ROCK GLACIERS, WATER SECURITY AND CLIMATE CHANGE IN THE BOLIVIAN ANDES

Submitted by
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to the University of Exeter as a thesis for the degree of
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Under the supervision of

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and

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I certify that all material in this thesis which is not my own work has been identified and no material has previously been submitted and approved for the award of a degree by this or any other University.

(Signature)…………………………………………………………………..

Abstract

Water security in the Bolivian Andes is projected to decrease with population growth and climate change. As one of the poorest countries in the region, Bolivia is particularly vulnerable to such changes due to its limited capacity to adapt. Key gaps exist in our knowledge of the Andean cryosphere, including a lack of information on alternative mountain water sources, such as ‘rock glaciers’. The presence and hydrological importance of these cryospheric features is unknown for the Bolivian Andes. Yet, with current and projected [ice] glacier recession forecasted to negatively impact water availabilty, it is important to gather data and understanding on these cryospheric landforms.

Consequently, this PhD has created the first rock glacier inventory for the Bolivian Andes, estimated rock glacier water stores, assessed their hydrological importance in comparison to glaciers and modelled the implications of projected rising temperatures on rock glacier activity and permafrost extent. This information has contributed to scientific knowledge about the Bolivian cryosphere and, more specifically, has increased knowledge of the frozen store of water in rock glaciers in the arid mountains of Bolivia where future water security issues are expected in response to climatic change. The rock glacier inventory for the Bolivian Andes was built through expert photomorphic mapping of freely available, high resolution satellite data (Google Earth), supported by a programme of field work during July - August 2011 and July - August 2012. A total of 94 rock glaciers were found to exist in the Bolivian Andes between 15° and 22° S, of which 54 were classified as active, estimated to contain between 0.05 and 0.14 km^3 of water. At the national scale, research demonstrated that Bolivian rock glaciers were not as relatively important as hydrological stores when compared to estimations of glacier water equivalences. At the regional scale, three study regions were identified and analysed: Cordillera Real, Sajama and Western Cordillera. Along the Western Cordillera where glaciers are absent, the hydrological stores of the rock glaciers could be considered important. With current and projected glacier recession, it can be assumed that the relative importance of rock glaciers will increase in the Cordillera Real and Sajama.

Climate modelling of the the 0 °C isotherm as a proxy for permafrost extent also highlighted this projected decrease. The projected impact of this warming on

permafrost extent is modelled to be a loss of up to 95% by 2050 and 99% by 2080 from present day extent. These results were disseminated back to residents of La Paz through a conference held in the third field season (2014). This research is valued as important as continued climate change and population growth are projected to reduce water security in arid regions of the South American Andes. Due to its elevation and high levels of poverty Bolivia is vulnerable to climate change with limited ability to adapt. Specifically for the city of La Paz, its heavy dependence on the glaciers of mountains for potable water supply leaves it particularly vulnerable, especially during the dry season.

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Declaration of Authorship

I, Sally Rangecroft, declare that the thesis entitled:

'Rock glaciers, water security and climate change in the Bolivian Andes'

and the work presented in it are my own. I confirm that:

1. The work was undertaken while in candidature for a research degree at this University
2. No part of this thesis has previously been submitted for a degree or any other qualification at this university or any other institution;
3. Where I have consulted the work of others the source is always given;
4. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all sources of help and contribution;
6. Some parts of this work have been published as:

Rangecroft, S., Harrison, S., Anderson, K., Magrath, J., Castel, A. P., Pacheco, P. 2013. Climate change and water resources in arid mountains: an example from the Bolivian Andes. *AMBIO*. 42: 852 – 863.

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Table of abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ELA	Equilibrum Line Altitude
ENSO	El Niño Southern Oscillation
GCM	Global Climate Model
GIS	Geographical Informations System
GPR	Ground Penetrating Radar
HEP	Hydro Electric Power
MAAT	Mean Annual Air Temperature
MAF	Mean Altitude at rock glacier Front
NGO	Non Governmental Organisation
RS	Remote Sensing
SEV	Verical Electrical Sounding

Chapter 1 : Introduction

The research contained in this PhD is focused on improving academic understanding of the Bolivian cryosphere, and is specifically concerned with improving understanding of the water resource implications of future climate change in rock glaciers in the Bolivian Andes. Bolivia is a country that is experiencing rapid population, economic and environmental change. It is at the nexus of current and future issues regarding climate change, cryospheric water storage decline, water security and population change. As a result, Bolivia provides a unique system in which to study and build understanding of relationships between environmental change and societal resilience. This study is focused on Bolivia due to its sensitivity and vulnerability to climate change, partly due to its elevation and high levels of poverty (Winters, 2012). Currently, the lack of observation and monitoring of climate systems, water supplies, and critical gaps in knowledge of the Andean mountain cryosphere are prohibiting better water resource management (IPCC, 2007b; Azócar and Brenning, 2010).

This PhD uses remotely sensed data coupled with a field validation and data collection programme in the Bolivian Andes to create the first rock glacier inventory for the Bolivian Andes and estimates the water content and hydrological importance of these features. Establishing the scientific knowledge to address the lack of data regarding rock glaciers in Bolivia allows for the implications for potential future climate warming to be investigated and discussed in the context of water security in the region. Therefore this PhD is interdisciplinary, working between the physical and social sciences. The problems that this PhD addresses are a complex combination of the the socio-economic situation and the lack of data existing for the Bolivian Andes, complicated by the geographical location.

1.1 Research Content

It is expected that continued climate change will reduce water security in arid regions of the South American Andes (Barnett et al., 2005; Bradley et al., 2006; IPCC, 2007a; Painter, 2007; Vuille et al., 2008; Chevallier et al., 2011; IPCC, 2014).

Changes to water supply are predicted in response to changes in temperature, precipitation patterns, and glacier recession (Vuille et al., 2003; Vergara et al., 2007a; IPCC, 2014), negatively affecting water availability (Magrin et al., 2007; IPCC, 2014). Future temperature increases in the tropical Andes are projected to be of a similar magnitude to those in the Arctic, with the Intergovernmental Panel on Climate Change (IPCC) predicting a maximum warming of 6.7 °C by 2100 across South America (Magrin et al., 2014). In the Andes, the consequences of this warming will directly affect a greater population (Vergara, 2009), where the existing estimated population is thirty times the size of that in the Arctic (Bogoyavlensky and Siggner, 2004; Galarza and Gómez, 2011). In conjunction with predicted decreasing water supplies, increases in water demand are anticipated as a result of projected population growth and the westernisation of lifestyles in Latin America (Bradley et al., 2006; Painter, 2007; Jeschke, 2009; Vanham and Rauch, 2010; WMO, 2011). These changes to water supplies and increasing societal demands for potable water will have critical negative impacts on water security, affecting environmental, economic and social systems (Bradley et al., 2006; Bigas et al., 2012).

1.1.1 Geographic location

Mountain regions are likely to experience the impacts of a changing environment more severely than lower lying regions (Bradley et al., 2006). This is illustrated in Figure 1.1; the rate of warming in the lower troposphere is expected to increase with altitude, impacting high mountains severely (Bradley et al., 2006). The strong altitudinal gradients that are characteristic of mountain environments 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 in which to study the effects of hydrological, cryospheric and ecological changes associated with climate change (Rangecroft et al., 2013).

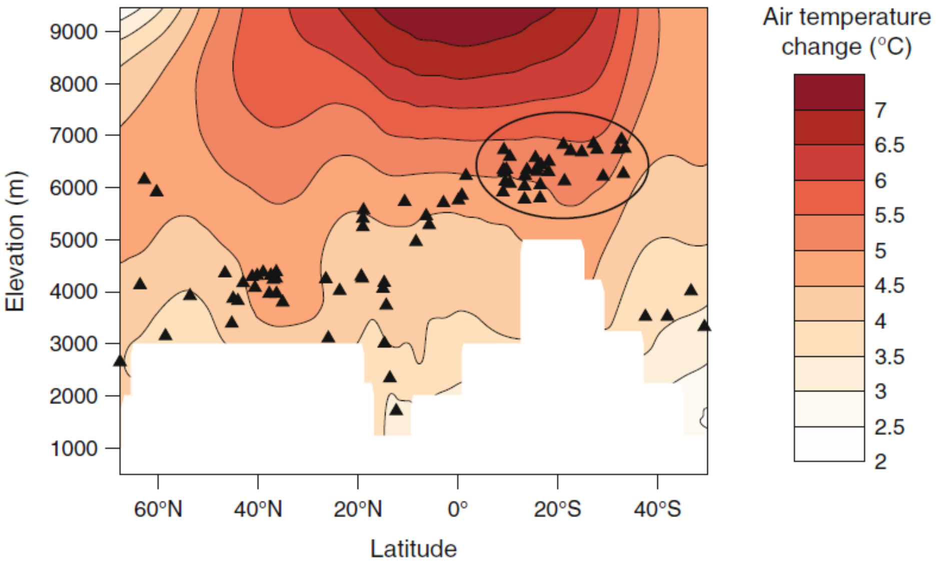

Figure 1.1 Visual representation of predicted global warming (adapted from Bradley et al. 2006, p. 1755). Projected changes in mean annual free-air temperatures between (1990 to 1999) and (2090 to 2099) along transect from Alaska (68°N) to southern Chile (50°S) using the mean of eight different Global 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. Used in Rangecroft et al. (2013, p.853).

1.1.2 Poverty

Bolivia has some of the highest levels of poverty and social inequality in Latin America and is particularly vulnerable to the impacts of climate change with limited capacity to adapt (Winters, 2012). Poverty affects the quality of life for the majority of the population, many of whom are without access to sufficient opportunities to improve it. Overall, it is estimated that 60% of Bolivian inhabitants live in poverty (defined as 'below the national poverty line') (Winters, 2012). One third of the population live in rural areas with 80% of this rural population living in rural poverty, equating to a quarter of the total Bolivian population living in rural poverty (Winters, 2012). Of the poor rural population, 31% live on the Altiplano where the most intense poverty is found (Winters, 2012). Equally, it is estimated that 50% of the urban population live in urban poverty, resulting in a third of the country's population in urban poverty (Winters, 2012). Climate change affects the poor in different ways in rural areas and cities: rural poverty is acknowledged to have more significant challenges and problems compared to urban poverty (Winters, 2012). It is estimated that only 56% of Bolivia's rural population have access to safe drinking water

(Jeschke et al., 2012). As well as poverty, the Andean cities and mountain communities are also vulnerable to the impacts of climate change because of their elevation with greater exposure to more pronounced climate change than surrounding lowlands (see Figure 1.1). The threats posed by climate change to mountain regions directly threaten livelihoods (Akin, 2012).

1.1.3 Water availability

La Paz relies upon rainfall and glacier meltwater from nearby Andean mountains in the Cordillera Real as its two main sources of water for drinking, agriculture and energy generation (Jordan, 1998; Vuille et al., 2008; Chevallier et al., 2011). Glaciers are especially important during the dry season (May – October) (Bradley et al., 2006; Vanham and Rauch, 2010). It is estimated that the glaciers of the Cordillera Real supply between 12-40 % of potable water for the city (Vergara, 2009; Soruco, 2012), however with current and predicted glacier recession, this contribution to water supplies is expected to reduce significantly (UNFCCC, 2007). Published work has shown that Bolivian glaciers have lost nearly half of their ice mass over the past 50 years (Rabtel et al., 2013). Although melting glaciers will result in enhanced runoff in the short term, in the long term these changes will lead to local and regional water supply issues (Beniston, 2003) as contribution of these hydrological buffers will disappear with glacier recession.

Outside the city there are numerous mountain communities who depend upon the meltwater and groundwater from the Andes. Inhabitants of these communities tend to be more dependent on the land for their subsistence and livelihood than urbanised communities, making them especially vulnerable to changes to their land and the climate (Akin, 2012). Changes are likely to affect agriculture and water availability, which will in turn have a negative effect on indigenous communities (Akin, 2012), through reduced food and water security.

Reduced water availability will adversely affect economic development, and increase social, political, and ecological instability. 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). Most Andean governments are poorly equipped and have limited resources, socially, technologically and financially (UNFCCC, 2007; WaterAid, 2007), to deal with serious water challenges (Hays, 2011); especially as adaption measures can be costly. Managing water resources in a dynamic society is challenging, and climate change will certainly add to this complexity (Buytaert and De Bièvre, 2012). This is a particular concern in an Andean city like La Paz where geographical barriers and elevation gradients restrict economically feasible water supply areas (Buytaert and De Bièvre, 2012).

1.1.4 Rock glaciers in the Bolivian Andes

The role of ‘rock glaciers’ (debris covered periglacial features with ice cores (Harrison et al., 2008; Berthling, 2011)) in Bolivia is significantly understudied with a lack of data on Bolivian rock glaciers inhibiting the assessment of their existence and importance. The importance of glaciers and their role in regulating hydrological processes in mountainous regions worldwide has been widely studied and is generally well-understood (e.g. Ramirez et al., 2001; Brenning, 2005a; Bradley et al., 2006; Vuille et al., 2008; Bolch et al., 2010; Chevallier et al., 2011). In contrast, the contribution of rock glaciers to mountain water supplies is ambiguous and relatively understudied. Furthermore, research and data on the existence and role of rock glaciers in Bolivia is extremely limited. Just one rock glacier, Caquella, (21.5° S) has been studied in detail by Francou et al. (1999) and Bodin et al. (2010a). The studies showed the rock glacier degrading and retreating.

Although rock glaciers have been shown to be abundant and very well developed forms of locally significant long term water storage in the South American Andes where glaciers are absent or limited (Trombotto et al., 1999; Brenning, 2005a), critical gaps in present knowledge of the Andean mountain cryosphere remain (Seligman, 2009; Azócar and Brenning, 2010). This is particularly true with regard to rock glacier research in Bolivia. Data on rock glacier abundance, location, size, basic characteristics and their possible contribution to hydrological resources, prior to this research, were unknown. With projected increases in water stress in arid mountains, a re-evaluation of water resources and their management is needed. A new focus on the other elements of the mountain cryosphere and their inputs into the hydrological cycle is required. While this has been partly achieved in other parts of the Andes (e.g. Chile, Brenning, 2005a; Argentina, Falaschi et al., 2014), little is known from the Bolivian Andes.

Rock glaciers are mesoscale landforms of rock debris and ice (Brenning, 2005a), which act as important water reservoirs, and critical semi-permanent resources of ice in arid environments (Monnier et al., 2011; Toomey, 2011). It is estimated that active rock glaciers typically contain between 40 – 60% ice (Brenning, 2005a) (see section 2.4.6). Areas of the Chilean Andes between 27° – 33° S host some of the highest rock glacier densities worldwide and contain some of the largest known rock glaciers (Brenning and Azócar, 2008). Although rock glaciers are individually much smaller than most glaciers, overall they can contain a considerable amount of water due to their high abundance, especially where glaciers are limited. Brenning (2005a) argued that the importance of rock glaciers as stores of water in the Dry Andes of Chile was one order of magnitude greater than in temperate and more humid mountain areas such as the Swiss Alps. He reported a ratio of rock glacier to glacier water equivalence of 3:1 for the Chilean Andes (29° – 33° S) compared to a calculated ratio of 1:83 for the Swiss Alps (Azócar and Brenning, 2010). This work was the first to show the local importance of rock glaciers as water resources (Brenning, 2005a), yet this assessment is also needed for the Bolivian Andes.

1.2 The study region

1.2.1 The Bolivian Andes

The Bolivian Andes are situated centrally within the 7,000 km stretch of the South American Andes. The Andes can be split into three different topoclimatic zones: The Northern Andes comprise Venezuela and Columbia and are typically wet and warm. The Central Andes includes Ecuador, Peru, and Bolivia and are dry. The Southern Andes of Chile and Argentina are wet and cool. Given these climatic differences, another classification of the Andes is by climate, resulting in three slightly different geographically distributed regions: Tropical (11° N - 20° S), Dry (20° - 35° S) and Wet (35° - 55° S) Andes, illustrated in Figure 1.2. This research is based in the Bolivian Andes which are centrally located, extending into the ‘Dry Andes’.

The Bolivian Andes (14° – 22° S) are divided into 2 major mountain ranges: Cordillera Oriental [east] and Cordillera Occidental [west] (Fig. 1.2). Between the two Bolivian Cordilleras lies the high and arid plateau known as the 'Altiplano' at ~4000 m a.s.l (Fig. 1.2). This PhD studies rock glaciers across both of the Cordilleras with fieldwork located along both mountain ranges. Here, the two Cordilleras are described with reference to their location, climate, and topography. It is important to understand the similarities and differences within the Bolivian Andes to understand any differences between rock glaciers identified and the relative importance of these water stores.

The Cordillera Oriental contains two main glaciated massifs: Cordillera Apolobamba (which extends into Peru) and Cordillera Real (Fig. 1.2). The Cordillera Real (15° - 17° S) is the northern, highly uplifted and eroded part of the Bolivian Cordillera Oriental closest to La Paz (Fig. 1.3), where the main geology of this region is granite. Due to its proximity to the Amazon lowlands and associated moist air masses, the Cordillera Real is a relatively densely glaciated part of the Bolivian Andes (relative compared to the Cordillera Occidental) (Fig. 1.3a), especially considering its latitude. These glaciers are important sources of water to the La Paz and El Alto basins, the city inhabitants and the local mountain communities.

The Cordillera Occidental runs along the western side of Bolivia, bordering Chile (Fig. 1.2). It hosts several active volcanoes (e.g. Volcán Ollagüe, 21°18'08"S, 68°10'45"W) and geothermal hotspots (e.g. Sol de Mañana, 22°26'6"S, 67°45'28"W). The topography of the Cordillera Occidental is comprised of old large stratovolcanoes, with isolated mountains of volcanic origin; sometimes with a characteristic snow cap (Fig. 1.3b). The main glaciated region of the Bolivian Cordillera Occident is in 'Sajama' (18 °S) (Fig. 1.3b). Further south along the Cordillera Occidental, glaciers are absent in the 'Western Cordillera' region (18° - 22° S) (Fig. 1.3). It is the aridity of the Cordillera Occidental that is thought to limit and restrict glacier existence (Jordan, 1998). The Cordillera Oriental (Cordillera Real and the Bolivian part of the Cordillera Apolobamba) is estimated to host 98% of Bolivia's glaciers (Jordan, 1998).

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 Cordillera Real receives more precipitation (because of its close proximity to the Amazon lowlands and associated moist air masses) than along the Cordillera Occidental, which receives less than 200 mm annually (Fig. 1.2). As a result of this limited precipitation along the Cordillera Occidental, the environment is hostile and barren. The implications of distinct wet/dry seasons means hydrological buffers are of great importance for maintaining water supplies throughout the year, especially during the dry season.

Figure 1.2 Map showing the study area
Study area (left) situated within Bolivia (top) and South America (bottom). The map showing the annual precipitation (left) is taken from Jeschke (2009, p.21).

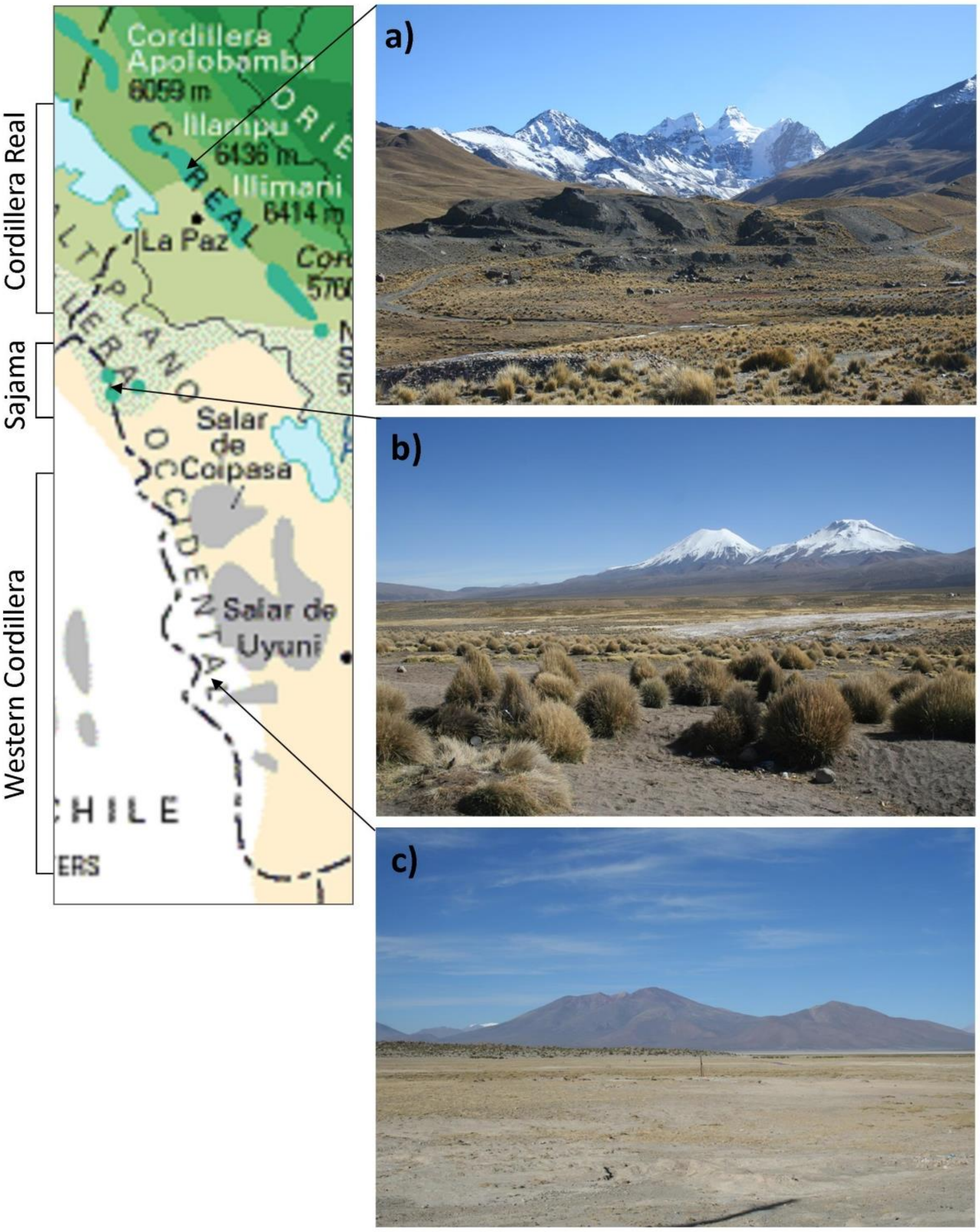

Figure 1.3 Example landscapes along the Bolivian Andes
a) Cordillera Real, Tuni Condoriri (16°11’ S, 68°14’ W); b) Western Cordillera, Sajama region (18°09’ S, 69°05’ W); c) Western Cordillera, Chiguana (21°05’ S, 67°49’ W). Map taken from Jeschke (2009, p.21), photos by S. Rangecroft, 2012.

1.2.2 La Paz

Built on the steep hills of a canyon incised into the edge of the Altiplano (Fig. 1.4; Fig. 1.5), the Bolivian administrative capital city of La Paz is situated at an elevation range of 3,200 m to 4,000 m a.s.l. (16°30'S, 68°09'W). At the highest extents of La Paz, it merges with its poorer sister city, El Alto (16°31'S, 68°10'W) (Fig. 1.4). Usually the term 'La Paz' is used to represent both cities as they are so closely interlinked. The population of both cities combined is estimated to be greater than 2.3 million people (Vergara, 2009; WMO, 2011). The glaciated mountain of Illimani (6,438m; 16°38'00"S, 67°47'27"W) provides a backdrop to La Paz (Fig. 1.5a) and visibly illustrates the current glacier recession (Chapter 2, section 2.2) to residents of the cities (Orlove, 2008).

Generally, income decreases with altitude for the residences of the city: rich middle- and upper-class suburbs have developed over the past 30 years in the south of La Paz (Arbona and Kohl, 2004), Zona Sur, where the terrain is flatter and the climate is warmer. The hillsides of the La Paz basin have been prone to landslides and slips in previous years due to poor/lack of infrastructure and excessive rainfall during the wet season. In February 2011 a landslide removed four neighbourhoods from South La Paz following heavy rainfall (LAB, 2012), scarring the landscape and leaving hundreds of people living in emergency camps across the city. In contrast to the steep slopes of La Paz (Fig. 1.5b) which physically limits expansion, El Alto which is situated on the edge of the expansive Altiplano, offers the best location available to absorb poorer immigrants (Arbona and Kohl, 2004). El Alto is characterised by congested dirt roads, unpaved sidewalks and buildings in varying stages of completion (Arbona and Kohl, 2004). It is estimated that 50% of the houses in El Alto are not connected to the water and sewage system due to the cost (Shahriari, 2012).

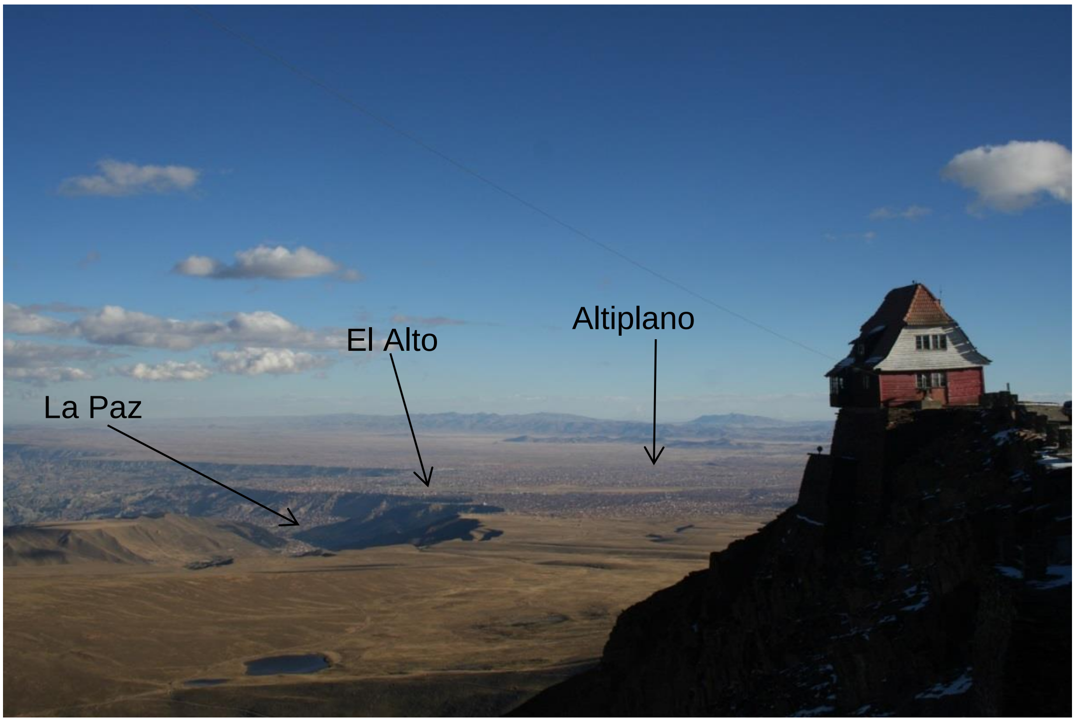

Figure 1.4 Chacaltaya mountain hut, Bolivian Altiplano
Chacaltaya mountain hut, former ski resort, with a view of the altiplano (~4,000 m a.s.l.). The edge of the altiplano where El Alto is rapidly expanding, leads to the steep sided canyon of La Paz. Photo: S Rangecroft, June 2011.

Figure 1.5 The city of La Paz, Bolivia
La Paz, Bolivia (16°S, 68°W) showing demonstrate its physical surroundings, densely populated housing and close proximity to the mountains and glaciers of the Andes: a) Illimani in the background of La Paz; b) Densely populated housing in upper La Paz sprawling onto the 4000m Altiplano plateau of El Alto. Photo credit: S Rangecroft, July 2012.

1.3 Introduction to NGO partners

This PhD is funded by NERC with the active partners of Oxfam and Agua Sustentable who have provided funds and field support throughout the PhD and the field work. One of the aims of the research and the rationale for involving these non-governmental organisations (NGOs) was to help enhance the knowledge of mountain hydrological stores and supplies in this under-studied region of the Andes. Research undertaken for the PhD will be essential for understanding the current situation, assessing the impacts of climate change, helping towards adaptation, and improving future water management in Bolivia. The following sections describe the two partner NGOs.

1.3.1 Oxfam

Oxfam is an international charity with its main focus on tackling poverty. Oxfam seeks to tackle the causes of poverty such as food, water, health, education, women's rights, conflicts, disasters, and climate change. Oxfam aims to reduce the impact of global warming, and to help poorer populations adapt to a changing climate who are experiencing the full impacts of climate change despite being the smaller contributors. Oxfam are working with local communities, and local partners, to provide long-term, cost effective solutions to water issues. Oxfam has been operating in Bolivia since 1988 working with NGOs such as Agua Sustentable and Christian Aid. In Bolivia, Oxfam's main focus is on: reducing vulnerability to disasters and adaptive solutions to climate change; strengthening the capacity of people; programs for sustainable livelihoods; training and empowering women, indigenous people and youth, especially in popular urban neighbourhoods. For more information about Oxfam Bolivia please visit: http://www.oxfam.org/en/bolivia

Oxfam GB provided support in the initial setting up of the project and the project aims and monitoring of the project throughout. Oxfam Bolivia provided important support at the start of the first field season through a tour of the landslide site and emergency camps (July 2011) for myself and Dr. Stephan Harrison.

1.3.2 Agua Sustentable

Agua Sustentable is a Bolivian NGO with the motto “Water for Life”. Their aim is to contribute to reducing climate change impacts in Bolivia through adaptation and research. Their main research areas are: water and food security; water environment; legislation and policy; and water, climate change and risk management. They work directly with local mountain communities who are experiencing the impacts of climate change and changes in water supplies, including communities in the Illimani region such as Khapi and Pinaya (16°38’S, 67°51’W). Agua Sustentable look at how to improve domestic water supply for irrigation through increased water capture and storage, efficient irrigation systems and water sharing between communities. They also aim to generate information and knowledge on vulnerability and exposure to climate variability and develop strategies and plans for adaptation. For more information about Agua Sustentable please visit: http://www.aguasustentable.org/

Agua Sustentable provided significant practical support during all three the field seasons through provision of office space, transport to the field, field assistants, contacts in the field and guidance around La Paz.

1.4 Aims of the PhD

The overarching aim of this PhD was to extend scientific knowledge and understanding on the Andean cryosphere and, more specifically, to increase knowledge of the frozen water store in rock glaciers in the arid mountains of Bolivia. Before this research was undertaken, information on the nature of Bolivian rock glaciers was sparse. Thus, a major underpinning aim of the PhD was to produce the first rock glacier inventory for the Bolivian Andes. Currently no information exists regarding the number of rock glaciers in the Bolivian Andes. Consequently, this research aims to address this lack of knowledge through the completion of a rock glacier inventory, identifying rock glacier locations along the Bolivian Andes and gathering data on their frequency, location and hydrological importance using a range of methods.

Through a process of identification and analysis by remote sensing methods, an understanding of the importance of rock glaciers as a water source for Bolivia will be established separately from the retreating glaciers. With this new data of rock glacier locations and size, in combination with current and future climate data, the relationship between rock glaciers and the present 0 °C isotherm was analysed. The implication of future warming on permafrost extent and active rock glaciers in the Bolivian Andes was also explored. The focus throughout the thesis remains on the sister cities of La Paz and El Alto because both have growing water stresses, growing populations and are predicted to be the world's first major urban casualty of climate change (Rosenthal, 2009).

Additionally, the secondary aim of this PhD was to achieve knowledge transfer between scientific work and Bolivian communities. NGOs like Agua Sustentable and Oxfam can utilise the data collected to help improve knowledge in the fields of climate change and potential impacts, advice local policy makers, and improve scientific communication to end-users of such research. This PhD plays an important role in increasing scientific knowledge whilst linking it directly to the socio-cultural nature of the context and future water stresses.

1.5 Research questions

For this PhD, a set of research questions were formed. These questions have been addressed through this PhD and are presented in the following chapters:

1.5.1 How many rock glaciers are there in the Bolivian Andes? [Chapter 3]

- How many are classified as active?
- What are their main characteristics (elevation, aspect, length, width)?
- Do their characteristics differ regionally?
- Can rock glaciers be mapped through freely available satellite data?

These data are needed for fundamental steps towards assessing the spatial distribution and surface coverage of these periglacial features, necessary for improved water resource management. Looking at the similarities and differences of rock glaciers across the Bolivian Andes will contribute towards the gap in knowledge surrounding these features in Bolivia. Understanding the current distribution, climate and setting of rock glaciers is also a crucial step to predicting the implications of climate change on rock glaciers and water resources in this region.

1.5.2 What is the water equivalence of these rock glaciers and the relative importance to regional water supply? [Chapter 4]

The hydrological importance of rock glaciers in the Bolivian Andes has not been previously assessed. Assessing the frequency, activity and size of rock glaciers will allow for an estimation of the amount of ice contained, and thus determine their importance as water sources in the Bolivian Andes. This hydrological assessment can be conducted in comparison with estimated glacier water stores.

Based on research in other areas of the arid Andes (e.g. Chilean Andes, Brenning, 2005a) rock glaciers are expected to be an important water source in the arid Andes of Bolivia where the presence of glaciers is limited. Understanding the input of rock glaciers into the mountain hydrological system will be important for current and future water resource information and, therefore, management.

1.5.3 What are the implications of projected future warming on the Bolivian cryosphere? [Chapter 5]

This PhD also aims to evaluate the impact of increasing temperatures on active rock glaciers and permafrost extent in the Bolivian Andes. Such prognoses are necessary for the Southern Hemisphere as current literature and research solely focuses on the Northern Hemisphere (e.g. IPCC, 2014). The lowest limit of active rock glaciers is known to represent the lower limit of permafrost (Haeberli, 1985; Giardino et al., 1987; Barsch, 1996). Therefore the rock glacier inventory and climate data can be used to assess the impact of projected climate warming, assessments which are needed for future planning.

1.5.4 Can rock glaciers be objectively, automatically or semi-automatically identified from satellite data? [Chapter 6]

Rock glacier satellite data characteristics and automated mapping potential are still yet to be fully researched. The lack of spectral difference between rock glaciers and the surrounding rock currently limit automated mapping of rock glaciers (Brenning, 2009; Shukla et al., 2010). However, the most visible features of rock glaciers are the surface ridges and furrows created through movement (Burger et al., 1999) and the potential exists for texture/spatial analysis to be used to identify this surface morphology. The research will test whether these textural signatures can be used to objectively, automatically or semi-automatically identify rock glaciers, to potentially improve the method used to identify rock glaciers.

1.5.5 What is the baseline understanding of rock glaciers, climate change, glacier recession and water security in La Paz amongst the local population and stakeholders? [Chapter 7]

Using the opportunity of a conference on the final field season in La Paz (27/05/2014), questionnaire data will be collected to gather a baseline understanding of the five topics covered in this PhD thesis: rock glaciers, climate change, glacier recession, water resources, and water security. The feedback gained after the oral presentation at a conference can be used to assess the impact and importance of this research. This will help to assess the importance and need for this research as well as being an important part of communicating science. Using the questionnaire and data gathered from meetings and interactions with the Bolivian NGO's and academics, ideas and solutions can be presented for addressing projected reduced water security for La Paz and the Andean communities.

Chapter 2 : Literature review

This review will critically evaluate, summarise and identify key issues in the main literature surrounding this PhD on climate change, glacier recession, water supplies, rock glaciers and their role in the hydrological system. The literature review on climate change, glacier recession and associated water resources in the Bolivian Andes composes a significant part of an AMBIO review article (Rangecroft et al., 2013; Appendix 1). AMBIO was chosen for this review article because as an interdisciplinary, international journal it has explicit policy and management recommendations and a broad readership. With this research it was important to get this review on current and future research to a wide audience.

2.1 Global climate change

Over recent decades, changes in climate have caused impacts on natural and human systems worldwide (IPCC, 2014). Multiple lines of evidence show these changes in the form of instrumental observations showing a trend of increasing land and sea surface temperatures over the past century (Fig. 2.1a), observations from satellites and the field suggesting reductions in glaciers, ice sheets and Arctic sea ice, changes in sea level, changes in atmospheric water vapour and changes in precipitation (IPCC, 2013). Globally averaged land and ocean surface temperature data shows a warming of 0.85 °C [0.65 – 1.06 °C] over the time period 1880 – 2012 (IPCC, 2013), with further warming expected and changes in precipitation patterns projected worldwide (Fig 2.1b, IPCC, 2013).

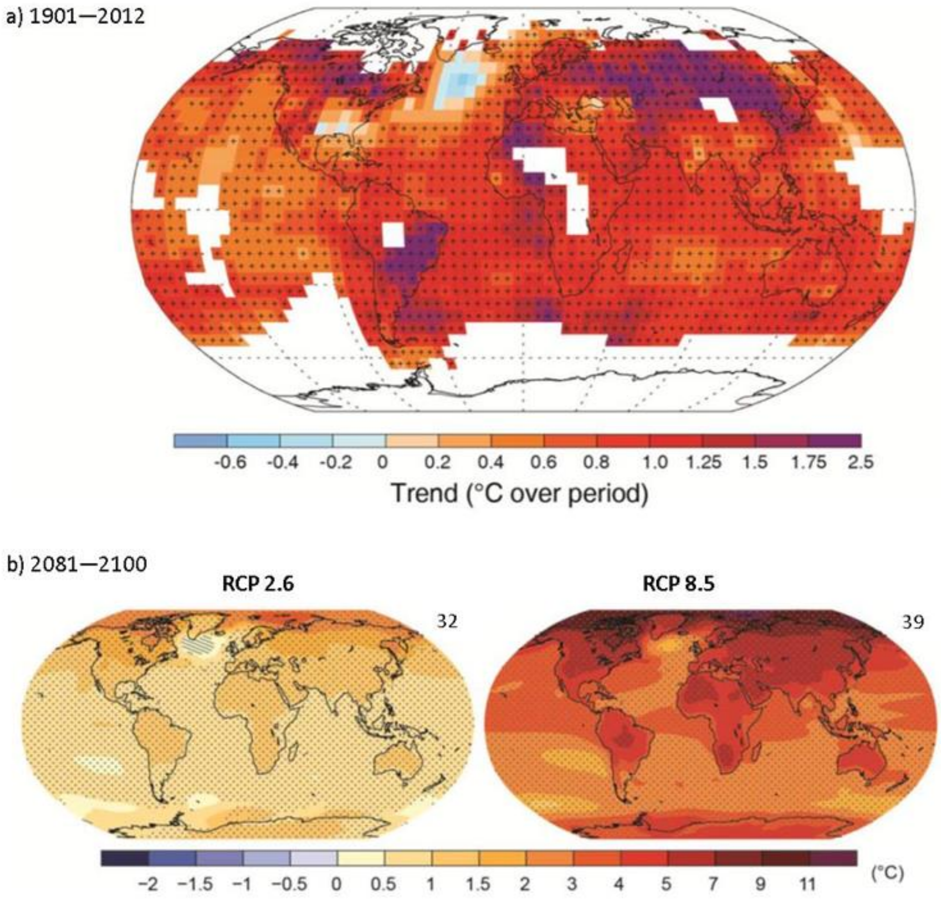

Figure 2.1 Changes in average surface temperature
a) Observed change in average surface temperature 1901 – 2012 (IPCC, 2013, p. 27). Trends have been calculated where data availability permits a robust estimate, other areas are signified by white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. b) Projected change in average surface temperature (1986 – 2004 to 2081 – 2100) using the CMIP5 multi-model mean results for the IPCC scenarios RCP 2.6 (left) and RCP 8.5 (right) relative to 1986-2005 (IPCC, 2013, p.34). The total number of CMIP5 models used to calculate the multi-model mean is indicated in the upper right corner of each visual output.

2.1.1 Trends of climate change in the Andes

Pronounced changes in the climate in the Andes over the past half a century have been measured (Vuille et al., 2008; IPCC, 2014). Mountain station records from the tropical Andes (1° N - 23° S) showed that annual average surface temperatures increased by 0.1 °C/decade between 1939 and 1998 (Fig. 2.2a), higher than the global average rate of 0.06 °C/decade (Bradley et al., 2006; Vuille et al., 2008). MAATs increase their acceleration over the latter parts of these timescales (1980 – 2005) to ~0.33 °C/decade (Barry, 2005). Unlike temperature trends, changes in precipitation across South America are less clearly seen. Minor changes in precipitation patterns have been detected across the Andes (Vuille et al., 2003).

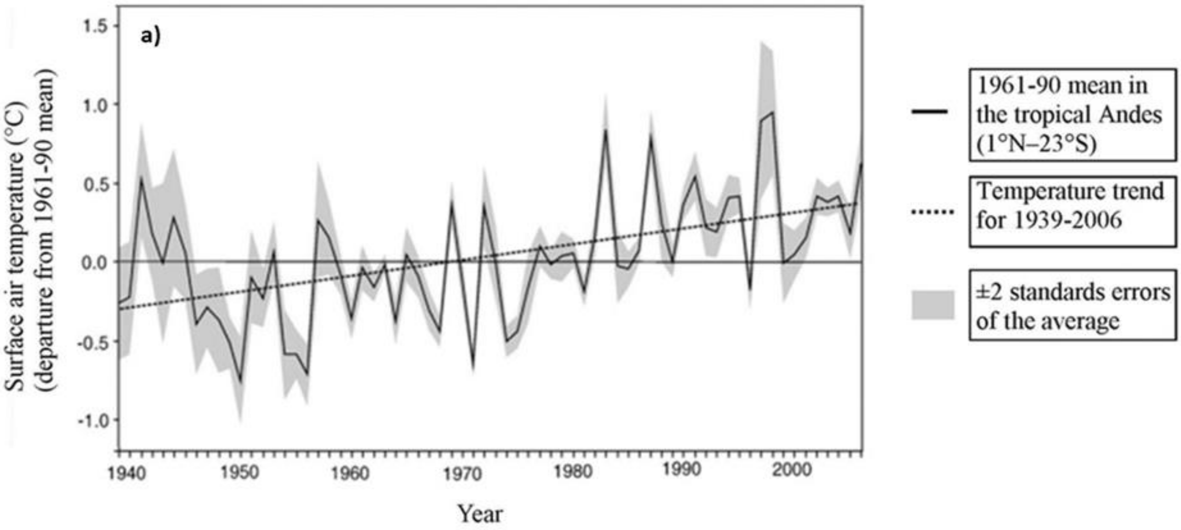

Figure 2.2 Annual temperature in the tropical Andes
Annual temperature deviation from the 1961–90 average in the tropical Andes (1°N–23°S) between 1939 and 2006 based on a compilation of 279 station records (adapted from Vuille et al., 2008, p.84). Black line shows long-term warming trend (0.10 °C/decade) based on ordinary least square regression. Taken from Rangecroft et al. (2013, p.854).

These observed temperature increases, allied to changes in precipitation, consequently led to glacier recession across the whole of the Central Andes (Francou and Vincent, 2007) (see section 2.2). However, there are few instrumental observations of climate available above 4000m where Andean glaciers exist and therefore the impact of recent temperature change on glacier behaviour is relatively poorly documented (Bradley et al., 2006).

Climate projections for South America suggest an increase in temperature and an increase or decrease in precipitation by the end of the century with medium confidence (IPCC, 2014). 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. 1.1). Continued warming is projected across much of Latin America; IPCC SRES 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. 2.3). The most recent IPCC report (2014) shows medium confidence that mean warming for Latin America by 2100 could reach between 1.7 – 6.7 °C (Magrin et al., 2014).

Global climate models (GCMs) disagree on the extent and direction of the changes in precipitation for South America, with model outputs ranging from a reduction of up to 40% to an increase of 10% for 2080 (Magrin et al., 2007) (Fig. 2.3). However, overall a number of them predict considerable drying in the region (Magrin et al., 2007; Viviroli et al., 2011). Precipitation patterns are also complicated by the occurrence of the El Niño Southern Oscillation (ENSO) resulting in years with intensified rainfall or drought. Droughts related to La Niña create severe restrictions for water supply and irrigation demands (Margin et al., 2007). Projected with medium confidence, the frequency and intensity of weather and climate extremes are also likely to increase across South America (IPCC, 2014).

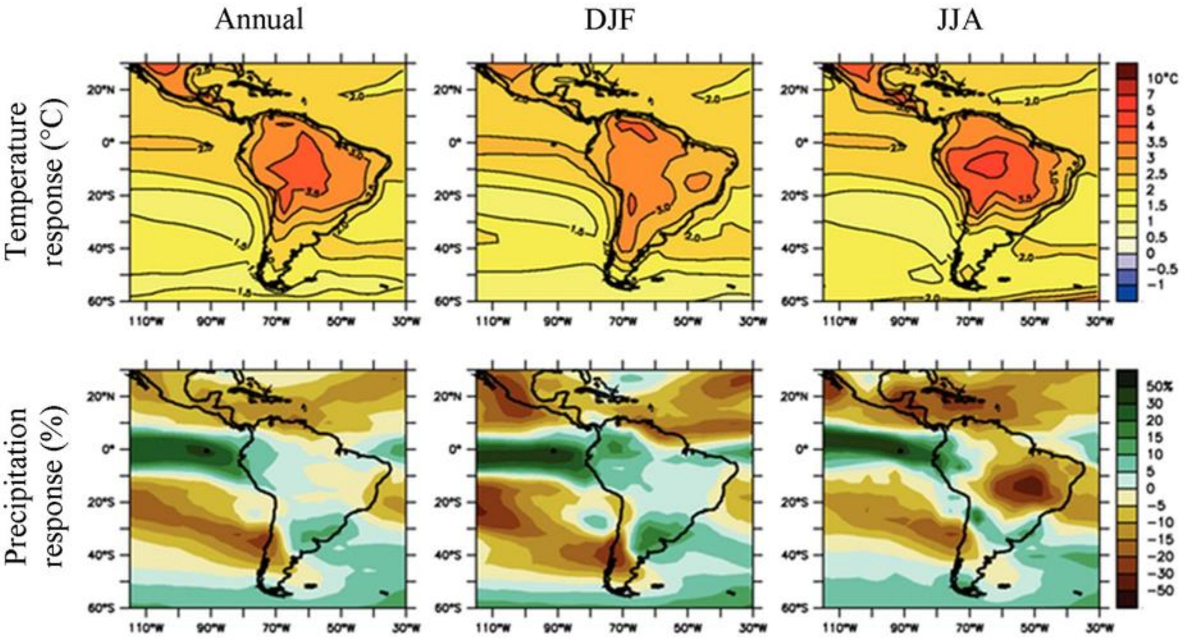

Figure 2.3 Temperature and precipitation changes over South America from the MMD-A1B simulations (IPCC, 2007, p. 895). Top row shows: i) Annual mean; ii) December January February; and iii) June July August temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Bottom row shows the same as top, but for fractional change in precipitation. Taken from Rangecroft et al. (2013, p. 853).

Global and regional model projections of precipitation with relatively 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 great 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 these uncertainties surrounding climate projections and the need for downscaling, current models do agree that the tropical Andes are forecasted to experience changes in precipitation patterns and increases in temperature and these are predicted to have serious consequences for the hydrological cycle in the Andes (Barnett et al., 2005).

2.1.2 Trends of climate change in the Bolivian Andes

Overall, there is a lack of published data describing observed temperature changes in the Bolivian Andes. Climate data for La Paz detail an increasing trend in recorded maximum temperatures showing an increase of ~ 0.7 °C per decade between 1975 and 2009 (Fig. 2.4) (Agua Sustentable, 2011), which is in agreement with trends found by Valdivia *et al.* (2013) for the Altiplano.

A slight drying trend has been observed in Western Bolivia (Vuille et al., 2003) and meteorological data from the Bolivian Altiplano, Valdivia *et al.* (2010) show a decline in the monthly rainfall for the early season months (Oct – Dec) but no significant trends or changes in annual precipitation (Valdivia et al., 2013).

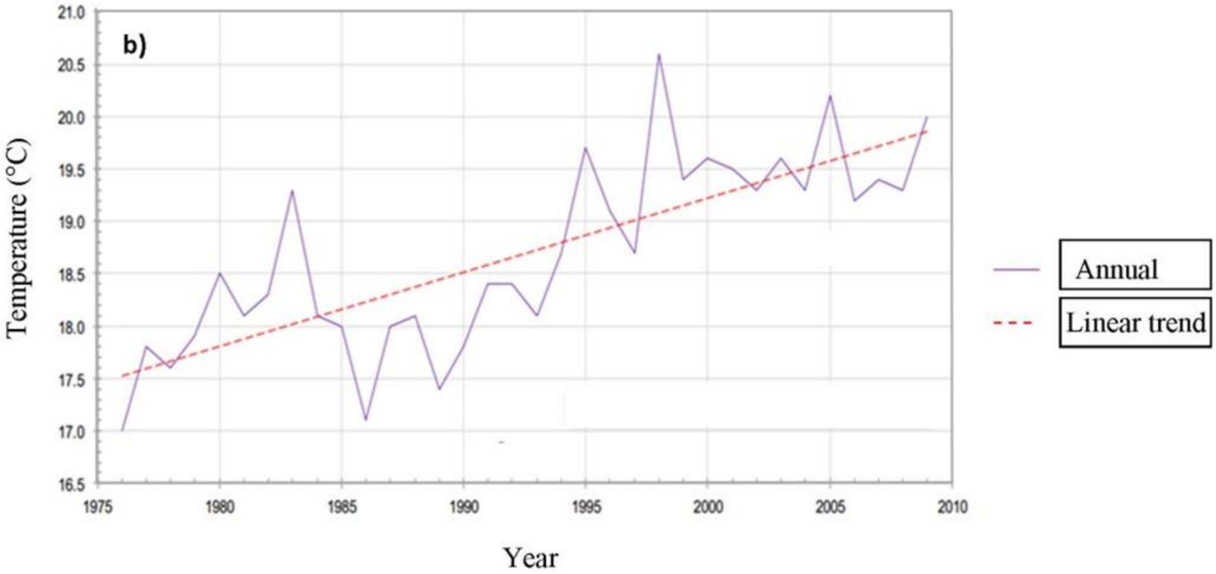

Figure 2.4 Maximum temperature in La Paz city 1975 – 2009 (taken from Agua Sustentable, 2011, p.3).

Analysis of future regional climate projections remains very limited for the Bolivian Andes. Seiler *et al.* (2013) suggest that Bolivia's climate will be warmer and drier than average in the near-term future. Temperature increases for Bolivia are projected to be within the range of 3.5 – 5.9 °C by the end of the 21st century (Mitchell and Hume, 2000). Climate projections for the end of the 21st century for the Altiplano include increases in extreme event frequency, changes in the timing of rainfall and reduction of soil humidity (Valdivia et al., 2013). Although projected changes in precipitation show less agreement, Seth *et al.* (2010) suggest that a shift in the annual cycle of precipitation in the Altiplano is to be expected, to a shorter, more intense rainy season: reduced early season rains (October – December) and increased peak season rains (January – March) (Thibeault et al., 2010). These changes are likely to lead to continued glacier recession and will directly and indirectly affect water availability in Bolivia.

2.2 The cryosphere

Glaciers have been receding worldwide affecting water resources downstream (IPCC, 2014), and continued recession will have negative impacts on water availability in the long term (Barnett et al., 2005). The South American Andes contain 99% of the world's tropical glaciers, with Bolivia hosting 20% of these Andean glaciers (Vuille et al., 2008; Ramirez et al., 2012). As a response to increasing temperatures, glacier recession has been observed across all the regions of the Central Andes (Francou and Vincent, 2007), leading to the disappearance of some of the smallest and lowest altitude glaciers (Chevallier et al., 2011). Estimates from the World Bank (2008) suggest that glacier recession and disappearance across the Andes within the next 20 years will threaten water supplies for 100 million people.

2.2.1 Observed glacier recession in the Andes

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 lost around 48% of their ice between 1963 and 2006 (Soruco et al., 2009), leading to the disappearance of many small glaciers. This is illustrated by the well documented retreat of Chacaltaya glacier (Bolivia, 16°21'S, 68°07'W) which disappeared in 2009, six years earlier than predicted (Fig. 2.5a; Fig. 2.5b; Fig. 2.6a) (Ramirez et al., 2001; IPCC, 2007a; Painter, 2007; Vergara et al., 2007a). Most noticeably from La Paz has been the retreat of the iconic Illimani mountain glacier (Fig. 2.6b) which is the backdrop to the city (Orlove et al., 2008). Figure 2.7 shows the locations of the main glaciers studied in Bolivia.

