AMBIO 2013, 42:852–863
DOI 10.1007/s13280-013-0430-6

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

REVIEW

Climate Change and Water Resources in Arid Mountains: An Example from the Bolivian Andes

Sally Rangecroft, Stephan Harrison, Karen Anderson, John Magrath, Ana Paola Castel, Paula Pacheco

Received: 12 March 2013 / Revised: 20 June 2013 / Accepted: 5 July 2013 / Published online: 15 August 2013

Abstract Climate change is projected to have a strongly negative effect on water supplies in the arid mountains of South America, significantly impacting millions of people. As one of the poorest countries in the region, Bolivia is particularly vulnerable to such changes due to its limited capacity to adapt. Water security is threatened further by glacial recession with Bolivian glaciers losing nearly half their ice mass over the past 50 years raising serious water management concerns. This review examines current trends in water availability and glacier melt in the Bolivian Andes, assesses the driving factors of reduced water availability and identifies key gaps in our knowledge of the Andean cryosphere. The lack of research regarding permafrost water sources in the Bolivian Andes is addressed, with focus on the potential contribution to mountain water supplies provided by rock glaciers.

Keywords Climate change · Water resources · Glacier recession · Permafrost · Rock glaciers

INTRODUCTION

It is expected that continued climate change will reduce water security in arid mountain regions globally (Beniston 2003; Barnett et al. 2005; Kundzewiz et al. 2008). In the South American Andes this is a clear threat to livelihoods (Bradley et al. 2006; IPCC 2007a; Painter 2007; Vuille et al. 2008; Chevallier et al. 2011). Changes to water supply are predicted through changes in temperature and precipitation patterns and glacier recession (Vuille et al. 2003; Vergara et al. 2007a), negatively affecting water availability (Magrin et al. 2007). Future temperature increases in the tropical Andes are projected to be of a similar magnitude to those in the Arctic (Fig. 1a), with the Intergovernmental Panel on Climate Change (IPCC) predicting a maximum warming of 7.5 °C by 2080 using all climate change scenarios (Magrin et al. 2007) (Fig. 1b). However, in the Andes the consequences of this warming will directly affect a greater population (Vergara 2009) with an estimated population size of 30 times that of the Arctic (Bogoyavlenskiy and Siggner 2004; Galarza and Gómez 2011). In conjunction with predicted decreasing water supplies, increases in water demand are anticipated from a continually growing population in Latin America (Bradley et al. 2006; Painter 2007; Jeschke 2009). These changes to water supplies have critical negative impacts on water security, affecting environmental, economic and social systems (Bradley et al. 2006; Bigas et al. 2012).

A review of current understanding of water resources and the main contributors and drivers of change is required to gather information for future projections and management. This paper focuses on future water security in dry mountain regions, using Bolivia as a case study due to its vulnerability and sensitivity to the impacts of climate change. There is relatively little scientific research on water resources, climate change, sustainability and resource management for many arid regions of the world, and this is particularly the case for the Bolivian Andes. This paper attempts to address this by identifying the driving factors of reduced water availability and outlining existing gaps in our understanding and knowledge. The paper provides an agenda for future research to aid water resources management in arid glaciated mountains.

ANDEAN WATER RESOURCES: A BOLIVIAN PERSPECTIVE

Mountain regions are likely to experience the impacts of a changing environment more than lower lying regions

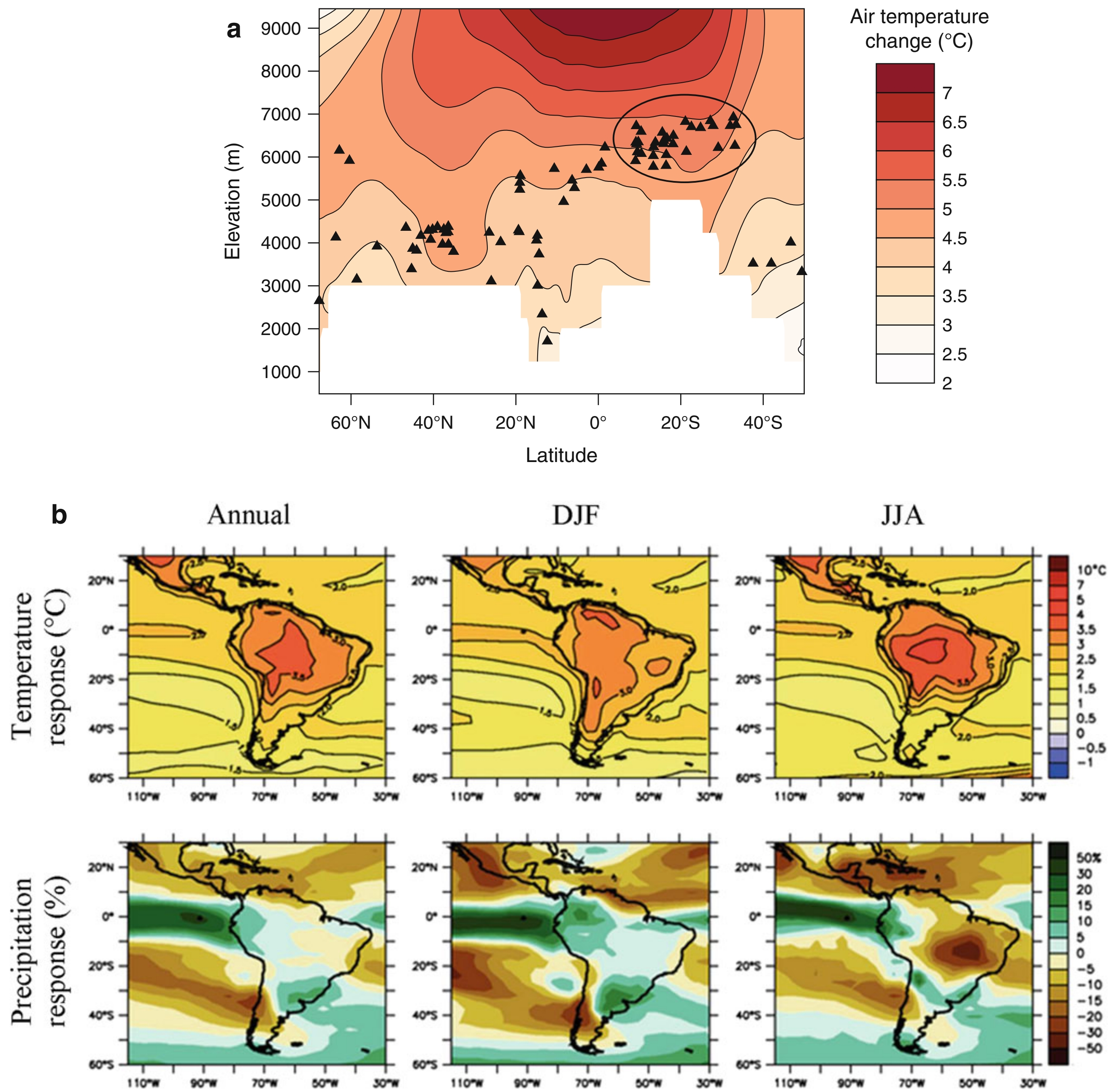

Fig. 1 **a** Visual representation of predicted global warming (adapted from Bradley et al. 2006, p. 1755). Projected changes in mean annual free-air temperatures between (1990–1999) and (2090–2099) along transect from Alaska (68°N) to southern Chile (50°S) using the mean of eight different Global Climate Models (IPCC using CO_2 levels from scenario A2). *Black triangles* symbolize the highest mountains for each latitude; with the highest air temperature change predicted, the South American Andes are *circled.* **b** Temperature and precipitation changes over South America from the MMD-A1B simulations (IPCC 2007a, p. 895). *Top row* (i) Annual mean, (ii) December January February, and (iii) June July August temperature change between 1980–1999 and 2080–2099, averaged over 21 models. *Bottom row* shows the same as *top*, but for fractional change in precipitation

(Fig. 1a) and with strong altitudinal gradients they offer unique opportunities to identify and analyse global change processes and phenomena (Becker and Bugmann 1999). As a result, regions such as the Bolivian Andes should be considered as important areas to study the effects of hydrological, cryospheric and ecological changes associated with climate change.

