CCP5

Mountains

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Frequently Asked Questions

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Executive Summary

Mountains are highly significant regions in the context of climate change and sustainable development. They lie at the intersection of accelerated warming and large populations that depend directly or indirectly on them. They are regions of high biological and cultural diversity and provide vital goods and services to people living in and around mountain regions and in downstream areas. Building on the IPCC's Fifth Assessment Report (AR5), Chapter 2, 'High Mountain Areas', of the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (Hock et al., 2019), and the IPCC Working Group I contribution to AR6 (IPCC, 2021), this Cross-Chapter Paper (CCP) assesses new evidence on observed and projected climate change impacts in mountain regions, their associated key risks and adaptation measures.

Observed changes, their impacts and adaptation responses in mountains

Climate change impacts in mountains and their attribution to human influence have increased in recent decades with observable and serious consequences for people and ecosystems in many mountain regions (*high confidence*[1]). Observed changes include increasing temperatures, changing seasonal weather patterns, reductions in snow cover extent and duration at low elevation, loss of glacier mass, increased permafrost thaw and an increase in the number and size of glacier lakes (*high confidence*). {CCP5.2.7, Figure CCP5.4, SROCC Chapter 2, WGI Section 9.5}

The spatial distributions of many plant species have shifted to higher elevations in recent decades, consistent with rising temperatures across most mountain regions (*high confidence*). Around two-thirds of treeline ecotones have also shifted upwards in recent decades, though these shifts are not ubiquitous and slower than expected based on rising temperatures (*high confidence*). Impacts on biological communities and animal species are also increasingly being reported, with species of lower elevations increasing in mountain regions, creating more homogeneous vegetation and increasing risks to mountain-top species (*medium confidence*). {CCP5.2.1; 2.4}

Climate and cryosphere change have negatively impacted the water cycle in mountains, including variable timing of glacier melt and snowmelt stream discharge (*high confidence*). These changes have variable impacts on water availability for people and economies, contributing to increasing tensions or conflicts over water resources, especially in seasonally dry regions (*medium confidence*). Mountains are an essential source of freshwater for large and growing populations; the number of people largely or fully dependent on water from mountains has increased worldwide from approximately 0.6 billion in the 1960s to approximately 2 billion in the past decade, and globally two-thirds of irrigated agriculture depends on essential runoff contributions from mountains. {CCP5.2.2; Figure CCP5.2; SROCC Chapter 2; 4.2.2.3; 4.4.4.1}

Climate-change-driven changes in precipitation, river flow regimes and landslides affect the production and use of energy in mountain regions, in particular hydropower (*high confidence*). Billions of USD in investment and assets of energy production are exposed to changing mountain hazards. The combined effects of climate change, hydropower development and other human interventions have exacerbated water security problems and social injustice (*medium confidence*). {CCP5.2.2, SROCC Chapter 2}

Observed climate-driven impacts on mountain ecosystem services, agriculture and pastoralism are largely negative in most mountain regions (*medium confidence*). Agriculture has been negatively affected through increased exposure to hazards such as droughts and floods, changes in the onset of seasons, the timing and availability of water, increasing pests and decreasing pollinator diversity, which in turn have negatively influenced overall food production, dietary diversity and the nutritional value of food (*medium confidence*). Negative climate impacts on pastoralism, such as drought-induced degradation of rangelands and pastures, have affected livestock productivity and the livelihood of pastoralists, while other non-climatic factors, such as land use change and management, also play a role (*medium confidence*). {CCP5.2.3; CCP5.2.5; Table CCP5.2; SROCC Section 2.3.1.3.2; SROCC Section 2.3.7}

While contributing to poverty reduction in some mountain regions, there is *limited evidence* of adaptations effectively contributing to the remediation of underlying social determinants of vulnerability, such as gender and ethnicity (*medium confidence*). Exposure and vulnerability exacerbate the negative effects of climate impacts on livelihoods and intertwine with power imbalances and gender and other inequalities (*medium confidence*). {CCP5.2.7; CCP5.3.2.2}

Observed changes in seasonality (timing and extent) are negatively affecting mountain winter tourism and recreation (*high confidence*) and variably affect tourism and recreation activities in other seasons (*medium confidence*). For winter activities such as skiing, diminishing snow at lower elevations has challenged operating conditions (*medium confidence*), increasing the demand for and dependence on snow management measures such as snow-making (*high confidence*). Climate-induced hazards are negatively affecting some climbing, mountaineering and hiking routes (*medium confidence*). In some regions, options to change routes or shift seasons to reduce hazard exposure have been employed as adaptation strategies, with variable outcomes (*medium confidence).* In some cases, higher temperatures and extreme heat conditions at lower elevations have made some mountain destinations more appealing, increasing the potential for summer visitation demand (*medium confidence*). {CCP5.2.5; Table CCP5.2; SROCC Section 2.3.5}

Climate-related hazards, such as flash floods and landslides, have contributed to an increase in disasters affecting a growing number of people in mountain regions and areas

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[1] In this report, the summary terms 'limited', 'medium' and 'robust' are used to describe the available evidence; for the degree of agreement, *low*, *medium*, or *high* are applied. A level of confidence is expressed using five qualifiers—*very low*, *low*, *medium*, *high*, and *very high*—which are set in italics, for example, *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

further downstream (*high confidence*). As a result, the number of disasters has increased; however, there is *limited evidence* that this is due to changes in the underlying hazard processes, pointing mainly to increasing levels of exposure (*medium confidence*). {CCP5.2.6; CCP5.2.7; CCP5.3.2.1}.

Adaptation responses to climate-driven impacts in mountain regions vary significantly in terms of goals and priorities, scope, depth and speed of implementation, governance and modes of decision-making and the extent of financial and other resources to implement them (*high confidence*). Observed adaptation responses in mountains are largely incremental and mainly focus on early warning systems and the diversification of livelihood strategies in smallholder agriculture, pastoralism and tourism. However, there is *limited evidence* of the feasibility and long-term effectiveness of these measures in addressing climate-related impacts and related losses and damages, including in cities and settlements experiencing changing demographics. {CCP5.2.4; CCP5.2.7.2}

Projected impacts, key risks and limits to adaptation in mountains

Increasing temperatures will continue to induce changes in mountain regions throughout the 21st century, with expected negative consequences for mountain cryosphere, biodiversity, ecosystem services and human well-being (*very high confidence*). Many low-elevation and small glaciers around the world will lose most of their total mass at a 1.5°C global warming level (GWL) (*high confidence*). A large majority of endemic mountain species will be at risk of extinction; regions heavily relying on glacier melt and snowmelt for irrigation will face erratic water supply and increased food insecurity, whereas agriculture in some regions might see positive changes. Damages and losses from water-related hazards such as floods and landslides are projected to increase considerably between 1.5°C and 3°C GWL. {CCP5.3.1}

Projected changes in hazards, such as floods and landslides, as well as changes in the water cycle, will lead to severe risk consequences for people, infrastructure and the economy in many mountain regions (*high confidence*). These risks will be more pervasive and increase more rapidly in south and central Asia and northwestern South America. However, nearly all mountain regions will face at least moderate and some regions even high risks at around 2°C GWL (*medium confidence*). {CCP5.3.2.1, CCP5.3.2.2}

There is an increasing risk of local and global species extinctions where species are not able to move to higher elevations or other cooler locations (*high confidence*), with risks from extreme events such as wildfire potentially exacerbating those risks (*medium confidence*). The topographic variation in mountains, such as elevation or aspect, may mean that some species will be able to survive in cooler microclimates. Mountain regions may act as refugia for some species from lower elevations if they can move into them. This may enable some species to persist in a region, though it may pose a threat to cold-adapted species, including endemics, which may be outcompeted (*high confidence*); invasive non-native species may become an increasing problem in some places. {CCP5.3.2.3, Box CCP5.1; CCP1.2.2.1; 2.6.6; 16.6.3.1}

Climate change is projected to lead to profound changes and irreversible losses in mountain regions with negative consequences for ways of life and cultural identity (*medium confidence*). Intangible losses and loss of cultural values will become increasingly more widespread in mountain regions, mainly driven by a decline in snow and ice and an increase in intangible harm to people from hazards (*medium confidence*). However, there is *limited evidence* on the magnitude of the consequences. {CCP5.3.2.4; 16.5.2.1; 16.5.2.3.7}

Options for future adaptation and climate-resilient sustainable development in mountains

The current pace, depth and scope of adaptation are insufficient to address future risks in mountain regions, particularly at higher warming levels (*high confidence*). While the incremental nature of most implemented adaptations will not be sufficient to reduce severe risk consequences, options exist which offer practical and timely prospects to address risks before limits to adaptation are reached or exceeded. Reducing climate risks will depend on addressing the root causes of vulnerability, which include poverty, marginalisation and inequitable gender dynamics (*high confidence*). {CCP5.4.1, Figure CCP5.7: CCP5.4.2, Cross-Chapter Box DEEP in Chapter 17; Cross-Chapter Box LOSS in Chapter 17; 17.3, 17.6}

Adaptation decision-making processes that engage with and incorporate people's concerns and values and address multiple risks are more robust than those with a narrow focus on single risks (*medium confidence*). Risk management strategies that better integrate the adaptation needs of all affected sectors, account for different risk perceptions and build on multiple and diverse knowledge systems, including Indigenous knowledge and local knowledge, are important enabling conditions to reduce risk severity (*medium confidence*). {CCP5.2.6, CCP5.4.2; 17.3; 17.4; Cross-Chapter Box PROGRESS in Chapter 17; Cross-Chapter Box DEEP in Chapter 17}

Regional cooperation and transboundary governance in mountain regions, supported by multi-scale knowledge networks and monitoring programmes, enable long-term adaptation actions where risks transcend boundaries and jurisdictions (*medium confidence*). Collectively, they show potential to form an important component of the adaptation solution space in mountains. There are increasing calls for more ambitious climate action in mountains, providing impetus for stronger cooperation within and across mountain regions and downstream areas (*medium confidence*). {CCP5.4.2; CCP5.4.3}

With warming above 1.5°C, the need for adaptation to address key risks in mountains becomes increasingly urgent (*high confidence*). Pathways and system transitions that strengthen climate-resilient sustainable mountain development are starting to receive attention, but current levels of resourcing are substantially insufficient to support timely action. {CCP5.4.2; CCP5.4.3; CCP5.5; 18.1; 18.2}

CCP5.1 Point of Departure

Mountains are an extensive and significant *typological region* (Section 1.3.3 and Annex II: Glossary) in the context of climate change and sustainable development, with large populations directly or indirectly depending on them. Further, mountains are areas of high biological and cultural diversity that provide vital goods and services—such as water, food, energy, minerals, medicinal plants, tourism and recreation and aesthetic and spiritual values—to people living in and around these mountain regions and in downstream areas. Mountain regions are hotspots of climate-related losses in, for example, ecosystems, landscapes, culture and habitability, and while mountain people are adaptive, resourceful and independent, they live in highly fragile environments and in some regions under challenging socioeconomic circumstances that increase their vulnerability to climate change (Alfthan et al., 2018).

Chapter 2, 'High Mountain Areas', (Hock et al., 2019) of the IPCC's SROCC, presented an assessment of observed changes in the high mountain cryosphere, their impacts in situ and further downstream and the state of adaptation responses to these impacts. Before SROCC, the last time climate change in mountain regions had been systematically assessed in IPCC reports was in Chapter 5 of the Second Assessment Report (SAR) (Beniston et al., 1996). Projections made at the time for climate-related changes in mountain regions were expected towards the middle and the second half of the 21st century, rather than as early as recent decades (Haeberli and Beniston, 2021), underscoring the striking pace of change already observed in mountain regions.

Whereas SROCC focused on impacts from a changing climate on the high mountain cryosphere, this CCP on mountains synthesises key relevant content from across the AR6 WGII report with a broader scope on the impacts of and adaptation to climate change in mountain regions as defined for this assessment (Figure CCP5.1, SMCCP5.1). It provides a wider assessment of the solution space and consequences for sustainable development due to climate change in mountain regions and downstream areas.

To define the geographical scope of the assessment in this CCP and to quantify the human population residing within these regions, the mountain characterisation given by Kapos et al. (2000) (Figure CCP5.1a and SMCCP5.1), minus Antarctica, Svalbard and Greenland (which fall under the assessment scope of CCP6 Polar Regions), was employed. This characterisation is consistent with the mountain region extents used in the AR6 WGI report (see AR6 WGI Atlas (Gutiérrez et al., 2021)) and yields a global mountainous area of 31.74 million km^2, which corresponds to approximately 23.5% of the global land surface. In 2015, a total of 1.28 billion people resided in mountain regions as delineated for this CCP (SMCCP5.1).

The scope of the assessment presented in this CCP covers observed and projected climate change impacts in mountains, present, emerging and future key risks and observed adaptation responses, leading to an exploration of the adaptation solution space and climate resilient development (pathways) in mountains. Section 5.2 presents observed impacts and adaptation responses by synthesising information on mountains in the sectoral and regional chapters of WGII AR6, additional supporting evidence found in the literature, a detection and attribution assessment (SMCCP5.2) and a reanalysis of the mountain literature collected and synthesised in the Global Adaptation Mapping Initiative (GAMI) (SMCCP5.3). Section 5.3 presents an assessment of future key risks in mountains drawing from the regional and sectorial chapters and a key risks assessment carried out for this CCP (SMCCP5.4). Section 5.4 explores the solution space for future adaptation opportunities and constraints as well as climate resilient development in mountains. This CCP concludes with key assessment limitations and knowledge gaps and prospects for addressing these gaps in Section 5.5.

CCP5.2 Observed Impacts and Adaptation in Mountain Social-Ecological Systems

CCP5.2.1 Ecosystems and Ecosystem Services

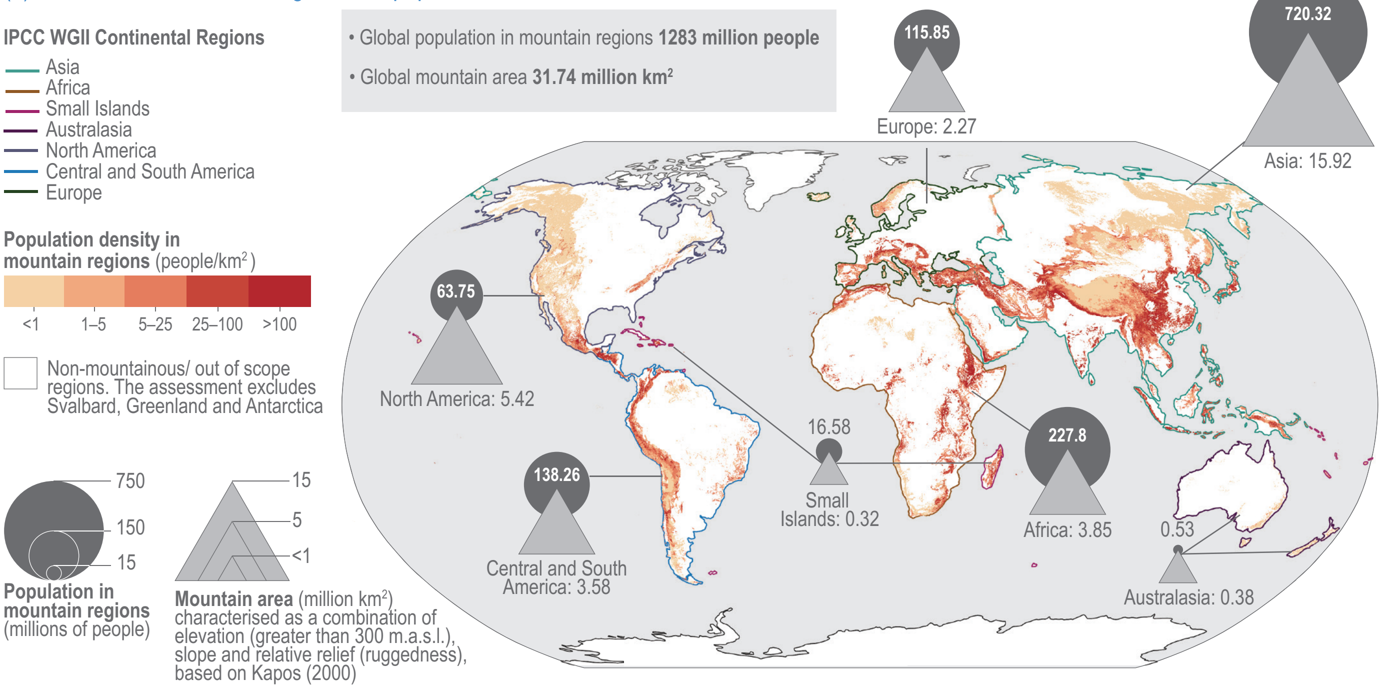
Changes in climate over short distances in mountains are reflected in large ecological gradients. AR5 reported new evidence that plant species of mid and low elevations were starting to colonise higher elevations in mountains. Since AR5, new studies have been published (e.g., Steinbauer et al., 2018; Payne et al., 2020), including in some previously less well studied areas such as the Andes (e.g., Morueta-Holme et al., 2015; Báez et al., 2016) and parts of Asia (e.g., Telwala et al., 2013; Artemov, 2018). There is now *high confidence* that many plant species' distributions have shifted to higher elevations in recent decades, consistent with climatic warming (Sections 2.4.2, 10.4.2.1.1, 13.3.1.1). In recent years publications have also started to show similar trends in some animal species, including birds (Freeman et al., 2018; Bani et al., 2019; Lehikoinen et al., 2019) and snails (Baur and Baur, 2013). Other climatic variables besides temperature can also affect elevational limits of species (Section 2.4.2) and sometimes in ways that contrast with temperature, for example increasing precipitation can allow some species to occur at lower elevations in dry climates (Crimmins et al., 2011; Coals et al., 2018). Tsai et al. (2015) reported large changes in the montane bird community in Taiwan, which they link to changes in weather patterns, including more severe typhoons. Changes in the amplitude and frequency of bank vole population waves in the Ilmen Nature Reserve in the Middle Urals can be linked to longer frost-free periods (Kiseleva, 2020).

There are interactions with land use, for example a decrease in forest cover can exacerbate the effects of rising temperatures (Guo et al., 2018). In contrast, Bhatta et al. (2018) showed a downward shift of species assemblages in Langtang National Park, Nepal, most likely related to interactions with land use, especially reduced grazing. Where glaciers retreat, new areas become available for pioneer species to colonise and new communities to form (Cuesta et al., 2019; Hock et al., 2019; Muhlfeld et al., 2020). The risk of extreme events such as wildfire, drought, floods and landslips is increasing in a wide range of places as a result of climate change, and the evidence of the disturbance they cause to ecosystems has grown in recent decades (Section 2.3.1, Box CCP5.1). The impacts of such extreme events may be greater than those of incremental changes.

