ROCK GLACIERS AND CLIMATE CHANGE IN THE BOLIVIAN ANDES

Mapping new water resources

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Climate change is affecting glaciers worldwide and the vulnerability and sensitivity of glaciers in the Bolivian Andes mean that they can be seen as a warning ecosystem for mountain regions in other areas. Rock glaciers are protected under rock formations and can play an important role in long-term water storage. They should be factored into water management and climate change adaptation strategies. This report describes research to create the first rock glacier inventory for Bolivia, and highlights the need to prioritize the preservation of areas where rock glaciers are located in the interests of water security for vulnerable populations.

Agua Sustentable

OXFAM

CONTENTS

EXECUTIVE SUMMARY

Reduced water security is projected for the Bolivian Andes due to both an expected increase in demand and a decline in the supply of water. This will result in negative impacts on water availability, and therefore on food security, power generation and livelihoods. Rising temperatures due to climate change are associated with glacier retreat across the Andes, which is one factor affecting the supply of water. Therefore it is important to gather information about other sources of high altitude water in the Bolivian Andes and other similarly arid high mountain regions facing similar stresses.

Rock glaciers are masses of ice that are covered by a thick layer of rock. Because of their ice content, they are potentially important water sources, especially in arid regions. However, little is known about their spatial distribution and nature. They are smaller, occur at lower altitudes and are less obvious than regular ice glaciers.

With the purpose of better informing future water management in Bolivia, this research, which was conducted with the assistance of Oxfam and Agua Sustentable, has created the first rock glacier inventory for the country (15–22°S) and has established the number, size and distribution of these rock glaciers. In total, 94 rock glaciers were discovered in the Bolivian Andes, of which 54 are estimated to contain ice and are therefore active sources of water. It was possible to make an estimation of their importance as water stores for local communities, in comparison with regular glaciers.

Climate change impacts on glaciers and other water resources are occurring at a rapid rate in the Bolivian Andes and Bolivia can be used as an early warning indicator of problems in arid regions worldwide. The rock cover on rock glaciers will insulate them to some extent and as temperatures rise, will make them more resilient to melting than ice glaciers. In highlighting the presence of rock glaciers and in setting out methods for identifying them, this research seeks to contribute to improving the knowledge of water resources in the Bolivian Andes and to make a contribution to similar studies elsewhere. It also highlights the need to prioritize the preservation of areas where rock glaciers are located in the interests of water security for vulnerable populations.

The rock glacier inventory resulting from this research is held by Agua Sustentable, see http://www.aguasustentable.org

1 INTRODUCTION

Increasing demand for water is connected with continued population growth and other factors, while simultaneously climate change is accelerating glacier melting, raising serious water resource management concerns for arid and mountainous regions (Bradley et al., 2006; Painter, 2007; Jeschke, 2009). Providing an adequate water supply poses one of the greatest challenges for many countries in the 21st century.

Bolivia is one of the most vulnerable countries to climate change impacts due to its high levels of poverty and inequality, yet it has a very limited capacity to adapt. Vulnerable social groups will be affected the worst, as they are the most ill-equipped to deal with the impacts of climate change (Oxfam, 2009).

The water resources of landlocked Bolivia are not evenly distributed: the eastern lowlands are wet and tropical, while the dry Altiplano and mountains of the Andes cover the west of the country. The Altiplano receives very little rain and experiences a long dry season (May to October). Bolivia’s capital, La Paz (Figure 1) is situated at ~4,000m asl in the Altiplano and has limited water sources; its two main water sources being rainfall and glaciers. Conventional ‘ice glaciers’ are especially important during the dry season for their meltwater. Glaciers provide one of the main sources of water for drinking, agriculture and energy generation (Jordan, 2008; Vuille et al., 2008; Chevallier et al., 2011). It is estimated that the glaciers of the Cordillera Real supply between 12 and 40 percent of potable water for La Paz (Vergara, 2009; Soruco, 2012).

In the Andes, glaciers, debris-covered glaciers and rock glaciers are the three main features of the cryosphere, the frozen portion of the earth’s surface (Bodin et al., 2010). However, glaciers have been retreating worldwide, affecting water resources downstream (IPCC, 2014). Bolivian glaciers have lost roughly half of their volume in the past 60 years (Soruco et al., 2009), leading to the disappearance of many small glaciers. One such example is the famous Chacaltaya glacier close to La Paz (Figure 2) which vanished in 2009, six years earlier than predicted. Water security is projected to become a bigger issue for La Paz because of the stresses of population growth, glacier retreat and changes in temperature and precipitation patterns, the impacts of which are already being witnessed in the form of glacier recession, flooding and changes in seasons and weather patterns. Reduced water security will have a detrimental impact on the livelihoods of potentially millions of people.