Many large cities in the arid Andes are located above 2500 m and rely almost entirely on high-altitude water stocks such as glaciers and lakes to complement limited rainfall (Bradley et al. 2006) making them vulnerable to water scarcity caused by climate change (World Bank 2010). High levels of poverty and inequality, as well as its topographic situation (World Bank 2010; Winters 2012), mean that Bolivia is expected to be one of the countries most affected by continued reductions in water supplies and climate change (Winters 2012). Socioeconomic variables are important factors determining the ability to adapt and mitigate. It is estimated that 80 % of Bolivia's rural population live in poverty and of this rural population, only 56 % have access to safe water (Jeschke et al. 2012). This vulnerable social group will be affected the worst as they are the most ill-equipped to deal with the impacts of climate change (Oxfam 2009).

The Bolivian administrative capital city of La Paz is situated on the Altiplano at higher than 3500 m above sea level and, including its rapidly growing adjacent city El Alto, supports a population of over 2.3 million in an arid environment (Vergara 2009; WMO 2011). Bolivia has distinct wet (November–April) and dry (May–October) seasons. During winter months, dry conditions prevail over the Altiplano. Based upon climate data from the Chacaltaya region (16°21′S, 68°08′W) in the Cordillera Real, 90 % of the annual precipitation (668 mm) falls during the summer wet season (Francou et al. 2003). The city relies upon this rainfall and glacier meltwater from the nearby Andean mountains, the Cordillera Real, as its two main sources of water for drinking, agriculture and energy generation (Jordon 2008; Vuille et al. 2008; Chevallier et al. 2011). It is estimated that the glaciers of the Cordillera Real supply between 12 and 40 % of potable water for the city, depending on seasonal variation (Vergara 2009; Soruco 2012); however, with current and predicted glacier recession ("Glacier Recession in the Andes"), this contribution to water supplies is expected to reduce (UNFCCC 2007).

Current urban water shortages in Bolivia represent a major social and economic problem (World Bank 2010). Restricted supplies occurred during the wet season of 2008 and again in 2009 (World Bank 2010). There are suggestions that continued water supply reductions in the Bolivian Andes will exacerbate droughts and increase competition and possible conflict, including social and economic conflicts (Magrath 2005; IPCC 2007a; Vuille 2007). Parallel with a predicted decrease in water availability, an increasing population is predicted to place higher demand on water supplies (Vanham and Rauch 2010; WMO 2011). Bolivia's population reached 9.8 million by 2009, an increase of 21 % within a decade. This figure is expected to double by 2050 (Machicao and Garcia 2007). Over the past decade El Alto has expanded more rapidly than La Paz, with a growth rate of 8 % annually compared to La Paz's 4 % annual increase (Water.org 2012), which in part is due to the restrictive physical shape of La Paz's steep sided basin (Arbona and Kohl 2004). Population increase is a common pressure on water resources worldwide; however it is a factor which is often not fully considered in the scientific literature and in projections for future Andean water resources.

Climate Change

In the tropical Andes, mountain station records showed that annual average temperatures increased by 0.1 °C/decade between 1939 and 1998 (Fig. 2), higher than the global average rate of 0.06 °C/decade (Bradley et al. 2006; Vuille et al. 2008). Recent temperature increases have tripled in the Andes (~0.33 °C/decade from 1980 to 2005) (Barry 2005) and these, allied to changes in precipitation, consequently led to glacier recession across the whole of the Central Andes (Francou and Vincent 2007). However, there are few instrumental observations available above 4000 m where Andean glaciers exist and therefore the impact of recent temperature change on glacier behavior is poorly documented (Bradley et al. 2006).

A changing climate is predicted to have serious consequences for the hydrological cycle in the Andes through

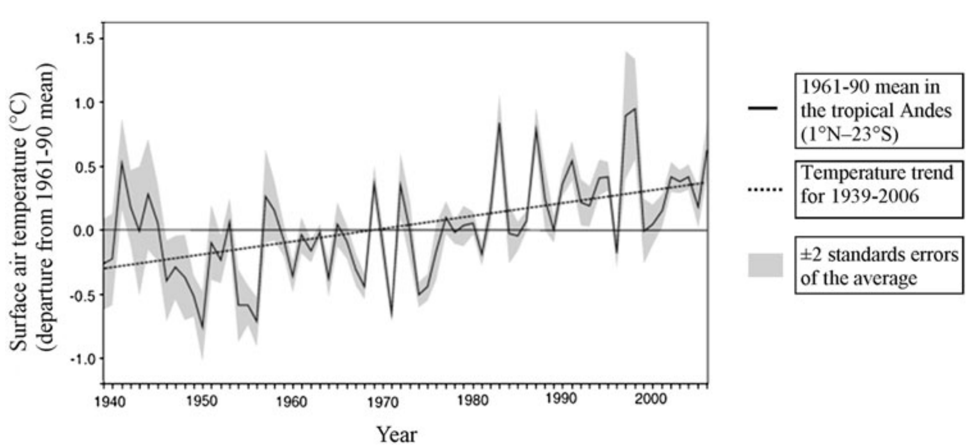

Fig. 2 Annual temperature deviation from the 1961–1990 average in the tropical Andes (1°N–23°S) between 1939 and 2006 based on a compilation of 279 station records (adapted from Vuille et al. 2008, p. 84). *Black line* shows long-term warming trend (0.10 °C/decade) based on ordinary least square regression

temperature increase and changes to precipitation patterns (Barnett et al. 2005). Associated with current climate change, model projections suggest that the rate of warming in the lower troposphere is likely to increase with altitude, impacting high mountains (Bradley et al. 2006; Fig. 1a). Continued warming is projected across much of South America; IPCC model projections suggest warming of 0.4–1.8 °C by 2020 and 1.0–7.5 °C by 2080 (Magrin et al. 2007) (Fig. 1b). While many global climate models disagree on the extent and direction of the changes in precipitation for South America, a number of them predict considerable drying in the region (Magrin et al. 2007; Viviroli et al. 2011) (Fig. 1b).

Global and regional projections of precipitation rely on models which, due to their coarse spatial resolution, are not capable of resolving the fine spatial patterns in temperature and precipitation that exist over small areas in regions of high relief such as the Andes. As a result, climate change impacts are not well captured by these models in fine enough spatial resolution to allow adequate water supply planning to be undertaken (Vergara 2009). Furthermore, there is a difference in the spatial scale between data gained from global climate projections and data needed for water resource management (Buytaert et al. 2010). Climate models run at too coarse a resolution produce a smoothing out of local precipitation and temperature gradients which are important for many local hydrology processes. Therefore, the downscaling of climate projections is necessary (Buytaert et al. 2010).

Whilst acknowledging the uncertainties surrounding climate projections and the need for downscaling, current models do all forecast changes in precipitation patterns and increases in temperature. These changes will lead to continued glacier recession and will all significantly affect water availability in Bolivia.

