt (SREB) development initiative during a speech in Kazakhstan on 7 September 2013. Other Silk Road countries have welcomed the initiative. The Old Silk Road (at a higher latitude) crosses China, Mongolia, Russia, Central Asian countries and Europe; the other (longitudinal) Silk Road stretches from northern Mongolia down to northeast India, and from the north of Central Asia down to Afghanistan, Pakistan and India; finally, the SREB also includes the maritime routes connecting Europe, Africa and Asia (Figure 7.1). The Chinese government and various institutions are promoting related initiatives meant to foster economic development while protecting the environment. The SREB encompasses many mountain regions which will require special attention in order to balance goals of economic development and environmental security [9].

Global, regional and national mechanisms must be developed that recognize and compensate mountain communities for their contributions to maintaining ecosystem services that benefit us all. Policies must also provide incentives to mountain communities to continue conserving natural resources, enhancing the provision of ecosystem services and generating income in environmentally friendly ways. Promising areas for investment in mountains include ecotourism and the processing and marketing of niche products (e.g. medicinal plants). Examples of pro-poor policies in mountains include specialized payments (Box 3), REDD+ (reducing emissions from deforestation and forest degradation; see Box on 4) and payments for ecosystem services (PES).

Enhancing the position of women – a challenge in mountain development (Courtesy ICIMOD)

Box 3 Policies to sustain mountain agriculture: the example of Switzerland

The Swiss Government provides increased direct payments to mountain farmers according to specific parameters (e.g. slope and elevation) as a way of compensating them for the additional work involved in sustainably managing watersheds and landscapes on behalf of mutually beneficial ecosystem services. Approximately 68 percent of Swiss mountain farmers receive government support, amounting to about US$ 150 million per year [10]. Interest-free loans are also provided for investment in mountain areas. Such policies support sustainable agriculture, the mountain economy and mountain livelihoods and encourage private investment in mountain areas [11].

Box 4 Community-based REDD+ approach: a win-win solution

A large proportion of Nepal's population relies heavily on forests for its livelihood, putting significant pressure on these resources. In 2009, ICIMOD initiated a four-year REDD+ pilot project to test the feasibility of implementing a REDD+ incentive mechanism. The project provided an economic incentive for biomass improvement, helping to reduce carbon emissions, enhance forest growth and promote carbon sequestration, whilst improving people's livelihoods [12].

Rural–urban dichotomy: Alpacas grazing in town, Peru (B. Wolfinger)

Alpacas or Llamas? Management of Uncertainty Among Livestock Keepers in the High Andes

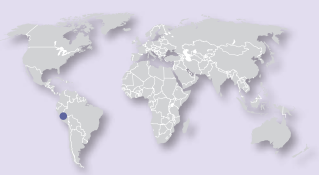
The lives of smallholder farmers in the high Andes have always been shaped by harsh climatic conditions. Crop production is virtually impossible above 4 000 m. Instead, livestock production has guaranteed smallholders a modest livelihood for centuries. But nowadays smallholders' livelihood practices are being made increasingly difficult by environmental and economic change. Climatic conditions have become more unpredictable, the quality and quantity of pastures and water has declined, and market conditions are highly volatile.

Marlene Radolf
Gustavo A. Gutierrez Reynoso
Maria Wurzinger

Alpaca herd in Peru (M. Radolf)

In the provinces of Pasco and Daniel Alcides Carrion in the central Andes of Peru, the predominant livelihood strategy of smallholders is diversification of livestock production. Most farmers keep several livestock species in different combinations, including alpacas, sheep, llamas and cattle. They see diversification as a way of decreasing their vulnerability to environmental and economic changes or shocks. Tradition also plays a major role, as farmers continue to keep the same livestock species that have been kept for generations. They view specialization in individual species as risky, so very few practise it. Those that do tend to focus on alpacas, since the global market for alpaca fibre has been relatively strong in recent decades. Other smallholders who maintain diversified herds have also increased the number of alpacas they keep, simultaneously reducing their sheep flocks due to falling wool prices.

Annual rainfall has been declining in the region over the last decade; it now stands at 900 mm per year according to the National Service of Meteorology and Hydrology (SENAMHI). In addition to overgrazing and mining activities that diminish local



Llamas: champions at adapting to difficult environmental conditions

Llamas (*lama glama*) belong to the family of the *Camelidae*. They have developed various adaptations that enable them to cope better with the harsh environment of the Andes, producing meat and fibre under extreme conditions. Their adaptations include:

- High levels of haemoglobin and elliptically shaped red blood cells that enhance their uptake of oxygen, and a larger heart to pump oxygen and protect against altitude sickness.
- A slow-moving digestive tract that is able to digest poor-quality feed with high fibre content more efficiently.
- A metabolism that adjusts in times of low (energy) intake, lessening their protein and water requirements and thus making them suitable for dry areas with scarce feed resources.
- Llamas' grazing behaviour is easier on pasture resources. They have split upper lips that are mobile and help them to select leaves from hard plant parts. Using their sharp incisors, they cut short and lignin-rich forages without harming the whole plant.
- Llamas also have softer pads than other livestock, which serve as a cushion and do not compact or erode soils to the same extent. [2–4]

grazing potential and grazing area, virtually all farmers consider climate change to be an important constraint on production, but opinions differ on its magnitude and the trajectory of change. Many farmers cite noticeable seasonal changes, with rain now occurring during the "dry season" and little or no rain falling during the "wet season". Some perceive less rain over the whole year, while others note an uptick in rainfall in just the last 5–10 years. Many farmers observe more frost and snow.

Alpacas and llamas – Peruvian farmers see llamas as more resistant to cope with climatic uncertainties (M. Radolf)

Llama champion at a local animal show in Peru (M. Wurzinger)

Homestead in the Andes of Peru (M. Radolf)

Farmers try to cope with these new weather patterns by adjusting their herd composition. When asked about future developments in the species composition on their farms, many describe plans to increase their number of llamas because they are seen as more resistant and possibly better equipped to cope with environmental and climatic uncertainties (Figure 7.2). Scientific evidence supports this view; llamas are an ideal livestock choice in times of uncertainty (see Box on page 119). However, demand for llama products is currently poor (as are prices), so farmers stand to lose income by keeping more llamas – not something they can afford. Already, about 65 percent of such livestock farmers must additionally pursue off-farm work to make ends meet, including jobs in construction, business, transport, teaching, etc. [1]. Most feel this is a growing trend. It will likely bring broader social and cultural changes as well, since emigration to urban areas can cause increasing farm abandonment, separation of families and mountain communities composed more of women, small children and the elderly. In addition, farmers' offspring increasingly state a preference for jobs not involving animal husbandry. For many members of the younger generation, staying and working on the farm in harsh environmental conditions holds little appeal.

Lessons learned

- A comprehensive approach to rural development in the high Andes is required to incentivize farmers and others to continue pursuing livelihoods there. Young people in particular need access to better education and income opportunities.
- Livestock farmers need strong technical support to improve their productivity and adapt new production strategies. This calls for a multi-stakeholder process involving farmers, NGOs, local governments, research institutions, universities and industry.

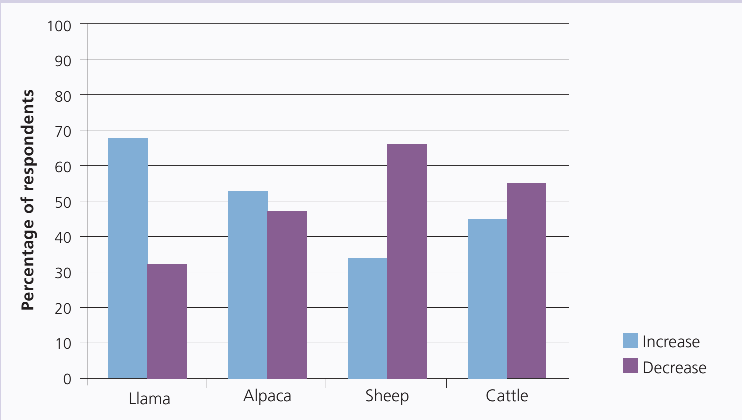


Figure 7.2. Farmers' plans for developing the composition of their herds. Source: [1]


Children are involved from their early days in herd management, Peru (M. Wurzinger)

Mountains and Climate Change

A Global Concern

Terrace cultivation in the Zerfshan Valley, Tajikistan (I. Weidmann)

Mountains and Climate Change: A Global Concern

Some of the clearest and most visible signs of climate change, such as glacier retreat, are found in mountain areas. But the implications of climate change in mountains extend far beyond mountain regions. Climate change in mountains is a global concern.

Key issues in brief

Climate change in mountains is a reality. Mountain regions have warmed considerably over the last 100 years, at a rate comparable with that of lowland areas. While temperatures in mountain areas are expected to continue rising across the globe, projections of precipitation display a more differentiated pattern, with some regions expected to receive more rainfall, including the tropical Andes, the Hindu Kush Himalayas, East Asia, East Africa and the Carpathian region. Regions expected to receive less rainfall include mountains in the Mediterranean, in Meso-America and South Africa, and the southern Andes. Overall, precipitation patterns may change and intensity increase (see Chapter 1).