In the light of worldwide glacier retreat and rising and changing water demand, research on stores of water at high elevations, such as rock glaciers, is therefore needed in many regions of the world (Brenning et al., 2007). Oxfam, the University of Exeter, NERC, and the Bolivian non-government organization (NGO) Agua Sustentable, funded a PhD research project to investigate the distribution, number and size of these rock glaciers in Bolivia. The research was carried out by this paper’s author, Sally Rangecroft, over a period of four years. The resulting rock glacier inventory is held by Agua Sustentable, see http://www.aguasustentable.org

Figure 1: Densely populated housing in upper La Paz (16.5°S, 68.15°W) sprawling onto the 4000m Altiplano plateau of El Alto. Photo: S Rangecroft, July 2012

Figure 2: Former ski resort on Chacaltaya close to La Paz. Photo: S Rangecroft, July 2011

2 ROCK GLACIERS

Rock glaciers (Figure 3) are ice and rock features generally occurring in high mountainous regions (Berthling, 2011). They are a core of ice or ice-cemented rock, with a thick layer of rock debris cover (~5m thick). It is estimated that rock glaciers contain a range of between 40–60 percent ice under this top layer of rock, which acts as insulation for the ice from temperature changes (Brenning, 2005a; Estrada, 2009). They have a steep front (snout) and side slopes and their length is generally greater than their width (Giardino & Vitek 1988; Summerfields 1991; Hamilton & Whalley, 1995; Benn & Evans, 1998; Evans, 2005; Jansen & Hergarten, 2006). The most distinctive feature is their surface morphology which consists of a series of ridges and furrows (Figure 3).

Rock glaciers can be classified in many different ways, but one of the most common is by their activity status. 'Active' rock glaciers contain ice and are currently still moving (usually mm to cms per year). The speed that rock glaciers move is a lot slower than glaciers, which are known to move tens to hundreds of meters annually. Former ('relict') rock glaciers no longer contain ice and are therefore no longer moving.

Although rock glaciers hold much less ice than glaciers in arid regions, in many situations ice glaciers are absent or limited. Therefore rock glaciers are known to be key stores of frozen water (Francou et al., 1999; Brenning, 2005a; Azócar & Brenning, 2010; Kellerer-Pirklbauer et al., 2012; Rangecroft et al., 2013). However, their importance as a water source had not been explored in Bolivia before this PhD research.

The PhD research established:

- the first rock glacier inventory for the Bolivian Andes;
- first estimates of the amount of water contained in the rock glaciers;
- projected temperature warming for the Bolivian Andes;
- possible implications of projected warming on rock glaciers.