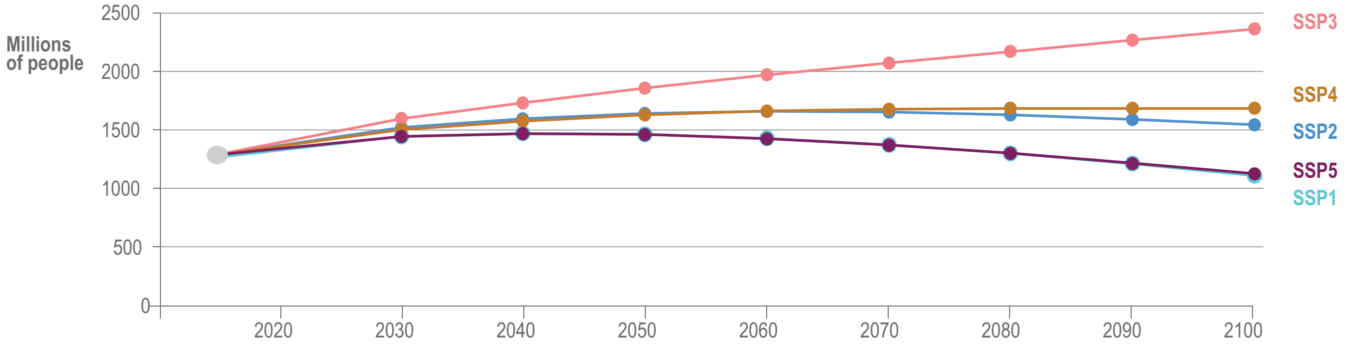
For species at lower elevations, mountains may represent refugia to which species can retreat. In this respect, Elsen et al. (2018) highlighted the importance of protecting areas along elevational gradients. This applies

Delineation of mountain regions, population densities and projections

(a) Delineation of mountain regions and population densities in 2015



(b) Global population projections in mountain regions by 2100 for different SSPs



(c) Projected population changes in mountain regions for different SSPs from 2015 to 2100, per IPCC WGII Continental Region

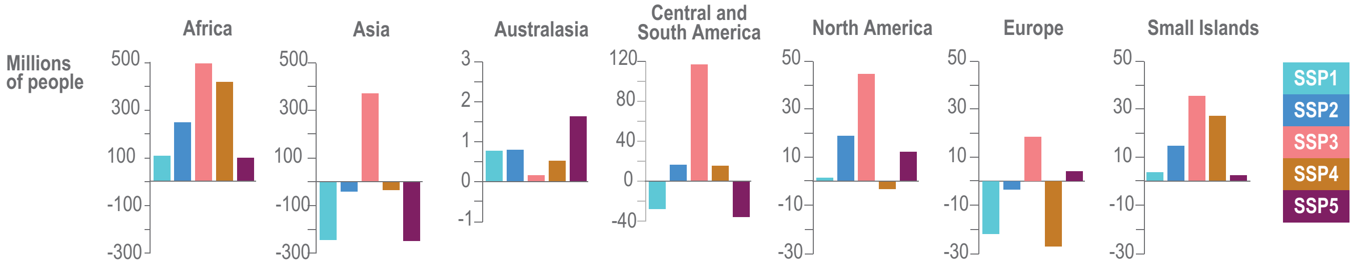


Figure CCP5.1 | Delineation of mountain regions in CCP Mountains, population numbers and densities in 2015 and their projections to 2100.

(a) Population in mountain regions in 2015 aggregated per IPCC WGII Continental Regions, considering population densities, mountain areas and total population in mountain regions.

(b) Population projections in mountain regions by 2100 for different Shared Socioeconomic Pathways (SSP) scenarios.

(c) Projected changes in population in mountain regions from 2015 to 2100 across five different SSP scenarios, per IPCC WGII Continental Region (SMCCP5.1 and Tables SMCCP5.1–5.4).

to freshwater and terrestrial habitats with mountain streams acting as potential refugia (Isaak et al., 2016). In contrast, species restricted to the highest elevations are increasingly at risk, including from competition with colonising species (Britton et al., 2016; Winkler et al., 2016). Mountain-top species are often separated from potential new habitats by large areas with unsuitable climates, and tropical mountain species often have particularly narrow thermal tolerance and limited dispersal capacity (Polato et al., 2018).

The risks posed by non-native species may increase with climate change (Carboni et al., 2018; Shrestha et al., 2018; Thapa et al., 2018). Koide et al. (2017) found that non-native plant species on Hawaii were moving to higher elevations, whereas native species' distributions were retracting at their lower elevational limit. Dainese et al. (2017) found that non-native plant species spread to higher elevations approximately twice as fast as native species. Following recent climate warming, invasive *Phyllostachys edulis* and *Phyllostachys bambusoides* (Poaceae) bamboo species in Japan have shifted northwards and upslope in the last three decades (Takano et al., 2017). New evidence has shown that variations in microclimate, with topography and cold groundwater seeps, can provide micro-refugia small areas of locally suitable conditions where cold-adapted species can survive (Bramer et al., 2018; Muhlfeld et al., 2020) (Section 2.6.2). Some alpine species have thrived in recent years, and the range of microclimates may partly explain this (Rumpf et al., 2018).

Treeline elevation is linked to temperature (Paulsen and Körner, 2014) but may also be affected by water supply (Sigdel et al., 2018; Lu et al., 2021) and land management. A recent summary of treeline shifts worldwide found that 67% of studied alpine treelines had shifted upwards while 33% remained stable (based on 142 published studies), and 88.8% of the 143 undisturbed alpine treelines across the Northern Hemisphere had shifted upwards (Hansson et al., 2021; Lu et al., 2021). Since AR5, new evidence of shifting treeline ecotones has emerged for a wide variety of species in different locations, including in Siberia (Pospelova et al., 2017), various parts of the Ural Mountains (Shiyatov and Mazepa, 2015; Zolotareva and Zolotarev, 2017; Sannikov et al., 2018), in the Canadian Rocky Mountains (Trant et al., 2020) and the Himalaya (Tiwari and Joshi, 2015; Chakraborty et al., 2016; Gaire, 2016; Yadava et al., 2017). Recent studies of treelines that have not or hardly shifted include those in the Himalaya (Singh et al., 2015; Sigdel et al., 2018), eastern Tibetan Plateau (Wang et al., 2020) and the Andes (Lutz et al., 2014). Migration rates are not proceeding as fast as warming rates, implying other processes also limit treeline ecotone response (e.g., Sigdel et al., 2020; Lu et al., 2021).

Whether treeline shifts occur, and if so at what rate, depends on a range of factors, including land use (especially livestock grazing and fire), species interactions, wildfires and climatic stress factors (wind, frost, drought, excess or shortage of snow) interacting with tree population processes (viable seed production, dispersal, seedling establishment, clonal propagation, growth, dieback, mortality). Differences in treeline shifts between north- and south-facing slopes have been demonstrated in the Rocky Mountains (Elliott and Cowell, 2015). Grigorieva and Moiseev (2018) showed that significant factors limiting the number of seedlings and shoots are the snow depth, the topsoil temperature dependent on it and the degree of competition from the parental tree stand and grass–shrub vegetation. In addition, land use and management exert an influence in many mountains around the world. Suwal et al. (2016) found that elevational shifts in Himalayan silver fir in Nepal were larger when areas were protected from management. Similarly, Lutz et al. (2014) found faster treeline shifts in the Peruvian Andes in protected areas than that in other areas, where cattle grazing and fires are more frequent. Treeline ecotones can also change independently of climate change if land use changes (Vitali et al., 2019; Körner, 2020).

Changes in community composition are also happening within ecosystem types. Duque et al. (2015) showed a change in the composition of northern Andean forests, and Feeley et al. (2013) showed such a change in that of forests up to 2800 m in Costa Rica. In both cases the proportion of species adapted to warmer conditions increased, driven primarily by patterns of mortality, indicating that the changes in composition are mostly via range retractions, rather than range shifts or expansions. An analysis of 200 forest inventory plots in the Andes likewise indicated a widespread, though not ubiquitous, thermophilisation of tree species' composition (Fadrique et al., 2018). Within a period of 8 years (2003–2010), significant shifts in communities of vascular plants, butterflies and birds were found in Switzerland (Roth et al., 2014). At lower elevations, communities of all species groups changed towards warm-dwelling species, corresponding to an average uphill shift of 8 m, 38 m and 42 m in plant, butterfly and bird communities respectively. However, rates of community change decreased with elevation in plants and butterflies, while bird communities shifted towards warm-dwelling species at all elevations (Roth et al., 2014).

Changes in mountain biodiversity and ecosystems have a wide range of impacts on ecosystem services and effects on people. Some mountain ecosystems, particularly those with peatlands or forests, are important carbon stores, and climate change presents a risk to these in some locations (Dwire et al., 2018) (Sections 2.4.3.8, 2.4.4.4 and 2.4.4.5). Palomo (2017) identified a wide range of threats to the lives, livelihoods and culture of mountain people as a consequence of the impacts of climate change on ecosystems. However, impacts are very heterogeneous between locations, even within the same region and ecosystem type (e.g., mountain forests in Europe) (Mina et al. (2017) and are not necessarily all negative. In addition to changes in services, other impacts on humans from a changing climate may be mediated through species and ecosystems, for example changes in vector distribution shifting disease incidence into higher elevation areas (Escobar et al., 2016).

CCP5.2.2 Water and Energy

CCP5.2.2.1 Water

Water is a fundamental source of life in mountain regions; it is also a central element and 'connector' in coupled natural–human systems and carries diverse meanings in different sociocultural contexts, including in indigenous ontologies (Boelens, 2014). In addition, water is a key component connecting upstream mountains and downstream lowlands (Salzmann et al., 2016; Di Baldassarre et al., 2018; Encalada et al., 2019). Mountains are of paramount importance as water towers for people living there and for around two billion people living in connected lowland areas (Immerzeel et al., 2020; Viviroli et al., 2020).

Mountain river systems are especially sensitive to and affected by climate change and continuing anthropogenic disturbance, including water pollution, hydropower development, water withdrawals for agriculture and human consumption and biodiversity loss and ecosystem changes (*high confidence*) (Honda and Durigan, 2016; Encalada et al., 2019; Bissenbayeva et al., 2021; Chen et al., 2021). The effects of climate and cryosphere change in mountains on downstream water and river systems have been studied and quantified for many regions worldwide (Barnett et al., 2005; Huss, 2011; Lutz et al., 2014; O'Neel et al., 2015; Huss and Hock, 2018). Comprehensive approaches focusing on both water demand and supply aspects provide regionally or locally specified information on water availability, scarcity and security (Buytaert et al., 2014; Drenkhan et al., 2015; Brunner et al., 2019) (Chapter 4). Present and potential future hotspot regions of water scarcity that rely heavily on mountainous water sources include Central Asia, South Asia, tropical and subtropical western South America and southwestern North America (*robust evidence, medium agreement*) (Kummu et al., 2016; Biemans et al., 2019; Immerzeel et al., 2020; Viviroli et al., 2020).

Figure CCP5.2 represents different levels of dependences of lowland areas on mountain water. At a global scale, 68% of irrigated agricultural areas in lowlands depend on essential runoff contributions from the mountains. The dependence of lowland populations on essential mountain runoff contributions increased by a factor of more than three from the 1960s to the 2000s, with increases of up to ten-fold in some major river catchments (Viviroli et al., 2020).

Many mountain regions have one or more cryosphere components (glaciers, permafrost and perennial or seasonal snow), and the mountain cryosphere is among the natural systems most sensitive to climate change worldwide (*high confidence*). The SROCC assessed a decline in all cryosphere components due to climate change over recent decades, i.e., for low-elevation snow cover (*high confidence*), permafrost (*high confidence*) and glaciers (*very high confidence*) (Hock et al., 2019). More recent studies using globally more complete data sets show a considerably higher glacier mass loss (267 ±16 Gt yr^{-1}) for 2000–2019 as compared to a (*very likely*[2]) range of 123 ±24 Gt yr^{-1} for 2006–2015 in SROCC, with a mass loss acceleration of 48 ±16 Gt yr^{-1} per decade over 2000–2019 (Hugonnet et al., 2021). Assessment conclusions in SROCC found with *high confidence* that glacier shrinkage and snow cover changes over the past two decades have led to changes in the amount and timing of runoff in many mountain regions (Hock et al., 2019).

The effects of climate and environmental changes in upstream areas on downstream water quantity and quality, including nutrient, pollutant, heavy metals and sediment flux, have been assessed in only a limited number of catchments (Rakhmatullaev et al., 2009; Dong et al., 2015; Milner et al., 2017; Ilyashuk et al., 2018; Lane et al., 2019; Li et al., 2020; Chen et al., 2021). Groundwater contributions to streamflow are highly variable in mountains but can be substantial (up to 70 to 80% or more) during low-flow periods (Frisbee et al., 2011; Baraer et al., 2015; Gordon et al., 2015; Käser and Hunkeler, 2016; Somers et al., 2019). Groundwater may provide some resilience to loss of melt water from glacier and snow decline, but in the longer term groundwater recharge and contribution to streamflow are expected to decrease with ongoing climate change (*medium confidence*) (Somers and McKenzie, 2020). In some mountain regions (e.g., in the Himalaya), springs are a particularly important source of water where large populations depend on them. Observations indicate a reduction of water provision from springs in recent years in the Himalaya, caused by multiple causal factors (human interventions, climatic) (Section 10.4.4.).

Both small-scale interventions (e.g., livestock grazing in sensitive high-elevation wetlands) and high-investment interventions (e.g., hydropower dams and plants) in upstream regions can strongly affect water availability, river connectivity, biodiversity and catchment management (Anderson et al., 2018; Ramsar Convention on Wetlands, 2018; Encalada et al., 2019) and are often contested and have led to conflict (*medium evidence, high agreement*) (Drenkhan et al., 2015; French et al., 2015). Climate change often exacerbates tensions or conflicts between different users over water at local, national and transboundary or regional scales, and many tensions and social or political conflicts are documented, especially in seasonally dry regions, where large power inequalities exist among users, where clear and established regulations are lacking, and especially in transboundary settings (e.g., Central Asia, Hindu Kush Himalaya [HKH], Andes) (Carey et al., 2014; Bocchiola et al., 2017; Yapiyev et al., 2017; Hock et al., 2019; Mukherji et al., 2019).

Water plays a fundamental role in climate change adaptation in mountains. A majority of documented adaptation efforts in mountain regions address water-related aspects (precipitation variability and extremes, including drought, water availability, floods) (*high confidence*) (McDowell et al., 2019, 2020). This is a robust finding across different mountain regions and adaptation project and programme types and is in line with findings for cryosphere-change-related adaptation, as reported in SROCC (Hock et al., 2019). Water also plays a role in adaptation in other sectors, such as agriculture, disaster management, and tourism and recreation (McDowell et al., 2019). There is *high confidence* that water conservation efforts, including restoration and protection of particularly vulnerable areas (e.g., wetlands) and increase in efficiency in water use, are robust, low-regret adaptation measures.

CCP5.2.2.2 Energy

Increasing temperatures and variability in precipitation and river flow affect energy availability and use in mountain regions. Mountain peoples, more so than national or global populations, are dependent on local sources of energy, accentuating climate adaptation cost and barriers (*medium evidence, high agreement*), while also offering

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[2] In this report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, and exceptionally unlikely 0–1%. Additional terms (extremely likely: 95–100%, more likely than not >50–100%, and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17–83% probability range.

Box CCP5.1 | Wildfires and Mountain Ecosystems

Mountain ecosystems have long been known to be highly sensitive to the direct impacts of climatic warming and drying (Beniston et al., 1994; Nogués-Bravo, 2009; Gottfried et al., 2012; Guisan et al., 2019). Furthermore, wildfires in these ecosystems, as in many others (Sections 2.4.4.2 and 2.5.3.2), are also expected to increase (Abatzoglou et al., 2019). This is because the occurrence and severity of fire are governed by four fundamental processes that are intricately linked to climate: 1) fuel biomass growth, 2) fuel moisture and type, 3) ignition source and 4) favourable weather conditions for fire spread (Bradstock, 2010).

In temperate and tropical mountain ecosystems, increases in fire activity are potentially linked to changing climate on most continents, including Europe (Dupire et al., 2017), North America (Westerling, 2016; Halofsky et al., 2020; Burke et al., 2021), South America (Román-Cuesta et al., 2014), Africa (Hemp, 2005), Asia (Tian et al., 2014) and Australia (Bradstock et al., 2014; Abram et al., 2021). In these ecosystems, fire frequency, severity and extent (i.e., the fire regime) are increasing because of climate-induced impacts on fuel moisture (Gergel et al., 2017; Littell et al., 2018), vegetation composition (i.e., fuel types) (Camac et al., 2017; Prichard et al., 2017; Zylstra, 2018), fire-conducive weather patterns and the length of fire seasons (Westerling, 2016; Fill et al., 2019; Di Virgilio et al., 2020).

Fire in mountain ecosystems alters many ecological processes and ecosystem services across all elevational zones, from foothill montane forests to high-elevation alpine (treeless) zones (Turner et al., 2003; Williams et al., 2008; Oliveras et al., 2014, 2018; Rocca et al., 2014). However, the magnitude of short-term and long-term fire impacts depends on the degree of novelty of future fire regimes and the capacity of species to adapt to change (Camac et al., 2017, 2021; Archibald et al., 2018).

Montane and sub-alpine ecosystems have variable ecological responses to fire that are ultimately influenced by long-term, historical fire regimes and the evolutionary forces that have governed post-fire regeneration strategies of the biota. Two contrasting strategies in temperate forests are illustrated here. SE Australian mountain ash (*Eucalyptus regnans*) forests are adapted to a high-severity fire regime, consisting of infrequent (>100 years), large stand-replacing wildfires (Bowman et al., 2016). Mountain ash is a long-lived obligate seeder but is slow to reach reproductive maturity (>20 years) (Bowman et al., 2016). As such, natural post-fire regeneration takes decades to centuries to recover to pre-fire conditions, and if fire reoccurs before reproductive maturity is reached, the species can be eliminated. By contrast, ponderosa pine (*Pinus ponderosa*) forests of the SW United States have evolved with a low- or mixed-severity fire regime, where fire is frequent (5–25 years), of low intensity, less likely to kill dominant stands and, thus, allow faster post-fire recovery (Prichard et al., 2017). However, post-fire recovery times in this ecosystem are also becoming longer due to a century of effective fire suppression, shifting the fire regime to one which is more infrequent, of high intensity, extensive and stand replacing (Prichard et al., 2017).

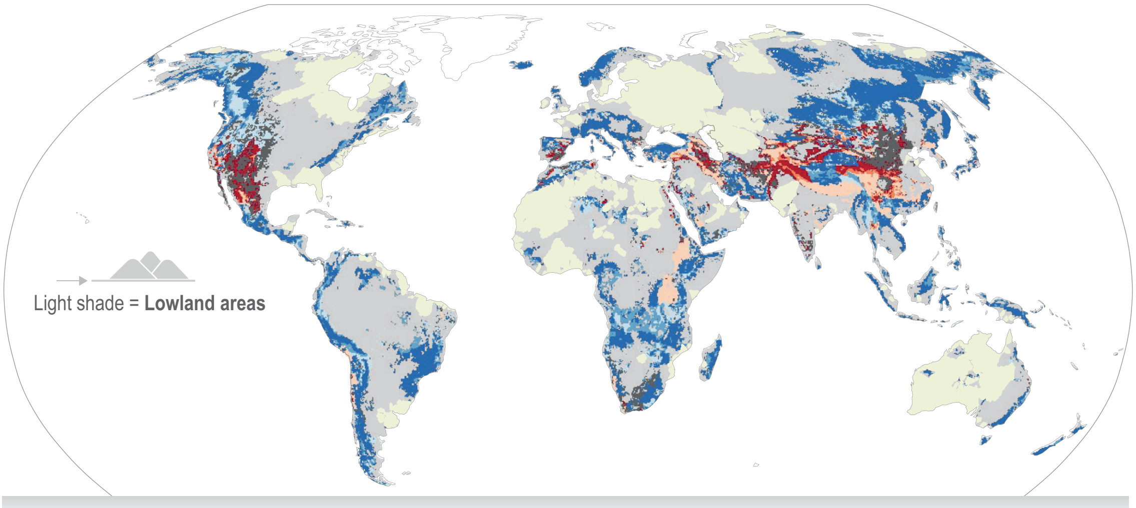
Above the treeline, fire is less common than in foothill forests. Post-fire recovery times also tend to be shorter (Williams et al., 2008; Camac et al., 2013; Verrall and Pickering, 2019) because of the dual influences of low flammability traits coupled with the fact that most alpine plant species exhibit strong resprouting strategies that have evolved in response to harsh climate conditions (Körner, 2003). However, fires in alpine treeless landscapes can still have long-term and catastrophic impacts on fire-sensitive vegetation types such as groundwater-dependent wetlands dominated by hygrophilous plants and peat soils (De Roos et al., 2018). Similar impacts can be severe on long-lived, slow-growing vegetation such as coniferous heathlands (Bowman et al., 2019) and highly restricted and threatened fauna (e.g., mountain pygmy possum) that depend on these plant communities (Gibson et al., 2018). Such fires have even been found to significantly impact sub-alpine treeline mortality rates (Fairman et al., 2017) and in some cases have resulted in treelines shifting to lower elevations (e.g., Hemp, 2005).

