Chapter 2: High Mountain Areas

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Executive Summary

It is *very likely*[1] that most high mountain regions are currently undergoing and will continue to undergo significant warming along with global temperature trends (*robust evidence, high agreement*[2]). In many cases, temperature trends depend on altitude and are *likely* to exceed global temperature increases at intermediate altitude levels (roughly corresponding to the 0°C average isotherm) (*medium evidence, medium agreement*) Precipitation trends are more difficult to detect, but regions and altitude levels corresponding to the snow/rain transition line are *very likely* to exhibit significant decreases of solid precipitation (*robust evidence*, *high agreement*). Other drivers such as the deposition and impact of light absorbing impurities play a significant role in the response of snow and ice to climate change, often leading to amplified responses. {2.2.1}

It is *very likely* that long-term seasonal snow conditions (characterized by snow depth, snow water equivalent, season length) undergo and will continue to undergo significant decreases, especially for locations corresponding to typical rain/snow transition altitude (corresponding in general to the mean 0°C altitude). In this altitude range, in mid-latitude mountain regions, it is *very likely* that seasonal snow will undergo a significant reduction in the 21st century (*high agreement, high confidence*). At higher altitude (i.e., significantly above the mean rain/snow transition altitude), trends are more difficult to detect for past conditions (in part due to the paucity of reliable long-term records), and it is *likely* that snow conditions will also be reduced in the 21st century, especially for higher global temperature scenarios (*medium agreement, medium confidence*). {2.2.2}

Since AR5, mountain glaciers have continued to decline in all glacierized regions with only a few exceptions, and are expected to continue to shrink throughout this century (*high confidence*). It is *likely* that the average mountain glacier mass loss rates in the early 21st century are unprecedented during the >70 year observational record. Relative volume and area reductions are largest in regions with predominantly smaller glaciers (*high confidence*). {2.2.3}

Mountain glacier shrinkage causes a temporary increase in glacier-derived runoff, followed by a decrease (*high confidence*), the timing and duration of which is regionally highly variable. In some regions with predominantly smaller glaciers, this turning point has already been reached or will be reached in the next two decades. It will be reached in almost all regions by the end of the century (*medium confidence*). {2.3.1}

Large permafrost areas, about XXX [PLACEHOLDER FOR SECOND ORDER DRAFT] million km^2, exist in high-mountains (*very high confidence*) and are subject to warming and thaw that is expected to persist and intensify. In the present-day period (~2005–2015), their permafrost temperatures have increased (*high confidence*) at a higher rate (*medium confidence*) than in the recent past reference period (~1986–2005). Active-layer thickness increased (*high confidence*) and many debris-ice landforms have increased rates of movement (*medium confidence*). Coarse-scale climate models without downscaling are of limited use for scenario simulations of permafrost in mountain areas. Finer-scale simulations suitable for mountain environments indicate widespread warming and thaw of permafrost until the end of the century. {2.2.4}

There is *high confidence* that current and projected retreat of mountain glaciers and thaw of mountain permafrost decrease and will continue to decrease the stability of mountain slopes. There is also *high confidence (medium agreement)* that glacier retreat leads to an increasing number or area of

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[1] FOOTNOTE: 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%, 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* (see Section 1.8.3 and Table 1.2 for more details).

[2] FOOTNOTE: In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *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 (see Section 1.8.3 and Table 1.2 for more details).

glacier lakes. It is expected with *high confidence (medium agreement)* that climate change will reposition high mountain landscape elements such as frozen slopes, glaciers, water bodies implying related disasters also to happen where there is no historical record of previous events. For instance, new lakes will develop closer to head walls where rock/ice falls could reach the lakes and trigger outbursts. There is also *high confidence (high agreement)* that glacier lake outbursts and landslide-generated impulse waves (tsunamis) will continue to happen under the expected increasing number of lakes and decreasing slope stability. {2.3.3.1}

It is more likely than not that avalanche activity has exhibited changes over the past decades (*medium confidence, low agreement*), in particular through a change in the partitioning from dry to wet snow avalanches, and a reduction of dry snow avalanches size and run-out distance. It is very likely (*high agreement, medium evidence*) that cryospheric changes in mountain regions will favour major shifts of avalanche activity and character, through prolonging the period when wet snow avalanches can occur, and reduce the overall number and runout distance of dry snow avalanches in regions and altitudes experiencing significant reduction of snow conditions. {2.3.3.1}

There is *high confidence* that the exposure of people and infrastructure in high mountain regions has increased over recent decades, and this trend is expected to continue in the future. Tourism has been the main driver of this change. Based on empirical evidence from past events, there is *high confidence (high agreement)* that cryosphere-related landslides and floods can have severe impacts on lives and livelihoods, often extending far beyond the directly affected region, and persisting for several years. {2.3.5.1}

Given the expected continued increase in exposure of people and assets in high mountains, compounding other environmental stresses, there is *high confidence (medium agreement)* that the impacts from high mountain floods and landslides will increase over the coming century in regions where risk reduction strategies and climate adaptation prove insufficient. Particularly for mountain regions, there is *high confidence (high agreement)* that integration of knowledge and practices across social, humanities and physical sciences is an important prerequisite for addressing complex hydrological challenges, hazards, and risks. {2.3.3.3}

Observed changes in the cryosphere are exerting considerable impacts in high mountain social-ecological systems, including many facets of biodiversity, and the ecosystem services that the cryosphere provides to humans (*high agreement, medium evidence*), while evidence on the long-term effectiveness of adaptation responses remain limited (*medium agreement, medium evidence*). Impacts of cryosphere change on human society is already evident in many mountain regions. Human response to cryosphere change varies across high mountain regions, with evidence of increasing implementation of formal and informal adaptation measures at local scales. However, these measures are generally limited in scope, are short-term focused, and are fragmented. Evidence on the collective long-term effectiveness of adaptation measures to address cryosphere change in high mountains is varied and limited, largely reflecting the diverse priorities, conditions and mechanisms available for their implementation and evaluation. {2.3.3.3, 2.3.4, 2.3.5}

There are limits to the adaptation capacity of socio-economic sectors under the influence of cryospheric change along with climate change (*high agreement, medium evidence*). Integrated (cross-sectoral) governance approaches hold potential in promoting socio-economic sectors' resilience and transformation, yet evidence on how these materialize to address cryosphere change in high mountain contexts remains low. Human habitability in mountain regions relies on multiple and diverse means to secure basic needs and sustain livelihood options, which are increasingly challenged by cryosphere change, induced by climatic change. Recognition for multiple ways of knowing / indigenous and local knowledge promote resilience and adaptation in a changing climate and cryosphere environment. {2.3.6}

2.1 Introduction

2.1.1 Characteristics and Relevance

Mountain regions share common features, including rugged terrain, steep slopes, institutional and spatial remoteness, which are linked to context-specific physical and social-ecological processes across vertical gradients. Due to their high elevation, mountains often feature cryosphere components, such as glaciers, seasonal snow cover and permafrost, and have distinct climatic and social-ecological characteristics as a connected system, with a significant influence on surrounding lowland areas even far from the mountains themselves. Hence the mountain cryosphere plays a critical role in large parts of the world (Beniston, 2003).

Seasonal and longer-term changes in the cryosphere regulate water, nutrient and sediment supply to mountainous and downstream ecosystems and are crucial for multiple societal needs. Of particular importance is the changing availability of water resources in response to declining snow cover and glacier mass (Sections 2.2.2, 2.2.3). Water demand itself is increasing, linked to the growth of population and consumption. Mountain regions are described as 'water towers' providing water to the mountain and downstream populations used for agriculture, domestic water use, and the generation of hydropower. Tourism, a growing economic activity in mountain regions, experiences a variety of impacts from cryosphere change (Section 2.3.5.1). In addition, cryospheric changes pose significant natural hazards with direct consequences for people and infrastructure, particularly glacier lake outburst floods (GLOFs), debris flows and rock/ice avalanches, and the destabilisation of landscapes caused by permafrost thawing (Section 2.3.3). The mass loss from mountain glaciers is also a significant contributor to current sea-level rise (Section 4.X). Hence, changes in mountain cryosphere can impact livelihoods of millions of people in different parts of the world.

Different approaches for delineating mountains exist for different purposes, each emphasizing different features or characteristics of the landscape. There is no universally agreed definition or delineation for the definition of mountains, and previous attempts at a definition have considered altitude, slope, ruggedness and various combinations of these parameters (e.g., Kapos et al., 2000; Körner et al., 2011). Accurately delineating mountains largely depends on which parameters or characteristics of the landscape are deemed relevant for a given purpose, and how these are to be measured. This chapter adopts the definition of high mountain regions as "mountain areas where seasonal or perennial cryosphere is present and poses a potential and serious risk to society related to water scarcity and disaster resilience" as resolved by the 69th Executive Council of the World Meteorological Organisation (WMO) in 2017.

Thus, in this chapter high mountains are considered as encompassing all mountain areas where glaciers, snow or permafrost are prominent features of the landscape, without a strict and quantitative demarcation, but with a focus on distinct regions (Figure 2.1). Many examples from specific localities in these regions will be relevant to similar mountain areas. Impacts and responses in socio-ecological systems in adjacent lowlands are included. Most mountain regions located in the polar regions are considered in chapter 3.

This chapter provides a wide-ranging assessment of the changes, impacts and risks associated with cryospheric changes in high mountain regions. Mountain environments also change in response to climate change related effects on biodiversity or the physical environments unrelated to the cryosphere or socio-economic developments. These non-cryospheric drivers are not considered here, although unambiguous separation can be difficult in some cases. Due to the close relationship between mountains and the cryosphere, it was considered imperative to assess changes occurring in mountains and their effects in a dedicated chapter within this special report.

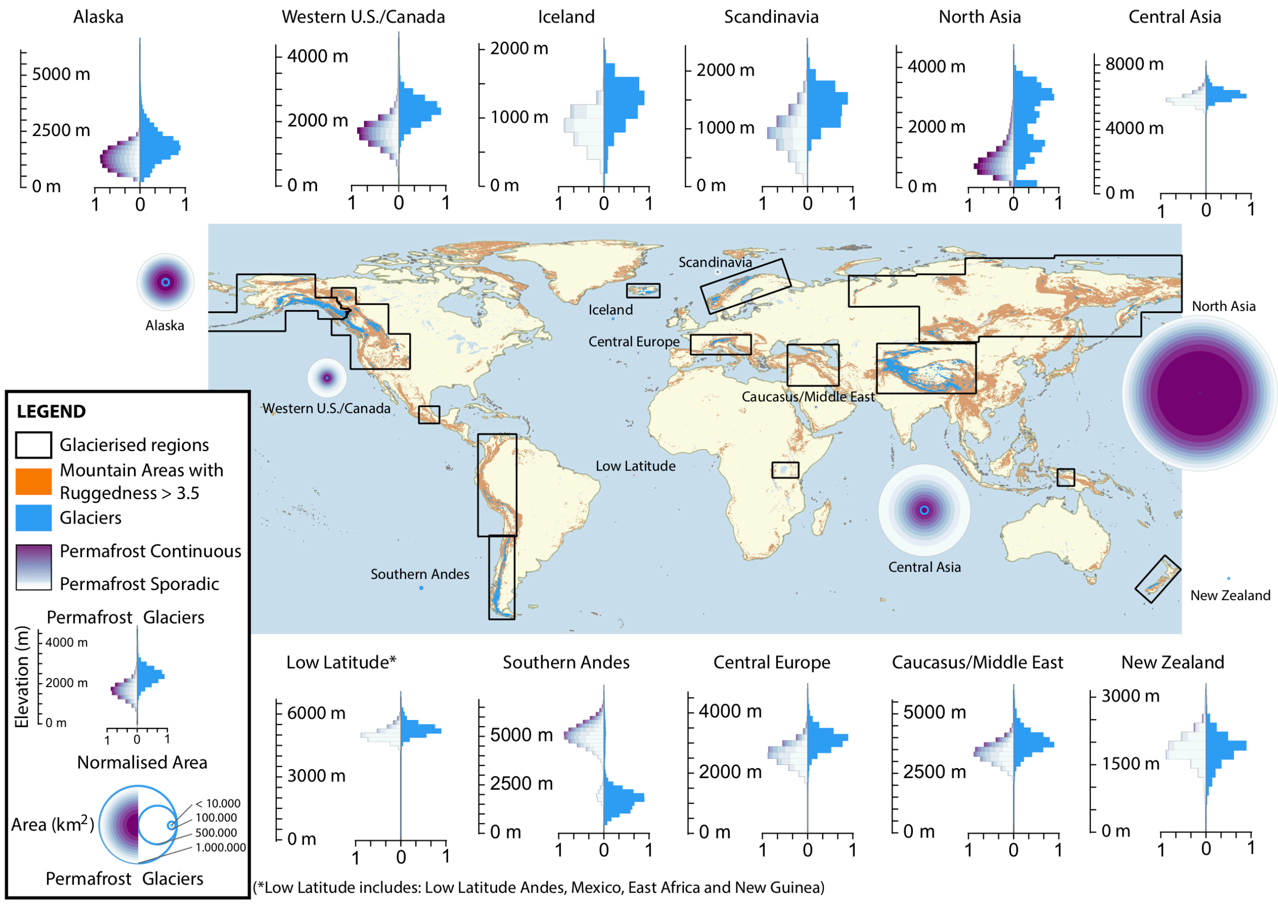

Figure 2.1: Distribution of mountain areas and glaciers. Mountains are distinguished based on a ruggedness index, a logarithmically scaled measure of relative relief (Gruber, 2012). Region outlines encompass 11 distinct regions with glaciers, largely matching the primary regions in the Randolph Glacier Inventory, RGI v6.0 (RGI Consortium, 2017), but cryosphere related impacts presented in this chapter are not strictly limited to these regions. Circles are proportional to glacier and permafrost area. Histograms show glacier and permafrost area for each elevation bin in fraction of total glacier area. Permafrost area bracket a minimum and maximum estimate (Gruber, 2012). Glacier area is based on RGI v6.0 (RGI Consortium, 2017). [PLACEHOLDER FOR SECOND ORDER DRAFT: circles to indicate minimum and maximum areas and for all regions; subplot permafrost area to bet normalized to total glacier area]

2.1.2 Services Provided by the Mountain Cryosphere

This chapter categorizes the impacts of cryospheric change from the perspective of the services the cryosphere provides—provisioning, regulating, supporting and cultural services (Figure 2.2). Provisioning services include runoff from glaciers and snow that is used for drinking water, irrigation etc., and energy from hydropower. These services also include the information provided by the cryosphere. For example, glaciers are a repository of information on climate and atmospheric composition. The cryosphere has a regulating effect on water availability, ecosystem stability and carbon sequestration. Supporting services of the cryosphere include those related to habitat, such as biodiversity and migration routes for people and animals. The cultural, religious, and spiritual services of the cryosphere that include aesthetic and recreational, are also subject to changes.

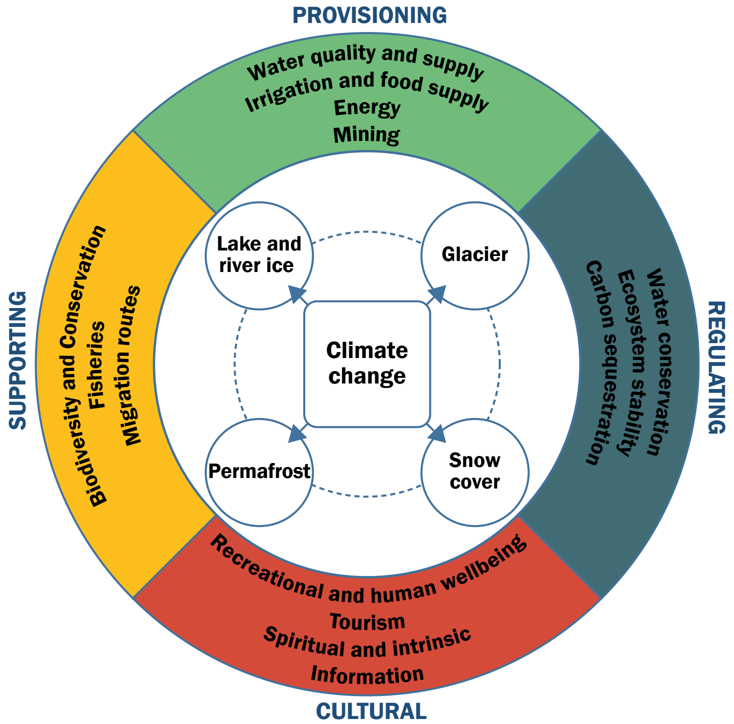

Figure 2.2: Services provided by the mountain cryosphere categorized into provisioning, regulating, cultural and supporting services.

[START BOX 2.1 HERE]

Box 2.1: How Do We Observe the Cryosphere?

Knowledge about changes in snow, permafrost, glaciers and ice sheets stems, and from a range of ground-based, air-borne and space-borne measurement methods and also from indigenous and local populations.

Snow

In-situ measurements traditionally comprise snow depth and snow water equivalent (SWE) at point stations, either manually or automatically. Such data can also be used to infer snow cover duration, that is, number of days with snow depth exceeding a threshold.

Remotely-sensed observations mostly address snow cover extent through optical remote sensing at various spatial resolutions and revisit frequencies, since the late 1970s at the earliest. Passive microwave data are mostly inappropriate in mountain regions due to their large measurement footprint (typically 25 km pixel size), and active microwave (radar) measurements have not been used to detect long-term trends of snow cover variations. Other remote sensing methods for monitoring snow are similarly used for glaciers and permafrost, and listed below.

Due to the multiplicity of variables and indicators describing seasonal snow state and variations, there is no universal indicator in the literature, which can be used to describe variations of snow conditions. A combined assessment must cope with this diversity of approaches.

In addition to direct observations, global and regional reanalyses driving snowpack models can be used to infer past changes of snow conditions in mountainous areas (e.g., Durand et al., 2009).

Glaciers

Measurements of glacier change are done through a wide range of variables such as changes in length/front position, area, elevation, volume, mass, velocity, albedo or snow line. The longest measurement time series stem from in situ glacier length changes and mass balance. In-situ glacier observations are time-consuming and laborious and thus restricted to only a small fraction of the glaciers.

Recent advances in photogrammetric processing open up for large-area analyses of historical aerial photographs (Kjeldsen et al., 2015; Midgley and Tonkin, 2017). Modern digital aerial photogrammetry and laser scanning are increasingly used for ice, but also snow and permafrost measurements from local to regional scales (Zemp et al., 2013; Nolan et al., 2015; Andreassen et al., 2016; Girod et al., 2017). Unmanned Air Systems, typically equipped with cameras and combined with modern digital photogrammetric processing, can be applicable in zones where terrestrial access or use of manned aircrafts are complicated or too expensive (Syromyatina et al., 2015; Bhardwaj et al., 2016; Eltner et al., 2016).

Satellite data from the 1960s and later have long been used for measuring glacier length changes, changes in glacier and snow-covered area, and glacier volume and mass changes on local to worldwide scales (Vaughan, 2013). A paucity of global-scale optical satellite data in the mid/late-2000s and early-2010s, mainly due to the partial failure of Landsat7, was followed by 10-30m resolution optical and radar images with global coverage available every few days, enabling dense and accurate measurements of ice and snow extent, surface properties, and lateral and vertical ground displacement. Improved satellite measurements of changes in glacier elevation and volume stem from differencing new regional (airborne) and global (e.g., TanDEM-X, ALOS Prism, WorldView, Spot) elevation data sets (Melkonian et al., 2016; Rankl and Braun, 2016; Neelmeijer et al., 2017; Round et al., 2017), enhanced processing of ICESat laser (Kääb et al., 2012; Treichler and Kääb, 2016) and CryoSat radar altimetry (Gray et al., 2015; Foresta et al., 2016; Gower, 2017), and time series of satellite stereo data (Brun et al., 2017). The main sources of uncertainty are the uncertain penetration of radar waves into snow and ice, the interpolation of spatially incomplete measurements, and the snow/ice density required to convert volume into mass changes. The GRACE satellite gravity mission continues to provide global-scale ice mass changes since 2003, in particular over large areas and where the separation of signals from hydrology and glacial isostatic adjustment is successful (Colgan et al., 2015; Sandberg Sørensen et al., 2017; Zhan et al., 2017).

Indigenous and local populations in mountain regions have knowledge of glacier retreat from direct observation (Gagné et al., 2014), from stories passed down from one generation to another within community (Stensrud, 2016) and from other sources. Residents of mountain areas can provide dates for previous locations of glacier fronts, sometimes documenting these locations through the presence of structures such as shrines [China] (Allison, 2015), herders' huts [Peru] (Postigo, 2014) and shelters [Italy] (Brugger et al., 2013). They also describe the changes in dark areas of exposed rock within the glacier surface (Konchar et al., 2015). Their observations often overlap with the record of instrumental observations (Deng et al., 2012), and can significantly extend this record (Mark et al., 2010). Mountain residents also link glacier retreat to decreased streamflow and shrinkage of pastures (Postigo, 2014) and to the formation of proglacial lakes and increased risk of GLOFs (Sherpa, 2014; Ikeda et al., 2016).

Permafrost

Permafrost is usually concealed by the active layer and therefore cannot be easily detected from the ground surface or with remote-sensing techniques. Observational estimates rely on inference from few observations at individual sites, which are not sufficient to provide a representative sample of all permafrost in polar or in high-mountain areas. For example, boreholes are drilled preferentially where access is simple, along roads or in the vicinity of cable cars in mountains, or in peatlands where handheld equipment can be used. Borehole monitoring data previous to the year 2000 is rare. During the International Polar Year (IPY) 2007–2009 a concerted effort was made to observe the thermal state of permafrost based on 575 boreholes globally (Romanovsky et al., 2010). Since then, only a limited number of new syntheses have been published.

Permafrost temperature is typically observed by repeated direct measurement in boreholes. At a depth of approximately 15 m, seasonal temperature fluctuations are minimal (depth of Zero Annual Amplitude, ZAA) and individual observations approximate annual average conditions. This depth also provides a smoothing of inter-annual variation and is suitable for the detection of trends. Data loggers allow obtaining annual average conditions closer to the surface based on averaging of frequently repeated observations. The phase change between ice and water within soil or rock pores occurs gradually just below 0ºC. The high amount of latent energy involved in melting subdues temperature change in thawing ground (Romanovsky and Osterkamp,

2000) and temperatures often stagnate just below 0ºC. Consequently, low or decreasing rates of permafrost temperature increase near 0ºC point to ice loss in the subsurface and may indicate stronger impacts than high rates of temperature increase in the ground that is several degrees colder.

Active layer thickness is another established metric of permafrost change because the intensity of summer warming largely controls the depth of thaw. When the active layer thickens into ice-rich permafrost, the ground surface subsides. This provides an additional important measure of permafrost change. The thickness is measured with differing techniques, some of which do not account for the confounding influence of surface subsidence (Brown et al., 2000).

Subsurface ice loss can be inferred from geophysical monitoring (Hilbich et al., 2008). A number of ground-based remote sensing techniques, equally used for glaciers and permafrost, have reached maturity, including terrestrial laser scanning (Kenner et al., 2014; Gabbud et al., 2015), terrestrial radar interferometry (Strozzi et al., 2012), automatic (web) cameras and Structure-from-Motion photogrammetry (Westoby et al., 2012; Kääb et al., 2014). Permafrost is a subsurface thermal phenomenon and as such generally inaccessible to air-borne and space-borne sensors, but repeat high-resolution images and radar interferometry reveal related slope movement and instability (Strozzi et al., 2010; Sorg et al., 2015; Strozzi et al., 2015). Velocity change of debris-ice landforms is observed as a proxy for permafrost change (Delaloye et al., 2010; PERMOS, 2016).

[END BOX 2.1 HERE]

2.2 Changes in the Mountain Cryosphere

[START BOX 2.2 HERE]

Box 2.2: Simulating Changing Climate and Cryosphere in Mountains

Global climate models (GCMs) are important tools for investigating climate and simulating future scenarios. Their horizontal resolution, however, is often too coarse (70–250 km) to represent the processes that are relevant in mountains (e.g., Eyring et al., 2016; Haarsma et al., 2016). Therefore regional climate models (RCMs), forced by boundary conditions from GCMs or reanalyses, are often used to perform climate change studies in mountains (Gao et al., 2015; Kotlarski et al., 2015). This so-called dynamical downscaling has the advantage of representing atmospheric dynamics when producing finer-resolution output. Most RCMs use a hydrostatic approximation, without explicitly representing convection in the atmosphere, and typically simulate continental-scale domains at 10–50 km resolution. However, the climate response in mountains can only be adequately captured at spatial resolutions finer than 5 km, requiring non-hydrostatic formulations (Prein et al., 2015) for resolving vertical motion and key processes like convection. Studies with non-hydrostatic RCMs and resolutions of few km are feasible (Kendon et al., 2014; Rasmussen et al., 2014) and allow for a better simulation of phenomena such as winds, extreme precipitation, or soil moisture-precipitation feedbacks (Rummukainen et al., 2015). Atmospheric reanalyses (e.g., Dee et al., 2011) assimilate remote sensing and other meteorological data into numerical weather prediction models, producing a consistent estimate of atmospheric variables. Several global reanalyses, often going back multiple decades, are available with horizontal resolutions of 30–150 km.

Climate model output can be used to assess the changes of mountain cryosphere components directly (Gobiet et al., 2014; Kotlarski et al., 2014; Smiatek et al., 2016; Beniston et al., 2018), in particular, snow. The joint analysis of snow cover and its drivers in climate model output is consistent with the regional climate response, and explicitly accounts for feedbacks (Steger et al., 2012; Frei et al., 2018). In mountains, RCMs often exhibit wet or cold biases (e.g., Frei et al., 2018), limiting the simulation quality of rainfall, snowfall and snow cover. These biases result from limitations in the process representations or parameterizations used (Ehret et al., 2012). For example, the cold bias has been attributed to simulated snow cover being too persistent (Vautard et al., 2013) or the representation of ice albedo (Mao et al., 1998; Su et al., 2013).