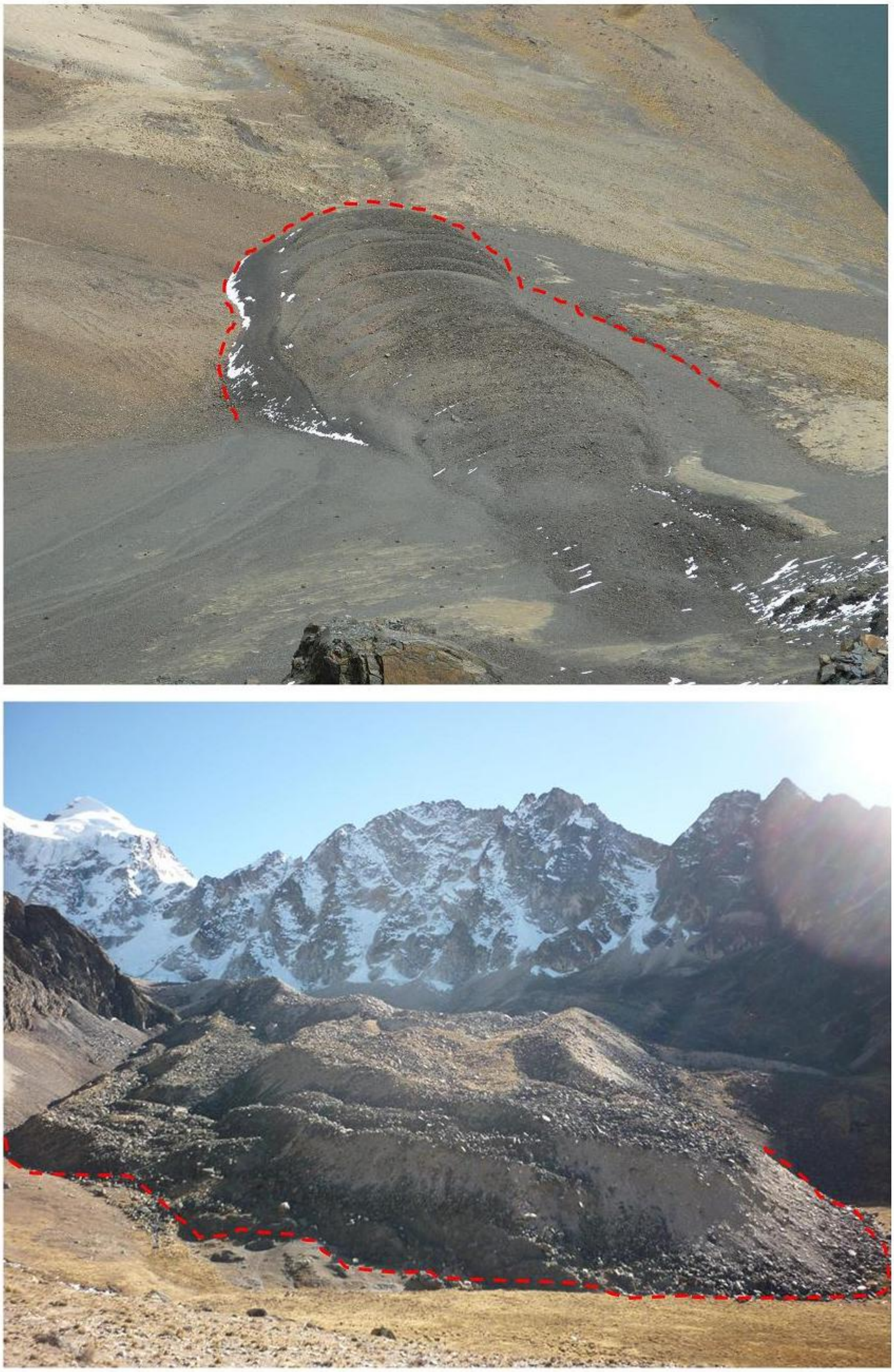

Figure 3: Typical Bolivian rock glaciers, extent marked; above, at Pico Austria, Tuni Condoriri region; below, at Huayna Potosi. Photo: S Rangecroft, July 2011, August 2012

3 ROCK GLACIER INVENTORY

Although rock glaciers occur globally in many of the major mountain regions, most research has been concentrated in the European Alps, although recently there has been more research emerging in the Chilean and Argentinean Andes. The first step towards assessing the spatial distribution and areal coverage of these ice features is the creation of a rock glacier inventory. This information is needed for water resource management.

The rock glacier inventory was generated through a combination of field work and visual analysis of satellite data. Rock glaciers were identified and mapped using high resolution satellite imagery from Google Earth (Figure 4), purchased satellite imagery and aerial photographs. Field surveys were conducted during July and August 2011 and July and August 2012 in order to assess the reliability of the mapping and rock glacier classification.

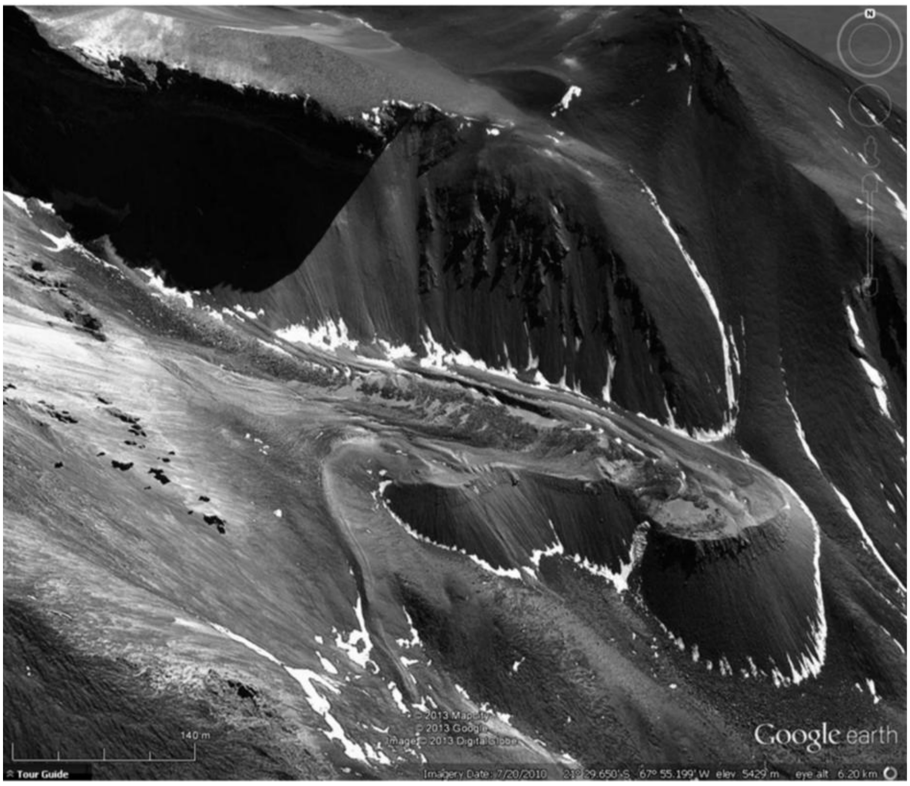

Figure 4: Bolivian rock glacier, Caquella (21.5 °S). Image credit: Google Earth

A total of 94 rock glaciers were identified in the Bolivian Andes, of which 54 were classified as active (containing ice) (see Figure 4). The remaining 40 (43 percent) were classified as relict (Rangecroft et al., 2014). The mean altitude for active rock glaciers was 4980m (measured from the bottom of the rock glacier). The mean altitude for relict rock glaciers was ~100m lower: 4870m. It is known that the 0°C isotherm has moved up the landscape due to rising temperatures, and this is illustrated by the 100m difference between present (active) and former (relict) rock glaciers.