The long-term implications of a warmer global climate, coupled with more frequent and/or severe fires in mountain ecosystems, are expected to be transformative for mountain biota. Fire-sensitive montane forests, such as Australia's alpine ash (*Eucalyptus delegatensis*), are expected to become highly susceptible to population collapse and local extinction as intervals between fire events contract and become too short for species to reach reproductive maturity (Bowman et al., 2014; Enright et al., 2015)—an impact that will *likely* be further exacerbated by recruitment failure caused by post-fire drought and moisture deficiencies (Davies et al., 2019; Halofsky et al., 2020; Rodman et al., 2020). Fire and climate change are also *likely* to act synergistically in mountainous ecosystems, via positive feedbacks that increase fire frequency by changing vegetation composition to more flammable fuel types, thereby increasing landscape susceptibility to future fire (Camac et al., 2017; Tepley et al., 2018; Zylstra, 2018; Lucas and Harris, 2021). More frequent fires in these ecosystems will also exacerbate native and exotic species invasions (Catford et al., 2009; McDougall et al., 2011; Gottfried et al., 2012; Kueffer et al., 2013), faunal population declines (Ward et al., 2020), poor air quality (de la Barrera et al., 2018; Burke et al., 2021) and soil erosion and landslide risk (de la Barrera et al., 2018) and reduce freshwater catchment volumes and quality (Rust et al., 2018; Niemeyer et al., 2020), all of which will impact negatively on human health and well-being (Ebi et al., 2021).

Taken together, this evidence suggests that a significant risk exists of wildfire exacerbating other impacts of climate change on already vulnerable ecosystems in many mountain regions (*medium confidence*).

Importance of mountain water resources for lowland areas and populations

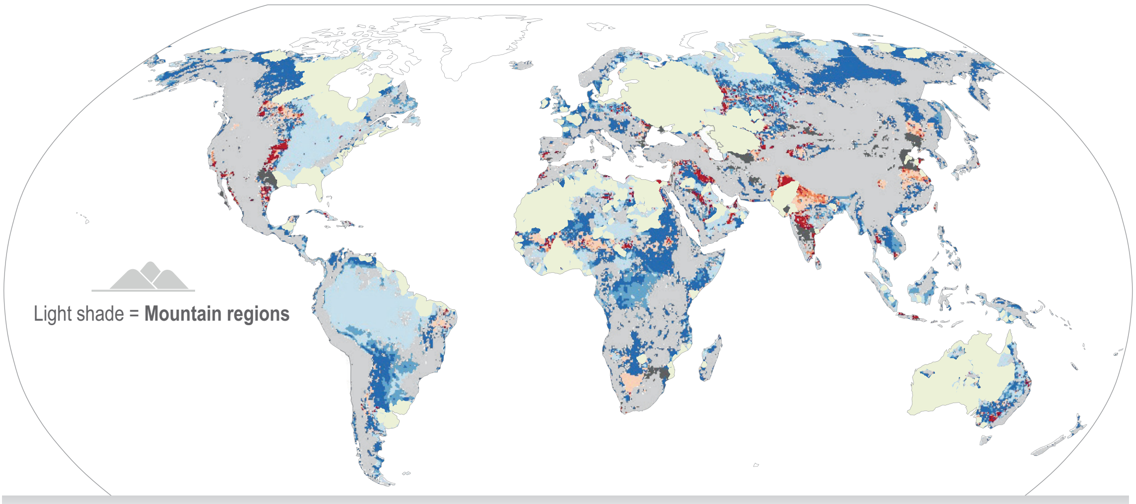
(a) Importance of mountain regions for lowland water resources (2041–2050, SSP2-RCP6.0)



Extent of importance and dependence

- 🟥 Essential but vastly insufficient
- 🟧 Essential but insufficient
- ▨ Essential and sufficient
- 🟦 Supportive
- ▨ Minor
- ▨ Negligible
- ⬛ No surplus
- 🟨 Share of mountain area in total catchment area <5%

(b) Lowland population dependence on mountain water resources (2041–2050, SSP2-RCP6.0)



(c) Lowland population dependence on mountain water resources over time

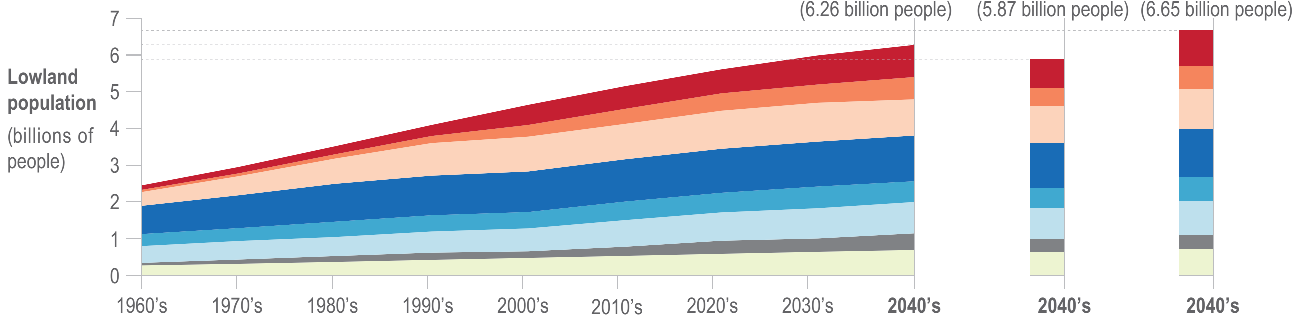


Figure CCP5.2 | Dependence of land surface areas and population on mountain water resources, 1961–2050. Results are shown as decadal averages for lowland populations in each category of dependence on mountain water from no surplus and negligible to essential;

(a) map of global mountain regions and their differentiated importance for lowland water resources;

(b) map of lowland populations and their differentiated dependence on mountain water resources, both for the scenario combination SSP2-RCP6.0 and for the time period 2041–2050;

(c) number of lowland populations and their differentiated dependence on mountain water resources from 1960s to 2040s for three different scenario combinations (based on Viviroli et al., 2020).

opportunities for mountain-specific solutions (*medium evidence, high agreement*). In mountain regions, inadequate infrastructure (Tiwari et al., 2018), remoteness and reliance on traditional forms of energy that may be difficult to diversify (Dhakal et al., 2019) exacerbate the impacts of climate change on energy use and demand.

A review of the renewable energy transition in the context of adaptation across global mountain regions, including hydropower, wind, solar and biomass, shows that observed climate change impacts on these energy sources include altered seasonality, timing as related to snow and glacial melt runoff (30.9% of analysed cases), variable or declining precipitation and runoff (26.4%), increased flooding (15.5%), altered wind patterns (8.2%) and other/unspecified effects (19.1%) (Scott et al., 2019). The combined effects of climate change, hydropower development and further anthropogenic effects in upstream mountain basins have increased and are expected to further negatively affect several aspects of ecosystem functioning and water security (e.g., negative effects on river geometry, water chemistry, sediment transport, fish composition and migration) (*high confidence*) (Anderson et al., 2018; Encalada et al., 2019; Lepcha et al., 2021).

With respect to hydropower, mountains play a unique role in the production of renewable energy for large downstream populations, but it also comes with important trade-offs affecting mountain ecosystems and populations (*high confidence*) (Farinotti et al., 2019; Viviroli et al., 2020; Vaidya et al., 2021). Climate change requires adaptation in the hydropower sector; for instance, some advocate for increased water storage in dams and the importance of mountains for pumped hydropower storage systems (Gurung et al., 2016; Hunt et al., 2020), while others emphasise adaptive water management (Gaudard et al., 2014; Caruso et al., 2017b). An example is the multi-purpose use of water strategies where water management storage is designed to accommodate different uses, including hydropower, agriculture and flood risk reduction (Haeberli et al., 2016a; Drenkhan et al., 2019) (Section 12.6.3). Hydropower is also especially vulnerable to glacier and snow decline (Schaefli et al., 2019) and is subject to risks from extreme events (Rangecroft et al., 2013; Schwanghart et al., 2016; Mishra et al., 2020; Shugar et al., 2021), social and political opposition (Ahlers et al., 2015; Díaz et al., 2017) and the resulting financial uncertainty for hydropower investors. There is still *limited evidence* on how climate change impacts wind, solar and biomass energy production and their use.

Overall, synergies between adaptation to climate change and renewable energy transition can be successfully generated where benefit-sharing improves local involvement and support, adaptive capacity is enhanced, local health and livelihoods supported, Sustainable Development Goals (SDGs) met, environmental justice considered and sustainable mountain development pursued (*high agreement, medium evidence*).

CCP5.2.3 Food, Fibre and Other Mountain Ecosystem Products

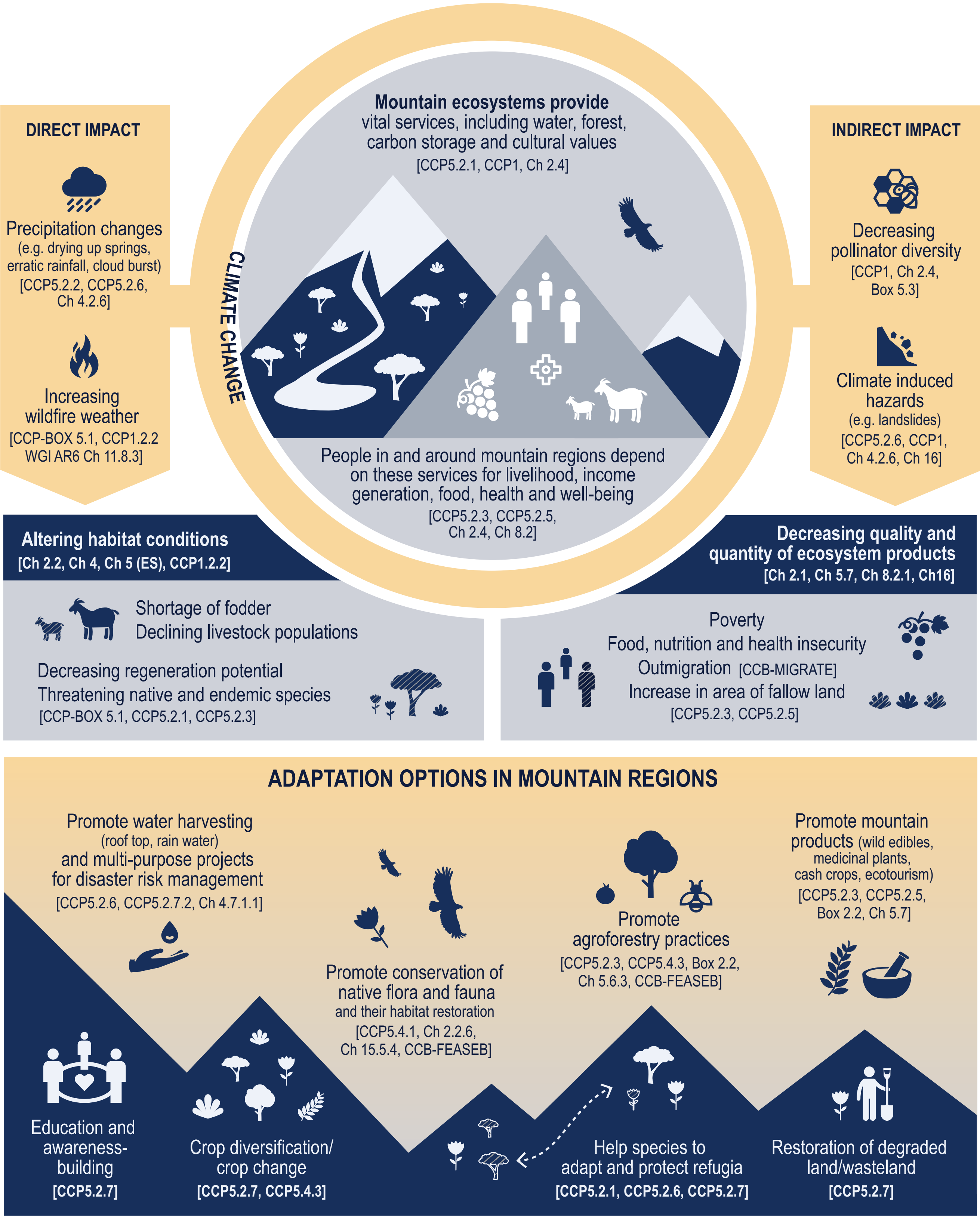
There is *high confidence* that climate change is largely negatively impacting food, fibre and other ecosystem products, including agriculture (Porter et al., 2014; Ingxay et al., 2015; Upgupta et al., 2015; Chirwa et al., 2017; Rojas-Downing et al., 2017; Chitale et al., 2018; Pretzsch et al., 2018; Barberán et al., 2019; Sultan et al., 2019; Huang and Hao, 2020; Godde et al., 2021), and ecosystem services (Grêt-Regamey and Weibel, 2020) across many different mountainous regions, for example in Africa (Bondé et al., 2019; Musakwa et al., 2020), Asia (Guo et al., 2018; Sunderland and Vasquez, 2020), Europe (Nair, 2019), North America (Hupp et al., 2015; Prevéy et al., 2020) and South America (Herman-Mercer et al., 2020) (Sections 5.4, 5.4.1, 5.5.1, 5.6.2, 5.7, 5.11.1.1).

Ecosystem products are vital to support the livelihoods and economic prospects for communities living in and around mountains (Figure CCP5.3). For instance, collection and trade of caterpillar fungus contributed to 53.3–64.5% annual household cash income in Nepal (Shrestha and Bawa, 2014; Shrestha et al., 2019); 40–80% in Bhutan (Thapa et al., 2018) and 60–78% in Uttarakhand, India (Laha et al., 2018; Yadav et al., 2019) (Section 5.7.1). Livelihood support from ecosystem products in southern Malawi (Pullanikkatil et al., 2020), southwestern Ethiopian mountains (Nischalke et al., 2017), Southern China (Min et al., 2017), Himalayan mountains (Nepal et al., 2018) and South Africa (Ngwenya et al., 2019) has been reported. Additionally, the sacredness of mountains in different religions and cultures is widely acknowledged (Ceruti, 2019; Benedetti et al., 2021).

Climate change and its associated impacts on multiple ecosystem services and related products (timber production, carbon sequestration, biodiversity and protection against natural hazards) have been observed across European mountains, for example in the central Iberian Mountains (Spain), Western and Eastern Alps (France, Austria) and Dinaric Mountains (Slovenia) (Mina et al., 2017). Dumont et al. (2015) demonstrated that climate change negatively affects forage nitrogen (N) content by 8% but increases total non-structural carbohydrate content by 25% in European mountains. Positive impacts have been reported on mushroom productivity in the mountains of Spain (Karavani et al., 2018) (Section 5.7.3.3), yet negative impacts have been reported on the *Ophiocordyceps* in the Himalayan region (Hopping et al., 2018), as well as on apple production in Himachal Pradesh, India, which declined by 9.4 t per hectare in the past two decades (Das, 2021). Shifts in the richness of crop wild relatives from south to north and an increase in the numbers of threatened taxa with an increase of 1.5°C and 3°C temperature rise have been observed in European mountains (Phillips et al., 2017).

Medicinal and aromatic plants and their secondary metabolites are also observed to be affected by climate change (*medium confidence*) (Das et al., 2016; Zhang et al., 2019a). Phenological changes like early flowering and reduced vegetative phase are negatively affecting the productivity of such plants (Harish et al., 2012; Gaira et al., 2014; Maikhuri et al., 2018). While increasing atmospheric temperature and CO_2 are reported to improve the biomass of *Gynostemma pentaphyllum* (Chang et al., 2016) (Section 5.7.3.3), they adversely affect its antioxidant compounds/activity, health-promoting properties and phytochemical content (Gairola et al., 2010; Das et al., 2016; Kumar et al., 2020). Experimental trials have shown that when medicinal plants are stressed by drought, phytochemical content increases, either by a decrease in biomass or by an increase in the actual production of metabolites (*medium confidence*) (Selmar and Kleinwächter, 2013; Al-Gabbiesh et al., 2015). The strong effects of climatic and non-climatic

Climate change and mountain social-ecological systems



Mountain ecosystems provide
vital services, including water, forest, carbon storage and cultural values
[CCP5.2.1, CCP1, Ch 2.4]

DIRECT IMPACT

Precipitation changes
(e.g. drying up springs, erratic rainfall, cloud burst)
[CCP5.2.2, CCP5.2.6, Ch 4.2.6]

Increasing wildfire weather
[CCP-BOX 5.1, CCP1.2.2 WGI AR6 Ch 11.8.3]

CLIMATE CHANGE

INDIRECT IMPACT

Decreasing pollinator diversity
[CCP1, Ch 2.4, Box 5.3]

Climate induced hazards
(e.g. landslides)
[CCP5.2.6, CCP1, Ch 4.2.6, Ch 16]

People in and around mountain regions depend on these services for livelihood, income generation, food, health and well-being
[CCP5.2.3, CCP5.2.5, Ch 2.4, Ch 8.2]

Altering habitat conditions
[Ch 2.2, Ch 4, Ch 5 (ES), CCP1.2.2]

Shortage of fodder
Declining livestock populations

Decreasing regeneration potential
Threatening native and endemic species
[CCP-BOX 5.1, CCP5.2.1, CCP5.2.3]

Decreasing quality and quantity of ecosystem products
[Ch 2.1, Ch 5.7, Ch 8.2.1, Ch16]

Poverty
Food, nutrition and health insecurity
Outmigration [CCB-MIGRATE]
Increase in area of fallow land
[CCP5.2.3, CCP5.2.5]

ADAPTATION OPTIONS IN MOUNTAIN REGIONS

Promote water harvesting (roof top, rain water) and multi-purpose projects for disaster risk management
[CCP5.2.6, CCP5.2.7.2, Ch 4.7.1.1]

Promote conservation of native flora and fauna and their habitat restoration
[CCP5.4.1, Ch 2.2.6, Ch 15.5.4, CCB-FEASEB]

Promote agroforestry practices
[CCP5.2.3, CCP5.4.3, Box 2.2, Ch 5.6.3, CCB-FEASEB]

Promote mountain products (wild edibles, medicinal plants, cash crops, ecotourism)
[CCP5.2.3, CCP5.2.5, Box 2.2, Ch 5.7]

Education and awareness-building
[CCP5.2.7]

Crop diversification/crop change
[CCP5.2.7, CCP5.4.3]

Help species to adapt and protect refugia
[CCP5.2.1, CCP5.2.6, CCP5.2.7]

Restoration of degraded land/wasteland
[CCP5.2.7]

Figure CCP5.3 | Impact of climate change on mountain social-ecological systems, including ecosystem services and products, livelihoods of mountain people and examples of adaptation options to address direct and indirect impacts.

factors have been observed to affect the distribution of selected medicinal plant species in northern Thailand (Tangjitman et al., 2015), as well as in Egypt, sub-Saharan Africa, Spain, Central Himalaya, China and Nepal, with some species at risk of extinction (Munt et al., 2016; Yan et al., 2017; Brunette et al., 2018; Chitale et al., 2018; Zhao et al., 2018; Applequist et al., 2020). Negative climate-related impacts on the distribution range of 41 medicinal plant species have been predicted for Spanish and Asian mountains (Munt et al., 2016) (Section 5.7.3.3), as has a decreasing size of fruits of *Myrica esculenta* in the Himalaya (Shah and Tewari, 2016).