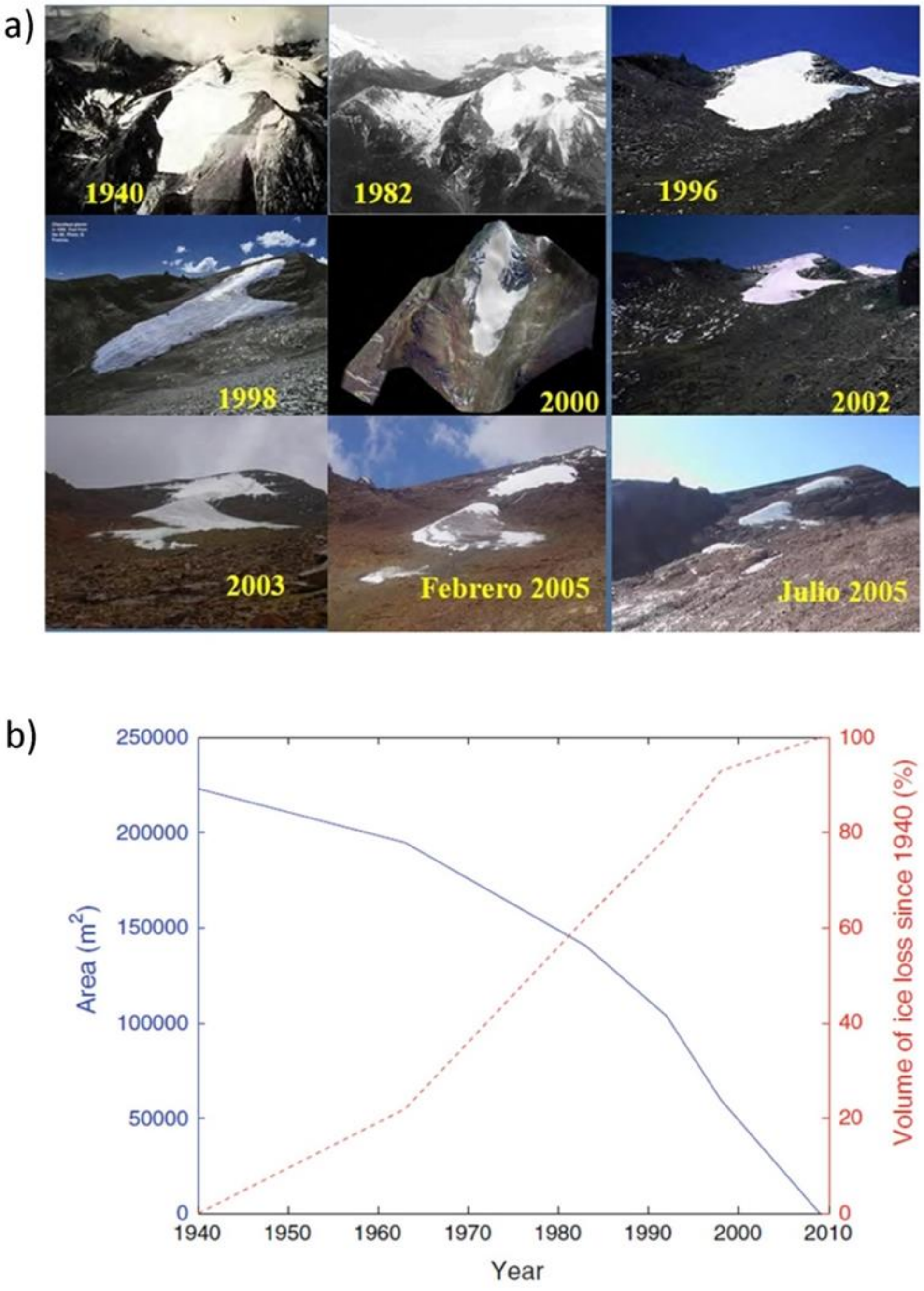

Figure 2.5 Disappearance of Chacaltaya glacier since 1940
a) Disappearance of the Chacaltaya glacier (16°21'S, 68°07'W) in Bolivia since 1940 illustrated through photography and modelling (taken from Vergara et al., 2007a, p.5); b) Graph showing the mass loss of ice from Chacaltaya during 1940 – 2009 in units of area and volume with its recession (data taken from Francou et al., 2000, p. 418). Taken from Rangecroft et al. (2013, p.856).

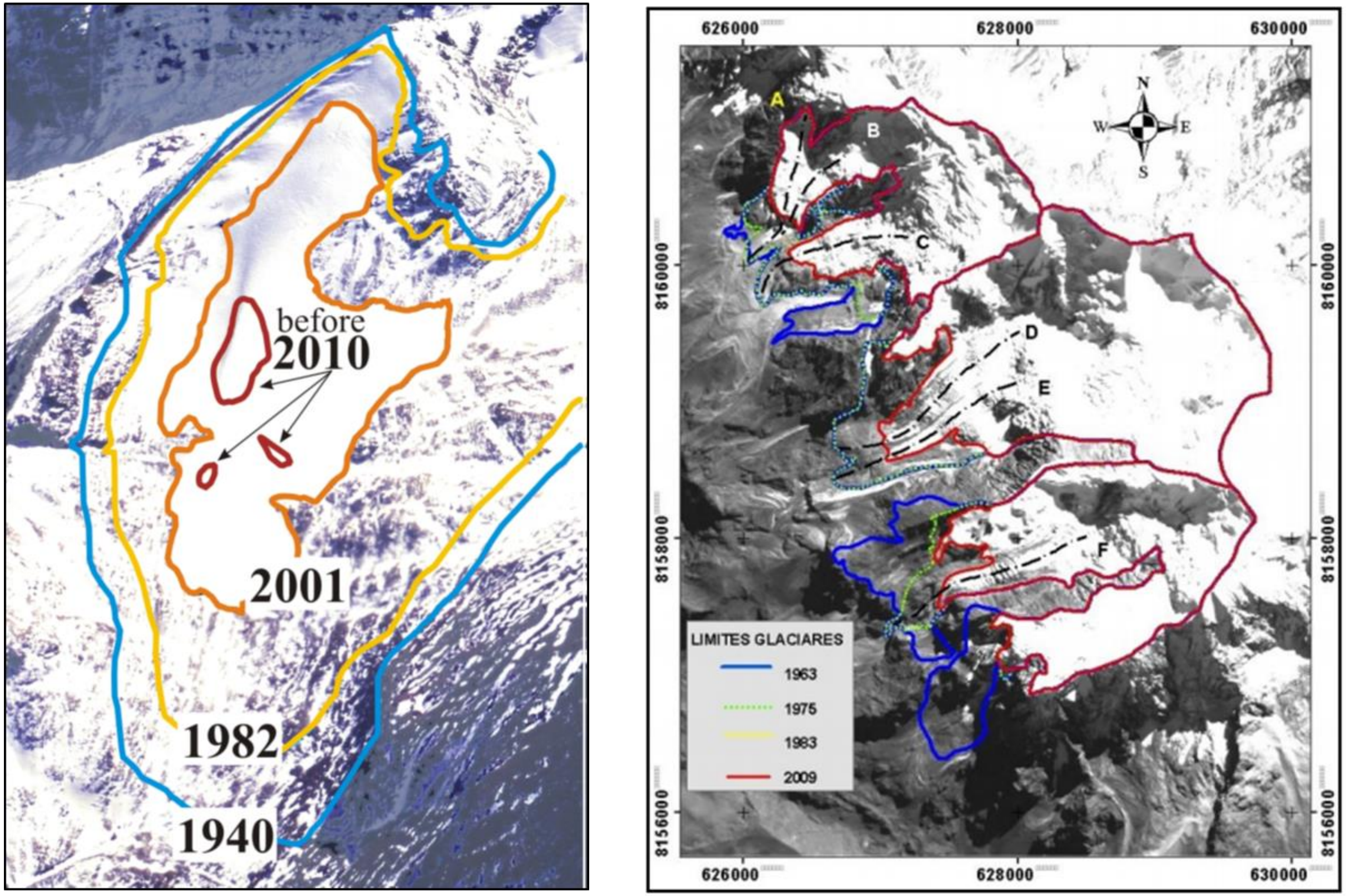

Figure 2.6 Mapped glacier retreats of Chacaltaya and Illimani

a) Mapped retreat of Chacaltaya (16°21’S, 68°07’W) on photo dated 2001 (Coudrain et al. 2005, p. 927); b) Illimani glacier (16°38’S, 67°47’W) extent for 1963 (blue), 1975 (green), 1983 (yellow) and 2009 (red) (Agua Sustentable, 2011, p.4).

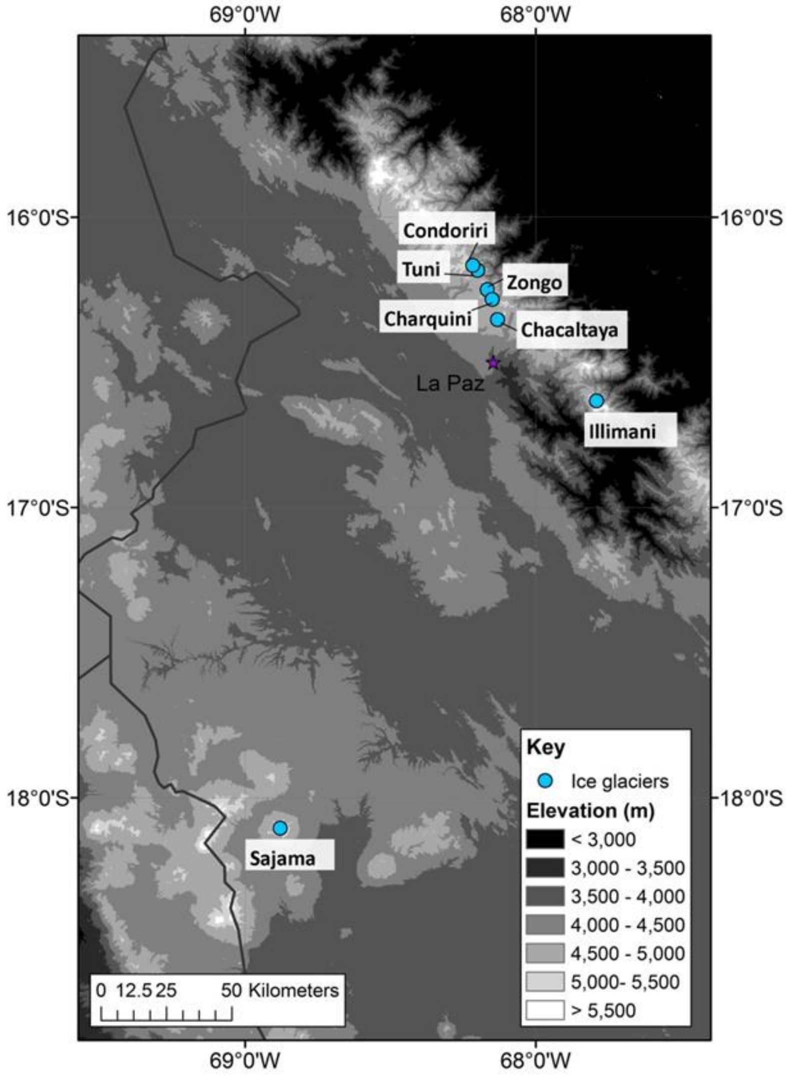

Figure 2.7 Location map of the main glaciers studied in the Bolivian Andes

Glacier recession is largely influenced by regional and local air temperature and precipitation, determining the extent of the area of accumulation and ablation (Carrasco et al., 2005). The location at which annual glacier accumulation and ablation are equal is defined as the Equilibrium Line Altitude (ELA) (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 ELA (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). Thus, glacier recession is seen as a visible impact of recent climate change in mountain regions (Francou et al., 2003; Vuille et al., 2003; Vuille et al., 2008; Mark et al., 2010).

However, although recent glacier recession is strongly correlated with rising atmospheric temperatures (Bradley et al., 2006; Mark et al., 2010), other effects such as changes in humidity on the glacier surface, energy balance, sublimation and surface albedo are needed to explain observed trends in glacier recession (Coudrain et al., 2005). Furthermore, because glacier behaviour in the Andes is partially driven by changes in precipitation, they are affected by changes in the 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).

Additionally, while recent glacier loss has been associated with climate change, Xu *et al.* (2009) suggest that it is anthropogenic soot which has led to recent accelerated glacier recession. It is proposed that black soot aerosols deposited on Tibetan glaciers have been a significant contributing factor to observed rapid glacier retreat (Xu et al., 2009) and decreased albedo (IPCC, 2007a), a positive feedback process (Paul et al., 2007). Similarly, the local aspects potentially accelerating glacier melting in the Andes include emissions of soot from the transport sector (Vergara and Rios, 2013).

2.2.2 Projected glacier recession

The mass balance of tropical glaciers is very different from that of mid- and high-latitude glaciers, and thus they are known to be particularly sensitivity to climate change (Vuille et al., 2008; Rabatel et al., 2013). For tropical glaciers, both ablation and accumulation coincide in austral summer (Sicart et al., 2002; Coudrain et al., 2005). It is this strongly related accumulation and ablation which makes summer-accumulation type tropical glaciers particularly vulnerable to possible climate warming (Sicart et al., 2002) as warmer temperatures will affect their accumulation and ablation. Furthermore, as previously stated, the rate of warming in the lower troposphere is likely to increase with altitude, and thus temperatures are expected to rise more in high mountains than surrounding lower regions (Bradley et al., 2006).

Glacier recession is more pronounced on smaller glaciers at low elevations (without a permanent accumulation zone) (Vuille et al., 2008; Chevallier et al., 2011; Rabatel et al., 2013) to changes in climate because at lower elevations they are exposed to ablation more than at higher elevations (Rabatel et al., 2013). 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 in Bolivia are classified as small glaciers (Francou et al., 2003), and therefore are particularly vulnerable to continued warming.

Glacier modelling, allied with climate projections, indicate that many of the lower-altitude glaciers are expected to disappear during the next 10 to 20 years (World Bank, 2008) given continued warming. Modelling of glacier recession based on observation data (1955 – 2007) by Ramirez et al. (2007) predicts that the glaciers of the Tuni Condoriri range (16°10'S, 68°13'W; Fig. 2.7) will disappear by 2025 (Tuni) and 2045 (Condoriri) (Fig. 2.8).

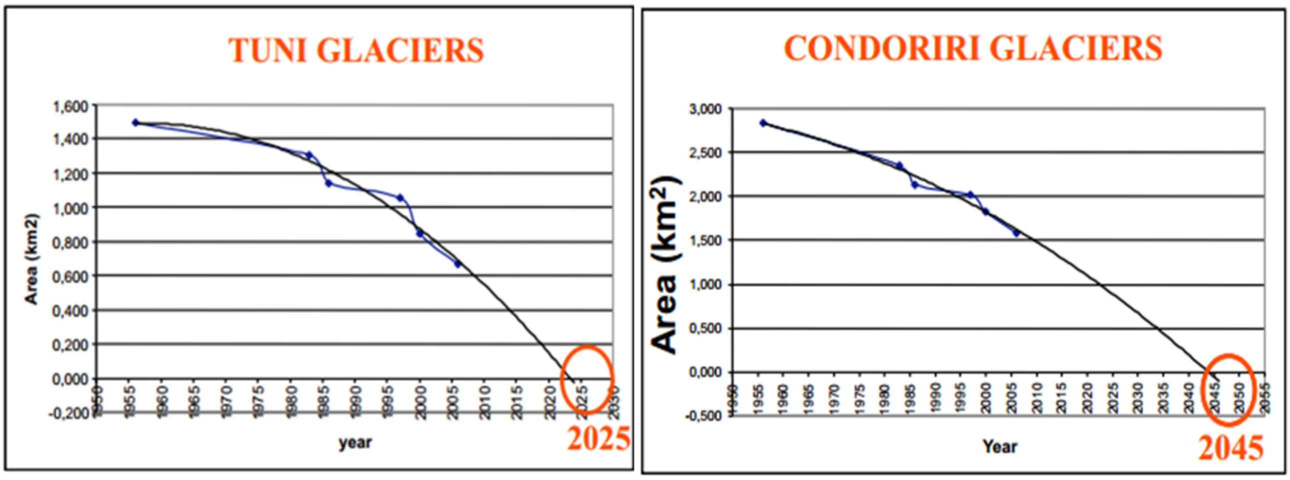

Figure 2.8 Observed and projected glacier recession for Tuni and Condoriri glaciers Tuni glacier (left) and Condoriri glacier (right) in the Cordillera Real (taken from Ramirez et al., 2007).

2.3 Bolivian water supplies

The relationship between water demands and predicted availability in dry seasons points to a serious problem in the future regarding water security in Bolivia (Mölg et al., 2008; Fig. 2.9). Ramirez *et al.* (2007) projected that water demand would start to outstrip supply during the wet seasons of 2008 and 2009, progressively getting worse with the stress also occurring in the dry seasons (Fig. 2.9). Indeed, the World Bank (2010) reported restricted supplies occurred during the wet season of 2008 and again in 2009, illustrated on Figure 2.9 in orange where water demand excelled water supply. In October 2009 La Paz officials began closing car washes until rain arrived in late November (Rosenthal, 2009).

Concurrent to the predicted decreases in water availability due to changes in climate and glacier storage, an increasing population will place further demands on water supplies (Vanham and Rauch, 2010; WMO, 2011). Buytaert and De Bièvre (2012) argue that threats from population growth outweigh those from climate change in Andean cities. However it is a combination of these pressures which all lead to projected increases on water stress, with climate change as a mutual factor (Fig. 2.10). Therefore, projected water shortages are expected to be accelerated by three factors: climate change, population rise and glacier retreat (Bradley et al., 2006; Painter, 2007; Jeschke, 2009; Vergara, 2009) (Fig. 2.10; Fig. 2.11). Furthermore, it is important to note that poor infrastructure also plays an important role in decreasing the amount of water available (SEI, 2013) (Fig. 2.11). These factors are discussed in further detail in the subsequent sections.

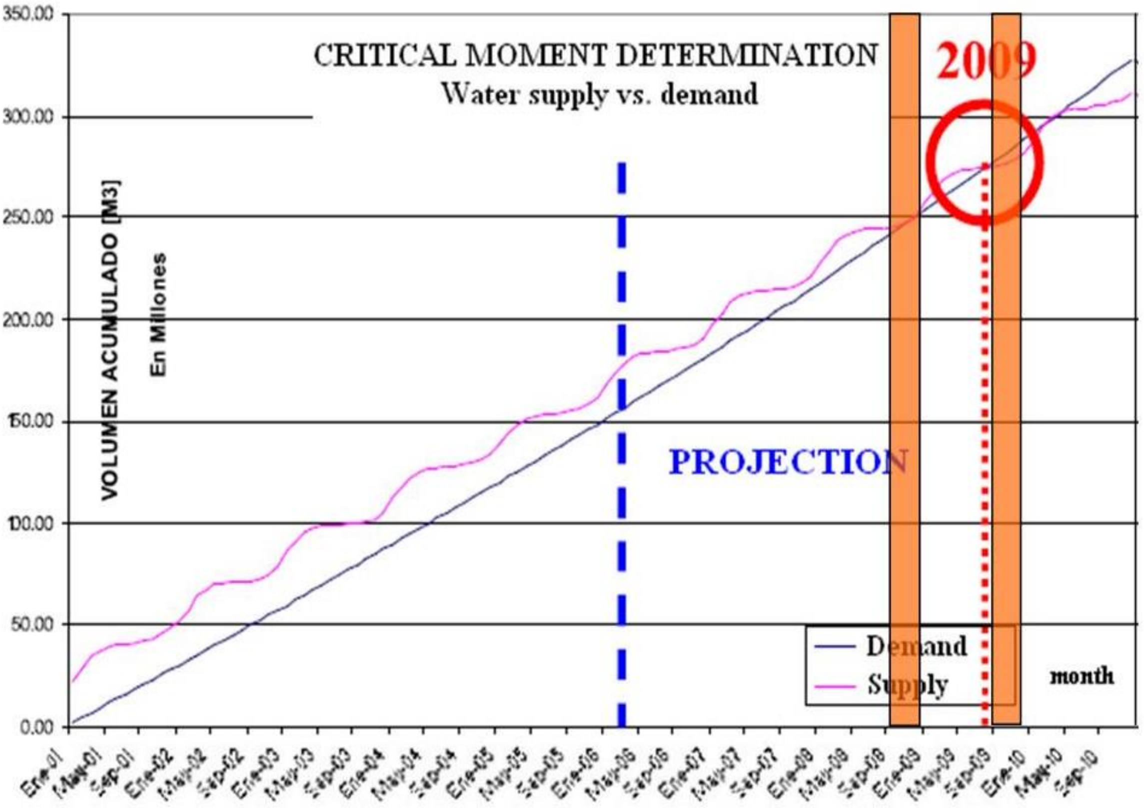

Figure 2.9 Water supply vs. demand graph
adapted from Ramirez et al. (2007) with overlaid information from World Bank (2010) in orange demonstrating the recent years that La Paz has experienced water stress.

2.3.1 Impacts of climate change on water supplies

High mountain environments are among the most sensitive to climate change (Vergara, 2009) because of their extreme altitudes (Bradley et al., 2006; Fig. 1.1), wide diurnal and annual temperature ranges, rapid nature of geomorphological change and fragile ecosystems (Akin, 2012). Changes in these environments can result in loss of habitat and species extinction and glacier melting (Akin, 2012).

Large cities in the Andes, such as La Paz, are located above 2500 m a.s.l. and depend almost entirely on high altitude water stocks to complement rainfall during the dry season (Bradley et al., 2006; Vanham and Rauch, 2010). The dams/reservoirs in La Paz are mainly fed from two sources, rainfall and the glaciers; both are affected by climate change. Changes to the hydrological cycle can affect the quantity, quality and accessibility of water supplies with important consequences for human populations, through impacts to agriculture and food security, health, economic activity, and conflict over water resources (WaterAid, 2007; World Bank,

2008) (Fig. 2.11). The impact of climate change and the degradation of natural resources have already heightened rural-to-urban emigration (Kaenzig, 2013). Without effective adaption, mountain communities like the Illimani community of Khapi (16°40’ S, 67°51’ W), could be forced to relocate (Earthjustice, 2009 cited in Kaenzig, 2013) because of their dependence on glacial meltwater; leading to increased stress and demand on existing services (Fig. 2.11). Power supplies will also be affected by the change in mountain hydrology as Bolivia relies heavily on hydropower, which accounts for half of the country’s energy production. The reduction in water flows in association with glacial retreat may reduce the potential for power generation in the long term. These changes may induce a carbonisation of the power sector, therefore increasing the greenhouse gas emissions of these systems (Vergara, 2009).

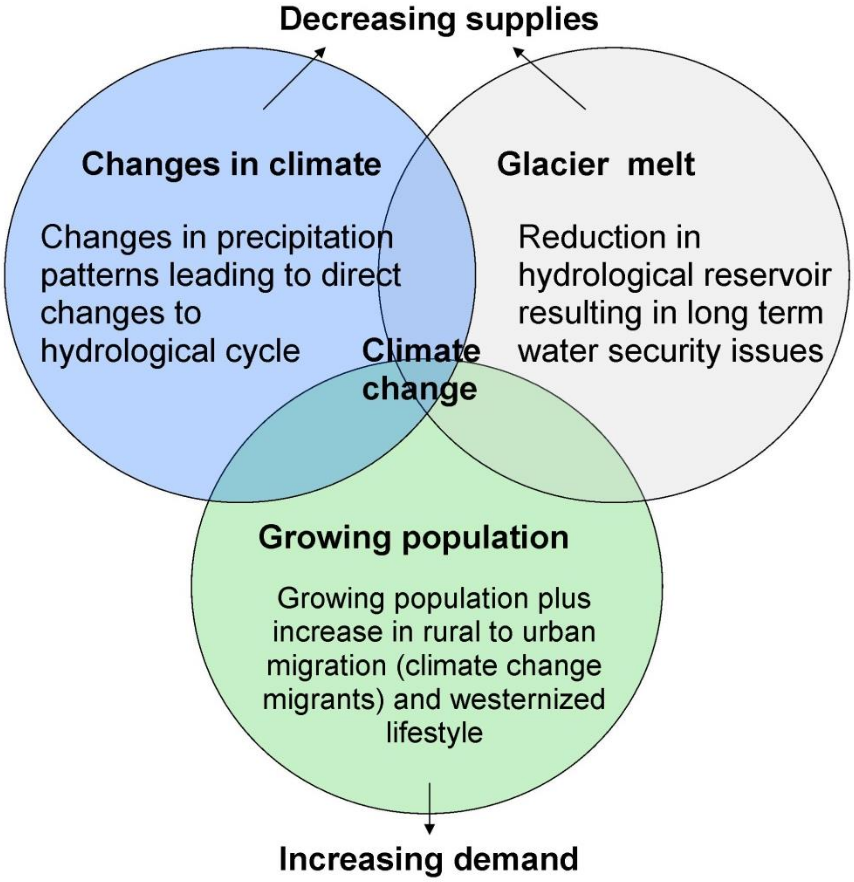

Figure 2.10 Venn diagram illustrating three main pressures on decreasing water supplies in Bolivia and the overlap of climate change on all three pressures.

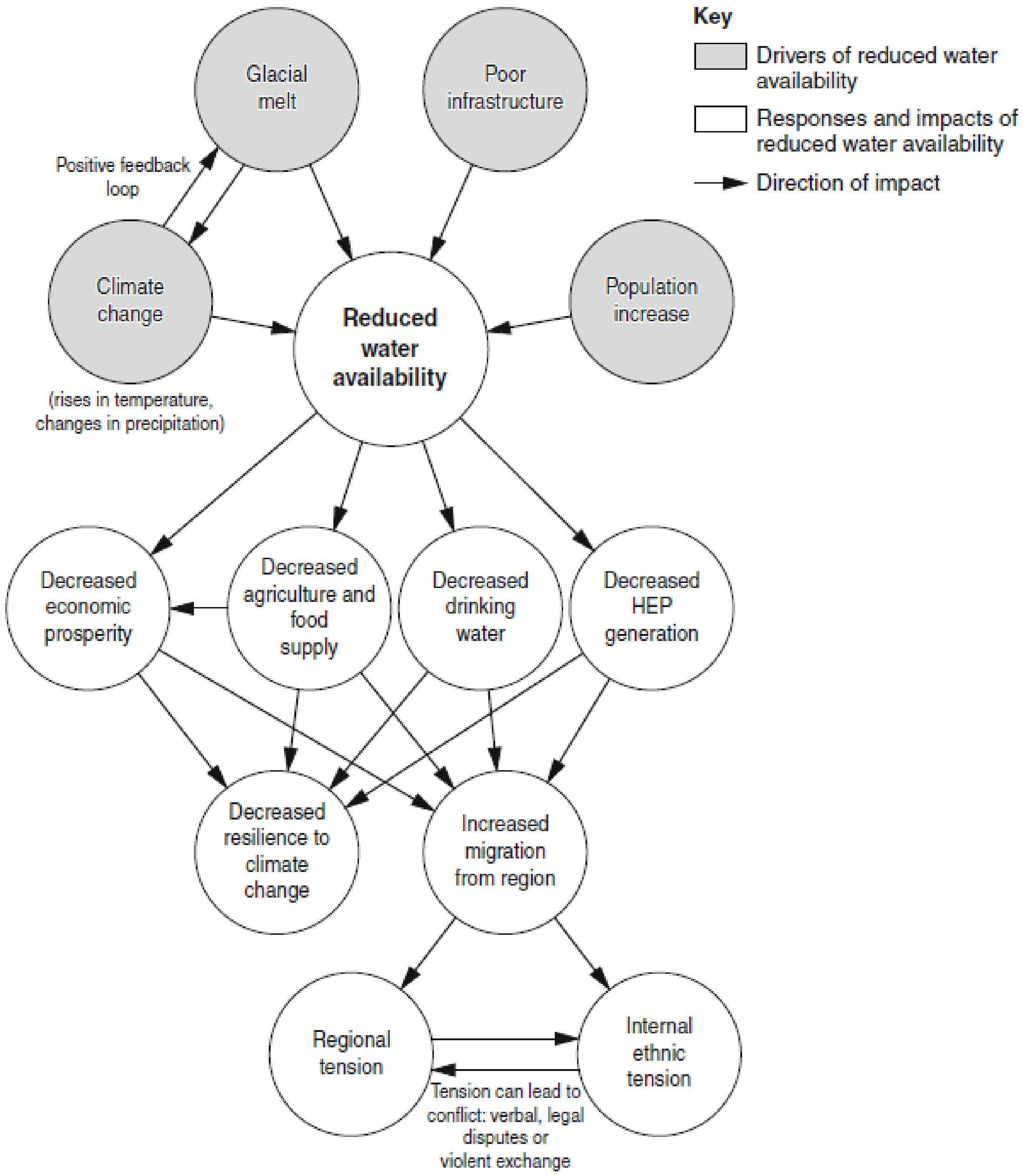

Figure 2.11 Network diagram outlining the drivers of water scarcity and impact relationships (adapted from Stewart 2010) for the Bolivian Andes. Grey circles represent drivers of reduced water availability and white circles represent the responses of reduced water availability and further impacts (taken from Rangecroft et al., 2013, p.257).

2.3.2 Impacts of population growth

Population growth is recognised as a major threat to water availability; Buytaert and De Bièvre (2012) believe that expected demographic changes are likely to outpace the impacts of climate change on water availability. Bolivia has the highest observed population growth (2000 – 2010) for the tropical Andes, with a growth of 20.6% (compared to 16.4% for Colombia, 13.4% for Peru and 11.9% for Ecuador), and the highest projected growth, 62.4% for the time period 2005 – 2050 (compared to 46.1% for Colombia, 42.9% for Peru and 37.7% for Ecuador) (Buytaert and De Bièvre, 2012). Bolivia's population reached 9.8 million by 2009, an increase of 21% within a decade. This population 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). The arrival of migrants from rural areas contributes towards the population increase in the two cities, more so for El Alto (Painter, 2007). El Alto's rapid growth, with its lack of urban planning laws and restrictions, has placed more pressure on infrastructure. An increasing population, westernisation of lifestyles and migration will place a higher demand on water supplies (Mölg et al., 2008; WMO, 2011; Vanham and Rauch, 2010; Buytaert and De Bièvre, 2012) requiring increasing volumes of water (Buytaert and De Bièvre, 2012) (Fig. 2.11); it is estimated that by 2050 the demand for water for irrigation and industry will increase by 150% and 250%, respectively (Winters, 2012). Rising population levels also exacerbate the problems of poverty and hunger as competition over limited resources is increased (Akin, 2012).

2.3.3 Impacts of poor infrastructure

Poor infrastructure, theft, and water demanding tourism add additional pressures on the already strained situation of water supply (Painter, 2007). 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 estimated that El Alto's water system loses ~40% of its water through inadequate water infrastructure (Farley and Liemberger, 2005; Lee and Schwab, 2005; SEI, 2013). Currently, the importance of improving infrastructure is often overlooked in the literature, yet the impact of reducing lost water would be beneficial to existing water supplies and increasing demands.

2.3.4 Future direction

While glacier recression will result in a temporary increase in runoff, once glaciers have disappeared, the hydrology regime will be severely affected as the glacier contribution will be eliminated and precipitation will not be naturally stored (Bradley et al., 2006; Vuille et al., 2008; Vergara, 2009; IPCC, 2014). Therefore, in the long term melting glaciers are predicted to lead to additional water shortages for millions of people in the Andes, raising serious water resource management concerns (Beniston, 2003; Bradley et al., 2006; Painter, 2007; Orlove et al., 2008; Jeschke, 2009).

These changes in the mountain landscape, warming temperatures and water supplies have already been witnessed by the local Andean communities (e.g. Pinaya, Illimani, 16°38'S, 67°51'W; Fig. 2.12): *"Here we are suffering the effects of climate change. Everyday I am looking up, so I see everything that is happening, how bare she [Illimani] is looking"* reports Alivio Aruquipa of the Andean mountain community reliant on Illimani for water (Christian Aid, 2012). Martin Vilela of Agua Sustentable states in the same video: *"In Andean communities they are already feeling the impacts of climate change… There's an obvious reduction in the glacial mass and a change in the rainfall"* (Christian Aid, 2012). Furthermore, the local Andean population realise the significant implications of glacier recession: *"If we don't have water from the glacier, what are we going to live from? There's no life without water. Water is life"* Lucia Quispe, Khapi community, Illimani (Oxfam, 2009, p.35).

To address this growing reality of reduced water security, water companies, governments and policy makers need better knowledge and information on current and future projections for water supplies at a finer spatial resolution than existing models can provide. To aid this knowledge base, research is needed on various key areas. Water managers need accurate and timely climate information to meet water demands, thus scientists are being integrated into the process of data gathering and monitoring to achieve this (e.g. Painter, 2007). 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 the identification, assessment and monitoring of mountain resources. With continued glacier recession, there is a need to better understand other sources of water from mountain ice storages, such as permafrost.

Figure 2.12 Photograph of the Pinaya community, Illimani living close to the retreating Illimani glacier and dependent upon the meltwater for subsidence and livelihoods (16°38'S, 67°51'W). Photo credit: S Rangecroft, June 2011.

2.4 Rock glaciers

Rock glaciers (Fig. 2.13) are landforms forming from ice-debris accumulation processes in the cryosphere, generally occurring in high mountainous terrain (Berthling, 2011; Brenning et al., 2012a; Lui et al., 2013). Landforms composed of a mix of angular rock with a core of ice or ice-cemented fine clasts, they usually have a distinct ridge and furrow surface pattern (Potter, 1972; Degenhardt and Giardino, 2003) (Fig. 2.13). It is these surface features of ridges and furrows and steep front and sides that allow for rock glacier identification from high resolution satellite images (Paul et al., 2003). However, there is considerable variation in surface morphology between locations in response to both topographic and lithologic variables (Giardino and Vitek, 1988). Rock glaciers are often classified by their activity status and sub-divided into ‘active’ and ‘inactive’ (containing ice, also known as ‘intact’) or ‘relict’ (not containing ice, sometimes referred to as ‘fossil’) (Barsch, 1996; Baroni et al., 2004; Krainer and Ribis, 2012; Falaschi et al., 2014). It is most commonly estimated that active rock glaciers contain a range of between 40 - 60% ice (Barsch, 1996; Haeberli et al., 1998; Arenson et al., 2002; Hausmann et al., 2007; Brenning, 2008; Krainer and Ribis, 2012) under a top layer of debris, usually a few meters of ice-free debris (3-5 m) (Piatek et al., 2013) (Fig. 2.14), which acts as insulation for the ice from low amplitude and high frequency temperature changes (Brenning, 2005a; Estrada, 2009). The active layer and sub-permafrost layer act as aquifers (Fig. 2.14) which vary in time with changing climatic conditions and inputs (Burger et al., 1999). Rock glaciers have a steep front (‘snout’ or ‘toe’) (Fig. 2.14) and side slopes (Giardino and Vitek, 1988; Summerfield, 1991; Hamilton and Whalley, 1995; Benn and Evans, 1998; Evans, 2005; Jansen and Hergarten, 2006) (Fig. 2.13).

Rock glaciers are believed to flow down slope through internal deformation (Benn and Evans, 1998; Evans, 2005) (Fig. 2.14) with resultant surface compression ridges running parallel to the direction of flow (Fig. 2.15). One of the most distinctive features of active rock glaciers is their low surface flow rates, especially relative to glaciers (Whalley and Azizi, 1994) with characteristic velocities of millimetres - centimetres per year (<1m a year) (e.g. Murtel rock glacier, Switzerland (Kääb et al., 1998; Fig. 2.15) and Doesen rock glacier, Austria, which moves several centimetres annually (Kaufmann, 1998)). Changes in rock glacier velocity occur in response to changes in climate and debris input (Kirkbride and Brazier, 1995), thus, debris supply and climate are considered to be the limiting factors on the activity of rock glaciers (Sandeman and Ballantyne, 1996).

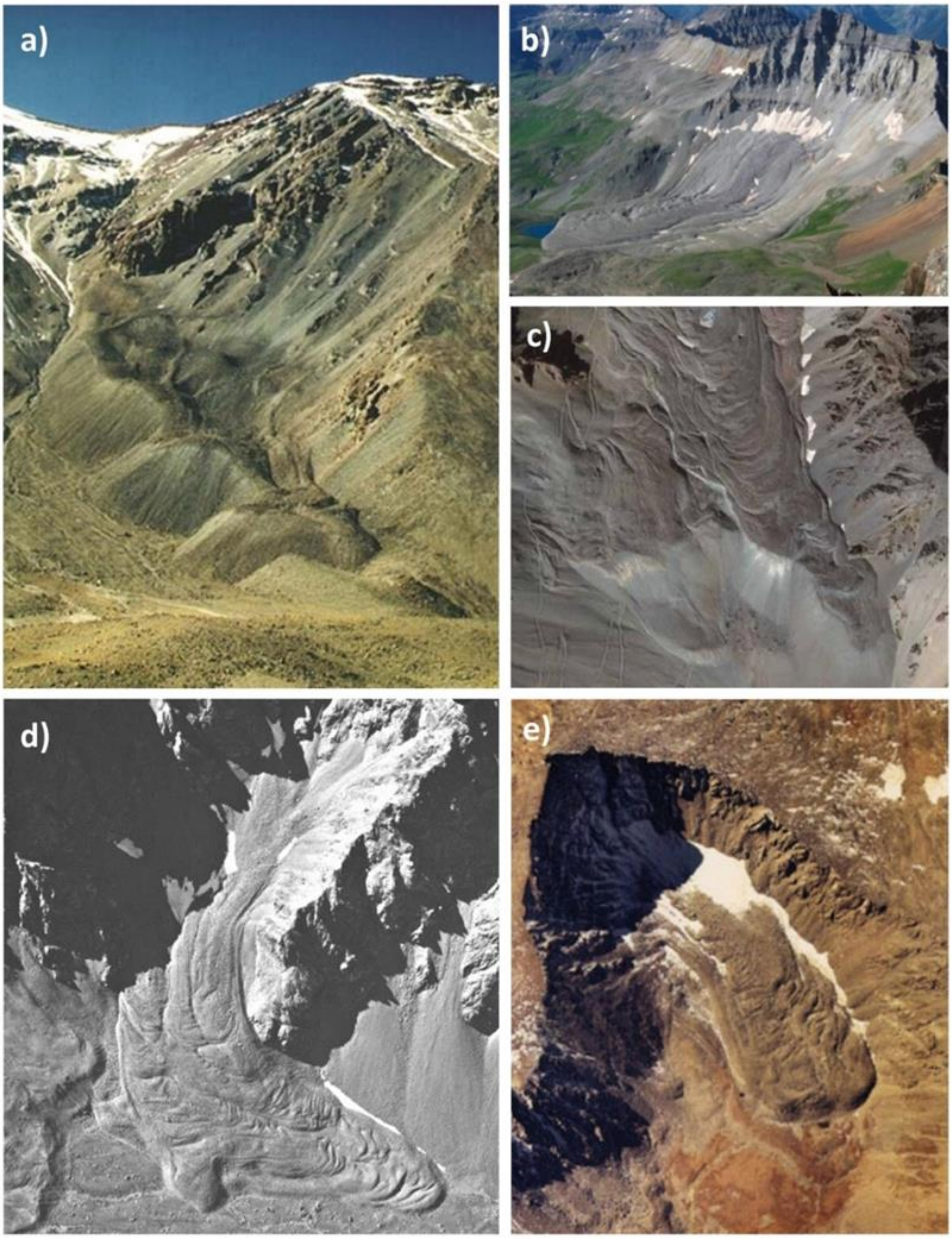

***Figure 2.13** **Example rock glaciers shown using photos and fine scaled satellite image data a) San Pedro-San Pablo 'PP-east' rock glacier in Central Chile (Payne, 1998); b) Gilpin rock glacier, Colorado** (http://www.summitpost.org/gilpin-rock-glacier/645639); **c) unnamed rock glacier in the Chilean Andes (Toomey, 2011); d) Muragl rock glacier, Switzerland** (http://www.geo.unizh.ch/~kaeaeb/img/muraglvd.JPG); **e) Spruce Creek rock glacier, Colorado** (http://glaciers.us/glaciers-colorado).*

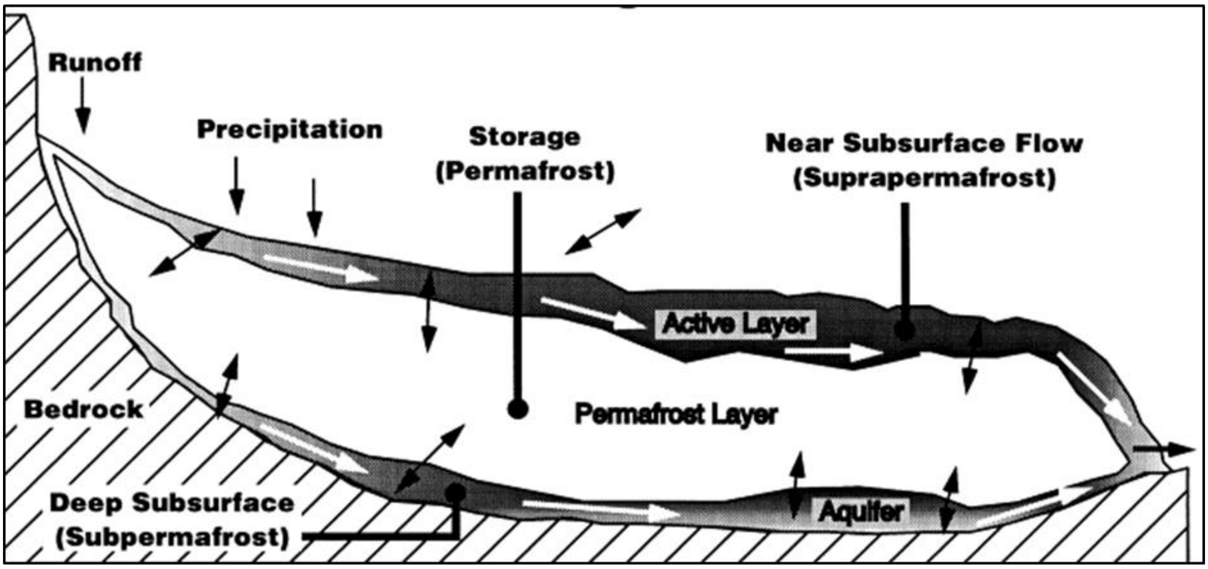

Figure 2.14 Annotated cross section image of a rock glacier to illustrate its internal structure (Burger et al., 1999, p. 123).

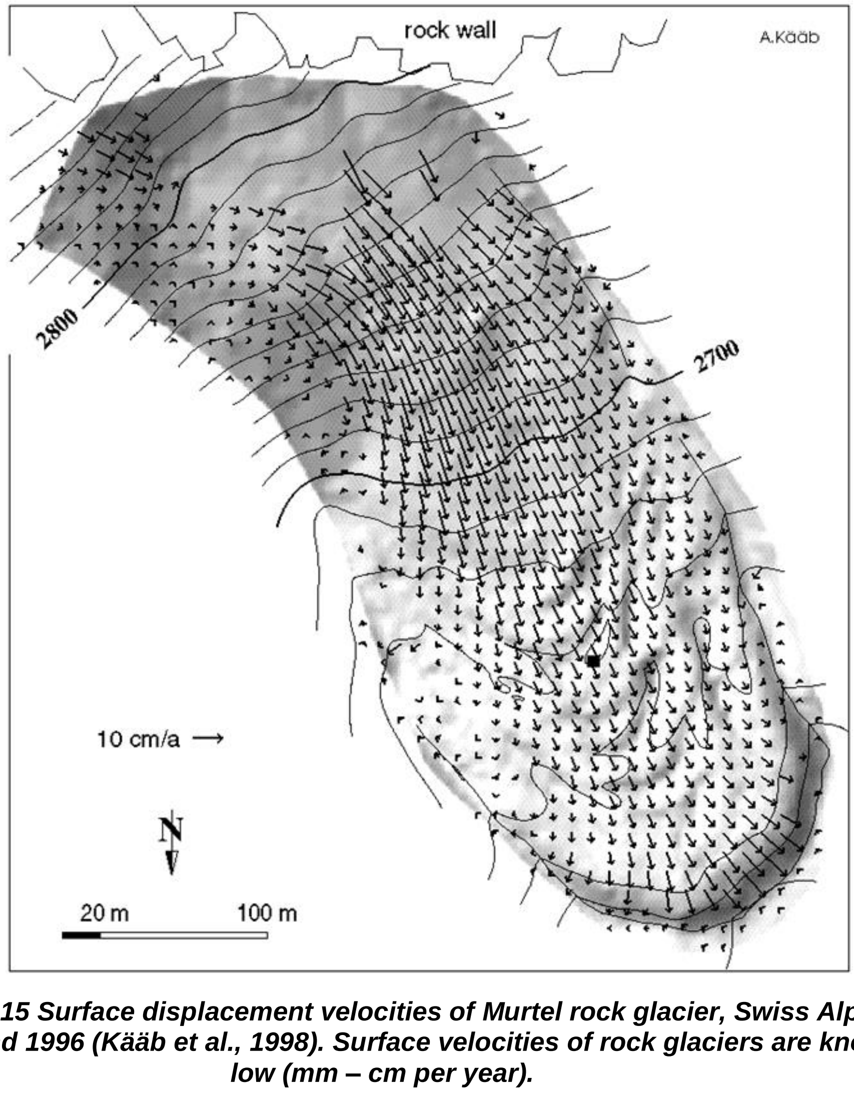

Figure 2.15 Surface displacement velocities of Murtel rock glacier, Swiss Alps between 1987 and 1996 (Kääb et al., 1998). Surface velocities of rock glaciers are known to be low (mm – cm per year).

Globally, rock glaciers occur in many of the major mountain regions, including the European Alps, the North American Rockies, the South American Andes, the Himalayas, and the Arctic and Antarctic. Dry, cold, continental environments are optimal conditions for rock glacier formation (Baroni et al., 2004; Zasadni, 2007) on slopes with reduced solar input (Gruber, 2005 cited in Arenson and Jakob, 2010). In the European Alps active rock glaciers exist where mean annual air temperature (MAAT) is less than -1/-2 °C and precipitation less than 2,000 mm (Barsch, 1996; Baroni et al., 2004). However, it can be hypothesised that these critical conditions might be different for the Bolivian Andes where elevations are higher, the climate is drier and rock type is different. For example, Brenning (2005a) found rock glaciers in the Chilean Andes to have a mean MAAT of +0.5 °C (see section 2.4.4). Active rock glaciers in high-mountain areas often mark the lower boundary of discontinuous permafrost (Haeberli, 1985; Giardino et al., 1987; Barsch, 1996) with the lowest altitude of rock glacier corresponding closely to the 0 °C isotherm (Payne, 1998).

2.4.1 Rock glacier features

Although rock glaciers can be classified in various ways (see section 2.4.3), activity status is one commonly accepted method and is used for the rock glaciers of this PhD thesis. According to the literature there are three types of activity status to classify rock glaciers: active (containing ice), inactive (not moving but still have ice content) and relict (no ice content) (Baroni et al., 2004; Seligman, 2009). Active rock glaciers can be identified by their well-defined flow lines and over-steepened frontal slopes (>30°) (Payne, 1998). Steep frontal and lateral slopes represent a swollen body due to ice content (Baroni et al., 2004). Baroni et al. (2004) used landform features to define the activity status of rock glaciers (Table 2.1). A key indicator that a rock glacier is active/ inactive is the angle of its front slope (shown in Fig 2.16) and well developed surface longitudinal and transversal ridges and furrows (Fig 2.16). Although frontal slopes are typically greater than 30° (Payne, 1998), gradient is in relation to the angle of repose (Rasemann et al., 2004), which is dependent of the material.

Relict rock glaciers (Fig 2.17) are generally found at lower elevations than active ones (Table 2.1). Inactive rock glaciers are often identified by frontal slope angles of less than 30° (Payne, 1998) (Table 2.1), and is a result of the removal of the ice content, flattening the body (Fig 2.17). Lichen and vegetation cover are also another key factor in identifying a relict rock glacier. The presence of these ecological features indicates a lack of movement of the exposed rocks for them to become established (Roer and Nyenhuis, 2007; Seligman, 2009).

Characteristic features used for identification	**Active**	**Relict**	**Notes**
Frontal ramp	Steep (≥30°)	Gently sloping (<30°)	Frontal slope representing a swollen body of ice (Baroni et al., 2004, p. 251)
Rock glacier body	Swollen body, indicating ice presence	A flattened body, result of ice disappearing	Possible swollen body indicating the presence of ice (Baroni et al., 2004, p. 251)
Surface texture	Signs of flow: e.g. ridges and furrows	Less defined flow lines	Well-developed longitudinal and transversal ridges and furrows which act as signs of flow (Kääb and Weber, 2004, p. 379)
	Little or no vegetation and/or lichen cover	Vegetation and/or lichen cover	Encroachment of vegetation and/or lichen on the rock glacier surface implies stationary status (inactive/relict) (Seligman, 2009, p. 7)
	Superficial boulders with little or no surface weathering	Weathered rocks	Exposure to weathering increases with stationary activity status (inactive/relict) (Baroni et al., 2004, p. 251)
Shape	Tongue shape: length>width; Lobate shape: length<width	Tongue shape: length>width; Lobate shape: length<width	An assessment of length to width ratio can also be used to help distinguish rock glaciers from other periglacial features (Harrison et al., 2008, p. 288)
Elevation	Between the 0°C isotherm and the snow line	Typically just below the permafrost level/ 0°C isotherm	Relict rock glaciers can be identified at lower elevations than active rock glaciers (Baroni et al., 2004)

Table 2.1 Criteria used to identify rock glaciers and discriminate active from relict rock glaciers gathered from literature.

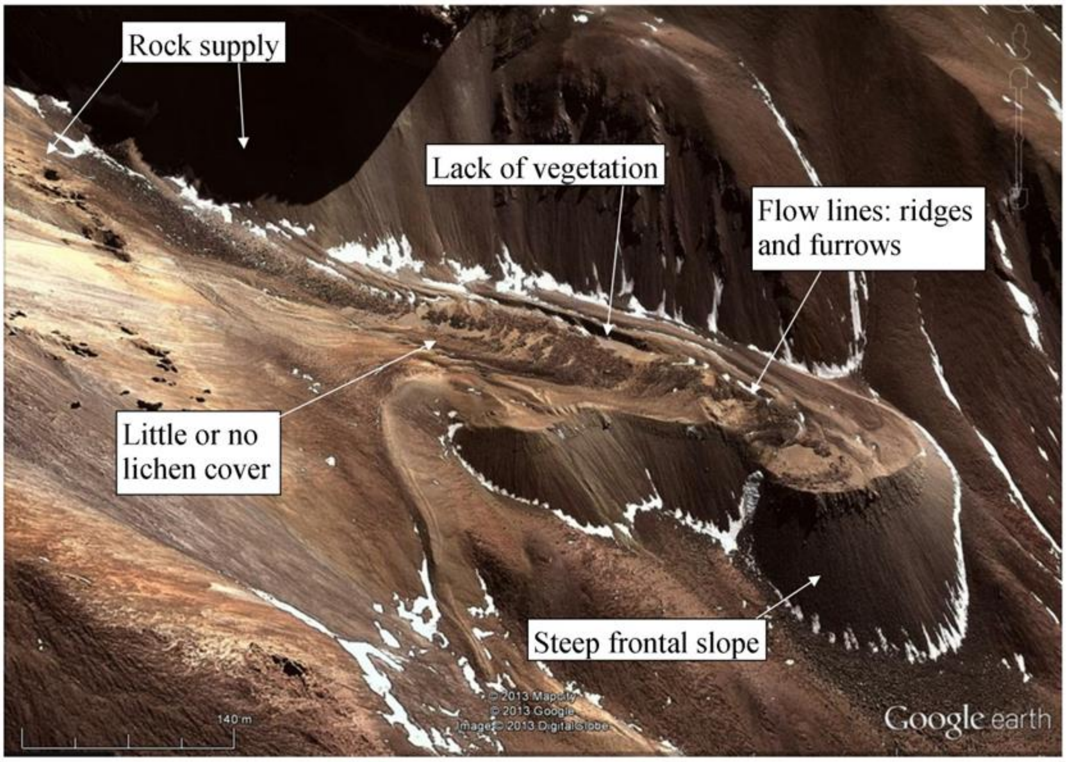

Figure 2.16 Annotated active rock
Caquella, Bolivia 21.5°S. Google Earth.

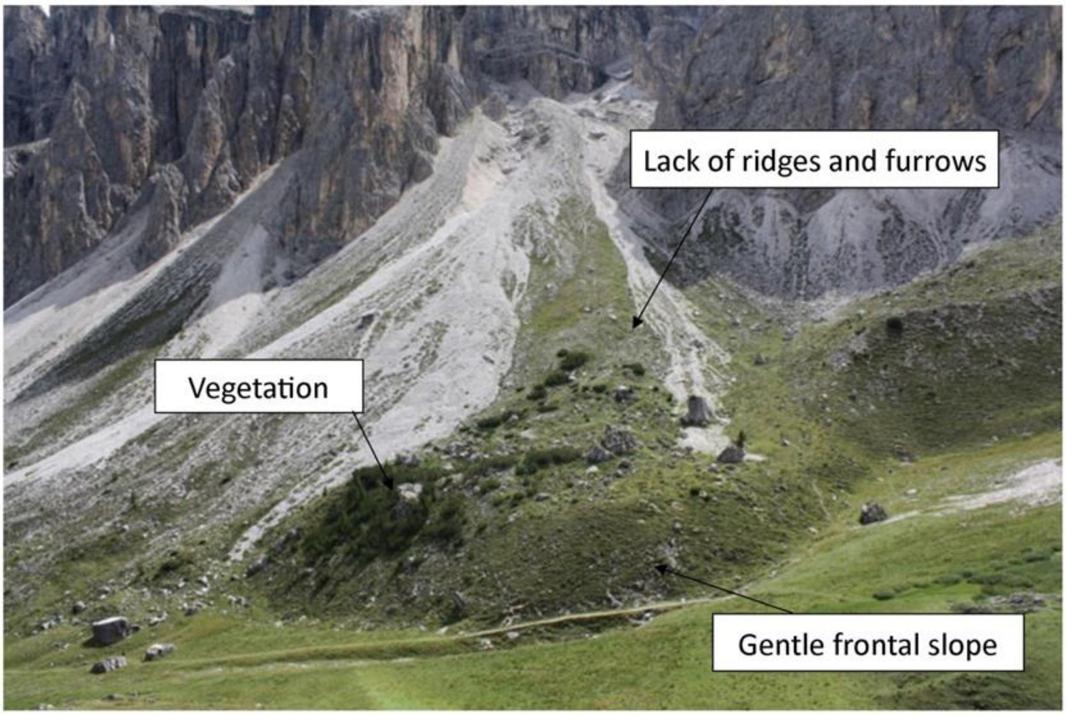

Figure 2.17 Annoted relict rock glacier
Antersac-Valley, Dolomites, European Alps.
http://historyofgeology.fieldofscience.com/2011_02_01_archive.html

2.4.2 Rock glacier origin and structure

The origin, internal structure and dynamics of rock glaciers are poorly understood and remain the subject of academic debate (Whalley et al., 1986; Clark et al., 1998; Ishikawa et al., 2001; Berthling, 2011) and there is still no unanimously accepted viewpoint concerning their origin (Clark et al., 1998). It was believed that rock glaciers are exclusively features of creeping permafrost and genetically distinct from glaciers (Clark et al., 1998); however some authors have demonstrated conclusively that at least some rock glaciers are glaciogenic (Potter, 1972; Whalley and Martin, 1992; Humlum, 1997).

