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Adaptation to mountain cryosphere change: issues and challenges

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ABSTRACT
The cryosphere provides multiple services to society, but mountain cryosphere is shrinking at an alarming rate worldwide due to climate change, threatening natural and human systems. Adaptation to cryosphere change is essential to avoid irreversible damage and to achieve the Sustainable Development Goals. Although documenting adaptation actions and challenges is vital for preparing and implementing adaptation strategies, efforts to document and understand current adaptation practices specifically in response to cryosphere change have been limited. This paper synthesizes adaptation actions currently practiced in the mountain ranges of the Andes, Alps, Pamir, Tien Shan and Himalaya in response to cryosphere change, discusses common constraints and suggests actions for creating an enabling environment for adaptation. It identifies various adaptation measures adopted by different actors. These range from changing current practices and behaviour at household level to collaborative monitoring at regional level. However, most adaptation measures are autonomous, narrowly focused and short term, without adequate planning and government support. The physical challenges of mountain terrain, low adaptive capacities, limited knowledge and high uncertainty about future risks constrain widespread adoption of adaptation measures. Further research is needed to better understand factors influencing adaptation actions, and the policy options and responses that can overcome existing barriers.

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Adaptation; mountain cryosphere change; climate change; barriers to adaptation; vulnerable communities; policy response; sustainable development goals

1. Introduction

The cryosphere system constitutes the frozen water on the Earth's surface in the form of snow, ice cover, permafrost, glaciers, ice caps and frozen ground. Seasonal changes in the cryosphere regulate water, nutrients and sediment supply to mountain and downstream ecosystems, and provide multiple services to society including sustaining agriculture, generating hydropower, supplying drinking water and providing recreational services to billions of people worldwide (Huss et al., 2017; McDowell et al., 2019; Milner et al., 2017). The cryosphere contributes to the regulation of the climatic conditions of the Earth, while seasonal melting of mountain snow and ice supplies freshwater for more than half of humanity (Milner et al., 2017; Qin & Ding, 2010; Xiao, Wang, & Qin, 2015). However, temperature increases in recent years have had significant impacts on the cryosphere system: with a few exceptions, mountain cryospheres are declining all over the world (IPCC, 2014). Both observed changes and projections indicate that they are expected to continue to shrink in coming decades (Huss et al., 2017; Kraaijenbrink, Bierkens, Lutz, & Immerzeel, 2017).

The evidence of rapid change to the high mountain cryosphere is provided in global-scale assessments such as the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (2007, 2014). For instance, the European Alps have lost 54% of their ice area since 1850 and only 4%–13% is expected to remain by 2100 (Huss, 2012; Milner et al., 2017; Zemp, Haeberli, Hoelzle, & Paul, 2006). In the last 50 years, Bolivian glaciers have lost nearly 50% of their mass (Rangecroft et al., 2013). Similarly, during the 1960s and 2000s, the area of glacier loss in other Andean regions ranged from 26% to 87% (Rabatel et al., 2013). In the Himalaya, the area of glaciers fell by 5% to 55% during the 1960s and 2010s (Bajracharya et al., 2015; Kulkarni, Sciences, Division, & Group, 2007). Kraaijenbrink et al. (2017) projected glacier loss from 49% ± 7% to 64% ± 5% by 2100 in the Asian high mountains.

Cryospheric services such as water supply, climate and runoff regulation, and cultural and habitat services are important to human and natural systems (Xiao et al., 2015). The contribution of meltwater from the cryosphere to global major rivers and aquifers is considerable in many regions (Huss & Hock, 2018; Kaser, Großhauser, & Marzeion, 2010; Viviroli, Dürr, Messerli, Meybeck, & Weingartner, 2007). Globally, over 600 million people depend on glacier-fed water resources directly (Schaner, Voisin, Nijssen, & Lettenmaier, 2012) and many more in the downstream for agriculture, livestock, domestic and industrial uses indirectly (Rasul, 2014).

Cryospheric change has increased water shortages as well as the frequency and intensity of hazards and risks that adversely affect socio-ecological systems far beyond the mountainous region (Milner et al., 2017). The people living in high mountain areas, particularly in developing countries, are vulnerable

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owing to their physical environment and underlying economic, social and political situations (Xenarios et al., 2018).

In this context, timely adoption of adaptation measures is essential to avoid irreversible damage, or the development efforts to achieve poverty alleviation and the Sustainable Development Goals (SDGs) may be undermined. The IPCC defines adaptation as 'the process of adjustment to actual or expected climatic and its effects' (IPCC, 2007, 2014). In the present paper, the term 'adaptation measures' refers to short- and long-term human interventions to moderate or avoid harm, or to capitalize on beneficial opportunities emerging from cryospheric change in the mountains. Understanding the key adaptation experiences, lessons learnt and common challenges emerging from different mountain regions worldwide in response to cryospheric change is essential for better adaptation planning. Despite the perceived need, there has been limited documentation and synthesis of current adaptation practices in response to cryospheric change. This pioneering work has provided a broad picture of adaptation in high mountain regions (e.g. McDowell, Stephenson, & Ford, 2014; McDowell et al., 2019), but it appears that to date no review work has focused specifically on adaptation action in response to cryospheric change. Such knowledge is critically important to inform policies and practices in high mountain areas. Knowledge of how people prepare specific responses to avoid negative impacts is important in designing and implementing adaptation plans. In view of this, the present study focused on the following two questions:

- How do people prepare responses to avoid the negative impacts of cryospheric change, and what types of adaptation actions are taken by different actors?
- What are the issues and challenges constraining adaptation in response to cryospheric change?

With these questions in mind, this research involved collecting and collating the available adaptation practices, identifying constraints and challenges, and suggesting approaches to reduce adverse effects on human societies in the mountains. The paper is organized as follows: Section 2 outlines a framework to guide the approach to adaptation measures for climate-induced change in mountain cryospheres. Section 3 follows with methods of collecting literature. Section 4 presents the current adaptation practices implemented in mountain regions worldwide. Section 5 describes the patterns of adaptation in place. Section 6 examines the key barriers and challenges that constrain effective adaptation measures in the mountain context. Finally, Section 7 draws conclusions and recommends approaches to enhance the current adaptive capacity of society to accelerating cryospheric change.

2. Understanding adaptation to cryospheric change: a conceptual framework

While literature on climate change adaptation in mountain regions is growing, studies explicitly evaluating responses to the impacts of cryospheric change are limited (McDowell et al., 2019; McDowell & Koppes, 2017). People living in high mountain areas close to the cryosphere live in a multi-hazard environment (Allen, Zhang, Cuaresma, & Bolch, 2019; Kääb et al., 2018; Seneviratne et al., 2012). Hazardous interactions between climatic and geological processes, poor infrastructure and limited access to institutional services all contribute to making adaptation to cryospheric change different from other forms of adaptation. It is, therefore, important to understand the concept of adaptation in the context of cryospheric change, because the nature of risks in high mountain areas and the options available there may require different adaptation responses (Carey et al., 2014; McDowell & Koppes, 2017; Seneviratne et al., 2012).

There are several dimensions to the physical and social impacts resulting from climate-induced changes in the mountain cryosphere. One way of looking at these impacts is to distinguish between slow-paced impacts (e.g. hydrology and landscape changes; water shortages; changing ecosystems) and sudden-onset events (e.g. glacial lake outburst floods (GLOFs); avalanches) (Allen et al., 2019; Carey et al., 2014). Slow-paced impacts may not be noticeable immediately, unless the impacts exceed the adaptive capacity threshold of human and natural systems (Scheffer & Carpenter, 2003; Smit & Wandel, 2006). The degree of public attention and responses to sudden-onset events is often much greater than to slow-onset events (Porfiriev, 2015). Another way of looking at impacts is to differentiate between those at high altitudes with sparse human populations, and those at lower elevations which are relatively more populated. From an adaptation point of view such differentiation is necessary, because the adaptation needs of society vary depending on the type and magnitude of impact (Doria, Boyd, Tomkins, & Adger, 2009).

Adaptation approaches can also vary considerably based on the socio-economic context and the nature and type of stress (Hallegatte, 2009; Rasul & Sharma, 2016; Sovacool, 2011). Adaptation can be anticipatory or proactive (action that takes place before impacts of climate change) and reactive (action that takes place after impacts of climate change); it can be planned (deliberate action) or autonomous (spontaneous action owing to stress) (IPCC, 2001). Similarly, adaptation action and response can also vary from soft to hard measures such as changing behaviour and practices, reforming and developing policies and institutional mechanisms, adopting new technologies or upgrading old technologies, building and improving physical infrastructures, and relocating human settlements (Biagini, Bierbaum, Stults, Dobardzic, & McNeeley, 2014; Parveen, Winiger, Schmidt, & Nüsser, 2015).

Government agencies and donor communities often focus on hard measures such as large-scale infrastructures (e.g. irrigation channels, flood control dams, water storage to reduce climate risks) (Molden, Vaidya, Shrestha, Rasul, & Shrestha, 2014; Muchuru & Nhamo, 2019; Rasul & Sharma, 2016; Rasul, Neupane, Hussain, & Pasakhala, 2019). Building and improving physical infrastructures are capital-intensive measures, and often fail to have the desired impacts because of poor implementation and maintenance, and lack of public ownership (Biagini et al., 2014; Eriksen & Brown, 2011; Sovacool, 2011). Moreover, large infrastructures can have many unintended social, economic and environmental consequences (Doria et al., 2009). In view of such a shortfall, several scholars (for instance Hallegatte, 2009; Magnan et al., 2016; McDowell et al., 2019; Sovacool, 2011) advocate for soft adaptation measures and strategies such as awareness-raising; educating the public; changing behaviour and practices; capacity building; and institutional reforms, as they are low cost and flexible enough to adjust to changing conditions and new knowledge.