Glacier Recession in the Andes

Glacier recession is seen as a clear visible reflection of recent climate change in mountain regions (Francou et al. 2003; Vuille et al. 2003, 2008; Mark et al. 2010) and continued recession will have negative impacts on water availability in the long term (Barnett et al. 2005). In the Andes field observations and historical records document the current pace of glacier recession (Vergara et al. 2007b), a process that has been occurring for the last 150 years. Over the past 30 years Bolivian glacier recession has accelerated in line with regional and global warming trends (Francou et al. 2003; Coudrain et al. 2005; Casassa et al. 2007; IPCC 2007a; Rabatel et al. 2013). Bolivian glaciologists have estimated that glaciers along the Cordillera Real range have lost roughly 48 % of their ice between 1963 and 2006 (Soruco et al. 2009), leading to the disappearance of many small glaciers already. This is illustrated by the well-documented retreat of the Chacaltaya glacier (Bolivia, 16°21′S, 68°07′W) which disappeared in 2009, 6 years earlier than predicted (Fig. 3a, b) (Ramirez et al. 2001; IPCC 2007a; Painter 2007; Vergara et al. 2007a).

Glacier recession in the Andes is expected to happen quicker than in many other mountain regions (Bradley et al. 2006) and will particularly affect the smallest and lowest glaciers because they are the most vulnerable (Vuille et al. 2008; Chevallier et al. 2011). Small glaciers (<0.5 km^2) are known to respond faster to changes in climate (Beniston 2003), and therefore are the most in danger of recession (Casassa et al. 2007); several have already disappeared in the region since their historic maximum extent (e.g., Chacaltaya). 80 % of the glaciers in the Cordillera Real mountain range in Bolivia are classified as small glaciers (Francou et al. 2003), and therefore are particularly vulnerable to continued warming. Glacier modeling, allied with climate projections, indicate that many of the lower-altitude glaciers are expected to disappear during the next 10–20 years (World Bank 2008), given continued warming.

Glacier recession is largely influenced by regional and local air temperature and precipitation, which determine the extent of the area of accumulation and ablation (Carrasco et al. 2005). The point at which this glacier accumulation is equal to the ablation is defined as the equilibrium line altitude (Coudrain et al. 2005). Observed glacier recession in the Andes is thought to be mainly in response to increasing temperatures resulting in an upward shift in the 0 °C isotherm and this equilibrium line altitude (Coudrain et al. 2005; Brown et al. 2008; Vergara 2009). An upward shift of the 0 °C isotherm (Diaz and Graham 1996; Carrasco et al. 2005) leads to increased melting and increased exposure of the glacier margins to rain instead of snow (Francou et al. 2004). However, although recent glacier recession is strongly correlated with rising atmospheric temperatures (Bradley et al. 2006; Mark et al. 2010), other meteorological parameters such as the effects of changes in humidity on glacier surface, energy balance, sublimation, and surface albedo are needed to explain observed trends in glacier recession (Coudrain et al. 2005). Glacier behavior in the Andes is also affected by changes in precipitation driven by El Niño Southern Oscillation (ENSO) (Coudrain et al. 2005; Jeschke 2009). Phases of El Niño, which may be increasing in their frequency, are linked to higher sea surface temperatures and are related to negative glacier mass balance (Francou et al. 2003; Coudrain et al. 2005; Jeschke 2009). Even though melting glaciers will result in enhanced runoff in the short term, in the long term it will lead to water supply issues (Beniston 2003; Orlove et al. 2008).

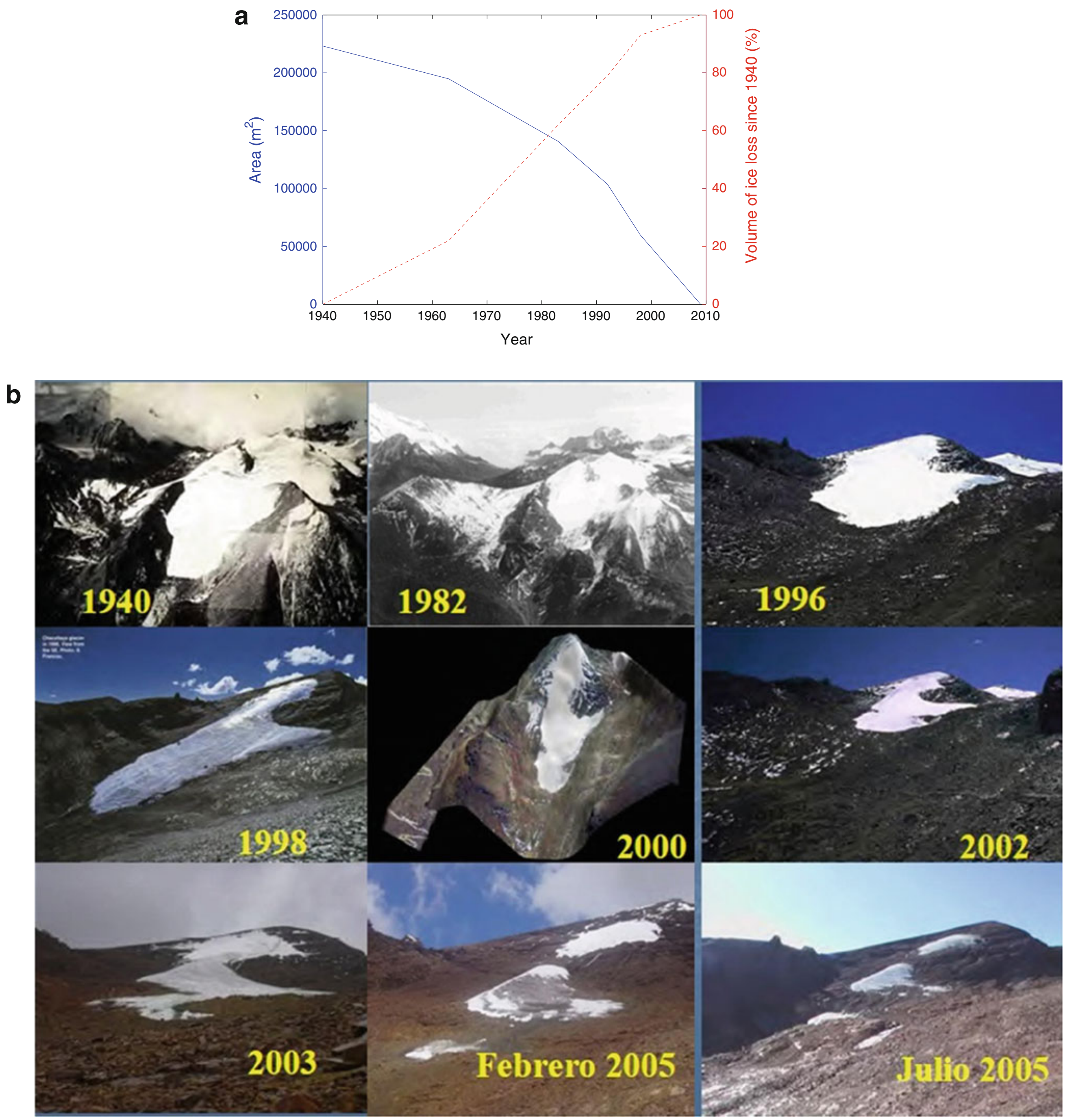

Fig. 3 **a** Graph showing the mass loss of ice from Chacaltaya during 1940–2009 in units of area and volume with its recession (data taken from Francou et al. 2000, p. 418). **b** Visual documented disappearance of the Chacaltaya glacier in Bolivia since 1940 through photography and modeling (taken from Vergara et al. 2007a, p. 5)

WATER RESOURCE MANAGEMENT

Continued glacier melting and climate change raises serious water resource management concerns for arid mountainous regions (Bradley et al. 2006; Painter 2007; Jeschke 2009). By identifying the main drivers of reduced water security and the sectors and users impacted (Fig. 4) appropriate integrated strategies can be implemented and supported. This approach also helps to put water scarcity in a wider context to help promote a more holistic view on problems and solutions.