The internal composition of a rock glacier is thought to be very variable, ranging from pure ice to an ice/rock mixture (Whalley and Azizi, 1994). Ice content within rock glaciers depends on water concentrations, which are found to always be higher in cirques, scree slopes, and confluences of couloirs (Francou et al., 1999). Results from sampling can show what ice composition lies under the rock, thus indicating the origin of the rock glacier. For example, ground penetrating radar (GPR) shows that the Yankee Boy basin rock glacier (Colorado, USA) was formed by permafrost processes rather than by covering a mass of remnant glacier ice (Degenhardt Jr and Giardino, 2003). However, the internal structure and composition of rock glaciers are typically difficult to investigate, because of their remote locations and difficult terrain (Goshorn-Maroney, 2012).

Although there is controversy surrounding the specific origin of rock glaciers, there are three (agreed) models of rock glacier formation: a permafrost origin, a glacier-derived origin, and a mass-wasting (or landslide) origin (Whalley and Martin, 1992; Whalley and Azizi, 2003). The permafrost model (Wahrhaftig and Cox, 1959; Haeberli, 1985; Barsch, 1996) requires a mean annual air temperature below -1.5 °C which supports the formation of “ice-cement” ice and debris from freezing water (Whalley and Azizi, 2003). Ice-cemented rock glaciers are also known as “talus-derived rock glaciers” in the literature (Fig. 2.18). The glacial-derived model (Whalley and Martin, 1992) involves the creep of an ice body (<50 m thickness), which is preserved by an insulating layer of weathered rock debris. It is this ice body which gives these rock glaciers the name “ice-cored” in some papers (Fig. 2.18). Finally, in the landslide model (Johnson, 1974, 1984) the presence of ice is not necessary. Deduced from the similarity of topographic forms rock glaciers may be derived from rapid landslides or rock avalanches and do not flow after emplacement (Whalley and Martin, 1992).

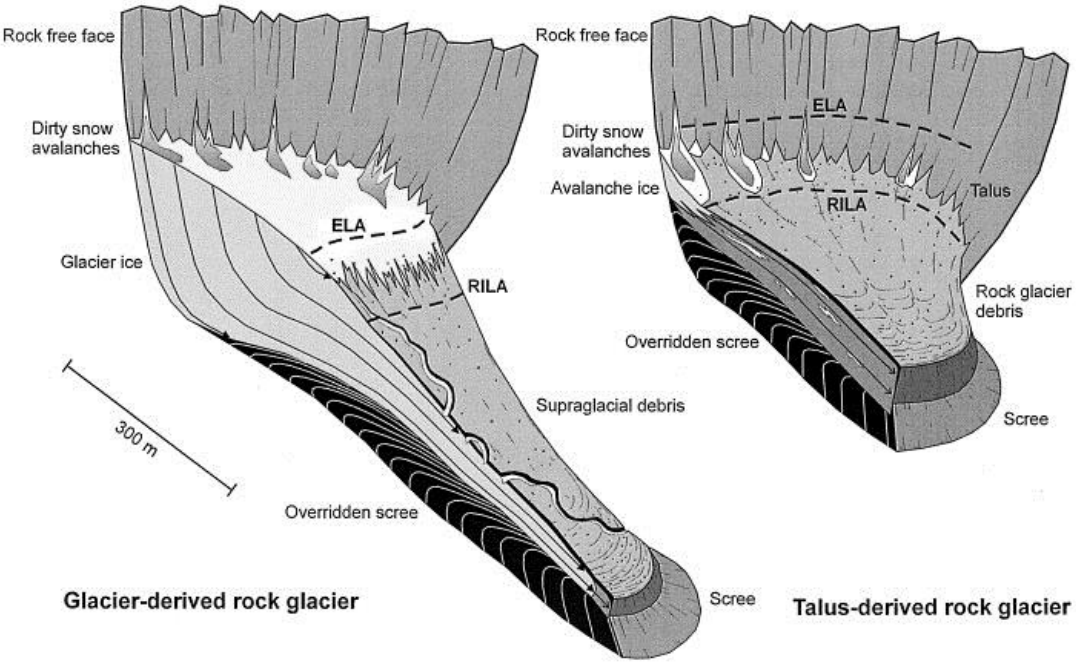

Figure 2.18 Illustrations of glacier-derived and talus-derived rock glaciers (ice-cored and ice-cemented, respectively) taken from Humlum (2000, p.52).

2.4.3 Rock glacier classification

Rock glaciers have been defined, identified and classified in multiple ways. Some rock glacier definitions are descriptive and based on observable morphological features whereas as others are genetic (Hamilton and Whalley, 1995; Berthling, 2011). Some rock glaciers are classified by their genesis (glacier-derived, talus-derived, Fig. 2.18); their activity status (active, inactive, relict, e.g. Whalley and Martin, 1992; Baroni et al., 2004; Seligman, 2009); their location (valley floor, valley wall); and their shape (tongue-shaped, lobate). Identifying rock glaciers through their physical shape results in two classifications: tongue-shaped and lobate. Commonly used geomorphometric parameters to characterise rock glacier shape include length (measured in the direction of flow) and width (perpendicular to the direction of flow). Tongue shaped rock glaciers have their length greater than their width, whereas lobate rock glaciers are broader than long (White, 1976). They often develop below alluvial and avalanche talus along valley walls below cliffs. Tongue shaped rock glaciers may become ‘spatulate’ when the rock glacier spreads laterally when it enters a wide valley (White, 1976; Fig. 2.19). Rock glaciers can be viewed as on a continuum with glaciers and other cryospheric features such as protalus lobes and protalus ramparts. Figure 2.19 illustrates these different features, and Figure 2.20 shows how they are situated on the continuum depending on ice and debris content.

Due to the uncertainty surrounding the various definitions of rock glaciers, and to avoid the controversy of their origin, rock glaciers are typically classified according to their activity status. However, due to the difficulties of differentiating between active and inactive rock glaciers remotely, throughout this thesis they are both considered as ‘active’, similar to Baroni et al. (2004), also termed ‘intact’ rock glaciers by other authors (e.g. Kellerer-Pirklbauer et al., 2012; Krainer and Ribis, 2012; Scotti et al., 2013). However, it should be noted that activity can only be truly assessed by direct or indirect measurements (e.g. boreholes or geophysical surveying) or movement detection (e.g. *in situ* methods of surface detection, remotely detected movement using InSAR).

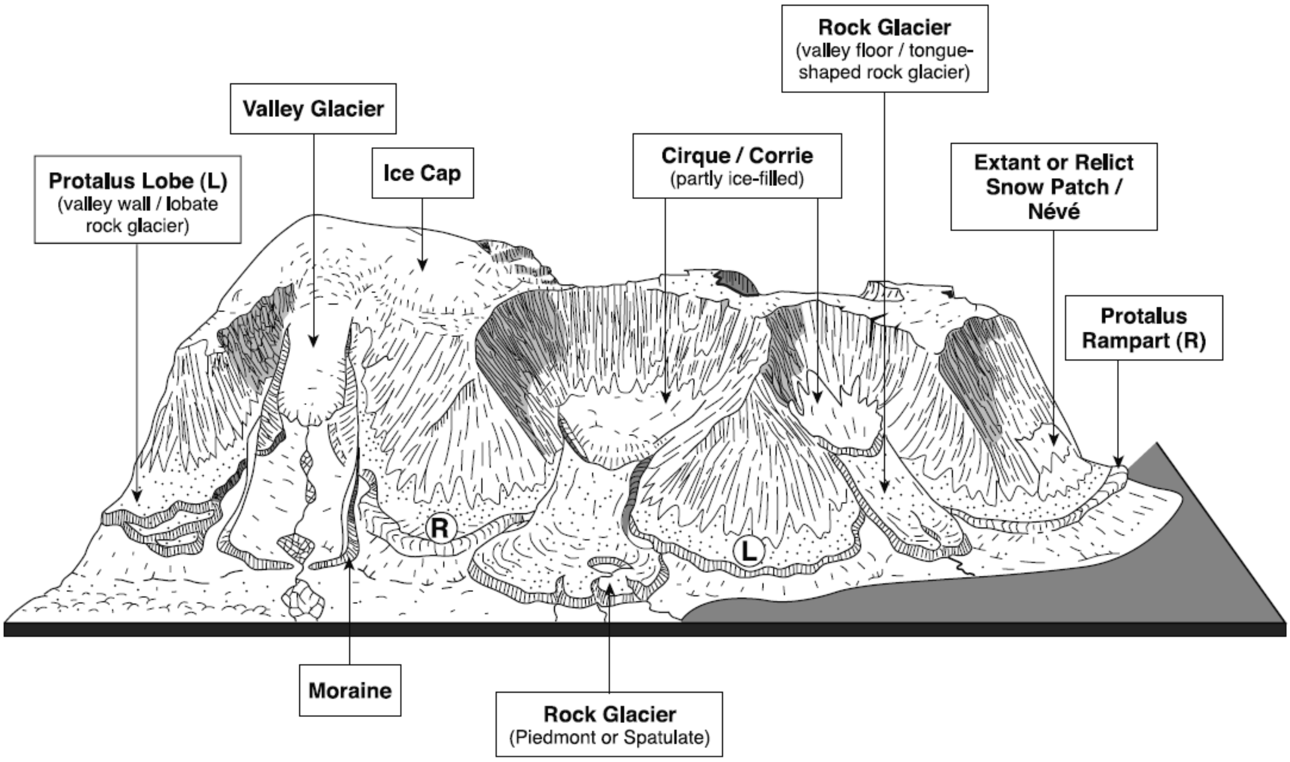

Figure 2.19 Visual representation of varying cryospheric features typically found, demonstrating tongue-shaped and spatulate rock glaciers (Whalley and Azizi, 2003, p.3).

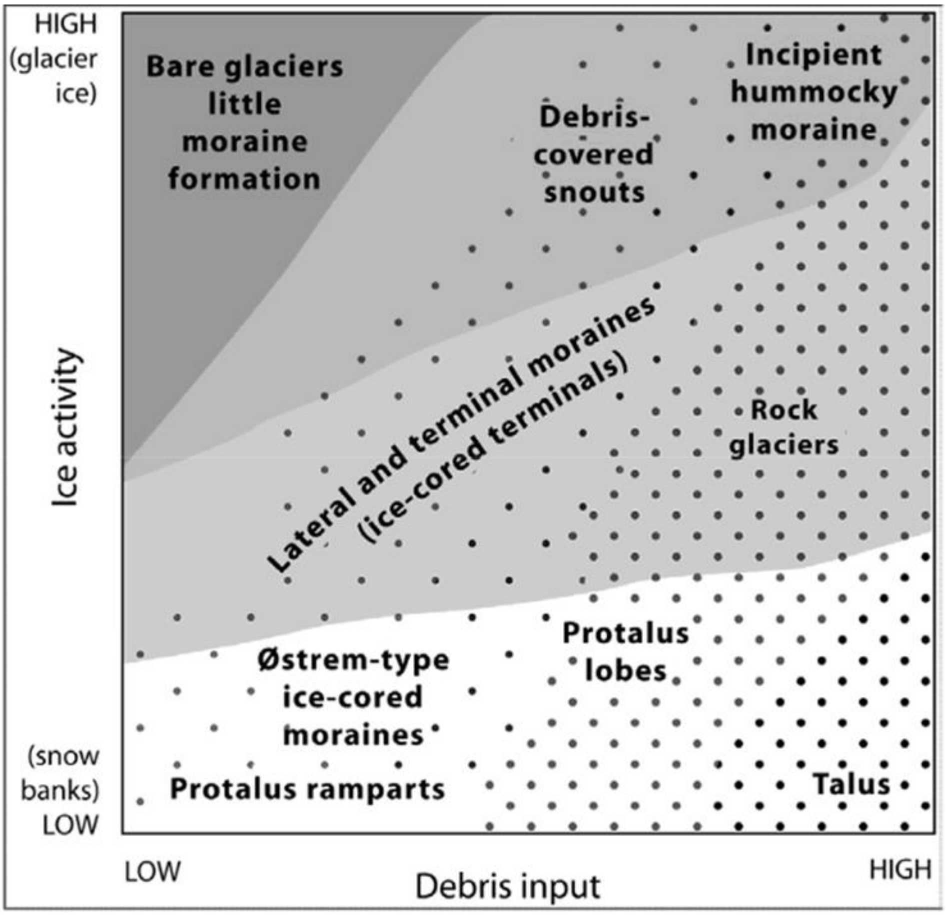

Figure 2.20 A schema illustrating the relative proportions of ice and rock weathering debris in a 'glacial' geomorphic system, demonstrating the glacial, rock glacier continuum. This schema shows the various features observed in the cryosphere (most are illustrated on Fig. 2.19) Taken from Whalley (2009).

2.4.4 Controls on rock glacier formation and existence

Rock glacier formation is driven by a different set of controls to those creating glaciers. Rock glaciers are common features in arid, cold climates of arctic and alpine environments (Millar and Westfall, 2008), found to exist between the 0 °C isotherm and the regional snow line (Milana and Maturano, 1999). Glaciers tend to occupy most rock glacier niches at high elevations, and in wetter climates, such as Peru in the Andes, glaciers will also occupy the areas where rock glacier might form (Francou et al., 1999; Brenning, 2005a; Bodin et al., 2010a). For rock glaciers, in addition to these climate controls, talus supply is a prominent control (Brenning and Trombotto, 2006). The geographical factors which strongly influence mountain climates, and thus rock glacier formation, are: latitude, continentality, altitude, and topography. Topography affects slope angle and aspect, causing striking differentiation of climates because slope and aspect have fundamental effects on radiation income and temperature conditions (Kelly et al., 2004). Solar and net radiation and temperature broadly decrease with increasing latitude. Altitude affects air pressure and density, vapour pressure, solar radiation, infra-red radiation, net radiation, temperature, and wind. Rock glacier distribution is found to be strongly controlled by topography and aspect (Francou et al., 1999). The continental climate, steep topography and intense frost-shattering of the central Andes, combined with low precipitation, produces ideal conditions for the development of numerous rock glaciers of different types (Corte, 1999). However, aridity may reduce rock supply directly through decreased weathering and indirectly through reduced periglacial activity (Azócar and Brenning, 2010). The greatest abundance of rock glaciers in the Andes of Santiago, Chile, are found between the modern regional -1 and +1 °C isotherms and the regional ELA of glaciers, with an average MAAT of +0.5 °C (Brenning, 2005a). A decrease in precipitation, or an increase in temperature resulting in more precipitation falling as rain rather than snow, is likely to increase the relative importance of the rock component in the rock glacier system, producing conditions more favourable for rock glaciers than glaciers (Evans, 2005).

Rock glaciers [and glaciers] in the tropics are different from alpine and polar regions for three main reasons: i) small seasonal temperature ranges; ii) high quantities of solar energy input to the ground surface all year round; and iii) the absence of long lasting snow cover. All these have consequences for the thermal regime and albedo of the ground (Francou et al., 1999). The weak seasonality and aridity means that the rock glacier structures are directly related to altimetric ranges, such as clear relationships parallel to annual isotherms. Snow cover being sporadic, a rock glacier surface receives great quantities of energy all year round due to high radiation intensity and low albedo.

For rock glaciers, it is suggested that the top layer of rock acts as a shield for the ice content underneath. As a result, rock glaciers are predicted to respond to climate warming slower than glaciers (Brenning, 2005a). Glaciers are generally sensitive to climatic change over a short timescale (10 years); whereas it is thought that the response of rock glaciers to climate is smoothed and delayed in time (Francou et al., 1999) and thus reflecting long-term trends (Guodong and Dramis, 1992).

2.4.5 Rock glacier research

Although rock glaciers occur globally in many of the major mountain regions, most research has been concentrated in the European Alps (e.g. Haeberli et al., 1998; Kääb et al., 1998; Kaufmann, 1998; Guglielmin and Smiraglia, 1998; Lieb, 1998; Baroni et al., 2004; Huasmann et al., 2007; Kellerer-Piklbauer et al., 2012; Krainer and Ribis, 2012; Scotti et al., 2013), although recently there has been more research emerging the Chilean and Argentinean Andes (e.g. Brenning, 2005a; Croce and Milana, 2002; Esper Angillieri, 2009; Azócar and Brenning, 2010; Falaschi et al., 2014). The nature of rock glacier research also appears to be changing; recent studies have concentrated on providing regional inventories, rather than just case studies of individual rock glaciers. This shift in spatial extent could be due to an increased use of satellite data which permits the analysis of greater spatial scales.

However, the research on impacts of projected climate change on rock glaciers is very limited. Permafrost and its projected response to climate change is well studied for the Northern Hemisphere, with the IPCC (2014) “virtually certain” that Northern Hemisphere permafrost will continue to decline during the first half of the 21st century. However, similar projections for Southern Hemisphere permafrost are not yet available. In theory, a rise in air temperature will cause an increase in ground permafrost temperatures, degradation and thawing (Haeberli et al., 1993). For instance, Janke (2005) models the impact of increasing temperatures on active rock glaciers in the North American Rockies, and shows that a temperature rise of 4 °C in the region will result in the loss of all active rock glaciers. However, this research has not been applied on a timescale of when these projected time increases are expected for the region.

2.4.6 Rock glaciers and water supply

Rock glaciers are important stores of frozen water, acting as water reservoirs where precipitation is very low (Francou et al., 1999; Trombotto et al., 1999). The role of rock glaciers within the hydrological system has been studied by various authors (Corte, 1976, 1978; Buk, 1983; Gardner and Bajewsky, 1987; Giardino et al., 1992; Schrott, 1998; Burger et al., 1999; Trombotto et al., 1999; Croce and Milana, 2002, all cited in Brenning, 2005a). 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. To investigate the internal composition of rock glaciers direct and indirect methods can be applied. Direct methods (e.g. coring and drilling) are labour- and time-intensive, whereas indirect methods (e.g. geophysical surveys) allow relatively rapid and inexpensive acquisition of three dimensional data. However, these geophysical surveys require equipment which can be difficult to access in a developing country such as Bolivia and difficult to transport to field sites.

Ice content varies considerably within rock glacier permafrost. Currently, estimates for ice content within rock glaciers range between 40 and 60% by volume (Barsch, 1996; Haeberli et al. 1998; Arenson et al. 2002; Hausmann et al. 2007; Brenning, 2008; Krainer and Ribis, 2012), with more recent estimates of 40 – 70% ice (Azócar and Brenning, 2010; Brenning, 2010). This is a large range and provides substantial potential for uncertainity, however, a lower and an upper estimate of ice content can be calculated using these ranges. Recent research (Arenson and Jakob, 2010) argues that even active rock glaciers may contain an average ice content of much less than 50% because a single ice-rich layer is sufficient to allow creep. As a result, the amount of water in rock glaciers is difficult to estimate due to the inherent variability and difficulty in determining exact genesis and subsequent depth and distribution of ice and debris in rock glaciers (Seligman, 2009).

Despite its importance, there is limited work estimating the water content of rock glaciers, especially for the South American Andes. Gaps in our understanding include work estimating the ice and water content of rock glaciers. First attempts to quantify ice content in the Andes were established by Croce and Milana (2002), finding an average ice content of 55.7 % for an Argentinean rock glacier. More recently, Arenson et al. (2010) also found in Argentina that all their test pits contained over 50 % ice content. Existing studies in the Andes have estimated the mean thickness of rock glacier ice-rich permafrost through an empirical rule established by Brenning (2005b) (Azócar and Brenning, 2010; Perucca and Esper Angillieri, 2011) (equation 1) based on field work from the Chilean Andes.

$$\text{Mean thickness [m]} = 50 \times (\text{rock glacier area [km}^2\text{]})^{0.2} \qquad [1]$$

Subsequent water equivalent volumes were calculated to allow for an assessment of the hydrological importance of these rock glaciers (Azócar and

Brenning, 2010; Perucca and Esper Angillieri, 2011). Azócar and Brenning (2010) estimated that the 147.5 km^2 of rock glaciers in Chile (27° - 33° S) held the equivalent of 2.37 km^3 water. Basing their method upon Azócar and Brenning (2010), Perucca and Esper Angillieri (2011) calculated a water equivalent of 0.12 km^3 for 6 km^2 of rock glaciers at 28° S, Argentina. Through these estimations active rock glaciers have been shown to contain significant volumes of water in the Chilean and Argentinean Andes where they are considered as key stores and sources of water, especially during the dry season (e.g. Croce and Milana, 2002; Brenning, 2005a; Brenning et al., 2007; Azócar and Brenning, 2010).

Water equivalent estimates can also be used to assess the hydrological importance of rock glaciers in context of surrounding glaciers. Using a direct comparison of rock glacier to glacier water equivalent ratio, Azócar and Brenning (2010) state a ratio of 1:2.7 for the Arid Chilean Andes between 27° and 29° S (Azócar and Brenning, 2010), a ratio of 3:1 between 29° and 32° S where rock glacier dominant (Azócar and Brenning, 2010), and a ratio of 1:7 further south for the Andes of Santiago, Chile (33 °S) (Brenning, 2005b). Therefore, work from the Chilean and Argentinean Andes demonstrates that rock glaciers are more hydrologically important than they are in the European [Swiss] Alps, where their ratio is stated to be 1:83 (Brenning, 2005b). This existing work highlights the absolute importance of rock glaciers as stores of water in semi-arid high mountain areas of the Andes of Central Chile.

2.5 Remote sensing methods for surveying rock glaciers

Remote sensing (RS) offers a powerful tool for extensive broad extent geomorphological surveys (Slaymaker, 2001). Due to the contactless method employed by RS instruments, the resultant data are especially suited to use in environments where access is often difficult and/or limited (Kääb et al., 2005), such as the Bolivian Andes. The high quality of images provided through satellite and airborne sensors allow rock glaciers to be identified and mapped (e.g. Fig. 2.21). Scientists undertaking rock glacier inventories elsewhere in the world have successfully utilised RS data (e.g. Guglielmin and Smiraglia 1998; Humlum, 2000;

Esper Angillieri, 2009; Scotti et al., 2013) with multispectral satellite data being the primary source of spatial information for mapping landforms (Bishop et al., 1995; Paul et al., 2004).

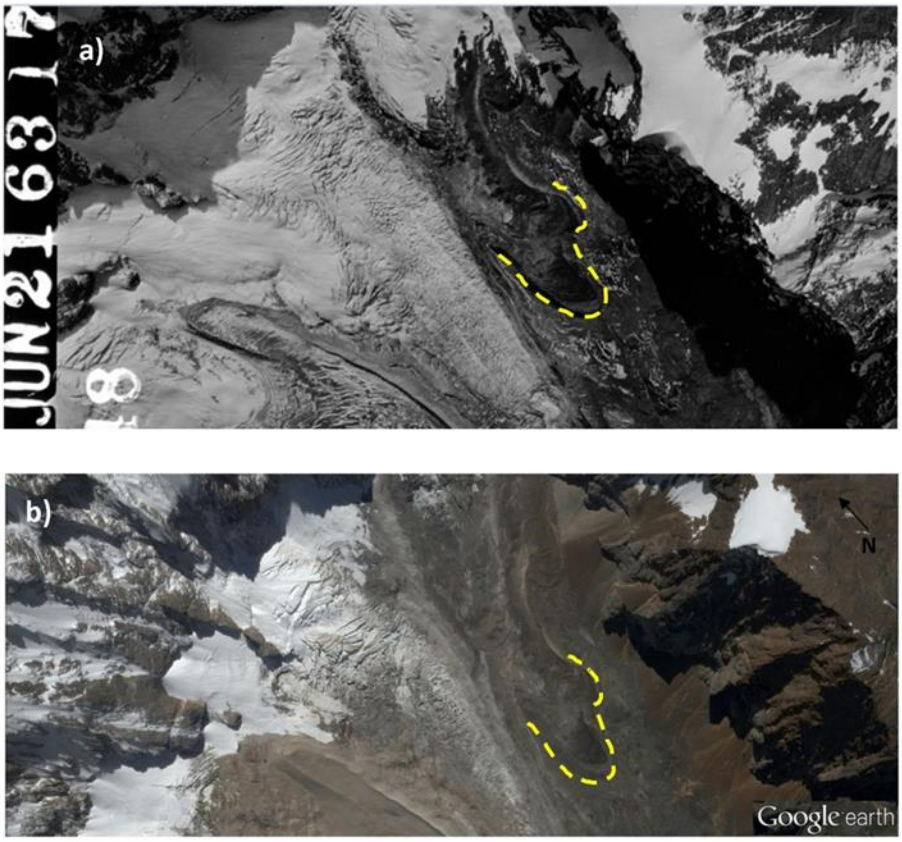

Figure 2.21 Fine resolution airborne and spaceborne RS data used for rock glacier identification and mapping. Bolivian relict rock glacier identified on Illimani using a) Aerial photography, 1963 (courtesy of Agua Sustentable) and b) Satellite image from Google Earth, 2014. Dashed yellow line represents the outline of the rock glacier lateral sides and front.

Fine (< 10 m) to moderate (10 - 100 m) spatial resolution satellite sensors (IKONOS, ASTER, SPOT 5, Quickbird, Landsat ETM+) provide useful data which can support the assessment of changes in the high-mountain cryosphere setting (such as change detection and monitoring of cryospheric features) (Quincey et al., 2005). One of the main advantages of using remotely sensed data collected from satellites is that it offers a synoptic monitoring capability with repeat-pass opportunities for long time series monitoring. Glacier length, area and volume changes can be monitored and measured with RS techniques that utilise repeat image data, and by including further data such as digital terrain models (DTM) (Kääb et al., 2002; Silverio and Jaquet, 2005; Kääb et al., 2006), enhanced mapping can be achieved. Therefore, this technique could potentially be used to monitor changes in rock glaciers, bearing in mind that a longer time period would be required to chart rock glacier dynamics as rock glaciers respond more slowly to environmental change than glaciers (Haeberli et al., 2006). At present, the most successful strategy for assessing the cryosphere, and forecasting changes, is through a combination of RS analysis embedded within geographical information systems (GIS) models and supported by field surveys for data validation and process understanding (Kääb et al., 2006). There is a risk of misinterpreting features seen on aerial photographs; therefore fieldwork is necessary to verify interpretations, demonstrating the importance of ground validation.

The ability to correctly identify landforms from remotely sensed data is partially determined by pixel size (spatial resolution) (Smith et al., 2000) alongside user expertise and ground validation data. In a comparative study by Paul *et al.* (2003), rock glaciers were identified using Landsat ETM+ satellite data (panchromatic band with 15 m spatial resolution) but surface morphology details were lacking because they were not resolved by the pixel resolution. It was only with satellite data with a spatial resolution finer than 5 m resolution where rock glaciers were shown to be able to be accurately mapped (Paul et al., 2003). However the cost per scene of sub-5 m resolution satellite data is expensive and this prevents the use of large extents spatially and/or temporally of satellite data (Table 2.2). This is especially a problem for NGOs with limited budgets for research and data acquisition. However, over recent years the use of Google Earth (e.g. Fig. 2.21) has allowed free access to fine spatial resolution data, although the data cannot be used the same way as they could be if the data were purchased directly from the supplier.

Dataset	Spatial resolution	Cost
IKONOS	<5 m [< 1m]	10 USD / km^2 (min 25 km^2)
RapidEye	<5 m	1.28 USD/ km^2 (min. 500 km^2)
SPOT	<5 m	2 Euro/ km^2 (min. 500 Euros)
Google Earth	Variable: <1 m to 30 m	Free
Landsat ETM+ / TM / MSS	Visible bands 30 m, thermal data 60 m	Free
ASTER DEM	Visible and NIR 15 m, short-wave infrared 30 m, thermal 90 m	Free
SRTM	90 m	Free

Table 2.2 Spatial resolution and cost of different satellite data

2.5.1 Mapping

Mapping is commonly used to determine the extent and distribution of glacial and periglacial landforms (Kääb et al., 2005). RS mapping techniques on aerial photography and satellite data can enable the production of a base map (Fig. 2.22) which should then be validated through fieldwork at a limited number of representative sites. Aerial photographs (e.g. Fig. 2.21a) have been used as the first step of mapping in numerous glacial and periglacial studies to identify and describe features such as rock glaciers (e.g. Smiraglia, 1992; Lieb, 1998; Payne, 1998; Baroni et al., 2004).

Currently, one key component inhibiting satellite data analysis is automated detection of rock glaciers (Bishop et al., 1995; Paul et al., 2004). Automated mapping has been used for glacial features (Brenning, 2009; Shukla et al., 2010) with glacier ice identification achieved through the combination of thermal data coupled with models that recognise pixels with high land surface reflectance. However, this is not easily transferred to rock glacier mapping. The debris surface of rock glaciers is thought to not produce a different spectral signal to the adjacent periglacial debris as both are derived from the same source, resulting in a lack of spectral discrimination (Brenning, 2009; Shukla et al., 2010). This poses a huge challenge for an automatic mapping approach (Brenning, 2009). Consequently, Brenning (2009) summarised that multispectral satellite data alone are not enough for the automatic detection of rock glaciers. This is a gap in rock glacier identification processing that has only recently been addressed (e.g. Toomey, 2011; Brenning et al., 2012a). Recent work is now exploring the possibility of using the most characteristic surface feature of ridges and furrows (Brenning et al., 2012a) as a possible method of identification, focusing on using complex computer vision approaches to achieve an automatic detection of rock glacier surfaces. This suggests the opportunity to explore pattern recognition and texture analysis of satellite data and this is addressed in Chapter 6 of the thesis.

Due to these inherent problems of rock glacier identification for automated mapping, the optimal approach for generating a rock glacier inventory is through manual identification of rock glacier features using expert knowledge (Casassa et al., 2002). Numerous rock glacier inventories have utilised manual mapping of rock glaciers from visual inspection of aerial photographs and satellite images (including Google Earth, Fig. 2.20b), supported by field work (e.g. Baroni et al., 2004; Brenning, 2005a; Esper Angillieri, 2009; Lillerorren and Etzelmuller, 2011; Kellerer-Pirklbauer et al., 2012; Krainer and Ribis, 2012; Scotti et al., 2013; Falaschi et al., 2014). Manual identification, delineation and hand digitisation of rock glaciers allows the information to be stored in a GIS for analysis (Fig. 2.22) which is beneficial because spatial variables describing, for example, their elevation, slope and length/width ratios, can be easily determined.

Terrain data, including digital elevation models (DEMs), are often RS derived, and are one of the most important data sets for investigating high-mountain environments, features and processes (Kääb et al., 2005), especially when combined with multispectral satellite data. DEMs can be used for visual analysis of topography, landforms and landscapes. They provide the most frequent method for extracting crucial topographic information (Kamp et al., 2005) such as elevation, aspect and slope, which can be used for rock glacier topographic analysis (Janke, 2005). For example, freely available ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM satellite data (30 m resolution) has been used to create a DEM of a volcano on the Chilean/Bolivian border and geomorphic parameters were extracted (Kamp et al., 2005). These parameters included elevation, aspect and slope angle. Kamp *et al.* (2005) found that the ASTER DEM was useful for macro- and meso-scale geomorphological interpretations. Paul *et al.* (2004) also state the importance of using DEMs derived from ASTER data for remote high-mountain regions.

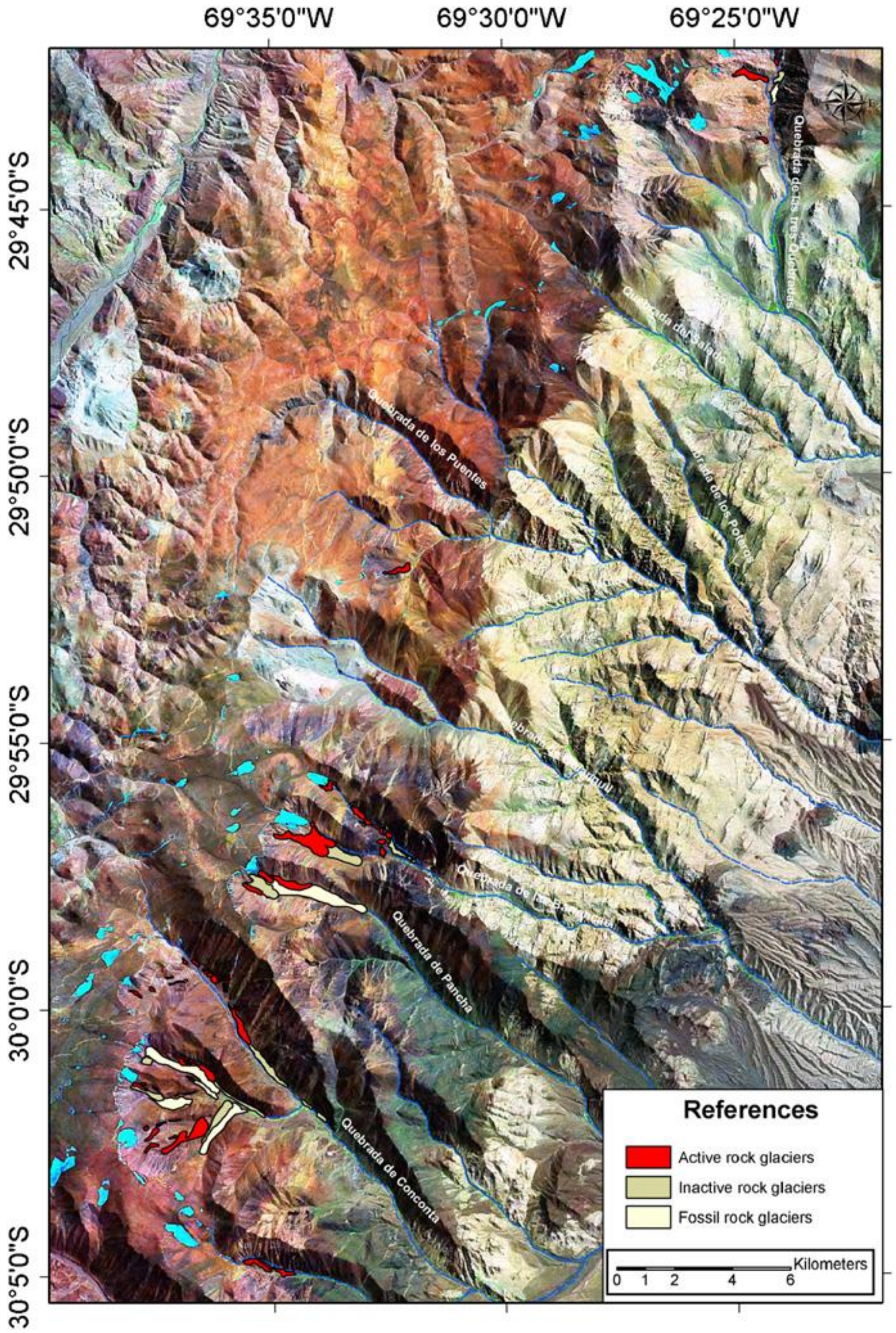

Figure 2.22 Rock glacier mapping in the Argentina Andes using remotely sensed data and complied in a GIS (Esper Angillieri, 2009, p. 154). Inventory completed using aerial photographs and digital satellite imagery (Landsat 7 TM+).

2.5.2 Limitations of using RS data in mountainous regions

Besides the advantages mentioned here, it is important to note that there are limitations associated with the use of RS data, especially in mountainous terrain, and these issues are explored in this section.

Identification and interpretation of rock glacier features using aerial photography and satellite data can be extremely time-consuming (Azócar and Brenning, 2010); however it does enable a much larger area to be covered compared to fieldwork, especially in such difficult terrain, with just a few sample sites needed for ground verification (Bolch et al., 2005).

Additionally, utilising RS can be very limited during unfavourable meteorological conditions such as cloud cover (Kääb et al., 2000). Mountainous regions accentuate errors caused by natural variations in topography, due to steep terrain and spatial complexity (Geospatial World, 2011) and several relief-induced factors can hinder, and in some cases prohibit, the use of spaceborne data. Relief can be problematic for high mountain cartography through horizontal displacements, shadows and differences in scale (Buchroithner, 1995). Climatic aspects which may also affect mountain cartography could include weather induced limitations such as clouds, cloud shadows, haze, ice and snow cover. There are also 'simple' effects of atmospheric aerosol contents which can result in differing grey values between the peaks and in the valleys due to the variation in thickness of the atmosphere (Buchroithner, 1995).

Procurement costs tend to increase in correlation with remotely sensed data spatial resolution, while the extent of the scene decreases (Paul et al., 2003) (Table 2.2). Although aerial photographs provide fine spatial resolution data (cms), aerial photographic surveys are generally very expensive to commission (Kaufmann, 1998) and this can prohibit the opportunity for repeat surveys at regular intervals. Some satellite data can now achieve similar resolution to aerial photography and even field mapping but costs are still high as these missions tend to be commercially operated. There are some satellite sensors that provide <1 m data resolution, such as QuickBird (Baltsavias et al., 2006), and more recently, commercial satellites that provide < 0.5 m data resolution (e.g. WorldView-2, WorldView-3). The potential for unmanned aerial vehicles (UAVs) to provide aerial photography at lower costs (Rango et al., 2006) could become prevalent in future rock glacier mapping.

Parallel to this cost, multiple surveys are required to enable monitoring of change over time so a long time series could cost a substantial amount. However, since the movement of rock glaciers tends to be slow, for example the Doesen rock glacier in Austria which moves several centimetres annually, the time period between sequential surveys should be at least two years (Kaufmann, 1998). Ideally, multiple images should be obtained at approximately the same time of year to limit the changes of cast shadow zones, which can disturb the visual analysis (Paul et al., 2007), and to enable comparisons of similar mass balance conditions. Access, availability and cost of this data are the main restrictions to using the finest spatial resolution data for NGOs.

In high mountainous terrain, orthorectification of satellite data is necessary if digitised rock glacier outlines wish to be combined with other georeferenced information (Paul et al., 2007). This is because high resolution data typically has a high relief displacement in hilly terrains. The orthorectifcation of satellite data is therefore necessary to correct for the spatial distances due to this displacement (Singh et al., 2010). This modelling requires a fine spatial resolution DEM parallel to accurate topographic maps for the collection of ground control points (GCPs) (Toutin and Chénier, 2011). GCPs are used to achieve a high geometrical accuracy (Marchesi et al., 2011) and enhance the orthorectification process. Spatial resolution affects topographic parameters (Lee et al., 2009); therefore, finer resolutions of DEMs can improve the more accuracy of the modelling output.

Despite these limitations, mapping and monitoring of the cryosphere can still be achieved, albeit with associated uncertainty. Furthermore, with increasing improvements and access to data, technology and computing there is potential for identification, mapping and monitoring improvements.

2.6 Summary

The existence and hydrological importance of rock glaciers in the Bolivian Andes has not been studied before, despite their hydrological significance in other parts of the Andes. Given the importance of high altitude hydrological buffers (e.g. glaciers) for Andean cities such as La Paz, especially during the dry season, it is important to investigate and quantify the other features of the cryosphere in the Bolivian Andes.

This is especially pertinent with the backdrop of current and future glacier recession. Changes in climate interlinked with glacier recession are projected to negatively affect water availability for domestic use, agriculture and HEP generation in the Bolivian Andes. Existing water supplies to the cities of La Paz and El Alto are already hampered by the loss in water through poor infrastructure. However, population increase and westernization of lifestyles is projected to put an increasing demand on water supplies, with negative implications on future water and food security.

Countries such as Bolivia are sensitive and vulnerable to this changing climate, and limited in their ability to adapt, due to high poverty levels and fewer resources to adapt. Furthermore, one restriction to adaption is the lack of observation and monitoring of climate systems and water supplies and critical gaps in present knowledge of the Andean mountain cryosphere, prohibiting better water resource management. Therefore, improving our understanding of rock glaciers will play a part in developing resilient water supplies for Bolivia and other arid regions.

Chapter 3 : Rock glacier inventory

Rock glacier distribution and characteristics have not been explored before in the Bolivian Andes. Here, this paper addresses this gap in knowledge of the Bolivian cryosphere through the completion of a rock glacier inventory, performed remotely using high resolution satellite data from Google Earth and validated by a program of field work. Further data and fieldwork photographs are provided here in the supplementary data. Rock glaciers were identified, classified (active or relict), and measurements such as elevation, aspect, length and width, were gathered. Using this data, key characteristics of Bolivian rock glaciers were analysed, both nationally and regionally. This rock glacier inventory was an important first step in producing the base of information needed for assessing hydrological importance (Chapter 4) and impacts of projected climate change (Chapter 5).

This paper has been published in *Permafrost and Periglacial Processes* (PPP) (Rangecroft et al., 2014b; Appendix 2). PPP was chosen for this manuscript because of the journal's relevant focus on cold, non-glacial geosciences, and on Earth surface cryogenic processes and landforms present in high mountain environments. PPP provided a platform for the effective communication of this research. I (SR) conducted the data collection and analysis and the write up of this manuscript. Karen Anderson (KA) and Stephan Harrison (SH) helped with advice regarding field work and contributed to the editing and formatting of the manuscript in line with their supervisory responsibilities. John Magrath (JM), Paula Pacheco (PP) and Ana Paola Castel (APC) all provided financial help and support with field work. Helen Jones from the University of Exeter drawing office, under guidance from myself, produced some of the figures for the manuscript.

A first rock glacier inventory for the Bolivian Andes

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Abstract

Rock glaciers in the arid Bolivian Andes are potentially important water sources, but little is known about their spatial distribution and characteristics. We provide the first rock glacier inventory for the region (15° - 22° S), based on mapping using remote sensing data in Google Earth, supported by field validation. Of the 94 rock glaciers identified, 57% were classified as active (containing ice) and the remaining as relict (not containing ice). The majority (87%) have a southerly aspect (SE, S, and SW), and the rock glacier length and area averages were 500 m and 0.12 km^2, respectively. We approximate the lower limit of permafrost to be at 4700 m in the Bolivian Andes, with the mean minimum altitude of rock glacier fronts (MAF) estimated to be 4980 m for active rock glaciers, and about 100 m lower for relict rock glaciers. The inventory provides an important first step towards assessing the spatial distribution of regional permafrost as well as information to allow permafrost-based water resources in the Bolivian Andes to be understood against a backdrop of severe glacier recession.

Keywords: Rock glacier, inventory, Bolivia.

3.1 Introduction

Rock glaciers are key stores of frozen water in arid mountains (Francou et al., 1999; Brenning, 2005a; Azócar and Brenning, 2010; Kellerer-Pirklbauer et al., 2012; Rangecroft et al., 2013). In the dry Andes, glaciers are small and limited in their distribution (Esper Angillieri, 2009) because the equilibrium line altitude (ELA), where glacier accumulation balances with ablation (Zemp et al., 2007), exceeds some of the highest peaks (> 6000 m) (Francou et al., 1999), and precipitation is scarce. Research on alternative stores of water at high elevations is needed in many regions of the world (Brenning et al., 2007) because of the projected scarcity of water if glacier recession continues (Bradley et al., 2006). Bolivian glaciers have lost roughly half of their volume in the past 60 years (Soruco et al., 2009) yet they provide one of the main sources of water for drinking, agriculture and energy generation (Jordan, 1998; 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 La Paz (Vergara, 2009; Soruco, 2012). In view of current and projected glacier recession, the contribution to water supplies from glaciers is expected to reduce (UNFCCC, 2007), whereas that from rock glaciers is likely to increase (Schrott, 1996; Millar and Westfall, 2008).

Rock glaciers have been inventoried in various mountain regions, with the highest density of research in the European Alps (e.g. Guglielmin and Smiraglia, 1998; Curtaz et al., 2011; Kellerer-Piklbauer et al., 2012; Krainer and Ribis, 2012; Scotti et al., 2013), with increasing research activity in the South American Andes (Brenning, 2005a; Esper Angillieri, 2009; Falaschi et al., 2014). Although rock glaciers are abundant and locally important to long term water storage in the semi-arid Chilean Andes (Trombotto et al., 1999; Brenning, 2005a), their contribution to mountain water supplies in other parts of the Andes, such as Bolivia, is uncertain. To mitigate the impacts of climate change it is important to understand all inputs to the mountain hydrological cycle, including rock glaciers.

The primary aim of this study was to map the distribution of rock glaciers across Bolivia, and summarise the results of this new inventory. This work represents an important first step towards addressing water resource issues in the region, and by undertaking a survey of the current permafrost based water resources, their hydrological contribution and importance at local, regional and national scales can be better understood. Rock glacier genesis is beyond the scope of this study.

3.1.1 Study Area

Bolivia is situated in the central, dry part of the South American Andes (Payne, 1998). Its distinctive climate has a wet season (Dec - Feb) and a dry season (May - Aug) (Francou et al., 2003), with aridity increasing southwards (Fig. 3.1). The rock glacier inventory encompasses the two Cordillera mountain ranges between 15° S and 22° S (Fig. 3.1), home to 20 % of the world's tropical glaciers (Rabatel et al., 2013). It divides the Bolivian Andes into three regions based on location, climate and topography where rock glaciers occur (Fig. 3.1): i) the Cordillera Real; ii) Sajama; and iii) the Western Cordillera.

The 'Cordillera Real' is a glaciated fold mountain range (15° - 17° S) close to La Paz. With the wettest climate of the Bolivian Andes (Fig. 3.1), this region contains the highest density of glaciers, and these are currently receding (Francou et al., 2003; Vergara et al., 2007a). The bedrock comprises mainly resistant rocks of early Paleozoic age that form prominent massifs. The 'Sajama' and 'Western Cordillera' regions are located along the Bolivia-Chile border in the mountain chain of the Cordillera Occidental, which is composed of Cretaceous-Tertiary volcanoes surrounded by Quaternary age deposits; all the high peaks there are volcanic cones. Sajama (17° - 18° S) is centred around the isolated ice-capped volcanic mountains in the Sajama National Park (Fig. 3.1). The Western Cordillera extends south of Sajama, along the dry, barren mountain range of the Cordillera Occidental (18° - 22° S) (Fig. 3.1). Almost no glaciers exist in this region (Francou et al., 1999) as rainfall is very low (Fig. 3.1); annual precipitation is estimated to be less than 250 – 300 mm on the summits (Vuille and Amman, 1997). This area is the best example of arid high mountains in the inner tropics (Francou et al., 1999).

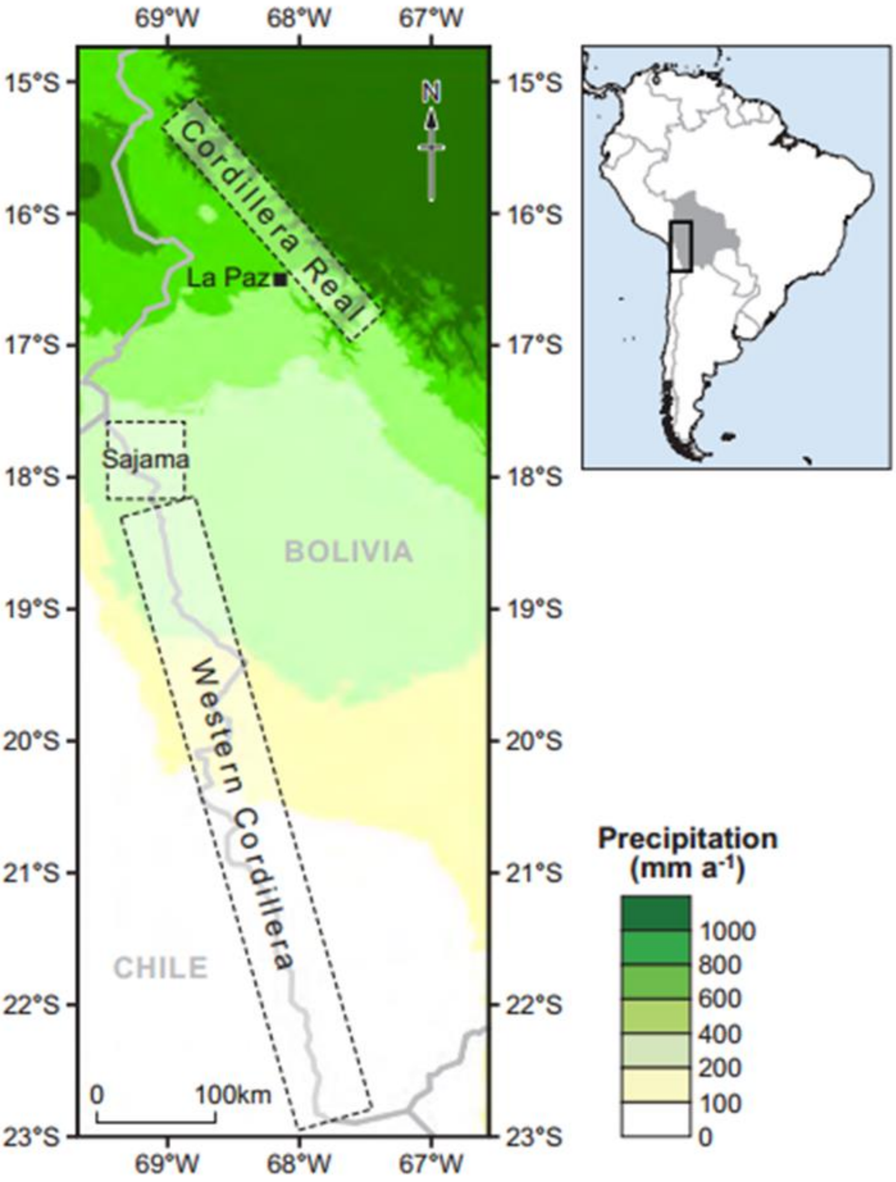

Figure 3.1 Map of the study area showing mean annual precipitation (MAP) rates along the Bolivia Andes using WorldClim (http://www.worldclim.org/) 0.5° resolution data for 1950 – 2000. Three study regions have been identified and are subsequently used in this research: i) Cordillera Real; ii) Sajama; and iii) Western Cordillera. Country boundaries are represented with a solid grey line.

3.2 Methods

Unlike glaciers, rock glaciers cannot easily be mapped automatically from remotely sensed data because they are spectrally similar to their surroundings (Brenning, 2009; Shukla et al., 2010). The optimal approach for generating this inventory was therefore to manually identify rock glaciers (Casassa et al., 2002) (Table 3.1) and digitise them. This inventory was achieved using expert photomorphic mapping from Google Earth and a 30 m Global Digital Elevation Model (GDEM) derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor.

Characteristic features used for identification	**Active**	**Relict**	**Notes**
Frontal ramp	Steep (typically ≥30°)	Gently sloping (typically <30°)	Frontal slope indicating the presence of ice (Baroni et al., 2004, p. 251). An angle exceeding the angle of repose indicates the presence of ice; however angle of repose depends on lithology.
Rock glacier body	Swollen body, indicating ice presence	A flattened body, result of ice disappearing	Possible swollen body indicating the presence of ice (Baroni et al., 2004, p. 251)
Surface texture	Signs of flow: e.g. ridges and furrows	Less defined flow lines	Well-developed longitudinal and transversal ridges and furrows which act as signs of flow (Kääb and Weber, 2004, p. 379)

Table 3.1 Characteristics used to identify active and relict rock glaciers

3.2.1 Remote sensing

Initial rock glacier mapping and evaluation used high-resolution (5 to 30 m) remote sensing data available through Google Earth (version 7.1.1.18888, Google Inc., California, USA), applying the criteria identified in Table 3.1, and supported with field validation. Google Earth provides a user friendly GIS tool that facilitates exploration of satellite data that are freely available and is well suited for assisting a developing world non-governmental organisation (e.g. the Bolivian NGO 'Agua Sustentable'). Additionally, such data are particularly useful in large-scale geomorphological surveys (Slaymaker, 2001; Shukla et al., 2010) and where field access is difficult and/or limited (Kääb et al., 2005). Google Earth data have been applied across a range of research areas (Butler, 2006; Nourbakhsh et al., 2006; Ballagh et al., 2007; Chang et al., 2009; Sheppard and Cizek, 2009; Ballagh et al., 2011; Yu and Gong, 2012) and complement other satellite data or aerial photographs for geomorphological mapping (e.g. Brenning, 2005a; Morén et al., 2011). Uncertainties to consider with this approach relate to the acquisition of remotely sensed data over mountainous terrain subject to unfavourable meteorological conditions, topographic distortions and geometric uncertainties (e.g. differences in scale, horizontal displacements and shadows; Buchroithner, 1995).