RCM output is also used to drive cryospheric impact models that cannot easily be incorporated into the RCM itself, for example, due to finer spatial resolution required to represent steep slopes. Impact models are then driven by RCM output, usually after adjustment to account for bias and scale mismatch. Statistical downscaling uses transfer functions to predict local climate information based on coarse-scale model output. These transfer functions are derived from analysis of local observation or heuristically based. These functions are then applied to model data to obtain local scale information consistent with the synoptic forcing of the model (Maraun et al., 2010). Statistical downscaling is particularly well suited for precipitation (D'Onofrio et al., 2014; Terzago et al., 2018). Methods for bias adjustments include simple correction of the long-term means, quantile mapping to correct higher statistical moments (Gudmundsson et al., 2012; Hempel et al., 2013), and multivariate methods that conserve the physical consistency among several variables (Vrac et al., 2015). Though bias correction has been criticized to remove the added values of RCMs compared to GCMs, it is often unavoidable for climate-change impact studies as uncorrected RCM results can propagate large uncertainties into impact simulations (Teutschbein and Seibert, 2013). Downscaling and bias-correction contribute additional uncertainty into the model cascade linking GCMs and impact models. The uncertainties and their propagation through the modelling chain need to be quantified and clearly communicated to end-users together with results from impact models (Ehret et al., 2012), with considerations regarding deep-uncertainty also relevant in decision-making contexts regarding model use and interpretation in mountain regions (Cross Chapter Box 1.4). Scientific methods making it possible to represent, quantify and convey numerically or graphically, to the largest possible extent, all uncertainty components (natural variability at relevant time scales, knowledge gaps in the model components, observation uncertainties) show greatest potential for appropriate use in a decision-making context (Brasseur and Gallardo, 2016).

[END BOX 2.2 HERE]

2.2.1 Atmospheric Drivers of Changes in the Mountain Cryosphere

2.2.1.1 Air Temperature

2.2.1.1.1 Observations

Air temperature trends in mountains regions are mostly studied in mid-latitudes. Between 1961 and 2012 the mean warming rate for stations above 2000, 3000 and 4000 m a.s.l. was 0.32, 0.33 and 0.36°C per decade, respectively, on the Tibetan Plateau, indicating warming with an elevation-dependent trend (Box 2.3) [PLACEHOLDER FOR SECOND ORDER DRAFT: reference to be added]. Over the more recent period 1991–2012 the enhanced warming at higher elevations has amplified, with annual trends approaching 0.7°C per decade above 4000 m a.s.l., compared with around 0.4°C per decade below 2500 m a.s.l.. The European Alps have undergone significant warming, exhibiting also an altitude dependency (Beniston et al., 2018). Warming has been detected in most mountainous regions of the world, often with a elevation dependent trend (Pepin et al., 2015). In high tropical mountains, there are relatively few studies of long-term temperature trends due to lack of data (Lawrimore et al., 2011). For instance, temperatures at low levels on the western slope of the Andes are strongly influenced by sea surface temperature and coastal cooling at low levels has caused elevation-dependent warming at higher elevations in the early 21st century in the Andes (Vuille et al., 2015). In the sub-Arctic mountains (e.g., Alaska and northern Canada, and Fennoscandia) rapid warming has been observed (over +0.5°C per decade in the second half of the 20^{th} century) but most studies take the Arctic as a whole (Comiso and Hall, 2014) and stress Arctic amplification as a regional phenomenon.

[PLACEHOLDER FOR SECOND ORDER DRAFT: reference/response to conclusions in SR1.5 regarding air temperature and warming trends to be included]

In summary, it is *very likely* that high mountains have been experiencing significant warming over the past decades (*high confidence, high agreement*). Furthermore, it is *likely* that high mountains are showing an amplified response to climate change with a faster rate of warming (between 1.5 and 2 times) in comparison with the global mean (*medium evidence, medium agreement*).

2.2.1.1.2 Scenarios

There is robust evidence that high mountain regions will experience further increases in air temperature over the 21st century, consistent with global trends. Simulations of surface air temperature averaged over the entire European Alpine region indicate a warming seasonally varying between +1.2°C in spring and +1.6°C in summer and winter until the mid of the 21st century and +2.7°C in spring and +3.8°C in summer until the end of the 21st century, compared to 1961-1990, with an annual rate of 0.25°C warming per decade until mid-21st century accelerating up to 0.36°C per decade in the second half of the century under a SRES A1B scenario (Gobiet et al., 2014) [PLACEHOLDER FOR SECOND ORDER DRAFT: upcoming studies using EUROCORDEX]. Warming is a robust signal across different model projections for the European Alps, but its amplitude is variable across the model ensemble (Heinrich et al., 2013). The tropical Andes are expected to undergo a continued warming throughout the 21st century with multi-model mean end-of-century warming of 1.8°C (RCP4.5) and 3.3°C (RCP8.5), with respect to the 1961–1990 values (Vuille et al., 2018). Across the Bolivian Andes, mean annual air temperature is projected to increase by a range of 2.7°C to 3.2°C by the 2050s and a range of 4.2°C to 4.9°C by the 2080s in the SRES A1B scenario, with respect to the 1950–2000 reference period (Rangecroft et al., 2016). Mountain regions in northwest America are also expected to undergo similar levels of warming (Diaz et al., 2014). Based on different studies using global (Kang et al., 2010; Rangwala et al., 2016) and regional (Kulkarni et al., 2013; Sanjay et al., 2017) climate model projections for the Hindu-Kush-Himalaya region, the mean annual temperature is projected to increase in a range of 1°C to 4°C by mid-21st century and 2°C to 6°C by the late-21st century relative to the late-20th century and considering scenarios from moderate to high greenhouse gas emissions. Dimri et al. (2018) found statistically significant rate of warming (between 0.3°C and 0.9°C per decade) in all seasons and RCP scenarios overall in the Himalayas, although with a large range of spatial variability and high uncertainty associated with model projections and scenarios.

There is high agreement among model projections that regional warming trends are elevation-dependent. Giorgi et al. (1997) illustrated elevation dependency in future warming rates for a 2 times CO_2 scenario in the European Alps, and Fyfe and Flato (1999) in the Rockies. In both cases the enhanced warming was concentrated in winter and spring and was attributed to rapid decrease in snow cover. In the tropics the dominant mechanism in future models is the enhanced free air warming around 5000 m a.s.l. which is due to a moistening of the atmospheric column (Collins et al., 2013). Kotlarski et al. (2015) examined elevation dependency of 21st century temperature change in the European Alps using the an ensemble of RCMs driven by CMIP3 GCM output. Except for northern Europe where the occurrence of temperature inversions complicates predictions, maximum warming typically occurs at medium to high elevations (>1500 m). Spring and summer showed pronounced elevation dependency in warming. Palazzi et al. (2017) analysed elevation dependency of future warming in 27 CMIP5 GCMs over the Tibetan Plateau and Himalaya/Karakorum and all show some enhanced warming at higher elevations, particularly where annual mean temperatures are currently below freezing.

In summary, it is *very likely* that high mountain areas will show continued warming consistent with global warming (*high confidence*). It is *likely* that they will show amplified warming rates during the 21st century in comparison with the global mean, particularly in the altitude range where the snowline retreats uphill (*medium confidence*). The *medium agreement* in quantitative estimates of climate projections in current literature is due to heterogeneity of observation density and quality, and of modelling tools employed to address future changes, between regions under considerations.

[START BOX 2.3 HERE]

Box 2.3: What is Elevation Dependent Warming?

There is increasing evidence that high mountains are showing an amplified response to climate change with a faster warming on average in comparison with the global mean (Pepin et al., 2015). The systematic and statistically significant change in warming rate with elevation has been termed elevation-dependent warming (EDW). The change is not necessarily linear (in many cases it is not), and it may not always be positive (amplification of warming with elevation), although this is often the case. It can be that warming is enhanced in a particular elevation band and decreases above, for example around a retreating snowline.

Most of the physical processes involved operate similarly with increasing latitude in polar areas and increasing elevation in mountains. For example, the sensitivity of temperature to radiative forcing is increased at low temperatures common in polar and mountain environments (Ohmura, 2012). Additional processes are unique to mountain environments. For example, increased latent heat release above the condensation level lowers the lapse rate in a warmer and moister atmosphere (Held and Soden, 2006). The relationship between specific humidity and down-welling longwave radiation is non-linear such that a given increase in specific humidity has a disproportionately large warming influence in the drier atmosphere common at high elevations (Rangwala et al., 2013; Chen et al., 2014). The cooling effect of aerosols, which also cause solar dimming, is most pronounced at low elevations and reduced in high elevation zones (Zeng et al., 2015) . Aerosol deposition on snow (Lawrence and Lelieveld, 2010; Ji et al., 2015) can enhance warming rates via increased snow-albedo feedback and is a particularly pronounced on the Tibetan Plateau (Lau et al., 2010).

There is a strong bias in the distribution of weather stations towards low elevations, where the majority of the world population lives. Less than 1% of stations in global observation datasets are above 3000 m a.s.l. (Lawrimore et al., 2011) and no long-term records (>15 years) exist above 5000 m a.s.l.. Additional problems include a bias towards valley floors, which often are dominated by distinct microclimates (Lundquist et al., 2008) and an under-sampling of steep slopes.

EDW exhibits large regional differences because climate and synoptic conditions influence the partitioning between driving mechanisms. Studies in Asian mountains (Liu and Chen, 2000; Liu et al., 2009; Guo and Wang, 2012; Yan and Liu, 2014) show peak warming around 4000–5000 m associated with retreating snow and ice. The snow-albedo feedback also dominates model experiments (Gao et al., 2015; Kotlarski et al., 2015; Guo and Wang, 2016) although its elevation depends on season and location. Expansion of treeline upslope may cause warming in Arctic and mid-latitude mountains as trees have a lower albedo than snow (Loranty et al., 2014).

The snow-albedo feedback is reduced in the tropics where snow covered area is small and treeline remains well below the snowline. By contrast, changes in the temperature profile as a result of moistening/drying are the main control on tropical mountain climate (Bradley et al., 2009; Loomis et al., 2017). As wetter conditions in the free atmosphere favour warming at high elevation, a future enhancement of the hydrological cycle (Held and Soden, 2006) is expected to cause EDW in the tropics. In contrast the effect of specific humidity in enhancing warming rates is strongest in mid-latitudes at night and in the cold season where the air is currently dry (Rangwala et al., 2016).

[END BOX 2.3 HERE]

2.2.1.2 Rain and Snow Precipitation

2.2.1.2.1 Observations

Changes in patterns of precipitation over the last century are less well quantified than changes in temperature patterns and can be very complex and heterogeneous within mountain regions (Hartmann and Andresky, 2013). In the European Alps precipitation changes were small over the last century and were not recognized as a major driving factor of changes in snow cover (Beniston, 2012). The tropical Andes were characterized by an alternation of relatively dry and humid periods in the last century, with no clear trends in annual precipitation or changes in the length of the rainy season (Kohler et al., 2010). Precipitation in the Hindu-Kush Himalayas exhibited heterogeneous spatial patterns reflecting the complex meteorological regimes acting on the eastern and western portions of the area, dominated by the summer monsoon and by winter/early spring western weather patterns, respectively. Precipitation averaged over the westernmost areas (Hindu-Kush and Karakoram) did not experience statistically significant winter precipitation trends (Palazzi et al., 2013), although studies at individual stations showed an upward trend in winter precipitation in the Karakoram in the period 1961–1999 (Archer and Fowler, 2004). An increasing but statistically insignificant trend in winter precipitation over the period 1866–2006 was found by Bhutiyani et al. (2010) for the northwestern Himalayan region. Positive glacier mass balances (Section 2.2.3) and distinct growth of endorheic (inland) lakes from the mid-1990s to the late first decade of 2000 (Song et al., 2015; Zhang et al., 2017a) in western Tibet suggest increases in precipitation, possibly related to changes in atmospheric circulation patterns (Mölg et al., 2014; Tao et al., 2014) or potentially even irrigation activity in the Tarim basin (Kok et al., 2018). The monsoon dominated regions in the easternmost Himalayas experienced negative trends in summer precipitation (Palazzi et al., 2013; Salerno et al., 2015). Precipitation over the Tibetan Plateau shows increased trends during 1979–2001 (You et al., 2015). In the Carpathian region, while precipitation totals did not appear to have changed significantly, intense precipitations increased over the last century (Kohler et al., 2010).

Snow precipitation is closely linked to air temperature. Increased air temperatures during the 20th century led to less snowfall in the Italian Alps (Valt et al., 2005), northern Greece (Baltas, 2007) and the Pyrenees (López-Moreno, 2005). A decrease in the ratio of snowfall to precipitation days has been documented also in Slovakia particularly in winter (Nikolova et al., 2013) and in Switzerland, where the negative trend in the ratio was stronger at locations with winter temperature closer to the melting point (Serquet and Rebetez, 2011). A large proportion of winter precipitation, in form of rain instead of snow, also occurred in the northwestern Indian Himalayas from 1866 to 2006 (Bhutiyani et al., 2010) and a shift from snow to rain was observed in other areas of the Hindu-Kush-Himalayas (Rikiishi and Nakasato, 2006). In middle and east Tienshan mountains, the snowfall fraction has decreased every decade since the 1960s (Chen et al., 2016a).

In summary, it is *likely* that most mountain regions have shown insignificant trends in total precipitation over the past decades (*medium evidence, medium agreement*). It is *likely* that most mountain regions have exhibited significant decreases of solid precipitation (snow) due to higher temperatures, especially for the altitude range of the typical rain/snow transition line (*medium evidence, medium agreement*).

2.2.1.2.2 Scenarios

Projections of precipitation in mountains display a differentiated pattern around the globe, with some regions expected to receive more precipitation, including the tropical Andes, the Hindu Kush Himalayas, East Asia, East Africa and the Carpathian region, while others expected to receive less precipitation including mountains in the Mediterranean, in South Africa, and the southern Andes. Overall, precipitation intensity is expected to increase and model projections indicate for the future decades an intensification of the hydrological cycle globally. In some mountains areas such as the Andes, this translates into an increase in precipitation during the wet season and a decrease during the dry season, a kind of behaviour already observed in the same area since the second half of the 20th century (Vuille et al., 2018). In the Tibetan Plateau, the average precipitation change relative to the 1961–2005 climatology is expected to increase of about 6% in the RCP2.6 scenario and 12% in the RCP8.5 scenario by the end of the 21st century (Su et al., 2013). Across the Himalayan-Tibetan Plateau mountains, the frequency and intensity of extreme rainfall events are projected to increase particularly during the summer monsoon season throughout the 21st century (Panday et al., 2015; Sanjay et al., 2017). This indicates a likely transition toward more episodic and intense monsoonal precipitation, especially in the easternmost part of the Himalayan chain (Palazzi et al., 2013).

The decrease in snowfall frequency and fraction experienced in many mountain areas of the globe over the last century is projected to continue in the future. In European mountains this will likely result from a slightly positive trend in winter precipitation from mid-century onward (Smiatek et al., 2016; Rajczak and Schär, 2017; Beniston et al., 2018) combined with temperature rise throughout the year (e.g., Gobiet et al., 2014; Smiatek et al., 2016). Snowfall over the European Alps is projected to be considerably reduced by the end of the 21st century. Averaged between September and May, alpine snowfall is projected to decline by 45% under the RCP8.5 scenario and by 25% under the RCP4.5 from the period 1981–2010 to 2070–2099 (Frei et al., 2018). The largest percent changes (more than 80% reduction) is expected to occur in lower-lying areas of the Alpine region, and will be enhanced for heavy snowfall events, while the highest elevations will only be weakly affected by changes in snowfall (Frei et al., 2018). Similarly, one study for the Pyrenees area (López-Moreno et al., 2011) projected a marked decrease in the frequency and intensity of heavy snowfall events at lower elevation (below 1000 m a.s.l.) while no change was projected for higher elevations from the period 1960–1990 to 2070–2100, under the SRES scenarios A2). These two examples reflect the behaviour overall simulated by the models over the entire Northern Hemisphere (O'Gorman, 2014), indicating that snowfall may increase only in regions with very cold temperatures such as high mountains, otherwise it is expected to decrease. For other European mountain areas such as Scandinavian mountains, projections under SRES A1B scenario indicate increasing precipitation at the highest elevations only (Räisänen and Eklund, 2011). Kawase et al. (2016) reported that under climate conditions corresponding to a 4°C global temperature increase since 1861–1880, mountainous areas in Central Japan would exhibit an overall reduction of snowfall but an increase in extreme daily snowfall amount, due to intensified extreme precipitation events related to increased moisture content of the atmosphere.

In summary, mountain regions will exhibit total and partitioned (rain vs. snow) precipitation trends showing distinct regional and altitude patterns in the 21st century. It is *very likely* that most mountain regions will experience significant decreases of solid precipitation (snow) due to the general increase of temperature, especially for the altitude range of the typical rain/snow transition line (*medium evidence, medium agreement*). At significantly higher altitudes where temperature will remain cold enough to not affect the phase of precipitation, snow precipitation trends will be dominated by total precipitation trends. Trends of total precipitation at high altitude are highly uncertain, due to the paucity of studies using most detailed modelling tools to address high altitude, cryospheric related issues (*low evidence, low agreement*).

2.2.1.1 Other Variables

Atmospheric moisture content in mountains affects latent and longwave heat fluxes with implications for the timing and rate of snow/ice ablation (Harpold and Brooks, 2018) and likely for ground temperatures, too. Atmospheric humidity has been shown to increase and to have a strong effect on increasing surface downwelling longwave radiation (Rangwala et al., 2013). Especially in a dry and cold atmosphere, this effect on longwave radiation can increase warming rates and affect their partitioning with seasons and with elevation (Box 2.3).

Solar radiation affects snow and ice melt and ground temperatures. Solar dimming and brightening are associated with changing anthropogenic emissions, such as sulphur and black carbon (You et al., 2013), and have been shown to be particularly sensitive in pristine regions such as mountains (Wild, 2014). For example, the solar brightening caused by declining anthropogenic aerosols in Europe since the 1980s had only minor effects at high elevation in the Alps (Philipona, 2013). The skill of GCMs in reproducing patterns of solar dimming and brightening is limited (Wang et al., 2014a).

Wind controls preferential deposition and post-depositional snow drift and both have implications for snow conditions and cascading consequences for the ground thermal regime and glacier mass balance. Wind speed has decreased on the Tibetan Plateau since the 1970s and since about 2002 may have stabilized or increased slightly (Yang et al., 2014; Kuang and Jiao, 2016). Nearly all stations show a decreasing trend and wind speed declines consistently at differing elevations (Kuang and Jiao, 2016). Similarly, sunshine duration on the Tibetan Plateau decreased significantly, and in all seasons, from 1970–2009 for most stations (Lin et al., 2013; Kuang and Jiao, 2016). Wind stilling is often related to changed atmospheric circulation, for example, in response to warming of Asia at higher latitudes (Lin et al., 2013). The skill of GCMs in reproducing patterns of wind stilling is limited (Jiang et al., 2017).

2.2.1.4 Aerosol Deposition

Mountain cryospheric components are generally not directly affected by greenhouse gases and other gaseous components. However, short-lived aerosol, particularly when they feature light absorbing characteristics, modify the albedo of snow- or ice-covered surface upon deposition, with potential impacts on the energy and mass balance of cryospheric components. This is an emerging and rapidly growing topic, showing significant influence of aerosol deposition on snow and ice evolution in the past and in the future. However, besides sensitivity and process studies, most climate projections of mountain cryospheric elements do not explicitly account for time and space variations of aerosol deposition and their impacts.

Investigations of past influence of aerosol deposition on snow and ice mostly rely on ice core records. They mostly focus on trends, melt amounts, source attributions, and radiative forcing and demonstrates increases in dust and/or black carbon deposition, hence radiative forcing, since the beginning of the 20th century, in many mountainous regions of the world (Ginot et al., 2014; Gabbi et al., 2015; Kutuzov et al., 2016; Matthew et al., 2016; Lim et al., 2017). There is *limited evidence* and *low agreement* that long-term changes in snow and ice are linked to snow-darkening effects (Painter et al., 2013; Sigl et al., 2018). Furthermore, the current knowledge on flushing efficiencies (scavenging efficiencies) of snow impurities by meltwater is very limited (Doherty et al., 2013; Yang et al., 2015; Li et al., 2017b; Niu et al., 2017) (*medium agreement*; *limited evidence*), limiting the ability of numerical models to account for effects arising from light-absorbing impurities (Qian et al., 2015). Nevertheless, there is increasing evidence from case studies in most mountainous regions, that snow and ice darkening is a critical component in cryospheric changes, with significant impacts on snow and ice radiative forcing, significantly contributing to interannual variability and long term trends of snow and ice conditions (Deems et al., 2013; Painter et al., 2013; Gabbi et al., 2015; Kaspari et al., 2015; Yasunari et al., 2015; Xu et al., 2016; Schmale et al., 2017; Zhang et al., 2017b; Zhang et al., 2018).

In summary, it is *likely*, that deposition of light-absorbing impurities (in particular, black carbon and dust) have played a significant role in changes of the mountain cryosphere (snow and glaciers mostly) as demonstrated especially in the Tibetan Plateau, Himalayas and the North American Rocky Mountains, and amplify the response of the mountain cryosphere to climate change via snow-albedo feedbacks (*medium confidence*). Under continued anthropogenic and natural emissions of black carbon, dust and other light-absorbing impurities, this amplification is *likely* to continue in the 21st century (*medium agreement, limited evidence*).

2.2.2 Snow

Snow on the ground is an essential component of the mountain cryosphere. It intrinsically contributes to mountain ecosystem services addressed in this report, and plays a major role in mass movement and floods in the mountains. Furthermore, it plays a key role in the lifetime of mountain glaciers, as the main source of ice and key insulating and reflective material when present at their surface. Snow responds in several ways to meteorological conditions, hence climate change. The onset and development of the snow cover depends on snow precipitation, which is highly temperature dependent. Snowmelt is enhanced under warmer conditions, too. Snow is also sensitive to other atmospheric variables through various terms of its energy balance, including the modulation of its albedo by aerosol deposition and intrinsic snow structure evolution (microstructure). Seasonal snow, especially in low-lying and mid-altitude areas of mountain regions, has long been identified to be particularly sensitive and exposed to climate change, generating interest and concern from multiple stakeholders due to projected drastic reductions.

2.2.2.1 Observed Change

Studies of the snow cover in Asia and Andes are mostly restricted to satellite-borne measurements, which span limited time coverage and lack support from in-situ observations (Rohrer et al., 2013; Zhong et al., 2018). Most recent studies rely on sensors launched at the beginning of the 2000s, in particular MODIS. In the high mountains of Asia and the Tibetan Plateau, there is evidence from satellite records of significant interannual variability and regional differences of the snow covered area (Tahir et al., 2015; Gurung et al., 2017; Li et al., 2018). Interannual fluctuations appear positively correlated to air temperature, and correspond to large-scale meteorological patterns. In the Andes, recent studies also indicate significant interannual variability, strong relationships to El Niño-Southern Oscillation, and a general decreasing trend since the early 2000s, although this time period is too short for revealing a significant long-term trend (Malmros et al., 2018; Saavedra et al., 2018).

In North American mountains, there is increasing evidence for widespread decline in seasonal snow, superimposed on significant interannual variability. Mote et al. (2018) report that most (92%) snow monitoring stations in the western United States of America exhibit downwards trends for springtime snow water equivalent since 1955. Since the beginning of the 20st century, the decline of April 1st snow water equivalent is on the order of 15 to 30% (Mote et al., 2018), although the variability hampers the statistical significance of the trends. Literature addressing analysis of snow cover trends for Canadian Rocky Mountains and Alaska is limited and often not specific to mountain environments. For the interior of western and northern Canada, DeBeer et al. (2016) conclude that annual snow cover duration has decreased 2 to 12 days per decade over the 1950–2012 for sites with in situ observations. Such analyses can be expanded using larger scale, remote-sensing or modelling approaches, showing mostly decreasing trends over the 20th century with significant uncertainty on absolute trend values (Mudryk et al., 2015; DeBeer et al., 2016; Kushner et al., 2018).

Seasonal snow in mountain areas of Australia exhibit significant variability but have shown decline, based on limited available in-situ data (Fiddes et al., 2015b). Published observation records in New Zealand and Japan span a too limited time period to ascertain long-term trends.

In the European mountain areas (Alps, Pyrenees, Central European mountains, Scandinavia), available in-situ snow depth data indicate a decreasing trend since the middle of the 20th century especially for the elevation range corresponding to wintertime mean temperature values close to 0°C (Beniston et al., 2018). The trend is not monotonous and superimposed on significant interannual and decadal variability. In particular, snow depth data exhibited a strong shift in the mid-1980s (Reid et al., 2016; Beniston et al., 2018). Similar trends have been described for snow water equivalent by Marty et al. (2017b) using more than 80 stations with more than 30 years of data in the European Alps, with more pronounced trends for April 1st data (most trends significant, all negative) than February 1st (fewer trends significant, although mostly negative) and with increasing relative magnitude with decreasing altitude. Remotely-sensed information at the scale of the entire European Alps for the period from 1985 to 2011 Hüsler et al. (2014) show significant interannual variability and no regionally significant trend at this scale, except for snow cover duration at low altitude (700–900 m altitude) areas in the south-eastern and south-western parts of the domain. The absence of significant trend is consistent with the rather short time period considered (shorter than 30 years).