CCP5.2.4 Cities, Settlements and Key Infrastructure

Mountain settlements and people are globally distributed and represent a significant proportion of the total global population that is exposed to the effects of climate change (Section CCP5.1, SMCCP5.1). Cities with one or several million inhabitants located in mountainous environments or at high elevations are predominantly found in Latin America (e.g., El Alto and La Paz, Bolivia; Quito, Ecuador; Mexico City, Mexico; and Bogota, Colombia), Asia (e.g., Kabul, Afghanistan; Kathmandu, Nepal; Srinagar and Dehradun, India; Peshawar and Quetta, Pakistan; and Xining and Kunming, China) and Africa (e.g., Harare, Zimbabwe; and Addis Ababa, Ethiopia) (Wang and Lu, 2018; Balderas Torres et al., 2021; Ehrlich et al., 2021). Mountain regions are also host to many settlements with fewer than 500,000 inhabitants (Alfthan et al., 2016). In many cases, particularly in developing countries, portions of the population also reside in informal and low-income settlements (French et al., 2021), where rates of poverty and inequality exacerbate people's vulnerability and exposure to climate-related hazards such as landslides (Alfthan et al. 2018) (Section CCP5.2.5.1), environmental pollution or even pandemic diseases (Marazziti et al., 2021).

In many mountain regions, particularly in developing countries, the increasing urban population has put considerable pressure on water services and basic amenities for urban dwellers (Singh et al., 2021), for example in cities such as La Paz (Kinouchi et al., 2019), which are regions already under pressure due to the negative effects of climate change, coupled with poor water availability and governance (Chapter 4; CCP5.2.2.1; FAQ CCP5.1; Hock et al. 2019). In many areas of the HKH region, water demand far exceeds municipal supply, and people cope with water insecurity in a variety of ways (Bharti et al., 2020; Sharma et al., 2020; Singh et al., 2020), such as by resorting to interbasin water transfers and deep pumping, to supply their water needs (Ojha et al., 2020). Additionally, influxes of migrants, tourists and retirees, combined with the growth of the incumbent population, place considerable stress on urban infrastructures that must supply adequate clean water and provide for sewage disposal (Prakash and Molden, 2020), which is also observable in other regions (Chapter 4; Section 6.4.7; Case Study 6.1 in Chapter 6). Energy provision in and around mountain settlements is another key sector affected by climate-related impacts (Hock et al., 2019; CCP5.2.2.2), which bears relevance for the adaptation prospects for urban mountain settlements (*medium confidence*).

CCP5.2.5 Mountain Communities, Livelihoods, Health and Well-Being

People living in and around mountain regions strongly depend for their livelihoods, health and well-being on the ecosystem functions, services and resources available in these areas. Overall, subsistence agriculture and livestock remain key sources of livelihood in many mountain regions (FAO, 2019), with non-agricultural income sources such as remittances, small businesses, medicinal plants, wage labour and tourism also contributing to these economies (Montanari and Koutsoyiannis, 2014; Palomo, 2017; Minta et al., 2018). This section provides an illustrative overview of key reported observed impacts of climate change on mountain communities and adaptation responses (Table CCP5.1), as well as impacts on livelihood activities and economic sectors such as agriculture and pastoralism and tourism and recreation (Table CCP5.2), reported since AR5.

Other sections in this CCP provide detailed assessments that synthesise impacts associated with the detection of climate change and the attribution of those impacts to anthropogenic climate change (CCP5.2.7), projected impacts and key risks (CCP5.3) and adaptation responses to reduce those key risks (CCP5.4.1).

CCP5.2.6 Natural Hazards and Disasters

Climate- and weather-related disasters in mountain regions have increased over the last three decades (*medium confidence*). Disaster frequency shows increasing trends in the HKH, the Andes and mountain regions in Africa, whereas no clear trends are observed for the European Alps and Central Asia (*medium confidence*) (Froude and Petley, 2018; Stäubli et al., 2018).

Floods, debris flows, landslides and avalanches are the most frequent hazards affecting the highest number of people in mountain regions (*medium confidence*) (Stäubli et al., 2018). Landslides count among the deadliest hazards globally, with over 150,000 reported fatalities for the period 1995–2014 (Haque et al., 2019). There is *high confidence* that the number of fatalities from landslides has increased globally over the past 20 years (Froude and Petley, 2018; Haque et al., 2019), but there is *limited evidence* that this is due to changes in landslide event frequency and/or magnitude. Infrastructure expansion on unstable terrain can increase disaster risk (Zimmermann and Keiler, 2015; Huggel et al., 2019; Kirschbaum et al., 2019; Schauwecker et al., 2019; Terzi et al., 2019; Motschmann et al., 2020a; Shugar et al., 2021). A study from western Nepal concludes that the exposure of people and infrastructure to hazards has been the main cause of disasters (Muñoz-Torrero Manchado et al., 2021). Decreasing numbers of fatalities from disasters resulting from decreasing vulnerabilities have been reported in Europe and North America (Section 13.2.2.1) (Gariano and Guzzetti, 2016; Strouth and McDougall, 2021). Evidence from Africa suggests that disasters from climate-induced natural hazards in mountain areas are often due to droughts, pests and changes in rainfall and associated impacts on smallholder farmers' agricultural livelihoods (Shikuku et al., 2017).

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Table CCP5.1 | Overview of key observed impacts and adaptation on mountain communities—livelihoods and poverty; migration, habitability and displacement; health and well-being.

Overview of key observed impacts on mountain communities and adaptation responses		References and relevant AR6 WGII sections
Mountain livelihoods and poverty		
Impacts	– In some mountain regions, the incidence of poverty can be higher compared to other areas, with observed impacts of climate change intensifying the deterioration of socioeconomic conditions that support livelihoods, thereby exacerbating already existing conditions of non-climate-related vulnerabilities and livelihood insecurity (*medium confidence*).	Gioli et al. (2019), Tiwari and Joshi (2012), Rasul and Hussain (2015), Hussain et al. (2019), McDowell and Hess (2012), FAO (2015, 2019), Shrestha et al. (2015), Motschmann et al. (2020a), Section 8.3
Responses and adaptation	– Diversification of livelihoods through integration of drought-resilient livestock and crops and changes in farming practices (i.e., water management or migration of crops from lowland to highland) with some shifting to non-agricultural livelihood options, reported for cases such as in the HKH, the Andes, Rwenzori Mountains of Uganda and Simien Mountains of Ethiopia.	Ashraf et al. (2014), Hussain et al. (2016a), Skarbø and VanderMolen (2016), Nkuba et al. (2020), Yohannes et al. (2020), CCP5.4.1
Migration, habitability and displacement		
Impacts	– There is growing evidence of links between climate change impacts and migration and mobility through a complex web of causal links (*medium confidence*). In mountain contexts, migration and mobility are indirectly impacted by climate change through adverse effects on mountain livelihoods that are dependent on mountain ecosystem services.	Wrathall et al. (2014), Hunter et al. (2015), Brandt et al. (2016), Mastrorillo et al. (2016), Gautam (2017), Sagynbekova (2017), Cattaneo et al. (2019), Maharjan et al. (2020)
	– Extreme events are resulting in temporary and, in some cases, permanent displacement of populations in mountains (*medium confidence*), with hazards such as floods and mass movement (avalanche, flood, landslide) leading to population displacements (e.g., in Afghanistan, Pakistan, Peru, Thailand and Uganda).	Iribarren Anacona et al. (2015), Stäubli et al. (2018), IDMC (2020), Wang et al. (2020)
	– Cases of entire settlements either abandoned or relocated due to prolonged slow onset events such as water shortage, drought and heat stress have been reported.	Mueller et al. (2014), Nawrotzki and DeWaard (2016), Prasain (2018)
	– In contrast, place attachment is increasingly cited as one of the reasons for the immobility choices for some people. However, in some cases, vulnerability to climatic events contributes to the in-migration decisions of vulnerable populations exposed to hazards from downstream to upland areas.	Adams (2016), Dandy et al. (2019), Khanian et al. (2019), Islam et al. (2020)
Responses and adaptations	– Migration, in turn, is often cited as a risk management strategy, where migration can lead to the diversification of livelihood options, improves access to information and resources and expands social networks, all of which can support households in their capacity to adapt to climate change impacts. – Migration is often gendered, with men migrating and leaving women to manage households at origin. Women's capacities are often constrained due to institutional barriers and social norms, resulting in low adaptive capacity and increased vulnerability to hazards. Capacity-building interventions strengthen adaptation capacity and links to access institutional support (*medium confidence*).	Banerjee et al. (2018), Banerjee et al. (2019), Siddiqui et al. (2019), Maharjan et al. (2020), Maharjan et al. (2021)
Health and well-being		
Impacts	– Direct links between climate change and health in mountain regions are reported in terms of physical injury or fatality due to exposure to climate-related hazards such as floods or landslides or to vector-borne diseases such as malaria or dengue fever reported at higher elevations with warming temperatures (*medium confidence*), such as in Mexico, Nepal, Ethiopia and Colombia.	Dantés et al. (2014), Siraj et al. (2014), Dhimal et al. (2015), Wu et al. (2016), Equihua et al. (2017), Alfthan et al. (2018), Gilgel et al. (2019), Chapter 7
	– Indirect impacts on health of climate change are linked to water-borne diseases and pathogens associated with floods and droughts.	Table 7.6
	– While reports on the ongoing challenges associated with the COVID-19 pandemic are emerging in relation to their compounding impacts on adaptive capacities, there is *limited evidence* to assess those effects with respect to other climate-related impacts on health.	Baiker et al. (2020), Cross-Chapter Box COVID in Chapter 7
	– Mental health issues associated with climate-related impacts have been reported with respect to climate anxiety and ecological grief and their effects on the well-being of individuals. For example, the grief and loss associated with changes in glaciated landscapes, such as the 'death' of the Okjökull glacier in Iceland. However, there is *limited evidence* on mountain-specific cases and experiences that would allow for an assessment of the broader and longer-term impacts on mental health associated with a changing climate in mountains.	Trombley et al. (2017), Cunsolo and Ellis (2018), Clayton (2020), Sideris (2020)
	– Other heightened vulnerability to climate-related impacts on health and well-being are also experienced by specific groups, for example Sami pastoralists facing changes in mountain snow cover that negatively affect their reindeer herding, a key activity for their identity and spiritual health.	Furberg et al. (2011), Section 7.1.7.2
Responses and adaptations	– Approximately a fifth of observed adaptations reported in the GAMI mountain reanalysis address health and well-being as an aspect of vulnerability. This includes raising communities' awareness of and coping strategies for climate-change-induced health issues.	Furu and Van (2013), Section CCP5.4.1

Table CCP5.2 | Overview of key observed impacts and adaptation on select livelihood activities and economic sectors—mountain agriculture and pastoralism, and tourism and recreation.

Overview of key observed impacts and adaptation on select livelihood activities and economic sectors		References and relevant AR6 WGII sections
Mountain agriculture and pastoralism		
Impacts	– Changes in temperature and seasonal precipitation patterns affect the timing and availability of water for agricultural activities (*high confidence*), for example in the Bolivian Andes; the Andean-Amazon foothills of Colombia, Ecuador and Peru; the High Atlas of Morocco; HKH; and the Golestan province of Iran.	Rangecroft et al. (2013), Kaboosi and Kordjazi (2017), Hussain et al. (2018), Kalbali et al. (2019), Zkhiri et al. (2019), Beltrán-Tolosa et al. (2020), Torres-Batlló and Martí-Cardona (2020)
	– Changes in temperature and seasonal precipitation patterns are reported to affect nutrient depletion of soils and increased incidence of pest attacks in crops (e.g., in cases in the HKH and in Peru); however, there is generally *limited evidence* on directs links specifically to climate-related changes in mountain regions.	Oliver-Smith (2014), Hussain et al. (2016b)
	– Climate-induced hazards, such as erratic precipitation (rain, snow and hail), floods, droughts and landslides, have negatively affected the stable supply and transport of agricultural products in and out of remote mountain areas, such as in the Peruvian Altiplano and HKH.	Hussain et al. (2016b), Gonzales-Valero (2018), Thapa and Hussain (2020)
	– Warming temperatures and changes in the timing of seasons and frost conditions needed for seeding certain tree crops impact lower-elevation mountain areas, such as in Oman.	Buerkert et al. (2020)
	– Drought conditions negatively affect mountain grasslands (*medium confidence*), as reported in cases in Tyrol (Austria), Nepal, Afghanistan, Pakistan and China, which can contribute to a decline in agrobiodiversity.	Ashraf et al. (2014), Zomer et al. (2014b), Grüneis et al. (2018), Adhikari et al. (2019), Chaudhary et al. (2020), Hussain and Qamar (2020)
	– In some cases, climate-related hazards lead to outmigration in mountain areas, with indirect negative impacts on labour deficits to support agricultural practices and productivity in mountain areas (*medium confidence*) (e.g., in Ghana, Tanzania, Thailand and HKH).	Warner and Afifi (2014), Wester et al. (2019)
	– Positive impacts (favourable growing conditions) are reported for the production of some fruits and vegetables in the Gilgit-Baltistan province of Pakistan and for the production of traditional crops (e.g., local beans) in the Karnali region of Nepal.	Hussain et al. (2016b), Thapa and Hussain (2020)
	– Impacts on pastoralism include changes in growing conditions associated with warming temperatures and declining precipitation, which in turn lead to negative impacts on livestock productivity, food security and livelihoods of pastoralist communities, including drought-induced degradation of rangelands (*medium confidence*) (e.g., in mountainous areas of Mongolia, Tanzania, Nepal and Ethiopia), which exacerbate impoverished conditions in pastoral communities.	Batima et al. (2013), Rasul et al. (2014), Gentle and Thwaites (2016), Kimaro et al. (2018), Mekuyie et al. (2018), Tiwari et al. (2020)
Responses and adaptations	– Recharging groundwater and adopting rainwater harvesting (including appropriate tillage methods to improve soil moisture), restoration and rehabilitation of land, diversification of agricultural crops (including introduction of stress resistant crop varieties), promotion of in situ (protected areas, conservation areas) and ex situ (nurseries, gene banks, home gardens) conservation strategies, afforestation and agroforestry.	Sections 4.7.1.1 and 5.6.3, Cross-Chapter Box FEASIB in Chapter 18
	– Local knowledge is used to help maintain the productive and cultural value of mountain agriculture and pastoralism, such as in the French and Italian Alps, Western Himalaya in India and the mountains of northern Morocco.	Fassio et al. (2014), Kmoch et al. (2018), Das (2021)
	– Ecosystem- and community-based adaptations contribute to supporting the diversity and complementarily of management options, permaculture and local capacities to adapt and support ecosystem functions vital for agrobiodiversity (*medium confidence*).	Reid (2016), Grêt-Regamey and Weibel (2020), Cross-Chapter Box NATURAL in Chapter 2
Tourism and recreation		
Impacts	– Since SROCC, the literature on climate change impacts on winter skiing tourism has remained dominated by studies focused on future climate change impacts and projected risks due to decreasing seasonal snow reliability (CCP5.3.1), most relevant when considering snow management and, in particular, snow-making.	Hock et al. (2019), Sauri and Llurdés (2020), AR6 WG1 Sections 9.5.3 and 12.4.10.4
	– Climate-induced hazards in mountains, such as rockfalls, negatively affect access to some climbing, mountaineering and hiking routes in summer (*medium confidence*), with cases mainly reported in the European Alps.	Hock et al. (2019), Mourey et al. (2019, 2020)
	– Higher temperatures and extreme heat conditions at lower elevations have made some mountain destinations more appealing for human comfort, increasing the potential summer visitation demand and opportunities for tourism and recreation in mountains, such as in the European Alps and the Catalan Pyrenees (*medium confidence*). However, there is *limited evidence* on similar trends in mountain regions outside of Europe.	Serquet and Rebetez (2011), March et al. (2014), Pröbstl-Haider et al. (2015), Steiger et al. (2016), Juschten et al. (2019a, b)

Overview of key observed impacts and adaptation on select livelihood activities and economic sectors		References and relevant AR6 WGII sections
Responses and adaptation	– Diversification of tourism activities to non-snow activities has been reported as an adaptation approach to maintaining economic viability in some winter ski areas, partly due to the high cost of running snow-making infrastructure in winter, for example in the Pyrenees (Europe) and Australian Alps.	Morrison and Pickering (2013), Sauri and Llurdés (2020)
	– In some cases, managing water resource availability and demand for snow-making is reported, with destination and large-scale governance highlighted as critical aspects for managing trade-offs, including overcoming conflicts arising from competing demands for environmental resources and land use (e.g., in French Alps and in Scandinavia).	Demiroglu et al. (2019), Gerbaux et al. (2020)
	– For snow management, examples exist of dedicated climate services designed to enable better-informed decision- making on appropriate long-term adaptation (e.g., through a dedicated Copernicus Climate Change Service or real-time early warning systems).	Köberl et al. (2021), Morin et al. (2021)
	– Barriers to adaptation strategies such as snow-making, for instance in Switzerland, have been linked to perceived economic constraints on their implementation, as well as the social acceptability of these measures.	Matasci et al. (2014), Moser and Baulcomb (2020)
	– Adaptation options to limit exposure to hazards in hiking, climbing or mountaineering activities include shifting the seasonal timing for these activities or changing routes entirely.	Hock et al. (2019), Mourey et al. (2019, 2020)
	– In some cases, such as in Bolivia, Peru and New Zealand, and more recently reported in the French Alps, 'last chance' tourism has increased the appeal of some mountain destinations, resulting in visitation demand to witness the effects of climate change on iconic mountain landscape features such as glaciers.	Hock et al. (2019); Salim and Ravanel (2020)

The characteristics of natural hazards in mountain areas have been widely explored, and evidence suggests that conditions favouring cascading impacts are a common feature (*high confidence*) (Section 8.2.1.1) (Zimmermann and Keiler, 2015; Huggel et al., 2019; Kirschbaum et al., 2019; Schauwecker et al., 2019; Terzi et al., 2019; Motschmann et al., 2020a; Shugar et al., 2021). Compound and cascading impacts have affected people, ecosystems and infrastructure and generate significant spillovers across numerous sectors, resulting in destructive impacts (Nones and Pescaroli, 2016; Kirschbaum et al., 2019; Schauwecker et al., 2019).

Most adaptation responses to natural hazards in mountain regions are reactive to specific climate stimuli or post-disaster recovery (*robust evidence, medium agreement*) (McDowell et al., 2019; Rasul et al., 2020). Hard structural measures such as dikes, dam reservoirs and embankments have been widely employed to contain hazards, along with early warning systems, zonation and land management (Box 4.1, 10.4.4.5, 12.5.3 and 13.2.2). Awareness raising, preparedness and disaster response plans are increasingly used in the context of more unpredictable hazard trends (see Cross-Chapter Box DEEP in Chapter 17) (Allen et al., 2016, 2018; Hovelsrud et al., 2018). Ecosystem-based adaptations (EBAs) are widely implemented to mitigate risks from shallow landslides (e.g., afforestation and reforestation and improved forest management), floods (e.g., river restoration and renaturation) (Renaud et al., 2016; Klein et al., 2019b) and droughts (e.g., adapting watershed) (Renaud et al., 2016; Klein et al., 2019b; Palomo et al., 2021).