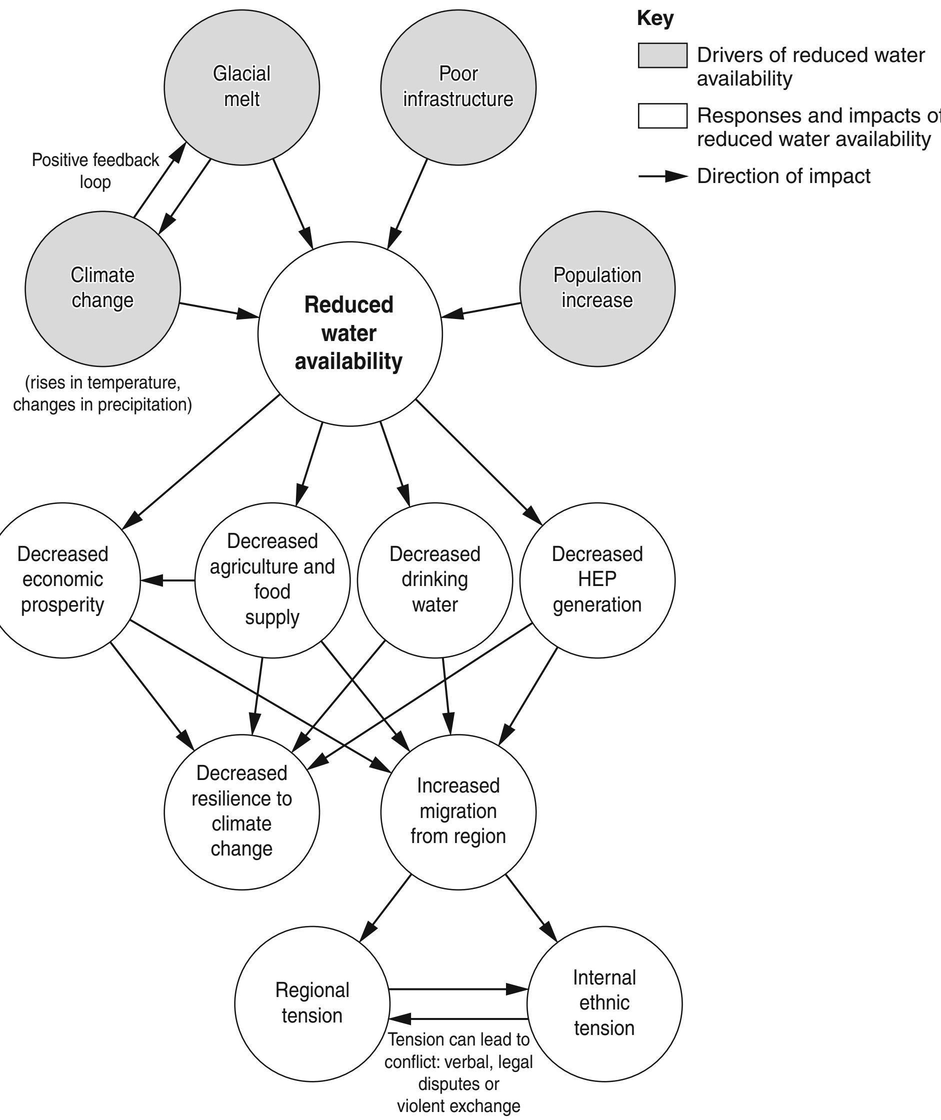

Fig. 4 Network diagram outlining the drivers of Bolivian water scarcity and impact relationships (adapted from Stewart 2010). *Gray circles* represent drivers of reduced water availability and *white circles* represent the responses of reduced water availability and further impacts

Impacts of Water Scarcity

We use Fig. 4 to represent a simplified network diagram of the four main drivers of reduced water availability in Bolivia (glacier recession, climate change, poor infrastructure, and population increase) and the subsequent impacts. Future water conflicts are predicted to be more likely with decreased water security (IPCC 2007a; Vuille 2007), and there is a severe risk that conflicts over water availability in glacier-fed areas could increase in likelihood with lower water availability in the dry season (Painter 2007). For example, climate change poses new threats through changing precipitation and evaporation patterns, as well as temperature changes. This in turn can directly reduce water availability, affecting agriculture, drinking water, and power generation, adding stresses on livelihoods that can contribute towards migration.

Population increase incorporates a continuingly growing population as well as changes in population distribution with urbanization (Rossing 2010). Poor rural and urban communities are likely to be the most affected and least well-equipped to adapt to the impacts of water scarcity and climate change (Oxfam 2009; Rossing 2010). An increasing population places stress on water supplies, without the added interaction of climate change and glacier melt, through increasing demand for water for agriculture, drinking, and power generation. Hydroelectric power (HEP) is the major source of energy for numerous Andean cities (Bradley et al. 2006); La Paz depends heavily on HEP for its electricity which is powered by glacier melt water, mainly from two glacier ranges of the Cordillera Real: Zongo valley and Charquiri (Painter 2007). Although the volume of melt water initially increases with the recession of glaciers, once glaciers have disappeared, the lack of glacier melt water will have a negative impact on HEP production in Bolivia, as well as the increase in river sediment load characteristic of rivers draining rapidly deglaciating catchments. Accordingly, adaptation should incorporate methods to reduce Bolivia's dependence on HEP and investment into other renewable energies is necessary to adapt for future glacier recession and disappearance. However, this can be costly, and might result in an increased dependence on fossil fuels (Bradley et al. 2006).

Common to a developing country, the water infrastructure is under-developed in Bolivia and storage capacity is low (World Bank 2010). Poor infrastructure constantly reduces the amount of water available from water pipes through leaks and the illegal action of tapping into pipes. It is probable that there is a high amount of non-revenue water lost through the inadequate water infrastructure in La Paz and El Alto (Farley and Liemberger 2005; Lee and Schwab 2005). Thus, key ways to increase usable water supplies can include repairing leaking pipes, reducing wastage and rehabilitating and updating existing water facilities. However, these changes are an expensive, time-consuming endeavor (Hays 2011) and need to be supported by an effective implementation of governance policies (Mejia 2012) and democratic involvement.

Potential Solutions

Physical infrastructural change is part of a large range of adaptive responses to water security suggested by the IPCC (2007b) which include technological (e.g., dams, infrastructure), policy (e.g., planning regulations), managerial (e.g., altered farming practices), and behavioral (e.g., altered food choices, changes in water use and waste) adaptations. Adaptation is seen as one of the best strategies to address changing climate issues and reduced water resources (IPCC 2007b); however, institutional, political, and financial constraints create barriers, limits and costs, restricting adaptation (Magrath 2005; IPCC 2007b; Viviroli et al. 2011) especially for developing countries (UNFCCC 2007). Most Andean governments are poorly equipped and have limited resources to deal with serious water challenges (Hays 2011). Adaption measures can be costly, so using the most appropriate approaches for water resource management will help countries adapt the most effectively.