For the mountain regions of the world where sufficient data has been gathered to address long-term changes in seasonal snow conditions, it is *very likely* (*high agreement*, *high confidence*) that long-term all snow indicators (snow depth, snow water equivalent, season length etc.) have been reduced since the beginning of the 20st century, especially for locations corresponding to typical rain/snow transition altitude (corresponding in general to the mean 0°C altitude). Regions with insufficiently long in-situ observations networks are being addressed through remote-sensing, which provides currently insufficient time span for solid trend analysis. It is *likely* that high altitude areas (significantly above the typical rain/snow transition line) exhibit insignificant trends, either positive or negative (*medium agreement* and *medium confidence*).

2.2.2.2 Scenarios

Very little literature describes specifically climate projections of snow conditions in the Andes (Vuille et al., 2018). In the High Mountains of Asia, climate projections directly using GCM output indicate a regionally variable reduction of the snow cover during the 21st century, on the order of 25 to 50% in the Himalayas (Terzago et al., 2014).

In western North American mountains, climate projections of snow conditions exhibit significant interannual variability and actual projections in the near and long-term are highly dependent on methodological choices (Deser et al., 2014; Rasmussen et al., 2014; Mendoza et al., 2015; Fyfe et al., 2017; Musselman et al., 2017). Common patterns of climate projections include a rising snowline (Hatchett et al., 2017) and the shift from snow to rain (Berghuijs et al., 2014; Klos et al., 2014; Mankin and Diffenbaugh, 2015). Snow projections are expected to interact with fire and ecosystem disturbance (e.g., Welch et al., 2015; Gergel et al., 2017) both as responses to snow changes and as feedbacks that change snow accumulation and melt dynamics. Lute et al. (2015) suggest that extreme snowfall events will make up a greater fraction of the total snowpack in their future climate simulations.

In New Zealand's mountains areas, downscaled CMIP3 GCM projections indicate a reduction of seasonal snow conditions (Hendrikx et al., 2012), showing greatest reductions below 1000 m and reductions in all but highest altitude locations. Generally similar results were obtained for Australia by Hendrikx et al. (2013), based on a limited set of SRES-based GCM runs. In Japanese mountains areas, Katsuyama et al. (2017) have reported numerical simulations showing significant decrease of the winter snow depth under a global 2°C warming. In Iceland, available climate projections also indicated a reduction of the snow cover (Gosseling, 2017).

In Europe (Alps, Pyrenees, Central European mountains, Scandinavia), direct and indirect use of RCM output all indicate in general a continuation of the downwards trend seasonal snow in the 21st century (Steger et al., 2012; Gobiet et al., 2014; Beniston et al., 2018), especially at altitude levels corresponding to the mean snow/rain transition line. A few recent studies have used CMIP5 GCMs for seasonal snow projections in Europe (using EUROCORDEX RCM). RCP2.6, RCP4.5 and RCP8.5 projections are rather similar until the mid-21st century, after which stronger decreases are projected in RCP8.5 than RCP4.5, RCP2.6 showing a stabilization of snow conditions at mid-21st century level until the end of the century (Marty et al., 2017a; Terzago et al., 2017; Hanzer et al., 2018; Verfaillie et al., 2018). For example, at the altitude of 1500 m in the Northern French Alps, with respect to the 1986-2005 period, Verfaillie et al. (2018) report a decrease of mean winter snow depth from 0.66 m (observed, reanalyzed and historical model runs) to 0.48, 0.40 and 0.32 m around 2050 and 0.44, 0.31 and 0.09 around 2090 for RCP2.6, RCP4.5 and RCP8.5, respectively. The interannual variability of snow conditions is projected to remain significant throughout the 21st century. Some studies based on direct regional climate model outputs suggest an increase in precipitation, hence seasonal snow, at high altitude. This directly stems from projected increases in high resolution locations from some model studies.

Climate projections of future changes of mountain snow conditions generally align with projected changes of air temperature, modulated by concurrent changes in precipitation. In mid-latitude mountain regions (Europe, North America, High Mountains of Asia, Japan, New Zealand and Australia, Southern Andes), it is *very likely* that seasonal snow will undergo significant reduction, especially at altitudes corresponding to the mean snow/rain transition line, also corresponding generally to the altitude of mean winter 0°C temperature (*high agreement*, *high confidence*). At higher altitude (i.e., significantly above the mean rain/snow transition altitude), it is *likely* that snow conditions will also be reduced, especially for higher global temperature scenarios (*medium agreement, medium confidence*). The higher uncertainty on projections at higher altitude are mostly due to the inability of regional climate models and downscaling methods to capture the subtle interplays between large-scale climate change and their impacts in complex topography (e.g., combined effects and feedback on regional and local atmospheric circulation, seasonality of precipitation along with regional temperature change).

2.2.3 Glaciers

The high mountain areas considered in this chapter (Figure 2.1, Table 2.1) include 173,000 glaciers covering an area of 252,000 km^2 (RGI Consortium, 2017), roughly 30% of global glacier area outside the Greenland and Antarctic ice sheets. These glaciers span an altitude range from sea-level to >7000 m a.s.l. and occupy diverse climatic regions. Their mass budget is determined largely by the balance between snow accumulation and melt at the glacier surface, primarily driven by atmospheric conditions. Refreezing of melt or rain water, calving and basal melting, are of lesser importance compared to polar regions (Chapter 3). Glaciers respond to imbalances in their mass budget by adjusting their volume, size and shape typically over time scales of decades or more. Rapid changes of mountain glaciers have multiple impacts for social-ecological systems, affecting not only bio-physical properties such as runoff volume and sediment fluxes in glacier-fed rives, and glacier-related hazards, but also human livelihoods, socio-economic activities and sectors such as agriculture and tourism, and other intrinsic assets such as cultural values.

2.2.3.1 Observed Change

Since AR5 the number of satellite-derived regional-scale mountain glacier observations has greatly increased, particularly in the High Asian Mountains. Satellite and in-situ observations of glacier area, length and mass changes show a globally coherent picture of continued mountain glacier recession in the last three decades (*very high confidence*) with only few exceptions. A global analysis of >1100 glacier front positions archived by the World Glacier Monitoring Service and dating back to the 16th century indicate a historical minimum glacier extent in the early 21st century in all regions (except for New Zealand possibly due to few observations; Zemp et al. (2015)). For Columbia Glacier, Alaska, the minimum extent is unprecedented in the last 900 years (Carlson et al., 2017). Steep glaciers have been found to retreat less than glaciers with more gentle slopes (Leclercq et al., 2014).

Mass balance observations indicate that on average mountain glaciers are currently losing mass worldwide (*very high confidence*). There is robust evidence from more than 5000 glaciological and geodetic observations since 1850 that the highest rates of mass loss per area are found in the early 21st century (Zemp et al., 2015). The global trend is negative and significant despite considerable year-to-year and regional variations (Medwedeff and Roe, 2017). These trends are also consistent with localized observations of indigenous and local communities (Bury et al., 2011; Sherpa, 2014; Ikeda et al., 2016), although few studies have integrated such knowledge with scientific measurements. Departures from this global trend of glacier recession occurred in some regions, but were generally short-lived or locally restricted (Section 2.2.3.2).

[PLACEHOLDER FOR SECOND ORDER DRAFT: additional text on regionally averaged mass-balance time series for 11 mountains regions – reference to Figure 2.3 and including mass change and area numbers]

Table 2.1: Regional glacier statistics and observed and projected glacier mass changes. Region names, number of glaciers (N) and area are based on the Randolph Glacier Inventory v6.0 (RGI Consortium, 2017). [PLACEHOLDER FOR SECOND ORDER DRAFT: numbers to be added]

	N	Area (km^2)	Volume (km^3)	Mass Change Rates	Period	Reference
Alaska	21108	86725				
Western Canada and US	18855	14524				
Iceland	569	11060				
Scandinavia	3417	2949				
North Asia	5151	2410				
Central Europe	3927	2092				
Caucasus	1888	1306				
High Mountain Asia	95536	97605				
Low Latitudes	2939	2341				
Southern Andes	15908	29429				
New Zealand	3537	1162				
Total	172835	251603				

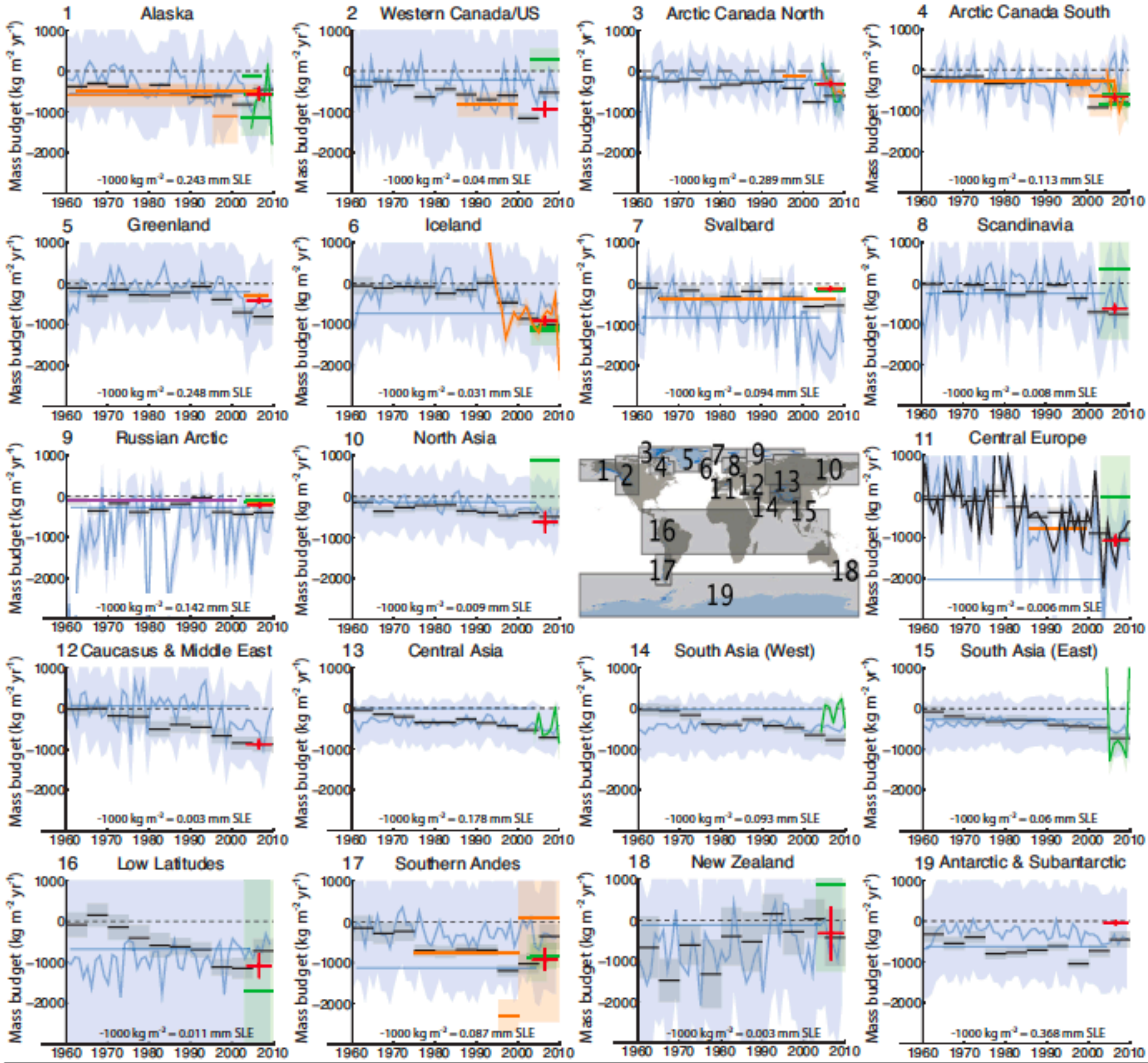

Figure 2.3: Glacier mass budgets of 11 glacierized mountain regions (Figure 2.1). Estimates are from [REFERENCE] [PLACEHOLDER FOR SECOND ORDER DRAFT: Figure is taken from AR5, update of global estimates currently underway in community effort]

There is *medium confidence* that glacier flow velocities of non-surge-type glaciers in some regions including central Asia, Alaska and Patagonia, have decreased in recent decades in response to glacier thinning, especially in their lowermost parts or debris-covered tongues (Heid and Kääb, 2012; Waechter et al., 2015; Wang et al., 2017c). There is *limited evidence* that sub-surface temperature in high-elevation cold accumulation areas have increased in response to atmospheric warming and release of latent heat from increasing amounts of surface melt or rain water (Gilbert et al., 2014). Enhanced meltwater percolation has been observed in the uppermost parts of high-elevation glaciers in Tibet (Kang et al., 2015) and the tropical Andes (Thompson et al., 2017). Changes in temperature regime can affect a glacier's stability and pose a hazard (Section 2.3.3).

2.2.3.2 Scenarios

Due to the pronounced mass imbalance, glaciers in mountain regions will *very likely* further recede to adjust their geometry to current climate conditions, even if climate were to remain stable (Mernild et al., 2013; Marzeion et al., 2018). Model simulations using climate scenarios indicate that mountain glaciers are *very likely* to lose substantial mass by the end of the century, but relative mass reductions vary greatly between and within mountain regions (Figure 2.4). Global-scale glacier projections from four glacier models forced by 8 to 15 Global Circulation Models (GCMs) and different emission scenarios, including the Representative Concentration Pathways (RCPs) used in AR5, and the scenarios from the Special Report on Emissions Scenarios (SRES) used in TAR and AR4 indicate volume losses by 2100 compared to 2015 of 14–48% (multi-GCM means; Slangen et al. (2017)). Projected relative volume losses by 2100 (multi-GCM means) tend to be largest (70–90%) and the spread between GCMs smallest in regions dominated by smaller glaciers and relatively little current ice cover (e.g., Central Europe, Caucasus, Low Latitudes).

These global-scale projections are consistent with results from local or regional-scale studies. For example, Kraaijenbrink et al. (2017) projected mass losses for all glaciers in High Mountain Asia of 49 ± 7% (RCP4.5) to 64 ± 5% (RCP8.5) by the end of the century. A loss of 36 ± 7% was estimated for a global temperature rise of 1.5°C. A high-resolution regional glaciation model including ice dynamics surface mass balance indicated that by 2100, the volume of glacier ice in western Canada will shrink by 70±10% relative to 2005 with the maximum rate of ice volume loss, corresponding to peak input of meltwater to rivers, predicted to occur in 2020–2040 (Clarke et al., 2015). Low-elevation icefields have been shown to be particularly sensitive to atmospheric warming, due to a positive feedback between mass balance and elevation as the surface is lowered and becomes exposed to higher temperatures. Trüssel et al. (2015) projected almost complete loss of >340 km^2 low-lying Yakutat Glacier in Alaska by 2070 under a warming scenario and by 2110 when the current climate was assumed stable. It is very likely that many very small mountain glaciers (<0.5 km^2), which account for more than 80% of the total number of glaciers in mid- to low-latitude mountain ranges, will disappear by the end of the century. Ice patches may survive despite unfavourable climate due to local effects such as pronounced shading or avalanching (Huss and Fischer, 2016).

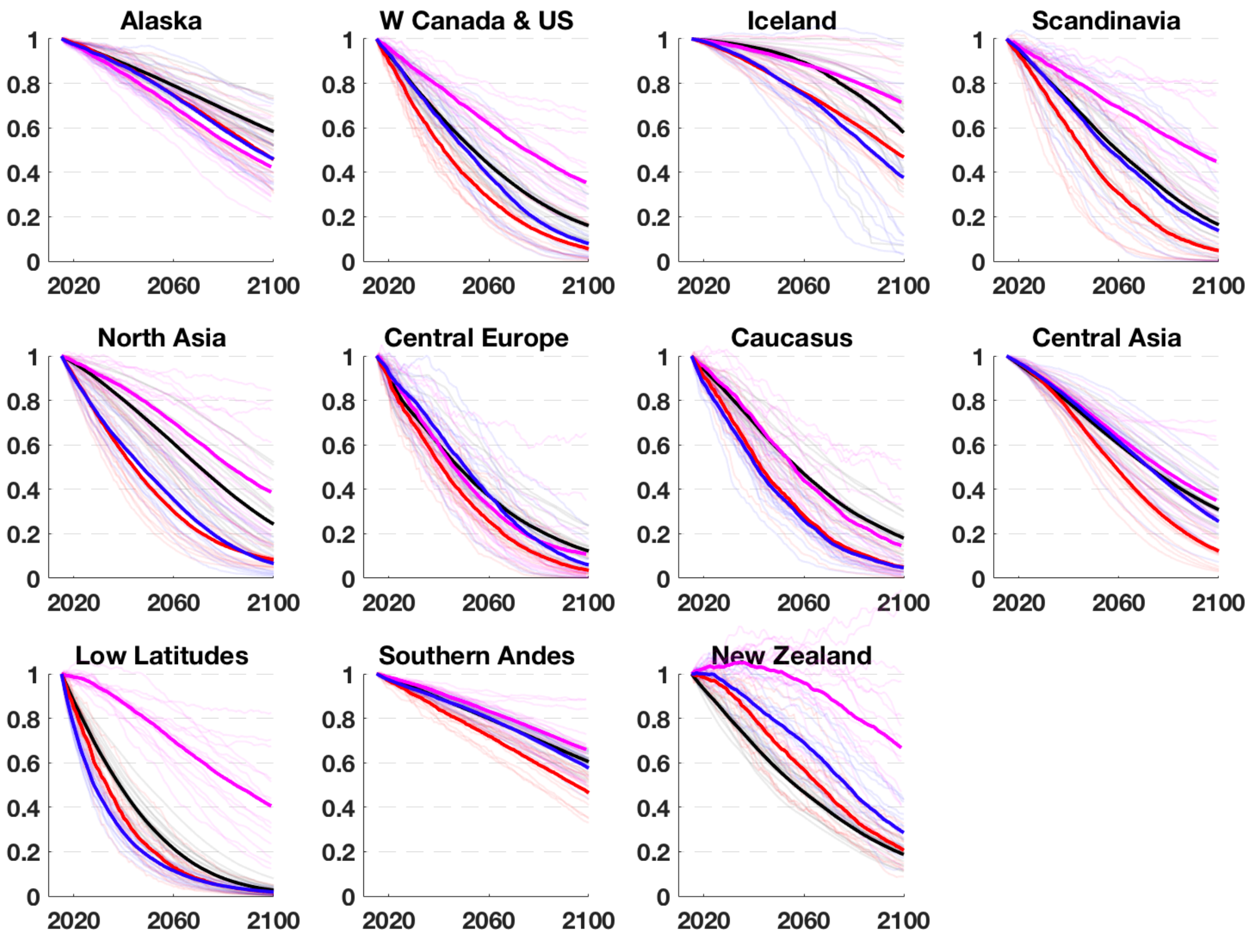

Figure 2.4 Projected regional mountain glacier volume changes. Projections taken from four global glacier evolution models forced by 8-15 GCM temperature and precipitation scenarios under the RCP4.5 emission scenario (data from Slangen et al. (2017)). Thin lines refer to individual GCMs, thick lines represent multi-GCM means. [PLACEHOLDER FOR SECOND ORDER DRAFT: figure, more models, axes labels and legend to be added]

2.2.3.3 Attribution

It is *very likely* that the trend of global mountain glacier recession during the last 100 years is primarily due to global atmospheric warming. Statistical analyses confirm that natural climate variability can be excluded as cause (Roe et al., 2017). Global modelling including all glaciers outside Greenland and Antarctica estimated the anthropogenic fraction of global glacier loss and found an increase from 25 ± 35% during the period 1851–2010 to 69 ± 24% during 1991–2010 (Marzeion et al., 2015).

Other factors such as changes in other meteorological variables, deposition of light absorbing impurities (Section 2.2.1.4) or local topography have modified the temperature-induced glacier response in some regions. For example, the mass balance variations of glaciers in the tropical Andes are strongly influenced by the El Niño-Southern Oscillation (Veettil et al., 2017). Glacier mass loss over the last seven decades in the European Alps was exacerbated by increasing long-wave irradiance and latent heat due to enhanced humidity (Thibert et al., 2018). In the Tien Shan in central Asia changes in atmospheric circulation in the north Atlantic and north Pacific in the 1970s resulted in an abrupt reduction in precipitation and thus snow accumulation, amplifying temperature-induced glacier mass loss.

Glacier advances in Scandinavia in the 1990s and in New Zealand between 1983 and 2008 have been attributed to local increases in snow precipitation (Andreassen et al., 2005) and lower air temperatures (Mackintosh et al., 2017), respectively, caused by changes in atmospheric circulation. 36 marine-terminating glaciers in Alaska exhibited a complex pattern of periods of significant retreats and advances during 1948-2012, highly variable in time and lacking coherent regional behaviour (McNabb and Hock, 2014). These fluctuations can be explained by internal retreat-advance cycles typical of tidewater glaciers that are largely independent of climate (Brinkerhoff et al., 2017). Irregular glacier advances in the Karakoram (often termed ‘Karakoram anomaly’) have been associated with surge-type flow instabilities (Bhambri et al., 2017). In contrast, balanced or slightly positive mass budgets since the 2000s over the Karakoram as well as the western Tibetan Plateau, the West Kunlun Shan, and Pamir mountains (Gardelle et al., 2013; Kääb et al., 2015; Azam et al., 2018) have been related to meteorological conditions, such as low sensitivity of winter accumulation to warming (Kapnick et al., 2014; Sakai and Fujita, 2017).

2.2.4 Permafrost

For permafrost globally, AR5 reported a general increase in temperature (*high confidence*) and active-layer thickness (*medium confidence*). For mountain areas, it mentioned the acceleration and destabilisation of rock glaciers and the occurrence of near-isothermal temperature-depth profiles.

There is *very high confidence* that large permafrost areas exist in high-mountains (Figure 2.1, Table 2.2) based on simple maps and models (Gorbunov, 1978; Brown et al., 1997; Gruber, 2012), observations (Cremonese et al., 2011; Schmid et al., 2015), and spatial modelling (Boeckli et al., 2012; Bonnaventure et al., 2012; Ran et al., 2012; Fiddes et al., 2015a; Westermann et al., 2015). Even fewer long-term observations of permafrost are available in mountains than in polar areas. Together with the well-observed changes in glaciers and snow cover, the *high agreement* of the *limited evidence* on permafrost allows, nevertheless, to infer changes to permafrost in mountains globally with *medium to high confidence*.

2.2.4.1 Observed Change

Permafrost temperatures in mountains have increased during the last decade (Table 2.2, *high confidence*). Bedrock shows stronger warming than debris or soil and colder permafrost shows stronger warming than warmer permafrost. This is due to ground-ice melt, which retards temperature change close to 0°C, and consistent with observations in polar areas. Thermal gradients at depth allow inferring a multi-decadal warming of permafrost in bedrock on the order of 0.6°C in Europe during the late 20th century (Harris et al., 2003; Gruber et al., 2004). Together with the evidence in Table 2.1 and higher warming rates in the second half of the present-day period (PERMOS, 2016; Biskaborn et al., 2018), this points to increasing rates of permafrost warming (*medium confidence*).

Active-layer thickness increased in mountains during the present-day period (Table 2.3, *high confidence*). In the European Alps, inter-annual variability is high and extreme events such hot summers affect active-layer thickness (PERMOS, 2016). Electrical-resistivity monitoring at selected Swiss borehole sites and a rock glacier in France reveals an increasing proportion of subsurface liquid water content (Hilbich et al., 2008; Bodin et al., 2009; PERMOS, 2016) in line with rising temperatures indicating gradual ice loss. Rock glacier velocities observed in the 1990s were in the order of a few decimetres and the same landforms today often move about 2–10 times faster (Bodin et al., 2009; Lugon and Stoffel, 2010; PERMOS, 2016). For similar ice-debris landforms in the Alaska Brooks Range, the majority of investigated forms accelerated since the 1950s while few others have slowed down in the same period (Darrow et al. 2016). In the present-day period, destabilization (Delaloye et al., 2010; Buchli et al., 2013; Bodin et al., 2016) of rock glaciers is observed in the European Alps. Many debris-ice landforms have increased their rate of movement in the present-day period (*medium confidence*).

2.2.4.2 Scenarios

An end of century scenario for the Tibet Plateau results in 3–55% of permafrost area remaining in an RCP2.6/8.5 bracket. In steep mountain areas, however, coarse-scale simulations of future permafrost conditions (Guo et al., 2012; Slater and Lawrence, 2013; Guo and Wang, 2016) are mostly of limited use due to coarse spatial resolution or lacking representation of topographic effects (Pastick et al., 2015). Simulation studies suitable for mountain environments indicate widespread warming and thaw of permafrost. They point to regional and elevational patterns (Bonnaventure and Lewkowicz, 2011; Hipp et al., 2012; Farbrot et al., 2013), differences between individual sites (Marmy et al., 2016), as well as sensitivities to warming differing between seasons (Marmy et al., 2013). Permafrost thaw at depth is a slow process that can persist for decades and centuries. In steep mountains, however, it can be accelerated by lateral warming (Noetzli and Gruber, 2009) or by the deep percolation of water in fractures or unsaturated coarse materials (Hasler et al., 2011). Peaks in the European Alps can lose permafrost completely by the end of the century (Magnin et al., 2017).

2.2.4.3 Attribution

There is *high confidence* that decadal permafrost warming and thaw are controlled by air temperature and strongly moderated by snow conditions (Wu and Zhang, 2008). The attribution of differences in warming rates to either regional climate patterns or local characteristics (surface/subsurface) is difficult with few long-term observations. For example, differing warming rates in the European Alps and on the Tibet plateau may be due to different materials and surfaces being measured (local variation) or due to differences in forcing (regional variation). Periods of cooling, one or a few years long, have been observed and attributed to extraordinary snow conditions (PERMOS, 2016). Feedback mechanisms such as desertification (Wu et al., 2017) and thermokarst (Lin et al., 2016) exert self-reinforcing effects on warming. Similarity and synchronicity of inter-annual to decadal velocity changes observed in the European Alps (Bodin et al., 2009; Delaloye et al., 2010) and inferred in the Tien Shan (Sorg et al., 2015), suggests common external climatic forcing of rock-glacier velocities such as summer air temperature or snow cover as important drivers.