Bolivian rock glaciers were found to be on average 500m in length. The average rock glacier area was calculated to be 0.12km^2 which is the equivalent of 17 football fields.

Bolivian rock glacier abundance is less than in other locations in the Andes (Chile, Argentina), American Rockies and European Alps (Rangecroft et al., 2014).

Details of the rock glacier inventory are published in the academic journal 'Permafrost and Periglacial Processes' (Rangecroft et al., 2014), and available at www.aguasustentable.org

4 THE IMPORTANCE OF ROCK GLACIERS AS WATER STORES

Rock glaciers are known to be important stores of frozen water, acting as water reservoirs where precipitation is very low (Francou et al., 1999; Trombotto et al., 1999). It is important to quantify the water contributing to the regions hydrology in order to improve water resource management. Despite this importance, there is limited work estimating the water content of rock glaciers, especially for the South American Andes.

Ice content is known to vary considerably within a rock glacier. Some workers suggest that ice content ranges from 40 to 60 percent in active rock glaciers (Barsch, 1996; Haeberli et al., 1998; Arenson et al., 2002; Hausmann et al., 2007; Brenning, 2008; Krainer & Ribis, 2012). To estimate the importance of rock glaciers as stores of water and ice, their frequency needs to be known and then their ice content can be assessed with the water equivalent content calculated. Currently there is no field data investigating the ice content or ice thickness of Bolivian rock glaciers. Therefore, estimates were used for this project.

Estimates of rock glacier ice content were based on the literature, using a lower estimate of 40 percent and a higher estimate of 60 percent ice.

To estimate rock glacier ice thickness, two methods were used. For both these methods, information on rock glacier size (surface area) was needed. Method 1 used an established equation by Brenning (2005b) from fieldwork in the Chilean Andes (Azócar & Brenning, 2010). Method 2 used a consistent minimum rock glacier permafrost thickness of 20m for all sites (Brenning, 2008).

Using information of rock glacier size from the rock glacier inventory (Rangecroft et al., 2014), estimates of ice content and subsequent water equivalence were calculated. Results suggest that rock glaciers of the Bolivian Andes contain between 50 and 140 billion litres of water. This is between 20,000 and 56,000 Olympic-sized swimming pools.

For this study, three sub-regions were analysed: Cordillera Real (15° - 17° S), Sajama (17–18°S) and Western Cordillera (18°–22°S) (Figure 5).

- Sixteen active rock glaciers are located in the Cordillera Real, with surface area coverage of 1.07 km^2. These rock glaciers of the Cordillera Real contain between 7 and 17.6 billion litres (L) of water. This is the equivalent of 2,800–7,040 Olympic swimming pools. This gives an average of 10 billion L, which is the same as 4,000 swimming pools.
- Fifteen active rock glaciers were identified in the Sajama region, covering 2.98 km^2. These rock glaciers contained between 21 and 65 billion L, which is between 8,400 and 26,000 swimming pools. Here, the average is 50 billion L, the equivalent of 20,000 swimming pools.
- Twenty-three active rock glaciers were discovered in the Western Cordillera region, covering 2.88 km^2. These are estimated to contain between 21 and 54 billion L, the equivalent of between 8,400 and 21,600 swimming pools. This gives an average of 40 billion L, 16,000 Olympic swimming pools.