While soft adaptation measures are easy to implement, technological development such as developing early-warning systems, establishing effective communication systems are critically important (Vaidya et al., 2019). Knowledge, technology and financial resources influence the capacity to develop adaptation plans and implement them effectively (IPCC, 2014). Generating science-based knowledge, documenting local knowledge and sharing this knowledge are, therefore, critically important when designing and undertaking informed and planned adaptation responses (Mishra et al., 2019; Vaidya et al., 2019).

Although knowledge and technology are critically important for effective planning and for implementing adaptation, the policy and institutional environment shapes adaptation action by creating the conditions for it (Sud, Mishra, Varma, & Bhadwal, 2015). To improve policy and institutional mechanisms, the engagement of key stakeholders such as local communities, government, research organizations and non-governmental organizations can expand the range of adaptation options by contributing knowledge, experience, and resources, and by reducing adaptation constraints and limits (Amundsen, Berglund, & Westskog, 2010; Dovers & Hezri, 2010; IPCC, 2014) and by strengthening cross-scale linkages and coordination at multiple levels (Adger, Arnell, & Tomkin, 2005; Rasul & Sharma, 2016). In certain situations, however, in situ adaptation measures may fail if human settlements are at high risk (Allen et al., 2019; Parveen et al., 2015) and a more strategic adaptation approach may be needed, such as moving people from the exposed place and resettling them elsewhere in a safer environment (Tan, 2017).

Adaptation decisions are influenced by a number of factors, including the risk perception by individuals and their socio-economic context (Luís, Vauclair, & Lima, 2018; McDowell et al., 2014, 2016, 2019). Socio-economic factors often interact across scales and sectors, and their effects are often more immediate and of greater significance to local communities (Adger et al., 2005). Interactions between the impacts of cryospheric change and other non-cryospheric drivers increase the complexity, and result in multifaceted and cascading consequences on ecosystems as well as on communities.

In high mountain areas, adaptation planning becomes more complex because of the existence of both sudden-onset and slow-paced disasters. Greater complexity also stems from a higher degree of uncertainty pertaining to the magnitude and timing of future cryospheric change (Bolch et al., 2012). In addition to the nature of complexity and high level of uncertainty about risk, adaptation is also constrained by financial resources, technology and knowledge, particularly in poorer households (Castells-Quintana, Lopez-Uribe, & McDermott, 2018). Making adaptation effective in the context of high mountain areas to avert the impacts of cryospheric change a varieties of activities ranging from generating knowledge, raising awareness, developing technologies, developing policy and institutional support and engaging different actors and stakeholders at multiple scale from local to national, regional and global are necessary. Figure 1 illustrates the key aspects of adaptation action and responses in the context of cryospheric change.

3. Methods

3.1. Approach

This study was guided by two broad research questions: (1) How do people prepare responses to avoid the negative impacts of cryospheric change and what types of adaptation actions are taken by different actors? (2) What issues and challenges do they face? This study focused on adaptation action that is motivated by changes in the cryosphere, although often it is difficult to separate cryospheric factors and other, non-cryospheric, climatic factors. While documentation of adaptation to climate change is increasing globally, understanding of adaptation within the high mountain cryosphere remains limited (McDowell et al., 2019).

There are number of ways of synthesizing research evidence. To synthesize adaptation evidence, this study made a systematic review following McDowell et al. (2019). Systematic reviews have become well established as a means to bring together diverse evidence in a methodical way. As there are few reports of cryospheric-induced adaptation, a narrative synthesis was used that included collections of qualitative information from multiple sources to establish a chain of evidence.

3.2. Collection of information

The main focus was to identify adaptation actions and response measures, actors involved in adaptation initiatives and the scale of measures. The primary emphasis was on peer-reviewed journal articles. The search string terms included combinations of 'climate change', 'mountains' and 'adaptation', and the review was limited to the Andes, Alps, Pamir, Tien Shan and Himalayan mountain ranges. This resulted in a list of 405 peer-reviewed articles published in English over a 30-year period (January 1989–December 2018) using the Scopus database. Article selection was based on specific inclusion and exclusion criteria. The main **inclusion criteria w**ere: (1) articles reviewing or mentioning observed adaptation actions motivated by stress due to cryospheric change; (2) articles covering the Andes, Alps, Pamir, Tien Shan or Himalayan mountain ranges; and (3) those published in the English language. The main **exclusion criteria** were: (1) adaptation actions that were not triggered by, were not related to or did not deal with the impacts of cryospheric change; (2) articles describing non-human and biological adaptations; (3) those describing methodologies of adaptation assessments; and (4) those making theoretical recommendations on adaptation strategies.

With the inclusion criteria in mind, the review process first considered the titles and abstracts, and then the full texts, and unsuitable articles were removed. Conference and workshop proceedings were also excluded. In total, 56 peer-reviewed documents were suitable for the study. These 56 articles were studied in detail, analyzed and used in the paper. We analyzed the responses and grouped them in six major categories – change in current practices and behaviour, awareness and education, improving physical infrastructure and adopting new technologies, migration and relocation and reforming and developing policy and institutional mechanisms.

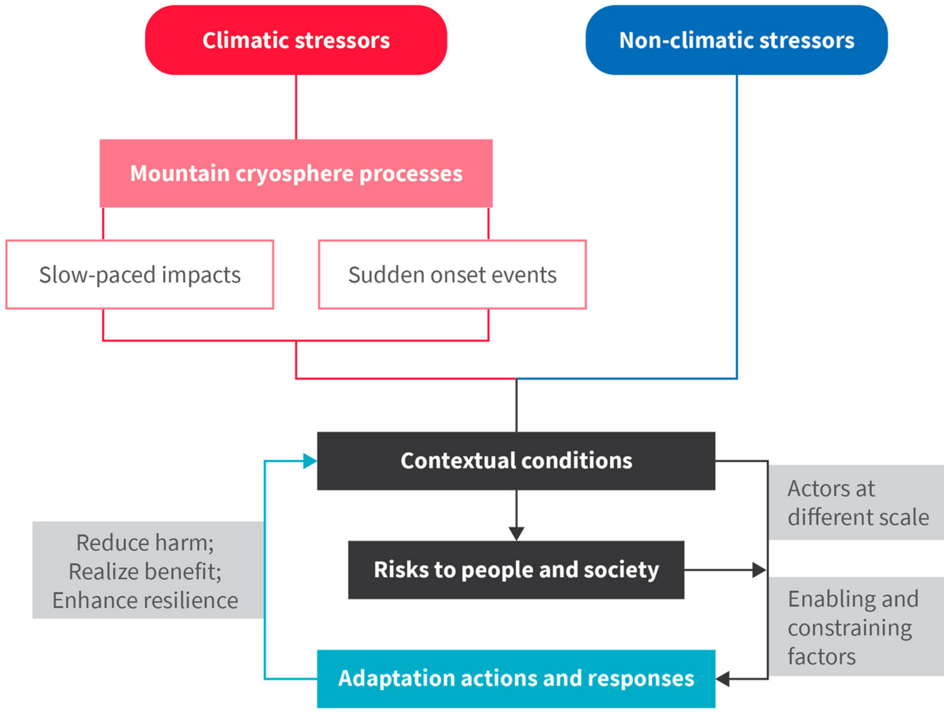

Figure 1. Analytical framework of the study.

4. Results: societal responses to cryospheric change

The review found that mountain communities have adopted a varieties of adaptation measures in different sectors to avert the impacts of cryosphere change (McDowell et al., 2014, 2019; McDowell & Koppes, 2017) though types of adaptation response varies across the mountain regions. Major adaptation measures are related to water, agriculture, livestock, and disasters moderation. The following sections describes the key adaptation measures in different sectors.

Table 1. Adapting to water stress.

Mountain region	Responses	Actors	Scale	References
Changes in practices				
Coquimbo, Chile	Water rationing; monitoring water use; purchasing additional water-use rights for irrigation in response to flow variability in snow and ice-fed rivers	Individual, private	Local	Young et al. (2010)
Imbabura, Ecuador	Purchasing additional domestic and irrigation water-use rights	Individual	Local	Skarbo and VanderMolen (2014)
Solukhumbu, Nepal	Water rationing; collecting water from distance sources for domestic consumption in response to decreasing water flow in snow-fed rivers	Community, private	Local	McDowell et al. (2013)
Myagdi and Mustang, Nepal	Use of organic manure to grow crops (reduced soil fertility resulting from low snow accumulation on land)	Individual	Local	Dangi et al. (2018)
Structure and technology				
Coquimbo, Chile	Constructing storage ponds; using drip irrigation and concrete line for efficient water use in response to flow variability in snow and ice-fed rivers	Individual, community, private	Local	Young et al. (2010)
Lima, Peru; Quito, Ecuador	Constructing water-storage infrastructure and pipeline networks of interconnected lakes and reservoirs in response to inter-annual variation in water supply	Government	Local, sub-national	Bury et al. (2013); Buytaert et al. (2017)
Palca, Bolivia; Gilgit -Baltistan, Pakistan	Constructing water channels for irrigation and domestic water supply	Local government; international donor	Local	McDowell and Hess (2012); Nüsser and Schmidt (2017)
Jammu and Kashmir, and Himachal Pradesh, India	Constructing artificial glaciers, ice stupas and snow barrier bands for irrigation and water conservation	*NGO, community-based organization	Local	Banerji and Basu (2010); Clouse (2016); Nüsser and Baghel (2016); Nüsser et al. (2018)
Solukhumbu, Nepal	Installing roof water collection system	Individual	Local	McDowell et al. (2013)
Policy and institution				
Peru	Promulgating National Water Authority 2009 to promote integrated water management in response to growing water competition and shortage	National government	National	Bury et al. (2013)
Kazakhstan, Turkmenistan, Uzbekistan Tajikistan and Kyrgyzstan	Establishing a regional centre to strengthen partnership for transboundary water governance to mitigate glacier retreat impacts	National government	Regional	Hoelzle et al. (2017); Sorg et al. (2014)

*NGO, non-governmental organization.