Table 2.2: Observed permafrost temperature changes in mountain regions. Values are based on individual boreholes or ensembles of several boreholes reported. Underscored temperatures are averages during observation period, underscored years are approximate start/end of ensemble. The mean annual ground temperature (MAGT) refers to each period's last year and is taken from a depth of 10–20 m unless the borehole is shallower.

Elevation [m asl]	Surface Type	Measurement Depth [m]	Period	MAGT [ºC]	Temperature Trend [ºC (10 yr)$^{-1}$]	Reference
Global						
>1000	various (43)	10–20	2006–2017		0.2 ± 0.05	(Biskaborn et al. 2018)
European Alps						
2500–3000	debris or coarse blocks (>10)	20	1987–2005	> –3	0.0–0.2	(PERMOS 2016; Noetzli et al. 2018)
			2006–2017		0.0–0.6	

3500–4000	bedrock (4)	10–20	2008–2017	>–5.5	0.0–1.0	(Pogliotti et al. 2015; F. Magnin et al. 2015; PERMOS 2016; Noetzli et al. 2018)
Scandinavian mountains						
1500–1800		6–9	1999–2009	>–3	0.1–0.9	(Isaksen et al. 2011; Christiansen et al. 2010)
Asia						
		20	2005–2016		0.3	(Noetzli et al. 2018)
3500 (Tien Shan)	meadow	15	1992–2003 2003–2011	–1.5 –1.2	0.09 0.38	(Liu et al. 2015)
Asia: Tibet Plateau						
~4650	meadow (6)	10	2002–2012	–1.52 to –0.41	0.08 to 0.24	(Wu et al. 2015)
~4650	steppe (3)	10	2002–2012	–0.79 to –0.17	0.09 to 0.18	
~4650	bare soil (1)	10	2003–2012	–0.22	0.15	
4500–5000	unknown (6)	10	2002–2011	–1.5 to –0.16	0.08 to 0.24	(Peng et al. 2014)

Table 2.3: Observed changes of Active-Layer Thickness (ALT) in mountains. The mean annual ground temperature (MAGT) refers to each period's last year and is taken from a depth of 10–20 m unless the borehole is shallower. Asterisk (*) indicates mean value over observation period.

Elevation [m asl]	Surface Type	Period	ALT in Last Year [m]	MAGT In Last Year [°C]	ALT Trend [cm (10 yr)$^{-1}$]	Reference
Scandinavian mountains						
353–507	peatland (9)	1978–2006 1997–2006	~0.65–0.85	–	7–13 13–20	(Åkerman and Johansson 2008)
European Alps						
2500–2910	bedrock (4)	2000–2014	4.2–5.2	–1.3 to –0.08	10–100	(PERMOS 2016)
Asia: Tibet Plateau						
4629–4665	meadow (6)	2002–2012	2.11–2.32	–0.41 to –1.52*	34.8–45.7	(Wu et al. 2015)
4638–4645	steppe (3)	2002–2012	2.54–3.03	–0.17 to –0.79*	39.6–67.2	
4635	bare soil (1)	2002–2012	3.38	–0.22*	18.9	
4848	meadow	2006–2014	*1.92–2.72*	–1.2 to –0.6	15.2–54	(Lin, Luo, and Niu 2016)
Asia						
3500	meadow	1992–2011	1.70	–1.2	19	(Liu et al. 2015)

2.2.5 Lake and River Ice

2.2.5.1 Observed Change

Observations of extent, duration and thickness of lake and river ice rely mostly on in-situ measurements, air photography and, during most recent years, satellite observations (Chu and Lindenschmidt, 2016; Beckers et al., 2017; Du et al., 2017; Gou et al., 2017a; Pour et al., 2017). The longest observational records date back to the 15th Century (Lake Suwa, Japan) and the 17th century (Torne River, Finland), both clearly demonstrating later ice freeze (4.6 days per decade in Lake Suwa) and earlier ice breakup (0.66 days per decade in River Torne) following the start of the Industrial Revolution (Sharma et al., 2016). On a global scale, rates of change in ice phenology are highly variable (Du et al., 2017), but even on a regional scale, in particular in mountainous regions, ice phenology can show highly variable and even contrasting trends. On the Tibetan Plateau it has, for example, been observed that the mean rate of change in ice cover duration varied from +2.6 days yr^{-1} in one particular region to –1.1 days yr^{-1} in another region during 2001 to 2010 (Kropacek et al., 2013). The high variability in mountainous regions depends on altitude and mean annual air temperature as well as local lake conditions such as salinity, lake morphometry and wind exposure (Kropacek et al., 2013; Song et al., 2014; Yao et al., 2016; Gou et al., 2017b).

Despite high spatial and temporal variability in lake and river ice phenology, in particular in mountainous regions and over shorter time periods, there is, based on freeze and thaw/breakup dates for 865 lakes and rivers in the Northern Hemisphere, robust evidence and *high confidence* in a general shift towards later freezing, earlier break-up, and shorter ice cover over the past years (Benson et al., 2012; Sharma et al., 2016). This global trend in ice phenology has been confirmed by satellite microwave assessment (Du et al., 2017), and is consistent with a global trend towards warmer lake surface water temperatures (O'Reilly et al., 2015), mainly driven by increased air temperatures.

2.2.5.2 Scenarios

Based on observations and modelling, three future scenarios for ice cover dynamics have been inferred (Weyhenmeyer et al., 2011; Benson et al., 2012; Gebre et al., 2014; Du et al., 2017): 1) Ice records of lakes and rivers around the globe, including mountainous regions, will continue to shift towards later freezing, earlier break-up, and shorter ice cover, 2) The year-to-year variability in ice cover dynamics will increase along with increasing air temperature. In the warmest regions where lakes and rivers still have an ice cover year-to-year variations of 25 days in the ice cover duration have to be expected, 3) About 3.7% of the 117 million lakes on Earth (Verpoorter et al., 2014) are at risk of transition from strictly dimictic, ice-covered systems to monomictic, open-water systems. As these lakes are located in geographical regions with a T_m over T_a ratio (where T_m is the mean annual air temperature and T_a is the mean annual air temperature amplitude) between 0.5 and 0.8, probably only comparably few mountainous lakes on Earth are presently at risk to become open water systems in near future.

2.2.5.3 Attribution

Air temperature and solar radiation are the most important drivers to explain global patterns of lake and river ice dynamics (Magnuson et al., 2000; Weyhenmeyer et al., 2011), while additional lake morphometric and local meteorological variables are needed to model lake ice phenology and to make predictions with a very high precision (Gebre et al., 2014). On a global scale, lake and river ice also follows to some extent Quasi-Biennial Oscillation patterns such as the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), solar sunspot cycle, and multi-decadal oscillations but these oscillation patterns could only explain 26% of the total variance in time series of lake ice phenology of thirteen lakes in the Northern Hemisphere, including lakes in the Swiss mountains (Sharma and Magnuson, 2014).

2.2.6 Local, Regional and Global Climate Feedbacks Involving the Mountain Cryosphere

Cryospheric components interact with their environment and contribute to several climate feedbacks. Particularly prominent among the climate-relevant feedbacks are ones associated with snow cover. The presence or absence of snow on the ground drives profound changes to the energy budget of land surfaces, hence influences the physical state of the overlying atmosphere. The reduction of snow on the ground, potentially amplified by aerosol deposition, contributes to a powerful local feedback loop directly acting on elevation-dependent warming (Box 2.3). This feedback mostly operates at the local scale and is seasonally variable (most visible effects on the fringes of the snow season, when it is defined). Regional feedbacks have only been detected in sufficiently large mountain regions such as the Himalayas, using global and regional climate models (Box 2.2) (Qian et al., 2011; Ménégoz et al., 2014; Qian et al., 2015; Yasunari et al., 2015; Ji, 2016; Xu et al., 2016). There is no evidence for global climate feedbacks specifically involving the mountain cryosphere, largely because of the limited spatial scale of cryospheric components specifically located in mountain regions, at the global scale. For example, climate feedbacks involving continental snow at the global scale also incorporate mountain snow component, but not specifically. Changes of the mountain cryosphere have long-lasting consequences at the global scale, including sea level rise, but this does not constitute *per se* a global feedback mechanism. Last, measures intended to respond and adapt to changes of the mountain cryosphere (e.g., artificial snowmaking, Section 2.3.5.1 , Box 2.5) induce additional energy consumption – hence greenhouse gas emission. There is however no quantification of this burden at the global scale, making it impossible to assess as a global feedback mechanism.

2.3 Change in Mountain Ecosystems, their Services, Managed System and Human Responses

2.3.1 Water Supply

Freshwater provided by mountain areas represents an important ecosystem service. The runoff (per unit area) generated in mountains is on average approximately twice as high as in lowlands (Viviroli et al., 2011) making mountains a significant source of water in adjacent lowlands, thus supporting livelihoods in and beyond mountain ranges. The presence of snow, glaciers and permafrost can exert a strong control on the amounts, timing and biogeochemical properties of runoff (Box 2.4). Changes to the cryosphere due to climate change may alter this provision of fresh water with direct consequences for the downstream populations (Barnett et al., 2005; Beniston, 2005).

[START BOX 2.4 HERE]

Box 2.4: How Glaciers, Snow and Permafrost Affect Runoff?

The presence of glaciers, snow and permafrost can significantly alter runoff totals and seasonality even in catchments with low ice cover or permafrost extent. In ice-free snow-dominated catchments, runoff typically shows a distinct peak in spring, when the winter snow cover melts. Runoff from glaciers outside the tropics peaks during summer rather than spring since melt of glacier ice continues to contribute to runoff even when the winter snow has melted due to the dominance of glacier meltwater over precipitation. Snow and in particular glacier runoff display pronounced diurnal fluctuations caused by peaks in melt during the day when temperatures and solar radiation input are highest. Glaciers also tend to dampen interannual streamflow variations, since enhanced meltwater during hot dry years may offset low precipitation. In contrast to snow cover, glaciers can strongly alter annual runoff totals depending on their mass budget. In years of negative glacier mass balance, water is released from the long-term glacial store, augmenting downglacier runoff, while runoff is reduced in years of positive mass balance.

In case of continuous atmospheric warming glacier annual snowmelt runoff will decrease and the spring peak will occur earlier. In contrast glacier runoff is expected to initially increase in response to the warming as the glacier melts at a faster rate. However, there will be a turning point (‘peak water’) upon which glacier runoff will decrease as the glacier declines and eventually wastes away.

Permafrost affects runoff by providing an impermeable hydrological barrier constraining subsurface water percolation and reducing soil water storage capacity. Degrading permafrost may affect runoff directly through release of water from melting ground ice, but also indirectly through changes in the hydrological pathways to the river system as the subsurface barrier degrades and surface water is allowed to percolate deeper thus delaying runoff and reducing evaporation.

[END BOX 2.4 HERE]

2.3.1.1 Changes in River Runoff

Since AR5 a large number of studies has emerged that assesses past and future changes of runoff in glacierized catchment with a strong regional focus on High Mountain Asia.

Detected trends in recorded runoff in glacierized mountain regions are generally consistent with observed regional changes in precipitation and temperature, and associated changes in meltwater from snow and ice (*high confidence, robust evidence*). The increasing trend in runoff observed in many glacial- and snowmelt-dominated regions including the European Alps (Bard et al., 2015), High Mountain Asia (Kriegel et al., 2013; Duethmann et al., 2015; Chen et al., 2016b; Engelhardt et al., 2017c; Wang et al., 2017d) and Alaska (O'Neel et al., 2014) is attributed to recent increase in meltwater from snow and ice. Some rivers in North America show a decreasing trend in runoff due to a decrease in snowfall driven by recent warmer climate (Brahney et al., 2017). In the Tien Shan region of China a 20% reduction in volume of 446 glaciers within the region over the period 1964–2004 is already affecting the sustainability of the region’s water sources

(Wang et al., 2014b; Milner et al., 2017). In the Austrian Alps, hot and dry summers reduce the amount of water recharging the aquifers, decreasing water availability (Vanham et al., 2009). Many parts of the Hindu Kush Himalayan region are also experiencing water shortages (Bolch et al., 2012).

Analysis of past simulated streamflow supported the strong relation between climate-driven changes in cryosphere and runoff. In Bolivia, simulated glacier runoff shows no trend as increasing meltwater from ice compensates for decreasing precipitation (Soruco et al., 2015). In Peru, a number of tributaries of a major river, have passed peak flow associated with shrinkage of glaciers, such as in Yanamarey watershed (Bury et al., 2011) and the Santa (Baraer et al., 2015; Drenkhan et al., 2015), but another major river, the Vilcanota, shows no net trend for the period 1958-2013 (Baraer et al., 2015; Drenkhan et al., 2015). Local-scale studies in Himalayan and Tibetan Plateau basins show increasing runoff trend in the past (Wang et al., 2015; Tong et al., 2016; Engelhardt et al., 2017a; Engelhardt et al., 2017c; Wang et al., 2017a; Wang et al., 2017c; Xu et al., 2017; Yin et al., 2017), while a decreasing runoff trend is simulated in some rivers in North America (Naz et al., 2014) and Switzerland (Uhlmann et al., 2013b). Most of these studies are, however, at local scale and changes in runoff varies among basins, depending on the changes in climate and cryosphere.

The contribution of meltwater from glacier ice typically peaks during the summer except in low-latitude regions, when runoff from other sources is typically low (Kaser et al., 2010; Milner et al., 2017). The contribution is relatively high in arid and semi-arid river basins such as in High Asia and South America (Table 2.3), preventing drought in some regions by buffering the dry season stream discharge. Model-based estimates showed that the contribution of glacier runoff has increased since the 1990s in regions such as Western Himalaya (for Chhota Shigri glacier), the Tibetan Plateau (for Tuotuo River) and the Beida River catchment (Qilian Mountain) (Engelhardt et al., 2017c; Wang et al., 2017a; Wang et al., 2017c). Noted that as concepts to calculate glacier runoff vary among different studies (Radić and Hock, 2014), runoff contribution of glaciers may not be directly comparable.

Associated with projected shrinkage of mountain glaciers, glacier runoff is *likely* to decline by the end of 21st century in many high mountains (*high agreement, medium evidence*), indicating that peak water has already been reached or expected to occur in the early decades in the 21st century (Figure 2.5). In a global analysis of simulated glacier runoffs (2000-2100), most regions in high mountains show significant decreasing trend (Bliss et al., 2014; Huss and Hock, 2018). Regional and local-scale analyses show decreasing trend in glacier runoff in High Asian Mountains (Engelhardt et al., 2017a) , Central Europe (Bavay et al., 2013; Uhlmann et al., 2013a; Farinotti et al., 2016; Etter et al., 2017), South America (Frans et al., 2015; Ragettli et al., 2016) and North America (Beamer et al., 2016; Frans et al., 2016; Moyer et al., 2016). Some regions exhibit a steady increase in runoff (Lutz et al., 2014; Koppes et al., 2015) or increase followed by decrease until the 21st century (Nepal and Shrestha, 2015; Duethmann et al., 2016; Farinotti et al., 2016; Hasson, 2016; Engelhardt et al., 2017c). In some basins in High Mountain Asia, contribution of ice melt to total runoff will almost remain stable until 2050 (Lutz et al., 2014), 2070 (Su et al., 2016a), until 2080 (Prasch et al., 2013) or even until the end of 21st century (Immerzeel et al., 2013).

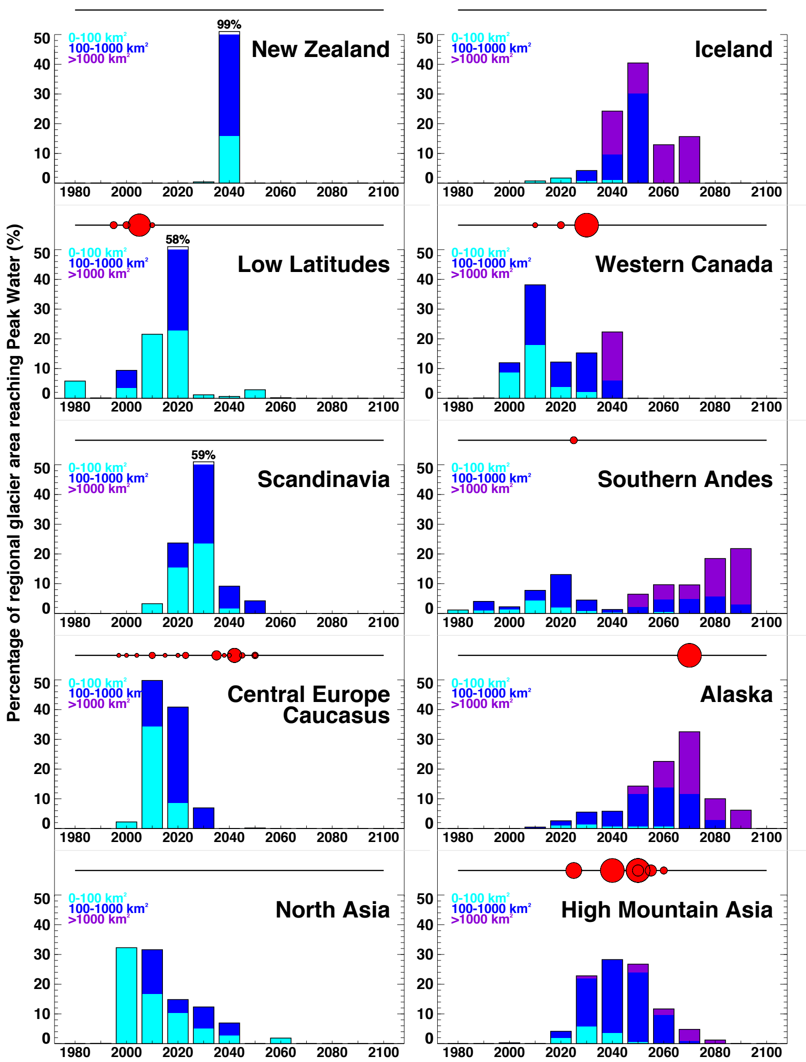

Figure 2.5: Timing of peak water from glaciers in different regions. Depicted is the fraction of regional glacier area as a function of peak water aggregated in 10-year bins. Peak water refers to the year when annual glacier runoff will decrease due to glacier shrinkage after a steady melt-induced increase. The bars refer to the data by Huss and Hock (2018) who used a global glacier model to compute the runoff of all glaciers per region until the year 2100 based on 14 GCMs and the RCP4.5 emission scenario. Red circles mark peak water estimates from individual case studies; circle diameter is proportional to investigated glacier area [PLACEHOLDER FOR SECOND ORDER DRAFT: additional studies to be included and reference to table with references of these case studies in Supplementary Material].

Total runoff will increase or decrease, depending on the balance between changes in precipitation and meltwater from ice and snow or the timing to reach its peak (Bliss et al., 2014). For example, Shigar river in Karakoram in Pakistan, glacier melt contribution turned from increase to decrease but the ice loss was compensated by precipitation increase (Soncini et al., 2015).

Regions with a high contribution of glacier runoff to total runoff may be highly affected by glacier runoff changes as glaciers shrink. Catchments with large ice volumes project an increase in runoff but regions with smaller ice volumes presently project decrease in runoff (Huss et al., 2017). In tropical Andes accelerated glacier melt may further increase a glacier's contribution to river flow because of the glacier's negative mass balance (La Frenierre and Mark, 2014). But this effect is temporary and will decline with decreasing glacier size (Pouyaud et al., 2005). Given that uncertainty in observation and ability to model precipitation in high mountains, however, uncertainty is still high in projected runoff in high mountains.

AR5 recognized consistent seasonal changes in areas influenced by snowfall and snowmelt. The latest analysis of observed and simulated runoff confirms the earlier shift of peaks in runoff in high mountains influenced by seasonal snow and glacier melt (*high confidence*). Earlier peaks in runoff are observed (Shen et al., 2018), simulated (Kriegel et al., 2013; Duethmann et al., 2015; Engelhardt et al., 2017b) or projected in many mountain regions (Addor et al., 2014; Gan et al., 2015; Ma et al., 2015; Ragettli et al., 2016; Engelhardt et al., 2017a; Etter et al., 2017).

2.3.1.2 Hydropower

Changes in river runoff, as a result of cryosphere change, can result in considerable impacts to the provision of water for power generation. There is a close association between hydropower and mountainous regions, giving the amount of power that can be generated is directly proportional to the difference in height between the inlet and the outlet (e.g., McMahon, 1992), and thus hydropower installations are typically in mountainous areas. Water for hydropower reservoirs and plants often originates from glacier and snowmelt in the high altitude areas, so changes in the cryospheric components can directly affect water availability for hydropower. Hydropower comprises about 16% of electricity generation globally but is a substantial proportion, sometimes close to 100%, in many mountainous countries. It is difficult to ascertain the exact impact of glacier recession on hydropower as the impacts can vary substantially across a region, but different studies predict that it may eventually lead to marked impacts on the seasonality and volume of streamflow (Rasul and Molden, in review).

Many hydropower plants were constructed according to existing historical meteorological and hydrological data, and may need considerable modification to operate under a different streamflow and climate regimes (Section 2.3.1.1). An increase in frequency or magnitude of extreme events will increase risk for hydropower plants and may bring risks to energy security. For example, glacier retreat in the Cordillera Blanca, Peru, can have a negative impact on hydropower production because of the likely decrease in river discharge during the dry season (Mark et al., 2010; Chevallier et al., 2011; Baraer et al., 2012; Condom et al., 2012). Hydropower constitutes a major component of the power mix in many Andean countries (Vergara et al., 2007). When glacier runoff declines, it will often be necessary to construct additional storage to maintain the same level of power production.

While more even contribution from runoff might advantage reservoir management, a decrease in total annual runoff expected for reservoirs fed by ice melt is likely to negatively affect production in Canton Valais, Switzerland (Fatichi et al., 2013). At the upper Rhone Basin in Switzerland, the management of hydropower reservoirs is affected by significant reduction in glacier melt runoff and seasonal shifting of runoff (Clarvis et al., 2014). Although in the short run increasing flows in Upper Rhone Basin may favour higher production in ice-fed reservoirs, the longer term total annual decrease in ice-fed reservoirs is likely to negatively affect production (Fatichi et al., 2013; Gaudard et al., 2013; Gaudard et al., 2014).

Response measures for hydropower to accommodate changes in the cryosphere fall into two categories. The first is response necessary due to the long-term changes in runoff available for hydropower, which can be caused by changes in the cryospheric reservoir (usually the change in glacier volume) and by a change in the seasonality of snowmelt runoff. The other category is response measures due to extreme events such as floods and droughts. Floods, and especially glacier floods can cause a sudden increase in sediment input to a reservoir or hydropower plant.

However, hydropower reservoirs can also be used for response concerning issues related to changes in the cryosphere. As water is available for use downstream of the hydropower facility, a reservoir can be used to safeguard freshwater supply for drinking and irrigation. Reservoirs downstream of glaciers are especially useful in alleviating the effects of glacier floods (Box 2.4) (Jackson and Ragulina, 2014; Colonia et al., 2017a).

Many hydrological models either do not or only very simplistically incorporate glacier changes (Section 2.3.1.1). Furthermore, access to hydrological data is often difficult in high mountains (Box 2.1). These issues make it difficult to forecast the capacity of hydropower (e.g., the Santa River drainage in Peru) (Condom et al., 2012), even though mitigation of the effects of changes on hydropower is constrained by many factors, not only the natural ones concerning climate change.

For mature technologies such as large hydropower, a large fraction of available technical potential in Organisation for Economic Cooperation and Development (OECD) countries has been exhausted and the largest future expansion is expected in the non-OECD countries of Asia and Latin America. Hence, for mitigation to be successful, the problems concerning data access and incorporation of knowledge into operational procedures need to be addressed.

According to a survey carried out by the International Hydropower Association, 98% of the polled organisations agree that the effects of climate change are already being felt by their organisation or will be felt within the next 30 years (IHA, 2017). Most hydropower agencies and regulatory bodies are responding to projected changes in water resources by focusing on studies that quantify the projected hydrological changes for their regions, sometimes combined with estimates of generation losses [refs, examples]. However, others are more focused on developing possible adaptation strategies given the anticipated changes in the hydrological regime. Only a few organisations are incorporating current knowledge of climate change into their investment decisions, or into production and maintenance planning. Due to the large uncertainty in different climate change projections and output from different models, some hydropower agencies or investors have looked at several different scenarios and different models [PLACEHOLDER FOR SECOND ORDER DRAFT: reference to Tajikistan study to be added]. However, the World Bank (who have approved around 150 projects related to hydropower since 2003) have used a decision tree approach as an alternative to basic project level climate change assessments (Bonzanigo et al., 2015). This begins by outlining key uncertain factors that may affect a project. Potential vulnerabilities that a project incurs if one or a combination of these factors falls into problematic ranges are then identified. This is accomplished using a "climate stress test" which is a carefully structured sensitivity analysis. It does not restrict the range of climate changes considered to simply the range that global climate models produce, since these models do not necessarily delimit the true range of uncertainty.