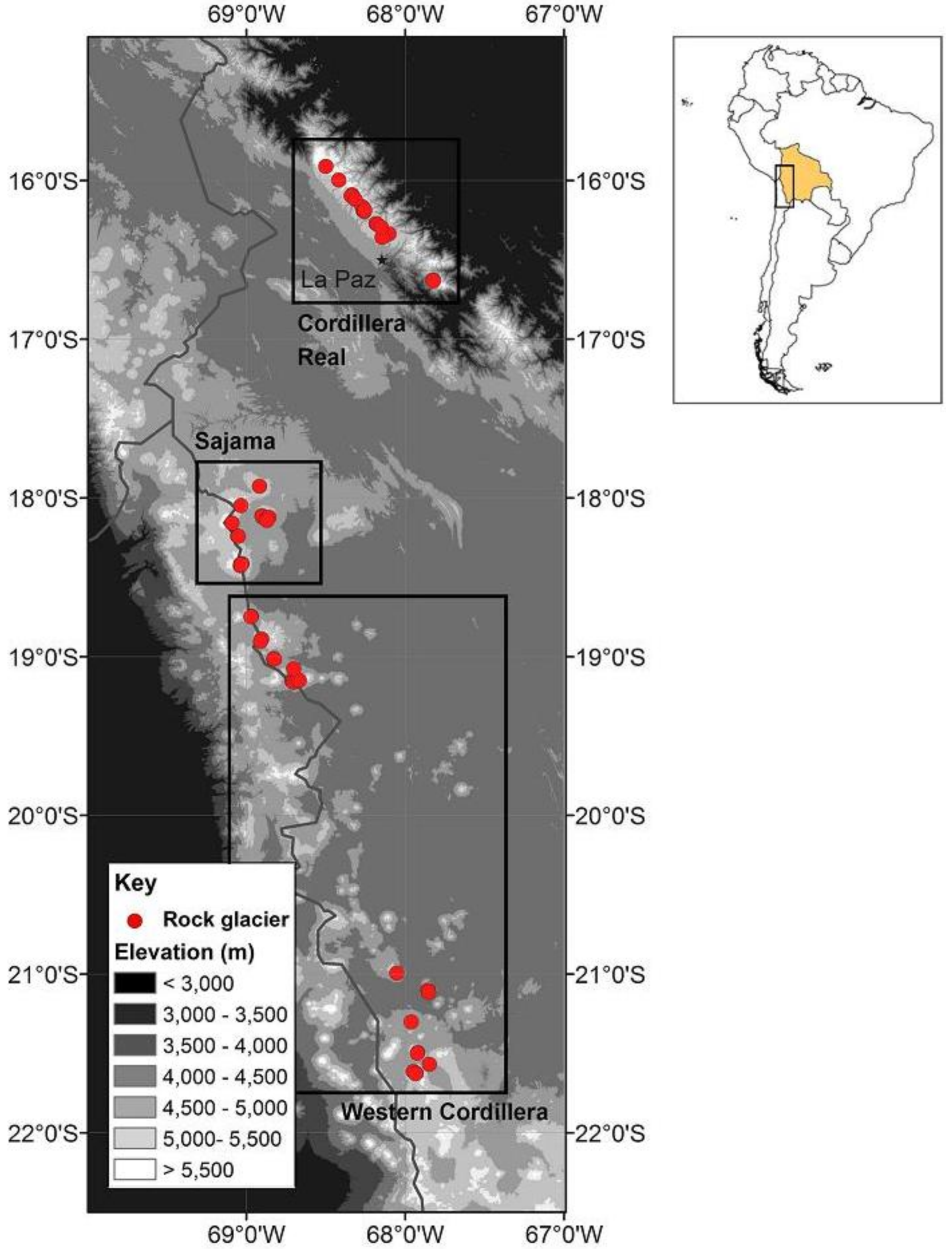

Figure 5: Active rock glaciers in the Bolivian rock glacier inventory. Red dots indicate the location of rock glaciers along the Bolivian Andes. Each dot may indicate the presence of several rock glaciers. Image credit: Rangecroft et al. 2015

Using these results, an assessment of the importance of rock glaciers as water sources compared to ice glaciers was conducted (Rangecroft et al., 2015). Although data on current ice glacier coverage across the Bolivian Andes is limited, the most recent estimate for the Cordillera Real is 185.5 km^2 (Ramirez et al., 2012). There are also glaciers in Sajama, but there is a lack of recent data for this region. This highlights an important gap in existing knowledge of the Bolivian Andes as there is no current estimate of ice glacier extent across the whole region. Recent research has focused purely on the Cordillera Real (Sorcou et al., 2009; Ramirez et al., 2012; Lui et al., 2013).

Overall, across the Bolivian Andes the rock glacier to ice glacier ratio for water equivalence was estimated to be ~1:40. Glaciers were found to dominate in the Cordillera Real region with a regional rock glacier to ice glacier ratio of 1: 264. Rock glacier to ice glacier water equivalence was ~ 1:9 in the Sajama region. In the Western Cordillera, in the absence of ice glaciers, and with very limited rainfall, it can be assumed that rock glaciers in this region in particular act as important hydrological buffers to adjacent local mountain communities.

From this inventory, estimated active rock glacier coverage across the Bolivian Andes is 6.92 km^2, corresponding to a minimum estimated water content of 50 million L. Using the World Health Organization target of 50 litres per person per day (Howard & Bartram, 2003, p.1), this estimates that the water contained in Bolivian rock glaciers is equivalent to the amount of water that would be used by 2,739,726 people in one year. However, it is important to note that the water available from rock glaciers is not instant; it is released slowly over time.

It is important to consider that rock glaciers are not evenly distributed in the Bolivian Andes. Given the lack of ice glaciers in the Western Cordillera, this rock glacier inventory has shown that rock glaciers, and their estimated minimum of 21 billion L of water, can be considered as particularly important local sources of water for mountain communities in the Southern Andes of Bolivia (18°–22°S). Similarly, in Sajama where ice is also limited, it can be assumed that the water estimated to be contained in rock glaciers (a minimum 21 billion L) may be important for local mountain communities and the Sajama National Park. Ice glaciers dominate in Cordillera Real, with an estimated coverage of 185.5 km^2 (Ramirez et al., 2012), while rock glaciers are less abundant and smaller in this region. Here, we estimated that rock glaciers cover 1.07 km^2; hence, we argue that rock glaciers are not an important source of water (in comparison with ice glaciers) for the La Paz region.

Bolivian rock glaciers contained far less water than those of the Chilean Andes (Azócar & Brenning, 2010) and Argentinean Andes (Perucca & Esper Angillieri, 2011); in both these countries rock glaciers are much more abundant. However, as stated above, rock glaciers are likely to be important sources of water to mountain communities in some parts of Bolivia.