3.2.2 Digitising landform characteristics

Planimetric landform characteristics extracted and recorded for each rock glacier (Fig. 3.2) included geographic coordinates, elevation (minimum and maximum), length (parallel to flow), width (perpendicular to flow), aspect (main aspect of flow), and surface texture and features. The Minimum Altitude at the Front (MAF) of each rock glacier was determined by locating the elevation of the lowest point on the rock glacier snout where it meets the slope beneath it. The maximum elevation at the head of the rock glacier (MaxE) was similarly recorded; however, it is acknowledged that defining the upper boundary of a rock glacier is difficult (Krainer and Ribis, 2012). Consistent judgement was made on where the upper boundary of the rock glacier meets the input accumulation zone above it. Measurements of rock glacier length and width used the ruler tool on Google Earth (Fig. 3.2). Aspect was divided into 8 classes and manually defined along the main direction of the flow of the rock glacier (Fig. 3.2). Rock glacier surface area (km^2) of the digitised polygons was calculated using Google Earth Pro.

Although rock glaciers are difficult to identify due to their composition of rock debris supplied from surrounding slopes (Shukla et al., 2010), morphological analysis can help to distinguish them from protalus lobes, debris-covered glaciers, rock slope failures and rock avalanches (Hamilton and Whalley, 1995; Seligman, 2009; Jarman et al., 2013). The length:width ratio distinguishes rock glaciers from other periglacial features (Harrison et al., 2008) such as protalus lobes and ramparts. A length:width ratio greater than 1 represents a tongue-shaped rock glacier (Guglielmin and Smiraglia, 1998; Harrison et al., 2008) and a ratio of less than 1 implies a lobate rock glacier or a protalus lobe or rampart. Although other permafrost features were identified (e.g. detachment failures), only active and relict rock glaciers meeting the identification criteria in Table 3.1 were analysed.

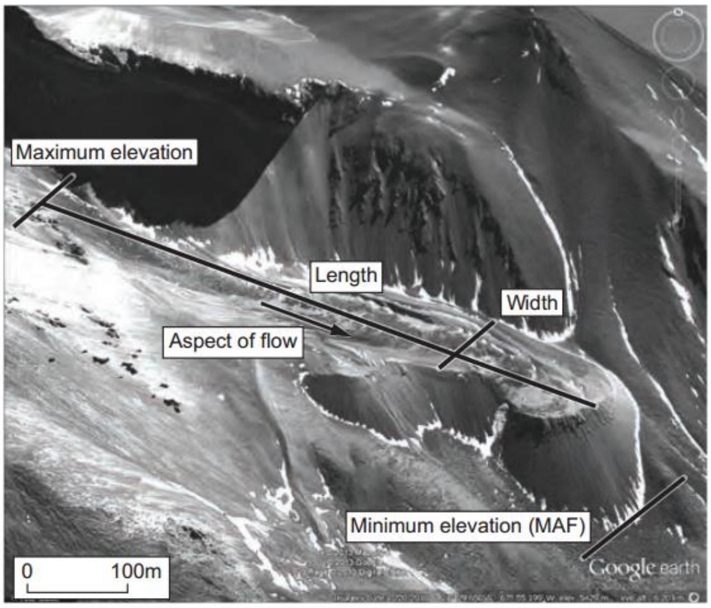

Figure 3.2 Annoted diagram of rock glacier parameters on Caquella rock glacier [C110a], Bolivia (21°05'S, 67°92' W). Source: Google Earth: DigitalGlobe, 2013; Mapcity, 2013, imagery date 20/07/2010.

The activity status of rock glaciers was determined according to their assumed ice content and flow behaviour using morphological and geomorphological criteria from satellite image interpretation (Table 3.1) and/or field surveying. We sub-divided them as active/inactive (containing ice) or relict (no ice content) (Barsch, 1996; Baroni et al., 2004). Key features for identification include: surface micro-relief such as ridges and furrows, representing decelerating flow (Barsch, 1996); steep well-defined lateral margins; and a steep frontal snout, if ice is present (Payne, 1998; Harrison et al., 2008). Frontal slopes, with an angle usually greater than that of repose (~30-35°, depending on the material), indicate ice within the rock glacier mass (Barsch, 1996). Active rock glaciers are known to contain 40 – 60 % ice (Barsch, 1996; Brenning, 2005a). Inactive rock glaciers also contain an ice core protected by sediment but are no longer mobile due to melting of most of the upper layers within the frontal slope (Barsch, 1996; Scotti et al., 2013). Relict rock glaciers no longer contain ice and are characterized by collapse structures on their surface, more subtle surface relief and shallower frontal and lateral slope angles (< 30°, depending on the material) (Barsch, 1996; Scotti et al., 2013) than active features, and often have vegetated surfaces (Scotti et al., 2013). Relict rock glaciers are usually found at lower elevations than active rock glaciers (Baroni et al., 2004). Active rock glaciers typically occur between the 0 °C isotherm and the snow line, whereas relict rock glaciers generally occur just below the permafrost level/0 °C isotherm.

Mean rock glacier parameters were statistically compared between regions using SPSS (version 19, IBM Corp, Armonk, NY, USA). ANOVA, General Linear Models and Tukey post hoc tests were used to investigate regional differences in rock glacier parameters according to their activity. All statistical significance was tested at the 0.05 level. ArcGIS (version 10.1, ESRI, Redlands, CA, USA) and R (version 3.0.0, R Core Team, Vienna, Austria) were used to assess the relationship between mountain slope aspect and rock glacier orientation.

3.2.3 Field validation

Field surveys were conducted during July - August 2011 and July - August 2012 in order to assess the reliability of the photomorphic mapping and rock glacier classification. Rock glaciers surveyed are identified in Tables 3.5 – 3.10 in the supplementary data file. Surveys validated rock glacier identification and activity classification by observing their features and measuring their frontal slope angle using an inclinometer. In existing rock glacier inventories vegetation has been used as a further characteristic for determining rock glacier activity (e.g. Seligman, 2009; Scotti et al., 2013); however, here we refrained from relying on this proxy without further information on the ecology and plant types. Furthermore, in Bolivia's arid environment vegetation is sparse and with a lack of other studies from the region, it was not a critical factor in classifying rock glacier activity.

3.3 Results

A total of 94 rock glaciers were identified in the Bolivian Andes (Table 3.2; Fig. 3.3; Fig. 3.4), of which 54 (57 %) were designated as active and the remaining as relict (43 %). 89 % of the rock glaciers were classified as tongue-shaped. 87 % were developed with a southward flow direction. 90 % of the rock glaciers were situated between 4700 and 5200 m altitude, with 6 % occurring above 5200 m and 4 % below 4700 m. The calculated mean MAF for active rock glaciers was 4983 m (± 30m), and 4870 m (± 30m) for relict ones (Table 3.2). Rock glacier characteristics were analysed at a national and a regional level. Tables S3.1 – S3.6 in the supplementary data file detail the information for each rock glacier recorded.

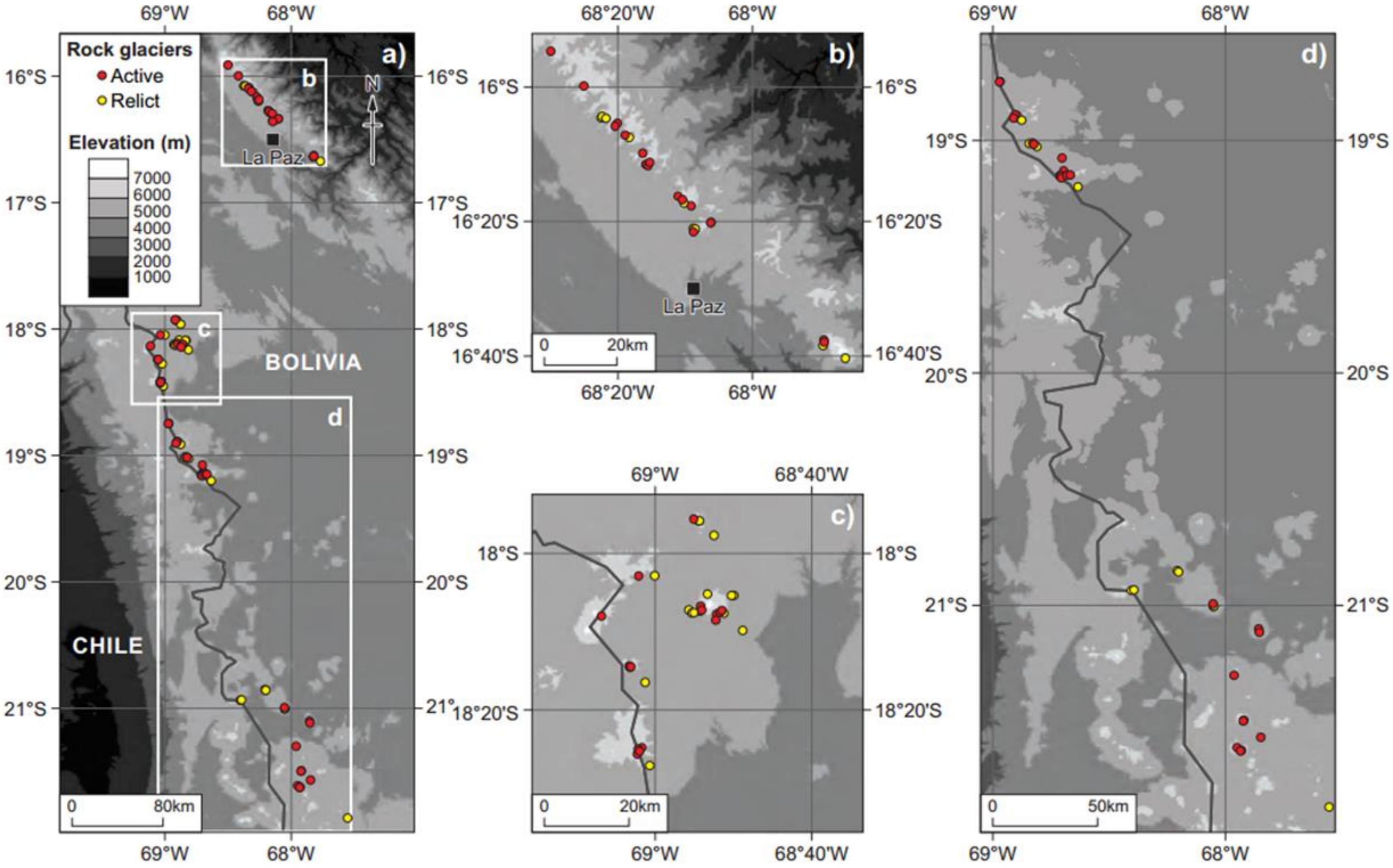

Figure 3.3 National and regional rock glacier inventories for the Bolivian Andes using ASTER GDEM (30 m resolution): a) Nationally (15°-22°S) with regions outlined in boxes; b) Cordillera Real (15°-16°S); c) Sajama region (17°-18°S); d) Western Cordillera region (18°-22°S).

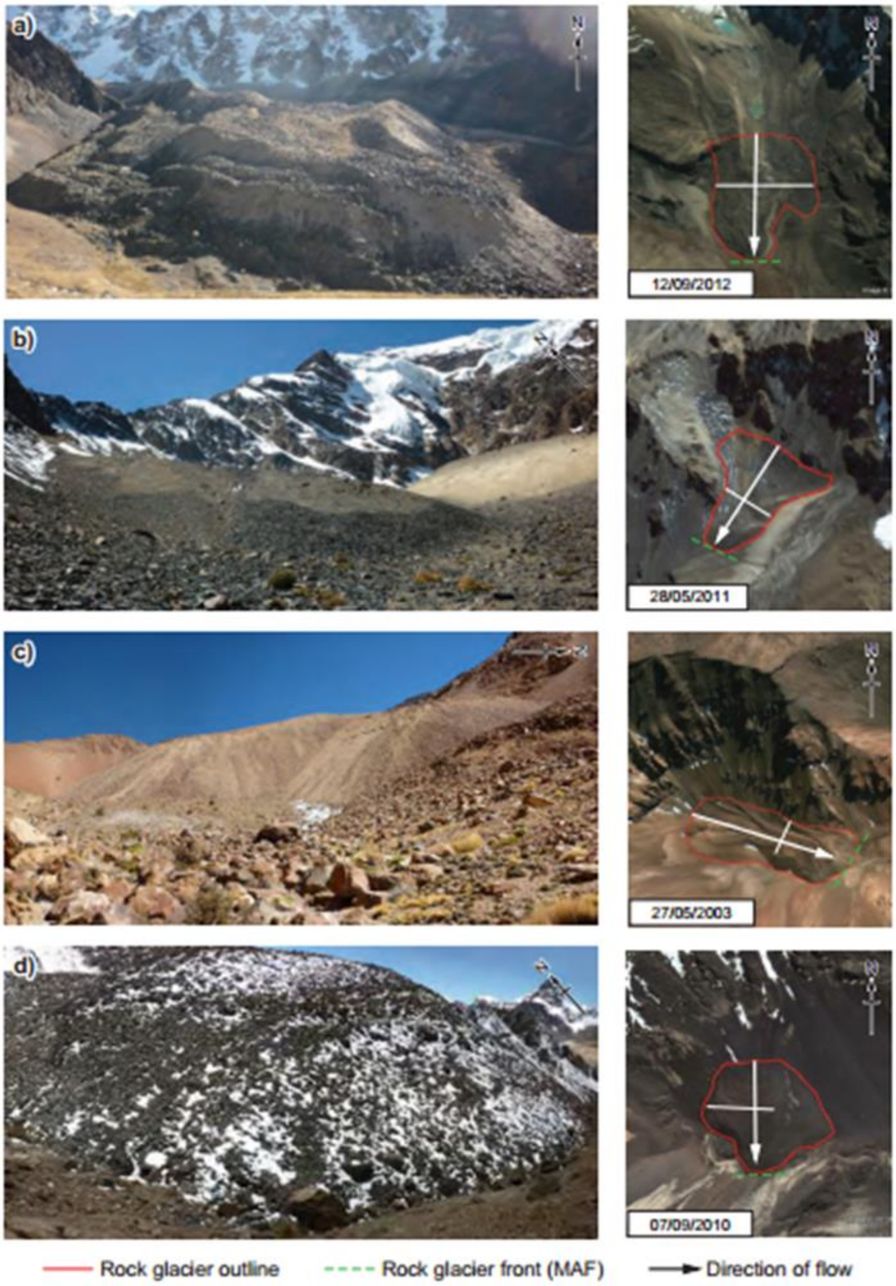

Figure 3.4 Rock glaciers visited during field work 2011 and 2012 with corresponding Google Earth screen shots with imagery date: a) Huayna Potosi rock glacier [A39a] 16°17’55 S, 68°09’05W; b) Illimani rock glacier [A40a] 16°37’44 S, 67°49’25 W; c) Chiguana rock glacier [C107a] 21°06’09 S, 67°51’13 W; d) Tuni rock glacier [A20a] 16°11’48 S, 68°15’28 W. Rock glacier outlines and fronts are highlighted on the Google Earth images. Approximate orientations of the rock glaciers and the photographs are indicated.

	Number of features	(%)	MAF* (m)	MaxE** (m)	Length (m)	Width (m)	Area (km^2)	Aspect
Active	54	(57)	4983	5162	552	239	0.132	SE
Relict	40	(43)	4870	5009	432	253	0.108	S

Table 3.2 Key mean characteristics for active and relict rock glaciers
****Minimum altitude at Front. **Maximum Elevation of rock glacier.***

3.3.1 Rock glacier elevation and range

Rock glaciers occurred within an elevation range of 4475 m to 5345 m (Fig. 3.5; Fig. 3.6). On average, active ones occurred at higher elevations than relict ones. Nationally, the mean MAF for all active rock glaciers was ~4985 m (± 30 m) (Table 3.2), with a range of 4709 to 5345 m (Fig. 3.5; Fig. 3.6a), while the most frequent elevation band was 4900 - 5000 m (28 %). Over half of the active rock glaciers (52 %) were situated in the elevation bands 4900 - 5100 m (Fig. 3.5). The highest active rock glacier was located in the Sajama region [B124a]. The mean MAF for relict rock glaciers was roughly 100 m lower, at 4870 m (± 30 m) (Table 3.2), with a range of 4475 to 5202 m (Fig. 3.5; Fig. 3.6b). The highest relict rock glacier was also situated in the Sajama region [B118b]. Over a third of the relict rock glaciers were situated in the elevation band 4800 - 4900 m (35 %), with 58 % of them between 4800 and 5000 m (Fig. 3.6b). The box plots of Figure 3.5 show that the Western Cordillera had the largest elevation spread of both active and relict rock glacier elevations, whereas the Cordillera Real had the smallest range of active rock glacier MAFs (Fig. 3.5).

Regionally, larger differences were observed between active and relict rock glacier elevations (MAFs) than on the national scale, although no significant difference was found (ANOVA: F-value = 5.756, *df* within groups = 1, between groups= 88*, p = 0.138*), presumably because of similar MAFs in the Cordillera Real (Fig. 3.7). Active rock glaciers in Sajama were on average at 175 m higher elevations than relict ones. Equally, active rock glaciers in the Western Cordillera were 173 m higher than relict ones there (Table 3.3). Across the regions, combined active and relict rock glaciers of Sajama were found at significantly different elevations compared to those in the Western Cordillera region (*p=0.007*) and also the Cordillera Real (*p=0.001*) (Linear Model: F-value: 3.697, *df* within groups = 2, between groups = 88). However those in the Cordillera Real and Western Cordillera were not of significantly different elevations (*p=0.949*).

Tukey post hoc testing (ANOVA: F-value: 8.161, *df* within groups = 5, between groups = 88, *p* = <*0.001*) showed that active rock glacier MAFs in Sajama were statistically at higher elevations than in the other regions (Fig. 3.7): Cordillera Real (*p* = *0.002*) and Western Cordillera (*p* = *0.018*). Sajama's relict rock glacier MAFs were also found at significantly higher elevations than relict MAFs in the Western Cordillera *(p=0.048).*

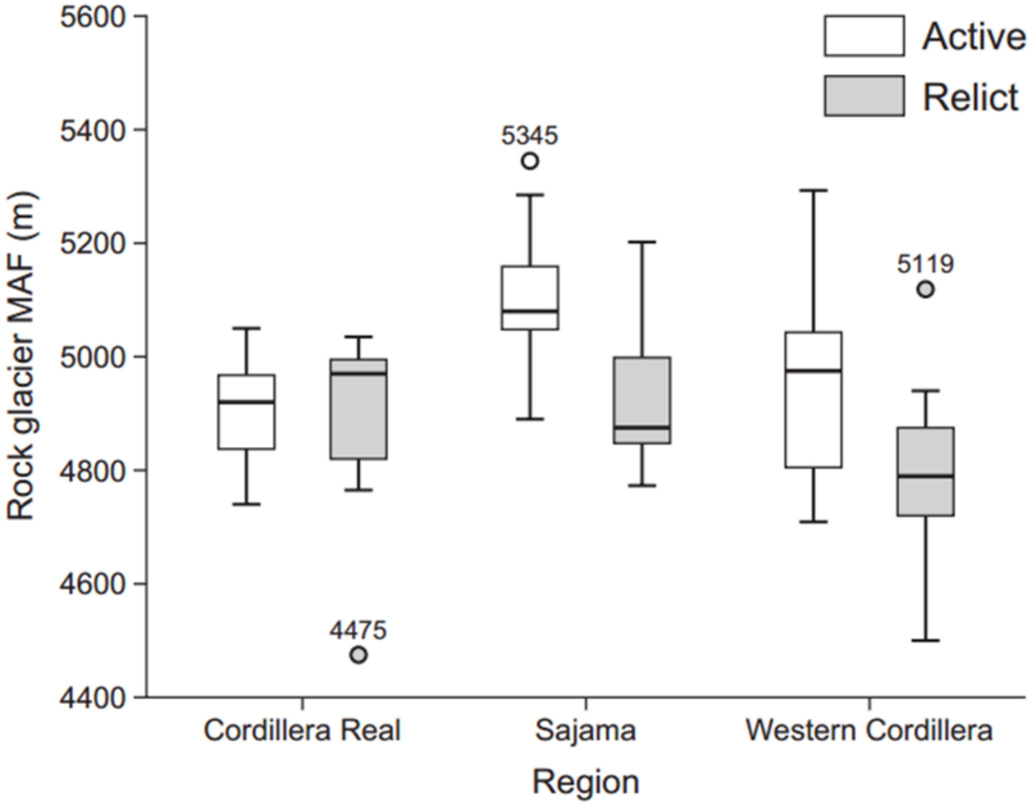

Figure 3.5 Box plots illustrating the regional analysis for rock glacier MAFs. Active rock glaciers are white and relict rock glaciers are grey.

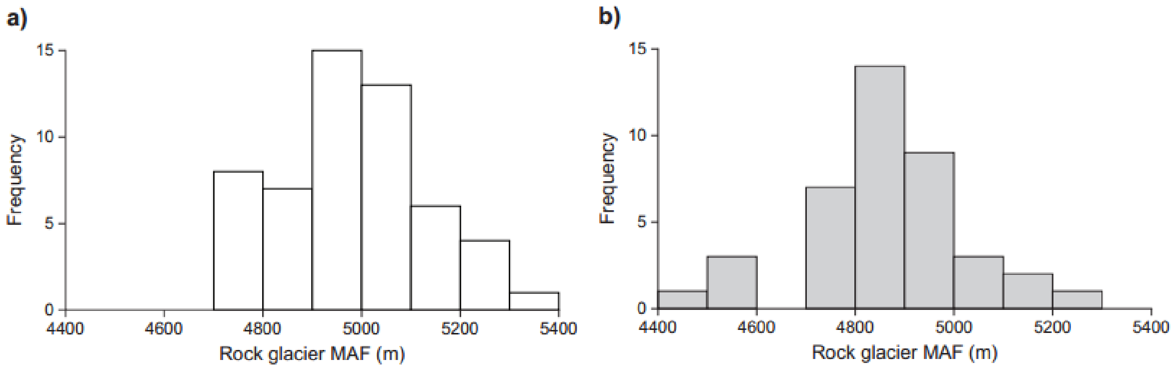

Figure 3.6 National rock glacier MAF analysis: Histograms for a) active and b) relict rock glacier MAF elevations.

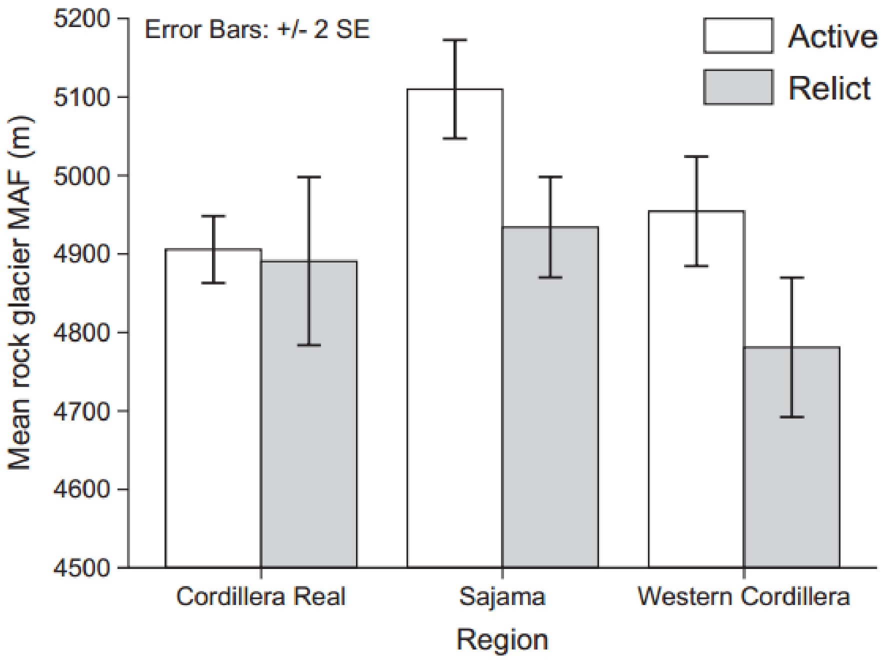

Figure 3.7 Regional analysis of active and relict rock glacier elevation represented by average MAFs with ± 2 standard error bars.

Region	Area of region (km^2)	Activity Status	Number of features	Mean MAF* (m)	Mean MaxE** (m)	Mean feature length (m)	Mean feature width (m)	Mean area (km^2)	Modal aspect
Cordillera Real	~7050	Active	16	4906	5033	380	212	0.07	SW
		Relict	10	4891	5036	378	150	0.08	S
Sajama	~4000	Active	15	5110	5307	753	242	0.20	SE
		Relict	16	4934	5073	519	252	0.13	S
Western Cordillera	~25000	Active	23	4954	5158	541	253	0.13	SE
		Relict	14	4781	4915	373	328	0.09	SW
Total	36050		94						

Table 3.3 regional rock glacier characteristics
****Minimum altitude at Front. **Maximum elevation of rock glacier.***

3.3.2 Aspect

South-facing slopes are the most suitable for rock glacier development and formation. 87 % of rock glaciers in the inventory have developed on south-facing aspects (SE, S and SW) (Fig. 3.8), with SE being the predominant aspect (34 %). 88 % of the active rock glaciers had a main flow direction to the south, and 86 % of the relict ones also had south-facing aspects. Such aspects have allowed rock glaciers to exist at lower elevations (Fig. 3.8a), in varying sizes, including the largest rock glaciers in the country (Fig. 3.8b). Figure 3.9a shows that the frequency of hillslope aspects in the Bolivian Andes is relatively uniform, whereas Figure 3.9b shows a strong clustering of active rock glaciers on southerly-facing slopes. Further analysis of these data sought to determine rock glacier density at each aspect for all pixels above the lowest MAF (4709 m; Figure 3.9c); this figure also indicates that south facing slopes having a much greater propensity for rock glacier formation and persistence.

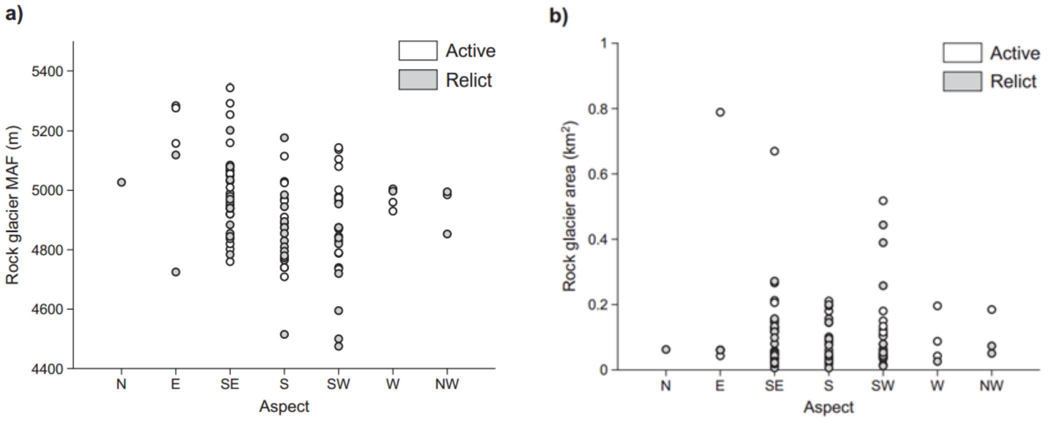

Figure 3.8 Scatter plots of rock glacier aspects
a) Scatter plot of all MAF elevation against categorised rock glacier aspect. b) Aspect plotted against rock glacier area. Active and relict rock glaciers are denoted by the colours white and grey, respectively.

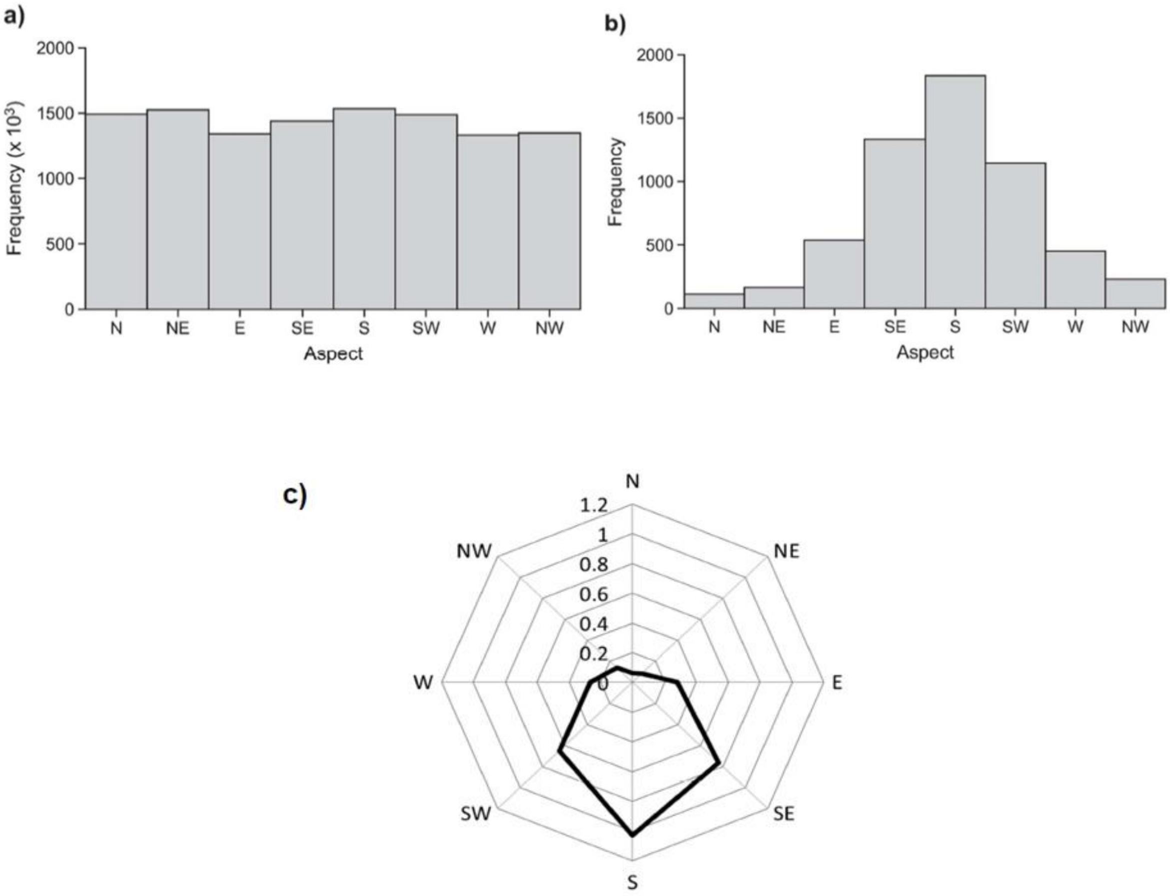

Figure 3.9 Histrogram of slope aspect
for a) all mountain slopes in the study regions; and b) only active rock glaciers; c) Radar plot demonstrating the active rock glacier densities for each aspect for all data in the Bolivian Andes above the lowest MAF (4709m). Data extracted from ASTER GDEM (30 m resolution).

3.3.3 Rock glacier morphology

89 % of the rock glaciers in the study area are tongue-shaped, and this proportion is similar between active and relict forms (91 % and 87 % respectively). Each region had at least one rock glacier longer than 1 km, but overall 93 % of the rock glaciers were less than 1 km long, with an overall average length of 500 m. On average, Sajama had the longest active ($\bar{x}$ = 753 m ± 30 m) and relict ($\bar{x}$= 519 m ± 30 m) rock glaciers in Bolivia (Fig. 3.10a) and the Cordillera Real had the smallest active ($\bar{x}$ = 380 m ± 30 m) and relict ($\bar{x}$ = 378 m ± 30 m) ones (Table 3.3; Fig. 3.10a). However, rock glacier length did not differ significantly between regions (ANOVA: F-value = 5.18, *df* within groups = 2, between groups = 88, *p=0.162*).

In total, it is estimated that rock glaciers cover 11 km^2 of the Bolivian Andes (Table 3.4). Individually, rock glacier area varies between 0.006 - 0.789 km^2, a similar range to that in the Chilean Andes (Brenning, 2005, p.234). Mean rock glacier area was 0.12 km^2, with a median area of 0.08 km^2 (Table 3.4). In total, 56 % of the rock glaciers were smaller than 0.1 km^2. The largest rock glaciers were found in Sajama, with active ones averaging 0.2 km^2 (Table 3.3). No correlation was observed between rock glacier length and elevation (Linear model: *r=0.07*, *df=92, p=0.501*) (Fig. 3.10b), and between rock glacier area and elevation (*r=0.01, df=92, p=0.929*). Similarly, no significant correlation was seen between latitude and both rock glacier length (*r=0.056, df=92, p=0.591*) and area (*r=0.052, df=92, p=0.616*). Bolivian rock glaciers are of similar size or slightly larger than rock glaciers elsewhere (e.g. Colorado, Austria) (Table 3.4), but their abundance in Bolivia is much lower.

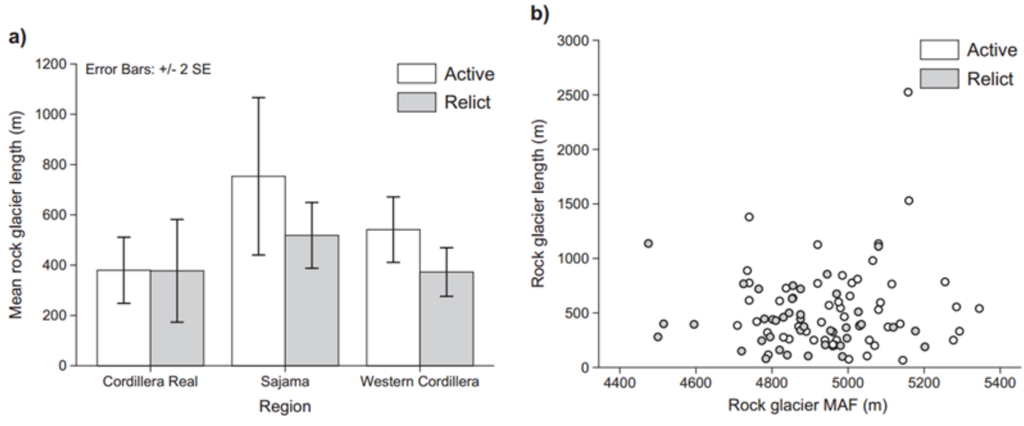

Figure 3.10 Rock glacier length
a) Regional analysis of average rock glacier length with error bars representing ± 2 standard error; b) Elevation, represented by rock glacier MAF, plotted against length.

Inventory	**Number of rock glaciers**	**Average rock glacier area (km^2)**	**Median rock glaciers area (km^2)**	**Total rock glacier surface area (km^2)**	**Reference**
Bolivia	94	0.12	0.08	11	-
San Juan mountains, Colorado	756	0.064	0.051	70	Brenning et al., 2007
Tyrolean Alps, Austria	3145	0.088	-	167.2	Krainer and Ribis, 2012
Eastern European Alps	347	0.061	-	21.3	Kellerer-Pirklbauer et al. 2012

Table 3.4 Rock glacier size from this inventory compared to other rock glacier inventories

3.4 Discussion

This Bolivian rock glacier inventory has identified 54 active (and 40 relict) rock glaciers in the high arid mountains. Along the Cordillera Occidental, rock glaciers cluster around a few isolated mountain peaks (e.g. Sajama 18° S, 68° W). This is recognised as 'island permafrost', common across other parts of the Central Andes (Travassos et al., 2008). The MAF for rock glaciers is often considered a good approximation of the lower limit of discontinuous permafrost (Scotti et al., 2013). No active rock glaciers are found below 4,700 m, implying that this is the lower limit of permafrost in the Bolivian Andes. This value is slightly higher but broadly consistent with that of 4,500 m for the lower limit of active rock glaciers in the Argentinian Andes at 22° 30’ S (Corte et al., 1982). Bolivian rock glaciers occur at higher elevations (> 4,400 m) than of those in the Chilean Andes, where Brenning (2005) identified rock glaciers at 3,000 m and higher. Rock glacier size appears to be similar to those in recent European rock glacier inventories (Krainer and Ribis, 2012; Kellerer-Pirklbauer et al., 2012), yet their frequency is lower, and thus their total surface area is less than those in the European Alps (Table 3.4).

Optimum conditions for rock glaciers occur in areas with high elevation, cold temperatures and low precipitation (Baroni et al., 2004): conditions characteristic of the Bolivian Andes. The key controls on rock glacier characteristics and formation are thought to be climatic conditions, glacial history and rock supply (Johnson et al., 2007; Guglielmin and Smiraglia, 1998). On a regional scale, rock glacier distribution is climatically controlled by precipitation and temperature, the latter dependent on elevation and aspect. Despite the availability of appropriate climatic conditions for rock glacier formation and persistence in the Bolivian Andes, the distribution of these landforms there is limited. This suggests that other factors such as rock supply, lithology, glacial history, competition with glaciers and geothermal fluxes (Brenning, 2005a; Johnson et al., 2007) ultimately determine the locations where they form and persist. Unfortunately, high quality lithological data were not available for use in this study.

Even though temperature is a key control on rock glacier activity, no correlation was observed between elevation and rock glacier length (*r=0.07*) or area (*r=0.01*), also suggesting the importance of other factors such as debris supply. However, the inventory did show that aspect is an important parameter for rock glacier formation (Fig. 3.9b). In the Southern Hemisphere south-facing slopes are more likely to host glaciers and rock glaciers (Esper Angillieri, 2010) in association with reduced insolation and increased accumulation of snow, ice and rock debris (Esper Angillieri, 2009). This inventory also suggests that southerly aspects, with their reduced insolation, allow rock glaciers to exist at lower elevations than at other aspects (Figure 3.8a).

Rock glaciers develop between the 0 °C isotherm and the regional snow line (e.g. Payne, 1998; Milana and Maturano, 1999). The elevation at the front of active rock glaciers, the MAF, corresponds closely to the 0 ℃ isotherm, which this inventory suggests lies at 4900 – 5000 m. Relict features interpreted as former rock glaciers reflect a change in the 0 °C isotherm elevation, associated with changes in climate and/or debris supply (Esper Angillieri, 2010). The mean difference of 100 m that we observed between active and relict rock glaciers (Table 3.2) represents this upward shift in the isotherm over time. The modern 0 °C isotherm descends from north to south along the Western Cordillera (Payne, 1998) but the ELA increases with aridity, leading to a bigger niche for rock glaciers. This is demonstrated by the larger range of rock glacier MAFs in this region (Fig. 3.5). However, with rising regional temperatures there will be smaller niches for active rock glaciers to occupy as the 0 °C isotherm moves closer to, or above, mountain summits. Therefore a warming climate will decrease the number of active rock glaciers and increase the number of relict ones (Krainer and Ribis, 2012). Equally, it can also be hypothesised that rock glaciers may become more frequent in the Cordillera Real as glaciers retreat and increased debris supply buries their surfaces, producing glacial-derived rock glaciers.

In the wetter climate of the Cordillera Real, conditions favour glaciers. This smaller niche for rock glaciers was confirmed by our analyses, which determined that the Cordillera Real had the smallest elevation range of active rock glaciers (4740 – 5050 m) of the three regions of Bolivia (Fig. 3.5). The drier Western Cordillera had a larger total area of rock glaciers, a surface area of 2.88 km^2 for active rock glaciers, and the largest range of elevations of all regions (4500 – 5255 m). From the remotely sensed data we observed that rock glaciers were also better developed in the Western Cordillera. Collectively, these observations suggest that conditions in the Western Cordillera region are the most conducive for active rock glaciers in the Bolivian Andes.

Given the lack of glaciers in the Western Cordillera, this rock glacier inventory indicates that rock glaciers there could be considered as hydrologically important features to mountain communities (18° - 22° S). Similarly, in Sajama where glacier ice is also limited, rock glaciers may be important for local mountain communities and the Sajama National Park. However, glaciers dominate in Cordillera Real, with a recent estimated coverage of 185.5 km^2 (Ramirez et al., 2012), while rock glaciers are less abundant and smaller (Table 3.3). Here, we estimated that rock glaciers cover 1.07 km^2 and hence we argue that they are not an important source of water (in comparison to glaciers) for the La Paz region. However, unlike glacier ice, the ice within rock glaciers is protected from small thermal changes by the insulating rock layer, resulting in a longer lag time in their response to climate change, responding on the decadal time scale (Haeberli et al., 2006). Therefore, rock glaciers are likely to become increasingly important in mountain regions for water reservoirs given climate warming (Schrott, 1996; Millar and Westfall, 2008). Hence there is a need to understand current controls on rock glacier development and explore the impact of climate change on rock glaciers.

3.5 Conclusions

This new inventory of rock glaciers in the Bolivian Andes has identified 94 such landforms, covering an estimated 11 km^2, of which 57 % were classified as active and the remaining as relict. The majority (87 %) of rock glaciers had a southerly aspect (SE, S and SW), suggesting the importance of reduced solar input for their development. The lower limit of permafrost is thought to be at 4700 m in the Bolivian Andes, an estimation which is in agreement with those of surrounding regions. Regional differences in rock glacier elevation, distribution and size were found between the Cordillera Real, Sajama and Western Cordillera and result from variations in aridity, rock supply and direct competition with glaciers. The Western Cordillera has the largest niche zone for rock glacier formation and development, which has led to some of the largest and most developed rock glaciers in the Bolivian Andes. Rock glaciers in Bolivia are important sources of water in the Western Cordillera, and may become increasingly important in the Cordillera Real region, where there is growing evidence of severe glacier recession.

Acknowledgements

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Supplementary data tables

Table 3.5 Cordillera Real active rock glaciers.

ID	Lat (S)	Long (W)	MAF(m)	MaxE(m)	Length(m)	Width(m)	Area(km^2)	Aspect	Shape ratio
A1a	15°53'46	68°30'53	4920	5165	771	242	0.146	SE	3.19
A2a	15°59'22	68°25'52	4920	5150	1126	141	0.153	SE	7.99
A11a	16°05'29	68°20'01	4990	5220	465	170	0.058	SE	2.74
A12a	16°05'52	68°20'23	4910	4945	250	87	0.036	S	2.87
A14a	16°07'15	68°18'51	4970	5075	210	440	0.089	S	0.48
A16a	16°09'51	68°16'22	4970	5090	250	530	0.107	SW	0.47
A19a*	16°11'35	68°15'53	4870	4990	375	100	0.043	SW	3.75
A20a*	16°11'48	68°15'29	4965	5010	205	135	0.032	S	1.52
A21a*	16°11'15	68°15'12	5050	5115	105	150	0.011	SE	0.70
A27a	16°16'20	68°10'59	4960	5040	196	197	0.039	SW	0.99
A29a*	16°16'43	68°10'27	4960	5050	210	170	0.043	W	1.24
A34a*	16°20'18	68°06'05	4802	4995	440	175	0.046	SE	2.51
A37a*	16°21'36	68°08'47	4845	4955	260	200	0.047	SW	1.30
A39a*	16°17'55	68°09'05	4740	4890	615	360	0.145	S	1.71
A40a*	16°37'44	67°49'26	4830	4940	277	108	0.034	SW	2.56
A42a*	16°37'59	67°49'23	4788	4890	320	180	0.038	SW	1.78

** indicates rock glaciers that were visited for field validation.*

Table 3.6 Cordillera Real relict rock glaciers.

ID	Lat (S)	Long (W)	MAF(m)	MaxE(m)	Length(m)	Width(m)	Area(km^2)	Aspect	Shape ratio
A7b	16°04'37	68°22'27	4985	5030	100	78	0.006	S	1.28
A8b	16°04'29	68°22'17	4980	5110	200	125	0.018	SE	1.60
A9b	16°04'23	68°22'02	4960	5110	325	135	0.044	SE	2.41
A13b	16°06'00	68°18'49	4995	5135	365	170	0.051	NW	2.15

A30b	16°17'23	68°09'59	5035	5165	395	75	0.027	SE	5.27
A33b	16°20'11	68°06'06	4895	4935	105	60	0.006	S	1.75
A35b	16°21'05	68°08'47	4820	4885	160	75	0.012	SW	2.13
A36b	16°21'07	68°08'34	4997	5143	268	97	0.026	W	2.76
A43b*	16°38'37	67°49'44	4475	4900	1137	395	0.444	SW	2.88
A49b	16°40'32	67°46'09	4765	4950	720	290	0.157	S	2.48

** indicates rock glaciers that were visited for field validation.*

Table 3.7 Sajama active rock glaciers.

ID	Lat (S)	Long (W)	MAF(m)	MaxE(m)	Length(m)	Width(m)	Area(km^2)	Aspect	Shape ratio
B50a	18°02'37	69°02'35	5105	5195	371	200	0.064	SW	1.86
B54a*	18°06'36	68°54'24	4980	5175	545	210	0.103	SW	2.60
B56a	18°07'16	68°54'08	5080	5337	530	305	0.150	SW	1.74
B58a	18°07'54	68°52'08	5115	5290	765	280	0.180	S	2.73
B59a	18°07'41	68°51'30	5065	5280	980	250	0.213	SE	3.92
B60a	18°07'29	68°51'15	5080	5265	1135	235	0.266	SE	4.83
B62a*	18°08'35	68°52'14	4890	5040	330	105	0.024	S	3.14
B68a	18°14'28	69°03'17	5070	5140	200	188	0.033	SE	1.06
B70a	18°14'35	69°03'01	5031	5120	388	155	0.057	SE	2.50
B76a	18°25'50	69°01'57	5160	5590	1530	430	0.669	SE	3.56
B77a	18°24'57	69°01'40	5158	5505	2525	365	0.789	E	6.92
B120a	18°08'08	69°06'40	5005	5290	655	418	0.196	W	1.57
B124a	18°44'58	68°58'02	5345	5515	540	255	0.126	SE	2.12
B134a	18°24’57	69°01’59	5285	5485	555	85	0.061	E	6.53
B135a	18°25’18	69°01’55	5277	5374	250	200	0.043	E	1.25

** indicates rock glaciers that were visited for field validation.*

Table 3.8 Sajama relict rock glaciers

ID	Lat (S)	Long (W)	MAF(m)	MaxE(m)	Length(m)	Width(m)	Area(km^2)	Aspect	Shape ratio
B51b	18°02'23	69°00'57	4875	5010	445	345	0.145	S	1.29
B52b	18°05'03	68°53'21	5027	5201	510	118	0.063	N	4.32
B57b	18°07'40	68°54'16	4875	5080	720	390	0.389	SW	1.85
B61b	18°07'56	68°51'08	4945	5080	855	285	0.196	S	3.00
B63b	18°07'16	68°55'46	4840	4920	114	595	0.054	SW	0.19
B64b	18°07'45	68°55'18	4830	4975	460	320	0.101	S	1.44
B65b	18°07'43	68°55'02	4875	5010	485	210	0.095	S	2.31
B66b	18°05'28	68°49'51	4773	4840	245	240	0.060	S	1.02
B67b	18°05'29	68°50'12	4810	4915	430	150	0.048	S	2.87
B69b	18°14'41	69°03'12	4970	5160	675	280	0.157	SE	2.41
B71b	18°14'56	69°02'56	4855	5010	750	190	0.134	SE	3.95
B79b	18°25'15	69°01'25	5080	5280	1110	270	0.272	SE	4.11
B112b	18°07'48	68°54'53	4855	4988	637	301	0.200	S	2.12
B118b	17°55'55	68°54'22	5202	5315	189	95	0.018	SE	1.99
B119b	17°55'55	68°54'18	5177	5305	334	97	0.028	S	3.44
B121b	17°56'13	68°55'04	4954	5082	337	150	0.061	SW	2.25

Table 3.9 Western Cordillera active rock glaciers.

ID	Lat (S)	Long (W)	MAF(m)	MaxE(m)	Length(m)	Width(m)	Area(km^2)	Aspect	Shape ratio
C84a	18°44'58	68°58'02	5010	5325	775	190	0.147	SE	4.08
C85a	18°45'02	68°58'14	5030	5185	380	75	0.039	S	5.07
C86a	18°53'24	68°54'00	5085	5220	595	225	0.118	SE	2.64
C87a	18°54'32	68°54'39	4740	5090	1380	300	0.518	SW	4.60
C92a	19°07'41	68°41'50	4985	5250	844	200	0.185	NW	4.22
C93a	19°09'18	68°42'47	4975	5150	600	215	0.124	SW	2.79

C94a	19°09'09	68°42'29	5137	5285	400	310	0.115	SW	1.29
C95a	19°09'55	68°42'22	4735	4990	888	220	0.180	SW	4.04
C96a	19°09'11	68°40'51	4950	5205	570	240	0.117	SE	2.38
C97a	19°09'11	68°40'01	4740	5060	775	200	0.211	S	3.88
C101a	20°59'36	68°03'15	4930	5075	415	250	0.087	W	1.66
C107a*	21°06'09	67°51'13	4820	4990	610	200	0.127	SE	3.05
C108a	21°07'03	67°51'08	4760	4880	420	150	0.052	SE	2.80
C109a	21°18'13	67°57'41	5025	5330	810	200	0.093	S	4.05
C110a	21°29'52	67°55'06	5255	5510	785	145	0.206	SE	5.41
C111a	21°29'57	67°55'16	5293	5414	332	126	0.050	SE	2.63
C113a	21°34'09	67°50'45	4939	5056	250	132	0.035	SE	1.89
C114a	21°37'00	67°56'51	5144	5293	66	882	0.078	SW	0.07
C115a	21°37'45	67°55'45	5002	5232	75	1072	0.134	SW	0.07
C116a	21°37'41	67°56'01	5056	5177	250	121	0.037	SE	2.07
C126a	19°00'54	68°49'37	4837	5225	727	95	0.131	SE	7.65
C128a	19°01'08	68°49'23	4709	4849	385	176	0.079	S	2.19
C130a	19°04'37	68°42'08	4790	4853	116	90	0.016	SW	1.29

** indicates rock glaciers that were visited for field validation.*

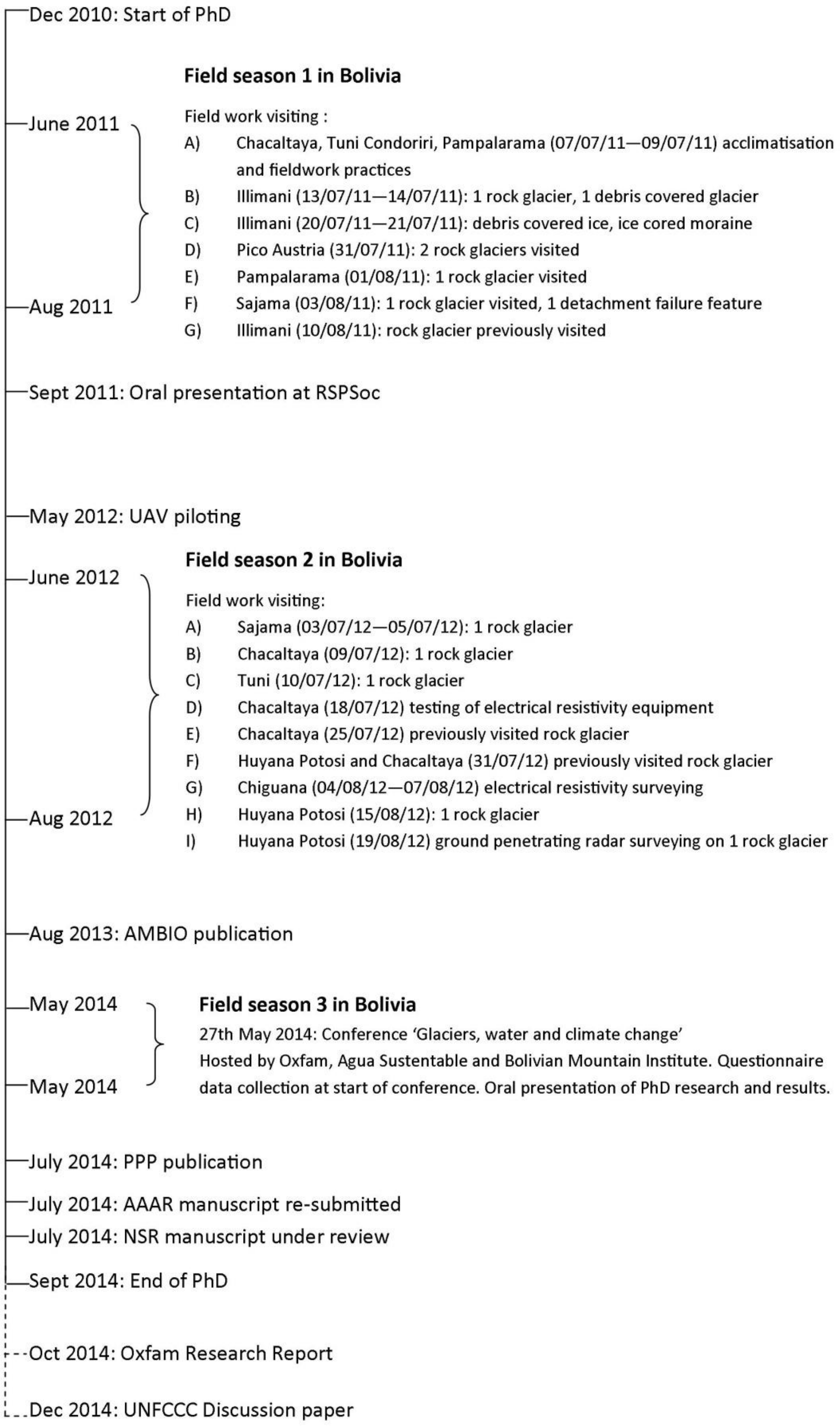
Table 3.10 Western Cordillera relict rock glaciers

ID	Lat (S)	Long (W)	MAF(m)	MaxE(m)	Length(m)	Width(m)	Area(km^2)	Aspect	Shape ratio
C88b	18°54'00	68°53'55	4795	4880	280	150	0.042	S	1.87
C89b	18°54'08	68°53'40	4720	4800	150	830	0.080	SW	0.18
C90b	18°53'38	68°53'41	4845	5025	500	190	0.080	SE	2.63
C91b	18°53'10	68°53'44	4940	5020	207	860	0.117	SE	0.24
C98b	19°10'02	68°39'01	4500	4630	280	1320	0.258	SW	0.21
C99b	20°51'08	68°12'31	4595	4695	395	120	0.044	SW	3.29
C100b	20°51'33	68°12'02	4515	4665	400	130	0.048	S	3.08
C102b	21°00'25	68°03'10	4780	4950	445	165	0.075	S	2.70

C103b	21°00'19	68°03'00	4875	5020	340	175	0.053	SW	1.94
C117b	20°56'12	68°24'07	5119	5335	368	128	0.061	E	2.88
C127b	19°00'58	68°49'35	4784	4832	80	182	0.022	SE	0.44
C129b	19°00'46	68°50'37	4884	5057	375	130	0.099	SE	2.88
C132b	21°28'55	67°57'35	4853	4982	631	134	0.073	NW	4.71
C136b	20°56’01	68°23’20	4725	4915	767	75	0.06	E	10.23

3.6 Supporting field work material

This following section contains data from the field seasons conducted the Bolivian Andes during austral winter and supports the rock glacier inventory. To illustrate the chronological order of research and field season data collection, Figure 3.11 shows a timeline of this PhD and Figure 3.12 shows a work flow for the creation of the rock glacier inventory. Certain aspects of the field work were piloting tests, of which some were successful and others unsuccessful. The application of a UAV to potentially obtain fine scale remote sensing data in the field was trialled in the UK in May 2012 (Fig. 3.11). The UAV was taken out to Bolivia for the second field season, however the use of it was unsuccessful due to the altitude. It would appear that elevations above 3,500 m a.s.l. require the (copter-based) UAV to have more momentum for uplift as the air is thinner. Geophysical surveying (electrical resistivity and ground penetrating radar) were also piloted and deployed during the second field season (Fig. 3.11). Details of the electrical resistivity surveying are discussed in section 3.7.3 and also in Chapter 4 (section 4.3.4). However details of the GPR survey are not discussed because the data was inconclusive.