2.3.1.3 Water Quality

Cryosphere change in the mountains can significantly influence water quality, affecting both humans and ecosystems. For example, soluble reactive phosphorus (SRP) concentration in rivers downstream of glaciers is predicted to decrease with declining glacier coverage in watersheds (Hood and Berner, 2009) (*high confidence)*. A large proportion of the reactive P flux is loosely associated with suspended sediment (Hawkings et al., 2016). In contrast dissolved organic carbon (DOC), Dissolved Inorganic Nitrogen (DIN) and Dissolved Organic Nitrogen (DON) concentrations in pro-glacial rivers are likely to increase with glacier shrinkage (Milner et al., 2017) (*medium confidence)*. However as DOC increases with more glacial melt, DOC bioavailability will change because DOC derived from glacier runoff is highly bioavailable (Hood et al., 2009) and can be readily incorporated into downstream biota (Fellman et al., 2015). Globally, mountain glaciers are estimated to release about 0.6 Tg yr^{-1} of DOC to downstream ecosystems and future increases in runoff from glaciers is to release of as much as 10 Tg of glacier-derived DOC by 2050 (Hood et al., 2015). The rate at which dissolved organic carbon (DOC) was released from glaciers in the high mountains of the Tibetan Plateau was estimated to be ~0.03 Tg yr^{-1}, which suggests that DOC is released more efficiently from Asia mountain glaciers than from the Greenland ice sheet (Liu et al., 2016).

Besides the effect on changes of the mountain cryosphere by decreasing the surface albedo (Section 2.2.1.4), black carbon release is also associated with other legacy pollutants notably persistent organic pollutants (POPs), particularly polycyclic aromatic hydrocarbons (PAHs), and heavy metals (Hodson, 2014). The melting of alpine glaciers in the Himalayas contributes POPs to the surface waters in the nearby Gangetic Plain during the dry season (Sharma et al., 2015). PCBs have been linked to glacial melt and although their use has declined or ceased there is lag time of release from glaciers (Li et al., 2017a). Glaciers also represent the most unstable stores of dichlorodiphenyl-trichloroethane (DDT) in European and other mountain areas flanking large urban centres and has accumulated in lake sediments downstream from glaciated mountains (Bogdal et al., 2010).

Of the heavy metals, mercury is of particular concern and an estimated 2.5 tonnes has been released by glaciers to downstream ecosystems across the Tibetan Plateau over the last 40 years (Zhang et al., 2012). In more pristine areas, geogenic Hg contributions from sediment-rich glacier runoff can be as large or larger than the flux of Hg released from melting ice (Zdanowicz et al., 2013). Both glacier erosion and atmospheric deposition contributed to the high rates of total Hg export found in a glacierized watershed in coastal Alaska (Vermilyea et al., 2017) However, a key issue is how much of this glacier-derived Hg, largely in the particulate form, is converted to toxic methyl mercury downstream. The release of toxic contaminants, particularly where glacial meltwaters are used for irrigation and drinking water in the Himalayas and the Andes, is potentially harmful (Hodson, 2014) (*medium confidence)*. In addition, water originating from areas of permafrost degradation can also contribute heavy metals that exceed guideline values for drinking water quality (Thies et al., 2013). Based on the dilution with direct runoff and water from non-permafrost areas, these permafrost effects on water quality are likely most pronounced in small and arid catchments. Bioflocculation increases residence time on the glacier and may reduce overall toxicity of contaminants (Langford et al., 2010) and wetland vegetation can remove some of the heavy metals from reaching downstream area.

2.3.1.3.1 Agriculture and irrigation

The evidence on the impacts of cryosphere change on agriculture consists largely of case studies, unevenly distributed across regions. The reported findings emphasize the effects of changes in glaciers and snow cover on river runoff, which provides irrigation water that is important for cultivation of crops and pasture. The high spatial variation in these changes lead to high variation in changes of river runoff. Some areas have already been observed to face reductions in irrigation water (*medium evidence, high agreement*), with many other projected to do so by the end of the century (*very high confidence*).

The evidence for attributing changes in irrigation supply to cryosphere processes and river runoff is based on both scientific observations and indigenous and local knowledge, the former often more systematic in nature and more focused on large rivers in middle and lower portions of major basins, the latter often more localized and more focused on rivers of different sizes in upper portions of basins. There have been few efforts to compare, reconcile and integrate these two sets of observations.

In addition, cryosphere changes may affect agriculture through their impacts on land cover and on soil (*medium confidence*). Reduction in snow cover and thawing of permafrost have increased erodibility of mountain soil, which were previously less erodible (Chaulagain, 2015); these changes may have cascading effects on agriculture and food production. Change in hydrological regimes also contributes to changes in the land cover and land use, which may affect the role of forests in protecting soil and storing water, with potential cascading effects on downstream areas.

Climate change impacts agriculture in high mountain regions in other ways as well. Increasing temperatures will increase crop evapotranspiration, thus increasing water demand for crop production to maintain optimal yield (Beniston and Stoffel, 2014) (*high confidence*). Rising temperatures are associated with upslope movement of cropping zones, which favours some farmers in high mountain areas, who have become able to cultivate new crops. Irregular precipitation and increased frequency and intensity of extreme events also impact food production (Fuhrer et al., 2014). Agriculture in high mountain areas is sensitive to non-climate drivers (Porter et al., 2014) as well, such as market forces and political pressures (Montana et al., 2016; Sietz and Feola, 2016; Figueroa-Armijos and Valdivia, 2017) though these lie largely outside the scope of this chapter.

The current state of knowledge on adaptation activities in mountain agriculture rests largely on case studies of specific communities, valleys or watersheds, and thus limited to their spatial and temporal scope and context. Large-scale review and synthesis studies, based also on other complementary data sourced from remote sensing, national statistics, or other systematic methods to establish trends over space and time, remain limited. The extent of adaptation activities is variable, with significant efforts in some locations, and little or none in other. The majority of the activities are autonomous, though some are planned, or carried out with support from national governments, NGOs, or international aid organizations (*medium confidence*).

A number of distinct foci of adaptation activities for mountain agriculture have been reported, both within agricultural production systems and in related livelihood activities, though adaptation activities are absent in a number of cases. Systematic evaluations of these efforts are few, though some case studies indicate that shifts in agricultural practices have contributed to the maintenance of livelihoods and food security, while others find that limitation of these adaptation activities have led to increased outmigration (Section 2.3.6.2) (*limited evidence, medium agreement*).

[START BOX 2.5 HERE]

Box 2.5: Local Adaptation Responses to Cryosphere Shrinkages and Water Shortage in Northwest India

Cryosphere changes have impacted water resources and livelihoods in Ladakh, a cold mountain desert located in the western Himalaya in the Indian state of Jammu and Kashmir (Clouse et al., 2017). Agriculture in Ladakh has long confronted water scarcity, particularly before the monsoon, when river flow, which supports irrigation, is low (Bhasin, 1997; Nandargi and Dhar, 2011). Reduced snow and glacier retreat over the last three decades has reduced meltwater contributions to rivers, exacerbating chronic drought (Crook and Osmaston, 1994; Clouse, 2016). To address the water shortage for irrigation, villagers in the region have developed a number of adaptation measures and techniques, including ice stupas (Box 2.5, Figure 1), frozen ponds and snow barriers, which store meltwater as ice in winter and release it in spring.

To construct an ice stupa, glacier meltwater is conveyed by pipes at night to vertically-mounted sprinklers located above fields. It falls in small droplets and freezes, forming the characteristic stupa-like shape. It remains frozen until spring, when it melts and flows down to the fields (Clouse 2016, 2017). Frozen ponds are formed from water which is conveyed across a slope through channels and check dams to shaded surface depressions near the villages. The diverted water freezes into ice reserves, known locally as 'artificial glaciers,' which melts in the spring and flows to fields (Vince, 2009; Clouse, 2016; Shaheen, 2016). Snow barriers bands collect snow rather than meltwater. They consist of free-standing masonry walls, located near high mountains passes, which trap snow that would otherwise be carried by wind into other drainages. The stored snow melts in the spring, flowing down to fields (Chalise and Khanal, 1996; Clouse, 2016).

These three interventions irrigate fields which otherwise would be uncultivated, thus supporting local agriculture. The ice stupas have the potential to support tourism, and to maintain local social and religious identities (Clouse et al., 2017). These adaption measures and techniques, particularly snow barriers, use local materials and draw on local knowledge (construction techniques), suggesting that they are easily replicable with appropriate support, particularly financial resources (Clouse, 2016). Ice stupas and frozen ponds may require regular management and maintenance. The three innovations might be useful to address irrigation water shortages in areas impacted by glacier retreat.

Box 2.5, Figure 1: Glacier ice stupa in Ladakh, India (Clouse et al., 2017).

[END BOX 2.5 HERE]

Adaptation activities within agricultural systems include a variety of practices and measures. The most widely reported types are presented below.

1. Adoption of new irrigation technologies. Water-delivery technologies which reduce loss are adopted Chile (Young et al., 2010). Similarly, greenhouses are adopted in Ecuador (Knapp, 2017) and Nepal (Konchar et al., 2015) to reduce evapotranspiration, and reduce frost damage . Limited access to finance is a barrier to these activities. For a discussion of innovative irrigation practices in India (Box 2.5).
2. Making investments to tap more distant sources of irrigation water. For a discussion of such efforts in northern Pakistan, (Cross-chapter Box 1.2).
3. Adoption of new crops and varieties. Farmers who rely on irrigation in the Naryn River basin in Kyrgyzstan have shifted from the water-intensive fruits and vegetables to fodder crops such as barley and alfalfa, which overall are more profitable. Upstream communities, with greater access to water and more active local institutions, are more willing to experiment with new crops than those further downstream (Hill et al., 2017). In other areas, crop choices also reflect responses to rising temperatures along with new market opportunities such as the demand for fresh vegetables by tourists in Nepal (Konchar et al., 2015; Dangi et al., 2017) and the demand for roses in urban areas in Peru (SENASA, 2017). Non-climatic factors also facilitate the adoption of new crops such as indigenous and local knowledge, access to local and regional seed supply networks, proximity to agricultural extension and support services.
4. Adaptation within pastoral systems. Reduced river flow has impacted irrigated pastures as well as crops production. Local pastoral communities have responded to these challenges with techniques broadly similar to those in agricultural settings by expanding irrigation facilities for instance in Switzerland (Fuhrer et al., 2014). Indigenous pastoral communities have strengthened the control of access to existing irrigated pastures, and tapped into new water sources to irrigate new areas in Peru (Postigo, 2014) and Bolivia (Yager, 2015). Local institutions and embedded social relations play vital role in enabling communities to respond to the impacts. In an example of indigenous populations in the US, the two tribes who share a large reservation in the northern Rockies rely on rivers which receive glacier meltwater to irrigate pasture, and to maintain fisheries, domestic water supplies, and traditional ceremonial practices. Tribal water managers have sought to install infrastructure to promote more efficient water use and to protect fisheries, but these efforts have been impeded by land and water governance institutions in the region and by a history of social marginalization (McNeeley, 2017).
5. Supplementary off-farm income. Agricultural households supplement livelihoods with off-farm income from tourism (Section 2.3.5.1) and wage labour (Section 2.3.6.1) to cope with challenges brought by cryosphere change.
6. Integration of multiple adaptation activities. In some cases, several of these adaptations are carried out simultaneously. Local water user associations in Kyrgyzstan and Tajikistan have adopted less water-intensive crops and reorganized the use and maintenance of irrigation systems, investing government relief payments after floods. (Stucker et al., 2012). Similar combinations are reported from India (Dame and Mankelow, 2010; Clouse, 2016; Nüsser and Schmidt, 2017) and Peru (Postigo, 2014). In contrast, fewer steps have been adopted in Uzbekistan, due to low levels of capital availability and rigidities in national agricultural policies (Aleksandrova et al., 2014).

In some cases, research studies report an absence of such practices and measures. Adaptation efforts in the agricultural sector are sometimes scanty or entirely absent (*medium evidence, high agreement*). Planted areas have been reduced in a number of different areas in Nepal (Sapkota et al., 2010; Gentle and Maraseni, 2012; Sujakhu et al., 2016; Bastakoti et al., 2017) and in India (Bastakoti et al., 2017). Though local residents perceive the impacts on agriculture and livelihoods, few undertake adaptation activities. Barriers include a lack of finance and technical knowledge, weakness of community and state organizations, and ambiguous property rights. In the Cordillera Blanca in Peru, there have also been reports of declining agricultural yields, due to cryosphere changes, in the absence of adaptation activities. Irrigation water is less available in some tributaries of the Santa River, while dry spells and unseasonal frosts have also impacted agriculture, creating food insecurity (Bury et al., 2011); market pressures and shifts in water governance also put pressure on agriculture (Rasmussen, 2016).

Traditional Saami reindeer husbandry in northern Scandinavia is highly threatened by climate warming, in particular rain-on-snow events, to which few responses are available (Keskitalo, 2008; Forbes and Kumpula, 2009; Eira, 2012; Mathiesen et al., 2013; Cramer, 2014). Ice layers in the snow lead to reindeer starvation in their wintering habitats, and to massive abortion before springtime calving or calves with reduced vigour.

2.3.1.3.2 Drinking water supply

Very few studies provide thorough empirical assessments of the effects of cryosphere change on drinking water supply. The Andes have received the most attention, especially the national capitals of Quito, Ecuador; Lima, Peru; and La Paz, Bolivia (Chevallier et al., 2011). Of these, the cryosphere impacts are most severe in La Paz (Buytaert and De Bièvre, 2012). The contribution of glacier water to the city between 1963 and 2006 was assessed at 15% (Soruco et al., 2015), though rising as high as 86% during drought months (Buytaert and De Bièvre, 2012). It shows the vulnerability of the city to future water scarcity from cryosphere changes.

Other Andean cities also face threats to their water supplies from glacier retreat, such as Huancayo and Huaraz, in Peru. The fraction of glacier meltwater that flow into the rivers that serve these cities is 13% and 19%, respectively; these cryosphere contributions to the cities' water supplies have seen significant decline in recent decades. Population growth and poor infrastructure maintenance in these cities exacerbate water scarcity (Buytaert and De Bièvre, 2012; López-Moreno et al., 2014; Somers et al., 2018).

Similarly, in the Himalaya region many densely populated large cities such as Islamabad and Delhi are situated in the bank of rivers and depend partly on glacier melted water for urban water supply (Rasul and Molden, in review). Shrinkages of cryosphere may bring risk of water supply.

2.3.1.4 Water Governance and Response Measures

Changes in the cryosphere, as a response to climatic change, contribute to the observed and projected changes in hydrological regime (Section 2.2.3) and river runoff (Section 2.3.1.1), with consequences for the water provisioning services that are important local and other social-ecological systems at the catchment level and further downstream. In addition to the biophysical and socio-economic drivers and feedbacks for changes described in earlier sections, a key consideration for the assessment of impacts and responses through adaptation and mitigation, rests on how water is accessed, utilized, managed and governed across scales, i.e., its governance (Debarbieux and Price, 2008; Price, 2015). Despite its importance, a broader assessment of the many and complex interlinkages between multiple socio-economic and cultural aspects that are important and relevant for water governance, these fall outside the scope of assessment for this chapter. However, a changing cryosphere poses certain risks to the governance of water resources, given reported examples of conflict and tensions among key actors in high mountains and neighbouring regions (Bocchiola et al., 2017; Milner et al., 2017).

Despite growing recognition of and advocacy for transboundary cooperation as a means to support the governance of water as a common good (Rasul and Sharma, 2014), evidence of implementation and evaluation of their effectiveness to mitigate conflict risks has remained limited, with few exceptions. Coordination and mainstreaming of common transboundary adaptation strategies remains a key challenge for many mountain regions, primarily due to weak institutional capacities and limited voice of mountain communities in key decision making policy processes at local, regional, national and transboundary water systems. For example, differences in political and other interests along transboundary river systems, are reasons for conflicts between the upstream and downstream communities in different countries in the Hindu Kush Himalayas (Molden et al., 2014; Rasul and Sharma, 2014; Rasul, 2015).

Transboundary policies that account for adaptation to climate change can address conflict management and improve co-management of transboundary resources, such as in the context of a changing mountain cryosphere (e.g., Immerzeel et al., 2010; Lutz et al., 2014). Adaptation policies that connect local and national adaptation efforts at the transboundary level are also receiving attention in the literature as a key consideration. For example, the upcoming Bangladesh Delta Plan 2100 makes a provision for strengthening international cooperation and transboundary river management with neighbouring countries. However, its implementation is complex, due to different socio-economic and political conditions in the four countries. For example, in Nepal, the adaptation policy in mountain areas focuses largely on forestry and soil conservation, while in Bangladesh the focus is on water and flood management (Pandey et al., 2016; Gain et al., 2017). Moreover, India has a strong domestic agricultural market and thus focuses on the resilience of its agricultural sector and related activities. Despite their common element in addressing water and its governance, the differences in how these policies frame adaptation and their intended effects make it difficult to implement as a common transboundary adaptation strategy, resulting in low scalability or transferability of policies across cases and mountain regions (Vij et al., 2017).

Recently, however, a few efforts have been made in different mountain regions for transboundary cooperation on monitoring and assessing glacier balance, river runoffs and better management of cryosphere challenges. A few examples are given below.

- In Alps, Governments of Austria, France, Germany, Italy and Switzerland initiated a joint project to monitor permafrost changes and developing common strategy for managing permafrost risk and better water resource management and disaster risk reduction (Mair et al., 2011).
- In Andes, Regional Project for Adaptation to the Impact of Rapid Glacier Retreat in the Tropical Andes was launched in 2008 by the World Bank to strengthen resilience against the impacts of glacier retreat (CARE, 2010).
- In Central Asia, five countries Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan initiated a regional collaboration on glacier monitoring and strengthen partnerships for transboundary water management (Komagaeva, 2017).

[PLACEHOLDER FOR SECOND DRAFT: assessment of key literature linking and addressing governance issues related to adaptation to climate change and water in high mountains at global and regional scales (e.g., Price, 2015), including e.g., key Conventions and other global treaties].

2.3.2 Other Provisioning Services

In some mountain regions glacier retreat and related processes of change in the cryosphere have afforded greater accessibility for extractive industries and development of other activities that can be broadly categorised as a provisioning service. Accelerated cryosphere shrinkage has made possible and facilitated cold mountain mining activities in South America, North America, and Central Asia, which involve complex interactions with social, cultural, economic, political, legal, ecological, hydrological, hazard, or nature-protection issues, where climate change impacts also play a role (Evans et al., 2016; Petrakov et al., 2016). However, there is limited evidence with medium agreement of the extent that impacts to, and from these extractive activities, relate directly to climate change.

[PLACEHOLDER FOR SECOND ORDER DRAFT: assessment of other key literature submitted that addresses other provisioning services; title of section may change accordingly].

2.3.3 Landslide, Avalanche and Flood Hazards

High mountains are particularly prone to mass movements such as snow, rock or ice avalanches, rock or debris slides, debris flows or floods, due to their relief energy and climatic settings. Where these mass movements interact with human activities, settlements or infrastructure, they generate risk, and specific risk management measures adapted to the special environmental conditions, vulnerabilities and exposures in mountains are necessary. Snow and ice above and below the surface play a key role in slope stability and mass movement. The behaviour of snow, ice, and frozen soil or rock changes dramatically when approaching and passing 0°C leading to changes in many mass movement processes. This section assesses knowledge gained since previous IPCC reports, in particular Chapter 3 of the Special Report on 'Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation' (Seneviratne et al., 2012).

2.3.3.1 Observed and Projected Changes

The content of this section is divided according to the spatial reach of hazards and cascading events, ranging from localised effects on mountain slopes and adjacent valley bottoms (up to several kilometres) to events reaching far into major valleys and even surrounding lowlands (tens to hundred kilometres). The sporadic nature of disasters together with the strong geographic variability of vulnerability and exposure require to base assessments of change not only on statistical evidence from actual events but also on laboratory experiments and theoretical considerations.

Landslides can be identified using optical satellite data or aerial photographs but can go undetected even with repeat observations (Coe et al., 2018). More recent advances in radar remote sensing (Kääb, 2008), seismic teledetection (Ekstrom and Stark, 2013), and the exponential increase in free satellite data have resulted in more accurate and corroborative data collection. Landslide inventories may underrepresent the true landslide affected populations; therefore it is recommended that inventories span at least 30 years for properly assessing the changes over time (GAPHAZ, 2017). In addition, indigenous and local knowledge can provide information about cryosphere-related mass movements and floods, which killed people or impacted settlements, infrastructure and livelihoods (Cruikshank, 2014).

2.3.3.1.1 Close to medium reaching hazards

Permafrost thaw is likely to increase the rate of movement or subsidence of frozen debris bodies (Section 2.2.4). Landslides and permafrost-related subsidence can impact infrastructure on site, for example undermining foundations, or off-site, impacting objects some distance away. Local subsidence, heave, and creep of frozen ground typically affect only structures on them or in the immediate vicinity and can also cause problems for engineered structures such as cable car stations, hazard protection structures, lift pylons, roads, rail lines, trails, or buildings (Phillips, 2006; Phillips and Morrow, 2007; Jin et al., 2008). The causes and rates of slope movement and subsidence/heave are varied but strongly related to temperature and water input (Wirz et al., 2016; Kenner et al., 2017). Where massive ground ice is exposed, retrogressive thaw slumping can develop (Niu et al., 2012).

There is *high confidence* (*medium evidence*, *high agreement*) that rockfall increased within zones of thawing permafrost over the past half-century (Allen et al., 2011; Ravanel and Deline, 2011; Fischer et al., 2012; Coe et al., 2018). Inventories are often incomplete, and good permafrost data is lacking for many regions. At the same time, permafrost thaw is expected to increase the likelihood of rock fall and rock avalanches, based on theoretical considerations (Davies et al., 2001; Gruber and Haeberli, 2007; Krautblatter et al., 2013) and empirical evidence of ice being present in the detachment zone (Bottino et al., 2002; Geertsema et al., 2006; Ravanel et al., 2010; Phillips et al., 2017; Ravanel et al., 2017; Sæmundsson et al., 2018). Based on empirical evidence (Allen and Huggel, 2013; Ravanel et al., 2017; Coe et al., 2018) extreme events, such as summer heat waves, can trigger rock instability with only short delay. Summer heat waves may also have triggered for the 2010, largest recorded landslides in British Columbia, at Mount Meager (Roberti et al., 2018) and Sheemahant River (Ekstrom and Stark, 2013) that travelled 12 and 25 km into valleys, respectively. This is in line with theoretical considerations about fast thaw of frozen fractures by water circulation (Hasler et al., 2011) but may also be explained by mechanisms not involving permafrost (Luethi et al., 2015).

Similarly, permafrost thaw can increase the frequency and volumes of landslides from frozen sediments, as concluded from theoretical work and field evidence from polar areas (McRoberts and Morgenstern, 1974; Lewkowicz and Harris, 2005; Kokelj et al., 2009; Lacelle et al., 2015) and mountains (Lyle et al., 2004; Wei et al., 2006; Ravanel et al., 2010; Allen et al., 2011; Coe et al., 2018). A recent study of rock avalanches initiating from high elevation slopes in Alaska from 1984-2016, suggested that the most recent cluster of rock avalanches was a result of permafrost degradation in response to long-term and short-term warming. Annual landslide rates doubled in the last five years of the study, plus volumes and travel distances also increased (Coe et al., 2018). In an inventory of large landslides in northern British Columbia from 1973 to 2003, the number of rock avalanches, within zones of expected warm permafrost doubled in the last decade of the observation period.

The acceleration of rock glaciers can result in increased debris-flow activity by increasing material supply to debris-flow starting zones (Wirz et al., 2016; Kummert et al., 2017). However, the causative effects can be difficult to distinguish from other effects, such as precipitation (Stoffel and Graf, 2015).

Ice break-off and subsequent ice avalanches are often a natural form of ablation from steep glaciers and their fronts (Faillettaz et al., 2015). Where climatic changes alter the geometry and thermal regime of such steep glaciers, they may cause related ice avalanche hazards both to increase or decrease, depending strongly on local conditions (Fischer et al., 2006; Fischer et al., 2013; Faillettaz et al., 2015). General trends are unknown and are not expected theoretically. Several cases are known where large parts or even complete steep glaciers fail, and there is *high agreement* that for cold-based steep glaciers such failures are promoted by an increase in basal ice temperature (Fischer et al., 2013; Gilbert et al., 2014; Faillettaz et al., 2015).

Surges constitute a wide-spread form of glacier instability involving large parts of glaciers, but slower velocities of mass movement compared to ice avalanches (Harrison et al., 2015; Sevestre and Benn, 2015). In a number of documented cases, glacier advances due to surge dammed up a river causing a major flood hazard. In rare cases, glacier surges directly inundate agricultural land and damage infrastructure. Though not completely clear, surge initiation involves drastic spatio-temporal changes in the subglacial drainage system, possibly related to subglacial sediments or changes in the ice thermal regime. The positive feedback mechanisms involved in glacier surging do not require climatic changes in order to occur (Murray et al., 2003). Although climate-driven processes such as enhanced melt-water production have been shown to trigger or enhance surge-type instability (Dunse et al., 2015), there is *limited evidence* if and how climatic changes could alter the frequency and magnitude of surges and surge-like glacier instability.

A range of slope instabilities concerning glaciers is connected to glacier retreat, which often leaves behind unconsolidated morainic debris (Allen et al., 2011; Evans and Delaney, 2015). Moraine sections, typically over-steepened directly after glacier retreat, are documented to slide or collapse, leading typically only to local hazards, unless triggering down-stream chain reactions. Also high-mountain debris flows were shown to have their source in unconsolidated morainic material left behind by recent glacier retreat (Zimmermann and Haeberli, 1992). Over timescales of decades to millennia, or even over glacial cycles, rock slopes adjacent to glaciers or formerly covered by them tend to become unstable, start to creep and, in some cases, eventually collapse. Increased landslide activity in recently deglacierized zones has received increased attention (Evans and Clague, 1994; Ballantyne, 2002; Holm et al., 2004; Cossart et al., 2008; Korup et al., 2012; McColl, 2012; Deline et al., 2015; Kos et al., 2016). The major factor in these rock slides is the change in slope stress regime caused by de-buttressing of the valley flanks from glacier thickness loss, acting on specific geological circumstances, and possibly combined with other factors such as changes in the hydrologic and thermal regime. According to Cloutier et al. (2016) more than two-thirds of the large landslides that occurred in northern British Columbia between 1973 and 2003, occurred on Little-Ice-Age-exposed cirque walls. According to Gramiger et al. (2017), it is especially the glacial erosion during glacial cycles that causes debuttressing, and ice advance favors topping, while ice retreat favors sliding. In some cases, such as on the high Monta Rosa rock face, polythermal glacial retreat and permafrost degradation occur together, destabilizing the slopes (Fischer et al., 2006; Fischer et al., 2013; Deline et al., 2015), resulting in some 25 Mm^3 of material loss between 1988 and 2007.