For further information about the water estimates of Bolivian rock glaciers, see Rangecroft et al. (2015) in ‘Arctic, Antarctic and Alpine Research’.

5 THE IMPACT OF CLIMATE CHANGE ON ROCK GLACIERS

Using current climate data (http://www.worldclim.org/) and projected climate data (www.ccafs-climate.org/data/) we modelled the future climate warming expected for the Bolivian Andes under the IPCC A1B emissions scenario (IPCC SRES, 2000). The A1B emissions scenario is a medium scenario, used in the downscaling data due to it being an average.

Using this data, the current and future permafrost extent for the Bolivian Andes was modelled, using the 0°C mean annual air temperature (MAAT) as a proxy for the permafrost boundary. This project found that:

- projected temperature changes for the Bolivian Andes ranged between 2.7–3.2 °C by 2050 and 4.2–4.9 °C by 2080 (Figure 6);
- results suggest that this warming will decrease permafrost extent from present day extents by up to 95 percent by 2050 and 99 percent by 2080 (Figure 7);
- observations of MAATs at active rock glaciers sites show that rock glaciers cluster around the 0 °C isotherm, and this is known to have moved upwards over time with warming.

Projected temperature increases for Bolivia range from 3.5 to 5.9 °C by the end of the 21st century (Mitchell & Hume, 2000). The projections for the Bolivian Andes from this research lie at the higher end of this range.

Research to model permafrost response to climate has almost exclusively been confined to the Northern Hemisphere. It is ‘virtually certain’ that permafrost in the Northern Hemisphere will continue to decline during the 21st century (IPCC, 2014). Similar evaluations of Southern Hemisphere permafrost are not currently available, yet such assessments are required to inform decision making over future water supply and climate change adaptation strategies. Furthermore, publications that explore the impacts of climate change on mountain permafrost are very limited (Bonnaventure & Lewkowicz, 2011).

Looking to understand the implications of projected warming on currently active rock glaciers:

- we estimate that by 2050 34 percent of Bolivian active rock glaciers will remain within temperatures that sustain active status (<+2 °C);
- by 2080 only one rock glacier is modelled to remain situated within this MAAT threshold.

However, it is important to remember that rock glaciers respond slowly to changes in climate (on decadal scales), and therefore the responses modelled here will lag climate forcing. Nevertheless, the key message from the results remains that permafrost in rock glaciers, while more resistant to rising temperatures, is certainly not exempt from the implications of continued warming.