For Bolivia, a holistic and country-specific approach can be recommended, including local level resource management. General water resource management advice and strategy may not always be appropriate for a specific country or on a regional level. For example, at the turn of the century the former Bolivian national government privatized the water system of the Andean city of Cochabamba following the advice of the World Bank in 1999. Water privatization was viewed as the best approach to cover the costs of the dam building, expansion of the water system, and maintenance. However, the Cochabamba water war that subsequently occurred in 2000 demonstrated the successful fight of the Cochabambinos to reverse this privatization of their water supply, but at the expense of civil unrest and violent conflict (Olivera and Lewis 2004).

For successful long-term solutions to water challenges it is now clear that an inter-disciplinary approach is required involving consultation, involvement, and exchange of expert knowledge of many different types including engineering, climate, population, politics, economics, ecology, farming, the community, and local cultures (Viviroli et al. 2011). The important role of non-governmental organizations (NGOs), charities, governments, and research organizations should also be considered for their multi-disciplinary work, assistance for adaptation, resilience and increase in knowledge, and especially for their local knowledge. Successful water management and adaptation strategies should look to address problems at an integrated, local level. Resource management at local levels calls for greater cooperation between local government, civil society, and the private sector (Hay and Elliott 2008). For instance, community-based water resource management has been shown to be an effective way of empowering communities in certain arid environments, understanding their water resources and usage, and therefore manage them both directly and through influencing other levels of water governance (ICE 2011). Working on a community level, adaptation strategies can help strengthen the capacities and resilience of affected populations, such as mountain communities adapting to climate change. Physical adaptation for this can include the installation and use of low technology designs that can be replicated in the Andean communities and self-run through community organization to improve existing systems for management and distribution of water (such as channels, tanks, intakes, and water harvesting systems) and decrease the potential for conflict over water use by promoting cooperation among communities sharing water sources. Through consultation, inclusion, community-led local level resource management, cooperation can be increased (UN 2013) which can potentially decrease the risk of conflict.

FUTURE DIRECTION

To address the growing issue of water security in arid mountain regions, water companies, governments and policy makers need better knowledge and information on current and future projections for water supplies and at finer spatial resolutions than existing models can provide. This will allow them to anticipate water shortages and create physical and political infrastructure that could help compensate for reduced water availability (Magrath 2005). It is known that good decision making and policy development are dependent upon good information (WHO 2012).

To aid this knowledge base, research is needed on various key areas, with focus on local and regional scale implementation. Some example research areas for the Bolivian Andes include practical water conservation, better managed water use, low technology designs and schemes. For Bolivia, one of the first steps towards improving research is to gather data on all water sources contributing to the mountain hydrological cycle to increase the accuracy of water supply and availability projections. This includes identification, assessment, and monitoring of mountain water sources. Viviroli et al. (2011) highlight the importance of environmental monitoring at high altitudes and the general absence of observational data in the arid and semi-arid zones of the Tropics. This lack of observation and monitoring of climate systems limits the effectiveness of adaptation (IPCC 2007b). In Bolivia this lack of information and structure has been acknowledged, and there is now a move by the government meteorological office SENAMHI and NGOs to address this by increasing the number of meteorological stations across the Bolivian Andes and by developing a standardized collection of basic data on water levels and flow.

One example of a future research direction is explored further in this review; permafrost water resources. Currently, the identification and understanding of the importance of water sources other than ice glaciers in Bolivia, such as permafrost, is very limited.

Permafrost Water Resources

With continued glacier recession, there is a pressing need to better understand other sources of water from mountain ice storages. Permafrost exists in all mountain areas of sufficient elevation (Viviroli et al. 2011) (estimated between 4500 and 5000 m a.s.l. across the Bolivian Andes); however, critical gaps in present knowledge of the Andean mountain cryosphere exist (Azócar and Brenning 2010). For example, the importance of ice glaciers and their role in regulating hydrological processes in mountainous regions is well studied (Ramirez et al. 2001; Bradley et al. 2006; Vuille et al. 2008; Bolch et al. 2010; Chevallier et al. 2011), but in contrast, the contribution of "rock glaciers" to mountain water supplies is largely unknown. Rock glaciers are tongue-shaped bodies of frozen debris resembling a small glacier, with interstitial ice, ice lenses or a core of massive ice (Evans 2005; Jansen and Hergarten 2006). They are abundant in arid and semi-arid mountains and locally form elements of

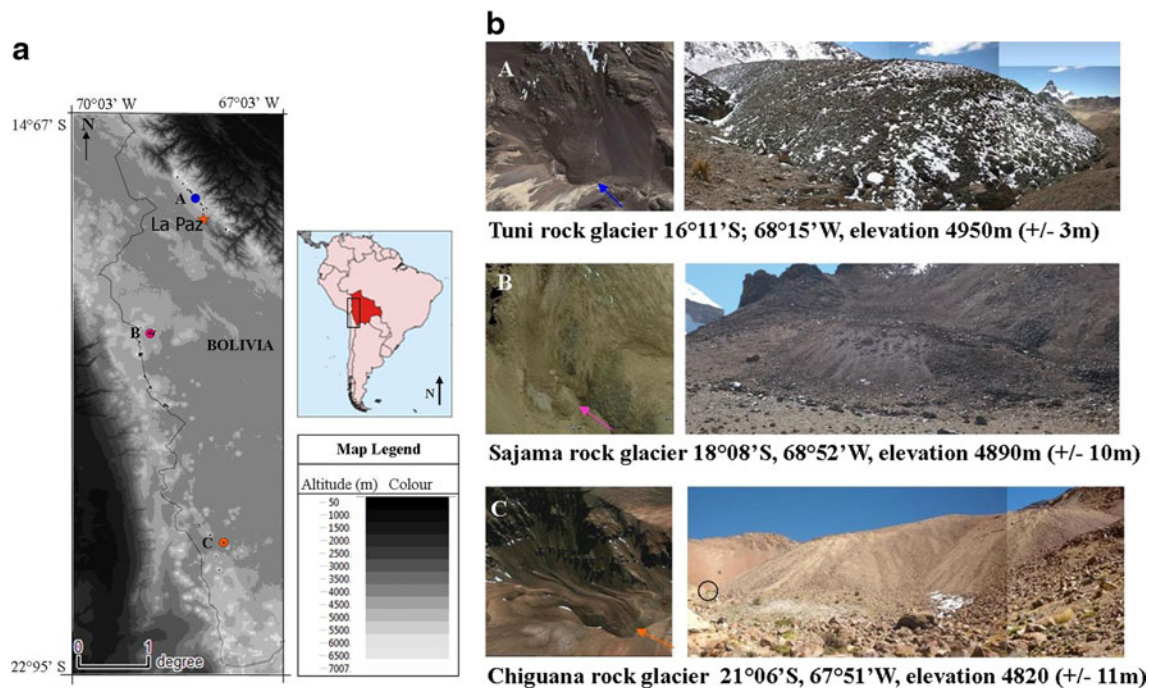

Fig. 5 **a** Map of rock glaciers along the Bolivian Andes with three example rock glacier locations labeled *A*, *B*, and *C* (shown in **b**). The *colored inset* shows the study region on a continental scale. Map is creating using Global Digital Elevation Model tiles from ASTER. **b** Google Earth screen shots and corresponding in situ photographs from example rock glaciers visited in July and August 2012. Rock glaciers shown are: (*A*) Tuni rock glacier; (*B*) Sajama rock glacier; (*C*) Chiguana rock glacier, from three different regions of the Bolivian Andes. The *circle* on photograph *C* highlights a person, showing the scale of the rock glacier which is around 50 m in height at the snout. *Colored arrows* on all of the Google Earth screen shots are for easy identification of the snout of the rock glaciers