4.1. Adaptation measures for water security

Cryospheric change affects the hydrological systems of major rivers, particularly in arid and semi-arid regions, where contributions from other water sources are limited (Huss et al., 2017; Huss & Hock, 2018; Kaser et al., 2010; Viviroli et al., 2007). It is essential to sustain and secure depleting water resources used for irrigation, drinking, energy generation, and domestic and industrial uses.

Change in hydrological regime brought by the cryosphere and climate change affected the mountain communities and a varieties of measures are adopted to moderate impacts. Table 1 presents some of the evidence of adaptation actions already practiced by mountain communities. The review found that in the mountain the capacity of households to adapt to water stress due to cryospheric change was influenced by their economic status. Individual households of low economic status adapted by limiting their domestic water consumption and collecting water from far-distant sources (McDowell, Ford, Lehner, & Sherpa, 2013). Financially secure households and private organizations purchased additional water-use rights, hired assistance or built pipelines and storage tanks to collect and store water from distant sources (McDowell et al., 2013; Skarbo & VanderMolen, 2014; Young et al., 2010).

Construction of water infrastructure to store and distribute meltwater and rainwater has been a common structural measure adopted by households, communities, and governmental and non-governmental organizations (NGOs) (Nüsser & Schmidt, 2017; Postigo, Young, & Crews, 2008). Governments have made huge financial investments in the construction of large water reservoirs and water treatment plants in Quito (Ecuador) and Lima (Peru) to mitigate water shortages for urban populations (Bury et al., 2013; Buytaert et al., 2017). Provincial governments in Huaytara (Peru) and the Tibetan Autonomous Region (China) have implemented structural and technical measures to protect and restore grassland needed for grazing animals (Huijun et al., 2009; Postigo et al., 2008).

Without significant support from governmental agencies and NGOs, customary institutions in the Hunza and Gilgit-Baltistan (Pakistan) adapted historically to changes in glacier and disaster risks by constructing and maintaining irrigation networks (Nüsser & Schmidt, 2017; Parveen et al., 2015). Combining local and scientific knowledge, engineers and local communities in Ladakh and Zanskar (India) have built innovative water infrastructures – artificial glaciers, ice stupas and snow barrier bands – for irrigation during periods of water deficit (Clouse, 2016; Nüsser, Dame, Kraus, Baghel, & Schmidt, 2018).

Institutional governance mechanisms are essential to maintain water infrastructures, as well as to develop and implement effective adaptation measures at a larger scale. In La Paz and El Alto (Bolivia) local communities devised water-sharing mechanisms and resorted to informal water infrastructures to reduce stress on the drinking water supply (Poupeau & Hardy, 2016). At a sub-national level, in 2009 the Peruvian legislators of the Santa River watershed passed a new water law to promote integrated water management (Bury et al., 2013). Countries have forged regional cooperation and partnerships to promote the formulation of plans, policies and data sharing for transboundary water management (Hoelzle et al., 2017; Sorg et al., 2014). With the support of international organizations, Kyrgyzstan and Tajikistan have formed a National Water Commission for allocating water in the transboundary Khojabakirgansai Basin (Stucker, Kazbekov, Yakubov, & Wegerich, 2012) (Table 1).

There have been efforts to develop and evaluate adaptation measures based on scientific assessments of the implications of climate change – including cryospheric change – on ecosystems and water-dependent sectors (Beniston & Stoffel, 2014; Huggel et al., 2015). Moreover, in response to seasonal shifts in meltwater runoff, hydrological models and scenarios have been developed to predict floods and optimize the operation of water reservoirs (Hernandez, Schleiss, & Boillate, 2011).

4.2. Adaptation to cryospheric-induced hazards

Technical and planned adaptation measures have been implemented to reduce the impact of cryospheric hazards on communities and infrastructure in the Andean, Alpine and Himalayan regions (Table 2). Common engineering techniques for mitigating glacial lake outburst risks in Peru, China, Nepal and Bhutan have included draining water from glacial lakes, and installing early-warning and monitoring systems (Cuellar & McKinney, 2017; Meenawat & Sovacool, 2011; Somos-Valenzuela et al., 2015). The measures were based on scientific assessments by research organizations and jointly implemented by governmental, intergovernmental and international donor organizations (Byers, McKinney, Thakali, & Somos-Valenzuela, 2014). The role of research organizations has been vital in supporting communities and governments in disaster preparedness and developing regulations for preventing the construction of infrastructure in risk-prone zones (Orlove, 2009) (Table 2).

Disasters have led inhabitants to abandon their land and settlements, and to move to new places deemed safer and with better resources (Kreutzmann, 2012). In Kedarnath valley (India), inhabitants abandoned their settlements after cryospheric-induced catastrophes (Maikhuri et al., 2017). The villagers of Amdo county, Nagchu Prefecture (China) moved to less-affected areas to avoid snow-induced hazards (Diemberger, Hovden, & Yeh, 2015). The government of Chile planned and relocated the settlement at Bahia Murta Viejo after the outburst of Engaño Lake in 1977 (Anacona, Mackintosh, & Norton, 2015).

GLOF events have pushed communities in Hunza (Pakistan) and Bahia Murta (Chile) to move from their villages to nearby relatives living in safe locations (Anacona et al., 2015; Ashraf, Naz, & Roohi, 2012). Multiple stressors from climate (including cryospheric) change and their implications for water availability and agriculture have forced young people from Yungay, Huaraz and Catac (Peru) and Uttarakhand (India) to migrate temporarily to cities for employment (Maikhuri et al., 2017; Wrathall et al., 2014).

In the Alps and Central Asia, regional countries have collaborated to minimize the risks of glacier hazards and transboundary impacts. In the Alpine region, multiple

Table 2. Responses to cryospheric-induced hazards.

Mountain region	Responses	Actors	Scale	References
Awareness and education				
Dolakha and Solukhumbu, Nepal	Awareness-raising of threat of glacial lake outburst and advocacy for installing early-warning system in Tsho Rolpa and Imja glacial lakes	Community, *NGO	Local	Kattelmann (2003)
Punakha-Wangdue and Chamkhar valleys, Bhutan	Awareness-raising to improve infrastructure, institutional and community resilience	National government, Intergovernmental	Local	Meenawat and Sovacool (2011)
Structural and technology				
Coquimbo, Chile	Constructing channels to divert river discharge and retain debris in response to increased ablation of snow and ice	Government	Local	Young et al. (2010)
Lake Paron, Peru	Constructing water gates and tunnel to reduce water level of glacial lake; generating hydroelectricity	Government, private	Local	Carey et al. (2012b)
Parvati valley, India; Tsho Rolpa and Imja glacial lakes, Nepal; Punakha-Wangdue and Chamkhar valleys, Bhutan	Draining water to reduce pressure on moraine dam walls; installing and operating early-warning system	National government, international donor, intergovernmental and community-based organization	Local	Allen et al. (2018); Carey et al. (2012a); Cuellar and McKinney (2017); Meenawat and Sovacool (2011); Somos-Valenzuela et al. (2015)
Migration (relocation)				
Bahia Murta, Chile; Hunza, Pakistan; Tibet Autonomous Region, China; Kedarnath valley, Uttarakhand, India	Relocating settlements	Individual, government	Local	Anacona et al. (2015); Diemberger et al. (2015); Kreutzmann (2012); Maikhuri et al. (2017)
Policy, institution and knowledge				
Ecuador, Peru, Colombia, Kyrgyzstan	Forming Global Terrestrial Network for Glaciers to monitor glaciers; technical and institutional capacity building; maintaining and sharing glacier database	Research institution, intergovernmental, government	Global and national	Nussbaumer et al. (2017)
Kazakhstan, Uzbekistan, Afghanistan, Pakistan, Tajikistan, Kyrgyzstan, China, India, Nepal, Bhutan, Bangladesh and Myanmar	Forming networks of research institutions to generate scientific knowledge on cryospheric change and suggest adaptation strategies	Research institutions	Global	Yao et al. (2012)
Parvati valley, India	Participatory and iterative integrated risk assessment approach; knowledge exchange and institutional capacity building	National and state government, international donor	Sub-national	Allen et al. (2018)
Punakha-Wangdue and Chamkhar valleys, Bhutan	Maintaining regional **GLOF database	National government, Intergovernmental	Local	Meenawat and Sovacool (2011)

*NGO, non-governmental organization; **GLOF, glacial lake outburst flood.

countries jointly implemented a project for monitoring changes in permafrost, to develop a common disaster-preparedness strategy and to manage water resources (Cremonese et al., 2011).