Evidence from different mountain regions shows that adaptation and risk reduction efforts are less successful if they focus on hazards or risks without considering diverse risk and value perceptions of the affected people (*medium confidence*) (French et al., 2015; Allen et al., 2018; Hovelsrud et al., 2018; Kadetz and Mock, 2018; Klein et al., 2019b). Previous experience and local social contexts of exposure to climate-related disasters affect people's perceptions and influence the patterns associated with disaster risk management and associated coping strategies (*high confidence*) (SROCC Chapter 2 (Hock et al., 2019)), (Kaul and Thornton, 2014; Shijin and Dahe, 2015; Landeros-Mugica et al., 2016; Wirz et al., 2016; Carey et al., 2017; Adler et al., 2019).

Important synergies exist between disaster risk reduction, climate change adaptation and sustainable development in mountain regions (*medium confidence*) (Zimmermann and Keiler, 2015), where the multiple and diverse perceptions of risk and risk tolerance for natural hazards are relevant considerations (Schneiderbauer et al., 2021). Global agreements for integrated disaster risk management and climate change adaptation (Alcántara-Ayala et al., 2017), including the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015), the SDGs (UN, 2015), the Paris Agreement (UNFCCC, 2015) and the New Urban Agenda-Habitat III (UN, 2016), create opportunities for synergies to address disaster risks (see also Section 6.3). Although these agreements are well established in international agendas, there is *limited evidence* of their implementation to address disaster risk reduction and adaptation in mountains (Alcántara-Ayala et al., 2017).

CCP5.2.7 Synthesis of Observed Impacts and Attribution and Observed Adaptations

CCP5.2.7.1 Observed Impacts and Attribution to Anthropogenic Climate Change

The assessment of observed impacts identified a large number of impacts across all major mountain regions of the world and for a large variety of systems, based on more than 300 references (SMCCP5.2).

The literature was assessed and the results classified on a per-region and per-system basis. Confidence statements on detection and attribution are based on expert judgement following IPCC guidelines (Section 1.3.4), building on evidence from multiple sources in the literature (Mach et al., 2017) (SMCCP5.2). Figure CCP5.4 provides an overview of the assessment results.

Climate change impacts have been documented in mountains on all continents. A wide range of human and natural systems have been affected by climate change to date, including the cryosphere, water resources, terrestrial and aquatic ecosystems, agriculture, tourism, energy production, infrastructure, health and life, migration, disasters and community and cultural values. The confidence levels for the detection of impacts are generally in the range of medium to high. The contribution of climate change to detected impacts varies depending on the affected system and on climatic and non-climatic drivers. The highest levels of confidence for the attribution of detected impacts to anthropogenic climate change are related to the cryosphere. More generally, those impacts are more strongly driven by increasing temperatures and show higher confidence for attribution than those impacts driven mainly by precipitation changes. The level of contribution of climate change to observed impacts is predominantly medium or high, indicating the high sensitivity of natural and human systems in mountains to climate change. Furthermore, the vast majority of detected impacts imply negative impacts on natural and human systems (*high confidence*).

Local knowledge plays an important role in documenting impacts of climate change in mountain regions. Since IPCC AR5, the evidence for meaningful climate change impacts being reported using local knowledge sources has increased substantially (*high confidence*). Similarly, important regional gaps present in the IPCC AR5 are addressed here (e.g., Africa), resulting in a much more comprehensive and regionally balanced assessment and perspective.

Furthermore, the science of attributing negative impacts of climate change to anthropogenic emissions or even individual polluters is becoming increasingly important for climate litigation (Marjanac et al., 2017; McCormick et al., 2017; Otto et al., 2017; Setzer and Vanhala, 2019), and there is emerging evidence that mountains are becoming sites of litigation cases, with cases, for instance, in Peru, Colombia and India (UNEP, 2017). Recent studies put litigation cases such as the Lliuya vs RWE (the German multi-national energy company) case, on the risk of glacier lake floods in Peru, in a broader context of differentiated responsibilities and justice (Huggel et al., 2020b).

CCP5.2.7.2 Synthesis of Observed Adaptation

Extending from recent assessments of observed adaptation in high mountain areas (Hock et al., 2019; McDowell et al., 2019) new evidence for the geographically larger space for mountains assessed in this CCP is available from a mountain-specific reanalysis of the GAMI data set, which contains 423 articles reporting adaptation in mountains (Berrang-Ford et al., 2021; McDowell et al., 2021b) (SMCCP5.3), some of which also include those reported in Section CCP5.2. In these articles, adaptation measures in mountains are reported from all regions worldwide, with a preponderance from Asia and Africa. Of all reported adaptations, 91% involve individuals or households, frequently engaged in smallholder agriculture and/or pastoralism; local governments are also often involved (31%), as are sub-national or local civil society actors (29%), while private-sector involvement remains scarce (below 10%). Food, fibre and other ecosystem products (76%) and poverty, livelihoods and sustainable development (55%) are by far the most often reported adaptations in mountains, followed by water and sanitation (28%) and health, well-being and communities (26%) (McDowell et al., 2021b) (SMCCP5.3.2).

Adaptation measures most commonly found include farming-related changes (e.g., resilient or drought-tolerant crop varieties, irrigation techniques, crop storage and livestock insurance schemes), infrastructure development, Indigenous knowledge, community-based capacity-building and ecosystem-based adaptation (*high confidence*) (McDowell et al., 2021b) (SMCCP5.3.2). Nature-based solutions (NbS) are an adaptation component in the nationally determined contributions (NDCs) of many mountain countries around the world (UNEP, 2021). Furthermore, Indigenous knowledge and local knowledge are often reported as informing adaptation efforts, and Indigenous Peoples, marginalised people and gender issues are recognised in several national adaptation strategies, but autonomous responses are often insufficiently understood (Mishra et al., 2019).

The GAMI-based reanalysis for mountains indicates that food security (75%), poverty (47%), consumption and production (36%), terrestrial and freshwater ecosystem services (19%) and clean water and sanitation (18%) are important aspects of vulnerability that adaptations address, with an emphasis on responses to climate-related shocks and stressors (McDowell et al., 2021b) (SMCCP5.2). The reanalysis also shows that more than 80% of adaptations in mountains are behavioural/cultural in nature, and more than 50% are ecosystem-based or technological or infrastructural.

About a third of the assessed adaptation activities are in the planning and early implementation stage, and around a fifth are in a stage of advanced implementation (McDowell et al., 2021b) (SMCCP5.3.2). Several lines of evidence converge, indicating that most observed adaptations in mountains are incremental in nature and not transformative (*high confidence*) (Mishra et al., 2019; McDowell et al., 2021b) (SMCCP5.3.2). Nevertheless, some adaptation measures such as NbS were found to have important transformative potential in mountains if different knowledge types are combined, and community engagement and ecosystem management processes are in place (Palomo et al., 2021).

Overall, and consistent with the findings in SROCC, the systematic monitoring and evaluation processes that have been implemented to track adaptation progress remain limited, and there is *limited evidence* and prevailing uncertainties on the extent to which observed adaptation efforts reduce risks (Hock et al., 2019; McDowell et al., 2021b; UNEP, 2021) (SMCCP5.3.2).

Limits to adaptation are found in a majority (>80%) of the assessed adaptation studies; around half of the studies reported soft limits, and less than a third identified both hard and soft limits to adaptation (*high confidence*) (McDowell et al., 2021b) (SMCCP5.3.2). Soft limits

Detection and attribution of observed impacts of anthropogenic climate change in mountain regions

	Africa	Asia	Australasia	Central and South America	North America	Europe	Global
Water	●●● 17 65%	●● 27 22%	●● 2 0%	●● 34 41%	●● 8 0%	●●● 19 0%	●● 107 29%
Cryosphere	●●● 8 13%	●●● 28 18%	●●●● 2 0%	●●● 35 9%	●●●● 2 0%	●●● 8 0%	●●●● 83 11%
Terrestrial Ecosystems	●● 14 29%	●●● 9 56%	●● 1 0%	●●● 17 24%	●●● 3 0%	●● 8 0%	●● 52 21%
Agriculture and livestock	●●● 57 89%	●●●● 33 100%	▨	●●● 11 91%	▨	●●● 1 0%	●●● 102 69%
Tourism	●●● 1 0%	●●● 3 33%	●● 1 0%	●●● 3 67%	●●● 5 0%	●●● 17 12%	●●● 30 17%
Migration	●●● 3 100%	▨	▨	●●● 4 100%	▨	▨	●●● 7 100%
Health and life	●● 1 100%	▨	▨	●●● 6 33%	▨	▨	●● 7 43%
Disasters	●●● 2 100%	●● 25 56%	●● 4 0%	●● 10 0%	●● 6 0%	●● 28 0%	●● 75 21%
Community change and cultural values	▨	●●●● 11 100%	▨	●●● 12 75%	▨	▨	●●● 23 87%

Figure CCP5.4 | Synthesis of detection and attribution of impacts of anthropogenic climate change on different natural and human systems in mountain regions. For each system and region assessed, the level of confidence for detection and for attribution to anthropogenic climate change is indicated. Also indicated is how strong the contribution of climate change is to the observed changes, considering climatic and non-climatic causal factors. Observed impacts were analysed in terms of negative impacts (e.g., economic or non-economic damages, losses, contribution to increasing risks for society), where the numbers refer to the percentage of references indicating negative impacts for a given impact. The percentage of local community perception indicates the percentage of all literature references for a given system and region that account for local knowledge. The number of references refers to the total number of literature references considered for an impact on a specific system and region. 'Not assessed' refers to *limited evidence* in the literature (SMCCP5.2 and Table SMCCP5.5–5.14).

are frequently related to governance, economics and social/cultural constraints and can be overcome in principle through targeted efforts to address social conditions that impede adaptation planning and action. Hard limits are more frequently described as biophysical, such as precipitous declines in water supply. Examples of adaptation limits include lack of access to credit and markets, fixed livelihoods, insufficient awareness of climate risk, poor access to technology, the erosion of existing skills and knowledge, social inequities, lack of trust and social cohesion, inequitable gender norms and perceptions of conflict or scarcity. Furthermore, land tenure insecurity, poor integration of adaptation programmes across governing scales and a lack of decision-making power among vulnerable groups, along with inadequate funding for government-implemented adaptation programmes, are reported to limit adaptation (Mishra et al., 2019; McDowell et al., 2021b) (SMCCP5.3.2). Hard limits imply that further adaptation action is unfeasible, ineffective or unacceptable, resulting in inevitable losses and damages in mountain areas (*medium evidence, medium agreement*) (Huggel et al., 2019).

Overall, adaptation in mountain regions is taking place in various ways, in different sectors, scales, levels, quality, and effectiveness (*high confidence*). Most responses are incremental, with asymmetries of power among state, institutions and individuals, costs or capital requirements of adaptation, lack of coordinated planning, resistance to institutional change, household risk aversion, and lack of access to information inhibiting more transformational responses (SMCCP5.3.2). Aside from poverty reduction, there is *limited evidence* of adaptations effectively remediating the underlying social determinants of vulnerability (e.g., gender, ethnic identity).

CCP5.3 Projected Impacts and Risks in Mountains

CCP5.3.1 Synthesis of Projected Impacts

Declines and extinctions have been projected in a range of montane plants and animal species, including rare endemic species and sub-species due to climate change (*medium evidence, high agreement*) (Li et al., 2017; Ashrafzadeh et al., 2019; Brunetti et al., 2019; Zhang et al., 2019b; Manes et al., 2021). Up to 84% of endemic mountain species are found to be at risk of extinction (Manes et al., 2021). Using a simple model, Helmer et al. (2019) predict a large-scale contraction in the next 25 years of alpine ecosystems above tropical mountain cloud forest in the Andes due to tree invasion. Topographic complexity can smoothen and delay the transition of montane forests in terms of size and composition for warming up to 3°C GWL (Albrich et al., 2020).

Hydrological changes will determine how some ecosystems change, more so than changes in temperature. For example, Dwire et al. (2018) found that changes in riparian areas, wetlands and forests were likely a result of climate change in the Blue Mountains in Oregon, USA, as a result of altered snowpack, hydrologic regimes, drought and wildfire. In the Bolivian Cordillera Real, wetland cover variations were associated with increases in extreme precipitation events and glacier melting over the 1984–2011 period but might be reversed with predicted future decreases in both total precipitation and glacier run-off (Dangles et al., 2017). About 30% of the wetland area in the Great Xing'an Mountains in northeastern China has been projected to disappear by 2050, with this value doubling by 2100 under the CGCM3-B1 scenario (Liu et al., 2011).

Climate change impacts on food, fibre and ecosystem products will be highly variable across mountain regions (*medium confidence*) (Briner et al., 2013; Rasul and Hussain, 2015; Mina et al., 2017; Palomo, 2017; Said et al., 2019; Xenarios et al., 2019) (Sections 10.4, 12.3, 13.5 and 14.4). In some regions, tree crops that are cultivated at certain elevations may reach the limit of their agroclimatic plasticity, for instance for crop types that require winter chills and where projected growing conditions are too warm (Buerkert et al., 2020). In the European Alps, agricultural production in some areas may benefit from temperature rises, as total productivity in grasslands is projected to increase (Mitter et al., 2015; Grüneis et al., 2018), whereas some areas in Asia and South America heavily dependent on glacier- and snow-fed irrigation will be at risk of food insecurity (Rasul and Molden, 2019). In a study in Eastern Pamir, Mętrak et al. (2017) found that summer droughts and water changes lead to functional transformations of the wetland ecosystems which can affect food security of the local population. Climate change affects the phenology of plants (Harish et al., 2012; Gaira et al., 2014; Maikhuri et al., 2018), secondary metabolites (Chang et al., 2016; Kumar et al., 2020) and pharmacological properties of medicinal plants (Gairola et al., 2010; Das et al., 2016).

Water resources in mountains and dependent lowlands will continue to be strongly impacted by climate change throughout the 21st century (*high confidence*). The difference in impacts will be particularly strong in regions that greatly depend on glacier and snowmelt and, in pronounced dry seasons (*high confidence*), in regions including Central Asia, South Asia, tropical and subtropical western South America and southwestern North America (Huss and Hock, 2018; Hock et al., 2019; Immerzeel et al., 2020). Glaciers are expected to continue to lose mass throughout the 21st century, with higher mass loss under high emission scenarios (AR6 WGI Chapter 9 (Fox-Kemper et al., 2021)). Many low-elevation and small glaciers around the world will lose most of their total mass at 1.5°C GWL (*high confidence*) (Marzeion et al., 2018; Vuille et al., 2018; Hock et al., 2019; Zekollari et al., 2020; Fox-Kemper et al., 2021) (WGI 9.5). For tropical and mid-latitude mountains, around half of the current ice mass can be preserved under low-emission scenarios, while between two-thirds and up to more than 90% will be lost under high emission scenarios compared to the 2000s (*medium confidence*) (Schauwecker et al., 2017; Vuille et al., 2018; Hock et al., 2019; Fox-Kemper et al., 2021) (WGI 9.5). Significant differences in impacts between the emission scenarios have also been assessed for declines in snow depth or mass at lower elevations [10 to 40% for RCP2.6 and 50 to 90% for RCP 8.5 by the end of the century (Hock et al., 2019)]. However, limitations in long-term climate, glaciological and hydrological monitoring data add uncertainty to the current understanding and adaptation support, for example, when peak water is reached in different mountain catchments (Salzmann et al., 2014; Hock et al., 2019). Furthermore, context-specific sociocultural and economic factors can magnify or moderate impacts related to hydrological change (McDowell et al., 2021a).

The dependence of lowland populations on mountain water resources will grow by mid-century across several climate and socioeconomic scenarios, and several seasonally dry or semiarid mountain regions (e.g., parts of South Asia, North America) are projected to be highly dependent on such resources (*medium confidence*) (Viviroli et al., 2020) (Figure CCP5.2). Changing sediment, nutrient and pollutant flows due to climatic and non-climatic drivers will impact populations and economic sectors (*medium evidence, high agreement*). Hydropower in all mountain regions will experience higher fluxes of water and sediment in some seasons but lower water flow with demand from other water uses (e.g., irrigation) (Chevallier et al., 2011) in other seasons (Beniston and Stoffel, 2014; Gaudard et al., 2014; Majone et al., 2016; Caruso et al., 2017a, b; Patro et al., 2018). Recharge from groundwater and its buffer function is expected to decrease in the longer term (Somers and McKenzie, 2020). Glacier and snow depth or mass decline will impact current hydropower facilities and production in various complex ways, requiring changes in hydropower management, with further potential for evidence-informed solutions (Gaudard et al., 2014; Schaefli, 2015; Schaefli et al., 2019). On the other hand, deglaciation in mountain regions opens topographic space and, thus, potential for additional long-term hydropower development and production (Haeberli et al., 2016a), with an estimated additional production of up to several hundred terawatt-hours per year, a potentially important contribution to national energy supplies, in particular in the High Mountain Asia region (Farinotti et al., 2019). However, water supply from glacier melt will decrease once source glaciers pass peak discharge (Huss and Hock, 2018), and the areas with available sediment will grow as glaciers shrink, posing potential risks to downstream populations and assets (*high confidence*) (Lane et al., 2019).

Since SROCC (Hock et al., 2019), several new studies have addressed projected impacts of future climate change on snow reliability in ski resorts, complementing previous findings or bridging existing knowledge gaps for winter tourism. This includes, in particular, new studies for China (An et al., 2019; Fang et al., 2019), showing that average ski seasons are projected to shorten (–4 to –61% for RCP4.5; –6 to –79% RCP8.5 in the 2050s) along with increases in snow-making water demand (27 to 51% for RCP4.5; 46 to 80% for RCP8.5 in the 2050s), with large differences across the country. Changes in future snow reliability are projected across Europe at the national or pan-European scale (Demiroglu et al., 2019; Steiger and Scott, 2020; Morin et al., 2021), highlighting strong contrasts at the local (across ski resort size and/or elevation range, or local social or environmental context) and continental scales. Higher-latitude and high-elevation locations generally exhibit delayed declines in snow reliability compared to lower-latitude and lower-elevation locations (*high confidence*), consistent with assessment conclusions reached in SROCC (Hock et al., 2019). In general, climate change impacts and risks to ski tourism are found to be spatially heterogeneous, within and across local and international markets, with potential for significant disruptions to related socioeconomic sectors due to a growing mismatch between ski area supply and skier demand in the coming decades (*high confidence*) (Fang et al., 2019; Hock et al., 2019; Steiger et al., 2021). These disruptions are plausible, even though a fraction of current ski resorts could technically operate in comparatively favourable locations (elevation, latitude) and operating models (business models, sociocultural assets and conditions, governance) (Steiger et al., 2020).

Severe damage and disruptions to people and infrastructure from floods are projected to increase in Northwestern South America (NWS), South Asia (SAS), Tibetan Plateau (TIB) and Central Asia (WCA) between 1.5°C and 3°C GWL, mainly driven by river floods and an increase in the number of glacial lakes with high potential for outburst (*high confidence*) (Drenkhan et al., 2019; Motschmann et al., 2020b; Furian et al., 2021; Zheng et al., 2021). For example, the formation of new lakes at the foot of steep icy peaks largely extends the hazard zones with respect to the earlier situation without lakes (Haeberli et al., 2016b). Projected changes in ice and snowmelt, as well as seasonal increases in extreme rainfall and permafrost thaw, will favour chain reactions and cascading processes, which can have devastating downstream effects well beyond the site of the original event (*high confidence*) (Cui and Jia, 2015; Beniston et al., 2018; Terzi et al., 2019; Vaidya et al., 2019; Shugar et al., 2021). The incidence of disasters is projected to increase in the future because some hazards will become more pervasive, with an increase in the exposure of people and infrastructure with future environmental and socioeconomic changes either contributing to reduce or enhance these disaster risks (*medium confidence*) (Klein et al., 2019b).

CCP5.3.2 Key Risks Across Sectors and Regions

Key risks are derived from the detection and attribution assessment (CCP5.2.7) and from the projected impacts and risks (CCP5.3.1). The assessment is informed by evidence in the regional and sectoral chapters and supports the key risk assessment in Chapter 16. Four key risks (KR1 to KR4) have been identified in this CCP and are presented in Sections CCP5.3.2.1–CCP5.3.2.4 (see SMCCP5.4 for methodology and references).