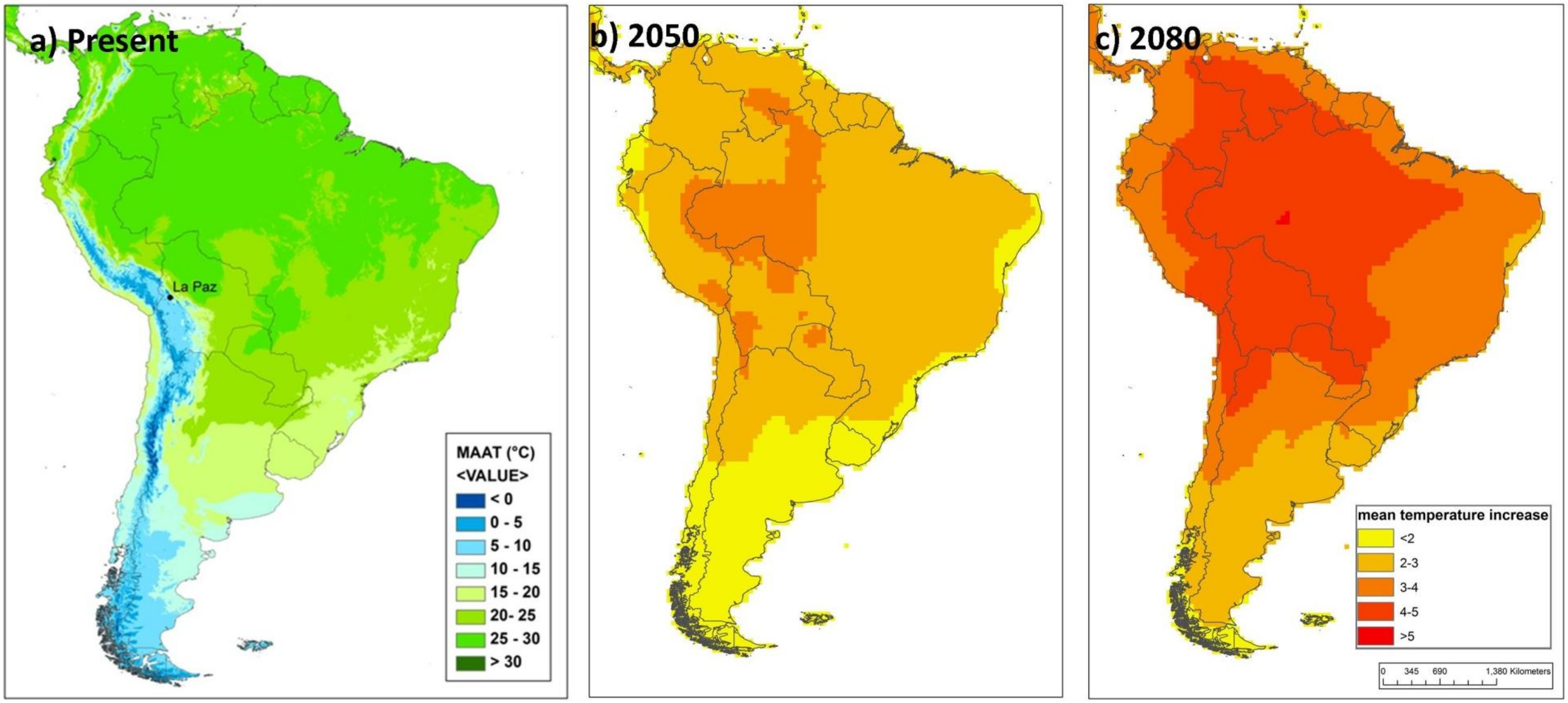

Figure 6: Mean annual air temperatures (MAATs) shown for a) present day (WorldClim data); and projected climate change using ClimGen downscaled outputs of the IPCC A1B scenario for the time periods b) 2050; and c) 2080. Source: Rangecroft et al. (in review)

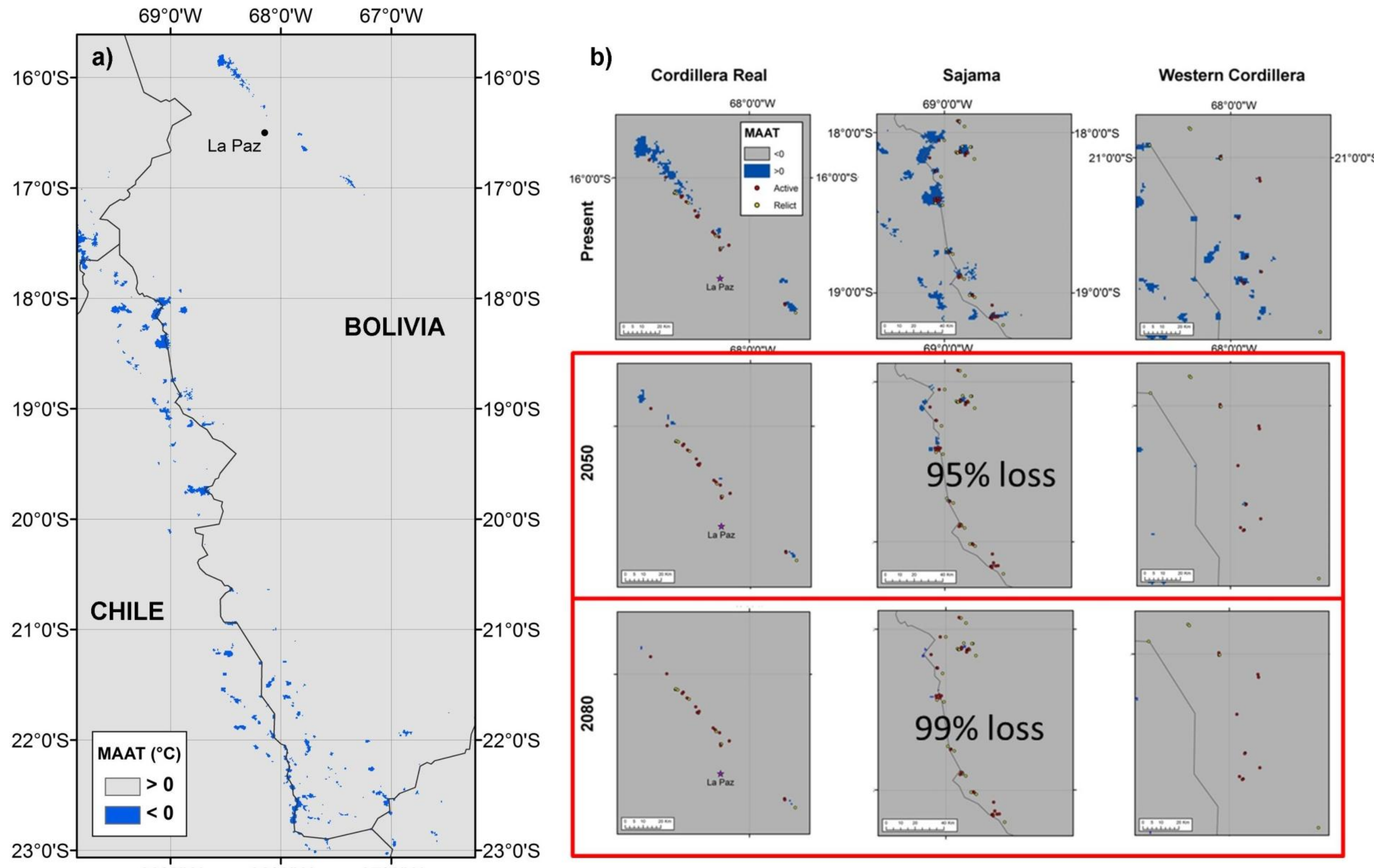

Figure 7: Permafrost extents and their influence on rock glaciers: a) Extent of current Bolivian permafrost; b) Permafrost extents for present day, 2050 and 2080. Source: Rangecroft et al. (in review)