4.3. Adaptation measures for livelihood security

The impacts of cryospheric change on the availability of water resources and the increase in natural hazards have direct and indirect implications for livelihoods, particularly those of people dependent on agriculture, livestock and tourism in high mountain areas. Table 3 presents key adaptation measures already practicing by mountain communities.

Changing their crops and cropping patterns were the most common reactionary adaptations of farmers. In Illam and Humla (Nepal), farmers planted drought-resistant crops such as buckwheat when snow cover and snowfall became less reliable (Chaudhary et al., 2011; Onta & Resurreccion, 2011). Responding to a warming climate, farmers in Sikkim (India) and Mustang (Nepal) introduced new vegetable crops (Ingty 2017; Manandhar, Vogt, Perret, & Kazama, 2011). Livelihood diversification, particularly engaging in non-farm sectors and temporary migration to urban centres, has been an important adaptation strategy, and evident in north-central Peru (Young & Lipton, 2006), Tibet, China (Fu et al., 2012) and Mustang (Nepal) (Manandhar et al., 2011). Changes in snowfall patterns have had implications for grassland ecology and fodder availability for animals. These impacts have led pastoral communities to change grazing patterns and locations, to shift from large to small animals and to plant fodder crops (Fu et al., 2012).

Private tourism companies have implemented behavioural and technological adaptations to safeguard the tourism industry against glacier thinning and decline in snowfall. In Austria, ski resorts use snow-making machines to overcome the losses in ice thickness and snow cover (Fischer, Olefs, & Abermann, 2011, 2016). The Austrian federal government and research institutions have also produced climate-related hazard zone maps of glaciated mountain regions for mountaineers (Ritter, Fiebig, & Muhar, 2012).

Various tourism opportunities are being explored so that glacier access can continue to be facilitated. In the Alps, the German and Swiss mountain tourism industries have tapped the potential of using their resorts as escapes from summer heat and warmer weather, and so increasing the number of mountain tourists (Pröbstl-Haider, Haider, Wirth, & Beardmore, 2015; Serquet & Rebetez, 2011). In response to changes in the quality and quantity of snow cover, ski tourists in the European Alps have adjusted their trips following snow forecasts, switched to snow-independent activities and changed their ski destinations (Steiger, Scott, Abegg, Pons, & Aall, 2017).

5. Patterns of adaptation to cryospheric change

The adaptation activities presented above can be categorized into six broad patterns and domains and five actors (Table 4). The domain of adaptation practices varies from raising awareness to changing current practices and behaviour; improving physical infrastructure; upgrading and adopting new technologies; changing policies and institutions; building capacities; and relocating settlements. Actors involved in initiatives include individual households and communities; public organizations; private organizations; research organizations; and international organizations. Other actors also engage in different activities. Individual households and communities are directly involved in on-the-ground adaptations. Public organizations are largely involved in creating enabling environments by raising awareness; sensitizing different stakeholders; building capacities; constructing large infrastructures; establishing early-warning systems; reforming policy and institutional mechanisms; and informing and preparing for adaptation. Private organizations engaged in the tourism sector have responded by adopting technologies for making artificial snow; diversifying mountain tourism activities; and developing environmental guidelines for tourist activities. Research organizations have been monitoring cryospheric change; assessing risks; and sharing knowledge. International organizations are largely supporting adaptation by providing financial and technical resources, and preparing the conditions for more substantive adaptive actions.

6. Key barriers and challenges

Although people living in high mountain areas are coping with and adapting to cryospheric change, existing efforts to mitigate their adverse effects are inadequate. There are multiple barriers to effective adaptation, and some of the most significant are discussed below.

One of the greatest challenges is inadequate knowledge about the present and future impacts of cryospheric change

Table 3. Adaptation measures for livelihood security.

Mountain region	Responses	Actors	Scale	References
Changes in practices				
Palca, Bolivia; Imbabura, Ecuador; Mustang, Nepal	Changes in crops and cropping patterns; chemical inputs to control pests and diseases in crops in response to increasing temperatures and changes in snowfall pattern	Community, *NGO	Local	Manandhar et al. (2011); McDowell and Hess (2012); Skarbo and VanderMolen (2014)
Huaraz, Peru	Changes in trails to reach base of glacier; bans on glacier crossing in response to glacier melting	Local government	Local	Bury et al. (2011)
Huaraz, Peru	Reducing herd size and diversifying livelihoods in response to glacial retreat and its impacts	Community	Local	Young and Lipton (2006)
Tyrol, Austria	Relocating skiing area in response to reduction in glacier thickness	Private	Local	Fischer et al. (2011)
Norway	Shortening trips to glaciers; glacier lake kayaking and glacier terminal face walking in response to glacier melting and less accessible glaciers	Private	Local	Furunes and Mykletun (2012)
Tibet Autonomous Region, China	Rotational grazing and efficient use of pastures; growing and storing fodder; communal pooling of labour for herding; shifting from yaks to goats and sheep; collecting and selling medicinal plants to reduce livelihood shocks after snow disasters	Community	Local	Fu et al. (2012)
Structure and technology				
Tyrol, Austria; Davos, Scuol and Braunwald, Switzerland; Yunnan, China	Artificial snow production in response to reduced snowfall and glacier retreat	Private, local government	Local	Rixen et al. (2011); Steiger and Mayer (2008); Wang, He, and Song (2010)
Tyrol, Austria	Repositioning pylons; covering glaciers with textiles; installing windbrakes; grooming and relocating snow in response to decline in snowfall and increase in snow and glacier melting	Private	Local	Fischer et al. (2011)
Knowledge				
Tibet Autonomous Region, China	Sharing knowledge of herding practice and pasture management in response to livestock losses after snow disaster	Community	Local	Fu et al. (2012)
Policy and institution				
Yunnan, China; Huaraz, Peru	Implementing environmental protection rules for tourists in response to glacier retreat	Private, local government	Local	Wang et al. (2010); Bury et al. (2011)
Himachal Pradesh, India	Forming apple growers' association to advocate for compensation and governmental support for their crops following changes in snowfall patterns	Community-based institutions	Local	Vedwan (2006)

*NGO, non-governmental organization.

Table 4. Patterns of adaptation to cryospheric change.

	Domains of adaptation					
Actors	Awareness and education	Changing current practices and behaviour	Improving physical infrastructure and adopting new technologies	Relocation/ resettlement	Reforming and developing policy and institutional mechanism	Generating and sharing knowledge
Individual households and communities	Awareness-raising and advocacy to mitigate threat from glacial lakes	Diversifying livelihoods; changing cropping and livestock herding patterns; shifting to new crops and livestock; rationing water	Constructing physical infrastructures to collect, store and distribute water; upgrading irrigation systems; adopting efficient water-use technologies	Relocating settlements	Developing local rules for water distribution; irrigation and pasture management	Sharing local knowledge and adaptation experiences
Public organizations	Awareness-raising; capacity building		Constructing infrastructure to store and channel water; draining glacial lakes; installing and operating early-warning system	Relocating settlements	Modifying/ formulating/ adapting plans and policies; strengthening regional cooperation for transboundary water management; establishing and capacity-building institutions focused on cryospheric change	Monitoring and modelling cryospheric change
Private organizations		Modifying tourism activities; improving access to water sources	Making artificial snow		Implementing environmental protection guidelines for tourists	
Intergovernmental and international donor organizations	Awareness-raising; capacity building		Supporting drainage of water from glacial lakes; installing and operating early-warning systems		Establishing capacity-building institutions and networks focused on cryospheric change	Monitoring cryospheric change; maintaining database; sharing knowledge
Research organizations			Optimising reservoir water flow	Assessing suitability of a place for relocation	Forming network to cooperate on cryospheric-related issues	Monitoring and modelling cryospheric change; assessing impacts and vulnerabilities; sharing scientific knowledge

and the potential adaptation options (Vuille et al., 2018). There have been efforts by governmental agencies and various research organizations recently to prepare a GLOF database, identifying dangerous glacier lakes and forming cryospheric research networks. Translating research into actionable information, however, such as designing an early-warning system, remains a challenge. For instance, in Nepal 20 glacial lakes were identified as critically dangerous (ICIMOD, 2011), but mitigation measures have been taken for only two of them. Failure to undertake mitigation measures can result in natural disasters, often involving loss of life and damage to property. The 2013 GLOF incident in Kedarnath valley, Indian Himalaya, for instance, claimed the lives of more than 4,000 people and caused huge losses of property and infrastructure at a cost of about USD 665 million (Dani & Motwani, 2013).

Individual households and communities have adapted in various ways (including modifying agricultural production practices, livestock and pastures; diversifying livelihood strategies; and devising new local regulations for resource use and management) to cope with the adverse impacts of water stress and to maintain or enhance livelihoods. These soft autonomous measures are relatively cheap and flexible (Hallegatte, 2009), but the extent to which these new technologies can withstand future change remains uncertain. In the long run, they may become insufficient (Clouse, 2016) or the adaptive capacity of communities may gradually erode (McDowell & Hess, 2012) as projected change escalates. For instance, in the face of high temperatures and reduced snow cover, communities at high altitudes have introduced new crops (Chaudhary et al., 2011; Onta & Resurreccion, 2011). Such opportunistic measures need to be undertaken with adequate precautions or may result in unintended adverse consequences on the environment, such as the introduction of alien invasive species, pests and diseases. Similarly, modification of grazing patterns by herders to access limited available water resources may result in an increase in animal density in a small area, leading to overgrazing and risk of infectious disease transmission.