CCP5.3.2.1 KR1: People and Infrastructures at Risks from Landslides and Floods

The amount of people and infrastructure at risk of landslides will increase in regions where the frequency and intensity of rainfall events is projected to rise (Gariano and Guzzetti, 2016; Haque et al., 2019). Extreme precipitation in major mountain regions is projected to increase, leading to consequences such as floods and landslides (*medium confidence*). Rain-on-snow events, which can accelerate all flood stages and result in widespread consequence for societies, are projected to increase between 2°C and 4°C GWL (but decrease afterwards) (SROCC Chapter 2 (Hock et al., 2019), AR6 WGI Chapter 12 (Ranasinghe et al., 2021)). There is high confidence that glacial retreat, slope instabilities and heavy precipitation will affect landslides and flood activities, although for landslides there are considerable uncertainties in the direction of change (Patton et al., 2019, AR6 WGI Chapter 12 (Ranasinghe et al., 2021)).

Future risk consequences considered to be severe include, for example, an increase of 10–20% compared to present of the population exposed to landslide activities in certain regions (e.g., High Mountain Asia) (Kirschbaum et al., 2020). This does not consider the expected increase in landslide activity relating to glacier and permafrost changes (Picarelli et al., 2021, SROCC Chapter 2 (Hock et al., 2019)), so it is expected to be a conservative estimate. Other severe consequences are on average a projected twofold increase in the number of people exposed to inland flooding between 2°C and 4°C, with the highest increases in South Asia, Southeast Asia and South America (*high confidence* in the direction of change and *medium confidence* in the absolute values because they are based on global studies) (Hirabayashi et al., 2013; Allen et al., 2016; Arnell and Gosling, 2016; Zheng et al., 2021). Therefore, high to very high risks are expected between 2°C and 4°C GWL in several mountain regions (red and violet shaded bars in Figure CCP5.5). Many regions are projected to experience high risks due to the timing (potentially for severe consequences to happen sooner rather than later), the magnitude in terms of number of people and infrastructure affected and the persistence of hazard conditions (Figure CCP5.5, AR6 WGI Chapter 12 (Ranasinghe et al., 2021)). Comparatively, more severe risk consequences are expected under SSP3 and/or SSP4 given the high population projections in certain regions compared to SSP1 (*medium confidence*) (Kirschbaum et al., 2020) (Figure CCP5.1).

CCP5.3.2.2 KR2: Risks to Livelihoods and the Economy from Changing Water Resources

KR2 encompasses the relative and absolute dependence on water resources for economic activities and livelihood sustainment in mountain regions and in lowlands (Table SMCCP5.19). Particularly

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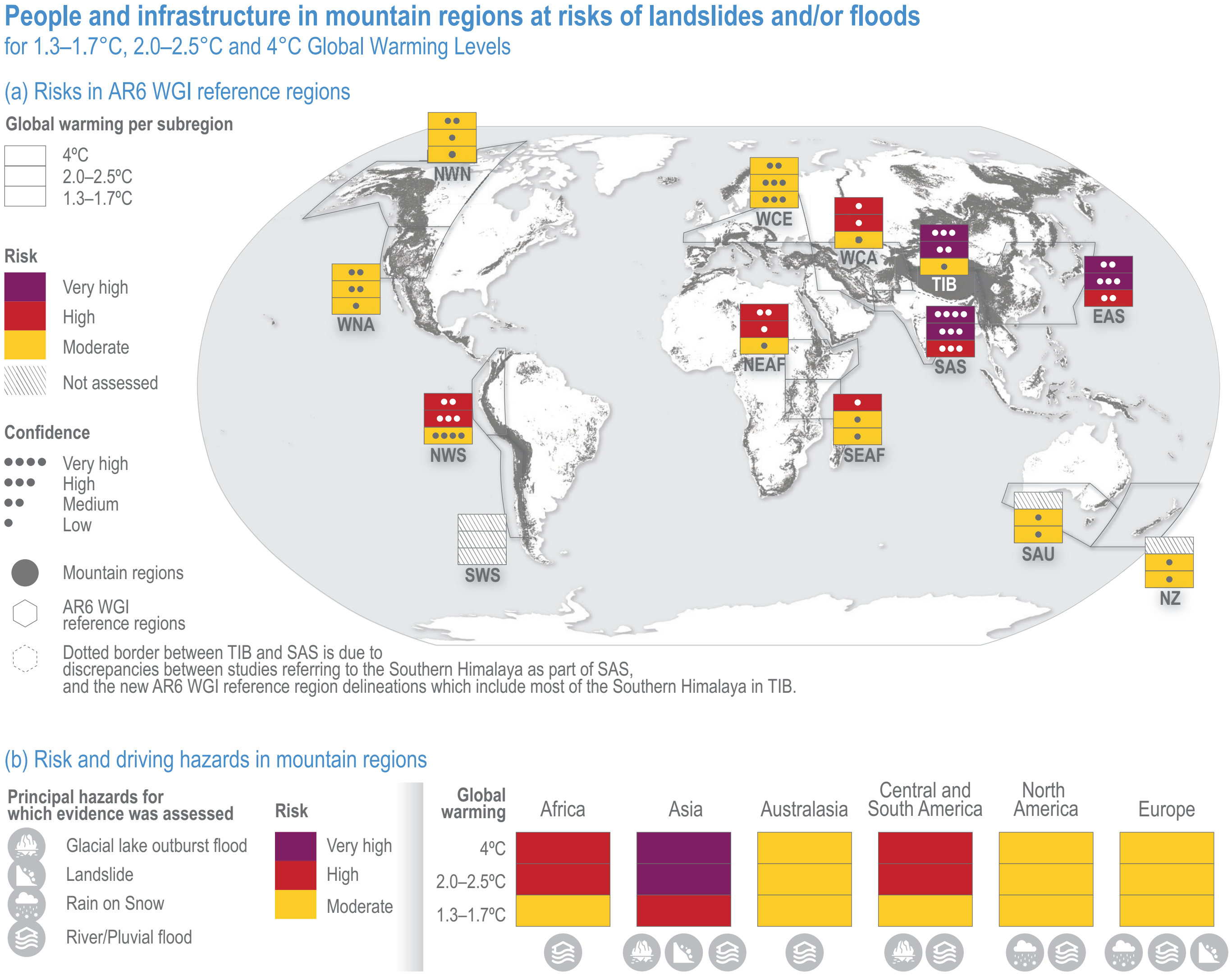

Figure CCP5.5 | People and infrastructure in mountain regions at risk of landslides and/or floods for various GWLs.

Panel a) shows the level of risk assessed per AR6 WGI reference region (AR6 WGI Atlas (Gutiérrez et al., 2021)). For some mountain regions, there is limited evidence for adequately assessing the level of risks against GWLs, so this is labelled 'not assessed'.

Panel b) shows the level of risk aggregated at the continent scale and the principal hazards for which evidence was available and assessed. Methodological details and traceability are provided in SMCCP5.4, Figure SMCCP5.1, Table SMCCP5.16 and SMCCP5.18.

affected by changes in water resources will be regions with (seasonally) high dependence on snow and glacier melt, i.e., arid and semiarid zones in the Andes, Central Asia and the Upper Indus Basin (Huss et al., 2017; Huss and Hock, 2018; Viviroli et al., 2020) (Section CCP5.3.1).

Consequences that are considered severe refer to the magnitude (number of people and economic activities affected), timing (increase of water stress as early as mid-century in several regions) and likelihood (severe risk consequences are more *likely* where high population density is projected) (*high confidence*) (Figures CCP5.1 and CCP5.6, Section 4..5.7 and 4.7) (Fuhrer et al., 2014; Wijngaard et al., 2018; Biemans et al., 2019; Immerzeel et al., 2020; Viviroli et al., 2020). Severe consequences are that by mid-century more than half of agricultural regions equipped for irrigation are projected to be dependent on mountain runoff and could therefore be unsustainably using blue water (e.g., water from river, lakes and aquifers) (Viviroli et al., 2020) or that the number of people being water stressed will increase by 50% to 100% in areas already currently water stressed (Munia et al., 2020). Hotspot regions are those with large lowland populations depending on essential mountain water resource contributions and include river catchments such as the Ganges, Brahmaputra, Meghna, Yangtze, Nile, Niger, Indus, Euphrates-Tigris or Pearl (*high confidence*) (Viviroli et al., 2020) (Figure CCP5.6). Limited governance and integrated management of water resources, power and gender inequalities and level of disruption of local community practices also contribute to making risks more severe (*medium confidence*) (Lynch, 2012; Boelens, 2014; Wijngaard et al., 2018; Scott et al., 2019; Immerzeel et al., 2020). Consequences for hydropower are comparatively less severe than for agriculture and domestic/municipal use, although this depends on region and timing (see also Section 5.2.2.2). For example, a study shows low risk to hydropower production in High Mountain Asia until the end of the century and even for warming levels beyond 3°C (*robust evidence, moderate agreement*) (Mishra et al., 2020).

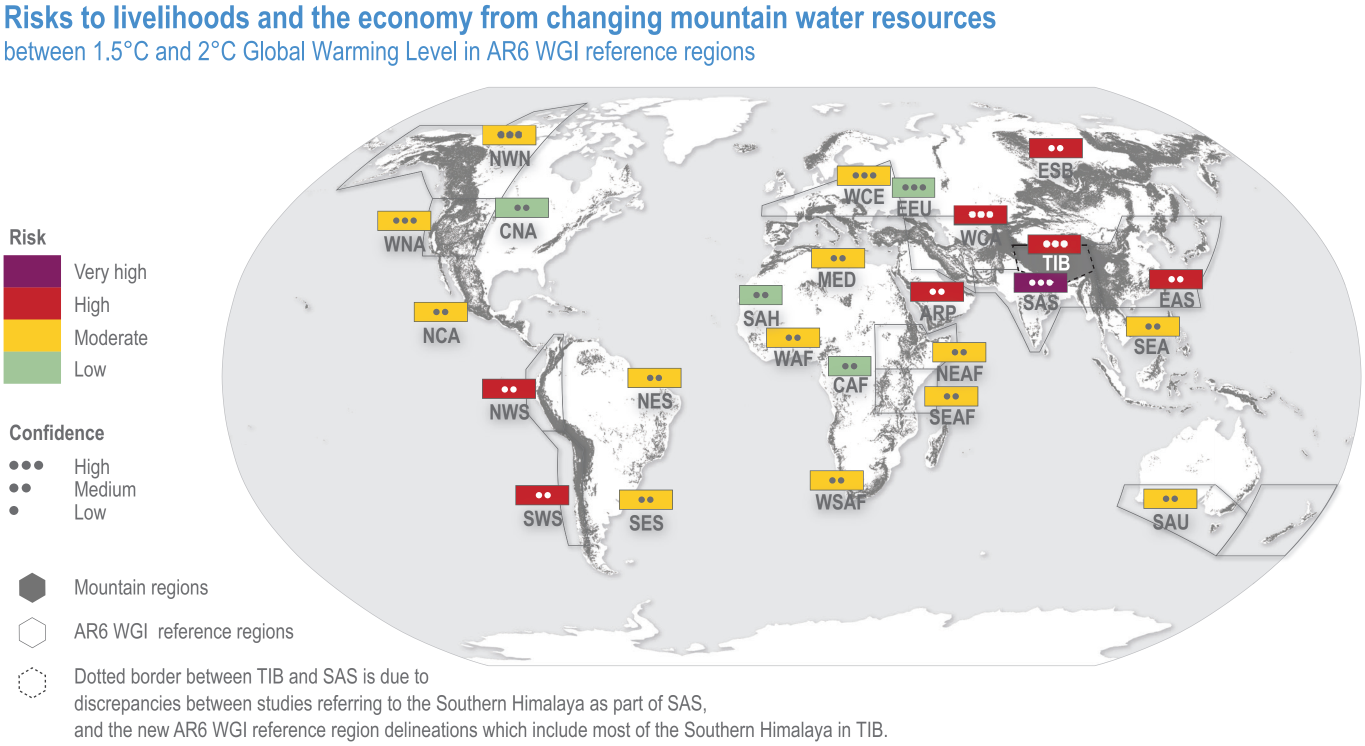

Figure CCP5.6 | Risk levels assessed per AR6 WGI reference region (AR6 WGI Atlas (Gutiérrez et al., 2021)). The majority of studies assessed focus on impacts up to mid-century (2030–2060) and for RCP-2.6, RCP-4.5 and RCP-6.0, which was converted into the corresponding warming level range 1.5°C–2.0°C GWL (Cross-Chapter Box CLIMATE in Chapter 1). Methodological details are provided in Section SMCCP5.4, Figure SMCCP5.1, Table SMCCP5.17 and SMCCP5.19. Due to the *limited evidence* available to determine risks against high GWLs and the relatively high uncertainty associated with future irrigation trends for the second half of the century (e.g., Viviroli et al., 2020), assessment of risks associated with GWLs greater than 2.0°C GWL was not conducted.

Large-scale and transformative interventions can reduce the high-end impacts of changing water resources and in particular the risks of water scarcity (Section CCP5.4.1). These interventions have long lead times, are costly and may face institutional constraints (Section 4.7), resulting in adaptation shortfalls. Therefore, high-risk to very high-risk levels cannot be excluded in regions where other key risk characteristics, such as magnitude, timing and likelihood, are assessed as high due to potential losses (e.g., in many Asian regions) (Figure CC5.6, SMCCP5.4 and Table SMCCP5.16).

CCP5.3.2.3 KR3: Risks of Ecosystem Change and Species Extinction

Risks to mountain ecosystems and the services they provide to people are varied in magnitude, timing, likelihood and potential to adapt and place specific. However, many mountain ecosystems are already showing impacts of climate change (CCP5.3.1), reflecting the strong influence climate exerts in many situations and indicating that risks are significant and immediate and will *likely* increase in the near as well as long term. There is *robust evidence* (*high agreement*) of vegetation zones and individual species shifting to higher elevations (CCP5.2.1 and Section 2.4), and projections indicate that current trends will continue and accelerate at higher rates of warming (*medium evidence, high agreement*) (Section 2.5).

Many mountain species are at risk of range contraction and ultimately extinction if dispersal at the upper range limit is slower than losses due to mortality at the lower range limit (observed for trees in the neotropics (Feeley et al., 2013; Duque et al., 2015) or if mountains are not high enough to allow species to move to higher elevations. Ramirez-Villegas et al. (2014) modelled 11,012 species of birds and vascular plants in the Andes and found large decreases by 2050 (SRES-A2 scenario); in the absence of dispersal, 10% of species could become extinct. Even assuming unlimited dispersal, most of the Andean endemics would become severely threatened. Other modelling studies have also projected declines in a range of communities and species, including rare endemics (Zomer et al., 2014a; Rashid et al., 2015; Bitencourt et al., 2016; Li et al., 2017; Rehnus et al., 2018; Ashrafzadeh et al., 2019; Zhang et al., 2019b; Cuesta et al., 2020; Hoffmann et al., 2020).

Many treelines will continue to shift to higher elevations with increasing temperatures (Chhetri and Cairns, 2018), although very few are changing as fast as the climate (Liang et al., 2016; Hansson et al., 2021) and some are not moving or even shifting to lower elevations (CCP5.2.1). If treelines fail to shift uphill, this will pose a risk for species of the upper-montane forest that experience range contraction at their lower range limit but lack a suitable habitat to expand into beyond their upper range limit (Rehm and Feeley, 2015). Changes in phenology can also pose risks to species and ecosystems (Chapter 2), including a potential desynchronisation of mutualistic relationships like pollination and increased freezing damage due to premature emergence from winter dormancy. In European broadleaf trees, for example, the upper elevational limits of different species involve a trade-off between maximising growing season length and limiting the risk of spring freeze damage (Vitasse et al., 2012; Körner and Spehn, 2016).

A wide range of mechanisms can cause changes within ecological communities, some of which are hard to predict, but an increasing number of studies illustrate some of the risks which are expected to be most common. If treelines shift upwards, this will pose a risk for alpine species, which cannot compete with trees. This may lead to the extinction of alpine species on mountains where there is insufficient room for the alpine zone to shift uphill. Shifts in species distributions, and in particular shifts in ecosystem types, can cause changes in ecosystem function, which may in turn have cascading impacts on people, for example leading to increased exposure to diseases such as malaria at high elevation (Section 2.4.2.7.2) as vector distribution changes and wider impacts on ecosystem services (Section 2.5.3) such as water supply, flood alleviation and food.

CCP5.3.2.4 KR4: Risk of Intangible Losses and the Loss of Cultural Values

The risk of intangible losses and loss of cultural values is associated with the decline of ice and snow cover and temperature increase, as well as the increase in intangible harm from hazards such as floods and droughts (*high agreement, medium evidence*) (Diemberger et al., 2015; Jurt et al., 2015; Vuille et al., 2018; Tschakert et al., 2019; Vander Naald, 2020). Losses are intangible because they characterise aspects which are difficult to quantify, i.e., loss of identity, loss of self-reliance, loss of rituals and traditions and place attachment (Allison, 2015; Baul and McDonald, 2015; Motschmann et al., 2020a; Schneiderbauer et al., 2021). A global systematic analysis of case studies shows that this risk is more prevalent in the Andes, the Himalaya and the Alps (Tschakert et al., 2019). Often mentioned across studies is the loss of intrinsic memories and culture related to changes in world heritage landscapes and iconic sites (Jurt et al., 2015; Sherry et al., 2018; Bosson et al., 2019). Changes in hazard landscapes are also reported to contribute to the loss of peace of mind and loss of well-being (Diemberger et al., 2015). Overall, there is *limited evidence but medium agreement* that the risk of intangible losses and the loss of cultural identity will rapidly increase and that consequences will go from reversible damage to irreversible losses (Tschakert et al., 2019).

CCP5.4 Options for Adaptation and Climate Resilient Development Pathways

CCP5.4.1 Synthesis of Adaptation Responses to Reducing (Key) Risks

More than half of the studies having a focus on mountains (423 articles) extracted from the GAMI data set report that adaptation responses contribute to reducing climate risks (Berrang-Ford et al., 2021; McDowell et al., 2021b) (SMCCP5.3.2). However, the extent of adaptation in terms of time (i.e., speed), scale of change (i.e., scope) and depth of change (i.e., degree to which a change is substantial) is low in mountain regions, with the level of agreement across studies varying from one region to the other (*medium confidence*) (Figure CCP5.7, SMCCP5.3.2). In regions where risk levels remain moderate, a low adaptation extent might be sufficient to constrain risks (Figures CCP5.5 and 5.6, Section 16.3.2.4).

Adaptation responses in mountains are mainly incremental changes from existing practices (*high confidence*) (McDowell et al., 2019, 2021b; Rasul et al., 2020), signalling that the potential of current and planned adaptation responses to reduce risks in the future will not be adequate to mitigate high to very high risks. For example, measures to contain floods or landslides (KR1) are designed with specific magnitudes and types in mind, often assuming stationarity of return periods (Montanari and Koutsoyiannis, 2014; Gariano and Guzzetti, 2016). In the case of events showing decreasing return periods, risk mitigation standards need to be elevated to provide for more protection in the future (Felder et al., 2018; François et al., 2019). The portfolio of adaptation options to mitigate risks from changing water resources (KR2) is large but challenging and includes integrated catchment management, implementation of multiple use of water strategies, improved water governance (including community-based and participatory water governance), overcoming power inequalities among users and sectors and balancing economic pressure and sustainable development (*high confidence*) (Bekchanov and Lamers, 2016; Yapiyev et al., 2017; Jalilov et al., 2018; Drenkhan et al., 2019; Allen et al., 2020; Aggarwal et al., 2021; Huang et al., 2021) (SMCCP5.3.2). There is *limited evidence* on the effectiveness of adaptation responses to reduce the severity of ecosystem change (KR3) (also see Section 16.3.1). Prevention rather than control and eradication efforts can contribute to curbing biological invasions of alien species in the short turn, whereas colonisation by native trees following land use abandonment can be more effective in the long run (Carboni et al., 2018). Reducing intensified grazing, agricultural expansion and conservation management in buffer zones of protected areas can limit the altitudinal range shift of endemic species (Kidane et al., 2019).