There is *high confidence* that glacier retreat destabilizes adjacent debris and rock slopes, but due to incomplete knowledge of such events for remote mountains and the influence of other local and regional factors (Allen et al., 2011), statistical spatial and temporal evidence of how the current global glacier retreat influences the frequency and magnitude of such instabilities remains incomplete.

Snow avalanches can occur spontaneously, following significant snow precipitation episodes or wet-snow conditions conducive to wet-snow avalanches. These natural correspond to most avalanches reaching valley bottoms and causing damages to infrastructures. Avalanches can also be triggered by the passage of skiers, snowmobiles or animal, fall of rocks or ice, or explosives (control measures). These are referred to as artificial avalanches in the following, and are the type of avalanches that cause fatalities among recreationists. It is expected based on theoretical and empirical considerations that changes in snow cover characteristics induce changes in natural avalanche activity, including on interannual timescales. Tree-rings and historical archives are used to infer longer-term changes of avalanche activity. Ballesteros-Cánovas et al. (2018) provided evidence for an increase in avalanche activity in Western Indian Himalaya over the past decades, which they related to climate change associated to increased frequency of wet-snow conditions, favouring wet-snow avalanches in the release areas. In the European Alps, changes in avalanche patterns were related to the end of the little ice age (Corona et al. (2012) in the Southern French Alps, Laternser and Pfister (1997) in Switzerland). McClung (2013) analysed correlations between avalanche activity and climate modes of variability on annual time scales, in North and South America. Past changes in meteorological and snow conditions were shown to correlate with avalanche frequency and runout altitude in the French Alps (e.g., Eckert et al., 2013). The ratio of wet-snow to frequency of spontaneous avalanches was shown to be increasing in the Swiss Alps (Pielmeier et al., 2013) and French Alps (Naaim et al., 2017) over the 20th century. In Europe, different studies suggest that large avalanches tend to become smaller (lower mass, lower run-out distance) and that this trend is accompanied with the decrease of the proportion of avalanches with a powder part along with the decline in snow conditions (duration, amount) observed there since the 1980s (Eckert et al. (2013) in the French Alps, Gadek et al. (2017) in Tatras mountains). Mostly inconclusive results were reported by Sinickas et al. (2015) and Bellaire et al. (2016) regarding the relationship between avalanche activity and climate change in North America. Yet, these remain difficult to detect because of confounding factors including land use in avalanche terrain and changes of disaster risk reduction measures (avalanche defence and control, evacuation procedures etc.). In summary, *it is more likely than not* that avalanche activity has exhibited changes over the past decades (*medium confidence in detection, low agreement*), in particular through a change in the partitioning from dry to wet snow avalanches, and a reduction of dry snow avalanches size and run-out distance.

Future projections mostly indicate an overall decrease in seasonal snow amounts at the annual scale, but the occurrence of occasionally high snow precipitation amounts should remain significant throughout most of the 21st century (Section 2.2.1.2). A few studies have directly addressed how natural avalanche activity may evolve in the future. Castebrunet et al. (2014) have shown that for the French Alps future climate conditions under an SRES A1B scenario in mid and end-century may favour the appearance of a wet snowpack at high elevations or earlier in the season, even in the core of the winter season, which could have important consequences on a risk management perspective due to the need to upgrade or modify the prevention measures (Ancey and Bain, 2015). Katsuyama et al. (2017) reached similar conclusions in Northern Japan (Hokkaido Island). A few studies only have directly addressed how natural avalanche activity may evolve in the future according to these. Castebrunet et al. (2014) estimated an overall 20-30% decrease of natural avalanche activity for mid and end of the twentieth century, respectively, under SRES A1B scenario, compared to the reference period 1960-1990. Changes are projected to vary as a function of the season and altitude. Marked reductions of avalanche activity are expected during the spring season as compared to the winter season due to increased snow scarcity. The overall trend in terms of total avalanche activity will depend on the regions and altitude, and in some areas may increase first due to increased wet snow conditions at high elevation while the snowpack remains deep enough, then a decrease due to the continued recession of seasonal snow (Castebrunet et al., 2014; Mock et al., 2017).

In summary, it is *very likely* (*high agreement, medium evidence*) that cryospheric changes in mountain regions will favour major shifts in avalanche activity and character, through prolonging the period when wet snow avalanches can occur, and reduce the overall number and runout distance of dry snow avalanches in regions and altitudes experiencing significant reduction in snow conditions.

There is no published evidence addressing the links between climate change and artificial avalanche risk, neither for past nor future conditions. The avalanche danger level may change due to changing snow conditions on climate time scales, but the resulting risk and number of casualties will also strongly depend on the behaviour of recreationists with respect to day-to-day fluctuations of snow conditions *(limited evidence, medium agreement)*.

2.3.3.1.2 Far reaching hazards

Hazards related to mountain snow, glaciers and permafrost not only affect immediate downslope areas and valley bottoms underneath but can reach far down into main valleys and even lowlands. Glacier-related floods, including glacier lake outburst floods (GLOFs), are documented for most glacierized mountain ranges and are among the most far reaching glacier hazards that affect areas tens to hundreds of kilometres downstream (Carrivick and Tweed, 2016). Retreating glaciers often leave behind permanent or temporary moraine-, rock- or ice-dammed lakes at their fronts and margins (Carey, 2005; Frey et al., 2010; Gardelle et al., 2011; Loriaux and Casassa, 2013). Lake systems are shown to often develop on downwasting, low-slope glaciers where they coalesce from temporally highly variable supraglacial lakes (Richardson and Reynolds, 2000; Benn et al., 2012; Narama et al., 2017). Advancing glaciers have been documented to temporarily dam rivers, for instance through surging (Round et al., 2017), causing floods with particularly large volumes, peak discharges and reaches, once the ice dams breach. There is *high confidence* that current global glacier shrinkage causes new lakes to form and existing lakes to grow (Carey, 2005; Gardelle et al., 2011; Loriaux and Casassa, 2013; Zhang et al., 2015).

There is also *high confidence* that the number and area of glacier lakes will continue to increase in the future. Due to glacier retreat, new lakes will thereby develop closer to steep and potentially unstable mountain headwalls where lake outbursts can be triggered by the impact of various types of landslides (Frey et al., 2010; Allen et al., 2016a; Linsbauer et al., 2016; Colonia et al., 2017b). However, how the number of related floods changed in the recent past is not well known (Clague, 2000; Richardson and Reynolds, 2000; Mergili et al., 2013; Anacona et al., 2015a; Carrivick and Tweed, 2016; Harrison et al., 2017), although a number of GLOF cycles have been documented, spanning decades (Mathews and Clague, 1993; Geertsema and Clague, 2005; Russell et al., 2011). A decrease in glacier lake floods in recent decades (Carrivick and Tweed, 2016; Harrison et al., 2017) could suggest a delayed response of lake outburst activity to glacier retreat (Harrison et al., 2017) but existing GLOF inventories might be incomplete and significantly underestimate the number of events (Veh et al., 2018). In contrast to the lakes themselves, lake outbursts are also not necessarily directly coupled to climatic changes as a number of other regional and local spatio-temporal factors are important, and advancing, stagnant or retreating glaciers may all produce water bodies.

The thawing of frozen soil and the melting of buried ice in natural dams (Watanabe et al., 1995; Haeberli et al., 2001; Fujita et al., 2013) or debris-ice landforms (Erokhin et al., 2017; Narama et al., 2017) have been shown to lower their stability and contribute to outburst floods.

A rare type of glacier instability with large volumes (~ 10^7–10^8 m^3) and high mobility (up to 200-300 km/h), is the complete collapse of large sections of valley glaciers and subsequent ice/rock/sediment avalanches. Clearly documented for only three cases (Kolka Glacier in the Caucasus Mountains in 2002 (Huggel et al., 2005; Evans et al., 2009), and the twin Aru events, western Tibetan Plateau in 2016 (Kääb et al., 2018)), the relation and possibly proximity of some other cases of massive glacier instability to such glacier collapses is still open. Whereas climate changes seem not to have played a direct role in the 2002 Kolka Glacier collapse, climate-driven changes in glacier mass balance, melt and rain water input into the glaciers, and partially frozen glacier beds were clearly involved in the 2016 twin Aru collapses (Gilbert et al., 2018). Besides the 2016 Tibet cases, there is limited evidence how climate change could alter the potential for such massive and rare collapse-like glacier instabilities.

Floods originating from the combination of rapid melting of snow and intense rain precipitation (rain-on-snow events), are one the of most damaging floods in mountain areas (Pomeroy et al., 2016; Il Jeong and Sushama, 2018). The hydrological response of a catchment to a rain-on-snow event involves complex phenomena, as it depends on the specific meteorological conditions during the event. This includes turbulent fluxes driven by wind and humidity, which are responsible of most of the melting energy (Pomeroy et al., 2016), and the snow conditions including the snow thickness and liquid water content of the snowpack (Würzer et al., 2016).

For mountain areas in the western United States over the period 1949–2013, McCabe et al. (2007) found a positive association for the occurrence of rain-on-snow events in high elevation zones, and a decrease in occurrence at the lowest elevations. For Oregon (USA), (Surfleet and Tullos, 2013) demonstrated that for the 1986–2010 period there was a reduction in peak flows triggered by rain-on-snow events at low and mid elevations, and an increase in the highest elevation basins. Similar findings have been documented from European mountains. Moran-Tejéda et al. (2017) reported a decrease in rain-on-snow events at mid and low elevations in Switzerland for the period 1972–2016, despite warmer temperatures that were associated with a decrease in precipitation events and a reduction in snow cover during autumn and spring. Freudiger et al. (2014) analysed rain-on-snow events in the major basins of central Europe for the period 1950–2010, and reported that they increased in frequency at all elevations in January and February, and decreased in April and May at high elevation. Based on reanalysis data, Cohen et al. (2015) reported that there was a clear latitudinal gradient in the occurrence of rain-on-snow events in the Northern Hemisphere over the period 1979–2014, with more frequent rain-on-snow events at high latitudes in Arctic regions. Putkonen and Roe (2003) also reported a 40% increase in rain-on-snow events at latitudes above 45°N, and Ye et al. (2008) reported an increase in such events at high latitude areas in Eurasia, despite a clear trend of warming. In summary, it is *very likely* that an increase in rain-on-snow events and associated floods has occurred at high elevations and/or in high latitude areas, particularly during transitions periods from autumn to winter and winter to spring. It is *very likely* that there has been a decrease in rain-on-snow events at low elevation or meridional areas, except for the coldest months of the year.

Scenarios for the future reflect a continuation of the trends observed in past decades. Il Jeong and Sushama (2018) projected an increase in rain-on-snow events and associated floods in the period 2041–2070 (RCPs 4.5 and 8.5) from November to March in North America, and a decrease in spring. Based on SRES A1B (scenarios 2025, 2055, and 2085), the frequency of rain-on-snow events in the Swiss Alps is expected to increase at elevations higher than 2000 m a.s.l., with no significant changes below this threshold.

Based on sensitivity analysis, Beniston and Stoffel (2016) showed that the number of rain-on-snow events may increase by 50%, and with it the likelihood for related floods in the Swiss Alps, with a regional temperature increase of 2°C–4°C, and decrease with a temperature increase exceeding 4°C. Scenarios for most of the world's mountains indicate that increased warming is likely to lead to thinner and wetter snowpack conditions, which will exacerbate the hydrological response of mountain basins to the occurrence of rain-on-snow events (Würzer et al., 2016), and probably explains the prediction (Il Jeong and Sushama, 2018) of a greater increase in rain-on-snow runoff events than rain-on-snow precipitation events.

In summary, it is *likely* that frequency of rain-on-snow precipitation and runoff events will increase in those areas where increased temperatures will not markedly affect the duration of the snowpack (high elevation and/or high latitude areas), but will happen earlier in spring and later in autumn. It is *likely* that their frequency will decrease at lower elevation and/or lower latitude areas as a consequence of a marked decrease in persistence of the snow cover. It is *very likely* that higher temperatures will favour snowpack conditions that increase the hydrological response during rain-on-snow events.

2.3.3.1.3 Combined hazards and cascading events

The largest mountain disasters in terms of volume, reach, damage and lives lost that involve ice, snow and permafrost occur through a combination of processes or chain reactions (Anacona et al., 2015b; Evans and Delaney, 2015). Some process chains are frequent and typical, but others are rare, specific to local circumstances and difficult to anticipate. Glacier lake outbursts are often triggered by impact waves from snow avalanches, landslides, or calving events (Richardson and Reynolds, 2000; Anacona et al., 2015a), or by temporary blockage of surface or subsurface drainage channels (Benn et al., 2012; Narama et al., 2017). Rock slope instability and episodic catastrophic failure along several Norwegian fjords, for example, cause impact-wave hazards. The glaciers have long vanished, but occasionally large rockslides produce significant tsunamis (Hermanns et al., 2014; Roberts et al., 2014). A recent example of a landslide-generated wave comes from Taan Fiord, Alaska (Dufresne et al., 2017). Two large failures occurred on a recently debuttressed slope. The last of these landslides occurred in 2015 and entered the fjord, creating a 193 m wave, evident from a trimline on the opposite slope and then travelled more than 20 km down the fjord removing trees and soil along its path (Higman et al. in review). A 2017 tsunamigenic landslide that occurred in western Greenland (Gauthier et al., 2017) may have been related to permafrost degradation. The landslide-generated wave damaged a village and caused four fatalities.

Landslides in glacier environments entrain snow and ice that fluidizes, incorporate additional various loose glacial sediments or water bodies, eventually multiplying the mobility and reach of such mass movements compared to those without snow and ice involved (Huggel et al., 2005; Schneider et al., 2011; Evans and Delaney, 2015). Frozen conditions in rock and debris slopes and the often-associated ground ice volume have been shown to play an important role in landslide process chains, both by enhancing, for instance through fluidisation of ground ice, or stabilizing, for instance by cementing debris deposits. Glaciated frozen rock walls constitute particularly complex thermal, mechanical, hydraulic and hydrologic interactions between steep glaciers, frozen rock and its ice content, and unfrozen rock sections (Harris et al., 2009; Fischer et al., 2013; Ravanel et al., 2017).

Fluidisation of snow and ice produce exceptionally violent lahars from ice and snow-clad volcanoes in the event of eruptions (Barr et al., 2018). Most prominently in recent history, a medium-sized eruption in 1985 of Nevado del Ruiz volcano, Colombia, melted substantial amounts of snow and ice, producing lahars that killed more than 20,000 people in the city of Armero some 70 km downstream of the volcano (Pierson et al., 1990). In terms of geographic distribution of ice-capped volcanoes and related hazards the Cordilleras of the Americas are a hotspot, with several additional important locations on the Aleutians, Kamchatka, Japan, New Zealand and Iceland (Seynova et al., 2018). Climate-driven glacier changes are expected to modify the character of volcanic activity and their impacts, though in complex and locally variable ways and time scales (Barr et al., 2018; Swindles et al., 2018).

Combined and cascading disasters related to mountain glaciers and permafrost are too variable to detect current trends reliably. The uncertainty in the detection of trends for individual hazard elements of these process chains and their expected future development propagates and increases towards event cascades. It is reasonable but there is *limited evidence* of how event chains involving slope instabilities related to permafrost or glacier shrinkage (*medium to high confidence* for expected shrinkage) or glacier lakes (*high confidence* for expected increase in number) could increase in frequency or magnitude.

2.3.3.2 Vulnerability, Exposure and Impacts

Integrating across the traditionally diverging perspectives from the disaster risk management and climate adaptation communities, the concept of climate risk has emerged as a central concept in the policy-science dialogue, where risk is defined as a physical event (hazard) intercepting with an exposed and vulnerable system (e.g., community or ecosystem) (IPCC SREX and AR5) (Figure 2.6). A clear distinction here is that vulnerability is linked to the inherent characteristics of a society or system, while changes in climate primarily influence hazards and related trends (floods, landslides etc.) (Figure 2.7). Impacts are then the realisation of risk. In theory, this conceptualisation provides a sound basis for the adaptation strategies that consider both the changes in frequency or magnitude of hazards due to climate change as well as societal dynamics that shape the exposure and vulnerability of people and social-ecological systems (Figure 2.5). However even at global scales, few studies have moved to a comprehensive risk approach (Muccione et al., 2017), and for mountain regions, systematic risk assessments considering all underlying components are lacking (Allen, in review).

2.3.3.2.1 Drivers of exposure

There is *high confidence* that the exposure of people and infrastructure in high mountain regions has increased over recent decades, and this trend is expected to continue in the future. Tourism has been a main driver of this change, with often poorly regulated expansion of infrastructure such as roads, foot-tracks, and overnight lodging bringing more visitors into remote valleys and exposed sites (Gardner et al., 2002; Uniyal, 2013). For example, many of the more than 350 fatalities resulting from the 2015 earthquake triggered snow-ice avalanche in Langtang, Nepal, were foreign trekkers and their local guides (Kargel et al., 2016), while several thousand religious pilgrims were killed during the 2013 Kedarnath GLOF disaster (Kala, 2014). The expansion of hydropower is another key factor, and in the Himalaya alone, up to two-thirds of the current and planned hydropower projects are located in the path of potential GLOFs (Schwanghart et al., 2016). The extent to which the exposure of local communities and indigenous settlements is changing is complex and varies regionally. Climate change, and related threats to traditional forms of livelihoods is leading to outmigration in some mountain regions (Tiwari Prakash and Joshi, 2014; Tiwari Prakash and Joshi, 2015), while other communities may relocate towards higher elevation, and potentially more exposed zones where crops can grow under a warmer climate (Malla, 2009).

2.3.3.2.2 Drivers of vulnerability

Considering the wide-ranging social, economic, and institutional factors which enable communities to adequately prepare, respond, and recover from climate shocks (Chen et al., 2013; Cutter and Morath, 2014), there is *medium confidence* that mountain dwelling communities, particularly within developing countries, are among the world's most vulnerable to the adverse effects of climate change. This assessment recognizes that there are few studies that have systematically assessed the vulnerability of mountain communities, and available literature is largely qualitative (Beniston, 2003; Xu et al., 2009; Viviroli et al., 2011), while more quantitative vulnerability indexes are typically too coarse to enable a clear distinction between e.g, coastal, urban, and mountain regions. Coping capacities within mountain communities may be limited because fundamental weather and climate information is lacking to support early warning and adaptation planning (Rohrer et al., 2013), communities may be politically and socially marginalised (Marston, 2008), incomes are typically lower and opportunities for livelihood diversification restricted (McDowell et al., 2013), emergency responders can have difficulties to access remote mountain valleys after disasters strike (Sati et al., 2011; Sati and Gahalaut, 2013), and because cultural or social ties to the land can limit freedom of movement (Oliver-Smith, 1996). Conversely, there is evidence that some mountain communities exhibit enhanced levels of resilience, drawing on long-standing experience and indigenous knowledge gained over many centuries of living with extremes of climate and related disasters (Gardner and Dekens, 2007). In the absence of sufficient data, few studies have considered temporal trends in vulnerability (Huggel et al., 2015a).

2.3.3.2.3 Impacts

Empirical evidence from past events shows that cryosphere-related landslides and floods can have severe impacts on lives and livelihoods, often extending far beyond the directly affected region, and persisting for several years. GLOFs alone have directly caused at least 400 deaths in Europe, 5745 deaths in South America and 6300 deaths in Asia (Carrivick and Tweed, 2016), although these numbers are heavily skewed by individual large events occurring in Huaraz and Yungay, Peru (Carey, 2005) and Kedarnath, India (Allen et al., 2016b). National-level economic impacts from GLOFs have been greatest in Nepal and Bhutan (Carrivick and Tweed, 2016). Fatalities from large rock or ice avalanches can be high in immediate populated areas, or linked to downstream transformation and secondary hazards (Evans and Delaney, 2015). The disruption of vital transportation corridors that can impact trading of goods and services (Gupta and Sah, 2008), and the loss of earnings from tourism can represent significant far-reaching and long-lasting impacts (Nothiger and Elsasser, 2004; IHCAP, 2017). Less tangible, but equally important impacts concern the cultural and social disruption resulting from temporary or permanent evacuation (Oliver-Smith, 1979). Over the period 1985–2014, absolute economic losses in mountain regions from all flood and mass movements (including non-cryospheric origins) were highest in the Hindu-Kush Himalaya region (USD45 billion), followed by the European Alps (USD7 billion), and the Andes ($US 3 billion) (Stäubli, 2018). Given the expected continued increase in exposure of people and assets in high mountains, compounding other environmental stresses, there is *high confidence* that the impacts from high mountain floods and landslides will increase over the coming century in regions where risk reduction strategies and climate adaptation prove insufficient.

2.3.3.3 Disaster Risk Reduction and Adaptation

Applying a risk perspective to flood and mass movement hazards in high mountain regions paves the way for integrative and forward-looking adaptation strategies that address the underlying components of hazard, exposure and vulnerability. While significant international aid and adaptation financing has been directed towards related adaptation and risk reduction over the past decades, critical scientific literature reflecting on the successes or lessons learned from these projects remains scarce. Strategies include hard engineering solutions such as glacial lake drainage or slope stabilisation that reduce the hazard potential, nature-based solutions such as revegetation efforts to stabilise hazard-prone slopes or channels, hazard and risk mapping as a basis for land zoning and early warning systems that reduce potential exposure, and various community-level interventions to develop disaster response programmes, build local capacities and reduce vulnerability. The evidence and learnings emerging from mountain regions generally reconfirms the findings from the SREX, including the requirement for multi-pronged approaches customised to local circumstances, integration of local indigenous knowledge together with improved scientific understanding and technical capacities, strong local participation and early engagement in the process, and a high-level communication and exchange between all actors. Particularly for mountain regions, there is *high confidence* that integration of knowledge and practices across social, humanitarian and physical sciences is an important prerequisite for addressing complex hydrological challenges, hazards, and risks.

There is a long history of engineered responses to reduce GLOF risk, most notably beginning in the mid-20th century in Peru (Carey, 2005) and Switzerland (Haeberli et al., 2001), and more recently in the Himalaya (Ives, 1986). Evidence from Cordillera Blanca shows that while these efforts have been effective, corresponding strategies to reduce social vulnerabilities have lagged behind (Emmer et al., 2018). Engineered responses are typically expensive, and moreover, although they reduce risks, they cannot fully eliminate them, potentially leading to a false sense of security for communities (Leslie, 2013). These strategies also raise complex issues of water management, as evident from examples where hydropower companies have opposed the artificial lowering of glacial lake levels or smallholder farmers raising concerns that their water for irrigation would be reduced (Carey et al., 2014). Early warning systems necessitate strong local engagement and capacity building to ensure communities know how to prepare and respond to any emergency, but also to ensure the long-term sustainability of any project. The need for ground-level education and communication has been demonstrated in Peru, where international cooperation led to the installation of a technologically advanced early warning system drawing on best practices from Europe (Munoz, 2016), only to have the equipment destroyed following opposition and mistrust from local communities (Fraser, 2017). In some cases, local residents have played active roles in detecting and communicating flood events and in formulating responses. In Bhutan, anecdotal evidence suggests that loss of life and property damage resulting from a GLOF in 2015 was less than might have otherwise occurred, with informal warnings passed between personal acquaintances providing information to downstream communities earlier than the national early warning system (Orlove, 2016), while in both Pakistan and Chile, GLOF warnings, evacuation and post-disaster relief have largely been community-led (Ashraf et al., 2012; Anacona et al., 2015a).

Cutter et al. (2012; SREX) highlight the post-recovery and reconstruction period as an opportunity to build new resilience and adaptive capacities. However, too often this process is rushed or poorly supported by appropriate sustainable long-term planning, as illustrated following the 2013 Kedarnath GLOF disaster, where guest houses and even schools are being rebuilt on-site in the same exposed locations, driven by short-term economic motives (Ziegler Alan et al., 2014). In mountain regions, there is a particular need for forward-thinking planning and anticipation of emerging risks and opportunities, as changes in the cryosphere, together with socio-economic, cultural and political developments are producing conditions beyond historical precedence (Haeberli et al., 2016).

Research on disaster risk response has found that different types of participants, such as researchers, policy-makers, international donors and local communities, operate on different time-frames. As a result, they do not always agree on the timing of different stages of disaster risk reduction projects and programs, impeding full coordination (Huggel et al., 2015b; Allen, in review). Carey et al. (2017) further call for an improved evidential basis to underpin adaption planning, arguing for a paradigm shift, whereby transdisciplinary and cross-regional collaboration places human societies at the centre of studies on water supply and management in mountain region, providing the basis for effective and sustainable adaptation strategies.