Water availability will be affected – the consequences will reach far beyond mountain regions. Mountains provide freshwater resources to half of the global population. Climate change is projected to affect the availability of these freshwater resources, even in those regions expected to receive higher rainfall. This is due to changing seasonal precipitation patterns and increasing rainfall at the expense of snowfall. As a result, less water will be available when it is needed most (Chapters 2 and 3), with major development implications in and beyond mountain areas, especially regarding water supplies for irrigation, urbanization, industrialization and the production of energy in the form of hydropower. This will make it necessary to use water more sustainably, for example by increasing storage, and to establish or to reshape arrangements for sharing water equitably within and between countries. As the case studies in this publication show, effective institutions and good governance at all levels – based on sound evidence and participation – are crucial to achieving such aims.

Climate change is likely to increase exposure to hazards. Mountain areas are typically exposed to multiple hazards. Extreme events such as storms, landslides, avalanches and rockfalls may become more common and intense in mountain areas. Permafrost decay and glacial lake formation will pose additional hazards. The expansion of settlements, roads and other infrastructure in hazard-prone mountain areas will place greater numbers of people at risk (Chapter 4). Key to addressing this will be integrated watershed management and integrated risk management, including improvements to early warning systems, land-use planning, emergency response and recovery efforts.

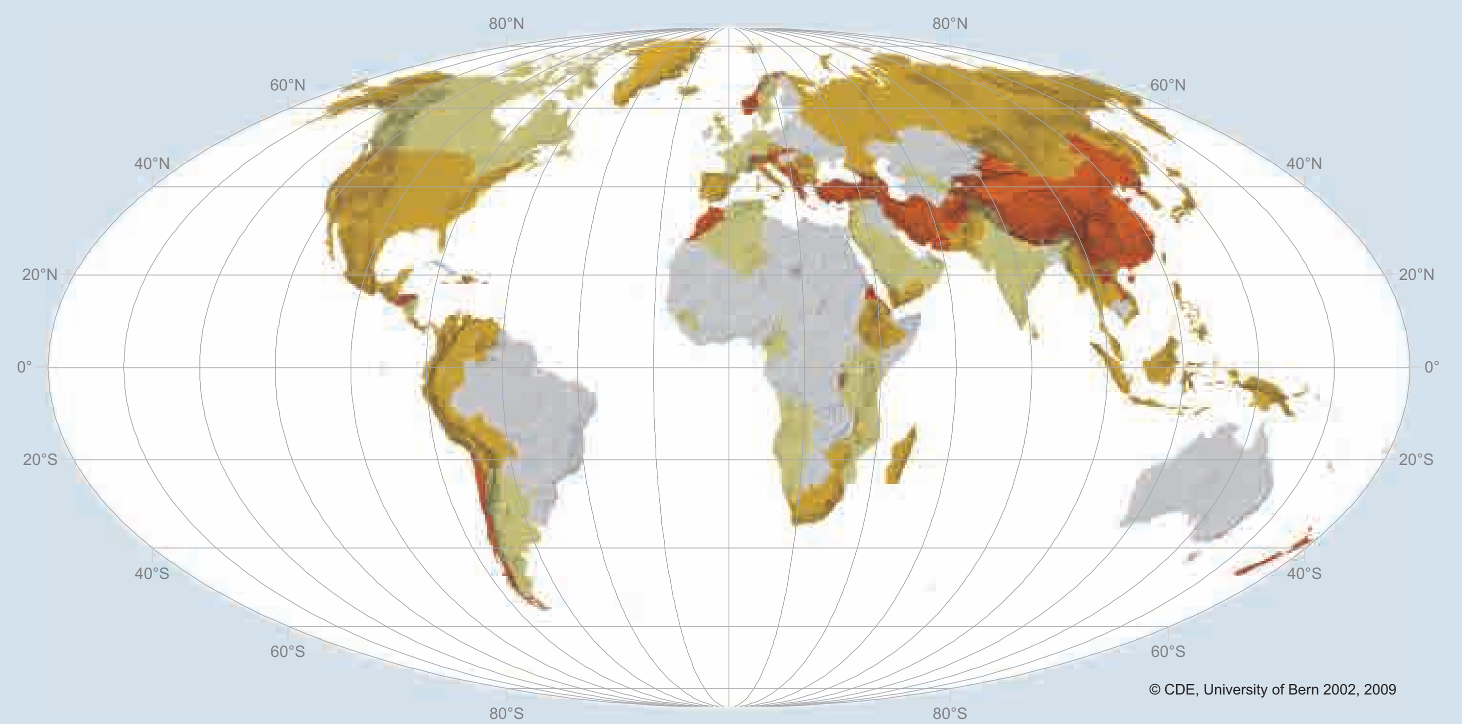
What does the future hold for mountain biodiversity? Mountains are home to about half the world's biodiversity hotspots. Exactly how climate change will affect this important global heritage is site-specific and subject to debate (Chapter 5). Direct human pressure on mountain resources such as land and minerals is also threatening biodiversity. On a positive note, much has already been achieved in protecting mountain biodiversity, including agrobiodiversity. Protected areas are one of the fastest-growing land-use categories worldwide, especially in mountain areas. However, mountain communities should experience more tangible benefits from such efforts than they have in the past. Compensation for environmental services is a key means to achieve this aim.