Adaptation is a deeply nested process and requires a comprehensive approach, but present efforts are mostly sectoral. Governmental organizations are predominantly focused on improving water availability and mitigating cryospheric-induced hazards through structural and technological fixes. The structural and technological measures are reported to be effective in mitigating water shortages and physical risks from the outburst of glacial lakes (Carey, Huggel, Bury, Portocarrero, & Haeberli, 2012a). However, structural and technological interventions are not adequate in themselves to address the social vulnerability of communities to cryospheric change (Eriksen et al., 2011). Efforts to facilitate or adopt adaptation measures that ignore the social, economic, political and institutional features of a society exacerbate existing inequalities and also lead to conflicts (Carey, French, & O'Brien, 2012b; Mills-Novoa et al., 2016; Skarbo & Vander-Molen, 2014). Adaptation planning needs to engage with local people and traditional institutions, incorporating their experiential knowledge as well as scientific information: an appropriate mix, therefore, of both top-down and bottom-up initiatives.

When uncertainty and difficult mountain terrain are combined with low adaptive capacity and weak institutional support, adaptation becomes difficult in high mountain areas. Threatened by cryospheric-induced natural disasters and other environmental changes, along with other socio-economic stresses, people are leaving high mountain areas (such as in the Himalaya) and relocating in relatively safer places. Outmigration of communities from hazardous glaciated areas indicates that there are limits to adaptive capacity (Maikhuri et al., 2017) and residual risk. Thus, the assistance of public, non-governmental, international donors and research institutions in facilitating community adaptation is essential (Spires, Shackleton, & Cundill, 2014). A review of the literature, however, has shown that their support to local communities has been very limited in the global south.

7. Discussion, conclusions and recommendations

In response to challenges posed by climate change, communities dependent on the cryosphere in different mountain regions have adopted different adaptation measures. These vary from adjusting to irrigation water shortages at a household level to collaborative monitoring at regional level. Most adaptation measures are local, and only a limited number extend across multiple countries.

The majority of adaptation measures are autonomous, narrowly focused, short term and reactive rather than preventive; they are incremental rather than transformative. Governments across the different mountain regions have yet to prioritize cryospheric adaptation measures in their development planning and decision making.

Adaptation to cryospheric change in high mountain areas faces multiple challenges: limited knowledge and understanding, low adaptive capacity, weak institutional support and bio-physical limitations. Local communities and governments face the daunting task of making adaptation decisions with limited information and in an uncertain environment. These constraints, along with poor understanding of socio-economic and cultural features of mountain communities made adaptation ineffective.

To overcome barriers it is important to create an enabling environment to share technical and financial resources, and knowledge; and to engage different actors and stakeholders. It is also vital to raise awareness of the risk of cryospheric change and to provide climate information (including early-warning systems). In formulating adaptation strategies, the nature of challenges faced by different actors and stakeholders needs to be recognized. The first step may be to promote better understanding of the nature of events (slow-paced and sudden-onset incidents, and their frequency and magnitude) and the local context (the socio-economic conditions of local people and the bio-physical environment) in which different actors make decisions. A better understanding of the local context allows different actors and stakeholders to act strategically to assess risks and opportunities in the context of both slow-paced and sudden-onset events. Understanding local conditions also helps in the development of contextually appropriate adaptation responses, combining soft and hard options (Hallegatte, 2009; Sovacool, 2011).

A better understanding of context is important, but not sufficient to promote effective adaptation action. Both a strategic global response and a bottom-up, locally suitable solution are needed to allow a collaborative, adaptive response that builds resilience. Instead of responding to surprises and making decisions on an ad hoc basis, it is important to take a structured approach and develop a risk-management strategy and framework to deal with the complex issue of cryospheric change and to manage both short- and long-term risks and impacts. Emerging risks need to be factored into existing development and adaptation plans and decision-making processes in an integrated manner. Anticipatory plans and strategies, and forward-looking adaptation strategies – as well as no-regret adaptation actions (Allen et al., 2016; Hallegatte, 2009) – are necessary. Efforts need to be made to minimize trade-offs and to promote synergies between adaptation actions across sectors and scales, both upstream and downstream in a glaciated river basin. Actions taken upstream may adversely affect communities downstream, but bring synergies if planned well and managed effectively. In Lake Paron (Peru), for example, the risk of GLOF hazards was mitigated, and hydropower was generated downstream, through the strategic discharge of water (French, Barandiarán, & Rampini, 2015). Priority should be given to adaptation options that have positive synergy with other sectors and adaptation efforts downstream (Rasul & Sharma, 2016).

Institutional mechanisms need to be developed to coordinate responses across sectors, scales and jurisdictions between and among individuals and organizations which may have competing interests, mandates and priorities (Rasul, 2014, 2016). In glaciated river basins, adaptive responses are complicated by national boundaries, because regional adaptive responses across borders are more challenging. Addressing the impacts of cryospheric change requires regional and international cooperation, policy innovations, and regional and global action for effective adaptation at basin level.

Mukherji et al. (2019) noted that cryospheric change has a disproportionately greater impact on people living in high mountain areas, and so special efforts are necessary, particularly for those living in the global south. They require special attention because they face greater adaptation challenges owing to weak socio-economic structures, limited governmental support, physical and social isolation, and marginalization. Without adequate support, they may fall into a poverty trap that they are unable to escape, which may frustrate the goal of achieving the SDGs, alleviating poverty and reducing inequalities (Hallegatte & Rozenberg, 2017).

7.1. Key knowledge gaps and future research needs

The review found a lack of knowledge about the social aspects of adaptation: the underlying factors that influence adaptation action and decision-making processes. Because of this, existing adaptation plans and programmes are often inadequate to overcome the social, institutional and technological barriers to adaptation and to provide incentives for taking adaptation measures. Only limited information exists about the future risks of potential socio-economic vulnerabilities to resource-poor individuals, women, those of low caste and ethnic minorities . Further research is needed to fill this gap, and particularly to deepen understanding of the implications of cryospheric change on human societies (Carey et al., 2017; McDowell et al., 2019).

Moreover, limited knowledge is available about how cryospheric change and associated stresses on water, agriculture, hydropower and livelihoods may propagate stresses in other sectors, and particularly on their social and economic implications. Future research needs to assess the relationship between such change and human mobility, especially on human security and on factors influencing decisions on mobility such as migration, relocation and resettlement. Further clarification is needed of the effectiveness of adaptation actions, and to understand the contextual factors governing why people adopt particular options in certain areas. More knowledge and understanding is also needed to understand the cross-border implications of adaptation action in glaciated river basins. Another possible area of future research could be how cooperation in knowledge generation and exchange among global, regional, national and local actors facilitates action for better adaptation and risk management; and to integrate scientific and local knowledge into adaptation plans.

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References

Adger, W. N., Arnell, N. W., & Tomkin, E. L. (2005). Successful adaptation to climate change across scales. *Global Environmental Change*, *15*(2), 77–86. doi:10.1016/j.gloenvcha.2004.12.005

Allen, S. K., Ballesteros-Canovas, J., Randhawa, S. S., Singha, A. K., Huggel, C., & Stoffel, M. (2018). Translating the concept of climate risk into an assessment framework to inform adaptation planning: Insights from a pilot study of flood risk in Himachal Pradesh, Northern India. *Environmental Science and Policy*, *87*, 1–10. doi:10.1016/j.envsci.2018.05.013

Allen, S. K., Linsbauer, A., Randhawa, S. S., Huggel, C., Rana, P., & Kumari, A. (2016). Glacial lake outburst flood risk in Himachal Pradesh, India: An integrative and anticipatory approach considering current and future threats. *Natural Hazards*, *84*(3), 1741–1763. doi:10.1007/s11069-016-2511-x

Allen, S. K., Zhang, G., Cuaresma, J. C., & Bolch, T. (2019). Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. *Science Bulletin*, *64*(7), 1. Pages 435–445. doi:10.1016/j.scib.2019.03.011

Amundsen, H., Berglund, F., & Westskog, H. (2010). Overcoming barriers to climate change adaptation—a question of multilevel governance? *Environment and Planning C: Government and Policy*, *28*(2), 276–289. doi:10.1068/c0941

Anacona, P. I., Mackintosh, A., & Norton, K. (2015). Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia : Lessons for GLOF risk management. *Science of the Total Environment*, *527–528*(15), 1–11. doi:10.1016/j.scitotenv.2015.04.096

Ashraf, A., Naz, R., & Roohi, R. (2012). Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan ranges of Pakistan: Implications and risk analysis. *Geomatics, Natural Hazards and Risk*, *3*(2), 113–132. doi:10.1080/19475705.2011.615344

Bajracharya, S. T., Maharjan, B. S., Shrestha, F., Guo, W., Liu, S., Immerzeel, W., & Shrestha, B. (2015). The glaciers of the Hindu Kush Himalayas: Current status and observed changes from the 1980s to 2010. *International Journal of Water Resources Development*, *31*(2), 161–173. doi:10.1080/07900627.2015.1005731

Banerji, G., & Basu, S. (2010). Adapting to climate change in Himalayan cold deserts. *International Journal of Climate Change Strategies and Management*, *2*, 426–448.