Dec 2010: Start of PhD

Field season 1 in Bolivia

June 2011

Aug 2011

Field work visiting :

A) Chacaltaya, Tuni Condoriri, Pampalarama (07/07/11—09/07/11) acclimatisation and fieldwork practices
B) Illimani (13/07/11—14/07/11): 1 rock glacier, 1 debris covered glacier
C) Illimani (20/07/11—21/07/11): debris covered ice, ice cored moraine
D) Pico Austria (31/07/11): 2 rock glaciers visited
E) Pampalarama (01/08/11): 1 rock glacier visited
F) Sajama (03/08/11): 1 rock glacier visited, 1 detachment failure feature
G) Illimani (10/08/11): rock glacier previously visited

Sept 2011: Oral presentation at RSPSoc

May 2012: UAV piloting

Field season 2 in Bolivia

June 2012

Aug 2012

Field work visiting:

A) Sajama (03/07/12—05/07/12): 1 rock glacier
B) Chacaltaya (09/07/12): 1 rock glacier
C) Tuni (10/07/12): 1 rock glacier
D) Chacaltaya (18/07/12) testing of electrical resistivity equipment
E) Chacaltaya (25/07/12) previously visited rock glacier
F) Huyana Potosi and Chacaltaya (31/07/12) previously visited rock glacier
G) Chiguana (04/08/12—07/08/12) electrical resistivity surveying
H) Huyana Potosi (15/08/12): 1 rock glacier
I) Huyana Potosi (19/08/12) ground penetrating radar surveying on 1 rock glacier

Aug 2013: AMBIO publication

May 2014

May 2014

Field season 3 in Bolivia

27th May 2014: Conference 'Glaciers, water and climate change'
Hosted by Oxfam, Agua Sustentable and Bolivian Mountain Institute. Questionnaire data collection at start of conference. Oral presentation of PhD research and results.

July 2014: PPP publication

July 2014: AAAR manuscript re-submitted

July 2014: NSR manuscript under review

Sept 2014: End of PhD

Oct 2014: Oxfam Research Report

Dec 2014: UNFCCC Discussion paper

***Figure 3.11 PhD timeline focusing on fieldwork periods and data collection*.**

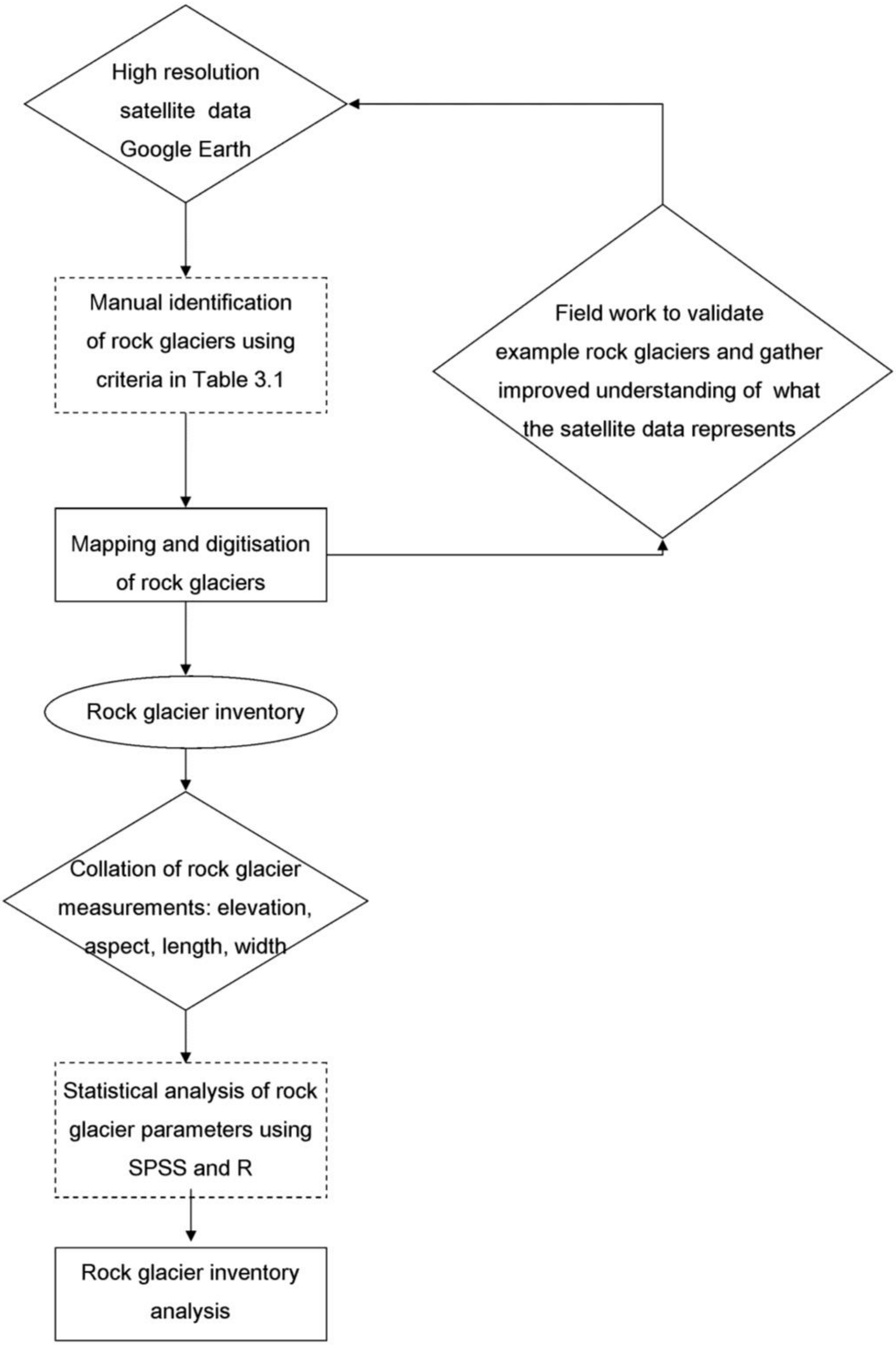
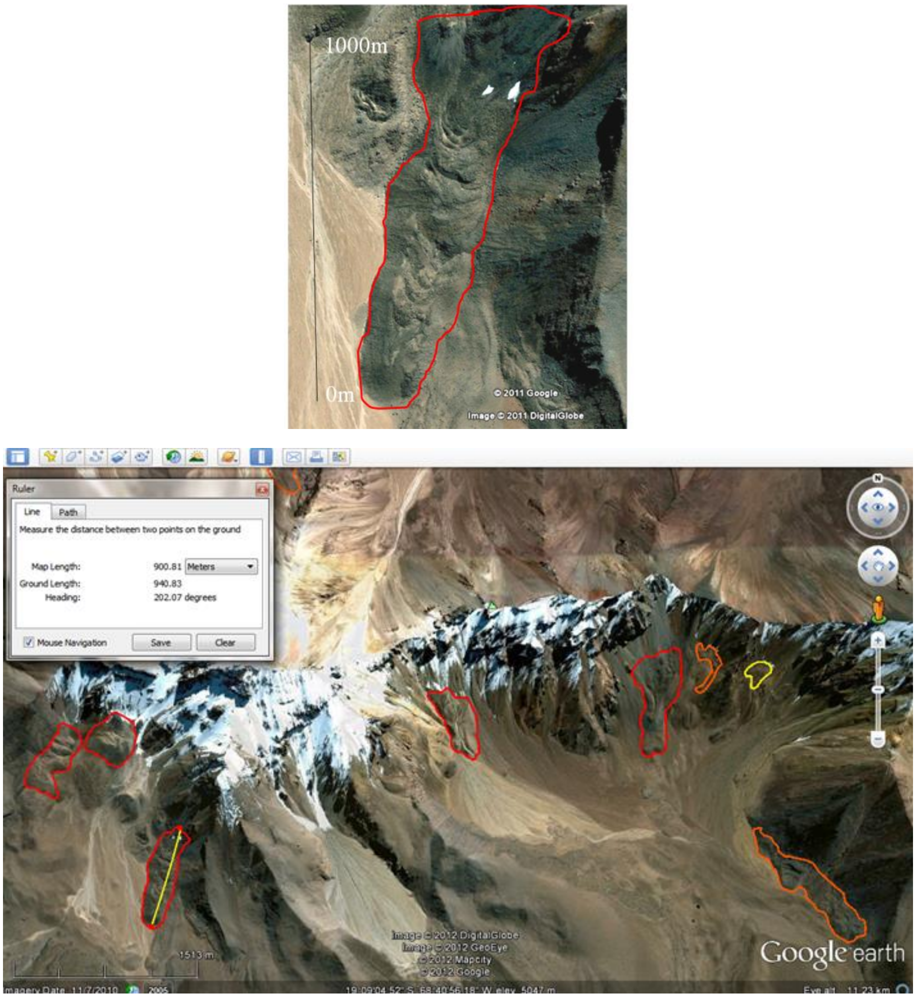


Figure 3.12 Workflow of the production and analysis of the Bolivian rock glacier inventory

3.6.1 Use of Google Earth for the rock glacier inventory

Google Earth has enabled the identification and mapping of rock glaciers on a national and regional scale. Google Earth is cost-free, user-friendly software available on the internet allowing public access to high-resolution aerial and satellite images of the entire Earth's surface (Barbosa and Campos, 2011). The imagery is adjusted to simple cylindrical projection (latitude/longitude) and Datum WGS84 (Barbosa and Campos, 2011). Google Earth is acknowledged as a technology resource which can aid problem solving and help make informed decisions (Patterson, 2007). Although Google Earth has limited tools and capabilities in comparison to a true GIS (such as ArcGIS) (Patterson, 2007) it is a valuable interactive tool which can facilitate mapping, visual analysis, identification of field sites, identification of condensed areas for the purchasing or downloading of satellite imagery for input into GIS. The ability to draw shapefiles using the polygon creation tool (Fig. 3.13) and save in KML (Keyhole Markup Language) format ready for exportation into a GIS software (QGIS, ArcGIS, ENVI) allows the easy combination of one's data with various other data sources, both qualitatively and quantitatively (Henry, 2009). For this research, not only was Google Earth used to build the rock glacier inventory, it was also used for an assessment of possible sites for field work by evaluating the accessibility to rock glaciers.

It is important to note that the classification of rock glaciers based on their activity status from satellite data alone is considered difficult (Arenson et al., 2010). High resolution satellite data may allow for vegetation and lichen cover identification, suggesting inactive or relict rock glaciers. But without repeated surveys to compare terminal moraine movement or *in situ* ice content measurements, activity classification cannot be verified. However, the identification and classification of rock glaciers based on the key charactersitics in Table 3.1 (and Table 2.1) is a well accepted and practised method for rock glacier mapping.



Measure the distance between two points on the ground

Map Length: 900.81 Meters

Ground Length: 940.83

Heading: 202.07 degrees

☑ Mouse Navigation

Figure 3.13 Google Earth screen shots showing the digitising of rock glaciers on Google Earth (top) and the use of the Ruler tool to obtain length measurements (bottom). Red outlines deplict active rock glaciers, orange outlines represents inactive and yellow outlines for relict.

3.6.2 Field work data collection

During two field seasons in austral winter 2011 and 2012, fieldwork in various study sites (Figure 3.14) focused on data collection for validation of the rock glacier inventory (Table 3.11; Table 3.12). The limited access and high altitude nature of the field sites (alttiudes ranging from 4,600m to 5200m), made complex field measurements difficult, therefore data collection involved field photographs, GPS surveying from a handheld Garmin system, and surveying tools such as abney level measurements, and transect sampling along rock glacier surfaces to capture fine scale detail and rock glacier location.

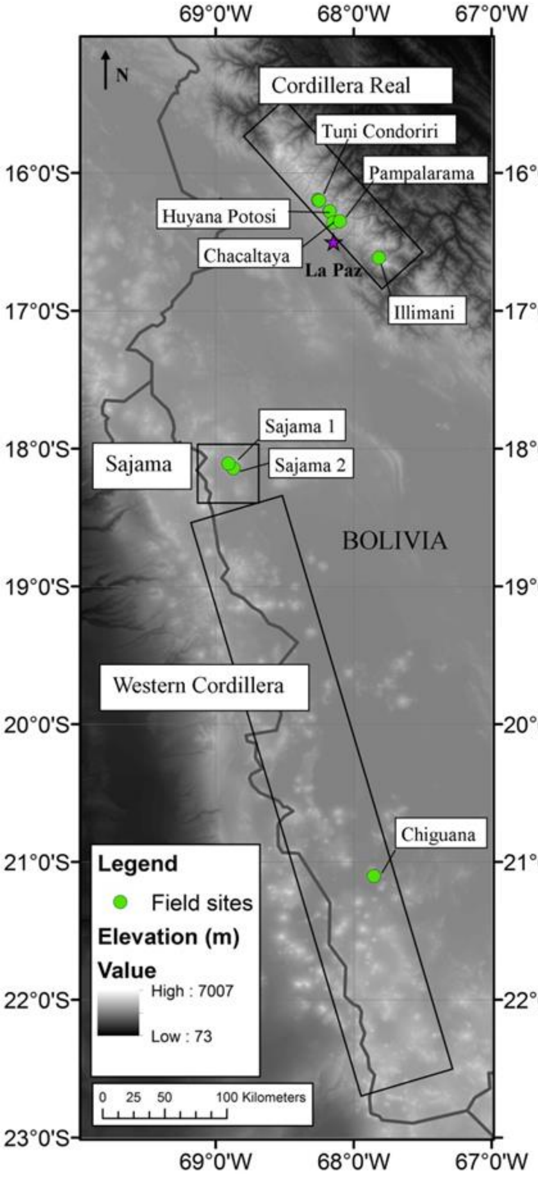


Figure 3.14 Map illustrating the field site locations of the two field seasons. Field sites visted are represented by coloured circle symbols.

Field season 1				
Date	**Location**	**Feature**	**Altitude**	**Data collected**
07/07/11	Chacaltaya 16°21.478’ S 68°08.088’ W	Vanished glacier	5255m +/- 15m	Acclimatization day hike, GPS reference point of laboratory
08/07/11	Tuni Condoriri 16°11.081’ S 68°18.500’ W	Glacial retreat features	4895m +/- 7m	Fieldwork practises
09/07/11	Pampalarama 16°18.815’ S 68°05.881’ W	Glacial retreat features	4774m +/- 9m	Fieldwork practises
13/07/11	Illimani, 16°37.946’ S 67°49.551’ W	**Rock glacier**	4879m +/- 10m	Slope angle 33° Field observations on surface topography and detail.
14/07/11	Illimani, 16°38.724’ S, 67°49.204’ W	Debris covered glacier	4820m +/- 10m	Field observations of meltwater lake, surrounding debris covered ice and debris covered glacier
20/07/11	Illimani, 16°38.434’ S 67°49.331’ W	Debris covered ice	4922m +/- 9m	Field observations on rocks – striations, angular, unweathered.
21/07/11	Illimani, 16°39.457’ S 67°49.148’ W	Ice cored moraine (yellow)	4798m +/- 9m	Slope angle 33° Water exiting the moraine
31/07/11	Pico Austria, Tuni Condoriri 16°11.654’ S 68°15.627’ W	**2 rock glaciers**	~5000m	Slope angle measured on one, 32°.
01/08/11	Pampalarama, 16°20.508 68°06.310	**Rock glacier**	4840m +/- 10m	Slope angle 33° Field observations
03/08/11	Sajama 18°06.239’ S 68°54.281	**Rock glacier**	5120m +/- 13m	Slope angle 31° Field observations on lack of lichens, different geology/soil
10/08/11	Illimani 16°37.980’S 68°49.599’ W	Rock glacier previously visited on 13/07/11	4841m +/- 10m	Slope angle in finer detail 29°, 30°, 32°. Transect along rock glacier width

Table 3.11 Field sites visited in field season 1 (June - August 2011)

Field season 2				
Date	**Location**	**Feature**	**Altitude**	**Data collected**
04/07/12	Sajama	**Rock glacier**	5255m +/- 15m	First field trip, however altitude sickness hindered the hike.
09/07/12	Chacaltaya	**Rock glacier**	4851m +/- 5m	Slope angles 31 - 34°, field observations
10/07/12	Tuni 16°11’48 S; 68°15’28 W	**Rock glacier**	4950m	Slope angles 28° - 35°, field observations.
18/07/12	Chacaltaya	Rock glacier previously visited		Electrical resistivity. However, contact was not good enough so measurements were not made. Perpendicular transect was made with lichen sizes and rock axis.
25/07/12	Chacaltaya	Rock glacier previously visited		Transect parallel to rock glacier flow of lichen sizes and rock axis.
31/07/12	Chacaltaya	Rock glacier previously visited		Transect perpendicular to flow of lichen sizes and rock axis every 5m.
07/08/12	Chiguana 21°06’09.84 S 67°51’14.51 W	**Rock glacier**	4825m +/- 10m	Electrical resistivity points, Lichen measurements, rock axis sizes, slope angle 32 - 33°.
15/08/12	Huyana Potosi 16°16’43 S 68°10’27 W	**Rock glacier**/ glacier retreat area	49722m +/- 9m	Slope angles 30° - 35°, lichen measurements, rock axis, general observations.
19/08/12	Huyana Potosi west 16°16’44.4 S 68°10’27.38 W	**Rock glacier**	4950m	GPR transects, slope angles 32° - 33°

Table 3.12 Field sites visited in field season 2 (June - August 2012)

Through field work validation of the remote assessment of these features could occur. The main factor which limited the options of sites that could be used for field work was their access. A large majority of the rock glaciers identified in the inventory were not easily accessible. Any rock glaciers further than 6 km from the nearest visible road (observed on Google Earth) were predicted to be too far for one day’s fieldwork, especially with altitude and difficult terrain, and thus were excluded from field site options. The furthest distance walked on field work in 2012 was 4 km hike in very arid conditions to Chiguana rock glacier, carrying heavy equipment and this took 5 hours. Field season 2011 involved the furthest hike of 5 km from Pinaya community to an ice cored moraine feature in Illimani, although staying in the mountain community of Pinaya allowed for hiking to start at sunrise.

Furthermore, field sites were also selected to represent the three different climates identified along the Bolivian Andes: the wetter more glaciated Cordillera Real; the drier Sajama; and arid and barren Western Cordillera. By conducting fieldwork in each region, the accuracy of identifying and validating rock glaciers is increased through the understanding of regional differences and characteristics. The final factor influencing decisions on field site locations was rock glacier typology. Field sites were chosen to represent active, inactive and complex rock glaciers along the Bolivian Andes.

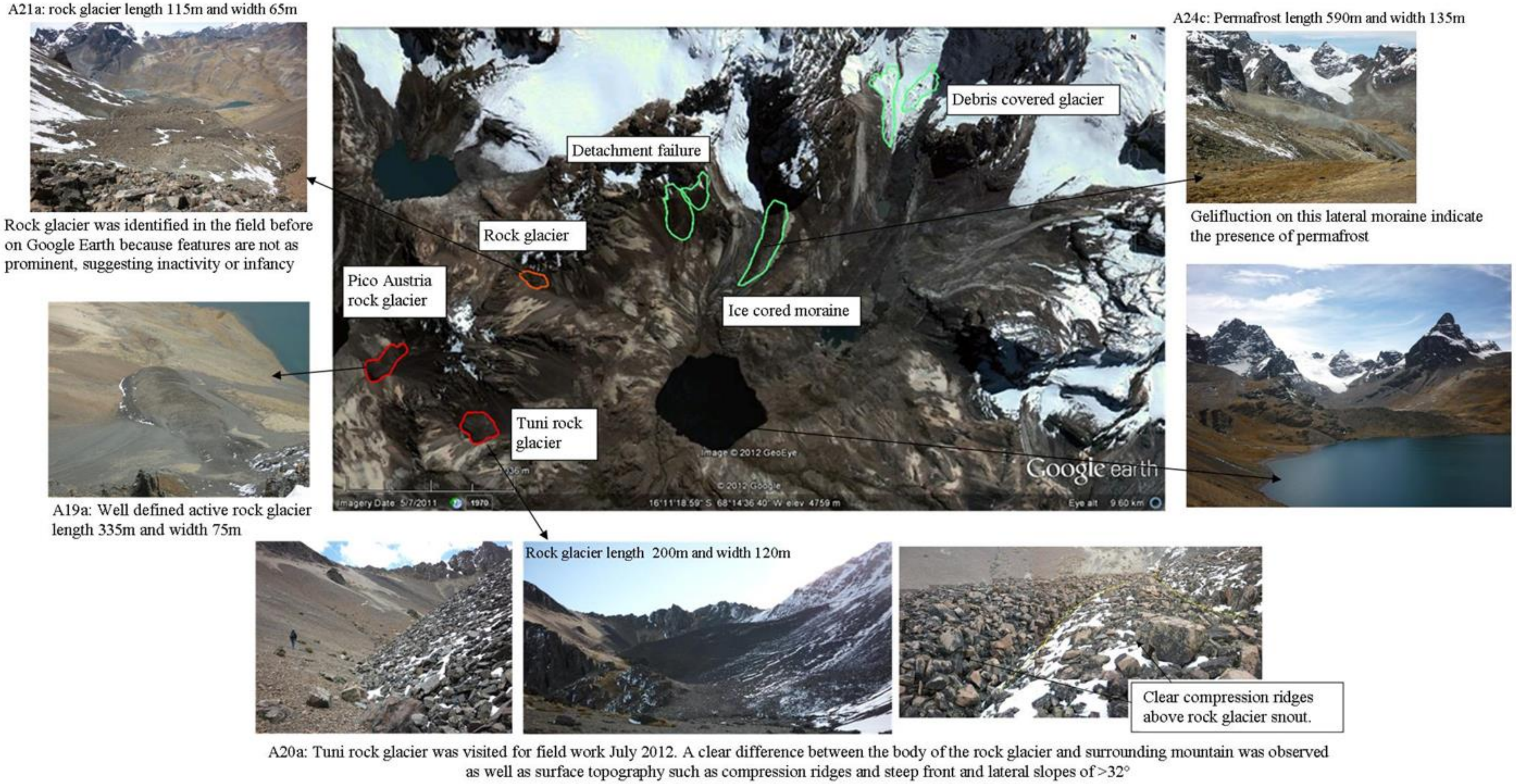
Existing research has solely identified rock glaciers through remotely sensed analysis (Strozzi et al., 2004; Brenning et al., 2012a), and limited field work (Brenning et al., 2005a; Scotti et al., 2013), especially in the South American Andes.

*3.*7 Fieldwork data

The following section includes annoted photographs (Google Earth screen shots and in situ photographs) of the field sites visited and the geomorphological interpretation.

3.7.1 Cordillera Real

The Cordillera Real region was the easiest to visit for field work given its close proximity to La Paz. Therefore a majority of the field sites were based in this region, especially as road access was usually well-known in comparison to the other regions. Four main areas of interest were visited: Tuni, Huyana Potosi, Chacaltaya and Illimani. Annotated photographs from the Tuni valley (Fig. 3.15) illustrate some of the landscape, terrain and features visited. Red features indicate active rock glaciers, orange features represent inactive rock glaciers, yellow outlined features represent relict rock glaciers and green features are other permafrost features.



A21a: rock glacier length 115m and width 65m

Rock glacier was identified in the field before on Google Earth because features are not as prominent, suggesting inactivity or infancy

A19a: Well defined active rock glacier length 335m and width 75m

A24c: Permafrost length 590m and width 135m

Gelifluction on this lateral moraine indicate the presence of permafrost

Rock glacier length 200m and width 120m

A20a: Tuni rock glacier was visited for field work July 2012. A clear difference between the body of the rock glacier and surrounding mountain was observed as well as surface topography such as compression ridges and steep front and lateral slopes of >32°

Figure 3.15 Annotated Google Earth screen shot of the Tuni Condoriri valley in the Cordillera Real using in situ photographs and field notes from field work conducted over the two field season (2011, 2012).

Tuni rock glacier

Tuni rock glacier (16°11’48 S; 68°15’28 W; MAF 4950m) is located in the Tuni Condoriri valley in the Cordillera Real. Figure 3.15 shows that from Google Earth itr can be seen that this valley contained a range of glacial and periglacial features. The field trip was used as a scouting trip with the anticipation of further work; however this site was unable to be revisited due to fresh snow cover on the planned day. The feature was identified as a rock glacier on Google Earth based on its visible characteristics and location in relation to glacial features. The rock glacier was classified as active due to its defined surface morphology implying flow and movement as well as steep prominent lateral sides and frontal slope (Fig. 3.16). On inspection, this rock glacier has characteristics signalling active/inactive rock glacier status, with steep slopes of nearly 35° and significant compression ridges and furrows (changes in surface topography >2m on the rock glacier). No vegetation was found on the rock glacier; although sparse lichen cover was seen on surface rocks.

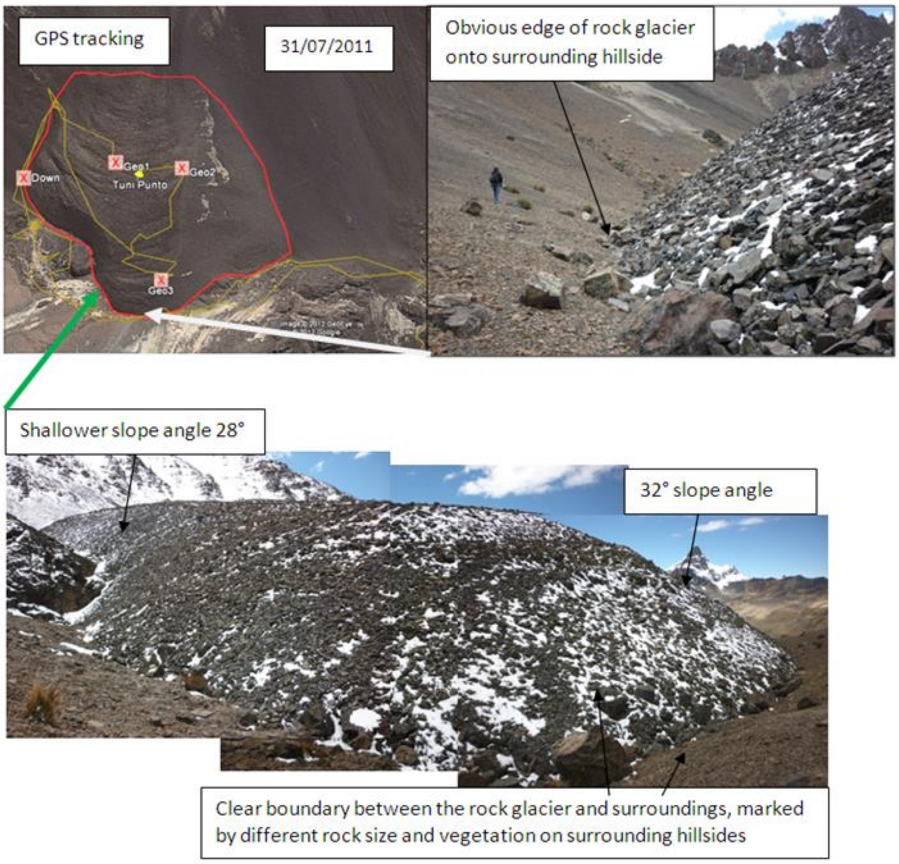


Figure 3.16 Tuni rock glacier field work, Cordillera Real Google Earth and photographs taken in the field.

Huyana Potosi

Huyana Potosi rock glacier (16°16’43 S; 68°10’27 W; MAF 4950m) is located on the west side of the Huayna Potosi glacier (Fig. 3.17) which has shown significant recent recession. The front part of this feature has the key characteristics of a rock glacier with a steep frontal slope, ridges and furrows and location close to a glacier. Fieldwork was undertaken to validate this feature.

Field work showed that this feature is complex and is best described as being on the rock glacier – glacial moraine continuum. Two transect sampling lines were conducted across the width and the front of the feature with observations, slope angles and lichen measurements. Steep frontal slopes were observed (33°-35°), as well as compression ridges and furrows on the surface. Lichen and vegetation cover varied spatially, with areas of vegetation, lichen cover mainly limited to the edges of the feature (lichen diameters ~2.5cm) but smaller (lichen diameters ~0.5cm) or no lichen cover across the middle of the rock glacier. Therefore, from the fieldwork it can be assumed that the majority of the body of the feature (labelled b in Fig. 3.17) contains an ice body because of its swollen body, steep slopes, surface morphology and lack of lichens (no lichens) (Fig. 3.17). Ridges and furrows were very deep (the largest of all the field sites) with some angles of 34° from ridge to furrow/peak to trough, implying the presence of ice (Fig. 3.17). However, sections on the edges of the feature suggest inactivity/relict status because of the lichen coverage (lichen diameters of 2.4cm) and vegetation implying a lack of movement (labelled c in Fig. 3.17). The only valid way to fully determine if this feature can be classed as a rock glacier would be the application of geophysical equipment to confirm the presence of ice under the rock debris. From surface inspection only, it can be assumed that this rock glacier is complex with a main active body and a relict section to the west of the rock glacier where ice has already melted out.

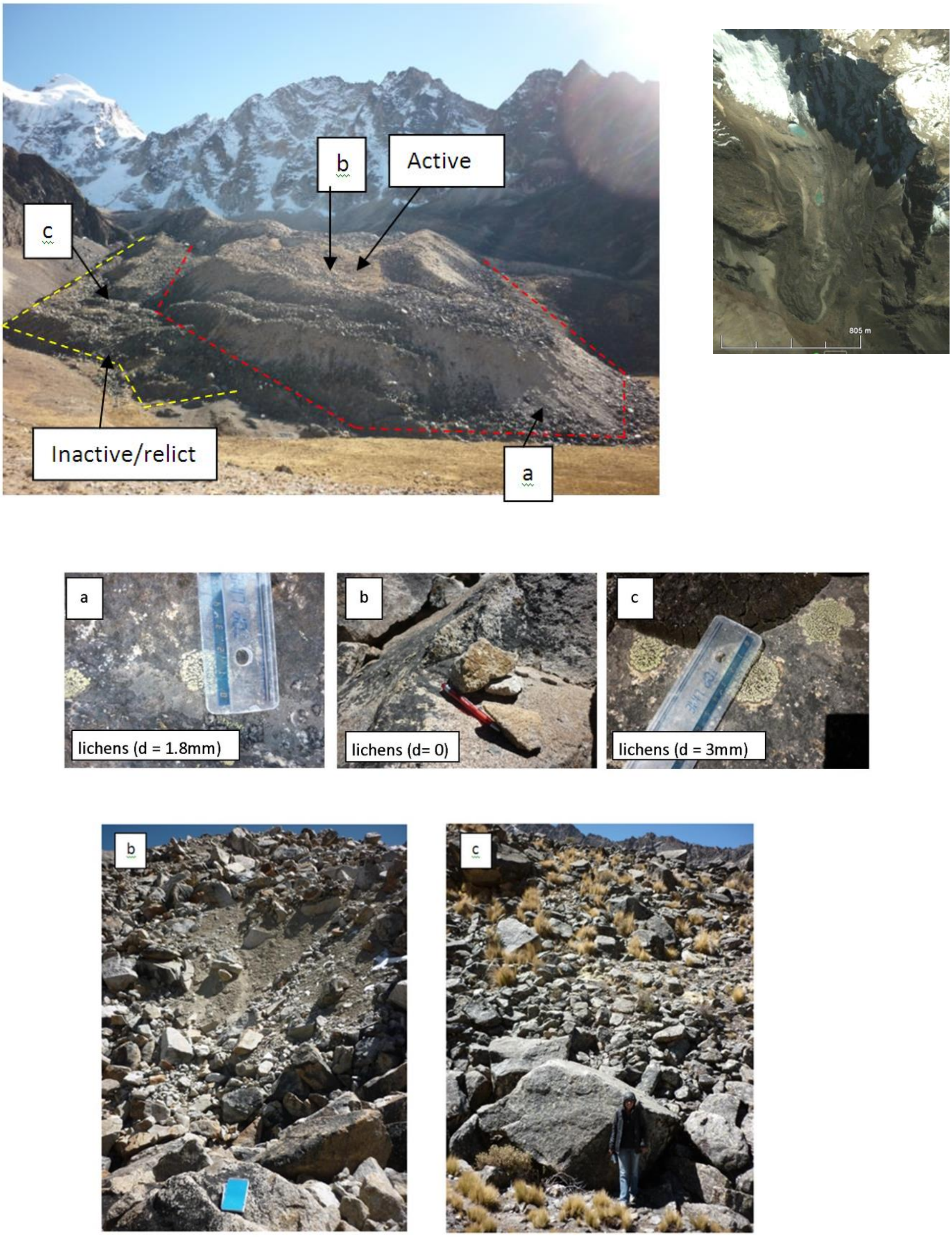


Figure 3.17 Huyana Potosi rock glacier field work, Cordillera Real
Photo taken in the field (top) depicts the complexity of the rock glacier: a) the frontal slope; b) show signs of an ice body and activity through the lack of lichens and steep surface morphology, other areas c) show significant signs of relict status with vegetation, shallower slope angles and large lichens (~3cm). Lichen photographs are displayed with a ruler for scale and the lichen diameter annotated (middle). Further photographs demonstrate the scale of the rocks found on this rock glacier (bottom).

Chacaltaya

Chacaltaya rock glacier (16°21’39.2”S, 68°08’50.7”W; MAF 4800m) is classified as inactive due to what appears to be a weathered surface and no significantly steep sides or frontal slope on the Google Earth image. Upon field work, some of the slopes reached 33° on the abney level (Fig. 3.18), suggesting the possibility of a remaining ice core creating a swollen rock glacier body. However, lichens were observed on many of the rocks on the rock glacier and its sides and vegetation was even observed on parts of the frontal slope, both suggesting inactivity. Sources of input rock fall are clear from the *in situ* visit and photographs above the rock glacier. Chacaltaya is the closest and easiest rock glacier to access from the city of La Paz, 20 km (however this can be a 2 hour drive depending on the traffic in La Paz and El Alto). Therefore this site was the location for the pilot use of electrical resistivity with a Geophysicist (Andres) employed through Agua Sustentable (Fig. 3.18).

The presence of ice under debris and rock cover can rarely be determined from remote sensing, or even close surface examination. Several geophysical techniques have been developed for the study of permafrost over the past 30 - 40 years (Kurfurst and Hunter, 1976), with the two most frequently used methods being refraction seismics and geoelectric (Garg, 1976; Schrott, 1994, cited in Croce and Milana, 2002; Degenhardt Jr. and Giardino, 2003). For rock glacier surveys, DC (electrical) resistivity methods are the most commonly used (Bucki et al., 2004). Strong dielectric contrasts between ice, water, sediments and rocks make possible identification of the thickness of ice (Drewry, 1983 cited in Gusmeroli, 2010). Electrical resistivity, which is dependent on ice content and type, ranges from 1 to 10,000 kΩm in frozen sediments (Haeberli and Vonder Mühll, 1996). Ice at marginal permafrost conditions has low resistivity (5–500 kΩm); massive ice has much higher resistivity (1,000–2,000 kΩm) (Degenhardt Jr. and Giardino, 2003).

However, the electrical resistivity was unsuccessful on Chacaltaya rock glacier. The equipment was checked on the soil ground next to the rock glacier and it worked. There were two hypotheses formed as to why it did not work: i) there was not enough contact between the large rocks that make up the rock glacier surface; ii) the rock glacier is relict and affects the equipment working. After communication with a local glaciologist, it was suggested that sponges were to be purchased and used to help increase the contact of the electrical resistivity equipment (electrodes) and the rock glacier structure. Water was suggested to help increase this contact. This advice was taken and sponge was purchased before the field trip to Chiguana. The electrical resistivity was successful on the Chiguana rock glacier with the addition of the sponge.

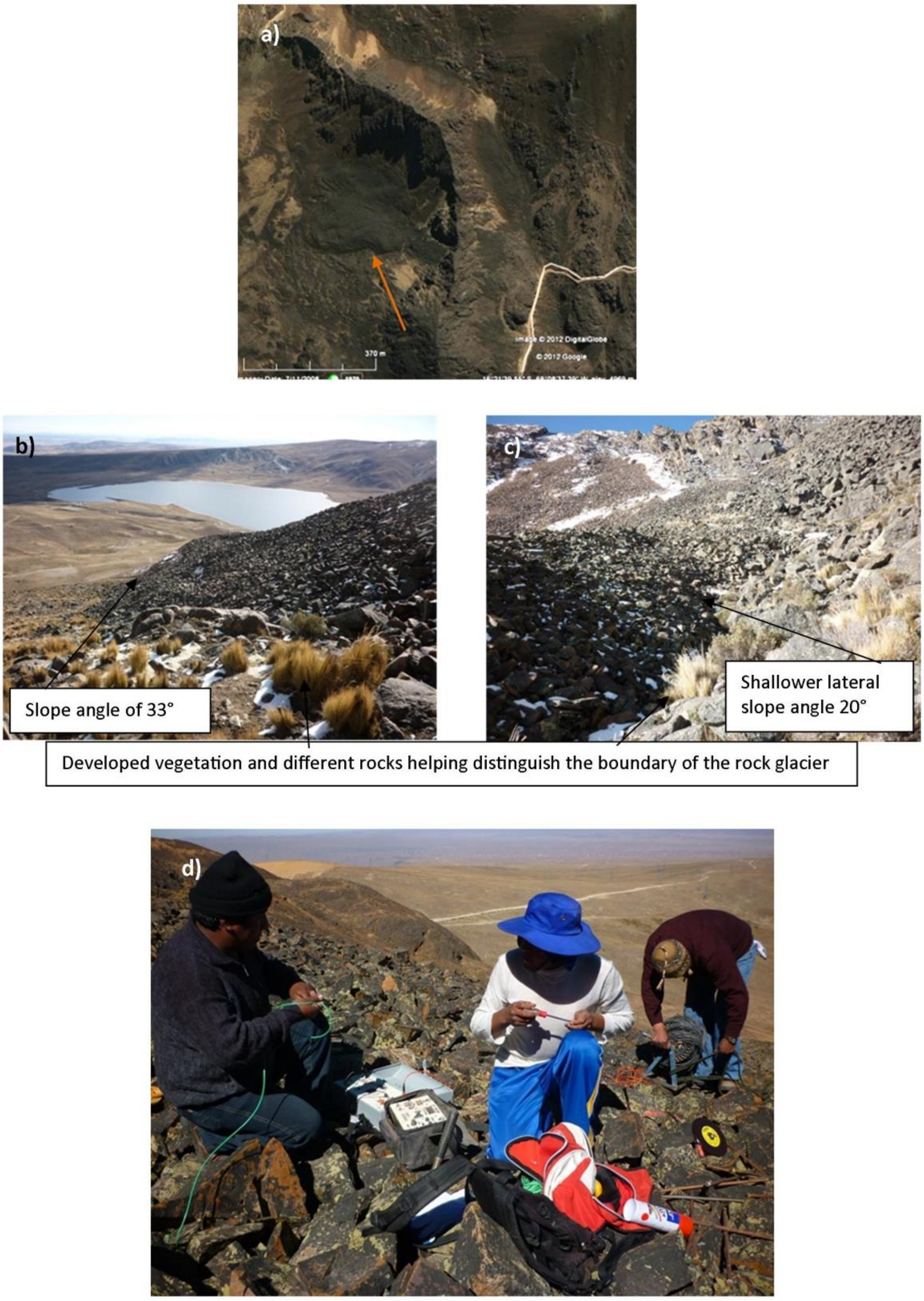
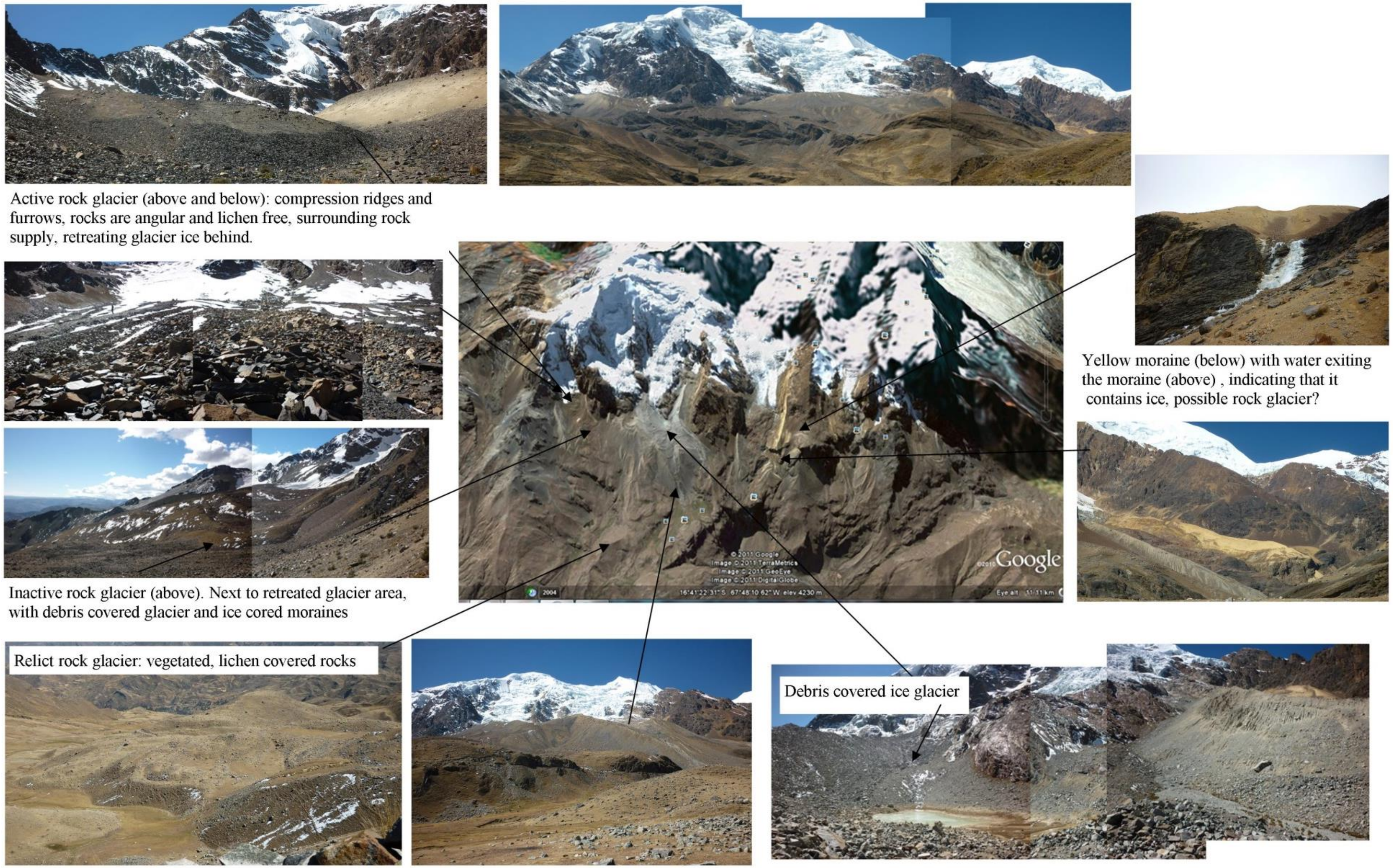


Figure 3.18 Chacaltaya rock glacier field work, Cordillera Real
a) Google Earth screen shot of the rock glacier; b) in situ photograph looking down the rock glacier with the frontal slope annotated; c) in situ photograph looking up the rock glacier with the lateral slope annotated; d) pilot testing of the electrical resistivity equipment on Chacaltaya rock glacier (18/07/2012).

Illimani

Illimani (16°38’00”S, 67°47’27”W) is a glaciated mountain 70 km from La Paz (3 – 4 hour car journey). It was the focus of three field visits (Table 3.11; Table 3.12) where we stayed in the community of Pinaya (16°38’S, 67°51’W) and walked daily to different field sites. Illimani was chosen as some of the first field sites of 2011 due to the strong link between Agua Sustentable and the local communities for accommodation and guides. Mapping from Google Earth prior to the field season had identified a number of cryospheric features, validated by the field work. Rock glaciers, ice cored moraines and debris covered glaciers were all visited (Fig. 3.19) and photographs, GPS points and abney level measurements were taken.



Active rock glacier (above and below): compression ridges and furrows, rocks are angular and lichen free, surrounding rock supply, retreating glacier ice behind.

Yellow moraine (below) with water exiting the moraine (above) , indicating that it contains ice, possible rock glacier?

Inactive rock glacier (above). Next to retreated glacier area, with debris covered glacier and ice cored moraines

Relict rock glacier: vegetated, lichen covered rocks

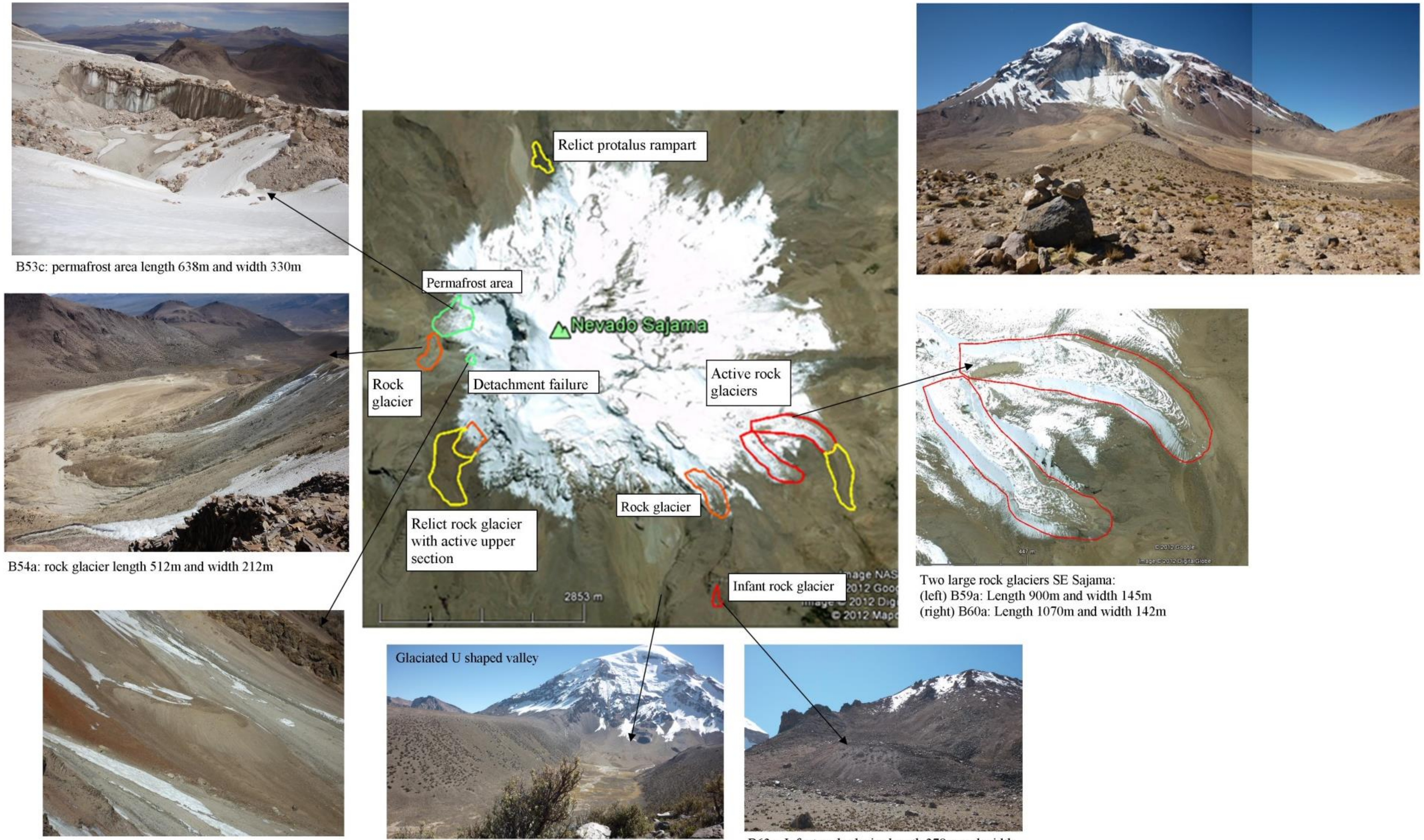
Debris covered ice glacier

Figure 3.19 Annotated Google Earth and in situ photographs of the Illimani field site and its features

3.7.2 Sajama

Sajama proved to be a difficult field site due to the high altitude (sleeping at 4,200 m a.s.l.) and difficult terrain. The altitude was higher for the features of interest (average lowest altitude of 5077m for rock glaciers in Sajama compared to 4800m for Illimani and 4845m for Pico Austria), suggesting a higher 0 °C isotherm and/or different climatic parameters such as precipitation and temperature.

The first field season placed the Sajama field trip at the end to maximise acclimatisation time, however it would appear that sleeping at that altitude was still too much and therefore the field trip was cut short (after the second day). Unfortunately the same problem with altitude sickness happened again on the second field season's trip to Sajama, and the field work was again cut short (after the second day). However, data in the form of in situ photographs (Fig. 3.20) and GPS survey points were still made. It was important to conduct field work in the Sajama region due to the shear lack of information on the area.



B53c: permafrost area length 638m and width 330m

B54a: rock glacier length 512m and width 212m

B55c: Detachment failure length 112m, width 89m

Two large rock glaciers SE Sajama:
(left) B59a: Length 900m and width 145m
(right) B60a: Length 1070m and width 142m

B62a: Infant rock glacier length 278m and width 84m

Figure 3.20 Google Earth screen shot of Sajama with field photopraphs and field notes

3.7.3 Western Cordillera

The Western Cordillera is a large, barren region extending from 18 °S to 22 °S. The distributions of the rock glaciers mapped in this region were very sparse (Fig. 3.21), in very remote locations making the planning and executing of field work very difficult. Caquella rock glacier has been studied before by Francou *et al.* (1999) and Bodin *et al.* (2010a). Rock glaciers along the Western Cordillera were found to be more developed with prominent surface morphology features, such as ridges and furrows. It was important to gather field data from a rock glacier in this region to represent the Western Cordillera.

Caquella rock glacier studied by Francou et al. (1999) and Bodin et al. (2010), established active rock glacier. Most prominent rock glacier along the Bolivian Andes

Chiguana active rock glacier visited on field work August 2012. Clear frontal slope and lack of lichens evident from field work indicate active status of this rock glacier, parallel to the work on a similar rock glacier in this region, Caquella

Features are sparsely distributed along the Western Cordillera and extremely difficult to access. Limited road access to within 4 km of rock glaciers resulted in only one field site being chosen here to field work, Chiguana. Field work and reference to previous studies provided confidence in the identification and classification of other rock glaciers in this region.