[START BOX 2.6 HERE]

Box 2.6: Challenges to Farmers and Local Population Related to Shrinkages in the Cryosphere: Cordillera Blanca, Peru

The Cordillera Blanca of Peru contains the majority of glaciers within the tropics. Glacier coverage in Peru's Cordillera Blanca declined from 723 km^2 in 1970 to 482 km^2 in 2010, representing a loss of approximately 34% during that period (Burns and Nolin, 2014; Mark et al., 2017) and a loss of 44-47% since the estimated 850-900 km^2 of glacier coverage at the end of the Little Ice Age maximum in the mid-1800s (Georges, 2004). Since the 1940s, glacier hazards such as rock-ice landslides and glacial lake outburst floods (GLOFs) have killed thousands (Carey, 2005; Carey, 2010) and remain threatening still today (Rivas et al., 2015; Emmer et al., 2016; Somos-Valenzuela et al., 2016; Emmer et al., 2018). Glacier wastage over time has also caused hydrologic variability, with "peak water" passed in most Cordillera Blanca basins several decades ago resulting in a reduction in glacier runoff ever since, particularly in the dry season (Baraer et al., 2012; Vuille et al., 2018). Residents living adjacent to the Cordillera Blanca have long recognized this glacier shrinkage, including rural populations living near glaciers and urban residents worried about GLOFs and glacier landslides (Carey, 2010; Bury et al., 2011; Jurt et al., 2015; Heikkinen, 2017; Walter, 2017). These glacier hazards and the glacier runoff variability overall tend to multiply and exacerbate existing threats to regional residents, increasing human vulnerability and uncertainty while diminishing adaptive capacity to any of the multiple risks affecting Andean populations (Rasmussen, 2016).

Cordillera Blanca residents' risk of glacier-related disasters is shaped by an assemblage of intersecting variables, with physical and societal factors intersecting to increase risk. Physical hazards include rapidly expanding glacial lakes, new lake formation in increasingly exposed and over-deepened glacier beds, slope instability, permafrost degradation, rising temperatures, and precipitation changes (Emmer et al., 2016; Colonia et al., 2017b; Haeberli et al., 2017; Emmer et al., 2018). Human vulnerability stems not only from these physical variables but also from many other factors, such as minimal access to education and healthcare, poverty, limited political influence and resources, weak government institutions, and residents' inhabitation of potential flood paths through and around cities that were founded by sixteenth-century Spaniards on alluvial fans and in riparian zones (Hegglin and Huggel, 2008; Carey et al., 2012a; Lynch, 2012; Carey et al., 2014; Heikkinen, 2017). Multiple and intersecting risks continue today, and early warning systems have been, or are being, installed at glacial Lakes 513 and Palcacocha to protect populations (Muñoz et al., 2016). Lake 513 was previously drained for GLOF prevention in the early 1990s but nonetheless caused a destructive GLOF in 2010 that damaged crops, pastures, infrastructure, and homes (Carey et al., 2012b; Schneider et al., 2014). The early warning system was subsequently installed, but some local residents destroyed it in 2017 due to political and social conflicts as well as divergent spiritual beliefs and values, showing how cultural and socio-political issues can predominate over climatic or cryospheric risks (Fraser, 2017). The nearby Lake Palcacocha also threatens populations. It currently contains more water than it did when it caused a catastrophic GLOF in 1941 that killed 1,800 people in the city of Huaraz, where more than 120,000 people currently live, including 50,000 in the Quillcay basin where Palcacocha drains (Wegner, 2014; Somos-Valenzuela et al., 2016; Heikkinen, 2017).

Vulnerability to hydrologic variability and declining glacier runoff is also shaped by intertwining human and biophysical drivers playing out in dynamic hydro-social systems (Bury et al., 2013; Carey et al., 2014; Rasmussen et al., 2014; Drenkhan et al., 2015; Carey et al., 2017; Heikkinen, 2017; Paerregaard, 2018). Water security is influenced by both water availability (supplies from glaciers) as well as by water distribution, which is affected by factors such as water laws and policies, global demand for agricultural products like asparagus grown in the lower-Santa River basin, energy demands and hydroelectricity production, potable water usage, and livelihood transformations over time (Carey et al., 2014; Vuille et al., 2018). In some cases, the formation of new glacial lakes can create opportunities alongside hazards, such as new tourist attractions and natural reservoirs for water use in agriculture or hydropower, thereby showing how socioeconomic and geophysical forces intersect in complex and sometimes contradictory ways (Carey, 2010; Colonia et al., 2017b). In the Cordillera Blanca's Recuay region, local farmers confront many climate-related uncertainties, including changing rainfall, shrinking glaciers, and periodic frosts and hail; yet they also face rising prices for sugar and fertilizer, crop diseases, burglars, death of livestock, and property fires, among other uncertainties that exacerbate or even predominate over climatic and cryospheric risks (Rasmussen, 2016). Hydrologic variability from glacier change thus adds an additional strain and a layer of uncertainty on residents, due to both seasonal and decadal shifts in water flows and perceived worries about diminishing future water supplies that already influence water-related behavior, actions, and resource management (Carey, 2010; Bury et al., 2013; Vuille et al., 2018).

Glaciers for Cordillera Blanca inhabitants are also more than just hazards and water resources; they are sources of identity and spiritual anchors. Residents trek to Cordillera Blanca glaciers to collect glacial ice to make *raspadillas* (flavoured ice), which forms a key community tradition, while others participate in an annual pilgrimage and take offerings to glaciers for the June 24 Fiesta de San Juan (Dunbar and Marcos, 2012; Jurt et al., 2015). While rural inhabitants observe glacier loss and even impacts on water supplies and hazards, many tend to attribute the changes to local or regional factors instead of global climate change (Walter, 2017). They may thus attribute glacier change to the sun being ill, divine punishment from God, the ancient Earth with glaciers now turning from pure white to dirty grey, mountaineers and tourists trampling on the glaciers and causing them to melt, contamination of the environment through mining or littering, inadequate respect for the environment or other people, abandonment of traditional practices and offerings to the mountains, or enchanted lakes that occasionally act up and break out of their lake beds in floods (Carey, 2010; Jurt et al., 2015; Walter, 2017). Explanations for glacier shrinkage and corresponding hazards thus illustrate the multiple threats in local communities, exacerbated by ice loss.

[END BOX 2.6 HERE]

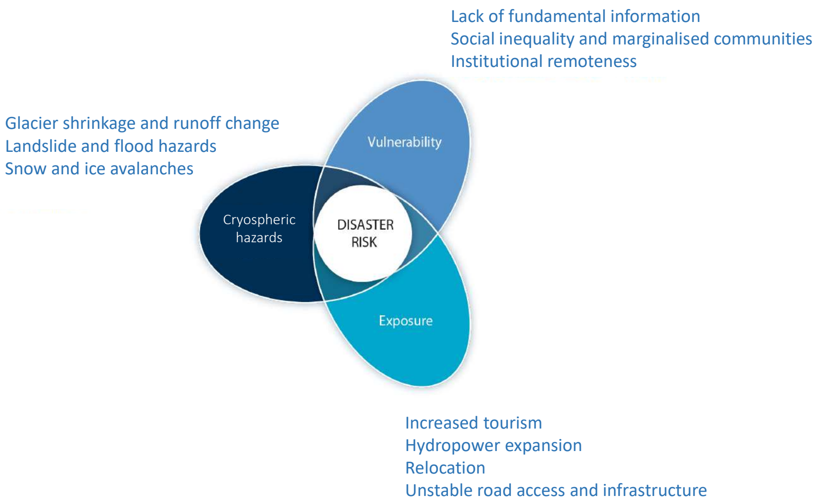

Figure 2.6: Key integrative concepts of climate risk (IPCC, 2014) in high mountain regions.

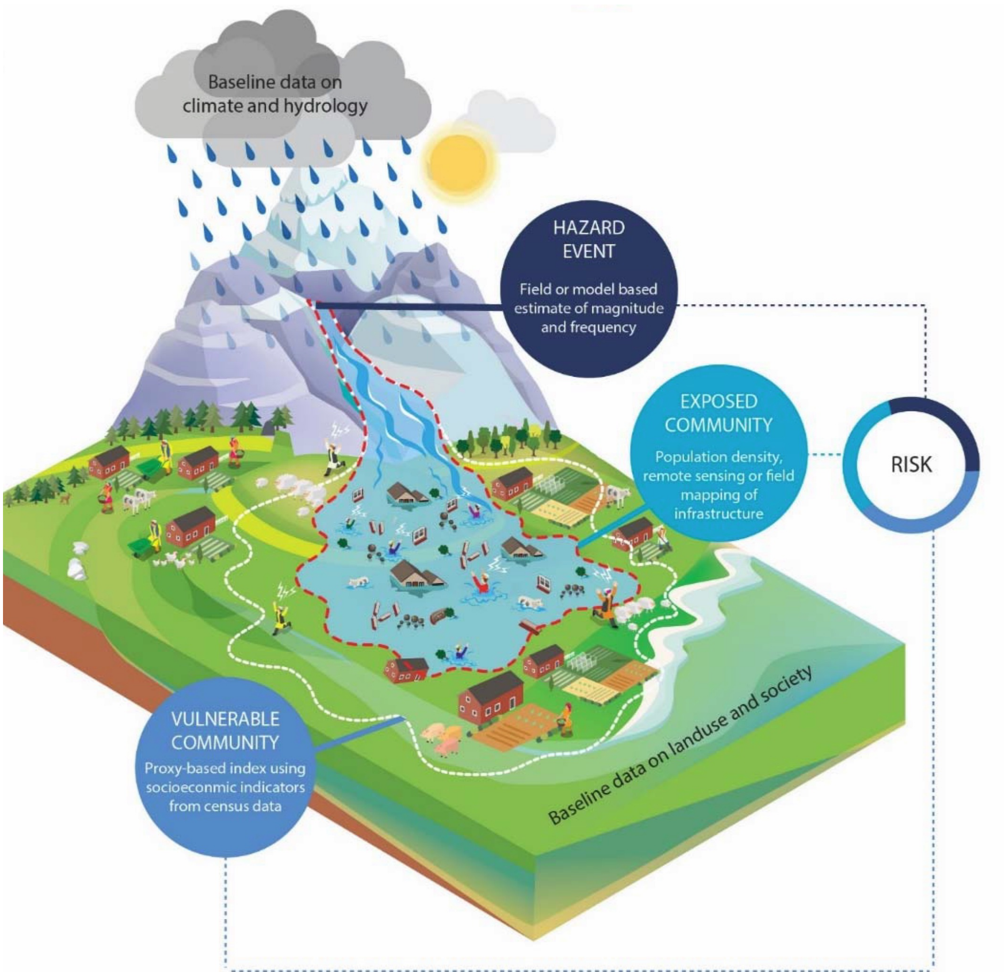

Figure 2.7: Operationalisation of the integrative concept of climate risk for the assessment of flood risk (IHCAP, 2017; Allen, in review). [PLACEHOLDER FOR SECOND ORDER DRAFT: will be adapted to cryospheric hazards.]

2.3.4 Terrestrial and Aquatic Biodiversity

2.3.4.1 Tipping Points and Loss of Endemic Species

Critical thresholds of cryosphere (glacier/snowmelt/permafrost) known as tipping points are important for conservation and mitigation in mountain environments (Khamis et al., 2014). Cryosphere shrinkages may affect the tipping point and affect aquatic biodiversity in high mountain areas. Permafrost thaw and its local disappearance imply marked changes to hydrology and the terrestrial ecosystems (IPCC, 2014) high confidence). In addition rising air temperature and shorter duration of snow cover directly influences growing season length and the phenology of plant production and consumers (Gottfried et al., 2012). Increasing snow depth and prolonged snow cover duration postponed start of growing season in the following year, while early snow melting propelled NDVI increasing in spring in the Tibetan Plateau (Wan et al., 2014). Snow cover effects on vegetation spring phenology are highly affected by temperature and precipitation (Wang et al., 2017b) (*medium confidence*). Furthermore, snow's propelling effects on vegetation were greater than the delaying effects (Wang et al., 2013). Two terrestrial ecosystems are expected to be most vulnerable even in a short-term perspective, namely the nival plant communities (Gottfried et al.) and the snowbed vegetation (Bjork and Molau, 2007). Vegetation associated with snowbeds are undergoing rapid change at present because of reduced annual snow duration (Bjork and Molau, 2007) *(high confidence*). Snowbed vegetation in mountain areas provide important ecosystem services, i.e., providing the below-lying areas with watering of the pastures throughout the summer, and (in the case of reindeer in the northern Scandes) a refugia for bugs and predators. In New Zealand, remaining snowbeds are strongholds for a number of endangered plant species (i.e., *Celmisia tomentosa*). With decreasing snow duration, a number of snowbed specialist plants will rapidly become outcompeted by invasive species from lower altitudes (Bjork and Molau, 2007) (*high confidence*). Snowbed plant communities were found to be especially affected in sub-alpine elevations in the Alps (Matteodo et al., 2016), whereas several snowbed species were counted more often than previously on high mountain summits in temperate and boreal Europe (Grytnes et al., 2014).

In the nival zone of high mountains, cushion and dwarf rosette plants are a prominent feature and all their abundance has declined at the alpine-nival study site Schrankogel in the central Alps (Pauli et al., 2012) and canopy cover of species restricted to high elevation was found to decrease more than the cover species with a broad vertical distribution range in the Rocky Mountains (Lesica, 2014) (*medium confidence*). Of particular concern with respect to the high degree of endemism is in alpine Mediterranean areas (Pauli et al., 2012) due to the combined effect of rising temperature and decreasing water availability (*medium confidence*).

Glacier retreat will lead to biodiversity loss in aquatic ecosystems (*high confidence*). Analysis of three comprehensive invertebrate datasets from equatorial (Ecuador), temperate (Italian Alps) and sub-Arctic (Iceland) regions indicated a distinct threshold in the number of taxa that decrease in density below 19-32% glacier cover in river basins (Milner et al., 2017). Other global-scale studies have identified 11-38% of the regional species pool would be lost when glacier cover falls below 5-30% (Jacobsen et al., 2012). There is clear evidence from Europe (Pyrenees) and North America (Rockies) that glacier loss threatens the existence of some endemic, cold-adapted invertebrates (Giersch et al., 2015; Giersch et al., 2017), which is likely to lead to a loss of genetic diversity (Jordan et al., 2016) whereas functional-trait diversity increases (Brown et al., 2018). Limited taxonomic and genetic knowledge of aquatic invertebrates in many other mountain zones limits our understanding of global biodiversity losses due to glacier retreat.

These findings suggest nonlinear responses of alpine aquatic assemblages to changes in glacier influence consistent with global patterns of macroinvertebrate alpha (local) diversity in glacier-fed rivers (Jacobsen et al., 2012). These tipping points with a shift to an alternate state is due to the loss of cold stenothermic species, many of them endemic, as glacial runoff decrease leading to a loss of beta (turnover between reaches) and gamma (regional) diversity as glaciers retreat and switch to a regime more dominated by snowmelt.

An in-situ plasticity response by invertebrates to these environmental changes is the most likely mechanism for taxa persistence compared to migration (as many headwater alpine taxa are dispersal limited) or adaptation (Hotaling et al., 2017). The extinction risk of range restricted prey taxa may increase as more favourable conditions will allow the upstream movement of large bodied predators (Khamis et al., 2015).

2.3.4.2 Hotspots of Biodiversity

A biodiversity hotspot is a biogeographic region with significant levels of biodiversity, many of them endemic, that may be threatened in the future and should be a priority for conservation. Alpine vascular plant diversity, however, is strongly co-determined by the size, glacial history and the degree of fragmentation of mountain systems. Within the humid tropics, for example, species richness pronouncedly differed among Eastern Africa, New Guinea, and the Andes, the latter reaching high biodiversity (Sklenar et al., 2014). In Europe, the Alps host the largest biodiversity of alpine vascular plant species (Väre et al., 2003), whereas Mediterranean mountains, such as the Sierra Nevada, Spain, reach exceptionally high proportions of locally endemic species (Mota et al., 2002).

Genetic diversity within individual riverine invertebrate species represents hotspots of biodiversity in mountain headwater areas. However, the loss of environmental heterogeneity in headwater habitats with less glacier runoff reduces the isolation of individuals and permits intermixing to a greater degree when mating thereby creating greater genetic homogeneity in mountain headwater streams and significantly reducing genetic diversity (Finn et al., 2013; Finn et al., 2016; Hotaling et al., 2018).

2.3.4.3 Vegetation Dynamics and Feedbacks

A meta-analysis of worldwide data indicates treeline has been advancing upslope at 52% of sites, but expansion in mountain areas can be restricted by drought and other extreme events (Barros et al., 2017). The movement of treeline at a low to moderate pace (Harsch et al. (2009); medium confidence), may be a result of several indirect drivers (e.g., Callaghan et al., 2013; IPCC, 2014). For example in northern Scandinavia, the movement of mountain birch has been counteracted by (1) increasing outbreaks of the autumn moth (*Epirrita autumnalis*) due to climate warming (Callaghan et al., 2013) and (2) winter grazing of emerging birch twigs by hares above treeline (Vowles et al., 2016). Early snowmelt decreases the mortality rates of some conifers and a greater incidence of summer drought are already affecting species such as *Pinus contorta*, increasing infestation risk by bark beetles (Coops et al., 2010). Upward migration of plant communities with a shrinking cryosphere reduces the availability of high mountain habitats, used by specialized high mountain species (Lubetkin et al., 2017)

Permafrost degradation has a marked impact on hydrology and ecosystem resilience in all mountain areas (*high confidence*) (Molau, 2010; IPCC, 2014). In a tussock tundra habitat in the mountains of the northern Scandinavia, an area of marginal permafrost, Molau (2010) showed that the plant community altered to more arid expressions after final permafrost thaw.

In high mountains, the ecotone between mid-alpine and high-alpine (nival) plant (and insect) communities is often subject to the presence of permafrost. In the upper region vegetation becomes discontinuous and rain water will not penetrate but causes major erosion in cases of heavy summer precipitation (Molau, 2016). The altitudinal borderline towards the high alpine (nival) zone ranges from 1300 m a.s.l. in the northern Scandes and the Urals to about 4400 m in the equatorial Andes and above 5000 m in the seasonal tropical Andean dry Puna region (Cuesta et al., 2017). In a climate change perspective, upward changes of the zonation and its ecosystems will have drastic consequences on biodiversity and ecosystem services (*high confidence*). The general trend of upward shifts was indicated through a transformation of species assembly on mountain summits distributed across Europe, by a gain in more warmth-demanding and/or a concurrent decline of cryophilic species, i.e., 'thermophilization' of alpine vegetation (Gottfried et al., 2012). A recent study, combining historical data back to the 19th century with shorter time series, reported an accelerating increase in species numbers on temperate to Arctic mountain summits across Europe in the recent decades; for example, during the past 10 years, five species on average have colonized the summits, compared to only one species during the same time-span in the mid-20th century (Steinbauer et al., 2018). The study also showed that increasing temperature, rather than changes in precipitation patterns or nitrogen deposition, were related to the accelerated increase in species numbers (*high confidence*). Decreasing snow cover and an earlier growing season can expose certain species to frost damage (Inouye, 2008).

The riverine fungal community may shift towards those taxa that prefer warmer waters (Freimann et al., 2015). Increased primary production dominated by diatoms and golden algae (*Hydrurus foetidus*) will probably occur as glacial runoff decreases, with increased algal species richness, density and diversity (Fell et al., 2017). Bryophytes may become more common as channels become more stable (Milner et al., 2017).

2.3.4.4 Fauna

With a warming climate in mountain regions, animals respond faster than the plant communities, and woody plants are generally slower to respond (IPCC, 2014). Good examples of newly established birds and voles far above the present treeline in the northern Scandes are provided in Callaghan et al. (2013). However, whereas there is a rather adequate record fort up-slope movements of vascular plants, the understanding of mobility of terrestrial animals (mammals and insects) lacks a global overview.

As meltwater from glaciers decreases with a shrinking cryosphere, particularly where glaciers are small in size, river flows will become more stochastic (Milner et al., 2017). However water temperature and channel stability should increase and overall these physiochemical conditions will enhance riverine alpha invertebrate diversity and abundance (Jacobsen et al., 2012). Riverine habitats have less heterogeneity (Giersch et al., 2017) in mountain headwater areas which will favour more generalist communities, particularly with respect to aquatic bacteria and fungi (Fell et al., 2017). A global analysis by Brown et al. (2018) indicate that predictable mechanisms govern river invertebrate community responses to decreasing glacier runoff worldwide. Analyses nested within individual regions identified an increase in functional diversity as glacier cover decreases and community assembly models demonstrated that dispersal limitation was the dominant process underlying these patterns, although environmental filtering was also evident in highly glacierized basins.

Semi-aquatic mammals (e.g., the water shrew (Soricinae) and desmans (Talpidae)) may be affected by the changes in the cryosphere. Reduced glacial influence may significantly impact the Iberian desman (*Galemys pyrenaicus*) (Biffi et al., 2016) because their range is influenced strongly by the presence of aquatic invertebrate prey from rivers with low temperatures and fast-flowing, oxygenated waters In contrast, glacier retreat has the potential to benefit amphibian species by creating more mountain river habitats with warmer waters and more abundant invertebrate prey (Ludwig et al., 2015)

2.3.4.5 Fisheries

Many climate variables influence fisheries through a range of direct and indirect pathways. The key variables or drivers of interest include: changes in air and water temperature, precipitation, salinity, ocean circulation and mixing (linked to glacial runoff), nutrient levels, ice cover, glacial melt, storm frequency and intensity, and flooding (Stenseth et al., 2003). For example in Alaska where salmon are important in both commercial and sport fisheries, will be affected by reductions in glacial runoff over time (Schoen et al., 2017). Cold mountain salmonid species, e.g., brook trout, will suffer a potential constriction of habitat and have to migrate further upstream to find suitable habitat and in some cases become extinct (Hari et al., 2006). Within the Yanamarey watershed of the Cordillera Blanca in Peru, fish stocks have either declined markedly or have become extinct in many streams, possibly due to seasonal reductions of fish habitat in the upper watershed because of the glacier recession (Bury et al., 2011; Vuille et al., 2018).

Glacial recession along the mountains of the Pacific Northwest and coastal Alaska have created a large number of new stream systems that can be potentially colonized by anadromous that contribute to fisheries, both commercial and sport (Milner et al., 2017; Schoen et al., 2017).

2.3.5 Aesthetic and Cultural Services

2.3.5.1 Tourism and Recreation

The mountain cryosphere provides important aesthetic and recreational services to society (Xiao et al., 2015). The cryosphere is also an important resource for tourism, providing livelihood options to mountain people. An increasing body of literature suggest that changes in the cryosphere has affected mountain tourism and recreation services in different ways, consequently affecting livelihoods of mountain people.

Tourism and recreation include primarily winter sports (ski tourism), sight-seeing in scenic or iconic regions of the world often including areas with (disappearing) glaciers, and other recreational activities in mountains areas (e.g., mountaineering, climbing, hiking). Tourism and recreation activities draw on ecosystem services such as freshwater supply or landscape aesthetics and compete with other socio-economic activities regarding access to these resources.

Winter sports (ski tourism), given its strong reliance on favourable atmospheric and snow conditions, is a socio-economic sector that has long been identified as particularly vulnerable to climate change in mountains (Arent et al., 2014). This sector is strongly affected by inter-annual variability of meteorological and snow conditions. Efforts to reduce this vulnerability to occasionally unfavourable meteorological conditions have been in place since the late 20th century. Such measures include improved slope preparation, i.e., grooming, snowmaking, i.e., artificial production of snow (Steiger et al., 2017), and more recently snow farming, i.e., storage of snow over the summer season (Grünewald et al., 2018). Whether these methods are appropriate and reliable for adaptation to long-term climate change depends on several interlinked factors. For example, success depends not only on their own sensitivity to atmospheric conditions (e.g., temperature thresholds for snowmaking), but also on other externalities such as the availability of water resources (required for snowmaking), energy resources, and associated operating costs (Dawson and Scott, 2013; Hopkins and Maclean, 2014; Steiger et al., 2017). Coupled with issues of socio-cultural perception and acceptability of high-tech measures, these can collectively set limits to the overall adaptation of this sector. In general, ski resorts located at lower altitude are more exposed to climate change effects than higher altitude resorts, because of the stronger variability and reduction of natural snowfall (Section 2.2.2), as well as more frequent (and increasing) periods of time when the air temperature conditions are inadequate for snowmaking (Steiger et al., 2017). However, assessing climate risks for ski tourism is complex, given local climate conditions that must be accounted for and other factors related to the demand-side and structural adaptive capacity of ski resorts and their communities, all of which play a significant role in their climate vulnerability. Steiger et al. (2017) also highlighted a paucity of studies regarding recent developments in ski tourism, in particular its transfer and geographic spread to other areas (Continental Asia and South America), which, may or may not meet the conditions for ski tourism development under a changing climate.

[PLACEHOLDER FOR SECOND ORDER DRAFT: link to tourism subsection of Chapter 3 of SR1.5]

Glacier skiing is a specific subsector of winter sports, enabling summertime skiing. In recent years several resorts operating on glaciers have stopped summertime operations (Chamonix, France, in the early 1990s, followed by Val Thorens and Alpe d'Huez, France in 1998, then La Plagne, France, Sölden, Austria, Les Diablerets, Switzerland more recently), due to unfavourable snow conditions and too high operating costs. Fischer et al. (2016) reported quantitative measures of the impact of managing glacier snow cover through snow production, snow relocation, snow covering by reflecting and insulating material, and piste grooming, on glaciers locations from 2700 to 3200 m altitude in the Austrian Alps. These practices have a significant and positive impact on the glacier mass balance, reducing the negative mass balance from -0.78 ± 0.04 m w.e. yr^{-1} (unmanaged) to -0.23 ± 0.04 m w.e. yr^{-1} (managed) over a ten years period. Summer ski resorts operating on glaciers increasingly rely on snow management and snow making on the glacier itself, although there is limited evidence of the long-term sustainability of this approach as an adaptation to increasingly challenging operating conditions.

A limited but growing number of studies has examined the relationship between tourism and glaciers (Purdie, 2013; Espiner and Becken, 2014; Welling et al., 2015; Stewart et al., 2016). Glacier retreat has created challenges for local communities, tourist enterprises and for government agencies which support tourism. Landscape change, increased hazards exposure and water scarcity are common problems. Diversification across types of tourism products and services, as well as across seasons, has been a common adaptation response. Climate change might increase or decrease tourism in high mountain areas in different regions, depending the tourism product that is adapted or enhanced with changing conditions.