Beniston, M., & Stoffel, M. (2014). Assessingt the impacts of climatic change on mountain water resources. *Science of the Total Environment*, *493*(15), 1129–1137. doi:10.1016/j.scitotenv.2013.11.122

Biagini, B., Bierbaum, R., Stults, M., Dobardzic, S., & McNeeley, S. M. (2014). A typology of adaptation actions: A global look at climate adaptation actions financed through the global environment facility. *Global Environmental Change*, *25*, 97–108. doi:10.1016/j.gloenvcha.2014.01.003

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J. G., … Stoffel, M. (2012). The state and fate of Himalayan glaciers. *Science*, *336*, 310–314. doi:10.1126/science.1215828

Bury, J., Mark, B. G., Carey, M., Young, K. R., Mckenzie, J. M., Baraer, M., … Polk, M. H. (2013). New geographies of water and climate change in Peru: Coupled natural and social transformations in the Santa river watershed. *Annals of the Association of American Geographers*, *103*, 363–374. doi:10.1080/00045608.2013.754665

Bury, J. T., Mark, B. G., McKenzie, J. M., French, A., Baraer, M., Huh, K. I., … Lopez, R. J. G. (2011). Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. *Climatic Change*, *105*(1–2), 179–206. doi:10.1007/s10584-010-9870-1

Buytaert, W., Moulds, S., Acosta, L., De Bièvre, B., Olmos, C., Villacis, M., … Verbist, K. M. J. (2017). Glacial melt content of water use in the tropical Andes. *Environmental Research Letters*, *12*, 1–8. doi:10.1088/1748-9326/aa926c

Byers, A. C., McKinney, D. C., Thakali, S., & Somos-Valenzuela, M. (2014). Promoting science-based, community –driven approaches to climate change adaptation in glaciated mountain ranges: HiMAP. *Geography*, *99*(3), 143–152.

Carey, M., French, A., & O'Brien, E. (2012b). Unintended effects of technology on climate change adaptation: An historical analysis of water conflicts below Andean glaciers. *Journal of Historical Geography*, *38* (2), 181–191. doi:10.1016/j.jhg.2011.12.002

Carey, M., Huggel, C., Bury, J., Portocarrero, C., & Haeberli, W. (2012a). An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from lake 513, Cordillera Blanca, Peru. *Climatic Change*, *112*(3–4), 733–767. doi:10.1007/s10584-011-0249-8

Carey, M., McDowell, G., Huggel, C., Jackson, J., Portocarrero, C., Reynolds, J. M., & Vicuña, L. (2014). Integrated approaches to adaptation and disaster risk reduction in dynamic socio-cryospheric systems. In J. F. Shroeder, W. Haeberli, & C. Whiteman (Eds.), *Snow and ice-related hazards, risks and disasters* (pp. 219–261). Amsterdam, Netherlands: Elsevier.

Carey, M., Molden, O. C., Rasmussen, M. B., Jackson, M., Nolin, A. W., & Mark, B. G. (2017). Impacts of glacier recession and declining meltwater on mountain societies. *Annals of the American Association of Geographers*, *107*, 350–359. doi:10.1080/24694452.2016.1243039

Castells-Quintana, D., Lopez-Uribe, M. D. P., & McDermott, K. J. (2018). Adaptation to climate change: A review through a development economic lens. *World Development*, *104*, 183–196. doi.org/10.1016/j.worlddev.2017.11.016

Chaudhary, P., Rai, S., Wangdi, S., Mao, A., Rehman, N., Chettri, S., & Bawa, K. S. (2011). Consistency of local perceptions of climate change in the Kangchenjunga Himalaya landscape. *Current Science*, *101*, 504–513.

Clouse, C. (2016). Frozen landscapes: Climate-adaptive design interventions in Ladakh and Zanskar. *Landscape Research*, *41*(8), 821–837. doi:10.1080/01426397.2016.1172559

Cremonese, E., Gruber, S., Phillips, M., Pogliotti, P., Boeckli, L., Noetzli, J., … Zischg, A. (2011). An inventory of permafrost evidence for the European Alps. *Cryosphere*, *5*, 651–657. doi:10.5194/tc-5-651-2011

Cuellar, A. D., & McKinney, D. C. (2017). Decision-making methodology for risk management applied to Imja lake in Nepal. *Water*, *9*(8), 591. doi:10.3390/w9080591

Dangi, M. B., Chaudhary, R. P., Rijal, K., Stahl, P. D., Belbase, S., Gerow, K. G., … Pyakurel, B. (2018). Impacts of environmental change on agroecosystems and livelihoods in Annapurna conservation area. *Nepal. Environmental Development*, *25*, 59–72. doi:10.1016/j.envdev.2017.10.001

Dani, S., & Motwani, A. (2013). *India Uttarakhand disaster June 2013: Join rapid damage and needs assessment report*. Washington, DC: World Bank.

Diemberger, H., Hovden, A., & Yeh, E. (2015). The honour of the snow mountains is the snow: Tibetan livelihoods in a changing climate. In C. Huggel, M. Carey, J. Clague, & A. Kaab (Eds.), *The high mountain cryosphere: Environmental changes and human risks* (pp. 249–271). Cambridge, UK: Cambridge University Press. doi:10.1080/24694452.2016.1243039

Doria, M. D. F., Boyd, E., Tomkins, E. L., & Adger, W. N. (2009). Using expert elicitation to define successful adaptation to climate change. *Environmental Science and Policy*, *12*, 910–819. doi.org/10.1016/j.envsci.2009.04.001

Dovers, S. R., & Hezri, A. A. (2010). Institutions and policy processes: The means to the ends of adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(2), 212–231. doi:10.1002/wcc.29

Eriksen, S., Aldunce, P., Bhanipati, S. C., Martins, R. D., Molefe, J. I., Nhemachena, C., … Ulsrud, K. (2011). When not every response to climate change is a good one: Identifying principles for sustainable adaptation. *Climate and Development*, *3*(1), 7–20. doi:10.3763/cdev.2010.0060

Eriksen, S., & Brown, K. (2011). Sustainable adaptation to climate change. *Climate and Development*, *3*(1), 3–6. doi:10.3763/cdev.2010.0064

Fischer, A., Helfricht, K., & Stocker-Waldhuber, M. (2016). Local reduction of decadal glacier thickness loss through mass balance management in ski resorts. *Cryosphere*, *10*(6), 2941–2952. doi:10.5194/tc-2016-61

Fischer, A., Olefs, M., & Abermann, J. (2011). Glaciers, snow and ski tourism in Austria's changing climate. *Annals of Glaciology*, *52*(58), 89–96. doi:10.3189/172756411797252338

French, A., Barandiarán, J., & Rampini, C. (2015). Contextualizing confl ict. Vital water and competing values in glaciated environments. In C. Huggel, M. Carey, J. Clague, & A. Kaab (Eds.), *The high mountain cryosphere: Environmental changes and human risks* (pp. 315–336). Cambridge, UK: Cambridge University Press.

Fu, Y., Grumbine, R. E., Wilkes, A., Wang, Y., Xu, J. C., & Yang, Y. P. (2012). Climate change adaptation among Tibetan Pastoralists: Challenges in enhancing local adaptation through policy support. *Environmental Management*, *50*, 607–621. doi:10.1007/s00267-012-9918-2

Furunes, T., & Mykletun, R. J. (2012). Frozen adventure at risk? A 7-year follow-up study of Norwegian glacier tourism. *Scandinavian Journal of Hospitality and Tourism*, *12*(4), 324–348. doi:10.1080/15022250.2012.748507

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. *Global Environmental Change*, *19*, 240–247. doi:10.1016/j.gloenvcha.2008.12.003

Hallegatte, S., & Rozenberg, J. (2017). Climate change through a poverty lens. *Nature Climate Change*, *7*(4), 250–256. doi:10.1038/NCLIMATE3253

Hernandez, J. G., Schleiss, A. J., & Boillate, J. (2011). Decision support system for the hydropower plants management: The MINERVE project. In A. J. Schleiss, & R. M. Boes (Eds.), *Dams and reservoirs under changing challenges* (pp. 459–468). London, UK: CRC press.

Hoelzle, M., Azisov, E., Barandun, M., Huss, M., Farinotti, D., Gafurov, A., … Zemp, M. (2017). Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia. *Geoscientific Instrumentation, Methods and Data Systems*, *6*, 397–418. doi:10.5194/gi-2017-31

Huggel, C., Scheel, M., Albrecht, F., Andres, N., Calanca, P., Jurt, C., … Zappa, M. (2015). A framework for the science contribution in climate adaptation: Experiences from the science-policy processes in the Andes. *Environmental Science and Policy*, *47*, 80–94. doi:10.1016/j.envsci.2014.11.007

Huijun, J., He, R., Cheng, G., Wu, Q., Wang, S., Lu, L., & Chang, X. (2009). Changes in frozen ground in the source area of the Yellow River on the Qinghai-Tibet Plateau, China, and their eco-environmental impacts. *Environmental Research Letters*, *4*, 1–11. Retrieved from http://iopscience.iop.org/1748-9326/4/4/045206

Huss, M. (2012). Extrapolating glacier mass balance to the mountain-range scale: The European Alps 1900–2100. *Cryosphere*, *6*, 713–727. doi:10.5194/tc-6-713-2012

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., … Winder, M. (2017). Toward mountains without permanent snow and ice. *Earth's Future*, *5*, 418–435. doi:10.1002/2016EF000514

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135–140. doi:10.1038/s41558-017-0049-x

ICIMOD [International Centre for Integrated Mountain Development]. (2011). *Glacial lakes and glacial lake outburst floods in Nepal*. Kathmandu: ICIMOD.