significant long-term water storage in the semi-arid Andes, especially in Chile (Trombotto et al. 1999; Brenning 2005). The estimated water equivalent held in the Chilean rock glaciers is one order of magnitude higher than in the Swiss Alps (Brenning 2005), indicating their local significance in South America and supporting the need for studies in other parts of the Andes. Improving understanding of these rock glaciers and their abundance is important as it is argued that the role of rock glaciers in prolonging water storage, and as a source of water, will become increasingly significant as glaciers continue to recede (Millar and Westfall 2008; Angillieri 2009; Seligman 2009). The internal composition of rock glaciers is known to be highly variable, ranging from pure ice to an ice/rock mixture depending on their origin of formation (Whalley and Azizi 1994). It is estimated that active rock glaciers contain a range of between 40 and 60 % ice under a top layer of rock, which acts as insulation for the ice from low amplitude and high frequency temperature changes (Brenning 2005), resulting in a slower response to fluctuations in climate in comparison to glaciers. Therefore the importance of rock glaciers as more robust sources of water is likely to increase with glacier recession (Angillieri 2009; Seligman 2009; Toomey 2011) and in areas where ice glaciers are absent.

The only published scientific research on rock glaciers in Bolivia comes from one site, Caquella (21°S) (Francou et al. 1999; Bodin et al. 2010), and to-date there has been no country-wide assessment of rock glaciers. Enhancing our knowledge of rock glacier distribution and water equivalence at a regional scale is an important step in assessing the state of the cryosphere. This knowledge is required for climate impact studies and water resource management (Brenning and Azócar 2008). Consequently, we have produced a preliminary rock glacier inventory mapping 79 rock glaciers across the high Andes of Bolivia (Fig. 5a). These features span from 15°S to 22°S along the two mountain ranges in Bolivia: Eastern and Western Cordillera. Example in situ photographs of rock glaciers of three different regions of the Bolivian Andes are shown in Fig. 5b. In areas without ice glaciers, such as along the Western Cordillera between 19°S and 22°S, rock glaciers are abundant, suggesting that they may be of significance for local water supplies, however, more research is required.

CONCLUSIONS

Continued climate change is likely to severely impact water availability in arid mountain regions. Countries of the Arid Andes are sensitive and vulnerable to this changing climate, and Bolivia is expected to be one of the countries most affected by future reductions in water supplies. Changes in temperature and precipitation are predicted to have serious consequences for the hydrological cycle in the Andes, linking to increased glacier melting. Glacier recession in the Andes is expected to happen quicker than in many other mountain regions, with 80 % of the glaciers in the Bolivian Cordillera Real predicted to vanish within the next few decades, significantly affecting water supplies. As well as the pressures of climate change and glacier recession, factors such as increasing population and poor infrastructure will contribute towards reduced water availability in La Paz, Bolivia with negative impacts on water for domestic use, agriculture, and HEP production.

Identifying and addressing all of these drivers and impacts promotes an integrated water management strategy to improve water resources in Bolivia. Immediate mitigation and adaptation is necessary, although there are multiple political and financial barriers which prohibit Bolivia from successfully adapting, therefore strategies need to be planned and implemented correctly. Developing long-term solutions to regional water challenges requires the use of inter-disciplinary approaches that maximize academic and local knowledge and community involvement. Community-based resource management adaptation strategies have been seen to empower users and provide a potential way forward to effectively strengthen their capacity and resilience to climate change and water scarcity.

One restriction outlined in this review is the lack of observation and monitoring of climate systems and water supplies, and critical gaps in present knowledge of the Andean mountain cryosphere exist, prohibiting better water resource management. Given the recession of ice glaciers, the contribution of other permafrost features, such as rock glaciers, to mountain water supplies are becoming increasingly important; yet these are largely unmapped and understudied. Improving our understanding of rock glaciers will play a part in developing resilient water supplies for Bolivia and other arid mountain regions.

Acknowledgments This research was funded by a Natural Environment Research Council CASE award with Oxfam and Agua Sustentable. The authors would like to thank the Agua Sustentable team in La Paz for their support and help with fieldwork in Bolivia. The authors would also like to thank Helen Jones at Exeter University for drawing the figures. The manuscript was improved by insightful comments from three anonymous reviewers.

REFERENCES

Angillieri, M.Y.E. 2009. A preliminary inventory of rock glaciers at 30°S latitude, Cordillera Frontal of San Juan, Argentina. *Quaternary International* 195: 151–157.

Arbona, J.M., and B. Kohl. 2004. City profile La Paz-El Alto. *Cities* 21: 255–265.

Azócar, G.F., and A. Brenning. 2010. Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile (27°–33°S). *Permafrost & Preiglacial Processes* 21: 42–53.

Barnett, T.P., J.C. Adam, and D.P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438: 303–309.

Barry, R.G. 2005. Alpine climate change and cryospheric responses: An introduction. In *Climate and hydrology in mountain areas*, ed. C. de Jong, D. Collins, and R. Ranzi, 1–4. Chichester: Wiley.

Becker, A., and H. Bugmann. 1999. Global change and mountain regions. The Mountain Research Initiative. Stockholm, Sweden: IGBP.

Beniston, M. 2003. Climate change in mountain regions: A review of possible impacts. *Climate Change* 59: 5–31.

Bigas, H., T. Morris, B. Sandford, and Z. Adeel. 2012. The global water crisis: Addressing an urgent security issue. Papers for the InterAction Council, 2011–2012. Hamilton, Canada: UNU-INWEH.

Bodin, X., B. Francou, Y. Arnaud, D. Fabre, and P. Wagnon. 2010. State and dynamics of a topical rock glacier on the Altiplano (Bolivia, 21.5°S). *Poster presentation, International Glaciological Conference VICC 2010: Ice and Climate Change: A view from the South Valdivia,* Chile, 1–3 February 2010.

Bogoyavlenskiy, D., and A. Siggner. 2004. Chapter 2: Arctic Demography, Arctic Human Development Report. Stefansson Arctic Institute, 27 pp. http://hdr.undp.org/en/reports/regionalreports/other/arctic_2004_en.pdf.

Bolch, T., B. Menounos, and R. Wheate. 2010. Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sensing of Environment* 114: 127–137.

Bradley, R.S., M. Vuille, H.F. Diaz, and W. Vergara. 2006. Threats to water supplies in the tropical Andes. *Science* 312: 1755–1756.

Brenning, A. 2005. Geomorphological, hydrological and climatic significance of rock glaciers in the Andes of Central Chile (33–35°S). *Permafrost & Periglacial Processes* 16: 231–240.

Brenning, A., and G.F. Azócar. 2008. Mapping and modelling rock glacier distribution in the dry Andes: A progress report. *Abstracts, 4th Alexander von Humboldt International Conference, The Andes—Challenge for Geosciences,* 24–28 November 2008, Santiago, Chile.

Brown, F., A. Rivera, and C. Acuña. 2008. Recent glacier variations at the Aconcagua basin, central Chilean Andes. *Annals of Glaciology* 48: 43–48.

Buytaert, W., M. Vuille, A. Dewulf, R. Urrutia, A. Karmalkar, and R. Célleri. 2010. Uncertainties in climate change projections and regional downscaling in the tropical Andes: Implications for water resources management. *Hydrology and Earth System Science* 14: 1247–1258.

Carrasco, J.F., G. Casassa, and J. Quintana. 2005. Changes of the 0°C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century. *Hydrological Sciences Journal* 50: 933–948.

Casassa, G., W. Haeberli, G. Jones, G. Kaser, P. Ribstein, A. Rivera, and C. Schneider. 2007. Editorial: Current status of Andean glaciers. *Global and Planetary Change* 59: 1–9.