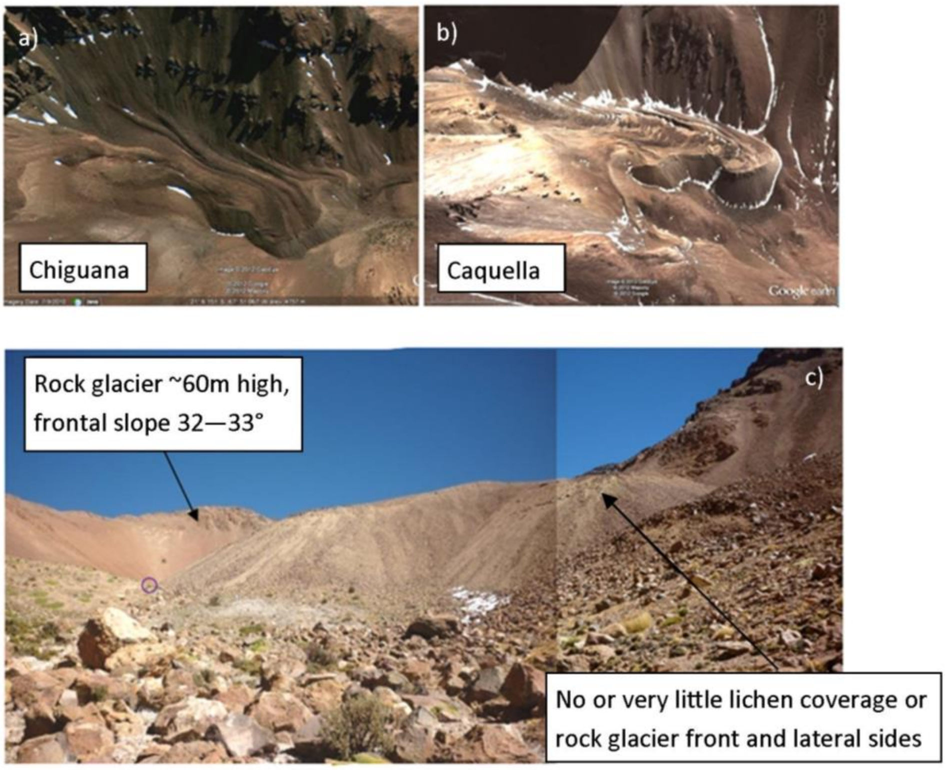
C109a: Length 678m and width 145m

C108a: Length 368m and width 90m

Figure 3.21 Annotated Google Earth screen shot for a section of the Western Cordillera fieldwork photos, close up Google Earth data and existing published work on Caquella rock glacier.

Chiguana rock glacier

One field site, Chiguana (21°06’09.84 S; 67°51’14.51 W; MAF 4825m) was selected based on its proximity to a community (San Juan) and a town (Uyuni). Prior to the field work, from Google Earth it can be seen that this rock glacier shares similar characteristics to Caquella (21°S), a rock glacier previously studied by Francou et al. (1999) and Bodin et al. (2010a) (Fig. 3.22).



Rock glacier ~60m high, frontal slope 32—33°

No or very little lichen coverage or rock glacier front and lateral sides

Figure 3.22 Chiguana and Caquella rock glaciers, Western Cordillera
a) Google Earth screen shots of Chiguana and b) Caquella rock glaciers; c) in situ photograph showing the frontal slope and size of the Chiguana rock glacier, 2012. The purple circle outlines the size of a colleague in comparison to the rock glacier height.

This rock glacier was situated 4 km away from the closest third class road found on Google Earth, resulting in a 5 hour hike carrying geophysical equipment. On arrival to the rock glacier, it took a further 20 minutes to climb up the lateral side of the rock glacier due to altitude and tricky terrain (loose rocks). Time was limited because field work needed to be completed before nightfall. Rock observations, axis and lichen measurements were made when visually the rock sizes changed significantly enough to denote a different area on the rock glacier along a transect parallel to rock glacier flow. GPS points were taken at appropriate changing points.

A large majority of the rocks were lichen free, and the few that did host lichens were not that large (diameters were roughly 0.2cm) with the exception of one or two rocks measured that had lichens that were ~1cm in diameter. These lichens were considerably smaller than those observed on rock glaciers of the Cordillera Real. The location, prominent steep frontal and lateral slopes, the height of the rock glacier body, the lack of lichens and vegetation across the rock glacier all imply that this rock glacier is active. Although the lack of lichens could be related to the activity of the rock glacier, it has to be remembered that the climate is different for this rock glacier than for those of the Cordillera Real.

Electrical resistivity was used on this study site to gather data on two sample points. The geophysical data was gathered by a private consultant, Andres, who performed the electrical resistivity and analysed the data. For this electrical resistivity, the method of study design used was the ‘OS Schlumberger’. This is a straight and symmetrical design, with common centre point is used ‘a’, with four electrodes that are aligned (Fig. 3.23).

Due to the nature of the rocks in this type of environment, it is quite complicated the use electrical resistivity methods. The sandy loam nature of the soil caused large gaps, which can cause a leakage in the current. However, to avoid this, sponge saturated with water were used at the contact points. This helped the current pass when it most likely would not without the sponge and water to help with conductivity. Advice regarding the use of sponge and water to address the soil issues was gained from conversations with the Bolivian glaciologist Alvaro Soruco, who has worked in this region before.

The presence of silty sands on the rock glacier was observed, something not seen on the Chacaltaya rock glacier. This made a suitable point for the electrical resistivity. On the basis of the fieldwork, it can be concluded that there are areas that are surrounded by ice, indicated by greater resistivity, over 15000 Ohm-m. Areas with lower resistivity, areas made up with fine materials, but under certain conditions are frozen (see Chapter 4, section 4.3.4). It is advised that for optimum use of electrical resistivity, clasts should be of a heterogeneous diameter, consisting of a sandy silt matrix minimally. However, this is rare for rock glaciers, and thus it can be implied that GPR is more appropriate method for the geophysical investigation of rock glaciers.

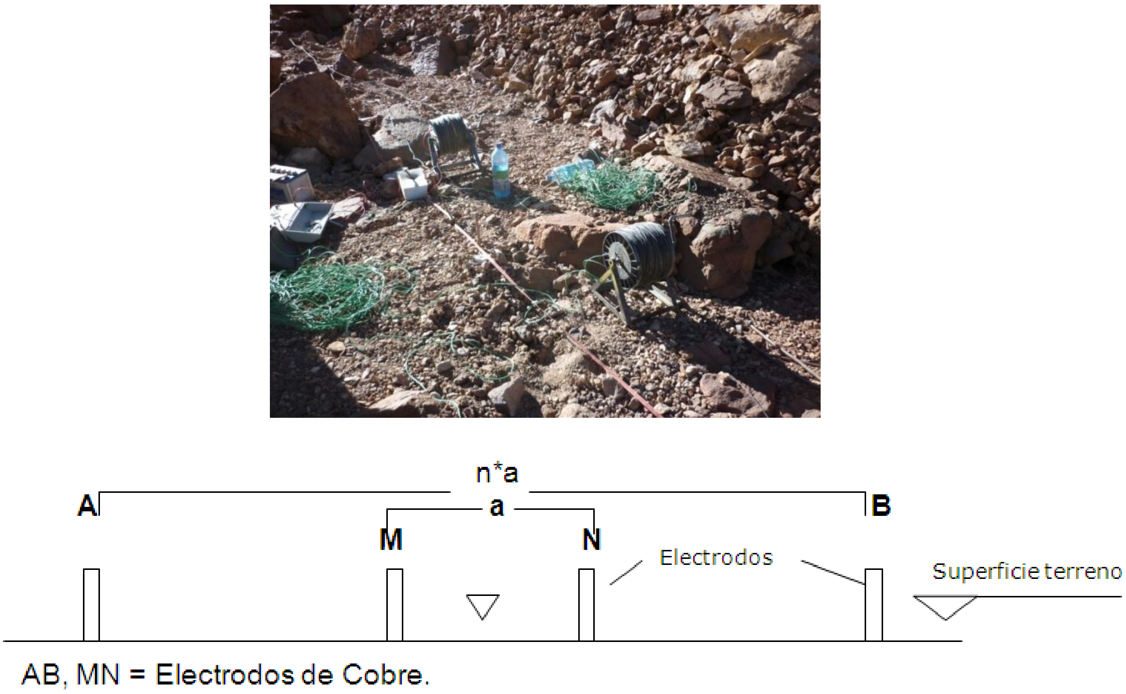


Figure 3.23 The geophysical quipment used on Chiguana rock glacier (above) and the layout of the survey design, OS Schlumberger (below).

Chapter 4 : Water content of Bolivian rock glaciers

As shown in Chapter 2, the hydrological importance of Bolivian rock glaciers is currently unknown. It is acknowledged that rock glaciers are important stores of frozen water in other regions (e.g. Chilean Andes) and likely future climate change means that there is a need for such an assessment to be undertaken in the arid Bolivian Andes. Here, we used estimates of rock glacier thickness and the rock glacier size to calculate ice volume and water equivalent volume for all active rock glaciers in Bolivia. Two methods to estimate the ice and water reserve held in the rock glaciers were used, one a more conservative method and one a well-established method of estimation of rock glacier thickness. These calculations have allowed for an assessment of the importance of these rock glaciers as water supplies on a regional level across Bolivia, and in the context of existing glacier stores.

This paper has been accepted for publication in *Arctic, Antarctic and Alpine Research* (AAAR) (Rangecroft et al., 2014a). AAAR was chosen for its wide readership and focus on the scientific and cultural aspects of high-altitude environments. SR conducted the data collection, analysis, calculations and writing up of this manuscript under the supervision of KA and SH.

Rock glaciers as water stores in the Bolivian Andes: an assessment of their hydrological importance

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Abstract

Water scarcity is a growing issue for high altitude arid countries like Bolivia, where serious water resource concerns exist because of climate change and population growth. In this study we use a recent Bolivian rock glacier inventory (Rangecroft et al., 2014) to estimate the water equivalent storage of these understudied cryospheric reserves. This paper shows that Bolivian rock glaciers currently store between 11.7 and 137 million cubic meters of water. Rock glacier water equivalents are compared to corresponding ice glacier water equivalent to allow an assessment of the hydrological importance of rock glaciers as water stores in this water scarce region. It can be seen that in the densely glaciated Cordillera Real (15° - 16° S), rock glaciers form a small component of mountain water stores; however along the Cordillera Occidental (17° - 22° S), where ice glaciers are absent, rock glaciers are a more important part of the cryospheric water store, suggesting that they could be important for local water management. This is the first time that the water equivalence of the Bolivian rock glacier store has been quantified and is a first step towards assessing the contribution and importance of alternative high altitude water sources.

4.1 Introduction

Water resources in Bolivia have been the subject of considerable debate over the last decade (Barnett et al., 2005; Bradley et al., 2006; Vuille et al., 2008). Over a third of the Bolivian population reside in high altitude cities in the Altiplano such as La Paz and El Alto (Vergara, 2009; WMO 2011; World Bank, 2014) and in mountain communities where water stores are limited. Consequently, rainfall and glacier melt are the two most important water sources providing water for domestic and industrial use, agriculture and power generation (Jordan, 1998; Vuille et al., 2008; Chevallier et al., 2011). During the dry season rainfall is limited (66 mm on average falls between May and September in the Cordillera Real; Francou et al., 2003) and thus glacier meltwater becomes the most important source of potable water during this time of year. It is estimated that glaciers of the Cordillera Real provide 12 – 40% of the potable water for the capital city La Paz (Vergara, 2009; Soruco, 2012).

However, glacier recession is widespread in the Bolivian Andes and is projected to accelerate in coming decades (Francou et al. 2003; Ramirez et al., 2007; Rangecroft et al., 2013). A decrease in the potable water supply from glaciers by 2050 is therefore projected for La Paz (Ramirez et al., 2007; Buxton et al., 2013), exacerbated by population increase (Magrath, 2005; IPCC, 2007a; Buytaert and De Bièvre, 2012). Current urban water shortages in Bolivia represent a major social and economic problem (World Bank, 2010) and the demand on dwindling water supplies is increasing with population growth, rural-to-urban migration and westernization of lifestyles (Painter, 2007; Mölg et al., 2008; Vanham and Rauch, 2010; WMO, 2011; Buytaert and De Bièvre, 2012; Rangecroft et al., 2013). All of these factors combine to produce strong evidence that Bolivia will continue to experience sustained water shortages in the future (Rosenthal, 2009; Rangecroft et al., 2013). There is now a pressing need for information about alternative stores of water at high elevations (Brenning et al., 2007; Rangecroft et al. 2013).

In the Andes, glaciers, debris covered glaciers and rock glaciers are the three main features of the cryosphere (Bodin et al., 2010a). Until now, most research has focused on rock glacier reserves in the Chilean Andes (Brenning, 2005a; Brenning and Azócar, 2008; Azócar and Brenning, 2010) and the Argentinean Andes (Schrott, 1996; Trombotto et al., 1999; Croce and Milana, 2002; Perucca and Esper Angillieri, 2008; 2011; Esper Angillieri, 2009; Arenson et al., 2010; Bodin et al., 2010a; Falaschi et al., 2014). Research in the Bolivian Andes is conversely quite sparse, with published information only on one, Caquella rock glacier (21.5° S) (Francou et al., 1999; Bodin et al. 2010b).

4.1.1 Rock glaciers

Rock glaciers (Fig. 4.1a) are cryospheric landforms developed from accumulations of ice and debris, generally occurring in high mountainous terrain (Harrison et al., 2008; Berthling, 2011). In shape they resemble small glaciers and form a mix of angular rock debris with a core of ice or ice-cemented fine clasts, usually with a distinct ridge and furrow surface pattern (Potter, 1972). Rock glaciers are often classified by their activity status and sub-divided into 'active' and 'inactive' (containing ice, also known as 'intact') or 'relict' (not containing ice, sometimes referred to as 'fossil') (Barsch, 1996; Baroni et al., 2004; Krainer and Ribis, 2012; Falaschi et al., 2014). Active rock glaciers are considered indicators of contemporary permafrost (Barsch, 1996; Burger et al., 1999; Haeberli, 2000). It is estimated that active rock glaciers contain a range of between 40 - 60 % ice covered by a surface layer of rock, which insulates the ice from low amplitude and high frequency temperature changes (Brenning, 2005a). They have a steep front [snout] and side slopes and give a visual representation of a swollen body due to ice content (Baroni et al., 2004). It is these surface features of ridges and furrows and steep front and sides that allow for rock glacier identification from high resolution satellite images for inventory mapping (Paul et al., 2003). However, there is considerable variation in surface morphology occurring between locations in response to both topographic and lithologic variables (Giardino and Vitek, 1988).

This study only focuses on active rock glaciers (those containing ice) and therefore those with relevance for water supplies. Active rock glaciers have been shown to contain significant volumes of water in the Chilean and Argentinean Andes where they are key stores and sources of water, especially during the dry season (e.g. Croce and Milana, 2002; Brenning, 2005a; Brenning et al., 2007; Azócar and Brenning, 2010). The hydrological role of the active layer in a rock glacier is important since it stores a significant quantity of water or ice due to the open debris texture (Croce and Milana, 2002). Rock glaciers trap and conduct water that enters with the active layer and sub-permafrost material of active rock glaciers producing temporary aquifers and a seasonal release of water from the active layer (Burger et al., 1999; Croce and Milana, 2002).

The hydrological function and importance of rock glaciers is relatively well studied in other mountain regions of the world (Giardino et al.,1992; Cecil et al., 1998; Arenson et al., 2002, Williams et al., 2006; Azócar and Brenning, 2010), however the hydrological importance of rock glaciers in Bolivia has never been assessed. Therefore, this research addresses this knowledge gap. We have documented the extent and size of the rock glacier resource in Bolivia in a previous study (Rangecroft et al., 2014), which concluded that there are 54 active rock glaciers covering a total surface area of 7 km^2 across the national extent of the Bolivian Andes (ranging from 15° - 22° S) (Fig. 4.1b). However the water storage potential of these permafrost features has not been explored and this is therefore the focus of this paper. This paper aims to estimate the ice content of Bolivian rock glaciers, calculate the water equivalent for Bolivian rock glaciers and ice glaciers and therefore allow a comparison of these hydrological stores.

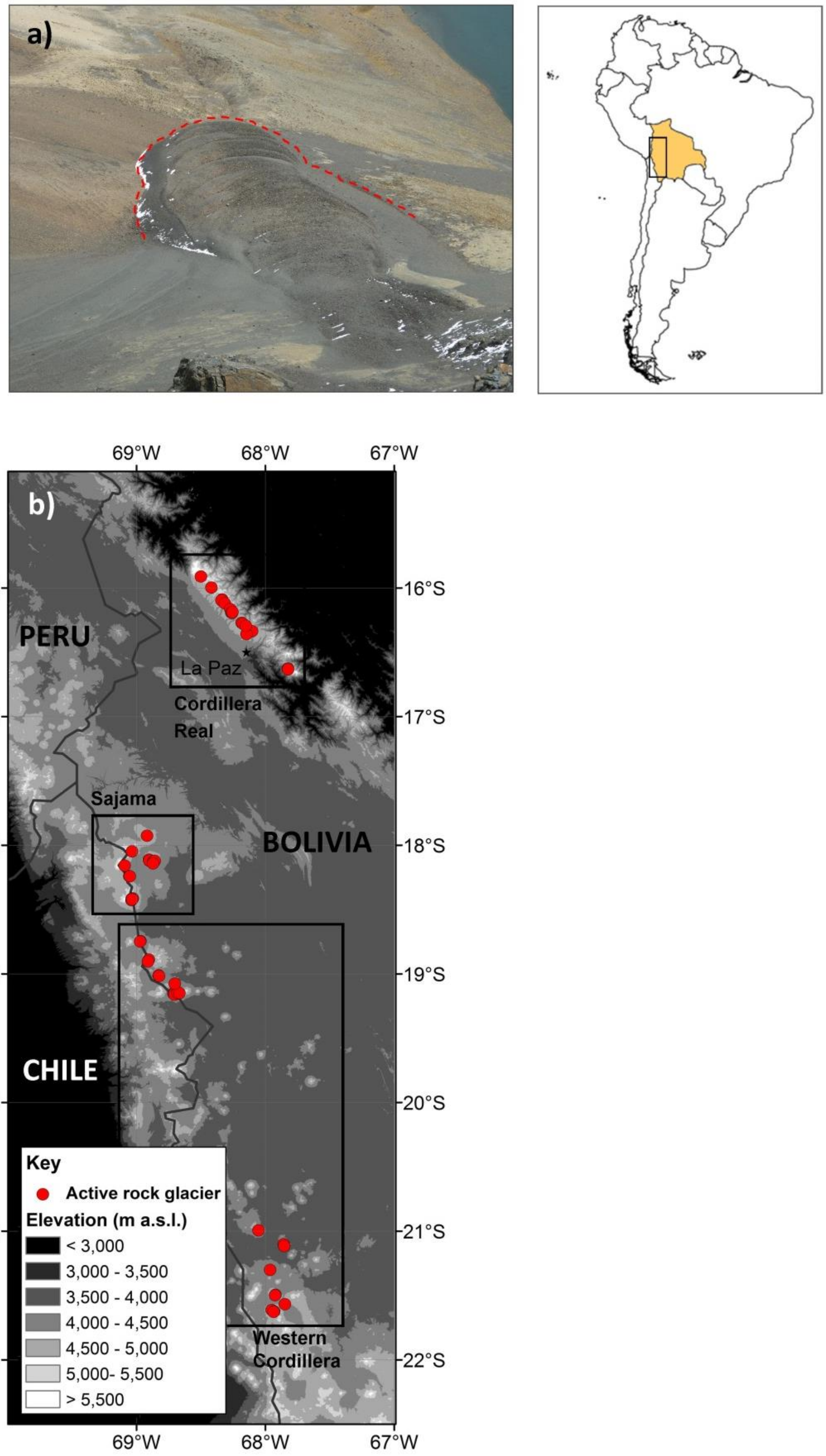

Figure 4.1 Study region
a) example photograph (Authors own) of a Bolivian rock glacier with the sides and frontal slope indicated with a red dashed line (Pico Austria rock glacier in the Cordillera Real region, 16°11'35 S, 68°15'53 W; b) the location of active rock glaciers in the Bolivian Andes on an elevation map of the study region with the three main regions discussed in this paper are annotated here: Cordillera Real, Sajama and Western Cordillera.

4.1.2 Study Area

Bolivia is located in the centre of the South American Andes (Payne, 1998), a region also known as the dry Andes. The rock glacier inventory (Rangecroft et al., 2014) encompasses the two Cordillera mountain ranges of Bolivia between 15° S and 22° S (Fig. 4.1b), home to 20% of the world's tropical glaciers (Rabatel et al., 2013). Bolivia has a distinctive climate consisting of a dry season (May - August) and a wet season (December - February) (Francou et al., 2003), with aridity increasing towards the south of the country, resulting in no current ice glaciers in the south (Jordan, 1998). The Bolivian Cordillera Oriental is estimated to host 98% of Bolivia's glaciers (Jordan, 1998).

Three climatically and topographically distinct regions were identified along the Bolivian Andes: the Cordillera Real (15° - 16° S), Sajama (17° - 18° S), and the Western Cordillera (18° - 22° S) (Fig. 4.1b). Along the Cordillera Oriental, the first region, 'Cordillera Real', is a glaciated mountain range situated close to La Paz (Fig. 4.1b). With the wettest climate of the Bolivian Andes, this region contains the highest density of glaciers in the Bolivian Andes. The second and third regions, 'Sajama' and 'Western Cordillera', are based along the Bolivia-Chile border in the mountain chain of the Cordillera Occidental. The Sajama region is situated around the isolated ice capped volcanic mountains in the Sajama National Park (Fig. 4.1b). The Western Cordillera covers the area southwards of Sajama, along the dry, barren mountain range of the Cordillera Occidental (Fig. 4.1b). Almost no ice glaciers exist in this region (Francou et al., 1999) as rainfall is very low. Annual precipitation here is estimated to be less than 250 – 300 mm on the summits (Vuille and Amman, 1997). With its dry climate, this area is the best example of arid high mountains in the inner tropics (Francou et al., 1999). Population densities differ in the three regions, with the Cordillera Real providing water for the cities of La Paz and El Alto (Vergara, 2009; Soruco, 2012). There are no cities located in close proximity for the other two regions, only mountain communities and towns. For all three regions, rock glacier volume and water equivalent were estimated and analysed.

4.2 Estimating water stores

4.2.1 Using the rock glacier inventory

Prior to this study, the first Bolivian rock glacier inventory was produced using fine spatial resolution satellite data, available through the platform of Google Earth (version 7.1.1.18888, Google Inc.), supported by a field mapping and validation programme undertaken in 2011 and 2012 (Rangecroft et al., 2014). Satellite data available through Google Earth ranged from 5 to 30 m spatial resolution imagery. Rock glaciers were identified and classified according to Baroni et al. (2004) (Rangecroft et al., 2014). The resulting inventory contained spatial data describing the location, shape, elevation and surface area of the rock glaciers along the Andean mountain ranges of Bolivia, the Cordillera Oriental and the Cordillera Occidental (Fig. 4.1b). A full list of active rock glaciers and their coordinates are available in Table 4.1.

The calculated mean minimum altitude at rock glacier front (MAF) for active rock glaciers was 4983 m (± 30m) (Rangecroft et al., 2014). The majority (88%) of the active rock glaciers had a main direction of flow as southerly (SE, S, and SW) (Rangecroft et al., 2014). Average active rock glacier length was 550 m (Rangecroft et al., 2014) and average active rock glacier area was 0.13 km^2, with a minimum of 0.01 km^2 and a maximum of 0.79 km^2 (Table 4.1). Average rock glacier area for the Cordillera Real region was 0.07 km^2, 0.20 km^2 for Sajama and 0.13 km^2 for the Western Cordillera (Table 4.1).

4.2.2 Estimating rock glacier thickness

Calculations of the water content of the rock glaciers were carried out, based on an estimation of the volume of ice (km^3) contained in the rock glacier (e.g. Barsch, 1996; Brenning, 2005a; Azócar and Brenning, 2010). To generate a value for ice volume (km^3), estimates of rock glacier thickness and surface area were multiplied together. However, in this study rock glacier thickness was an unknown variable because this cannot be measured from remote sensing instruments, and to-date there are no direct measurements of the thickness and average ice content of active rock glaciers in the Bolivian Andes. Existing studies elsewhere in the Andes have estimated the mean thickness of rock glacier ice-rich permafrost through an empirical rule established by Brenning (2005b) (Azócar and Brenning, 2010; Perucca and Esper Angillieri, 2011) (Equation 1; Table 4.2). However, it should be noted that more research is needed to improve the area-thickness relationship established by Brenning (2005b) for other regions.

$$\text{Mean rock glacier thickness [m]} = 50 \times (\text{rock glacier area [km}^2\text{]})^{0.2} \qquad \text{[Equation 1]}$$

Cordillera Real

ID	Lat (S)	Long (W)	Size (km^2)
A1a	15.89611	68.51472	0.146
A2a	15.98944	68.43111	0.153
A11a	16.09138	68.33361	0.058
A12a	16.09777	68.33972	0.036
A14a	16.12083	68.31416	0.089
A16a	16.16416	68.27277	0.107
A19a*	16.19305	68.26472	0.043
A20a*	16.19666	68.25805	0.032
A21a*	16.1875	68.25333	0.011
A27a	16.27222	68.18305	0.039
A29a*	16.27861	68.17416	0.043
A34a*	16.33833	68.10138	0.046
A37a*	16.36000	68.14638	0.047
A39a*	16.29861	68.15138	0.145
A40a*	16.62888	67.82388	0.034
A42a*	16.63305	67.82305	0.038

Sajama

ID	Lat (S)	Long (W)	Size (km^2)
B50a	18.04361	69.04305	0.064
B54a*	18.11000	68.90666	0.103
B56a	18.12111	68.90222	0.150
B58a	18.13166	68.86888	0.180
B59a	18.12805	68.85833	0.213
B60a	18.12472	68.85416	0.266
B62a*	18.14305	68.87055	0.024
B68a	18.24111	69.05472	0.033
B70a	18.24305	69.05027	0.057
B76a	18.43055	69.0325	0.669
B77a	18.41583	69.02777	0.789
B120a	18.13555	69.11111	0.196
B124a	18.74944	68.96722	0.126
B134a	18.41583	69.03305	0.061
B135a	18.42166	69.03194	0.043

Western Cordillera

ID	Lat (S)	Long (W)	Size (km^2)
C84a	18.74944	68.96722	0.147
C85a	18.75055	68.97055	0.039
C86a	18.89	68.9	0.118
C87a	18.90888	68.91083	0.518
C92a	19.12805	68.69722	0.185
C93a	19.15499	68.71305	0.124
C94a	19.1525	68.70805	0.115
C95a	19.16527	68.70611	0.180
C96a	19.15305	68.68083	0.117
C97a	19.15305	68.66694	0.211
C101a	20.99333	68.05416	0.087
C107a*	21.10250	67.85361	0.127
C108a	21.1175	67.85222	0.052
C109a	21.30361	67.96138	0.093
C110a	21.49777	67.91833	0.206
C111a	21.49916	67.92111	0.050
C113a	21.56916	67.84583	0.035
C114a	21.61666	67.9475	0.078
C115a	21.62916	67.92916	0.134
C116a	21.62805	67.93361	0.037
C126a	19.015	68.82694	0.131
C128a	19.01888	68.82305	0.079
C130a	19.07694	68.70222	0.016

Table 4.1 ID and coordinates of active rock glaciers identified in the Bolivian Andes divided into three corresponding regions. * indicates rock glaciers that were visited for field validation. Adapted from Rangecroft et al. (2014).

Characteristic	Values	Reference
Rock glacier permafrost thickness	50 x (surface area)$^{0.2}$	Brenning, 2005b, p. 24; Azócar & Brenning, 2010, Table 1
Percentage of rock glacier volume as ice	40 - 60 %	Barsch, 1996; Haeberli et al. 1998; Arenson et al. 2002; Hausmann et al. 2007; Brenning, 2008; Krainer & Ribis, 2012
Ice glacier thickness	28.5 x (surface area)$^{0.357}$	Chen & Ohmura, 1990, p. 128
Density of ice	0.9 kg/m^3	Azócar & Brenning, 2010, p. 45

Table 4.2 Values used for calculations of estimates of permafrost thickness, ice content and water volume in rock glaciers and ice glacier thickness and their sources.

4.2.3 Estimating ice content and water equivalents of rock glaciers

Once the thickness of a rock glacier was established, ice content needed to be accounted for as rock glacier permafrost is not composed of 100% ice. Ice content varies considerably within rock glaciers; therefore the amount of water in rock glaciers is naturally difficult to estimate due to the inherent variability and difficulty in determining exact genesis and subsequent depth and distribution of ice (Seligman, 2009). Currently, the worldwide estimates for ice content within rock glaciers ranges between 40 and 60% by volume (Barsch, 1996; Haeberli et al., 1998; Arenson et al., 2002; Hausmann et al., 2007; Brenning, 2008; Krainer and Ribis, 2012). A lack of studies investigating the ice content of rock glaciers in the Andes does not help to reduce this large range of uncertainty.

First attempts to quantify ice content in the Andes were established by Croce and Milana (2002), who found an average ice content of 55.7% for an Argentinean rock glacier. More recently, Arenson et al. (2010) working in Argentina showed that test pits dug in rock glaciers contained over 50% ice content. Similarly, Perucca and Esper Angillieri (2011) used the estimate of 50% ice content by volume for calculating water equivalents of rock glaciers at 28°S in the Argentinean Andes. Monnier and Kinnard (2013) found a much lower range of ice content in a small rock glacier in Chile (15 – 30%); however, there are some limitations about the coring technique utilised, and they concluded that the rock glacier was degrading. Therefore, due to the lack of ice content studies in the semi-arid Andes, it can be argued that using the range 40 – 60% ice content offers the best estimate currently available and allows a lower and an upper estimate of ice content to be calculated. From this, water content can be determined using the conversion factors for the density of ice and density of water shown in Table 4.2. An ice density of 0.9 g/cm^3 ($\equiv$ 900 kg/m^3) was used to convert ice volume into a water equivalent (Azócar and Brenning, 2010; Perucca and Esper Angillieri, 2011).

4.2.4 Estimating thickness and water equivalents of ice glaciers

One of the aims of this work was to compare the water equivalent storage of rock glaciers to that of ice glaciers. In order to make this comparison it was first necessary to establish current ice glacier coverage of the Bolivian Andes. Recent data describing the distribution of ice glaciers across Bolivia were not available, so it was necessary to use data from Ramirez *et al.* (2012) for the Cordillera Real and Jordan (1998) for the Cordillera Occidental. For the Cordillera Real only, we were able to use a recent inventory by Ramirez et al. (2012) where they estimated ice glacier coverage of 185.5 km^2 (Ramirez et al., 2012). Along the Cordillera Occidental, the only ice glaciers existing are those in the Sajama region, which Jordan (1998; Jordan et al., 1980) estimated to cover 10 km^2. South of this region, ice glaciers are absent (Jordan et al., 1980; Jordan, 1998).

Using the empirical relationship established by Chen and Ohmura (1990) used by Azócar and Brenning (2010) and Perucca and Esper Angillieri (2011), ice glacier thickness (and subsequent water equivalent assuming 100% ice content) was estimated using equation 2:

$$\textit{Mean ice glacier thickness [m]} = 28.5 \times (\textit{ice glacier area [km}^2\textit{]})^{0.357} \qquad \textit{[Equation 2]}$$

Ice glacier thickness had to be calculated on an individual basis to be comparable with the rock glacier estimates. However, data on all individual ice glacier sizes were not available; therefore an estimate of average ice glacier size was established using known total surface area and number of ice glaciers. For the Cordillera Real, the total number of ice glaciers within the inventory of Ramirez *et al.* (2012) was 476, giving an average ice glacier size of 0.39 km^2. Using this average, the mean ice glacier thickness equation could be applied and multiplied by the number of ice glaciers to find total ice volume and water equivalent. For the Sajama region, the 10 km^2 coverage was composed of the glaciated cone of Sajama (4 km^2), Payachata (4 km^2) and Quimsachata (2 km^2) (Jordan et al., 1980; Jordan, 1998).

To directly compare the water equivalents of ice glaciers and rock glaciers (as a ratio), the average ice content of 50% was used as a midrange between the lowest (40%) and the highest (60%) rock glacier ice contents.

4.2.5 Field work

To investigate the internal composition of rock glaciers, direct and indirect methods can be applied. Direct methods (e.g. coring, drilling, test pits) are labour- and time-intensive, whereas indirect methods (e.g. geophysical surveys) allow relatively rapid and inexpensive acquisition of data. Fieldwork was conducted on the Chiguana active rock glacier (21°06’09 S, 67°51’13 W) in the Western Cordillera region as this is a representative active rock glacier for the Bolivian Western Cordillera. Electrical resistivity surveys and test pits were conducted on lower parts of the rock glacier, close to the snout of the rock glacier. Electrical resistivity surveying used a Geo-receiver (JP), Geo-transmitter (JP-600) and electrodes to perform the Vertical Electrical Sounding (SEV) method.

Electrical resistivity is one of the most commonly used geophysical methods to investigate permafrost and rock glacier internal content and structure (Croce and Milana, 2002; Bucki et al., 2004) as the equipment is light and easy to use (Croce and Milana, 2002). Refraction seismics can provide detailed information on the structure of the upper layers, and when complemented with geoelectric methods, deeper information can be gained, such as permafrost thickness estimates (Croce and Milana, 2002). Additional geophysical methods should be applied to reduce ambiguities if possible. Geophysical surveys require verification by coring/drilling or other direct methods (Degenhardt Jr and Giardino, 2003) such as test pits. Well drilling combined with high-resolution reflection seismics is usually viewed as the best option for rock glacier investigation (Kääb et al., 1997), but is usually expensive.

4.3 Results of rock glacier water content calculations

4.3.1 Rock glacier permafrost thickness/ ice volume

Rock glacier permafrost thickness estimates ranged between 20 and 48 m (Table 4.2). Overall, these calculations resulted in an estimated total ice volume of 0.23 to 37.60 million cubic meters (Table 4.3).

4.3.2 Rock glacier water equivalent calculations

Results in Table 4.3 show that throughout the Bolivian Andes active rock glaciers are estimated to contain a total water volume equivalent of between 0.01 and 0.13 km^3 of water. Regionally, rock glaciers of the Cordillera Real (15° – 16° S) have been estimated to store the smallest amount of water, containing between 0.01 and 0.02 km^3 of water (Table 4.3). Sajama (17° – 18° S) and Western Cordillera (18° – 22° S) have been estimated to hold triple this water equivalent each (Table 4.3). In Sajama rock glaciers are estimated to hold 0.04 and 0.06 km^3 of water (Table 4.3). In the Western Cordillera rock glaciers contained between 0.04 and 0.05 km^3 of water (Table 4.3).

Region	**Rock glacier total surface area** (km^2)	**Ice content estimate**		**Ice volume** (km^3)	**Water volume equivalent** (km^3)
Cordillera Real (15° - 16° S)	1.07	Lower	40%	0.01	0.01
		Average	50%	0.02	0.01
		Upper	60%	0.02	0.02
Sajama (17° - 18° S)	2.98	Lower	40%	0.05	0.04
		Average	50%	0.06	0.05
		Upper	60%	0.07	0.06
Western Cordillera (18° - 22° S)	2.88	Lower	40%	0.04	0.04
		Average	50%	0.05	0.05
		Upper	60%	0.06	0.05
Total	**6.93**	Lower	40%	0.10	0.09
		Average	50%	0.13	0.11
		Upper	60%	0.15	0.14

Table 4.3 Table of ice volume and corresponding water volume equivalents for Bolivian rock glaciers regionally and nationally (total). These calculations cover a range of ice content estimates with a lower (40%), average (50%) and upper (60%) bound. Rock glacier surface areas were taken from Rangecroft et al. (2014).

4.3.3 Ratios of rock glacier to ice glacier water equivalents

On average, the Cordillera Real hosts rock glaciers that we estimated to contain 0.01 km^3 water (coverage of 1.07 km^2) and 185.5 km^2 of ice glaciers (Ramirez et al., 2012) which were estimated to contain 3.34 km^3 of water (Table 4.4). This resulted in a ratio of rock glacier to ice glacier water equivalence of 1:228, implying that ice glaciers contained a store of water 228 times bigger than that of the rock glaciers in the same region. In Sajama (17° – 18° S), rock glaciers contained an estimated average of 0.05 km^3 of water (2.98 km^2), and 10 km^2 of ice glacier coverage which equated to 0.39 km^3 of water (Jordan, 1998) resulting in a ratio of rock glacier to ice glacier water equivalence of 1:7 (Table 4.4). In the Western Cordillera (18° - 22° S) there are no ice glaciers due to limited precipitation (Jordan, 1998; Vuille, 2007), yet rock glaciers in this region contained an estimated 0.05 km^3 of water (2.88 km^2), indicating a hydrological store in the absence of ice glaciers. However, this regional water store is for the largest region analysed (Table 4.4; Fig. 4.1b).

Region	**Region area** (km^2)	**Rock glacier**		**Ice glacier**		**Ratio**
		Area (km^2)	Water equivalent (km^3)	Area (km^2)	Water equivalent (km^3)	Rock glacier: Ice glacier water equivalent
Cordillera Real (15° - 16° S)	~ 7050	1.07	0.01	185.5 (Ramirez et al., 2012)	3.34	1: 228
Sajama (17° - 18° S)	~ 4000	2.98	0.05	10.00 (Jordan, 1998)	0.40	1: 7
Western Cordillera (18° - 22° S)	~2500	2.88	0.05	0 (Jordan, 1998; Vuille, 2007)	0	∞
Total	**36050**	**6.93**	**0.11**	**195.5**	**3.73**	**1: 33**

Table 4.4 Regional and total area and corresponding water equivalents for Bolivian rock glaciers and glaciers with a final column comparing these water equivalents directly as a ratio. Values are reported to 2 decimal places. Rock glacier water equivalents use the 50% ice content (average ice content).

4.3.4 Electrical resistivity

From fieldwork conducted in the Bolivian Andes, the presence of ice was confirmed within the Chiguana active rock glacier (Fig. 4.2a,b). Test pits confirmed the presence of ice (Fig. 4.2c). However, these surveys did not extend deeper than 5m, therefore ice content values through the entire depth of the rock glacier were not established. Previous research suggests that resistivity readings greater than 20,000 Ω represent an ice rich layer (e.g. Francou et al., 1999). Survey site 1 (Fig. 4.2d) (21°06'06.93 S, 67°51'17.95 W) showed that within the first meter readings were characteristic of an ice rich layer (19,817 Ω at 0.89 m), followed by a layer characteristic of substrate without ice (2,003 Ω) until a depth of 5.22 m. Below this resistivity values of 31,640 Ω were measured, implying ice underneath an active layer of ~5 m. Site 2 (Fig. 4.2e) (21°06'06.46 S, 67°51'19.44 W) showed a similar pattern; an ice rich layer at 1 metre depth (512,580 Ω between 0.14 – 0.79 m), then a zone of substrate without ice (220 Ω) followed by an ice rich layer below this at 2.39 m (Fig 4.2e). These results from the SEV surveys at Chiguana rock glacier in Bolivia (Fig. 4.2d,e) demonstrated a similar pattern found by Croce and Milana (2002) for a rock glacier in the Argentinean Andes. Resistivity values greater than 20,000 Ω were found within the few meters of the survey sites in Argentina, and then again below what could be considered the active layer (the first 1-5 m), implying an upper dry deposit layer was found over a second wet debris layer with poor conductivity (2-5 m thick) followed by a highly resistive layer of frozen debris (permafrost) (Croce and Milana, 2002).

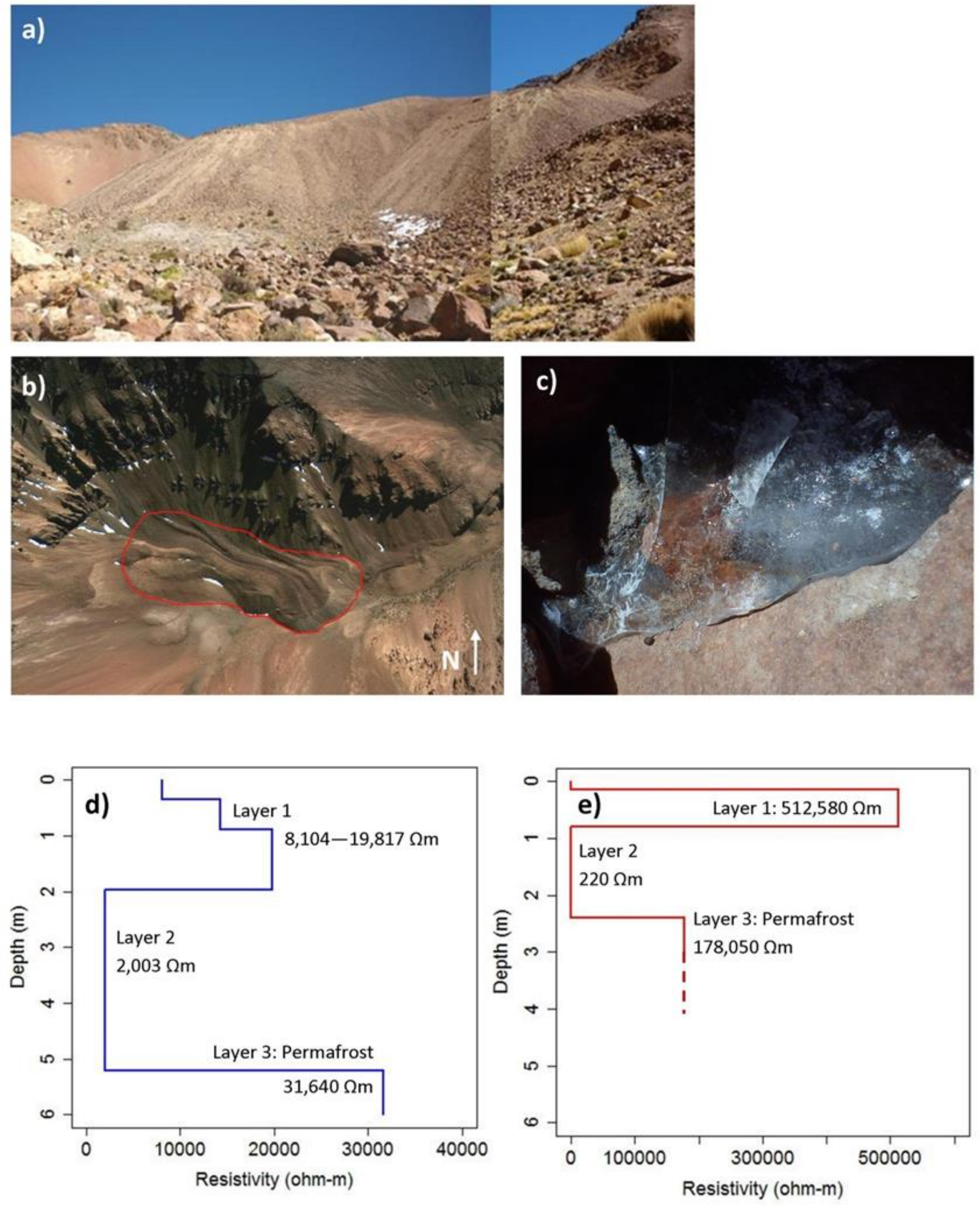

Figure 4.2 Electrical resistivity surveys and test pits conducted on Chiguana rock glacier (21°06'09 S, 67°51'13) in August 2012. a) Photograph of the rock glacier front [snout] (Authors own); b) High resolution Google Earth image of Chiguana rock glacier; c) ice was found to be present within a metre from the surface in the areas surveyed; d) geoelectrical model for survey site 1 (21°06'06.93 S, 67°51'17.95 W); e) geoelectrical model for survey site 2 (21°06'06.46 S, 67°51'19.44 W).

4.4 Discussion

4.4.1 Rock glacier water content

In comparison to the limited number of studies on rock glacier water stores, Bolivian rock glaciers contained far less water than those of the Chilean Andes (Azócar and Brenning, 2010) and the Argentinean Andes (Perucca and Esper Angillieri, 2011). Azócar and Brenning (2010) found 147.5 km^2 of rock glaciers in Chile (27° - 33° S), which they estimated to hold the water equivalent of 2.37 km^3. Therefore the hydrological store of rock glaciers is much greater further south in the Andes (27° - 33° S) than Bolivia (15° - 22° S). Our results are more comparable to those of Perucca and Esper Angillieri (2011) in Argentina who calculated a water equivalent of 0.12 km^3 for 6 km^2 of rock glaciers in a 1 degree region at 28° S. This result is a similar estimate to that stored in Bolivian rock glaciers but covering a much smaller area. Overall, rock glaciers are relatively more important as water stores in Bolivia with a national ratio of 1:33 rock glacier to ice glacier water equivalent (Table 4.4) than they are in the European (Swiss) Alps, where their ratio is calculated to be ~1:83 (Brenning, 2005b).

However, it is the regional impact of these water resources which is important to consider when evaluating the absolute values, and their presence in comparison to other water stores (such as ice glaciers). For example, Table 4.3 shows that there are noticeable differences in rock glacier water content when viewed regionally. Rock glaciers of the Sajama region's contained the largest amount of ice covering the smallest regional area (Table 4.4), and therefore have the greatest potential as water sources. Conversely, the Cordillera Real's rock glaciers contained the least amount. Exploring these regional differences in the context of population pressures and other water stores (e.g. glacial ice) is important if the significance of the rock glacier water storage is to be understood.

4.4.2 Hydrological importance of rock glaciers

Rock glaciers of the Cordillera Real stored the lowest amount of water out of the three regions (corresponding to the smallest surface area) (Table 4.3), yet this region of Bolivia is the most densely populated region with the basins of the Cordillera Real supplying water for around 2.3 million people living in La Paz and El Alto (Vergara, 2009; WMO, 2011). From the comparison of rock glacier to ice glacier water equivalent in Table 4.4 it is clear that rock glaciers contribute less to regional water supply in the Cordillera Real where ice glaciers dominate. However, with rapid glacier recession evident in this region (Soruco et al., 2009; Ramirez et al., 2012), we hypothesise that the relative importance of rock glaciers to ice glaciers will increase. The ice in rock glaciers is protected from small thermal changes by an insulating debris layer, resulting in a longer lag time than ice glaciers in their response to climate change, which is known to be on decadal timescales (Schrott, 1996; Haeberli et al., 2006). This makes rock glaciers more resilient water stores (Millar and Westfall, 2008) so it is likely that rock glaciers will persist as longer-term stores of water in mountain regions, even when ice glaciers have retreated or disappeared. It is important to note that response to climatic change is a size dependent process, with smaller rock glaciers being more susceptible to thawing. However, we also argue that, given appropriate conditions, retreating ice glaciers may also begin to incorporate significant debris cover and, over time, may undergo a transition to rock glacier forms.

In Sajama, rock glaciers have a higher relative importance as water stores in comparison to ice glaciers than in the Cordillera Real region, with a ratio of 1:7 rock glacier to ice glacier water equivalence (Table 4.4). This ratio is similar to that of the Andes of Santiago, Chile which is also 1:7 (Brenning, 2005b), but of lower importance than that of the Arid Chilean Andes between 27° and 29° S, where ratios are 1:2.7 (Azócar and Brenning, 2010) and between 29° and 32° S where rock glaciers dominate with a ratio of 3:1 (Azócar and Brenning, 2010). It can be noted that with recent glacier recession the ice coverage of the Sajama region is likely to be currently less than 10 km^2, especially given glacier recession trends in the Cordillera Real, however there is a lack of published data for this region. Also, similarly to the Cordillera Real, the estimated rock glacier reserve of Sajama will also increase in relative importance with projected glacier recession in Sajama.

In the Western Cordillera (18° - 22° S), without the contribution of ice glaciers to the hydrological cycle in this region, and with the very limited rainfall (< 300 mm a^{-1}), here potentially rock glaciers may act as an important water store. However, rock glaciers are still sparse in this region in comparison to those of the Chilean Andes

(Azócar and Brenning, 2010) and population levels along the Western Cordillera are low.

4.4.3 Future research

Rock glaciers are long-term stores of frozen water but the total water stores calculated in this research may not represent water that is readily available for release for human consumption. Research and data on rock glacier and ice glacier water discharge are crucial for improving scientific understanding of local cryospheric reserves and their importance to the hydrological cycle and for future water resources management. It is also clear from this paper that more recent data on ice glaciers across the whole of the Bolivian Andes is needed and that field studies on ice content of Bolivian rock glaciers is necessary to improve and refine our understanding and the information established here. Furthermore, research on the impacts of future temperature and precipitation changes on the hydrological function of rock glaciers is needed to fully implement the information provided here in a future context. As rock glaciers are known to exist close to the mean annual air temperature 0 °C isotherm (Payne, 1998; Avian and Kellerer-Pirklbauer, 2012), it is important to investigate the potential implications of projected climate change for rock glaciers and their water stores.

4.5 Conclusions

Currently, little is known about Bolivian rock glacier water resources and their hydrological importance at local, regional and national scales. This is the first time the water equivalents of Bolivian rock glaciers have been estimated, and in comparison to ice glaciers in the region. Overall, rock glaciers in the Bolivian Andes can be considered as relatively locally important water stores in regions of limited or no ice glacier coverage, such as in the Western Cordillera and Sajama. Relative importance of rock glacier stores compared to ice glaciers along the Bolivian Western Cordillera mountain range are similar to regions of the Chilean Andes, however in the Cordillera Real ice glaciers dominate as hydrological stores. With projected glacier recession, this relative importance of rock glaciers in the Cordillera Real may increase. Although rock glaciers are of a similar size to other regions such as the Chilean Andes, their coverage is sparser along the Bolivian Andes, resulting in a much smaller total coverage than other regions of the Andes, and therefore their role in the hydrological cycle in general is less significant. This work has improved knowledge and understanding of rock glaciers in the Bolivian Andes, contributing to the first step of sustainable water management: mapping and gathering information on current water resources, however, more research is required regarding rock glacier discharge data and impacts of future projections on rock glaciers and their water stores.

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4.6 Supplementary material

Table 4.5 demonstrates the calculations used to estimate rock glacier water volume from rock glacier area. Rock glacier area (RG_A) was used as the initial data input and the rock glacier ice content ($\%_{ICE}$) varied depending on the threshold being investigated: lower boundary of 40%, average of 50% and upper boundary of 60%. Subsequent data of individual rock glacier areas, estimated permafrost thicknesses, ice volume and water equivalents are presented in Table 4.6.

Variable	**Rock glacier area** (km^3)	**Rock glacier mean thickness** (m)	**Rock glacier permafrost volume** (m^3)	**Rock glacier permafrost volume** (km^3)	**Rock glacier ice content** (%)	**Rock glacier ice volume** (km^3)	**Rock glacier water volume** (km^3)
Symbol	RG_A	RG_T	RG_V	RG_{VOL}	$\%_{ICE}$	RG_{ICE}	RG_{WATER}
Equation		$50 \times (RG_A)^{0.2}$	$RG_T \times RG_A$	$RG_V \times 10^{-9}$		$\%_{ICE} \times RG_{VOL}$	$0.9 \times RG_{ICE}$

Table 4.5 Table demonstrating the equations used to calculate rock glacier water volume from rock glacier area

Table 4.6 Tables of rock glacier ID, size and subsequent permafrost thickness presented in the three different regions.