Ingty, T. (2017). High mountain communities and climate change: Adaptation, traditional ecological knowledge, and institutions. *Climatic Change*, *145*(1–2), 41–55. doi:10.1007/s10584-017-2080-3

IPCC [Intergovernmental Panel on Climate Change]. (2001). *Climate change 2001: IPCC third assessment report*. Geneva: IPCC Secretariat.

IPCC [Intergovernmental Panel on Climate Change]. (2007). *Climate change 2007: Impact, adaptation and vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge: Cambridge University Press.

IPCC [Intergovernmental Panel on Climate Change]. (2014). *Climate change 2014: Impact, adaptation and vulnerability. Part B: Regional aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press.

Kääb, A., Leinss, S., Gilbert, A., Bühler, Y., Gascoin, S., Evans, S. G., … & Farinotti, D. (2018). Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability. *Nature Geoscience*, *11*(2), 114–120. doi:10.1038/s41561-017-0039-7

Kaser, G., Großhauser, M., & Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *PNAS*, *107*, 20223–20227.

Kattelmann, R. (2003). Glacial lake outburst floods in the Nepal Himalaya : A manageable hazard ? *Natural Hazards*, *28*, 145–154. doi:10.1023/A:1021130101283

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F., & Immerzeel, W. W. (2017). Impact of a 1.5°C global temperature rise on Asia's glaciers. *Nature*, *549*, 257–260. doi:10.1038/nature23878

Kreutzmann, H. (2012). After the flood. Mobility as an adaptation strategy in high mountain Oases: The case of Pasu in Gojal, Hunza valley. *Die Erde, Journal of the Geographical Society of Berlin*, *143*(1–2), 49–73.

Kulkarni, A. V., Sciences, E., Division, H., & Group, W. R. (2007). Glacial retreat in Himalaya using Indian remote. *Current Science*, *92*(1), 1–6. doi:10.1117/12.694004

Luís, S., Vauclair, C.-M., & Lima, M. L. (2018). Raising awareness of climate change causes? Cross-national evidence for the normalization of societal risk perception of climate change. *Environmental Science & Policy*, *80*, 74–81. doi:10.1016/j.envsci.2017.11.015

Magnan, A. K., Schipper, E. L. F., Burkett, M., Bharwani, S., Burton, I., Eriksen, S., … Ziervogel, G. (2016). Addressing the risk of maladaptation to climate change. *WIRES*, *7*(5), 646–665. doi:10.1002/wcc.409

Maikhuri, R. K., Nautiyal, A., Jha, N. K., Rawat, L. S., Maletha, A., Phondani, P. C., … Bhatt, G. C. (2017). Socio-ecological vulnerability: Assessment and coping strategy to environmental disaster in Kedarnath valley, Uttarakhand, Indian Himalayan region. *International Journal of Disaster Risk Reduction*, *25*, 111–124. doi:10.1016/j.ijdrr.2017.09.002

Manandhar, S., Vogt, D. S., Perret, S. R., & Kazama, F. (2011). Adapting cropping systems to climate change in Nepal: A cross-regional study of farmers' perception and practices. *Regional Environmental Change*, *11*, 335–348. doi:10.1007/s10113-010-0137-1

McDowell, G., Ford, J. D., Lehner, B., & Sherpa, A. (2013). Climate-related hydrological change and human vulnerability in remote mountain regions : a case study from Khumbu, Nepal. *Regional Environmental Change*, *13*(2), 299–310. doi:10.1007/s10113-012-0333-2

McDowell, G., Ford, J., & Jones, J. (2016). 25 years of community-level climate change vulnerability research: Trends, progress, and future directions. *Environmental Research Letters*, *11*, 033001.

McDowell, G., Huggel, C., Frey, H., Wang, F. M., Cramer, K., & Ricciardi, V. (2019). Adaptation action and research in glaciated mountain systems: Are they enough to meet the challenge of climate change? *Global Environmental Change*, *54*, 19–30. doi:10.1016/j.gloenvcha.2018.10.012F

McDowell, G., & Koppes, M. (2017). Robust adaptation research in high mountains: Integrating the scientific, social, and ecological dimensions of glacio-hydrological change. *Water*, *9*(10), 739.

McDowell, G., Stephenson, E., & Ford, J. (2014). Adaptations to climate change in glaciated mountain regions. *Climatic Change*, *126*(1–2), 77–91. doi:10.1007/s10584-014-1215-z

McDowell, J. Z., & Hess, J. J. (2012). Accessing adaptation: Multiple stressors on livelihoods in the Bolivian highlands under a changing climate. *Global Environmental Change*, *22*(2), 342–352. doi:10.1016/j.gloenvcha.2011.11.002

Meenawat, H., & Sovacool, B. K. (2011). Improving adaptive capacity and resilience in Bhutan. *Mitigation and Adaptation Strategies for Global Change*, *16*(5), 515–533. doi:10.1007/s11027-010-9277-3

Mills-Novoa, M., Borgias, S. L., Crootof, A., Thapa, B., de Grenade, R., & Scott, C. A. (2016). Bringing the Hydrosocial cycle into climate change adaptation planning : lessons from two Andean mountain water towers. *Annals of the American Association of Geographers*, *4452*(October), 0–10. doi:10.1080/24694452.2016.1232618

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., … Hannah, D. M. (2017). Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(37), 9770–9778. doi:10.1073/pnas.1619807114

Mishra, A., Appadurai, A. N., Choudhury, D., Regmi, B. R., Kelkar, U., Alam, M., … Sharma, U. (2019). Adaptation to climate change in the Hindu Kush Himalaya: Stronger action urgently needed. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment- mountains, climate change, sustainability and people* (pp. 457–455). Cham, Switzerland: Springer Nature.

Molden, D. J., Vaidya, R. A., Shrestha, A. B., Rasul, G., & Shrestha, M. S. (2014). Water infrastructure for the Hindu Kush Himalayas. *International Journal of Water Resources Development*, *30*(1), 60–77. doi:10.1080/07900627.2013.859044

Muchuru, S., & Nhamo, G. (2019). A review of climate change adaptation measures in the African crop sector. *Climate and Development*. doi:10.1080/17565529.2019.1585319

Mukherji, A., Sinisalo, A., Nüsser, M., Garrard, R., & Eriksson, M. (2019). Contributions of the cryosphere to high mountain communities of the Hindu Kush Himalaya: A review. *Regional Environmental Management*. doi:10.1007/s10113-019-01484-w

Nussbaumer, S. U., Hoelzle, M., Hüsler, F., Huggel, C., Salzmann, N., & Zemp, M. (2017). Glacier monitoring and capacity building: Important ingredients for sustainable mountain development. *Mountain Research and Development*, *37*(1), 141–152. doi:10.1659/MRD-JOURNAL-D-15-00038.1

Nüsser, M., & Baghel, R. (2016). Local knowledge and global concerns: Artificial glaciers as a focus of environmental knowledge and development interventions. In P. Meusburger, T. Freytag, & L. Suarsana (Eds.), *Ethnic and cultural dimensions of knowledge* (pp. 191–209). Heidelberg: Springer.

Nüsser, M., Dame, J., Kraus, B., Baghel, R., & Schmidt, S. (2018). Socio-hydrology of "artificial glaciers" in Ladakh, India: Assessing adaptive strategies in a changing cryosphere. *Regional Environmental Change*. doi:10.1007/s10113-018-1372-0

Nüsser, M., & Schmidt, S. (2017). Nanga Parbat revisited: Evolution and dynamics of sociohydrological interactions in the Northwestern Himalaya. *Annals of the American Association of Geographers*, *107*(2), 403–415. doi:10.1080/24694452.2016.1235495

Onta, N., & Resurreccion, B. P. (2011). The role of gender and caste in climate adaptation strategies in Nepal: Emerging change and persistent inequalities in the far-western region. *Mountain Research and Development*, *31*(4), 351–356. doi:10.1659/MRD-JOURNAL-D-10-00085.1

Orlove, B. (2009). Glacier retreat: Reviewing the limits of human adaptation to climate change. *Environment Science and Policy for Sustainable Development*, *51*, 22–34. doi:10.3200/ENVT.51.3.22-34

Parveen, S., Winiger, M., Schmidt, S., & Nüsser, M. (2015). Irrigation in Upper Hunza: Evolution of socio-hydrological interactions in the Karakoram, Northern Pakistan. *Erdkunde*, *69*(1), 69–85. doi:10.3112/erdkunde.2015.01.05

Porfiriev, B. (2015). Climate change as a major slow-onset hazard to development: An integrated approach to bridge the policy gap. *Environmental Hazards*, *14*(2), 187–191. doi:10.1080/17477891.2015.1019823

Postigo, J. C., Young, K. R., & Crews, K. A. (2008). Change and continuity in a pastoralist community in the high Peruvian Andes. *Human Ecology*, *36*(4), 535–551. doi:10.1007/s10745-008-9186-1