Chevallier, P., B. Pouyaud, W. Suarez, and T. Condom. 2011. Climate change threats to environment in the tropical Andes: Glaciers and water resources. *Regional Environmental Change* 11: 179–187.

Coudrain, A., B. Francou, and Z.W. Kundzewicz. 2005. Glacier shrinkage in the Andes and consequences for water resources—Editorial. *Hydrological Sciences* 50: 925–932.

Diaz, H.F., and N.E. Graham. 1996. Recent changes in tropical freezing heights and the role of sea surface temperature. *Nature* 383: 152–155.

Evans, D.J.A. 2005. *Glacial landsystems*. London: Hodder Education.

Farley, M., and R. Liemberger. 2005. Developing a non-revenue water reduction strategy: Planning and implementing the strategy. *Water Science and Technology: Water Supply* 5: 41–50.

Francou, B., and C. Vincent. 2007. Les glaciers vont-ils disparaître? Les glaciers face au changement climatique. IRD Editions et CNRS Editions.

Francou, B., D. Fabre, B. Pouyaud, V. Jomelli, and Y. Arnaud. 1999. Symptoms of degradation in a tropical rock glacier, Bolivian Andes. *Permafrost & Periglacial Processes* 10: 91–100.

Francou, B., E. Ramirez, B. Cáceres, and J. Mendoza. 2000. Glacier evolution in the tropical Andes during the last decades of the 20th century: Chacaltaya, Bolivia, and Antizana, Ecuador. *AMBIO* 29: 416–422.

Francou, B., M. Vuille, P. Wagnon, J. Mendoza, and J.E. Sicart. 2003. Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16°S. *Journal of Geophysical Research* 108.

Francou, B., M. Vuille, V. Favier, and B. Cáceres. 2004. New evidence for an ENSO impact on low-latitude glaciers: Antizana 15, Andes of Ecuador, 0°28′S. *Journal of Geophysical Research* 109. doi:10.1029/2003JD004484.

Galarza, E., and R. Gómez. 2011. Cities in the Andes: Threats and hopes. Centro de Investigación, Universidad del Pacifico. Retrieved June 12, 2013, from www.grida.no/publications/et/ep4/page/2635.aspx.

Hay, J.E., and T.L. Elliott. 2008. New Zealand's glaciers: Key national and global assets for science and society. In *Darkening peaks: Glacier retreat, science, and society*, ed. B. Orlove, E. Wiegandt, and B.H. Luckman, 185 pp. London: University of California Press.

Hays, J. 2011. Water shortages: Solutions and innovations. Retrieved June 12, 2013, from http://factsanddetails.com/world.php?itemid=1534&catid=51&subcatid=325.

ICE. 2011. Managing water locally: An essential dimension of community water development. The Institution of Civil Engineers, Oxfam GB and WaterAid. Retrieved June 12, 2013, from http://www.ice.org.uk/ICE_Web_Portal/media/Ecomms/managing_water_locally.pdf.

IPCC. 2007a. Summary for policymakers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge: Cambridge University Press.

IPCC. 2007b. In *Climate Change 2007: Impacts, adaptation and vulnerability, contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. Van der Linder, and C.E. Hanson, 976 pp. Cambridge: Cambridge University Press.

Jansen, F., and S. Hergarten. 2006. Rock glacier dynamics: Stick–slip motion coupled to hydrology. *Geophysical Research Letters* 33.

Jeschke, M.L. 2009. Glacier recession in the Bolivian Andes as a consequence of global climate change: Impacts on regional water supply according to the simulation of future runoff from Zongo glacier. Dissertation, Universität Potsdam.

Jeschke, M., A. Popp, and H. Lotze-Campen. 2012. Adaptation options to climate-induced glacier retreat in Bolivia. In *Climate change, justice and sustainability: Linking climate and development policy*, ed. O. Edenhofer, J. Wallacher, H. Lotze-Campen, M. Reder, B. Knopf, and J. Müller, 195 pp. New York: Springer.

Jordon, E. 2008. Glaciers of South America: Glaciers of Bolivia. Satellite Image Atlas of Glaciers of the World. United States Geological Survey 18th March 2008. Retrieved June 12, 2013, from http://pubs.usgs.gov/pp/p1386i/bolivia/intro.html.

Kundzewiz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, B. Jimenez, K. Miller, T. Oki, Z. Şen, et al. 2008. The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal* 53: 3–10.

Lee, E.J., and K.L. Schwab. 2005. Deficiencies in drinking water distribution systems in developing countries. *Journal of Water Health* 3: 109–127.

Machicao, M., and E. Garcia. 2007. Global warming melts Andean glaciers towards oblivion. Planet Ark, June 8. Retrieved June 12, 2013 from http://earthhopenetwork.net/Global_Warming_Melts_Andean_Glaciers_Toward_Oblivion.htm.

Magrath, J. 2005. Glacier melt: Why it matters for poor people. Oxfam. Retrieved June 12, 2013, from http://www.scribd.com/doc/52828625/Glacier-Melt-Why-it-matters-for-poor-people.

Magrin, G., C. Gay García, D. Cruz Choque, J.C. Giménez, A.R. Moreno, G.J. Nagy, C. Nobre, and A. Villamizar. 2007. Latin America Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ed. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, 581 pp. Cambridge: Cambridge University Press.

Mark, B.G., J. Bury, J.M. McKenzie, A. French, and M. Baraer. 2010. Climate change and tropical Andean glacier recession: Evaluating hydrologic changes and livelihood vulnerability in the Cordillera Blanca, Peru. *Annals of the Association of American Geographers* 100: 794–805.

Mejia, A. 2012. Water scarcity in Latin America and the Caribbean: Myths and reality, Rosenberg international forum on water policy. Retrieved June 12, 2013, from http://rosenberg.ucanr.org/documents/argentina/Majia%20Final%20082010.pdf.

Millar, C.I., and R.D. Westfall. 2008. Rock glaciers and related periglacial landforms in the Sierra Nevada, CA, USA; inventory, distribution and climatic relationships. *Quaternary International* 188: 90–104.

Olivera, O., and T. Lewis. 2004. *¡Cochabamba! Water War in Bolivia*. Cambridge: South End Press.

Orlove, B., E. Wiegandt, and B.H. Luckman. 2008. The place of glaciers in natural and cultural landscapes. In *Darkening peaks: Glacier retreat, science, and society, pp 3*, ed. B. Orlove, E. Wiegandt, and B.H. Luckman, 3 pp. London: University of California Press.

Oxfam. 2009. Bolivia: Climate change, poverty and adaptation: Executive summary. Oxfam International. Retrieved June 12, 2013, from http://www.oxfam.org/sites/www.oxfam.org/files/bolivia-climate-change-adaptation-summary-0911.pdf.

Painter, J. 2007. Deglaciation in the Andean Region, Human Development Report 2007/2008: Fighting climate change: Human solidarity in a divided world. Human Development Report Office, Occasional Paper.

Rabatel, A., B. Francou, A. Soruco, J. Gomez, B. Cáceres, J.L. Cebellos, R. Basantes, M. Vuille, et al. 2013. Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *The Cyrosphere* 7: 81–102.

Ramirez, E., B. Francou, P. Ribstein, M. Decloitres, R. Guerin, J. Mendoza, R. Gallaire, B. Pouyaud, et al. 2001. Small glaciers disappearing in the tropical Andes: A case-study in Bolivia: Glaciar Chacaltaya (16°S). *Journal of Glaciology* 47: 187–194.