6 SUMMARY AND FINAL REMARKS

Rock glaciers, like ice glaciers, are an essential part of the hydrological regime of basins. Glaciers constitute important water reserves, particularly during dry seasons, and thus contribute to the surface and ground water cycles on which the livelihoods and the development of many highland communities depend. Glaciers may form the source, or one of the sources, of many rivers and preserving them is essential for healthy freshwater ecosystems and downstream water security.

Climate change is having impacts on glaciers worldwide and rock glaciers are not immune. The vulnerability and sensitivity of glaciers in the Bolivian Andes mean that they can be seen as a warning ecosystem for mountain regions worldwide.

Climate change is not a country-specific problem; it is a global issue and thus requires global solutions (Longden et al., 2012). At the same time as measures must be taken globally to radically reduce emissions of carbon dioxide and other greenhouse gases, action must also take place at the national level in vulnerable countries such as Bolivia. Climate change will bring changes to water regimes and in many cases, reduced water security for communities; therefore adaptation measures must be developed and implemented.

Rock glaciers show a relatively slow response to climate changes, being protected under rock formations. In some circumstances they can therefore play an important role in long-term water storage and they should be factored into water management and climate change adaptation strategies to a greater extent than hitherto.

At a policy level, the existence of an inventory of rock glaciers in Bolivia, which this research has created, will allow decision makers to prioritize the preservation of areas where rock glaciers are located. Understanding the amount of currently available water in rock glaciers is also important for improved water resource management and the implementation of policies to protect these resources.

In the Bolivian context it should also be noted that a further threat to rock glaciers comes from mining (Campanini, 2014). Rock glaciers, more than ice glaciers, are sensitive to damage from mining since they are mostly located in the lowest parts of mountain ranges. Using this inventory, locations of rock glaciers should be taken into account in assessments of where mining might take place. This form of protection of rock glaciers from mining activities has been seen to be successful in Chile and Argentina. In Argentina specific legislation has been passed for the protection of glaciers and their surroundings (Argentinian law, Ley 26.639, 2010). Similar legislation should be encouraged in Bolivia to guarantee the protection of glaciers, along with the conservation and restoration of wetlands and other ecosystems crucial to water storage and supply and ultimately, to the achievement of the human right to water.

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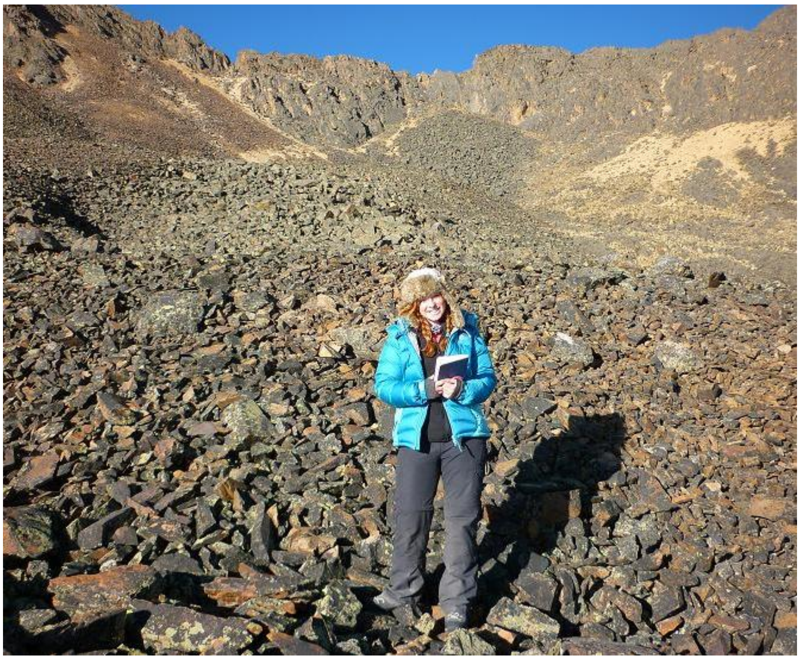

Dr Sally Rangecroft studied rock glaciers, water security and climate change in the Bolivian Andes for her PhD at the University of Exeter. She is pictured standing on a rock glacier near Chacaltaya in the Cordillera Real close to La Paz, where ice glaciers provide an important water supply. However, the region has been experiencing rapid ice glacier retreat, with projections showing a continuation of this as temperatures rise.

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Agua Sustentable holds the rock glacier inventory, see www.aguasustentable.org For more information on the issues raised in this report, contact Agua Sustentable.

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