Attempts to mitigate glacial retreat at scales that would cover the entire glacial area, have not materialized, although feasibility studies have been proposed. Beyond local management of snow on glaciers for summer ski tourism (see above), Oerlemans et al. (2017) quantified the summer snowmaking requirements in the ablation area for limiting the recession speed of the Morteratsch Glacier (Switzerland), and indicated that this could be effective to reduce snowmelt although further studies are warranted to assess potential side effects.

In the Austrian Alps, changing hydrology had led to growing glacier fore fields and to the development of outwash fans, as well as increased floods and destabilization of landscapes; one positive change has been the formation of proglacial lakes, which serve as a tourist and recreation attraction. As a result, the civil society organization known as Austrian Alpine Association, which manages trails, has closed some trails and re-routed others, and added infrastructure such as bridges and fixed ropes to facilitate hikers (Ritter et al., 2012). Some operators of glacier tour firms in Norway have shifted to new sites as glaciers where they previously brought tourists have become inaccessible after retreat. They have also diversified into new activities such as rafting. Others have simply reduced their activities (Furunes and Mykletun, 2012).

In Bolivia, a glacier had supported the world's highest ski resort (Chacaltaya, at 5400 m) for nearly 50 years, but the disappearing glacier led to the closing of this resort. Nonetheless, the existing access road and infrastructure continue to support tourism at the site, though at a lower level, offering mountain scenery and the opportunity to witness climate change impacts directly as alternatives (Kaenzig et al., 2016). In southwest China, tourism firm operators have undertaken a number of steps, including extending cable car networks to improve access to glaciers, adding telescopes to provide clearer views of distant glaciers, constructing a glacier museum, and promoting the glaciers through events such as photography contests and mass weddings (Wang et al., 2010). However, more recent research in this region indicates that tourism is placing stress on water supplies which are growing more scarce (Su et al., 2016b).

There are, however, some cases in which the impacts are compounded through interactions with other human-induced impacts and pressures. In a study in Nepal Himalaya, glacier retreat was not directly attributed to negative impacts on tourism, but rather point to road development, as well as corruption and governance issues, as much more serious issues, resulting in the diversion of investment funds for tourism (Dangi et al., 2017).

Some efforts have been made to use glacier retreat as a positive opportunity for awareness-raising and adaptation. Tourism providers have developed activities which use glacial retreat to attract visitors, either as 'last chance' tourism or as a way to raise awareness about climate change. However, these efforts have been met with limited success. In Peru, the Pastoruri Glacier was closed to tourists in 2007 due to safety concerns given its rapid retreat, resulting in reduced visitor numbers (from an estimated 100,000 visitors in the 1990s to 34,000 in 2012 (Palomo, 2017). Since then, an improved and better regulated trail was opened in [YYYY] (Bury et al., 2011) and labelled the "climate change route'', to attract tourists to the area again (Palomo, 2017). The national park service and local communities jointly manage the area, which remains as a most frequently visited area given its proximity to paved roads (Rasmussen, 2018).

Changes in the mountain cryosphere are reported to impact upon mountaineering and alpine climbing practices, particularly in terms of compromised safety along access routes to the mountain and mountain shelters, as well as the stability of shelters and mountain refuges themselves, where these are present. Examples from the literature include cases where rock fall hazard are increasingly being experienced by mountaineers in places such as Switzerland (Temme, 2015) and New Zealand (Purdie et al., 2015). Studies carried out in the Mont Blanc region in the French Alps, glacier retreat has been attributed to increased moraine wall instability resulting in the need to abandon and/or create new routes and the need to install ladders and other forms of fixed anchors on the rock to facilitate access (Mourey and Ravanel, 2017). Over the course of time and increased rate of changing conditions with retreating glaciers, these installations themselves need replacement and upgrading, resulting in the need to assess the feasibility of continued mitigation as an adaptation strategy in the long term.

Fluctuations in visitor numbers and changes in visitations patterns over peak tourism seasons are cited in some of the mentioned studies as a potential impact and consequence to climatic and cryospheric change. However, in general, these may be a poor proxy to establish direct potential links to climate change and a changing cryosphere with economic feasibility of mountaineering, given that other key factors that also determine visitation in high mountain regions for tourism and recreation purposes can play a much more significant role (*medium agreement, medium evidence*).

In summary, it is *likely* that cryospheric changes due to climate change have been driving changes in tourism and recreation activities in the mountains (ski, glacier tourism, mountaineering) (*medium agreement, medium* *evidence*). Adaptation measures already implemented include attempts to mitigate the local impacts of climate change (e.g., increased snow reliability for ski resorts through snowmaking) and more or less disruptive approaches favouring shifts in tourism offers. However, the extent to which monitoring and attribution of these impacts and adaptation in terms of economic viability, is less certain (*medium agreement, limited evidence*). Therefore, consolidated evidence in terms of successful adaptation measures to mitigate losses/impacts appears sporadic and with mixed results.

It is *very likely* that projected cryospheric changes will continue to pose challenges to current tourism activities in mountain regions. Existing local mitigation measures are *likely* to reach their limits within a few decades (*high agreement, medium evidence*), with increased reasons for concern after 2050 in higher end climate scenarios. Tourism activities related to the mountain cryosphere are *very likely* to undergo major changes in the 21st century, however changes will not only be climate change driven but also potential changes in user demand, transportation costs, and other issues related to legal aspects on access, mobility and governance of land may be important factors to consider.

2.3.5.2 Spiritual and Intrinsic Values, and Human Well-being

Cryosphere changes also impact spiritual and intrinsic values which are held by populations in high mountains and other regions around the world, often harming human well-being (*medium evidence, high agreement*). Spiritual and intrinsic values can include aesthetic dimensions, which are also an element of tourism and recreation (Section 2.3.5.1), though they focus more directly on ties to sacred beings or to inherent rights of entities to exist (Daniel et al., 2012). However, they overlap, since the visual appeal of natural landscapes links with a sense of the immensity of mountain landscapes, glaciers and fresh snow (Paden et al., 2013; Gagné et al., 2014). Moreover, different cultural services may be held by different groups, such as resident peoples, tourists and policy-makers (Schirpke et al., 2016).

Spiritual and intrinsic values often, but not exclusively, rest on deeply-held religious beliefs (*high agreement, medium evidence*). In high mountain regions, some communities understand mountains through a religious framework (Bernbaum, 2006). In settings as diverse as the Peruvian Andes, the Nepal Himalaya and the Hengduan Mountains of southwest China, local populations view glacial retreat as the product of their failure to show respect to sacred beings or to follow proper conduct; experiencing deep concern that they have disturbed cosmic order, they seek to behave in closer accord with established traditions, but fear that the retreat may continue, leading to further environmental degradation and to collapse (Allison, 2015). In the United States, the glaciated peaks of the Cascades have also evoked a deep sense of awe and majesty, and an obligation to protect them (Carroll, 2012; Duntley, 2015). Similar views are found in the Alps, where villagers in the South Tyrol of Italy speak of treating glacier peaks with "respect," and state that glacier retreat is due, at least in part, to humans "disturbing" the glaciers (Brugger et al., 2013; Sherpa et al., in review), resulting in what Albrecht et al. (2007) termed solastalgia, a kind of deep environmental distress or ecological grief (cf., Vince and Sale, 2011; Cunsolo and Ellis, 2018).

These spiritual and intrinsic values combine with other ecosystem services, leading local populations in mountain regions to observe and know glaciers well, and track them over time (*medium agreement, medium evidence*). In some areas, residents give names to specific features of glaciers. In the southern Peruvian Andes, terms in the indigenous Quechua language have been reported for moulins, crevasses, and areas of dust-covered ice (Ricard and Recarte, 2007; Sherpa et al., in review). They also have knowledge of glacier retreat, which they obtain through direct observation (Gagné et al., 2014), from stories passed down from one generation to another within community (Stensrud, 2016), and from other sources, including the use of traditional routes for trade or for travel to pasture [India] (Ikeda et al., 2016), pilgrimages (Peru, China) (Allison, 2015), and work as trekking guides [Nepal] (Allison, 2015), [Italy] (Brugger et al., 2013).

An additional cultural value is the contribution of glaciers to the understanding of human history. Glacier retreat has supported the increase of knowledge of past societies by providing access to archaeological materials and other cultural resources that had previously been covered by ice. The discovery of Oetzi, a mummified Bronze Age man whose remains were discovered in 1991 in the Alps near the Italian-Austrian border, marked the beginning of scientific research with such materials (Putzer and Festi, 2014). After 2000, papers began to be published, describing the finds that were uncovered in retreating glaciers and shrinking ice patches in the Wrangell-Saint Elias Range (Dixon et al., 2005), the Rocky Mountains (Lee, 2012) and

Norway (Bjørgo et al., 2016). The field has matured recently, with the appearance of global synthesis of the subject (Reckin, 2013) and the establishment of the Journal of Glacial Archaeology in 2014. This field provides new insight into human culture history and contributes to global awareness of climate change (Dixon et al., 2014). Though climate change permits the discovery of new artefacts and sites, it also threatens these objects and places, since they are newly exposed to harsh environmental conditions (Callanan, 2016).

In summary, spiritual and intrinsic values on components of the cryosphere are largely, but not exclusively, linked to religions and other local customs that are also deeply embedded and fostered through indigenous and local knowledge. Cryosphere change through a changing climate can induce spiritual loss, solastalgia or 'ecological grief', despite few studies conducted in high mountain areas to ascertain specific trends and consequences for intrinsic values held by local or other communities with close spiritual ties to the high mountain (*limited evidence, medium agreement*).

2.3.6 Livelihood, Habitability and Human Mobility

2.3.6.1 Livelihoods

The cryosphere plays an important role in sustaining livelihoods of mountain communities, particularly in high mountain areas (Rasul and Molden, in review). The published literature on livelihoods in high mountain regions points to two patterns, found in most regions of the world: a diversity of livelihoods to make use of production zones at different elevations, and a strong seasonality of particular livelihoods, as a means to accommodate to the constraints imposed by short growing seasons and seasonal patterns of travel (*very high confidence: high agreement, robust evidence*). In addition, depending on income sources other than agricultural production allows household to manage risk and uncertainty (Jimenez et al., 2013). The bulk of studies on mountain livelihoods in the context of cryosphere change focus on individual livelihoods, which are discussed elsewhere in this chapter, notably agriculture (Section 2.3.1.3.1), tourism (Section 2.3.5.1) and labour migration (Section 2.3.6.2).

The literature also contains case studies which point to positive relations among livelihoods, though there is little agreement on overall patterns of these relations. A study of a 2014 debris flow in Nepal found that it temporarily reduced agricultural productivity because of damage to irrigation, and that households increased other livelihoods, including migration (van der Geest and Schindler, 2016). A community of indigenous pastoralists in Bolivia increased their wage labour migration to purchase fodder for their animals, when glacier retreat reduced streamflow that supports irrigation of pastures (Yager, 2015). A review of migration in the Himalaya and Hindu Kush found that households that participated in labour migration and received remittances had improved adaptive capacity, and lowered exposure to natural hazards (Banerjee et al., 2018).

In other cases, the households and communities which seek to integrate different livelihoods encounter conflicts or incompatibilities between livelihoods, especially when they seek to diversify income through labour migration in contexts where climate-related shocks and uncertainty affect agricultural production and thus reduce income. Sustainable management of land, water and other resources is highly labour intensive, and thus labour mobility constrains and limits the adoption of sustainable practices (Gilles et al., 2013). Moreover, the labour available to a household is differentiated by age and gender, so wage labour migration, often of young males, entails either a loss of capacity to undertake specific tasks or a readjustment of the division of labour (Alata et al., 2017).

2.3.6.2 Mobility and Habitability

Cryosphere changes in high mountain areas influence human mobility by altering water availability and inducing exposure or vulnerability to mass movements and floods (Barnett et al., 2005; Carey et al., 2017; Rasul and Molden, in review). These changes can have negative impacts on livelihoods and on settlements and infrastructure, providing greater incentives to mountain people to engage in temporary or permanent migration with increased risks of disasters, poor livelihood conditions and limited economic opportunities, mountain people are increasingly leaving high mountain areas (*limited evidence*, *medium agreement*).

Human mobility is a centuries-old pattern in high mountain areas. Transhumant movements between summer and winter pastures of pastoral populations, participation in regional market networks, and regional labour migration are common in Asia, Europe and North and South America (Lozny, 2013). In the face of climate change, other environmental changes, and demographic, economic, social, cultural and political drivers, these patterns of movement have been changing in the recent past and present, and are projected to continue changing, at least in the near term (*high confidence: high agreement, medium evidence*). However, establishing a causal relationship between cryosphere stressors and human mobility in mountain regions is extremely complex, since decision-making about mobility involves interaction of multiple determinants at individual, household and societal levels (*high evidence*, *high agreement*).

It is worth noting that the research to date is based on case studies which rely on interviews; though some studies (e.g., Milan et al., 2015) use random sampling, many do not, relying on convenience or snowball sampling instead. These studies describe declines in transhumant pastoralism. They also show migration on several time scales, including short-term, long-term and permanent migration. Migration is usually described as taking place within the country of origin, and sometimes within the region; however, cases of international migration are also recorded. The research on migration from mountain countries with high rates of international migration often does not disaggregate the migrants by region of origin to permit a comparison of mountain and lowland regions, as shown for Nepal (Bardsley and Hugo, 2010; Mak et al., 2017), Tajikistan (Buckley and Hofmann, 2012) and Kyrgyzstan (Atamanov and Van den Berg, 2012).

There are no studies that link cryosphere changes to migration based on large sample surveys or census data that tease out statistical linkages among the drivers and migration responses, or that use remote sensing data to study migration (e.g., Mueller et al., 2014; Gray and Wise, 2016). There is a similar lack of literature on cryosphere change and habitability in the high mountain areas. Moreover, this literature is concentrated in certain cryosphere regions, particularly the Himalaya, Hindu Kush, Karakoram and Andes; other regions are relatively underrepresented.

Some literature, however, examines the risks to high mountain settlements due to climate change in general and cryosphere change in particular. Changes in glacier regimes and runoff from snow and ice, combined with changes in precipitation timing and intensity are weakening livelihoods, reducing habitability and increasing human vulnerability (*high confidence: high agreement, medium evidence*).

Though large sample surveys are lacking, some studies show that rates of outmigration are higher from sub-regions with greater dependence on glacier meltwater than from those which rely on snowmelt, rainfall and groundwater. A study in the central Peruvian Andes examined three different elevation zones in one region. It found that migration varies by elevation, with the highest zone more dependent on glacier meltwater showing longer-term migration, often to other countries; the lower zones showed more seasonal migration to nearby areas within Peru. However, other differences, including contrasting patterns of local livelihoods and different social networks within Peru, could also contribute to the varying types of migration (Warner et al., 2012). In another region, the reverse relationship was noted. In the Naryn River drainage in Kyrgyzstan, labour migration, lasting months or years, is more extensive from the downstream communities than the upstream communities, even though the latter rely more directly on surface water, with its large glacier meltwater component from the Tien Shan, for irrigation; this pattern reflects more efficient water management institutions in the former, which relieves the effects of water scarcity there (Hill et al., 2017).

With respect to changes in transhumant pastoralism, climatic and non-climatic factors pose a risk for transhumant practices, generally reducing it, though many of the major difficulties confronting pastoral communities may not be directly related to climate change (*medium agreement*, *limited evidence*). The changes in climatic stressors adversely affect herders at their summer residences and winter camps (Namgay et al., 2014). Erratic snowfall patterns, as well as a decrease of rainfall, are perceived by herders in Afghanistan, Nepal and Pakistan to have resulted in generally negative changes in vegetation composition (Shaoliang et al., 2012; Joshi et al., 2013; Gentle and Thwaites, 2016). Heavy snowfall incidents in winter caused deaths of a large number of livestock, as cited for northern Pakistan in 2009 (Shaoliang et al., 2012). Herders in Nepal reported of water scarcity in traditional water sources along migration routes (Gentle and Thwaites, 2016). However, rising temperatures, with associated effects on snow cover, have some positive impacts. Seasonal migration from winter to summer pastures start earlier in northern Pakistan, and residence in summer pasture lasts longer (Joshi et al., 2013), as it does in Afghanistan (Shaoliang et al., 2012). Various non-climatic factors also threaten this transhumance (e.g., market forces, conflict between herder and sedentary communities, lack of institutional arrangement and inadequate policy support) (Shaoliang et al., 2012; Gentle and Thwaites, 2016).

The most frequently mentioned driver of observed internal and international migration related to cryosphere processes is changing water availability, followed by mass movements and floods. In most cases, climate is only one of several drivers (employment opportunities and better educational and health services in lowland areas are others). A debris flow in central Nepal in 2014 led more than half the households to migrate for months (van der Geest and Schindler, 2016). In the Santa River drainage, Peru, rural populations have declined 10% between 1970-2000, and the area of several major subsistence crops also declined (Bury et al., 2013). Research in this region suggests that seasonal outmigration within subdrainages of the main Santa drainage increases as subdrainages move from a stage of peak water (Section 2.3.1.1) to later stages, with decreased dry season flow (Wrathall et al., 2014). Studies which project migration emphasize decreased water availability following glacier retreat as a driver in Kyrgyzstan, (Candonnet et al., 2015) and Peru (Oliver-Smith, 2014).

Water availability and natural hazards are cited as causes of spontaneous resettlement, a larger-scale process than labour migration. In southern Chile, an entire community relocated after a glacier lake outburst flood in 1977 (Anacona et al., 2015a). A village in western Nepal moved to lower elevation after decreasing snowfall reduced the flow of water in the river on which their pastoralism and agriculture depended (Barnett et al., 2005). A village in northern Pakistan moved to a lower elevation after massive debris flows disturbed irrigation channels, disrupted water supplies and damaged fields and houses (McDonald, 1989).

Three specific emerging themes in the study of cryosphere changes and migration are age-specific migration patterns, the influence of perceptions on influence migration, and the issue of habitability.

In the cases in which the age of migrants is discussed, young adults are reported to migrate more often, though their specific ages are not always stated. These migrants face non-climate drivers as well. Outmigration has increased in recent decades from two valleys in highland Bolivia which rely on glacier meltwater, as water supplies have declined, though other factors also contribute to outmigration, including land fragmentation, increasing household needs for cash income, the lack of local wage-labour opportunities and a greater interest among the young in educational opportunities located in cities (Brandt et al., 2016). A recent study documents the inter-generational dynamics of outmigration from a livestock-raising community in the Peruvian Andes, where glacier retreat has led to reduced flow in streams which support crucial dry-season pasture. Though people 50 years old or older are accustomed to living in the high pasture zones, younger people view livestock-raising as a means of accumulating capital that will facilitate their movement to towns at lower elevations. They invest in improved stock and artificial pasture, but then later sell off their animals. Some retain a fraction of their herds, leaving then with herders who are paid in a share of the increase. The human and animal populations of the communities are shrinking (Alata et al., 2017). In Nepal, young members of high-elevation pastoral households were increasingly engaged in tourism and labour migration (Shaoliang et al., 2012).

The topic of perception is addressed in studies which ask residents of high mountain regions to state reasons for migration. In these studies, cryosphere changes are typically not the ones most frequently mentioned (*medium agreement*, *medium evidence*). A study from Bolivia notes that migrants from a set of high-elevation areas which receive significant amounts of glacier meltwater cite four main reasons for their migration: small farm size, insufficient water availability, climate unpredictability (unseasonal hail and frosts), and insufficient educational opportunities. They do not mention glacier retreat as an important motive for migration. Water scarcity was linked by some to glacier shrinkage, but others stated that longer growing seasons and higher temperatures increase water demand, or mentioned an increase in cultivated area (possibly linked to population growth) (Kaenzig, 2015) Another study of communities in Bolivia, where glacier meltwater is also a source of irrigation water found migration, particularly seasonal migration to be a key element of livelihood strategies. Interviewees mentioned decreasing water supply as a factor which led to migration, but attributed this scarcity to intensification of agriculture, technical problems of irrigation systems, and the lack of water governance; glacier retreat was mentioned less frequently (Brandt et al., 2016). Survey research in Pakistan's western Karakoram, a region where 76% of households have members who migrate within the country, found that over 85% of local residents perceived climate change and variability as negatively affecting productivity; though they rely on glacier meltwater for irrigation, the most frequently mentioned changes were lower temperatures, erratic rainfall, floods and debris flows (Milan et al., 2015).

The issue of habitability arises in the cases, mentioned above, of communities which relocate after floods or debris flows destroy houses and irrigation infrastructure, or damage fields and pastures. It occurs as well in the cases of households with extensive long-term migration, where agricultural and pastoral livelihoods are undermined by cryosphere change (Barnett et al., 2005), particularly when only the elderly remain (Alata et al., 2017). In addition, the loss of spiritual and intrinsic cultural values (Section 2.3.5.2) can influence migration (Kaenzig, 2015). Combined with the patterns of permanent out-migration, this issue of habitability raises issues of the limits to adaptation in mountain areas (Huggel et al., in review).

2.4 Synthesis of Risks, Adaptation Experiences, and Pathways to Sustainable Development

2.4.1 What do We Know Across Regions and Cases

[PLACEHOLDER FOR SECOND ORDER DRAFT: provisory title]

[PLACEHOLDER FOR SECOND ORDER DRAFT: assessment to be compiled and summarised once all sections are written. The following will be addressed here: relate and compare: regions that suffer from both too much and too little water, and assess evidence for possible response strategies; hydropower risks relating to both quantity and quality of water, and also hazards…how do regions compare on impact/response?]

2.4.2 Linking Adaptation Experiences with Response to Address Global Policy Frameworks

[PLACEHOLDER FOR SECOND ORDER DRAFT: assessment to be compiled and summarised once all sections are written. The following is envisaged to be addressed here: How do adaptation/response strategies reported, align with expected responses under global policy frameworks such as Agenda 2030 (SDGs), Paris Agreement (adaptation/mitigation to CC), and Sendai Framework (DRR)?]

2.4.3 Key Knowledge Gaps and Open Questions

[PLACEHOLDER FOR SECOND ORDER DRAFT: assessment to be compiled and summarised once all sections are written for FOD. Below are some examples of – and not all - key conclusions/assessment assertions made in the chapter so far. Text will avoid repetition from other sections but will be referred to elaborate as basis for a summary on synthesis of key gaps and open questions.]

[PLACEHOLDER FOR SECOND ORDER DRAFT: knowledge gaps in terms of observations]
- Temperature: Elevated dependant warming is a key attribute and area for mountain-specific monitoring and observation – data records sparse. In high tropical mountains, there are relatively few studies of long-term temperature trends due to lack of data, as opposed to other regions such as mid-latitudes (e.g., Alps). Greatest extent of observed EDW in Tibetan Plateau (Section 2.2.1.1).
- Precipitation: Trends of total precipitation at high altitude are highly uncertain, due to the paucity of studies using most detailed modelling tools to address high altitude, cryospheric related issues (Section 2.2.1.2).
- Cryospheric component (snow): Studies of the snow cover in Asia and Andes are mostly restricted to satellite-borne measurements, which span limited time coverage and lack support from in-situ observations (Section 2.2.2)
- Indigenous and local knowledge - may not be yet sufficiently nor systematically accounted for and reported to compare across regions and /or at global scales (Section 2.2.3.1)

[PLACEHOLDER FOR SECOND ORDER DRAFT: knowledge gaps in terms of detection and attribution]
- In the high mountains of Asia and the Tibetan Plateau, evidence from satellite records of significant interannual variability and regional differences of snow covered area … (Section 2.2.2)
- The higher uncertainty on projections at higher altitude are mostly due to the inability of regional climate models and downscaling methods to capture the subtle interplays between large-scale climate change and their impacts in complex topography (e.g., combined effects and feedback on regional and local atmospheric circulation, seasonality of precipitation along with regional temperature change) (Section 2.2.1).

- Coarse-scale simulations of future permafrost conditions are mostly of limited use due to coarse spatial resolution or lacking representation of topographic effects. Simulation studies suitable for mountain environments indicate widespread warming and thaw of permafrost (Section 2.2.4.2)

[PLACEHOLDER FOR SECOND ORDER DRAFT: knowledge gaps in terms of systematic review of impacts]

[PLACEHOLDER f FOR SECOND ORDER DRAFT: knowledge gaps in terms of systematic review of adaptation and responses (systematic evaluation - effectiveness of adaptation strategies and formal/informal policies and measures)]
- On Hydropower: for mitigation to be successful, the problems concerning data access and incorporation of knowledge into operational procedures need to be addressed (Section 2.3.1.2)

[PLACEHOLDER FOR SECOND ORDER DRAFT: knowledge gaps in terms of response, alignment and monitoring of actions in High Mountains to global policy frameworks]

[START FAQ2.1 HERE]

FAQ2.1: How do resilience, adaptation and mitigation of climate change contribute to sustainable development in mountain regions?

[PLACEHOLDER FOR THE SECOND ORDER DRAFT]

[END FAQ2.1 HERE]

[START FAQ2.2 HERE]

FAQ2.2: Why do not all glaciers retreat with global warming?

[PLACEHOLDER FOR THE SECOND ORDER DRAFT]

[END FAQ2.2 HERE]

[START FAQ2.3 HERE]

FAQ2.3: How does glacier retreat affect water supplies further downhill?

[PLACEHOLDER FOR THE SECOND ORDER DRAFT]

[END FAQ2.3 HERE]

[START FAQ2.4 HERE]

FAQ2.4: How may climate change alter the tourism industry and livelihoods that depend on it?

[PLACEHOLDER FOR THE SECOND ORDER DRAFT]

[END FAQ2.4 HERE]

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