Poupeau, F., & Hardy, S. (2016). The social conditions of self-organized utilities: Water cooperatives in La Paz and El Alto, Bolivia. *Water International*, *42*(1), 1–19. doi:10.1080/02508060.2016.1219196

Pröbstl-Haider, U., Haider, W., Wirth, V., & Beardmore, B. (2015). Will climate change increase the attractiveness of summer destinations in the European Alps? A survey of German tourists. *Journal of Outdoor Recreation and Tourism*, *11*, 44–57. doi:10.1016/j.jort.2015.07.003

Qin, D., & Ding, Y. (2010). Key issues on cryospheric changes, trends and their impacts. *Advances in Climate Change Research*, *1*(1), 1–10. doi:10.3724/SP.J.1248.2010.00001

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Caceres, B., Ceballos, J. L., … Wagnon, P. (2013). Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *Cryosphere*, *7*, 81–102. doi:10.5194/tc-7-81-2013

Rangecroft, S., Harrison, S., Anderson, J., Magrath, A., Castel, P., & Pacheco, P. (2013). Climate change and water resources in arid mountains: An example from the Bolivian Andes. *Ambio*, *42*(7), 852–863. doi:10.1007/s13280-013-0430-6

Rasul, G. (2014). Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. *Environmental Science & Policy*, *39*, 35-48. doi:10.1016/j.envsci.2014.01.010

Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environmental Development*, *18*, 14–25. doi:10.1016/j.envdev.2015.12.001

Rasul, G., Neupane, N., Hussain, A., & Pasakhala, B. (2019). Beyond hydropower: towards an integrated solution for water, energy and food security in South Asia. *International Journal of Water Resources Development*, 1–25. doi:10.1080/07900627.2019.1579705

Rasul, G., & Sharma, B. (2016). The nexus approach to water–energy–food security: An option for adaptation to climate change. *Climate Policy*, *16*(6), 682–702. doi:10.1080/14693062.2015.1029865

Ritter, F., Fiebig, M., & Muhar, A. (2012). Impacts of global warming on mountaineering: A classification of phenomena affecting the alpine trail network. *Mountain Research and Development*, *32*(1), 4–15. doi:10.1659/MRD-JOURNAL-D-11-00036.1

Rixen, C., Teich, M., Lardelli, C., Gallati, D., Pohl, M., Putz, M., & Bebi, P. (2011). Winter tourism and climate change in the Alps: An assessment of resource consumption, snow reliability, and future snowmaking potential. *Mountain Research and Development*, *31*(3), 229–236. doi:10.1659/MRD-JOURNAL-D-10-00112.1

Schaner, N., Voisin, N., Nijssen, B., & Lettenmaier, D. P. (2012). The contribution of glacier melt to streamflow. *Environmental Research Letters*, *7*(3), doi:10.1088/1748-9326/7/3/034029

Scheffer, M., & Carpenter, S. (2003). Catastrophic regime shifts in ecosystems: Linking theory with observation. *Trends in Ecology and Evolution*, *18*, 648–656. doi:10.1016/j.tree.2003.09.002

Seneviratne, I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., … Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. In C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) (pp. 109–230). Cambridge, UK, and New York, NY, USA: Cambridge University Press.

Serquet, G., & Rebetez, M. (2011). Relationship between tourism demand in the Swiss Alps and hot summer air temperatures associated with climate change. *Climatic Change*, *108*(1–2), 291–300. doi:10.1007/s10584-010-0012-6

Skarbo, K., & VanderMolen, K. (2014). Irrigation access and vulnerability to climate-induced hydrological change in the Ecuadorian Andes. *Culture, Agriculture, Food and Environment*, *36*(1), 28–44. doi:10.1111/cuag.12027

Smit, B., & Wandel, J. (2006). Vulnerability, adaptation and adaptive capacity. *Global Environmental Change*, *16*(3), 282–292. doi:10.1016/j.gloenvcha.2006.03.008

Somos-Valenzuela, M. A., McKinney, D. C., Byers, A. C., Rounce, D. R., Portocarrero, C., & Lamsal, D. (2015). Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal. *Hydrology and Earth System Sciences*, *19*, 1401–1412. doi:10.5194/hessd-11-13019-2014

Sorg, A., Mosello, B., Shalpykova, G., Allan, A., Hill, M., & Stoffel, M. (2014). Coping with changing water resources: The case of the Syr Darya river basin in Central Asia. *Environmental Science and Policy*, *43*, 68–77. doi:10.1016/j.envsci.2013.11.003

Sovacool, B. K. (2011). Hard and soft paths for climate change adaptation. *Climate Policy*, *11*, 1177–1183. doi:10.1080/14693062.2011.579315

Spires, M., Shackleton, S., & Cundill, G. (2014). Barriers to implementing planned community- based adaptation in developing countries : A systematic literature review. *Climate and Development*, *6*(3), 277–287. doi:10.1080/17565529.2014.886995

Steiger, R., & Mayer, M. (2008). Snowmaking and climate change future options for snow production in Tyrolean ski resorts. *Mountain Research and Development*, *28*, 292–298. doi:10.2307/25578206

Steiger, R., Scott, D., Abegg, B., Pons, M., & Aall, C. (2017). A critical review of climate change risk for ski tourism. *Current Issues in Tourism*, 1–37. doi:10.1080/13683500.2017.1410110

Stucker, D., Kazbekov, J., Yakubov, M., & Wegerich, K. (2012). Climate change in a small transboundary tributary of the Syr Darya calls for effective cooperation and adaptation. *Mountain Research and Development*, *32*, 275–285. doi:10.1659/MRD-JOURNAL-D-11-00127.1

Sud, R., Mishra, A., Varma, N., & Bhadwal, S. (2015). Adaptation policy and practice in densely populated glacier-fed river basins of South Asia: A systematic review. *Regional Environmental Change*, *15*(5), 825–836. doi:10.1007/s10113-014-0711-z

Tan, Y. (2017). Resettlement and climate impact: Addressing migration intention of resettled people in west China. *Australian Geographer*, *48*(1), 97–119. doi:10.1080/00049182.2016.1266593

Vaidya, R. A., Shrestha, M. S., Nasab, N., Gurung, D. R., Kozo, N., Pradhan, N. S., & Wasson, R. J. (2019). Disaster risk reduction and building resilience in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. B. Shrestha (Eds.), *The Hindu Kush Himalaya assessment- mountains, climate change, sustainability and people* (pp. 457–455). Cham, Switzerland: Springer Nature.

Vedwan, N. (2006). Culture, climate and the environment: Local knowledge and perception of climate change among apple growers in Northwestern India. *Journal of Ecological Anthropology*, *10*, 4–18.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., & Weingartner, R. (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance. *Water Resources Research*, *43*, W07447. doi:10.1029/2006WR005653

Vuille, M., Carey, M., Huggel, C., Buytaert, W., Rabatel, A., Jacobsen, D., … Sicart, J. E. (2018). Rapid decline of snow and ice in the tropical Andes – impacts, uncertainties and challenges ahead. *Earth-Science Reviews*, *176*, 195–213. doi:10.1016/j. earscirev.2017.09.019

Wang, S., He, Y., & Song, X. (2010). Impacts of climate warming on Alpine glacier tourism and adaptive measures: A case study of Baishui glacier No. 1 in Yulong snow mountain, Southwestern China. *Journal of Earth Science*, *21*, 166–178. doi:10.1007/s12583-010-0015-2

Wrathall, D. J., Bury, J., Carey, M., Mark, B., McKenzie, J., Young, J., … Rampini, C. (2014). Migration amidst climate rigidity traps: Resource politics and social–ecological possibilism in Honduras and Peru. *Annals of the Association of American Geographers*, *104*(2), 292–304. doi:10.1080/00045608.2013.873326

Xenarios, S., Gafurov, A., Schmidt-Vogt, D., Sehring, J., Manandhar, S., Hergarten, C., … Foggin, M. (2018). Climate change and adaptation of mountain societies in Central Asia: Uncertainties, knowledge gaps, and data constraints. *Regional Environmental Change*, 1–14. doi:10.1007/s10113-018-1384-9

Xiao, C. D., Wang, S. J., & Qin, D. H. (2015). A preliminary study of cryosphere service function and value evaluation. *Advances in Climate Change Research*, *6*, 181–187. doi:10.1016/j.accre.2015.11.004

Yao, T., Thompson, L. G., Mosbrugger, V., Zhang, F., Ma, Y., Luo, T., … Fayziev, R. (2012). Third Pole Environment (TPE). *Environmental Development*, *3*, 52–64. doi:10.1016/j.envdev.2012.04.002

Young, G., Zavala, H., Wandel, J., Smit, B., Salas, S., Jimenez, E., … Cepeda, J. (2010). Vulnerability and adaptation in a dryland community of the Elqui valley, Chile. *Climatic Change*, *98*(1–2), 245–276. doi.org/10.1007/s10584-009-9665-4

Young, K. R., & Lipton, J. K. (2006). Adaptive governance and climate change in the tropical highlands of Western South America. *Climatic Change*, *78*, 63–102. doi:10.1007/s10584-006-9091-9

Zemp, M., Haeberli, W., Hoelzle, M., & Paul, F. (2006). Alpine glaciers to disappear within decades? *Geophysical Research Letters*, *33*, L13504. doi:10.1029/2006GL026319