EbA has been effective in mountain regions at reducing risks from floods (e.g., restoration of buffer zones and floodplains) and landslides (e.g., protective forests) (Muccione and Daley, 2016; Klein et al., 2019b; Lavorel et al., 2019). Ecosystem-based measures have been implemented for water management purposes to supply clean water and improve water quality (Section 4.6.6). Furthermore, they provide scope for conservation and improvement of habitats, e.g., forest ecosystems (Nagel et al., 2017; Lamborn and Smith, 2019) (*high agreement, medium evidence*). However, repeated and recurrent disturbances that increase recovery times can reduce the effectiveness of EbA (*medium confidence*) (Sebald et al., 2019; Scheidl et al., 2020).

Adaptation in mountain areas is currently constrained predominantly by soft limits related to existing social, economic and political conditions (*high confidence*) (Gioli et al., 2014; Sansilvestri et al., 2016). Progress in overcoming soft limits is currently minimal due to insufficient engagement with socioeconomic and political issues in existing adaptation (*medium confidence*) (McDowell et al., 2019, 2021b) (Section 8.4.5.3, Cross-Chapter Box LOSS in Chapter 17). This is expected to lead to an expansion of residual risks as risk severity increases (McDowell et al., 2021b).

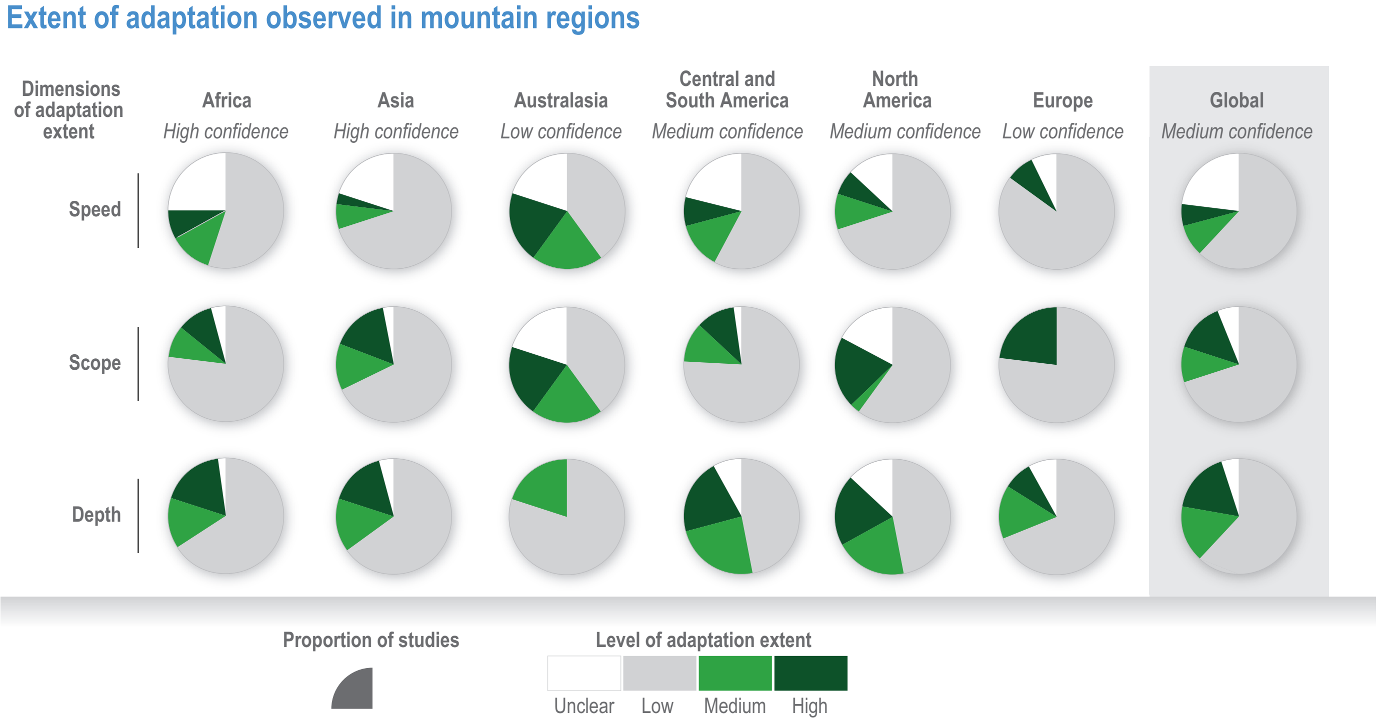

Figure CCP5.7 | Extent of planned and implemented adaptation actions observed in mountain regions shown in terms of three dimensions: i) speed (timeframe within which adaptations are implemented), ii) scope (scale of changes observed from adaptation action), and iii) its depth (i.e., degree to which a change reflects something new) (Section 16.3.2.4). The data are obtained from the Global Adaptation Mapping Initiative (GAMI) reanalysis for mountains (SMCCP5.3.2) (Berrang-Ford et al., 2021; McDowell et al., 2021b).

CCP5.4.2 Challenges, Opportunities and Solution Space for Adaptation in Mountains

The effects of climate change on mountain environments pose significant challenges for people, ecosystems and sustainable development, with issues such as difficult access, environmental sensitivity and socioeconomic marginalisation making adaptation particularly complex. Furthermore, varied and dynamic biophysical characteristics as well as high sociocultural diversity preclude one-size-fits-all responses; adaptation planning and action in mountains rooted in context-specific socioecological and climatic realities are more effective (*high confidence*) (Hock et al., 2019; Lavorel et al., 2019; McDowell et al., 2020). Despite these challenges, there is growing evidence of opportunities for advancing effective responses to climate risks in mountain areas (McDowell et al., 2020) (Section 16.3; Cross-Chapter Box NATURAL in Chapter 2).

The solution space for adaptation represents a realm of possibility for addressing climate risks; it is shaped by both socioeconomic and climatic factors that influence who adapts, when they adapt and how they adapt to climate change (Haasnoot et al., 2020) (Sections 1.5.1 and 17.4). The space includes both planned and autonomous responses (Hock et al., 2019; McDowell et al., 2019). Autonomous responses can be appropriate when local resilience is high (Mishra et al., 2019; Ford et al., 2020); however, many mountain communities continue to face socioeconomic challenges that constrain their adaptive capacity (*high confidence*). Planned adaptations are a critical component of the solution space, although external interventions can also reinforce, redistribute or create new vulnerabilities when they proceed without sincere engagement with local communities (Eriksen et al., 2021). The solution space also evolves as social and climatic conditions change and can be capped by social and biophysical limits to adaptation that render further responses to climate change inaccessible, unfeasible or ineffectual. Such limits are already observed and are *likely* to become more widespread as climatic stressors move beyond historical experience (*high confidence*) (IPCC, 2018; Hock et al., 2019; McDowell et al., 2020) (Section 17.3; Cross-Chapter Box DEEP in Chapter 17).

Evidence shows the significant potential of adaptation actions such as NbS or multiple uses of water approaches but with a need to carefully evaluate environmental, economic and social co-benefits and trade-offs (*high agreement, medium confidence*) (Yang et al., 2016; Drenkhan et al., 2019; Lavorel et al., 2019; McDowell et al., 2019; Palomo et al., 2021). The potential for adaptation to contribute to sustainable development and transformative change in mountains is also becoming increasingly evident (*medium confidence*) (Palomo et al., 2021), yet there is currently *limited evidence* with respect to the long-term effectiveness of adaptations in achieving such outcomes (Balsiger et al., 2020). To better achieve the adaptation potential in mountains, adaptation finance and private-sector inclusion and contribution are key enablers (*high confidence*) (Mishra et al., 2019; UNEP, 2021).

There is increasing recognition that inclusive and comprehensive adaptation approaches can be more successful (*medium evidence, high agreement*) (Allen et al., 2018; Hock et al., 2019; Huggel et al., 2020a, b).

Stakeholders such as local communities and government entities often prioritise different dimensions of climate-related risks (López et al., 2017; McDowell et al., 2020). Adaptation initiatives that identify locally relevant climate stressors and risks through knowledge co-production have the potential to be more acceptable and effective (*medium evidence, high agreement*) (Huggel et al., 2015; Muccione et al., 2016; Allen et al., 2018; Quincey et al., 2018; Balsiger et al., 2020; McDowell et al., 2020, 2021b) (Cross-Chapter Box DEEP in Chapter 17). However, tenable co-production requires recognition of the validity and integrity of diverse knowledges systems, including those held by Indigenous Peoples and local communities, as well as the provision of sufficient time and resources for meaningful engagement between stakeholder groups (Howarth and Monasterolo, 2016; Bremer and Meisch, 2017; Schoolmeester and Verbist, 2018; McDowell et al., 2019; Ford et al., 2020). Power imbalances and knowledge politics continue to impede the inclusion of historically underrepresented voices in adaptation planning and action (Ojha et al., 2016; Mills-Novoa et al., 2017). Citizen science plays an additional role in facilitating the inclusion of multiple knowledge traditions (Buytaert et al., 2014; Dickerson-Lange et al., 2016; Tellman et al., 2016; Njue et al., 2019).

Progress in addressing climate risks requires targeting the root causes of vulnerability, which are often socioeconomic in origin and can include poverty, marginalisation and inequitable gender dynamics (*high confidence*) (Ribot, 2014; Carey et al., 2017; Shukla et al., 2018; McDowell et al., 2019). Promoting resilience in many mountain regions requires responses that address the social determinants of susceptibility to harm. Context-specific manifestations of such determinants (and leverage points for positive action) can be identified through participatory processes with affected populations, with action on social determinants of climate change vulnerability having important co-benefits for equity, justice and sustainability. Addressing the root causes of vulnerability can also resolve soft limits to adaptation, thereby increasing the solution space (McDowell et al., 2020).

There is growing evidence of the potential for coordination and monitoring networks to overcome existing data deficiencies, to fill knowledge gaps and to streamline implementation, all of which currently impede adaptation in mountains (Salzmann et al., 2014; Muccione et al., 2016; Ryan and Bustos, 2019; McDowell et al., 2020; Shahgedanova et al., 2021; Thornton et al., 2021; Price et al., Accepted/In press). Furthermore, there is increasing evidence that key conventions related to mountains, such as the Alpine Climate Board (SROCC section 2.4 (Hock et al., 2019)), provide opportunities for accelerating adaptation efforts through mainstreaming responses into other policies aimed at addressing climate-related risks (*medium confidence*) (Balsiger et al., 2020). Regional cooperation among countries and transboundary landscape and river basin governance initiatives are an important mechanism for advancing adaptation in mountains (*high agreement, medium evidence*) (Molden et al., 2017; Mishra et al., 2019; Balsiger et al., 2020), particularly as many mountain ranges and mountain ecosystem services are transboundary in nature.

Access to major adaptation support programmes such as through the UN Framework Convention on Climate Change (UNFCCC), national governments, multi- and bi-lateral aid arrangements, the private sector and non-governmental organisations (NGOs) has been relatively limited to support adaptation action in mountain regions, indicating significant unutilised support options for increasing the solution space in mountains (McDowell et al., 2020). Enhanced uptake of available support and funding could help to ease the adaptation burden for mountain communities. This will require addressing soft limits to adaptation, which currently constrain the ability of actors to identify, access and mobilise resources for planned adaptations (McDowell et al., 2020).

More inclusive adaptation approaches, engagement with the root causes of vulnerability, improved coordination and monitoring activities and upscaling of support for adaptation are key enablers and are indicative of a substantial solution space for adaptation in mountain regions (*high confidence*). However, trajectories of climate change and the prospect of hard limits to adaptation, which are often biophysical in origin, portend climate futures that could overwhelm adaptation efforts. Success therefore hinges on increasing the quality and quantity of adaptation efforts, including through transformative action, as well as enhanced mitigation efforts, consistent with the recommendations of IPCC SR 1.5C (IPCC, 2018) (Cross-Chapter Box PROGRESS in Chapter 17).

CCP5.4.3 Climate-Resilient and Sustainable Development in Mountains

With accelerating warming and compounding risks increasing above 1.5°C warming, the need for climate resilient development in mountains is evident and intricately linked to achieving the SDGs and equity (*high confidence*). In this context, Chapter 18 draws attention to climate resilient development pathways (CRDPs) as processes that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation and mitigation. Pathways that strengthen climate-resilient sustainable mountain development are starting to receive attention (Chelleri et al., 2016; Trabacchi and Stadelmann, 2016; AlpineConvention, 2021). This section treats four domains of emerging evidence related to climate resilient development in mountains: 1) climate actions that support both adaptation and mitigation, 2) Indigenous knowledge and local knowledge in support of climate resilient development, 3) climate resilient development in climate policy and planning and 4) mainstreaming of climate action into development pathways.

NbS can be pursued in mountains that will mitigate climate change and its impacts while at the same time contributing to improving livelihoods, social and economic well-being and sustainable environmental management (*high confidence*). A global review of 93 NbS in mountains, such as afforestation, protection of existing forests, agroforestry and climate-smart agriculture, confirm the potential of NbS for change towards sustainable trajectories (Palomo et al., 2021). Agroforestry is widely cited for delivering on food security as well as increasing resilience and mitigating climate change (Mbow et al., 2014; Amadu et al., 2020; Gidey et al., 2020). Also, the prudent use of biomass for wood-based bioenergy in mountains can mitigate the impacts of climate change, reduce vulnerability to disturbance events such as fires and enhance rural socioeconomic development (Beeton and Galvin, 2017). Yet there can be trade-offs contingent upon place-based and context-specific social and environmental factors, such as between the use of bio-energy, agricultural production and conservation concerns (Beeton and Galvin, 2017). Evidence from the world's mountains highlights the importance of cross-scale partnerships and interdisciplinary, bottom-up approaches that facilitate stakeholders in envisioning locally tailored, climate-resilient and sustainable development pathways (Chelleri et al., 2016; Capitani et al., 2019; Klein et al., 2019b; Pandey et al., 2021).

Mountains are the home of many cultures and diverse Indigenous knowledge and local knowledge (systems), which can and do provide strong support for place-based integrated adaptation and mitigation strategies (Merino et al., 2019). Indigenous knowledge and local knowledge reinforce community adaptive capacity, yet governance structures and processes, including the deliberate design and implementation of climate policy, can constrain that capacity from being realised (*high confidence*) (Hill, 2013; McDowell et al., 2014; Wyborn et al., 2015; Klepp and Chavez-Rodriguez, 2018; Lavorel et al., 2019). Communities, particularly poor and remote mountain communities, are vulnerable to climate change, and there is a need for capacity-building in research, policy development and implementation to pursue climate resilient development (Manton and Stevenson, 2014). Climatic stressors and socioeconomic changes are changing traditional genderscapes in mountain communities (Goodrich et al., 2019). There is increasing evidence on the roles that gendered diversity in knowledge, institutions and everyday practices can play in addressing barriers and creating opportunities for achieving resilience, adaptive capacity and sustainability in societies (Gioli et al., 2014; Ravera et al., 2016; Su et al., 2017; Udas et al., 2018; Goodrich et al., 2019; Sujakhu et al., 2019).

Concerning climate policy and planning for climate resilient development in mountains, a review of mountain-specific priorities in the National Adaptation Programmes of Action (NAPA) submitted to the UNFCCC shows that countries have prioritised improving agricultural outputs by introducing climate-smart crops and upgrading and building climate-resilient irrigation infrastructure (UNFCCC, 2020c). Countries that have submitted their NAPAs to the UNFCCC have prioritised improving ecosystem resilience through conserving agro-biodiversity in mountains. Countries have also focused on achieving food security in mountain regions and laying foundations for food availability, stability, access and safety amid increasing climate risks (UNFCCC, 2020a).

In the NDCs where mountain regions are specifically mentioned, countries have prioritised climate-resilient solutions, including developing a low-carbon green economy through implementing low-carbon transport systems and encouraging sustainable waste management practices, as well as developing infrastructure for climate-resilient agriculture, the sustainable management of forests and the biodiversity conservation. Several countries have specifically pledged to build climate-resilient mountain infrastructure taking into account future climate uncertainties. Countries have also identified the need for capacity-building of national stakeholders and have pledged to provide relevant climate information (UNFCCC, 2020b).

Similar pledges have been announced in formal institutional arrangements such as the Alpine Convention and the Carpathian Convention. The Alpine Convention's climate action plan prioritises reaching a climate-neutral and climate-resilient Alps by 2050. For this, implementation pathways for specific sectors have been identified ensuring coherence with global and regional goals such as the Paris agreement, SDGs, EU and climate legislation (AlpineConvention, 2021). Likewise, the Carpathian Convention's working group on climate change has presented a long-term vision towards combating climate change through amending the article of the convention to focus specifically on climate change adaptation and mitigation (Carpathian Convention, 2020).

Sustainable and climate-resilient mountain development is predicated on effective and timely climate action building on cross-scalar partnerships among researchers, stakeholders and decision makers to jointly identify desired futures and pathways and assess trade-offs and synergies between climate action and the SDGs (*high agreement, medium evidence*) (Klein et al., 2019a; Pandey et al., 2021). Understanding of the complexity of mountain ecosystems as well as path dependency from earlier and current decisions is of critical importance for the sustainable future of mountain regions (Satyal et al., 2017; Chanapathi and Thatikonda, 2020; Berkey et al., 2021). Framing pathways through questions such as for whom or for what is climate action positive and which trade-off should be accepted, and why can serve as a tool for addressing sustainable development goals while avoiding lock-ins or unsustainable path dependencies (Chelleri et al., 2016). Increasingly, climate action is mainstreamed into sustainable development, which signifies a shift from climate policy as an end point to a continuing process for managing change and facilitating long-term sustainable development. The Ethiopian government's climate-resilient green economy (CRGE) strategy is an example of such a shift (Simane and Bird, 2017) as are emerging initiatives to build back greener in response to COVID-19 impacts (Schipper et al., 2020).

CCP5.5 Key Assessment Limitations and Relevant Knowledge Gaps

The assessment presented in this CCP has several limitations, principally in terms of the amount of often fragmented and biased geographic coverage or lack of relevant thematic scope covered in the literature published since AR5 and SROCC. Key assessment limitations and relevant knowledge gaps identified in this CCP fall within the following broad categories: 1) detection and attribution of observed impacts to climate change, 2) limitations and uncertainties associated with predictive models of projected impacts and risks, 3) integrated and systems-oriented research on mountain ecosystem services and their limits under climate change and 4) measurable tracking of adaptation action implemented in mountain regions and their suitability for addressing climate risks. These are summarised in Table CCP5.3. While these limitations and assessment-relevant gaps in knowledge offer important caveats for the interpretation of this assessment; they also highlight prospects to address and improve the evidence basis in future assessments.

Table CCP5.3 | Summary of key assessment-relevant knowledge gaps and limitations identified in CCP5.