Climate change impacts on poverty and food security. About 12 percent of the world's population lives in mountains, the great majority in developing countries. In many mountain areas, poverty rates are higher than in lowland areas and food inadequacy is more widespread. In general, the human development index and per capita income are lower in mountain areas than in surrounding regions (Chapters 6 and 7). Often far removed from centres of economic development, mountain areas typically provide residents a narrow range of options when it comes to secure livelihoods. This has led to widespread outmigration from mountain areas. Nevertheless, while climate change may present an added burden to mountain communities, it could also present opportunities: Rising temperatures could make it possible to grow crops that were previously limited to lower altitudes and could increase the productivity of pastures. Further, climate-smart agriculture is also on the rise in many areas.

Putting climate change in perspective

Mountain regions are exposed to numerous drivers of change, including urbanization, migration, market integration, competition for resources and the push for economies of scale. These broader trends can have more direct, immediate impacts on mountain regions than climate change. The same is true for conflicts and lack of human security. Action on climate change must therefore be embedded in a wider agenda of sustainable development. This agenda must acknowledge the great diversity of mountain regions in terms of their natural environment, peoples, cultures and economies (see map below). Development policies tailored to regional

Map of the countries of the world and their mountain areas



Percentage of mountainous area per country

0–10 %
25–50 %
10–25 %
50–100 %

Map scale: approx. 1:200,000,000

Map Source
Terrain data: resampled from GTOPO30, produced by US Geological Survey (UGS)
Administrative: ESRI Data and Maps
Map projection: Mollweide
Map authors: Sebastian Eugster, Hans Hurni, Albrecht Ehrensperger, Thomas Kohler and Kristina Imbach 2002 (CDE, University of Bern)
Map compilation 2009: Ulla Gaemperli Krauer (CDE, University of Bern)

needs and potentials, including climate-smart action, are one possible avenue of progress. Involving mountain populations in shaping these policies increases local ownership and provides opportunities to utilize their valuable knowledge of adaptation measures.

Climate change in mountains: a huge externality and a global responsibility

Many mountain areas are located in relatively small developing countries (see map on page 125). Though these may have contributed little to the causes of climate change, they must endure its effects. From the perspective of these countries, climate change is a major externality associated with growing costs. Nevertheless, measures of adaptation will have to be complemented by efforts towards mitigation. The root cause of the problem – greenhouse gas emissions – must be addressed. This requires action towards curbing emissions by lowland centres of population growth and trade in both industrialized countries and emerging economies. Some of the biggest emitters of greenhouse gases are countries with large mountain areas (see map on page 125).

Huayna Potosí, Bolivia (M. Andrade)

Policy Messages

Climate change could threaten the provision of mountain goods and services

1. Mountains provide essential goods and services, including freshwater resources to half of humankind, energy in the form of hydropower, rich biodiversity, important minerals and beautiful landscapes for recreation and tourism. Mountains are essential for global sustainable development. They must be included in global policy frameworks.
2. Climate change in mountains is a reality. Mountains have warmed considerably over the last 100 years and warming will continue. This could jeopardize the provision of goods and services from mountain areas.
3. Lack of data on climate change in mountains and its global effects hinders effective action. Long-term monitoring and free and unrestricted exchange of standardized data within and between countries must be improved substantially

Proven measures to address climate change in mountains

4. The time to act is now. Proven measures include improving watershed management at national and transboundary levels, enhancing water storage; expanding integrated risk management; conserving biodiversity and agrobiodiversity that benefit mountain communities; promoting effective institutions and adherence to principles of good governance; and building platforms for knowledge sharing and capacity building.
5. Numerous funding mechanisms exist for climate change adaptation and mitigation, especially from the public sector and civil society. Additional funding could come from the private sector, from remittances and from special sources such as funds that compensate mountain areas for the goods and services they provide.

The importance of sustainable development goals in mountains

6. Poverty alleviation and improvement of food security demand specific tools that go beyond climate change action. These tools can be complemented by climate-smart agriculture and economic diversification.
7. Considering their vital role in providing key goods and services to humankind, mountains must be included in the climate change debate as well as in the post-2015 development agenda and Sustainable Development Goals.

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Mountains and Climate Change: A Global Concern

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Mountains are among the regions most affected by climate change. The implications of climate change will reach far beyond mountain areas, as the contributions in the present publication prepared for the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 20) in Lima 2014 show. Themes discussed are water, glaciers and permafrost, hazards, biodiversity, food security and economy. The case studies included show that concrete adaptive action has been taken in many mountain areas of the world. The publication concludes with a series of recommendations for sustainable mountain development in the face of climate change.

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