Cordillera Real

Rock glacier ID	Rock glacier area (km^2)	Rock glacier mean permafrost thickness (m)	Rock glacier permafrost volume (m^3)	Rock glacier permafrost volume (km^3)	Ice volume			Water volume		
					40% (km^3)	50% (km^3)	60% (km^3)	40% (km^3)	50% (km^3)	60% (km^3)
A1a	0.1456	34.0112	4953153.1846	0.0050	0.0020	0.0025	0.0030	0.0018	0.0022	0.0027
A2a	0.1534	34.3649	5270333.7337	0.0053	0.0021	0.0026	0.0032	0.0019	0.0024	0.0028
A11a	0.0578	28.2677	1632659.2638	0.0016	0.0007	0.0008	0.0010	0.0006	0.0007	0.0009
A12a	0.0359	25.6986	921730.7317	0.0009	0.0004	0.0005	0.0006	0.0003	0.0004	0.0005
A14a	0.0889	30.8112	2737826.0103	0.0027	0.0011	0.0014	0.0016	0.0010	0.0012	0.0015
A16a	0.1072	31.9901	3429631.8088	0.0034	0.0014	0.0017	0.0021	0.0012	0.0015	0.0019
A19a	0.0425	26.5892	1130784.7828	0.0011	0.0005	0.0006	0.0007	0.0004	0.0005	0.0006
A20a	0.0323	25.1722	814093.2196	0.0008	0.0003	0.0004	0.0005	0.0003	0.0004	0.0004
A21a	0.0113	20.4062	231059.4914	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
A27a	0.0389	26.1169	1015504.1972	0.0010	0.0004	0.0005	0.0006	0.0004	0.0005	0.0005
A29a	0.0427	26.6114	1136466.6068	0.0011	0.0005	0.0006	0.0007	0.0004	0.0005	0.0006
A34a	0.0462	27.0349	1249390.7214	0.0012	0.0005	0.0006	0.0007	0.0004	0.0006	0.0007
A37a	0.0474	27.1713	1287704.0113	0.0013	0.0005	0.0006	0.0008	0.0005	0.0006	0.0007
A39a	0.1449	33.9768	4923170.4658	0.0049	0.0020	0.0025	0.0030	0.0018	0.0022	0.0027
A40a	0.0337	25.3864	856563.4604	0.0009	0.0003	0.0004	0.0005	0.0003	0.0004	0.0005
A42a	0.0377	25.9581	979009.5738	0.0010	0.0004	0.0005	0.0006	0.0004	0.0004	0.0005

Sajama

Rock glacier ID	Rock glacier area (km^2)	Rock glacier mean permafrost thickness (m)	Rock glacier permafrost volume (m^3)	Rock glacier permafrost volume (km^3)	Ice volume			Water volume		
					40% (km^3)	50% (km^3)	60% (km^3)	40% (km^3)	50% (km^3)	60% (km^3)
B50a	0.0643	28.8850	1858607.8649	0.0019	0.0007	0.0009	0.0011	0.0007	0.0008	0.0010
B54a	0.1033	31.7511	3278715.1692	0.0033	0.0013	0.0016	0.0020	0.0012	0.0015	0.0018
B56a	0.1503	34.2267	5144440.1360	0.0051	0.0021	0.0026	0.0031	0.0019	0.0023	0.0028
B58a	0.1802	35.4909	6395177.6204	0.0064	0.0026	0.0032	0.0038	0.0023	0.0029	0.0035
B59a	0.2128	36.6910	7807446.4232	0.0078	0.0031	0.0039	0.0047	0.0028	0.0035	0.0042
B60a	0.2663	38.3734	10217138.6805	0.0102	0.0041	0.0051	0.0061	0.0037	0.0046	0.0055
B62a	0.0242	23.7471	573872.9174	0.0006	0.0002	0.0003	0.0003	0.0002	0.0003	0.0003
B68a	0.0330	25.2672	832705.4313	0.0008	0.0003	0.0004	0.0005	0.0003	0.0004	0.0004
B70a	0.0575	28.2402	1623132.0289	0.0016	0.0006	0.0008	0.0010	0.0006	0.0007	0.0009
B76a	0.6694	46.1430	30887775.0415	0.0309	0.0124	0.0154	0.0185	0.0111	0.0139	0.0167
B77a	0.7887	47.6813	37604552.5004	0.0376	0.0150	0.0188	0.0226	0.0135	0.0169	0.0203
B120a	0.1960	36.0932	7074589.0887	0.0071	0.0028	0.0035	0.0042	0.0025	0.0032	0.0038
B124a	0.1262	33.0513	4171366.9430	0.0042	0.0017	0.0021	0.0025	0.0015	0.0019	0.0023
B134a	0.0607	28.5484	1732374.8401	0.0017	0.0007	0.0009	0.0010	0.0006	0.0008	0.0009
B135a	0.0432	26.6724	1152196.0247	0.0012	0.0005	0.0006	0.0007	0.0004	0.0005	0.0006

Western Cordillera

Rock glacier ID	Rock glacier area (km^2)	Rock glacier mean permafrost thickness (m)	Rock glacier permafrost volume (m^3)	Rock glacier permafrost volume (km^3)	Ice volume			Water volume		
					40% (km^3)	50% (km^3)	60% (km^3)	40% (km^3)	50% (km^3)	60% (km^3)
C84a	0.1472	34.0832	5016440.2574	0.0050	0.0020	0.0025	0.0030	0.0018	0.0023	0.0027
C85a	0.0390	26.1295	1018450.8975	0.0010	0.0004	0.0005	0.0006	0.0004	0.0005	0.0005
C86a	0.1184	32.6326	3864186.3986	0.0039	0.0015	0.0019	0.0023	0.0014	0.0017	0.0021
C87a	0.5176	43.8302	22687744.2024	0.0227	0.0091	0.0113	0.0136	0.0082	0.0102	0.0123
C92a	0.1847	35.6677	6588759.2032	0.0066	0.0026	0.0033	0.0040	0.0024	0.0030	0.0036
C93a	0.1236	32.9116	4066683.3243	0.0041	0.0016	0.0020	0.0024	0.0015	0.0018	0.0022
C94a	0.1153	32.4574	3741360.4942	0.0037	0.0015	0.0019	0.0022	0.0013	0.0017	0.0020
C95a	0.1803	35.4950	6399607.1413	0.0064	0.0026	0.0032	0.0038	0.0023	0.0029	0.0035
C96a	0.1173	32.5690	3819236.3755	0.0038	0.0015	0.0019	0.0023	0.0014	0.0017	0.0021
C97a	0.2109	36.6253	7723953.6628	0.0077	0.0031	0.0039	0.0046	0.0028	0.0035	0.0042
C101a	0.0875	30.7142	2686513.5778	0.0027	0.0011	0.0013	0.0016	0.0010	0.0012	0.0015
C107a	0.1269	33.0879	4199224.7912	0.0042	0.0017	0.0021	0.0025	0.0015	0.0019	0.0023
C108a	0.0525	27.7310	1455267.1785	0.0015	0.0006	0.0007	0.0009	0.0005	0.0007	0.0008
C109a	0.0930	31.0947	2892458.9832	0.0029	0.0012	0.0014	0.0017	0.0010	0.0013	0.0016
C110a	0.2059	36.4510	7505906.9824	0.0075	0.0030	0.0038	0.0045	0.0027	0.0034	0.0041
C111a	0.0496	27.4197	1359962.7138	0.0014	0.0005	0.0007	0.0008	0.0005	0.0006	0.0007
C113a	0.0353	25.6119	903228.1163	0.0009	0.0004	0.0005	0.0005	0.0003	0.0004	0.0005
C114a	0.0777	29.9937	2329884.3038	0.0023	0.0009	0.0012	0.0014	0.0008	0.0010	0.0013
C115a	0.1339	33.4433	4477149.5281	0.0045	0.0018	0.0022	0.0027	0.0016	0.0020	0.0024
C116a	0.0368	25.8239	949027.5421	0.0009	0.0004	0.0005	0.0006	0.0003	0.0004	0.0005
C126a	0.1307	33.2840	4350753.7577	0.0044	0.0017	0.0022	0.0026	0.0016	0.0020	0.0023
C128a	0.0785	30.0606	2361232.7428	0.0024	0.0009	0.0012	0.0014	0.0009	0.0011	0.0013
C130a	0.0163	21.9470	357604.7334	0.0004	0.0001	0.0002	0.0002	0.0001	0.0002	0.0002

4.7 Alternative ice thickness estimations

The AAAR paper used the area-thickness equation (Equation 1) to estimate ice glacier thickness dependent upon rock glacier size. This will now be referred to as method 1, as another method was also used in this PhD to estimate the ice volume and subsequent water equivalent of Bolivian rock glaciers. Method 2 used a consistent minimum rock glacier permafrost thickness of 20 m for all sites. This average thickness has been used by Brenning (2008, p. 200) and Brenning *et al.* (2007) to estimate rock glacier water equivalences. It can be argued that a thickness of roughly 20 m is necessary for active rock glaciers to flow (Barsch, 1996; Whalley and Palmer, 1998; Brenning, pers.com, 2014).

Once the area-thickness relationship (equation 1) had been applied to the data, the results showed no occurrences of rock glaciers with a mean thickness less than 20 m, which gave confidence that 20 m offered a conservative minimum value.

4.7.1 Water equivalence results

Overall, these calculations resulted in an estimated total ice volume of 0.101 to 0.152 km^3 using method 1 (Table 4.3; 4.7), and a range of 0.055 to 0.083 km^3 using method 2 (Table 4.7). The combination of both methods of rock glacier thickness resulted in different midrange values for rock glacier water equivalences, and thus different comparison values when compared to ice glacier stores (Table 4.8). As method 2 was a conservative minimum, the inclusion of these estimates lowered the overall water equivalence of the rock glaciers.

For the Cordillera Real the ratio of rock glacier to ice glacier water equivalence changed from 1: 228 (Table 4.4) to 1: 264 (Table 4.8). Similarly, for Sajama the ratio of rock glacier to ice glacier water equivalence changed from 1: 7 (Table 4.4) to 1: 9 (Table 4.8). Overall across the Bolivian Andes rock glacier to ice glacier water equivalence changed from 1: 33 (Table 4.4) to 1: 40 (Table 4.8). These changes in estimates did not change the interpretation and implication of the results reported in section 4.4.

		Cordillera Real (15° - 16° S)		**Sajama (17° - 18° S)**		**Western Cordillera (18° - 22° S)**		**Total**	
Total surface area (km^2)		1.07		2.98		2.88		**6.93**	
Ice content estimate		Lower 40%	Upper 60%	Lower 40%	Upper 60%	Lower 40%	Upper 60%	**Lower** **40%**	**Upper** **60%**
Method 1: Brenning's (2005b) area-thickness	Ice volume (km^3)	1.3×10^{-2}	1.95×10^{-2}	4.81×10^{-2}	7.22×10^{-2}	4.03×10^{-2}	6.05×10^{-2}	$\mathbf{1.01 \times 10^{-1}}$	$\mathbf{1.52 \times 10^{-1}}$
	Water volume equivalent (km^3)	1.17×10^{-2}	1.76×10^{-2}	4.33×10^{-2}	6.5×10^{-2}	3.63×10^{-2}	5.44×10^{-2}	$\mathbf{9.13 \times 10^{-2}}$	$\mathbf{1.37 \times 10^{-1}}$
Method 2: Assuming 20m thickness	Ice volume (km^3)	8.53×10^{-3}	1.28×10^{-2}	2.38×10^{-2}	3.57×10^{-2}	2.3×10^{-2}	3.45×10^{-2}	$\mathbf{5.54 \times 10^{-2}}$	$\mathbf{8.31 \times 10^{-2}}$
	Water volume equivalent (km^3)	7.68×10^{-3}	1.15×10^{-2}	2.14×10^{-2}	3.21×10^{-2}	2.07×10^{-2}	3.11×10^{-2}	$\mathbf{4.98 \times 10^{-2}}$	$\mathbf{7.47 \times 10^{-2}}$

Table 4.7 Table of ice volume and corresponding water volume equivalents for Bolivian rock glaciers regionally and nationally (total). These calculations cover a range of the two methods estimating ice thickness (method 1: Brenning's area-thickness; method 2: 20m thickness) and the lower and upper (40% and 60%) ice content bounds. Rock glacier surface areas were taken from Rangecroft et al. (2014).

Region	Rock glacier		Ice glacier		Ratio
	Area (km^2)	Water equivalent (km^3)	Area (km^2)	Water equivalent (km^3)	Rock glacier: Ice glacier water equivalent
Cordillera Real (15° - 16° S)	1.07	0.01	185.5 (Rameriz et al., 2012)	3.34	1: 264
Sajama (17° - 18° S)	2.98	0.05	10.00 (Jordan, 1998)	0.40	1: 9
Western Cordillera (18° - 22° S)	2.88	0.04	0 (Jordan, 1998; Vuille, 2007)	0	∞
Total	**6.93**	**0.10**	**195.5**	**3.74**	**1: 40**

Table 4.8 Regonal and total area and corresponding water equivalents for Bolivian rock glaciers and glaciers with a direct comparison of these water equivalents as a ratio. Values are reported to 2 decimal places, except ratios which are reported to the nearest interger. Rock glacier water equivalents are the midrange values from 40 – 60% ice content and method 1 and method 2 thickness estimates.

Chapter 5 : Rock glaciers and projected climate change

While much research has been published on the impact of climate change on mountain glaciers and water supplies, the response of ice-rich permafrost to continued warming has been relatively neglected, and this is especially true in the Southern Hemisphere. To redress this, the paper presented here models the impact of future warming on rock glaciers and permafrost extents. We have used the Bolivian Andes as an example system to explore the vulnerability of these water stores to future climatic change, and to highlight the climate change adaptation issues that follow. The work is novel because for the first time we have used downscaled GCMs (forced with IPCC A1B scenario) to show the impact of temperature changes on permafrost extent and rock glaciers in the arid South American Andes during the 21st Century.

This paper is currently under review in *Nature Scientific Reports* (NSR). Ranked 5th amongst all multidisciplinary science primary research journals with open access and global audience, NSR is an effective journal for communicating these results. SR conducted the field research in Bolivia. SR and Andrew Suggitt (AS) undertook the modelling and analysis of climate data. AS worked with SR to generate the figures in R. All authors contributed to writing and reviewing the manuscript.

Mountain permafrost in the Bolivian Andes will disappear under projected climate warming

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Abstract

Water resources in many of the world's arid mountains are under threat from climate change, and in parts of the Andes this is exacerbated by ice glacier recession and population growth. Alternative sources of water, such as rock glaciers and other permafrost features, will become increasingly important as warming continues. Although it is "virtually certain" that Northern Hemisphere permafrost will continue to decline during the 21st century, similar prognoses for Southern Hemisphere permafrost are not available. Such assessments are required to inform decision making over future water supply and climate change adaptation strategies. Here, we use downscaled outputs driven by the Intergovernmental Panel on Climate Change (IPCC) A1B scenario to model changes in permafrost extent from present day to 2050 and 2080 for an example region, the Bolivian Andes. These projections show that permafrost extent will shrink by up to 95% by 2050 and by 99% by 2080, implying an almost total loss of currently active rock glaciers in this region. In conjunction with ice glacier recession, a loss of permafrost extent of this magnitude represents a substantial water security problem for the latter part of the 21st century, and illustrates a growing reality for other arid mountain regions.

5.1 Introduction

Water security in many arid mountain regions is under threat from climate change, ice glacier recession and population growth (Barnett et al., 2005; Viviroli et al., 2011; Buytaert and De Bièvre, 2012; Rangecroft et al., 2013; IPCC, 2014). The South American Andes hold 99% of the world's tropical ice glaciers (Lui et al., 2013), and are experiencing widespread and continuing ice glacier recession (Ramirez et al., 2001; Soruco et al., 2009; IPCC, 2013; Lui et al., 2013). Here, the cryosphere acts as an important hydrological buffer, providing reliable stores of water for tens of millions of people (Rangecroft et al., 2013), yet future security of water supply for regions reliant on these features cannot be guaranteed. A lesser known component of the mountain cryosphere, rock glaciers (permafrost landforms consisting of frozen rock debris and ice (Barsch, 1996)), are already considered to be important sources of water in montane, arid environments like the Andes (Brenning, 2005), and may become more so as ice glaciers recede (Esper Angillieri, 2009). Although environmental conditions suitable for permafrost exist in most mountainous regions of sufficient elevation (Travasso et al., 2008; Viviroli et al., 2011), present understanding of Andean permafrost is limited (Azócar and Brenning, 2010; Lui et al., 2013; Rangecroft et al., 2013). It is known that mountain regions are already warming faster than the global average (Bradley et al., 2006); and the Andes warmed at 0.11 °C per decade in the latter part of the 20th century, some 0.06 °C per decade above the global average (Bradley et al., 2006; Vuille et al., 2008). Given that warming is projected to continue across the Andean region (Bradley et al., 2006; IPCC, 2013), it is essential to understand its potential impacts on permafrost extent and features such as rock glaciers, giving us insight into the sensitivity of regional water resources to projected climate change.

The location of mountain permafrost at local scales is controlled by topographic and site-specific variables, while at regional scales it is strongly related to the MAAT, with the 0 °C isotherm generally used to mark the lower altitudinal boundary (Avian and Kellerer-Pirklbauer, 2012). Although it is expected that atmospheric warming will cause an upward shift in this lower elevational boundary (Haeberli et al., 1993; Janke, 2005; Bonnaventure and Lewkowicz, 2011), the coarse spatial resolution of GCMs does not permit a precise understanding of likely changes to future permafrost extent at the regional level, thereby preventing water resource managers adapting their policies to climate change (Hijmans et al., 2005; Buytaert et al., 2010; Souvignet and Heinrich, 2011). Downscaling these climate projections to an appropriate spatial resolution is therefore a necessary first step towards understanding climatic impacts of future global warming on permafrost water stores at the regional scale (Marengo et al., 2010).

Bolivia is an example of a region particularly vulnerable to changes in mountain water supplies. Nearly 50% of glacier ice cover has been lost since 1960 (Soruco et al., 2009) and small and low-lying ice glaciers are projected to disappear in the Bolivian Andes within the next 20 years (Ramirez et al., 2001; Bradley et al., 2006). Water supply deficiencies are particularly acute in the dry season, when the region is currently reliant on meltwater for domestic use, agriculture and energy generation; it is estimated that glacial melt water provides 12 – 40 % of the potable water for the Bolivian capital city, La Paz (Rangecroft et al., 2013). Despite this vulnerability in Bolivia, and across South America as a whole, there has been no research examining the implications of projected warming for the continent's mountain permafrost. Here we provide such an assessment for a case study region, the Bolivian Andes (defined as land > 3,500 m a.s.l. within the Bolivian political boundary). Our study concentrates on active rock glaciers, which are indicative of contemporary permafrost (Barsch, 1996). We apply the latest statistically downscaled climate projections (Osborn, 2009) to a rock glacier inventory for the Bolivian Andes (Rangecroft et al., 2013), which identified 54 active rock glaciers (rock glaciers containing ice (Brenning, 2005a; Rangecroft et al., 2013). We model the MAAT and 0 °C isotherm for present and future climates, assessing the effect of 21st century projected warming on permafrost extent and currently active rock glaciers in the Bolivian Andes.

5.2 Results

We calculated the present day MAAT for the Bolivian Andes using WorldClim data (Hijmans et al., 2005) (Figure 5.1a). Using a downscaled multi-model ensemble of seven IPCC GCMs driven by the A1B emissions scenario (Mitchell and Osborn, 2005), we determined that MAATs across South America will have increased by 0.8 – 3.4 °C in 2050, (Figure 5.1b), and 1.4 – 5.1 °C in 2080 (Figure 5.1c), relative to present day conditions. Levels of warming projected for our mountain study region were at the higher end of these ranges (2.7 – 3.2 °C by 2050, 4.2 – 4.9 °C by 2080).

Using an MAAT of below 0 °C as a proxy the lower limit of permafrost (Avian and Kellerer-Pirklbauer, 2012), we mapped the area of the Bolivian Andes that is currently underlain by permafrost (Figure 5.2a). We also modelled the spatial extent of this isotherm for future climates, finding large reductions in its present day extent of approximately 95% by 2050 and 99% by 2080 (Figure 5.2b). The size of these reductions was largely insensitive to the choice of MAAT threshold; projected reductions in extent based on alternative plausible thresholds differed by less than 1% (Table 5.1).

Land area		**Time period**		
		1950 – 2000 baseline	**2050**	**2080**
< -1 °C	% of land area occupied	2.19×10^{-3}	8.81×10^{-5}	1.53×10^{-5}
	% loss from present day	Not applicable	95.98	99.30
< 0 °C	% of land area occupied	5.64×10^{-3}	2.80×10^{-4}	3.45×10^{-5}
	% loss from present day	Not applicable	95.04	99.39
< +1 °C	% of land area occupied	1.39×10^{-2}	7.59×10^{-4}	1.46×10^{-4}
	% loss from present day	Not applicable	94.54	98.95
< +2 °C	% of land area occupied	2.95×10^{-2}	2.28×10^{-3}	3.98×10^{-4}
	% loss from present day	Not applicable	92.28	98.65

Table 5.1 Land area suitable for permafrost in the Bolivian Andes and changes to this area under projected climate warming.
For each modelled isotherm threshold, the percentage of the total land cover (> 3,500 m) is shown for present day, 2050 and 2080 climates. The 2050 and 2080 extents are also given as a percentage loss in land area from present day extents.

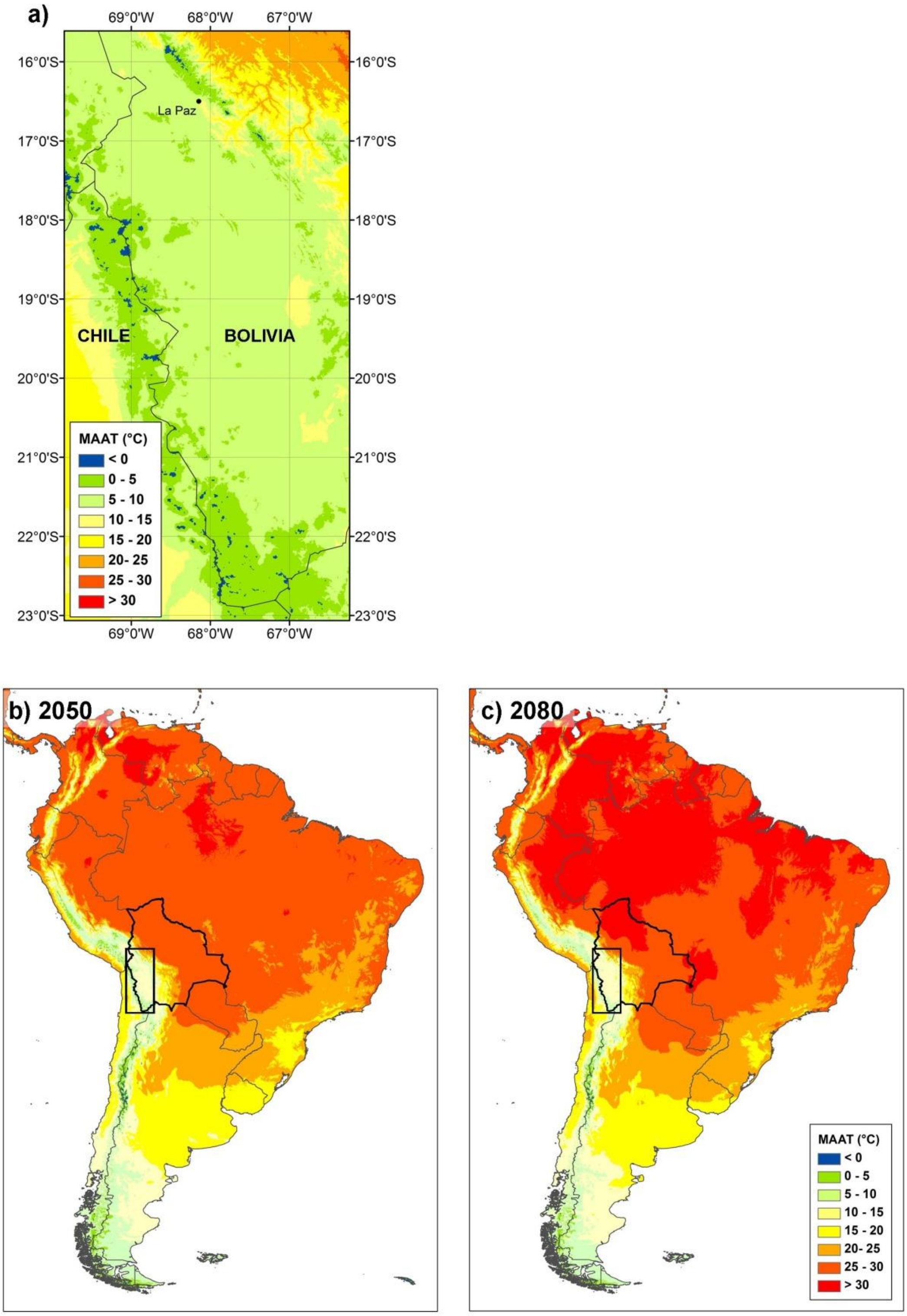


Figure 5.1 Present and future MAATs for the Bolivian Andes and South America
a) Present day (1950 – 2000) MAAT in the Bolivian Andes study region using WorldClim data. b) Multimodel ensemble mean projected MAAT from 7 downscaled GCMs for the IPCC A1B scenario for South America for 2050 and c) 2080 using ClimGen data (boundary of study region shown). MAATs were calculated in R (www.R-project.org) and subsequent maps were generated in ArcGIS (10.1).

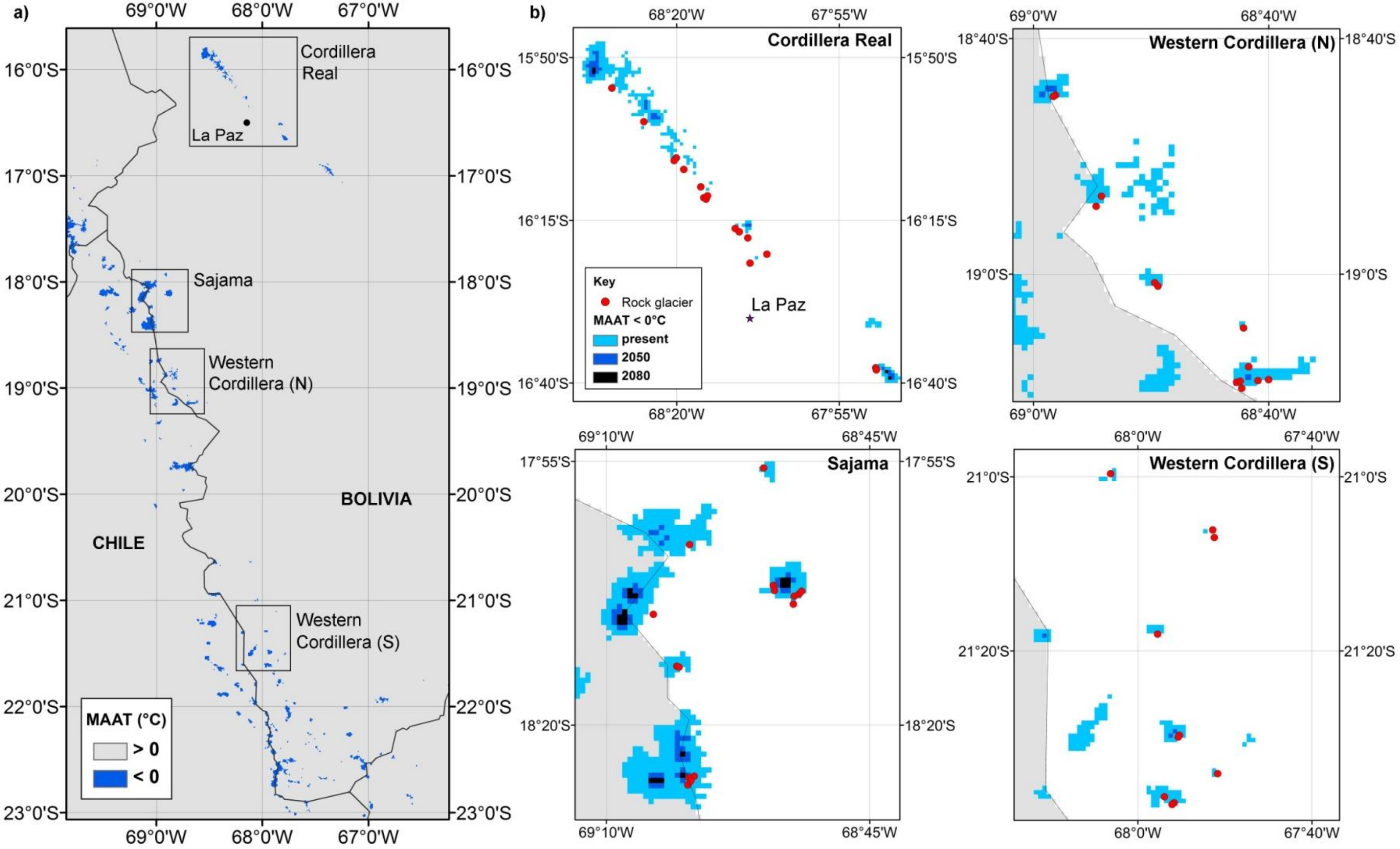


Figure 5.2 Mapped and modelled extent of the present and projected extent of MAATs below 0 °C as a proxy for permafrost. a) Present day MAAT 0°C isotherm for the Bolivian Andes. b) Present day and projected extent of MAAT below 0 °C in four example landscapes where rock glaciers are present in the Bolivian Andes. Maps were generated in ArcGIS (10.1).

We found that the thermal conditions necessary for the persistence of active rock glaciers will markedly deteriorate under future warming (Figure 5.2b, Table 5.2). While a MAAT of less than -1 or -2 °C is required for the development of active rock glaciers in the European Alps (Brenning, 2005), in Bolivia these features mostly cluster around the 0 °C threshold (Figure 5.3a), with an estimated average MAAT of 0.07 °C. This is likely a consequence of local topographic and/or microclimatic factors combining to preserve ice in otherwise climatically unfavourable locations (Bonnaventure and Lewkowicz, 2011).

Using future temperature projections at the 54 rock glacier sites, we found that all currently active rock glaciers in Bolivia are projected to have a MAAT above 0 °C by 2050. We also tested a more conservative threshold of +2 °C for the upper temperature limit for active rock glaciers, within which 50 of the current rock glaciers are located. Of these, we estimate that by 2050 34% (n = 17) will remain so, and by 2080, just one rock glacier will remain active (Table 5.2; Figure 5.3b). Based on our calculations, the relationship between MAAT and elevation did not differ substantially between present, 2050 and 2080 climates (lapse rate of ~ 1 °C/150 m, Figure 5.3a).

Time period	**Rock glaciers**	
	Number of rock glaciers < +2 °C	
	Count	Range across the models
1950-2000 baseline	50	Not applicable
2050	17	10 – 19
2080	1	0 – 3

Table 5.2 The number of rock glaciers with MAATs below +2 °C with the count and the range from the multi-model ensemble.

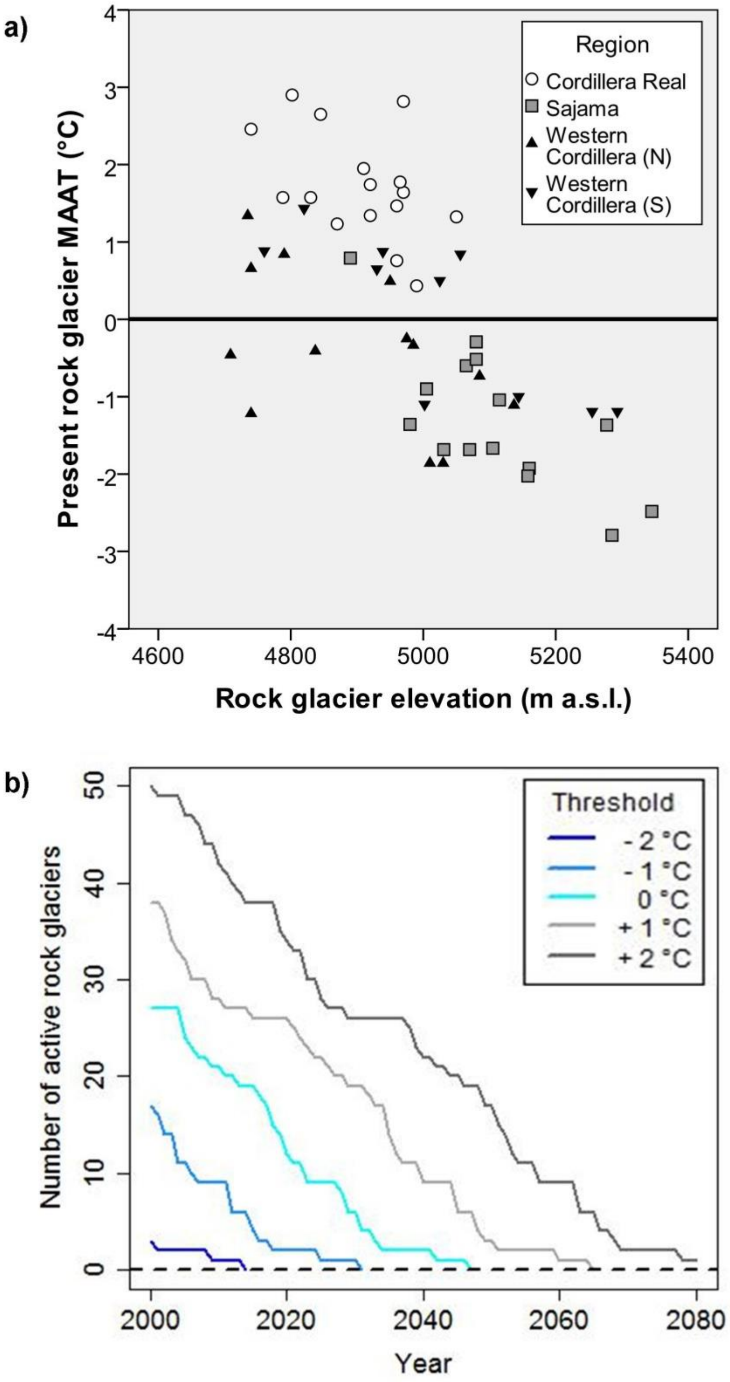


Figure 5.3 MAATs at active Bolivian rock glacier sites and the expected decline of active rock glaciers with projected temperature increase
a) Present MAAT at active rock glacier sites plotted against rock glacier front elevation, sub divided into four different example landscapes along the Bolivian Andes. This graph was generated in SPSS (IBM SPSS Statistics). b) Expected decline of active rock glaciers in the study region with projected temperature increase using five different thresholds of temperature defining rock glacier activity generated in R *(www.R-project.org).*

5.3 Discussion

Our projected losses of permafrost in the Bolivian Andes represents a further reduction of high mountain water storage in a region already suffering acute water shortages from ice glacier recession, carrying serious implications for regional economic and social development (Rangecroft et al., 2013). Although rock glaciers are known to respond more slowly to changes in temperature than ice glaciers (Janke, 2005), a similar loss in extent of this magnitude across the Andes would translate into a large reduction in hydrological buffers in the Andes over the second half of the 21st century onwards. With water stress already experienced over recent years in La Paz (World Bank, 2010), this represents an imminent threat to water security in one of South America's fastest growing cities (Buytaert and De Bièvre, 2012; Rangecroft et al., 2013), which will be amplified by projected increases in climate change rural-to-urban migration (Rangecroft et al., 2013). This research highlights the need for Bolivia, and other countries, to ensure that their water supply strategies are resilient to climate change. It is clear that more research on Andean permafrost distribution and rock glacier ice content is required, combined with a better understanding of the relationship between permafrost and climate change, to improve our anticipation of water supply shortages in the future. Given the sensitivity and vulnerability to climate change of countries such as Bolivia (Rangecroft et al., 2013), research on the Southern Hemisphere's cryosphere is valuable and necessary.

5.4 Methods

We used monthly temperature data from the WorldClim dataset (http://www.worldclim.org/) at 30 arc seconds (~ 1 km) horizontal resolution for 1950 – 2000 to represent the present baseline climate. These data are gathered from global weather stations (Hijmans et al., 2005) and interpolated using a thin plated smoothing algorithm in ANUSPLIN (Bonnaventure and Lewkowicz, 2011). These data have been used extensively (Hole et al., 2009; Loarie et al., 2009) in the climate impacts literature due to their high resolution. Monthly mean temperature data were used to compute MAATs (Figure 5.1a) in R (Version 3.0.0, R Foundation for Statistical Computing, www.R-project.org).

Future climate data representing mean temperatures were obtained from the ClimGen project (available at www.ccafs-climate.org/data/), consisting of the downscaled outputs of 7 GCMs (CCCMA-CGCM3.1; CSIRO-Mk3.0; IPSL-CM4; MPI-ECHAM5; NCAR-CCSM3.0; UKMO-HadCM3; UKMO-HadGEM1). These data provided climate projections for 2050 and 2080 at a horizontal resolution of 0.5 ° x 0.5 ° (~50 km in the Tropics) under the IPCC A1B emissions scenario (Mitchell et al., 2004). The A1B emissions scenario represents a future world of rapid economic and population growth, peaking mid-century (IPCC, 2000).

MAATs for 2050 and 2080 were established using this downscaled data. The 0 °C isotherm was calculated classifying pixels with sub-zero MAAT for the present and future climate data for the Bolivian Andes and a pixel count was conducted in ArcGIS software (Version 10.1, ERSI, Redlands, U.S.A.). We take the 'Bolivian Andes' to be land lying above 3,500 m a.s.l. within the political boundary of Bolivia. This was found to successfully isolate the mountains and exclude the Bolivian tropics.

The temperatures at all 54 active rock glacier sites in the study region were extracted from the present, 2050 and 2080 layers. Using a conservative threshold, any rock glacier with a MAAT of less than +2 °C was considered to still be active (Table 5.2). Rock glaciers can be defined as frozen debris and ice cryospheric features resembling a small glacier, generally occurring in high mountainous terrain (Barsch, 1996; Rangecroft et al., 2013). Active rock glaciers usually have surface morphology of ridges and furrows and a steep front at the angle of repose (Barsch, 1996) with low flow rates (<1 ma^{-1}), lower than those of ice glaciers. Active rock glaciers are estimated to contain between 40 – 60% ice (Brenning, 2005; Rangecroft et al., 2013).

Other climatic shifts, such as changes in the spatial and temporal distribution of precipitation (including snowfall), are likely to influence permafrost extent and could affect rock glacier development and persistence (Haeberli et al., 1993), however precipitation projections were not included in this analysis due to larger uncertainties surrounding the direction and magnitude of future change, whereas there is a clear consensus regarding the direction of projected temperature change (IPCC, 2013).

Acknowledgments

Thanks to Tim Osborn (Climatic Research Unit) for discussions re: ClimGen downscaled climate data. We would also like to thank Natural Environment Research Council, Oxfam and Agua Sustentable for funding and supporting this research (NERC CASE Studentship).

5.5 Supplementary material

5.5.1 Use of WorldClim and ClimGen

For many applications, data at a fine (<1 km^2) spatial resolution are necessary to capture environmental variability that can be partly lost at lower resolutions, particularly in mountainous and other areas with steep climate gradients (Hijmans et al., 2005). WorldClim may be taken to be representative of current climatic conditions (most of the data cover the period 1960 – 1990) (Jones et al., 2009).

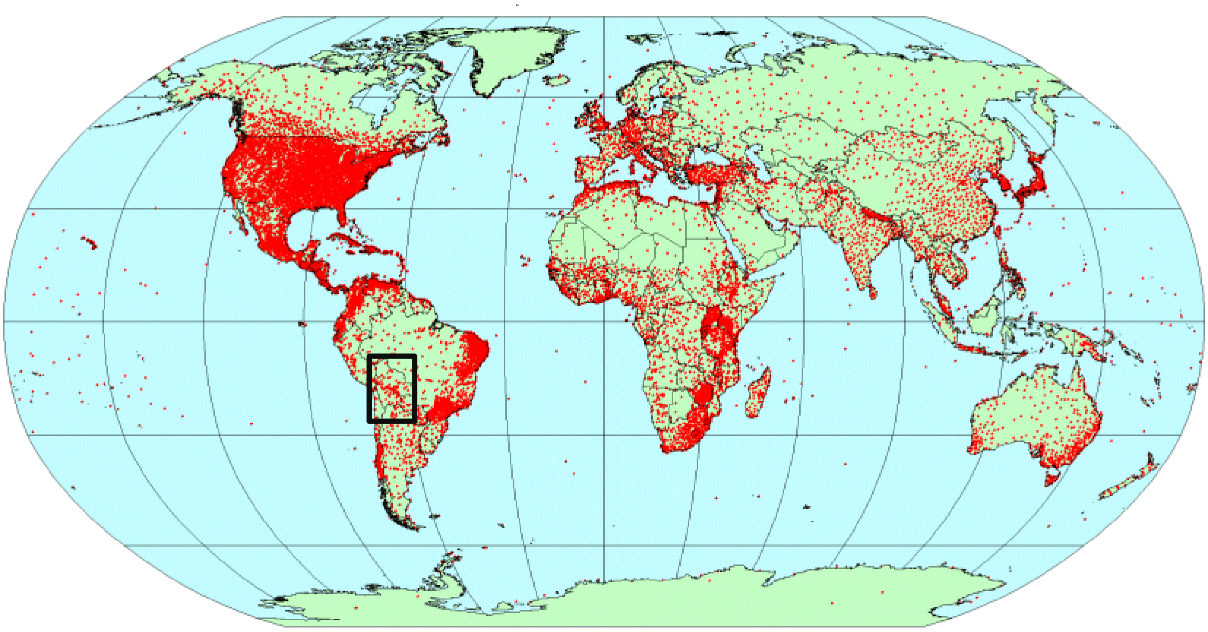


Figure 5.4 Location of climate stations with mean temperature data (WorldClim) Black box outlines the main study area, Bolivia.

ClimGen is a 0.5° spatial resolution dataset available for the timescale 2006 to 2100, developed by Osborn and Mitchell at the Climate Research Unit (CRU) at the University of East Anglia (CCAFS, 2014). Two statistical downscaling methods are offered by CRU: ClimGen and Delta method. The ClimGen statistical downscaling method was chosen for this modelling rather than the Delta method because it is acknowledged that topography can cause considerable variations in anomalies in the Delta method, with the Andes given as a named example (CCAFS, 2014).

> “We acknowledge that these assumptions might not hold true in highly heterogeneous landscapes, where topography could cause considerable variations in anomalies (i.e. the Andes)”
>
> CCAFS, 2014 http://www.ccafs-climate.org/statistical_downscaling_delta/

Therefore it was appropriate to avoid using the Delta method. ClimGen downscales from GCMs with resolutions of 5° to a 0.5° resolution data set. This is achieved by combing GCM-resolution climate change data derived from a “pattern-scaling” approach at 5° resolution with observations of climate at 0.5° resolution to simulate future climates at 0.5° resolution (Mitchell et al., 2004; Osborn, 2014). 8 climate variables are produced (mean temperature, max temp, min temp, precipitation, vapour pressure, cloud cover and wet-day frequency) (Osborn, 2014). ClimGen uses the AR4 datasets from the IPCC A1B emission scenario. More information about the ClimGen model is provided by Osborn (2014) and Mitchell *et al.* (2004).

5.5.2. Supplementary data and discussion

The multi-model ensemble used for this research produced downscaled estimates of projected temperature increases for Latin America and the Bolivian Andes (defined as land above 3,500 m a.s.l.) (Table 5.3; Figure 5.5), demonstrating that the Andes are expected to experience some of the greatest warming of the region. Analysing this multi-model ensemble further, the distributions of current and projected temperatures for the Bolivian Andes are illustrated in Figure 1c showing the shift to warmer temperatures away from the 0 °C isotherm (Fig. 5.6).

	Temperature increase range (°C)	
	2050	2080
Latin America	0.8 – 3.4	1.4 – 5.1
Bolivian Andes (> 3,500 m a.s.l.)	2.7 – 3.2	4.2 – 4.9

Table 5.3 Projected temperature increase ranges from the multi-model ensemble of ClimGen downscaled data

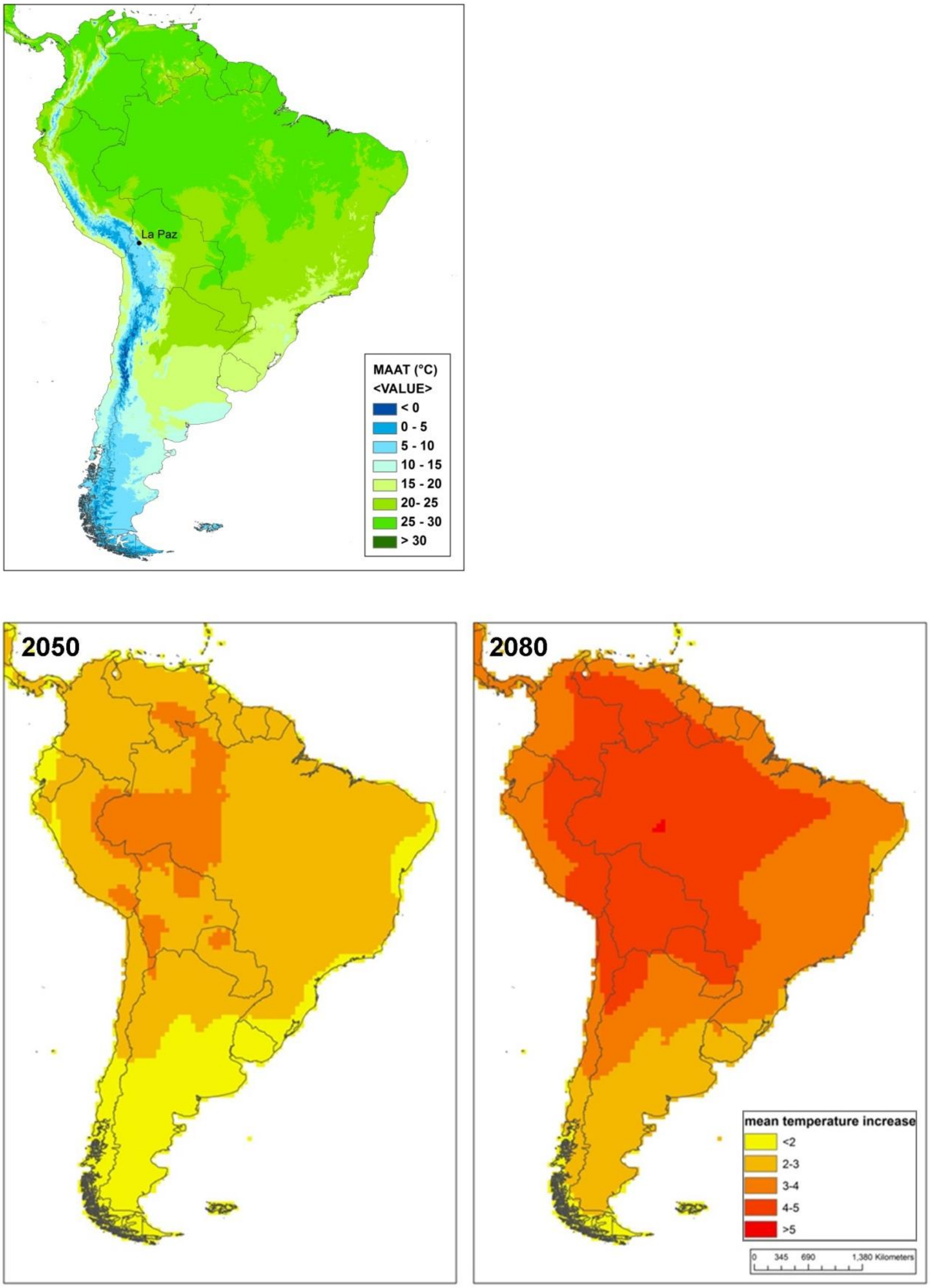


Figure 5.5 Present and projected MAATs for Latin America
Present day MAAT values using WorldClim 1 km resolution data (top) and mean temperature increases projected for Latin America for 2050 (bottom left) and 2080 (bottom right) using multi-model ensemble of seven ClimGen outputs.

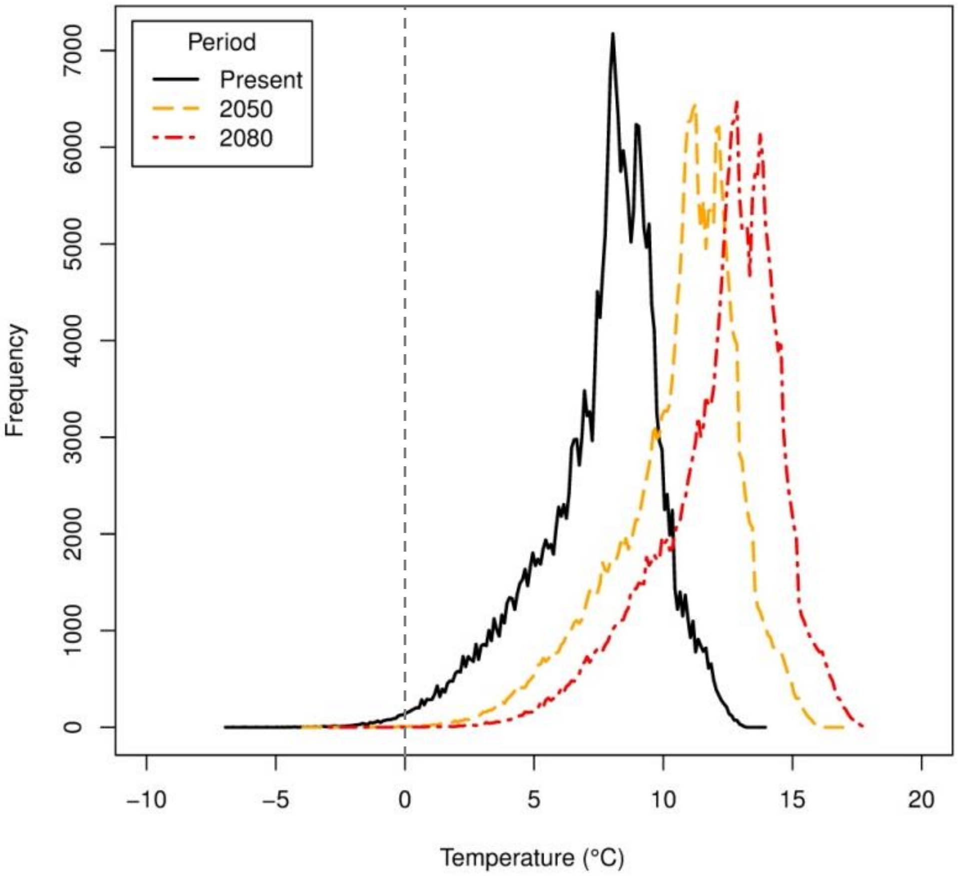


Figure 5.6 Distributions of climate data for the Bolivian Andes (> 3500 m a.s.l.) for present day (WorldClim), 2050 and 2080 (ClimGen). Frequency represents the number of (~1km) pixels in the Bolivian Andes (n=260985).

Through modelling of the current 0 °C isotherm across Latin America, the distribution of permafrost was explored. The sparse, isolated nature of Bolivian permafrost is shown in Figure 5.7, especially in comparison to the predominance of permafrost along the Chilean/Argentinean Andes between 27° and 35° S. This gives a better understanding to the differences found in rock glacier frequency and, subsequently, hydrological importance of rock glaciers in Bolivia compared to those of Chile and Argentina. Therefore, it is possible that the limited distribution of areas with MAATs below 0 °C in the Bolivian Andes could be one of the main contributors to the limited abundance of rock glaciers.

Figure 5.7 Present permafrost distribution across Latin America using WorldClim data

Rock glaciers are indicative of discontinuous permafrost (Barsch, 1996), and were found here to have a strong relationship with the 0 °C isotherm along the Western Cordillera in Bolivia, similar to that found by Payne (1998). Although in the European Alps rock glaciers are presumed to exist at MAATs of -1/ -2 °C, this research found that rock glaciers occur at higher MAATs, specifically in the Cordillera Real where ice glaciers dominate and precipitation is higher. In the Cordillera Real rock glaciers do not occur at temperatures below 0 °C, with an average MAAT of +1.7 °C and range of 0.4 to 3 °C (Table 5.4; Table 5.5). Sporadic active rock glaciers were found at MAATs of up to +3 °C, similar to the findings of Brenning (2005a) and Trombotto et al. (1997).

Region	MAAT (°C)		
	Average	Minimum	Maximum
Cordillera Real	1.7	0.4	2.9
Sajama	-1.3	-2.8	0.8
Western Cordillera	-0.2	-1.88	1.4
National	0.07	-2.8	2.9

Table 5.4 Table of regional and national rock glacier current MAATs estimated from WorldClim data (1 km): average, minimum and maximum values.

Cordillera Real

ID	Lat (S)	Long (W)	MAAT (°C)
A1a	15°53'46	68°30'53	1.74
A2a	15°59'22	68°25'52	1.34
A11a	16°05'29	68°20'01	0.43
A12a	16°05'52	68°20'23	1.95
A14a	16°07'15	68°18'51	2.82
A16a	16°09'51	68°16'22	1.64
A19a*	16°11'35	68°15'53	1.23
A20a*	16°11'48	68°15'29	1.78
A21a*	16°11'15	68°15'12	1.33
A27a	16°16'20	68°10'59	1.47
A29a*	16°16'43	68°10'27	0.76
A34a*	16°20'18	68°06'05	2.90
A37a*	16°21'36	68°08'47	2.65
A39a*	16°17'55	68°09'05	2.46
A40a*	16°37'44	67°49'26	1.58
A42a*	16°37'59	67°49'23	1.58

Sajama

ID	Lat (S)	Long (W)	MAAT (°C)
B50a	18°02'37	69°02'35	-1.67
B54a*	18°06'36	68°54'24	-1.36
B56a	18°07'16	68°54'08	-0.29
B58a	18°07'54	68°52'08	-1.04
B59a	18°07'41	68°51'30	-0.60
B60a	18°07'29	68°51'15	-0.52
B62a*	18°08'35	68°52'14	0.79
B68a	18°14'28	69°03'17	-1.68
B70a	18°14'35	69°03'01	-1.68
B76a	18°25'50	69°01'57	-1.93
B77a	18°24'57	69°01'40	-2.03
B120a	18°08'08	69°06'40	-0.90
B124a	18°44'58	68°58'02	-2.48
B134a	18°24'57	69°01’59	-2.79
B135a	18°25’18	69°01’55	-1.37

Western Cordillera

ID	Lat (S)	Long (W)	MAAT (°C)
C84a	18°44'58	68°58'02	-1.86
C85a	18°45'02	68°58'14	-1.86
C86a	18°53'24	68°54'00	-0.73
C87a	18°54'32	68°54'39	0.66
C92a	19°07'41	68°41'50	-0.33
C93a	19°09'18	68°42'47	-0.25
C94a	19°09'09	68°42'29	-1.11
C95a	19°09'55	68°42'22	1.34
C96a	19°09'11	68°40'51	0.49
C97a	19°09'11	68°40'01	-1.22
C101a	20°59'36	68°03'15	0.65
C107a*	21°06'09	67°51'13	1.43
C108a	21°07'03	67°51'08	0.88
C109a	21°18'13	67°57'41	0.50
C110a	21°29'52	67°55'06	-1.19
C111a	21°29'57	67°55'16	-1.19
C113a	21°34'09	67°50'45	0.88
C114a	21°37'00	67°56'51	-1.00
C115a	21°37'45	67°55'45	-1.10
C116a	21°37'41	67°56'01	0.84
C126a	19°00'54	68°49'37	-0.41
C128a	19°01'08	68°49'23	-0.46
C130a	19°04'37	68°42'08	0.84

Table 5.5 Present MAAT (°C) values for all Bolivian active rock glacier sites from WorldClim (1km).