Key assessment-relevant knowledge gaps and limitations		Relevant WGII report sections
Detection and attribution of observed impacts to climate change		
Limited amount and scope of literature available on impacts for assessment of detection and attribution to climate change	– While there is *high confidence* on the links between future impacts and risks associated with climate change, there is *medium evidence* available on robust detection and attribution of past changes in mountain regions. – Considerable assessment gaps exist given the limited scope (temporal, spatial or thematic coverage) and number of published studies reporting data and information that capture how mountain social-ecological systems function and their trends over recent decades, which may be applicable for the detection and attribution of changes to climatic change. – Additionally, there are limitations in current methodologies in terms of including and accounting for other knowledge traditions with respect to the detection and attribution of impacts to climate change in mountain regions (e.g., Chakraborty and Sherpa, 2021).	CCP5.2.7, Figure CCP5.4, SMCCP5.2
Consequences of shifting treelines and their interactions with other ecosystem functions	– The net effects of ongoing climate change with treeline advance and vegetation change on ecosystem carbon exchange, or possible effects on mountain hydrology, remain unresolved in the literature. – Uncertainties remain regarding the effects of ecosystem-level carbon storage, given that above-ground biomass is higher in forests than in alpine vegetation and (new) trees may change soil carbon fluxes, for instance by introducing new soil organisms, thereby increasing soil carbon flux (e.g., Tonjer et al., 2021). – The short- and long-term effects of combined warming and changed species cover on mountain soils are complex and insufficiently quantified (Hagedorn et al., 2019).	CCP5.2.1, CCP1-Biodiversity Hotspots
Limitations and uncertainties associated with predictive models of projected impacts and risks		
SSPs	– There are relevant knowledge gaps in the understanding of future vulnerabilities in mountain social-ecological systems in relation to highly variable and dynamic trends in projected demographic change, socioeconomic development pathways and demand for resources.	CCP5.3.1; SMCCP5.1
Species distribution models (SDM)	– SDMs, which rely on statistical correlations between occurrence records and environmental variables to make spatially explicit predictions, are commonly used to project climate change impacts on mountain ecosystems (Guisan et al., 2017). – However, they are associated with some limitations that can limit their utility in deriving reliable predictions of future mountain vegetation distributions and, thus, ability to provide a sound basis for mountain nature conservation and climate change adaptation. – In particular, they only indicate the potential future species distributions based on static relationships between species and predictors in calibration data; in reality, vegetation dynamics will be heavily modulated by phenomena that are commonly overlooked by such models as changing species interactions and competition due to variance in response rates among different species, dispersal limitations and demographic processes (Scherrer et al., 2020). – In addition, SDMs are often limited by data availability and therefore tend to omit several environmental factors known to be important for plants, such as soil formation processes, disturbances (e.g., rockfalls, avalanches) and microclimatic conditions (Scherrer et al., 2011; Enright, 2014; Mod et al., 2015; Bråthen et al., 2018). – More complex dynamic and process-based models are available but still rarely represent all potentially influential vegetation co-variates; applying both model types in conjunction holds potential (Horvath et al., 2021).	CCP5.2.1
Quantifiable estimates of monetary costs and potential material losses	– There is *limited evidence* on climate-related risks to economic sectors that are vital for mountain regions, specifically on quantifiable estimates of monetary costs and potential material losses for economic sectors and communities in mountains, adjacent lowlands and other regions dependent on these economic activities.	CCP5.3.1
Other model limitations	– Ecological models that could allow for better forecasts of the effectiveness of EbA as NbS, under different climate scenarios, have not been fully developed (Seddon et al., 2020).	CCP5.4
Integrated and systems-oriented research on mountain ecosystem services and their limits under climate change		
Water	– Few assessment-relevant integrative studies are available in the published literature that address relevant aspects of water security, beyond water availability from glacier-fed meltwater, or snow, groundwater and other water stores (e.g., wetlands and sediments). Likewise, few studies address seasonality with respect to a more systems-oriented approach to supply (e.g., water availability) and demand (irrigated agriculture and other multiple uses and user groups).	CCP5.2.2 Chapter 4
Measurable tracking of adaptation action implemented in mountain regions and their suitability for addressing climate risks		
Conditions under which adaptation interventions work against stated goals	– Few studies report on how adaptation measures and programmes function in mountain contexts that yield the outcomes reported (McDowell et al., 2020). – Despite transformative processes, to date there is *limited evidence* of how knowledge co-production activities support the planning and implementation of successful adaptations in mountain areas.	CCP5.4.2
Metrics and heuristics for tracking effectiveness	– Adaptation responses to intangible losses and loss of cultural values are reported and take different forms, as demonstrated in studies from various world regions (de la Riva et al., 2013; Wang and Qin, 2015; Vander Naald, 2020). However, there is *limited evidence* on their adequacy for addressing increasing losses, which remains largely unexplored in the available literature.	CCP5.3.2.4; Section 4.4.3.3

Key assessment-relevant knowledge gaps and limitations		Relevant WGII report sections
Methods and frameworks for monitoring and evaluation	– Regarding adaptation efforts and effectiveness, there are considerable gaps in adequate monitoring and appropriate evaluation of successful implementation of diverse adaptation measures. – Across mountain areas, integrated monitoring of key environmental and socioeconomic variables, including international efforts towards the acquisition and sharing of data, offers prospects for supporting the tracking of impacts and adaptation responses, including community-based monitoring initiatives (Shahgedanova et al., 2021; Thornton et al., 2021).	Section 17.5; CCP5.4.2
Feasibility and suitability of adaptation options for managing climate risks	– The feasibility of adaptation options for managing risks, for example those that could facilitate systems transitions with respect to energy, remains largely unexplored in the literature, with *limited evidence* on how projected climate change could impact prospects to develop wind, solar or biomass energy production and use in mountain contexts. – Given assessments on observed adaptation (Section CCP5.2) and adaptation responses (Section CCP5.4), few studies report a 'systems approach' to the study and evaluation of adaptations that combine all relevant aspects of the risk framework (i.e., hazards, exposure and vulnerabilities), including how synergies and trade-offs are considered in context for managing risks. – There is *limited evidence* on the feasibility and long-term effectiveness of adaptation measures to address climate-related impacts and related losses and damages in cities and settlements experiencing changing demographics.	CCP5.2.2.2; CCP5.4.2; CCP5.4.3

Frequently Asked Questions

FAQ CCP5.1 | How is freshwater from mountain regions affected by climate change, and what are the consequences for people and ecosystems?

Sources of freshwater from mountains, such as rainfall, snow and glacier melt, and groundwater are strongly affected by climate change, leading to important changes in water supply in terms of quantity and, partly, quality and timing (e.g., shifts and changes in seasonality). In many cases, the effects on ecosystems and people are negative, e.g., creating or exacerbating ecosystem degradation, water scarcity or competition or conflict over water.

River flow is a main source of freshwater both in mountain regions and downstream areas. Various sources contribute to it, including rainfall, snow and glacier melt and groundwater. Climate change affects these different sources in different ways. Climate change affects rainfall patterns, such as long-term increase or decrease, seasonal shifts or changes in rainfall intensity. Rising temperatures strongly influence snowmelt- and glacier-melt-generated river discharge; the snowmelt season starts earlier, less snow mass is available for melt, and snowmelt contribution to river flow thus decreases over the year. Whether rising temperatures produce meltwater from glaciers depends on the state and characteristics of the glaciers and the catchment basin. The concept of 'peak water' implies that, first, as glaciers shrink in response to a warmer climate, more meltwater is released until a turning point (peak water), after which glaciers melt, and so its contribution to river flow decreases. In many mountain regions worldwide, glaciers and their basins have already passed peak water, and the runoff contribution of glaciers is on the decline. Glacier shrinkage not only influences river discharge but also water quality. In the Andes of Peru, for instance, it has been observed that retreating glaciers expose bedrock, resulting in more acid water because of minerals that dissolve from the rock. Mountain ecosystems are also affected by changing freshwater availability. For instance, high-elevation wetlands in the tropical Andes critically depend on glacier meltwater during the dry season, and the disappearance of this freshwater source results in ecosystem degradation.

The effect of climate change on groundwater in mountains is insufficiently understood. Infiltrating water from glaciers and snowmelt plays an important role in groundwater recharge. Groundwater recharge is expected to decrease with continued climate change in several mountain regions. In the Himalaya many springs have already been observed to be in decline.

The availability of freshwater is a function of water supply and water demand, with the latter being determined by sectors such as agriculture, energy, industry or domestic use, as well as by competition among these sectors. Formal and informal water extraction and use prevail, and competition includes issues of inequality, power relations and asymmetry. Consequently, the effects of climate change on water resources, people and ecosystems are strongly modulated and often exacerbated by socioeconomic development and related water resource management. For example, the increasing frequency and intensity of droughts in the European Alps, combined with declines and seasonal shifts of river runoff from snowmelt and glacier melt, are expected to result in growing competition among different sectors, such as hydropower, agriculture and tourism. Similar developments are projected or have already been observed in many other mountain regions. This situation calls for strengthening and improving negotiation formats for water management that are transparent, equitable and socially and environmentally just. Management of water demand and strategies that entail multiple uses of water will become increasingly important in this context.

Frequently Asked Questions

FAQ CCP5.2 | Do people in mountain regions, and further downstream, face more severe risks to water-related disasters due to climate change, and how are they coping?

Mountain regions have always been affected by either too much or too little water. Because of climate change, hazards are changing rapidly and becoming even more unpredictable. Whether or not these changes will result in more disasters locally and further downstream depends on several factors, not least the fact that more people are settling in exposed locations. People in mountains have a history of developing skills to live in a dangerous and dynamic environment, which will be invaluable in the future when combined with inclusive and long-term disaster risk reduction measures.

Water-related hazards in mountains include rainfall (pluvial) and river (fluvial) floods, extreme rainfall-induced landslides, debris flows, ice and snow avalanches and droughts. When people are exposed and vulnerable to these hazards, disasters can result. Floods and landslides in mountains contribute to and count among the most devastating disasters globally, often resulting in significant losses such as high numbers of fatalities and economic and property damage. Climate change may alter rainfall frequency/intensity distributions, potentially leading to floods and droughts. Climate change may also lead to shifts in precipitation type, with more precipitation falling as rain rather than snow in the future, which will further impact both short- and long-term water storage and, therefore, will impact downstream ecosystems and cities.

Although climate change directly affects water-related hazards, studies indicate that above and beyond natural hazards, disaster risk and disasters are influenced to a major extent by vulnerability and exposure. This is of relevance in mountains, where disaster risk is influenced by population growth, induced displacements, land use changes and inefficient water distribution systems. For example, current trends suggest that more people are settling in exposed locations, with more infrastructure being built and activities such as tourism and recreation being promoted, exacerbating this exposure.

Experiences in dealing with water-related disasters provide a basis on which to build adequate responses to increasing risks in the future. For example, upgrading infrastructure like dams and embankments can help address water shortages, but diversification of income-generating activities, such as subsistence farming moving away from certain drought-sensitive crops, can also help.

The risk perceptions of people also shape their behaviours in coping with disaster risks. For example, based on their longstanding observations and local knowledge, communities in the southern part of the Peruvian Andes identified the shrinking of glaciers, more frequent and intense extreme weather events, more extreme temperatures and shortened rainy seasons as key challenges. The recognition of local knowledge is key to addressing these challenges, as well as providing a basis for the transformation of current systems. A lack of community involvement and participation in decision making on how to address disaster risk can contribute to mismatches between perceptions and behaviours in face of those risks, and the actions needed to reduce losses. Therefore, measures which are flexible, address the objectives and needs of all those affected by disasters and bring long-term benefits have more chances of being successful in dealing with future disaster risks.

Frequently Asked Questions

FAQ CCP5.3 | Does climate change pose a risk to mountain species and ecosystems, and will this affect people?

Treeline position, bioclimatic zones and species ranges move up in elevation as the climate warms, increasing the risk of extinction for species isolated on mountain tops as a result of exceeding their physiological limits, loss of habitat or competition from colonising species. Additionally, climate change may alter the quality and quantity of food and natural products on which the livelihood of many mountain communities depends.

Mountain regions cover about a quarter of the Earth's land surface, are scattered around the globe and may support a wide range of climates within short horizontal distances. Mountains have experienced above-average warming, and this trend is expected to continue. Mountains provide a variety of goods for people, are home to many Indigenous Peoples and are attractive for tourism and recreational activities. Mountain regions support many different ecosystems, and some are very species rich. Mountain regions can be vast and diverse, and climate change and its impacts on ecosystems vary greatly from location to location.

With increasing average global temperatures, the climatic conditions under which plants and animals can thrive are shifting to higher elevations. The movement of some plant taxa towards mountain tops has been observed in recent decades. However, for species restricted to the highest elevations, there is nowhere to move to, meaning they are increasingly at risk of extinction. Climatic conditions may exceed the physiological limits for species and habitats may become unsuitable for others. There is also a risk from competition with colonising native species and invading non-native species, spreading to higher elevations, and some species cannot move quickly enough to keep pace with changes in the climate. The most vulnerable species are those that reproduce and disperse slowly and those that are isolated on mountain tops, including endemic species, which may face global extinction. In other cases, species will be lost from some parts of their current range. Mountains can, however, allow other species to survive in areas where they otherwise would not because of small-scale variations in climate with elevation or different aspects of slopes.

Changes in snow cover and snow duration are related to changes in temperature and precipitation and are also critical for plants and animals. In particular, glacier retreat and changing snow patterns affect both streamflow dynamics (including extremes) and soil moisture conditions and can cause moisture shortages during the growing season. A change in snow patterns can critically affect animal movements in mountains. Other processes creating stresses on mountain ecosystems are direct human impacts, such as the influence of grazing, tourism, air pollution and nitrogen deposition on alpine vegetation. In some cases, these impacts can be so large on the goods and services provided by alpine ecosystems that they can overshadow the effects of climate change or exacerbate its effects.

In many mountain regions, multiple sources of evidence point to tree expansions into treeless areas above (and in some cases below) the forest belt. This may increase forest productivity at the upper treeline. Treelines have moved up in the last 30–100 years in many mountain regions, including, for example, the Andes, Urals and Altai. At the same time, since the 1990s, treeline responses in different parts of the Himalaya have been highly variable, in some places advancing upslope, in others demonstrating little change and in yet others moving downwards. This can be explained by site-specific complex interactions of the positive effects of warming on tree growth, drought stress, change in snow precipitation, land use change, especially grazing, and other factors. Treelines are affected by land use and management around the globe, and changing land use practices can supersede climate change effects in some mountain regions. An upward shift in the elevation of bioclimatic zones, decreases in the area of the highest elevation zones and an expansion of the lower zones can be expected by mid-century, for example in regions such as the Himalaya.

In some regions, the livelihoods of many local mountain communities depend on access to firewood, pastures, edible plants and mushrooms, and medicinal and aromatic plants. Climate change can alter the quality and quantity of these ecosystem services; however, the degree and direction of change are context specific. The appeal and feasibility of mountains for tourism and recreational activities are also affected by climate change.

Frequently Asked Questions

FAQ CCP5.4 | What types of adaptation options are feasible to address the impacts of climate change in mountain regions under different levels of warming, and what are their limits?

The feasibility of adaptation to address risks in mountain regions is influenced by numerous factors, many of which are unique to mountain people and their environment. Adaptation efforts in mountains mainly consist of small, largely autonomous steps. Robust and flexible adaptation measures have a better chance of addressing risks, but eventually large systemic transformation will be needed in the face of higher levels of warming. Empirical evidence on what works and what does not is largely absent but urgently needed.

The term feasibility refers to climate goals and adaptation options that are possible and desirable. Feasibility is influenced by factors such as economic viability, availability of technical resources, institutional support, social capital, ecological and adaptive capacity and biophysical conditions. Establishing the feasibility of options under changing climatic and socioeconomic conditions is not an easy task, mostly because even present feasibility is difficult to assess in mountains due to a lack of systematic information on opportunities and challenges of adaptation in practice.

Underlying environmental conditions, such as limited space, shallow soils, exposure to numerous hazards, climate-sensitive ecosystems and isolation, make it particularly difficult to implement adaptation at scales relevant for implementation. Common adaptation options are often implemented at the individual, household or community level. These options are incremental and have generated observable results and outcomes. Adaptation actions that involve partial changes that do not dramatically alter established practices and behaviours seem to have better chances of being implemented than systemic or structural changes. Formal or planned adaptation efforts that are more institutionally driven constitute only a small proportion of observed adaptation in mountain regions. Where adaptation options are implemented, they often target not only climate change but an array of other issues, priorities and pressures experienced by and in those communities (e.g., livelihood diversification in farming practices).

Whether or not adaptation options are feasible says little about their effectiveness, i.e., the degree to which adaptation has been or will be successful in reducing the risks of negative impacts. Adaptation is difficult to disentangle from other factors that contribute to both increasing and decreasing risks. Since adaptation in mountains is often autonomous and unplanned, measuring its effectiveness is complex and missed by more conventional, formal or structured monitoring and evaluation frameworks.

Evidence suggests that promising measures undertaken in mountains are those that are robust under uncertain futures, allow for adaptive planning and management and respond to multiple interests and purposes. For example, multi-purpose water reservoirs can alleviate multiple stressors and address several risks, such as those from natural hazards and water shortages. Capacity-building and awareness-raising can go a long way towards ensuring that these measures are also socially acceptable if combined with more structural and systemic changes. Indeed, transformations happen slowly in mountains and it is unlikely that small steps and incremental measures will be able to cope with more severe and pervasive risks.

Overall, empirical evidence on the effectiveness of adaptations at reducing risk is largely lacking but is urgently needed to better understand what works and what does not under certain circumstances.

Frequently Asked Questions

FAQ CCP5.5 | Why are regional cooperation and transboundary governance needed for sustainable mountain development?

Regional cooperation and transboundary governance are key to managing our vast mountain resources because they do not necessarily share political boundaries. Mountain countries need to come together, share data and information, form joint management committees, jointly develop policies and take decisions that benefit all countries equitably. A lack of cooperation may lead to missed opportunities to address climate risks and adequately manage mountain resources, which could cause social unrest and spark conflict within and between countries.

Mountains are climate change hotspots that are highly susceptible to climate change. Due to rapidly changing climatic conditions, climate change is one of the major issues that would benefit from regional cooperation. The transboundary management of mountains means shared legal and institutional frameworks for sharing the benefits and costs of managing mountain ranges across boundaries, whether local or district jurisdictions within countries or indeed across national boundaries.

The IPCC's Special Report on Oceans and Cryosphere refers to governance as an 'effort to establish, reaffirm or change formal and informal institutions at all scales to negotiate relationships, resolve social conflicts and realise mutual gains'. Governance is an act of governments, NGOs, private-sector institutions and civil society in establishing rules and norms for restricting the use of common goods. Institutions can guide, constrain and shape human interaction through direct control, incentives, and processes of socialisation. How do we apply the definitions of governance and institutions in the context of mountains? Since governance not only refers to government, which is a formal arm of the state, the report also talks about other agencies such as community organisations, non-profit organisations or businesses that play a vital role in society and influence individual or collective decisions and help in preventing the overexploitation of resources.

To comprehend the processes of governance in mountain areas, we need to recognise how each of these agencies adds to the enduring task of enabling and managing change at the system level but also to preserving social structures and reconciling disputes. For the sustainable and resilient development of mountain regions, governance mechanisms may be different than those applied to the management of other resources, such as coastal zones or rivers. Mountains are also mostly transboundary and do not necessarily follow political boundaries. Mountain governance, therefore, is about managing resources across political boundaries for the benefit of all countries. This includes downstream countries that also rely on resources such as water, silt and others from these mountain regions. These include high rangelands, biodiversity hotspots, forests and glaciers, for example.

There are several examples of regional cooperation in connection with the governance of shared resources in mountains. Some examples come from the Arctic (bottom-up and science-based evolution of Arctic cooperation), Southeast Europe (regionalisation of environmental benefits) and the HKH region (intergovernmental scientific institution for research and data sharing). Mountains share resources, so their management will benefit from cooperation among countries. Transboundary cooperation is needed not only to address transboundary climate risks and regional adaptation to climate change in mountains but also to work across countries to reduce greenhouse gas emissions.

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