Rossing, T. 2010. Water scarcity, climate change, and the poor. In *Reducing poverty, protecting livelihoods and building assets in a changing climate: Social implications of climate change for Latin America and the Caribbean*, ed. D. Verner, 21 pp. Washington, DC: World Bank.

Seligman, Z.M. 2009. Rock glacier distribution, activity, and movement, Northern Absaroka and Beartooth Ranges, MT, USA, MSc Thesis. Boulder, CO: University of Colorado.

Soruco, A.S. 2012. *Medio siglo de fluctuaciones glaciares en la Cordillera Real y sus efectos hidrológicos en la ciudad de La Paz*. La Paz: IRD. ISBN 978-99954-62-0.

Soruco, A., C. Vincent, B. Francou, and J.F. Gonzalez. 2009. Glacier decline between 1963 and 2006 in the Cordillera Real, Bolivia. *Geophysical Research Letters* 36.

Stewart, B. 2010. Melting Glaciers of Bolivia's Cordillera Real. ICE Case Studies Number 236, December 2010. Retrieved June 12, 2013, from http://www1.american.edu/ted/ice/aymara.htm.

Toomey, G. 2011. Discovering Chile's hidden water treasures—Rock glaciers. UniWorld Spring 2011. Retrieved June 12, 2013, from http://www.aucc.ca/wp-content/uploads/2011/07/lacreg-discovering-chiles-hidden-water-treasures-2009-2010-e1.pdf.

Trombotto, D., E. Buk, and J. Hernández. 1999. Rock glaciers in the Southern Central Andes (approx. 33°–34°S), Cordillera Frontal, Mendoza, Argentina. *Bamberger. Geographische Schriften* 19: 145–173.

UN. 2013. Internationally Decade for Action 'Water for Life' 2005–2015. Retrieved June 12, 2013, from http://www.un.org/waterforlifedecade/water_cooperation.shtml.

UNFCCC. 2007. Climate change: Impacts, vulnerabilities and adaptation in developing countries. United Nations framework convention on climate change. Retrieved June 12, 2013, from http://unfccc.int/resource/docs/publications/impacts.pdf.

Vanham, D., and W. Rauch. 2010. Mountain water and climate change. In *Climate change and water: International perspectives on mitigation and adaptation*, ed. J. Smith, C. Howe, and J. Hendersen, 21 pp. Denver: American Water Works Association.

Vergara, W. 2009. Assessing the potential consequences of climate destabilization in Latin America. Latin America and Caribbean region Sustainable Development Working Paper 32. The World Bank, Latin America and the Caribbean Region Sustainable Development Department.

Vergara, W., H. Kondo, E.P. Pérez, J.M.M. Pérez, V.M. Rueda, M.C.M. Arango, J.F.R. Murcia, G.J.A. Roldán, et al. 2007a. Visualizing future climate in Latin America: Results from the application of the Earth Simulator. Latin America and Caribbean Region Sustainable Development Working Paper 30. The World Bank, Latin America and the Caribbean Region Sustainable Development Department.

Vergara, W., A.M. Deeb, A.M. Valencia, R.S. Bradley, B. Francou, A. Zarzar, A. Grünwaldt, and S.M. Haeussling. 2007b. Economic impacts of rapid glacier retreat in the Andes. *EOS, Transactions, American Geophysical Union* 88: 261–268.

Viviroli, D., D.R. Archer, W. Buytaert, H.J. Fowler, G.B. Greenwood, A.F. Hamlet, Y. Huang, G. Koboltschnig, et al. 2011. Climate change and mountain water resources: Overview and recommendations for research, management and policy. *Hydrological and Earth System Sciences* 15: 471–504.

Vuille, M. 2007. Climate Change in the tropical Andes—Impacts and consequences for glaciation and water resources, Part 1: The scientific basis, Report for CONAM and the World Bank.

Vuille, M., R.S. Bradley, M. Werner, and F. Keimig. 2003. 20th Century climate change in the tropical Andes: Observations and model results. *Climatic Change* 59: 75–99.

Vuille, M., B. Francou, P. Wagnon, I. Juen, G. Kaser, B.G. Mark, and R.S. Bradley. 2008. Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews* 89: 79–96.

Water.org. 2012. Water and sanitation market assessment: potential regional viability of watercredit and microfinance solutions in Bolivia: Executive Summary. July 2012. Retrieved June 12, 2013, from http://watercredit.org/wp-content/uploads/2013/01/Bolivia-WC-RMA-Executive-Summary-July-2012-v2.pdf.

Whalley, W.B., and F. Azizi. 1994. Rheological models of active rock glaciers: Evaluation, critique and a possible test. *Permafrost & Periglacial Processes* 5: 37–51.

WHO. 2012. Linking poverty reduction and water management. Retrieved June 12, 2013, from http://www.who.int/water_sanitation_health/resources/povertyreduc2.pdf.

Winters, C. 2012. Impact of climate change on the poor in Bolivia. *Global Majority E-Journal* 3: 33–43.

WMO. 2011. Climate information and water management: Story from the Andes [Online]. World Meteorological Organization. Retrieved June 12, 2013, from http://www.wmo.int/pages/prog/wcp/cop16/COP16story_water.php.

World Bank. 2008. Retracting glaciers impacts economic outlook in the Tropical Andes, 23 April 2008. Retrieved June 12, 2013, from http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/LACEXT/0,,print:Y~isCURL:Y~contentMDK:21739254~pagePK:146736~piPK:146830~theSitePK:258554,00.html.

World Bank. 2010. *Adaptation to climate change—Vulnerability assessment and economic aspects: A pilot study of the economics of adaptation to climate change, Bolivia*. Washington, DC: The World Bank Group.

AUTHOR BIOGRAPHIES

Sally Rangecroft (✉) is a doctoral candidate working in the Environment and Sustainability Institute at the University of Exeter on water resources in the dry Andes of Bolivia, with specific focus looking at the contribution of rock glaciers to water supplies.
Address: School of Geography, CLES, University of Exeter, Cornwall Campus, Penryn, Cornwall TR10 9EZ, UK.
Address: Environment and Sustainability Institute, University of Exeter, Cornwall Campus, Penryn, Cornwall TR10 9EZ, UK.
e-mail: sr332@exeter.ac.uk

Stephan Harrison is an Associate Professor of Quaternary Science whose main research interests lie in geomorphological responses to climate change.
Address: School of Geography, CLES, University of Exeter, Cornwall Campus, Penryn, Cornwall TR10 9EZ, UK.

Karen Anderson is a Senior lecturer in Natural Environment with research specialisms in the field of remote sensing.
Address: School of Geography, CLES, University of Exeter, Cornwall Campus, Penryn, Cornwall TR10 9EZ, UK.
Address: Environment and Sustainability Institute, University of Exeter, Cornwall Campus, Penryn, Cornwall TR10 9EZ, UK.

John Magrath is a Programme Researcher at Oxfam UK whose focus is mainly on climate change and its implications for Oxfam's work.
Address: Oxfam GB, Oxfam House, John Smith Drive, Cowley, Oxford OX4 2JY, UK.

Ana Paola Castel is a member of the Agua Sustentable team in La Paz whose work focuses on water, climate change and risk management.
Address: Agua Sustentable, Calle Nataniel Aguirre No. 82 entre Calles 11D y 12, Irpavi, La Paz, Bolivia.

Paula Pacheco is the Head of the La Paz office for the Bolivian NGO Agua Sustentable.
Address: Agua Sustentable, Calle Nataniel Aguirre No. 82 entre Calles 11D y 12, Irpavi, La Paz, Bolivia.