However, applying the climate modelling to current rock glacier sites allowed an assessment of rock glacier temperatures in 2050 and 2080. Their clear shift away from the 0 °C isotherm towards warmer tempeatures can be seen (Fig. 5.8b), implying a loss of active rock glaciers. However, it is important to note that modelling rock glacier activity in a warmer climate is very difficult to predict. Whilst it is acknowledged, and modelled here, that rising tempeatures will reduce the suitable habitat for rock glaciers, it is possible that debris supply feeding rock glaciers could increase in a warmer climate. Frost shattering is controlled by freeze-thaw cycles, with an altitudinal range termed ‘talus window’ (Hales and Roering, 2005 cited in Kellerer-Pirklbauer et al. 2011). This talus window is expected to move towards higher altitudes with a changing climate. Rock glaciers are normally located in the upper part of the talus window; therefore, an increase in the talus production at this level could increase the debris supply to rock glaciers. On a longer time scale, the increase in volume of debris could result in the formation of new rock glaciers. However, this research argues that climate warming, and resultant permafrost degradation, will make the formation of new rock glaciers more difficult (Kellerer-Pirklbauer et al. 2011).

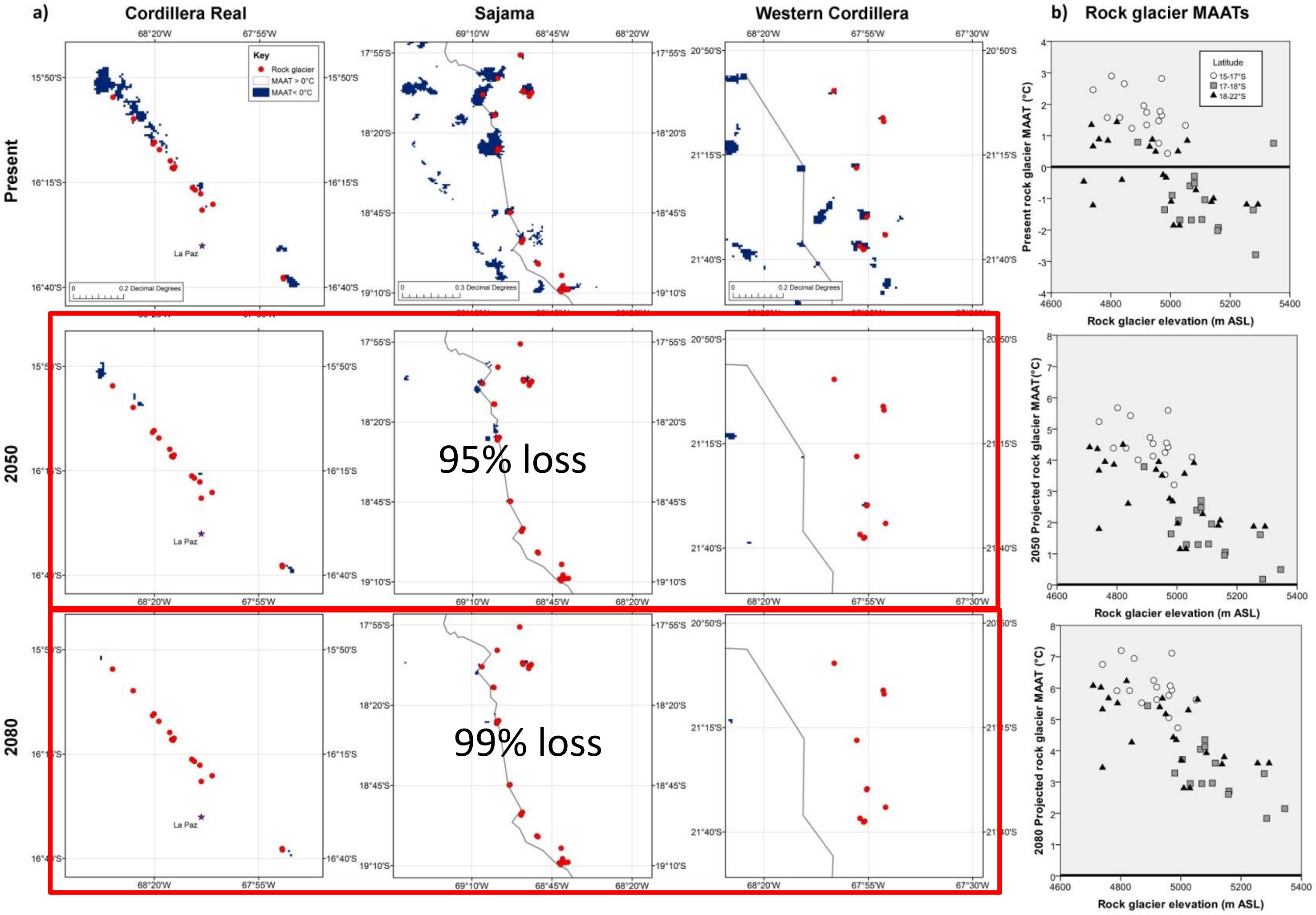


Figure 5.8 Present and projected permafrost extents and rock glacier MAATs

a) The current and projected areas <0°C MAAT with mapped active (red) rock glaciers for three different regions of the Bolivian Andes; b) Present and projected MAAT at rock glaciers plotted against rock glacier front elevation. Three different symbols are used to represent three different latitude regions. 0°C and +2°C thresholds are shown on the current and future graphs.

Chapter 6 : Exploring the potential for automated detection of rock glacier from RS image data

Currently, this research has demonstrated that rock glaciers can be mapped using expert photomorphic mapping methods applied to fine scale RS data. This technique has enabled the creation of the rock glacier inventory in Bolivia (Chapter 3), allowing water equivalents to be estimated and hydrological importance to be assessed (Chapter 4). There are many areas globally that offer potentially suitable geomorphic 'habitats' where environmental conditions would be considered suitable for rock glaciers to form, but where there is poor understanding of rock glacier distribution. Developing a more automated method for rock glacier mapping would be advantageous, especially for global extent identification.

This chapter investigates the possibilities of automated rock glacier detection using rock glacier attributes, landscape characteristics, and spectral and spatial RS data. Utilising freely available terrain and climate data, maps of the areas most suitable for rock glaciers were produced. Purchased fine resolution RS data is then utilised for unsupervised and supervised classifications to determine the capability of statistical algorithms based on pixel brightness values for mapping and discriminating rock glaciers from their surroundings. Statistical testing of this RS data suggested a lack of definitive 'rock glacier' spectral signature and resultantly, rock glaciers were not easily separated from their surrounding areas using such information alone. However, geospatial stastistics (semivariograms) showed a difference in the spatial pattern in optical and infra-red data between rock glaciers and surrounding areas. Therefore, there is potential for textural approaches applied to fine spatial resolution RS data to reveal the positon of rock glaciers once suitable geomorphic 'habitats' have been modelled.

6. 1 Introduction

Globally, mountain regions cover a quarter of all continental surfaces (Kapos et al., 2000 cited in Beniston, 2003); therefore there are many regions worldwide in which rock glaciers could persist given the correct climate and topography. However, no assessment over a global extent has been carried out. This thesis has shown and explained the reason why it is important to locate, quantify and assess rock glaciers and monitor their responses to current climate change. At present, manual identification of rock glaciers from fine spatial resolution RS data or field work is the most effective method of rock glacier mapping. However, field work in rock glacier regions is difficult, costly and time intensive. Manual identification from RS data is also time consuming and requires expert eye.

This research assesses the potential of automatically detecting rock glaciers from freely available satellite data. Currently the lack of automated detection of rock glaciers from RS data restricts the ability for a ‘product’ to be generated to describe their current distribution. This also limits the ability for scientists to use freely available and regular repeat pass satellite data to monitor and quantify changes in rock glacier distribution and activity in time. Other plentiful RS data exist that would allow scientists to easily determine geomorphic ‘habitats’ (i.e. areas harbouring suitable climatic and geomphoric conditions to permit rock glacier formation) for rock glaciers such as metrics like height, slope, aspect etc. This chapter seeks to address the question as to whether automated image processing techniques could be used within those ideal habitat regions, to map RGs automatically.

6.1.1 Automated mapping

Identifying rock glaciers using automated methods is a little studied area of research. Automated mapping has been used successfully for glacial features (Brenning, 2009; Shukla et al., 2010) with glacier ice identification being achieved through the combination of thermal sensors and land surface reflectance, such as multispectral classification using Landsat Thermatic Mapper (TM) band 4/ TM band 5 (Paul et al., 2004). However, this is not as easily applied to rock glacier mapping due to the surface layer of rock shielding the ice (Brenning, 2009; Brenning et al., 2012a; 2012b). Rock glacier debris surface has been shown to not produce a different spectral signal to the adjacent periglacial debris as both are derived from the same source; therefore, the rock fragments have similar mineralogy (Brenning, 2009; Brenning, 2010; Shukla et al., 2010). It is this lack of significantly different spectral signal in the optical and infra-red spectral domain which is thought to limit the possibility for a rapid, automated identification system (Bishop et al., 1995; Paul et al., 2004). Therefore, classification methods that use only spectral information are unlikely to be successful in automatically detecting rock glaciers.

Detection of rock glaciers by the human eye implies that some discrepancy exist allowing for their identification from surrounding areas. Computer algorithms may also be able to pick out these discrepancies. The above information however overlooks the fact that RS data are a rich source of spatial information: for example, structural patterns (evidenced through geostatistical approaches), or alternative regions of the spectrum (e.g. thermal regions of the electromagnetic spectrum) could be explored.

If successful, developing automated methods for rock glacier identification techniques could provide a three-fold beneficial approach: 1) objectively verifying the rock glaciers identified in the inventory conduced in Google Earth; 2) possibly identifying features that may have been overlooked in the inventory; and 3) exploring potential methods that, if successful in the pilot studies, could be used on an international global level to identify and map unknown rock glaciers.

6.1.2 RS data for rock glacier detection

Table 6.1 outlines the different datasets that were available for this research, their spatial resolution, and spectral band sets and coverage. Paul et al. (2003) claim that the success of correctly identifying landforms from remotely sensed data is largely determined by pixel size (spatial resolution) because fine-grained features such as the surface morphologies on rock glaciers occur at sub-pixel scales in satellite data from sensors <10 m resolution (Paul et al., 2003). In a comparative study by Paul et al. (2003) different satellite sensors were assessed for rock glacier identification, including Landsat Enhanced Thematic Mapper Plus (ETM+), Satellite Pour l'Observation de la Terre (SPOT) and IKONOS. The ETM+ sensor (15 m panchromatic band resolution) demonstrated that rock glacier detail occurred at sub pixel scale, thus details of the surface morphology were lacking and therefore the sensor was deemed not appropriate for clear identification and activity classification. With the SPOT sensor (10 m resolution), surface morphology was visible, however the outlines of relict rock glaciers were reported to be difficult to delineate. In contrast, the 1 m panchromatic band resolution IKONOS sensor provided the best level of detail needed for identification and classification. Economic considerations should be borne in mind however, as the cost of purchasing satellite data tends to increase with finer spatial resolution while the extent covered decreases (Paul et al., 2003).

	Dataset	Spatial and spectral capability	Cost
Satellite sensor	IKONOS	<5 m < 1 m panchromatic 4 m visible and near-infrared (NIR) bands	10 USD / km^2 (min 25 km^2)
	RapidEye	<5 m Visible, Red Edge and NIR	1.28 USD/ km^2 (min. 500 km^2)
	SPOT	<5 m 2.5 m Panchromatic <10 m multispectral model	2 Euro/ km^2 (min. 500 Euro)
	Landsat ETM+ / TM / MSS	15 m panchromatic 30 m visible bands resolution 60 m thermal data	Free
	Google Earth	Variable <1 m to 30 m	Free
DEM products	ASTER GDEM (ASTER Global DEM)	15 m visible and NIR 30 m short-wave infrared 90 m thermal	Free
	SRTM DEM (Shutter Radar Topography Mission DEM)	15 m visible and NIR 30 m short-wave infrared 90 m thermal	Free

Table 6.1 Table of available remotely sensed datasets with their spatial and spectral capability and associated cost.

The rock glacier inventory produced in Chapter 3 showed the advantage of using Google Earth as a platform for free, fine spatial resolution satellite image data, especially with readily available coverage across the whole of the Bolivian Andes (Fig. 6.1). Figure 6.1 demonstrates the resolution available through Google Earth, which is on par with RapidEye. Google Earth utilises DigitalGlobe satellites which include high resolution data from QuickBird, WorldView-1 and WorldView 2 (sub-5 m) and SPOT (2.5 m). As identified by Paul et al. (2003) it is this fine spatial resolution which is necessary for rock glacier identification and classification. However, it should be noted that Google Earth coverage of fine spatial resolution data and the regularity with which this is updated in the temporal domain is not necessarily globally uniform.

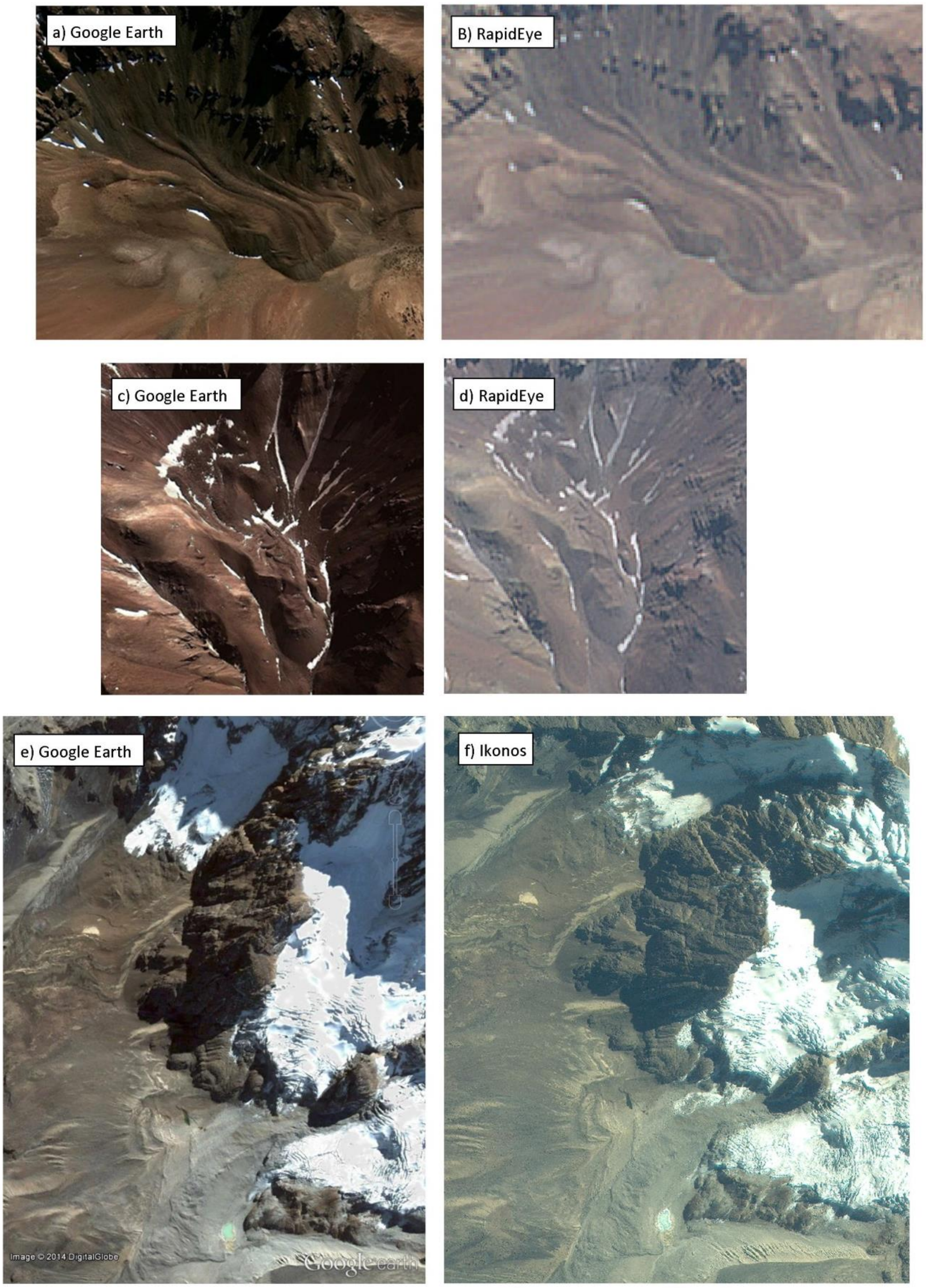


Figure 6.1 Example images of different purchased satellite data (RapidEye, IKONOS) and their corresponding Google Earth images.
Google Earth images are derived from fine spatial scale RS data such as DigitalGlobe, therefore similar spatial resolution but freely available.

6.1.3 Rock glacier habitat suitability mapping

Habitat suitability mapping is an ecological approach to identifying areas with optimal conditions for a species (Hirzel et al., 2002). The same approach can be applied to mapping areas with optimum geomorphic conditions for rock glacier formation and existence as there are well known topographic and climatic controls on rock glacier distribution (Brenning et al., 2007) (Table 2.1). Studying the availability of these optimum conditions helps to explain current frequencies and distributions of rock glaciers.

In a GIS, habitat suitability models require raster-based layers such as elevation, land cover and topographic position (slope, aspect etc). The predictive power for a number of environmental variables (e.g. elevation, temperature) to explain the likely location for rock glaciers has been explored (Brenning and Azócar, 2010). It is widely known that certain thermal conditions, such as air temperature, land surface temperature and solar radiation, typically below 0 °C have been found to have a close relationship with occurrence and activity of rock glaciers and mountain permafrost (Payne, 1998; Brenning, 2012) (Chapter 5).

6.1.4 Multispectral analysis: classifications

Land cover changes across the Earth’s surface absorb and reflect different amounts of energy at different wavelengths of electromagnetic radiation, known as their spectral response pattern (Aggarwal, 2003). Knowing these characteristics allows for the possible distinction, identification and mapping of Earth’s cover types, such as forests, soils, water and geological formations from remotely sensed data. This multispectral data will be ulitised for unsupervised and supervised classifications.

6.1.5 Statistical analysis

Statistical analysis of satellite data allows differences in the spectral values between rock glaciers and non-rock glacier regions to be explored. If statistical differences between rock glacier regions and non-rock glacier regions exist, then this could be used for an automated identification system.

6.1.6 Textural analysis

There is potential in identifying rock glaciers from RS data based on spatial patterns in brightness due to their characteristic surface morphology of ridges and furrows (Chapter 2 Fig. 2.13, Fig. 2.16). Active rock glaciers typically show these surface patterns of ridges and furrows (Fig. 6.2) as a result of internal deformation/ movement (Barsch, 1996; Kääb and Weber, 2004; Haeberli et al., 2006). They are the most characteristic feature of rock glacier morphology which can be used to identify rock glaciers in both the field and remotely (Burger et al., 1999). The extraction of textural features from fine resolution RS data is thought to provide an alternative method for identification or classification when the spectral information is not sufficient (Ruiz et al., 2004). Thus, it is possible that textural analysis could give an alternative method to “finding” rock glaciers in landscapes using automated RS techniques and computer vision approaches.

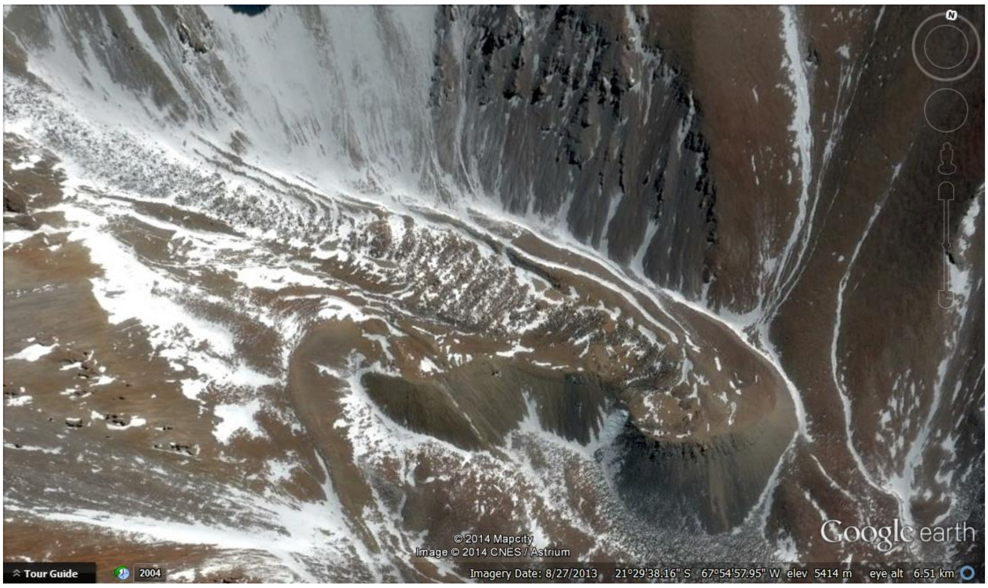


Figure 6.2 Google Earth image of rock glacier surface texture ridges and furrows demonstrated on Caquella rock glacier, Bolivia (C110a, 21°29’52 S, 67°55’06 W).

The texture of an optical or infra-red image is related to the spatial distribution and variation of the spectral brightness of digital numbers in an image (Ruiz et al., 2004; Racoviteanu and Williams, 2012). Texture analyses, which can include geostatistics (e.g. semivariograms), filters (e.g. Gabor) or transforms (e.g. fourier transform), allow surface characteristics of an image (Racoviteanu and Williams, 2012) to be explored. Using texture filters as an approach for such investigations have only just started to be explored using RS data in Matlab (e.g. Brenning et al., 2012a). Brenning *et al.* (2012a) has outlined the potential for this more objective identification process, investigating the use of a texture filter (Gabor filter) on IKONOS imagery in MATLAB to identify ridge and furrow patterns. Gabor filters can be used to detect periodic band patterns from a greyscale image or spectral band. In this research, Brenning *et al.* (2012a) established that using texture attributes along, or in combination with terrain attributes, outperformed just terrain attributes alone. As the Gabor filter is being investigated by Brenning, here the possibility of using semivariograms is explored.

This research looked at the potential of using geostatistics to identify rock glacier texture through the creation and analysis of semivariograms in R. It was hypothesised that there would be a textural difference between rock glaciers and their surrounding areas based on their distinctive ridges and furrows. This method could be applied after the suitability habitat mapping has identified key regions for further analysis.

6.2 Methods to investigate automated RS techniques

Using the rock glacier inventory as a base map validation dataset, this research aims to investigate different ways to potentially automate or semi-automate the detection of rock glaciers from RS data. Three different methods were conducted:

i) Rock glacier suitability 'habitat' mapping using GIS-based analysis of basic topographic (ASTER GDEM) and climatic (WorldClim, 2013) controls to identify potential rock glacier locations;

ii) Multispectral analysis of rock glacier regions of interest identified in RapidEye satellite image data used for unsupervised and supervised classifications and statistically tested for significant differences;

iii) Spatial analysis of rock glacier regions of interest identified in RapidEye satellite image data, using geostatistical approaches (semivariograms).

6.2.1 Rock glacier habitat suitability mapping

This method sought to use freely available data, analysing terrain attributes (e.g. elevation, aspect) from a DEM (ASTER GDEM, 30 m resolution) and WorldClim data (1 km resolution) for climatic controls (e.g. MAAT) to map rock glacier suitable habitats. These data sets were the best resolutions freely available. ASTER GDEM was used because it is currently the only high resolution (30 m) DEM with a global extent (Table 6.1).

Based on literature and the rock glacier inventory (Chapter 3) it was seen that the most probable locations for rock glaciers in Bolivia occurred at elevations greater than 4,500 m a.s.l. with south facing aspects (SE, S, SW). Because active rock glaciers can persist at temperatures greater than 0 °C due to local topography, a conservative upper MAAT threshold of +3 °C was used to classify the regions of likely rock glacier habitat, based on the results from Chapter 5 (section 5.2) (Table 6.2). Therefore, for the suitability habitat mapping, these controls were applied as factors in the GIS (Table 6.2). Generating a simple model to identify the spatial areas satisfying these requirements produced a habitat suitability map for rock glaciers (Fig. 6.3; 6.4), identifying the areas that they are most likely to form and persist across the Bolivian Andes.

Attribute	**Requirement for suitability**
Elevation (m)	> 4500
Aspect	SE, S, SW
MAAT (°C)	< + 3

Table 6.2 Factors for rock glacier suitability habitat mapping

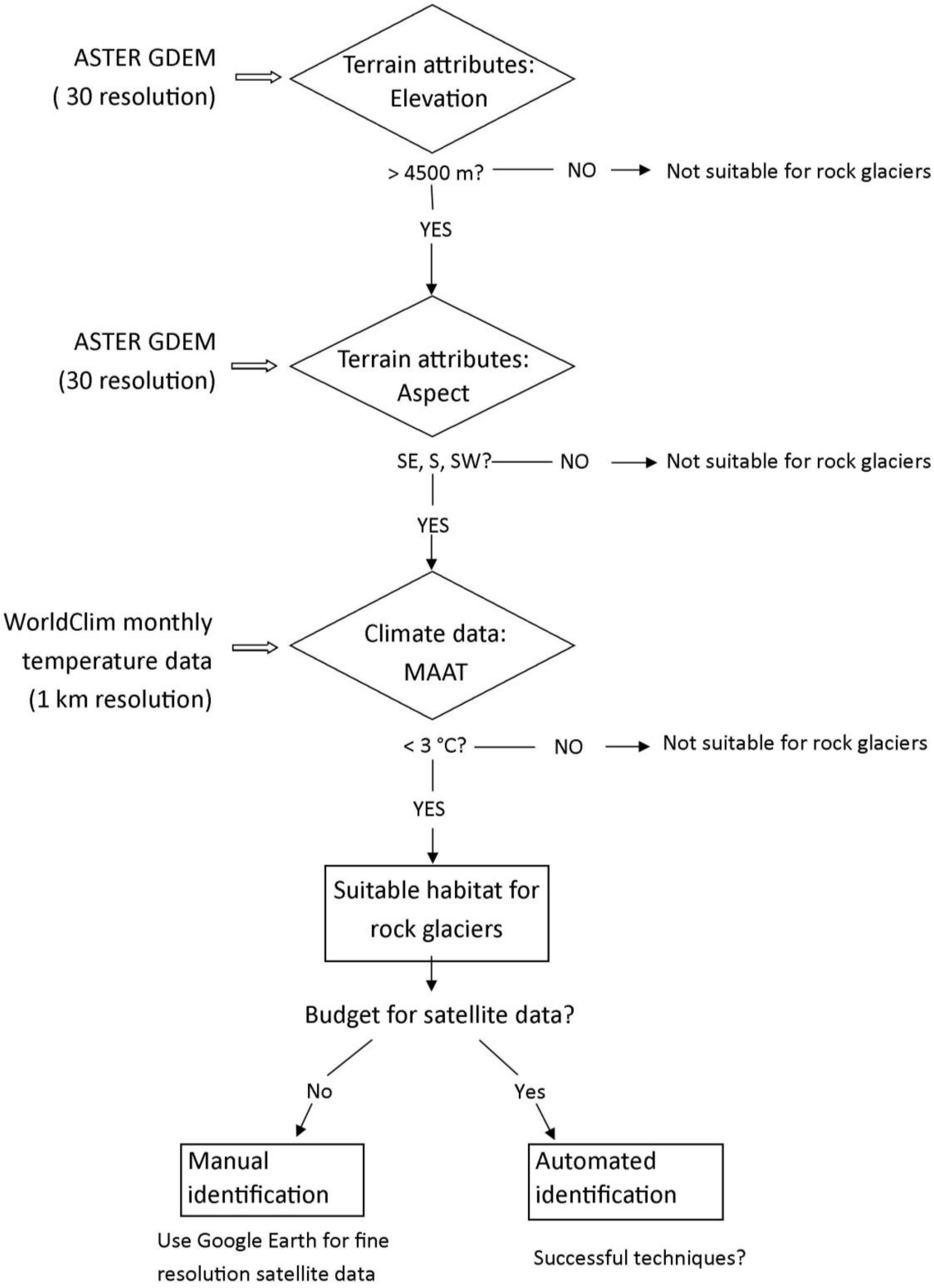


Figure 6.3 Flow diagram of the methodology used for the habitat suitability mapping and the potential use of the GIS layer produced.

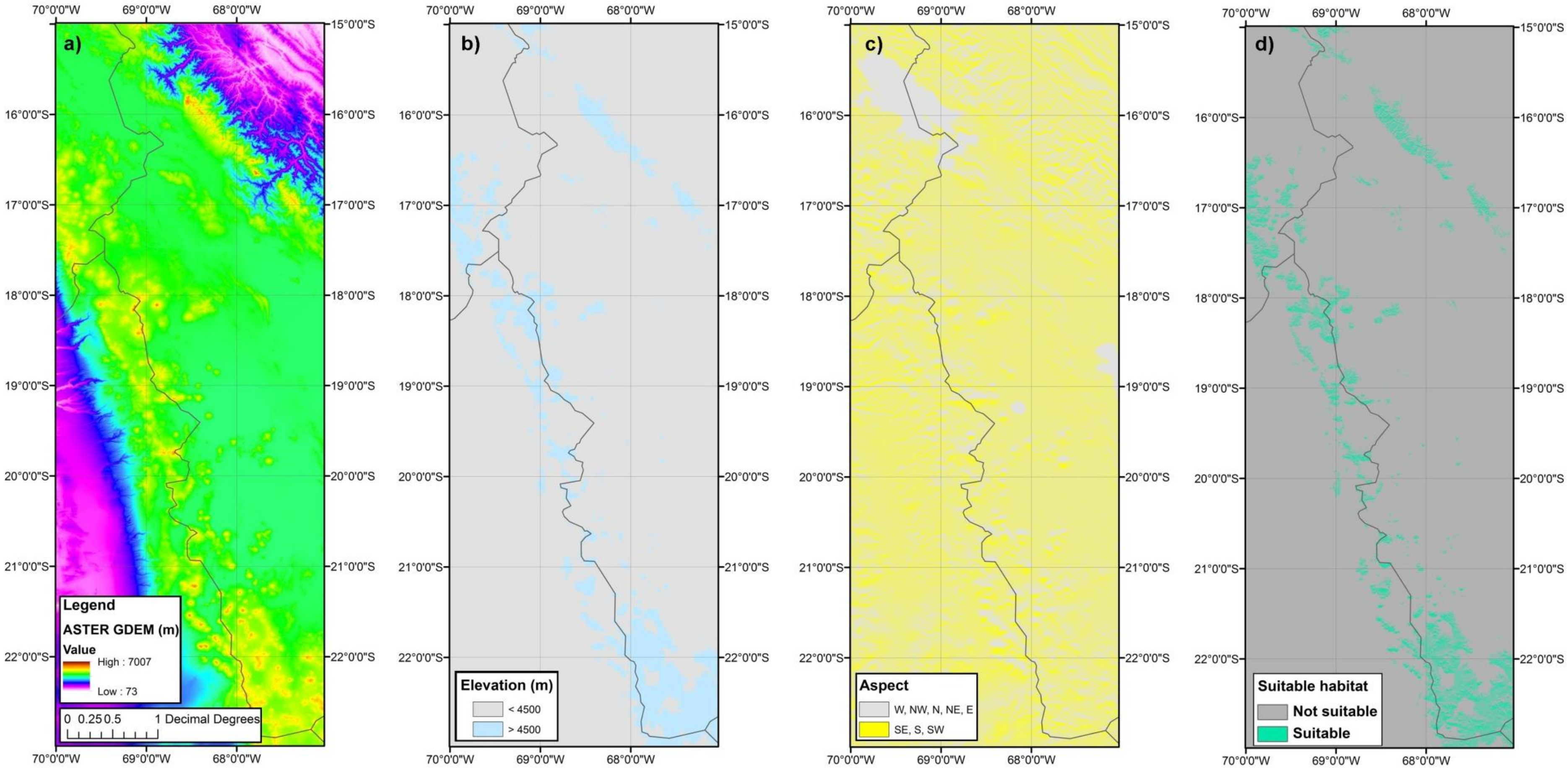


Figure 6.4 Using ASTER GDEM for producing a rock glacier habitat suitability map
a) ASTER DEM; b) Elevation > 4500m; c) aspect (SE, S, SW); d) combination of these elevation and aspect maps producing a probability map for rock glaciers across the Bolivian Andes

6.2.2 Multispectral analysis

An assessment of unsupervised and supervised classifications systems in ENVI to detect rock glaciers from their surroundings was made based on fine scaled satellite data (RapidEye, < 5 m resolution), for a study area in the Western Cordillera on an example rock glacier, “C109a” (21°18’13 S, 67°57’41 W) (Fig. 6.5). ENVI (EXELIS, v.4.3) image analysis software was used. Classifications utilise algorithms to identify spectral patterns in satellite data. Unsupervised classification algorithms were used to see if there was a statistical difference detected between rock glaciers and non-rock glaciers in the satellite data. Supervised classification algorithms were used to investigate if once given a training set of regions of interest (ROIs), algorithms could correctly identify rock glaciers from their surroundings.

Figure 6.5 Active rock glacier used for multispectral analysis, C109a

6.2.3 Unsupervised classification

Unsupervised classification approaches group pixels with those of similar values based on statistics (EXELIS, 2014). Using RapidEye satellite data, a region of interest containing the well-defined C109a rock glacier (Fig. 6.5) was selected and the two unsupervised classifications available in ENVI were run on the ROI: K-Means and ISODATA. Both these algorithms use iterative processes (Yale, 2014) to establish the classifications. K-Means classification “calculates initial class means evenly distributed in the data space. All pixels are classified to the nearest class” (EXELIS, 2014). Whereas ISODATA classification “calculates class means evenly distributed in the data space then iteratively clusters the remaining pixels using minimum distance techniques” (EXELIS, 2014). Both classifications were used to assess the success of their application in identifying rock glaciers from surrounding areas. A varying number of classes were defined (2, 5 and 10 classes) to explore the impact of classes on potentially detecting rock glaciers.

6.2.4 Supervised classification

Supervised classifications cluster the pixels in a dataset into a number of defined classes corresponding to user-defined training areas (EXELIS, 2014). They differ from unsupervised methods in that the end product is a categorical dataset, where each class is a ‘land cover’ type. ENVI has a range of supervised classification methods: Parallelepiped, Minimum Distance, Mahalanobis Distance and Maximum Likelihood. However only the Maximum Likelihood classification was used in this analysis as it is by far the most commonly used supervised classification (Conese and Maselli, 1992) as it is the only one which accounts for the variance, covariance and class mean (Lee and Warner, 2004). As such it is generally accepted as the most robust methodology because it uses the complete statistical description of the training data to assign unknown pixels to classes based on probability density functions.

Ten training sites (called ROIs) were used as the ‘user-defined training areas’ for the supervised classifications, representing 5 different classes (rock glacier, head wall, bare soil, bare rock, melt water). Therefore, each class had two training ROIs (Fig. 6.6). The resultant land cover map therefore assigned pixels to these 5 classes. A post-classification confusion matrix was run on the training ROIs and independent test ROIs following the same method as used in Anderson *et al.* (2010). This allowed an assessment of the accuracy and success of the supervised classification. The confusion matrix assessed the pixel classifications within independent test ROIs (Fig. 6.6). Table 6.3 outlines the numbers of pixels in the training and testing data.

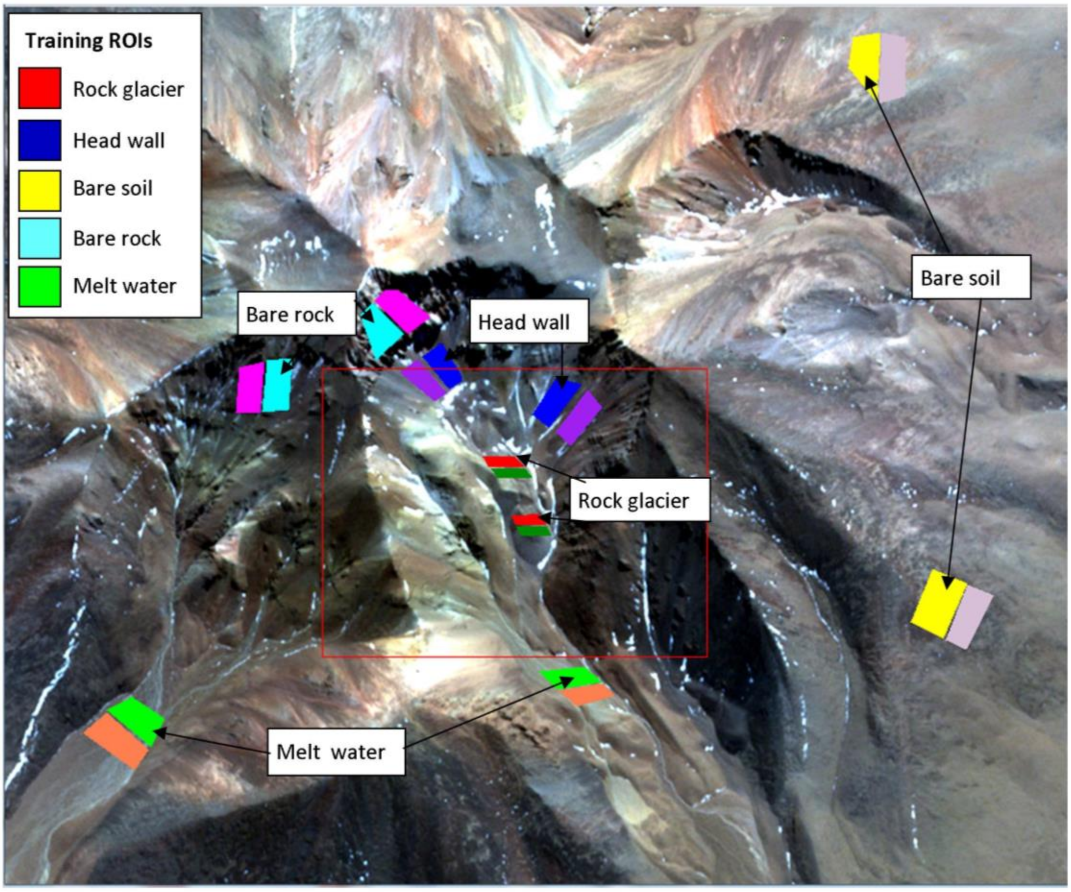


Figure 6.6 ROIs on RapidEye satellite data for supervised classification
Identified ROIs used to train ENVI for maximum likelihood supervised classification are shown by the key. Associated ROIs used as independent test ROIs.

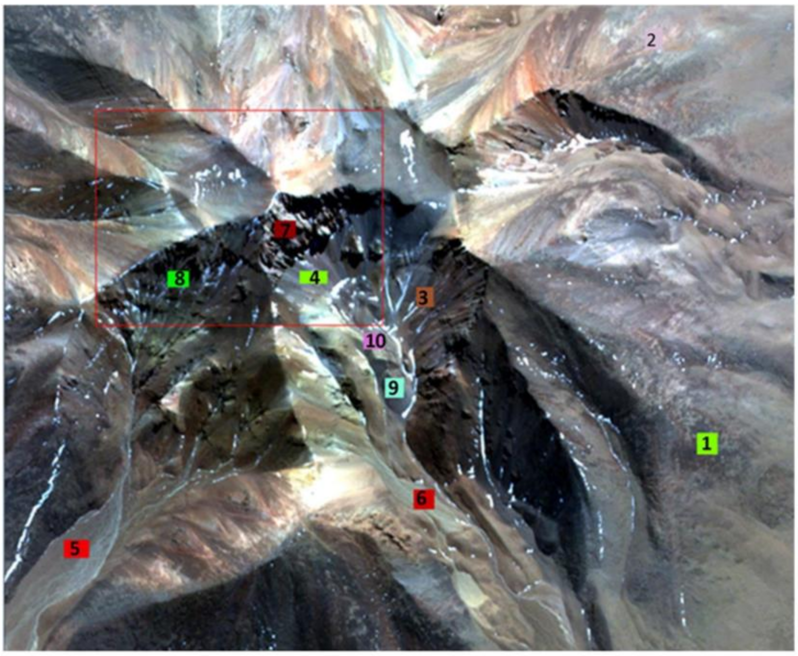
	Number of training pixels	Number of independent test pixels
Rock glacier	469	438
Head wall	1,398	1,322
Bare rock	1,802	1,673
Bare soil	2,528	2,205
Melt water	1,546	1,649
Totals	**7,743**	**7,287**

Table 6.3 Number of pixels used for training and testing the classification

6.2.5 Statistical testing

Using the same 10 ROIs as the supervised classification the mean spectral values (brightness values) for each ROI were tested for significant differences. This was performed using the ANOVA (analysis of variance) statistical test coupled with a post-hoc test (Tukey's) in SPSS. From the 10 ROIs used for the supervised classifications, smaller more similar sized ROIs were drawn and utilised for the statistical testing (Fig. 6.7). These ROIs were exported as ASCII files from ENVI and opened in Microsoft Excel to extract the data on the 5 spectral bands. Each ROI was classified as a region (labelled 1 to 10) (Fig. 6.7). This data was then inputted into SPSS. ANOVA for one factor ('region') was used to test the hypothesis that ROI spectral means were equal. Any ROIs with significantly different means were identified in the post-hoc results by their 'mean difference' and 'significant value'.

One-way ANOVAs can be used to determine any significant differences between the means of two or more independent groups. A significant value result greater than 0.05 represents no significant difference and that any difference between the means is likely due to chance. A significant value equal to or less than 0.05 represents a significant difference where differences between means are not likely to be due to chance.



Region	Type
Region 1	Bare soil
Region 2	Bare soil
Region 3	Head wall
Region 4	Head wall
Region 5	Meltwater
Region 6	Meltwater
Region 7	Bare rock
Region 8	Bare rock
Region 9	Rock glacier
Region 10	Rock glacier

Figure 6.7 ROIs used for statistical testing and the land cover associated with the ROI (region) number.

6.2.6 Textural analysis: Semivariograms

This spatial analysis investigated the possibility of a textural pattern specific to rock glaciers that could help aid the objective, automatic identification of rock glaciers. Most methods used for image texture analysis are based on statistical features, filtering processes or both (Durrieu et al., 2005). Geostatistics can be used as a tool to describe and explore spatial variation in remotely sensed data (Curran and Atkinson, 1998).

Semivariograms (Fig. 6.8) are a well-known geostatistical function used in texture analysis (Durrieu et al., 2005) to characterise the spatial correlation (Bohling, 2005), helping to assess spectral variability patterns in RS data (Bishop et al., 1995), and gaining information on the texture and spatial structure of features within digital images (Balaguer et al., 2010). From a semivariogram the extent of the spatial pattern (known as the ‘sill’, the y value where the graph levels off) and the length of the spatial pattern (known as the ‘range’, the x value at the sill) can be determined, as well as the ‘nugget’ which is the projected y value when $x = 0$ (Fig. 6.8). These features on the semivariogram have been used regularly for image classification (Treitz and Howarth, 2000 cited in Balaguer et al., 2010) and can help identify and quantify surface patterns.

Semivariogram analysis has been successfully used to quantitatively and spatially assess soil surface roughness (Croft et al., 2009), measure the scale of spatial dependence in vegetation structures and identify characteristic scales of pattern in ecology data (Anderson and Croft, 2009). Examples of semivariograms representing different surface textures can be seen in Figure 6.9.

RapidEye satellite images were subset in ENVI to only contain rock glaciers and their close surrounding area (e.g. Fig. 6.10). Rock glaciers from the Cordillera Real and along the Western Cordillera were analysed (Fig. 6.10). Within each subset, two ROIs were created to either represent rock glacier or non-rock glacier areas (Fig. 6.10h). For each ROI, the data was exported as an ASCII file and read in the free, open-sourced statistical software R to generate semivariogram graphs using the package ‘geoR’ with the function ‘variog’. Once produced, the semivariograms were analysed visually for differences in pattern/texture. A table of key features of the semivariograms (sill, range and nugget) extracted by eye to help identify any significant differences in spatial trends. As this is done manually, human error and subjectivity should be taken into account for.

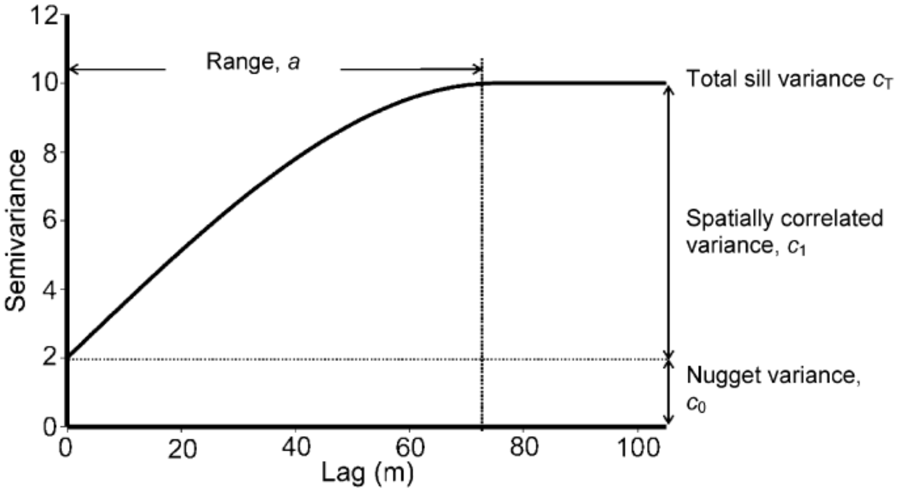


Figure 6.8 Key features of the semivariogram (Anderson and Kuhn, 2007, p. 9).

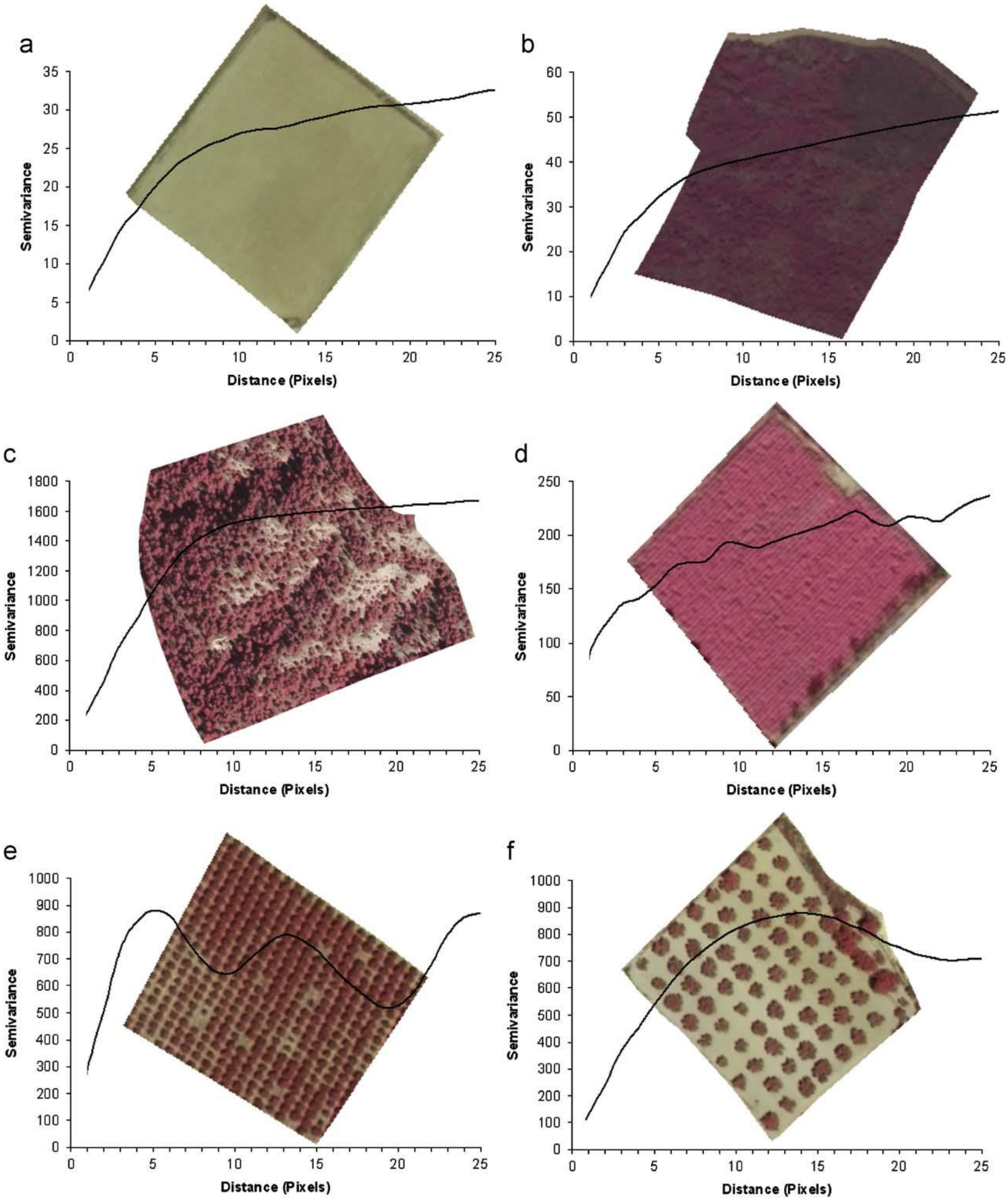


Figure 6.9 Examples of land cover and their respective experimental semivariogram superimposed
(Balaguer et al., 2010, p.236).

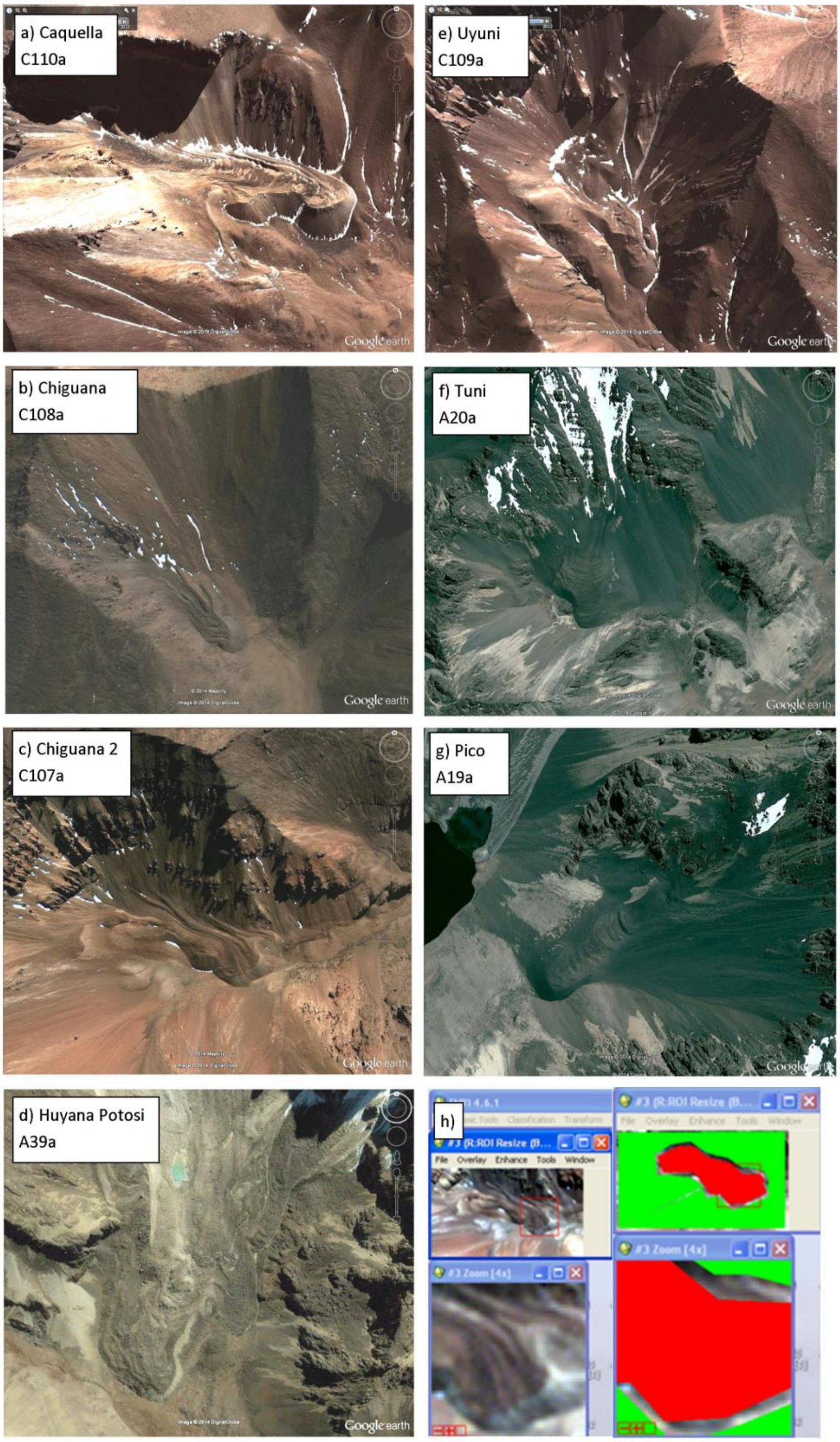


Figure 6.10 Rock glaciers used for semivariogram analysis
a –g) Google Earth screen shots of the rock glaciers used for the semivariogram analysi; h) subset area containing rock glacier (left) and two ROIs selected for analysis (right);

6.3 Results

6.3.1 Rock glacier suitability habitat mapping

Figures 6.11, 6.12 and 6.13 show the results of the rock glacier suitability habitat modelling for just the aspect and elevation attributes (left) and also including the climate data (right) with identified active rock glaciers plotted as red circles. It is evident that a difference in spatial resolution of the resulting GIS layer when climate data is used due to its coarser resolution (1 km compared to 30 m).

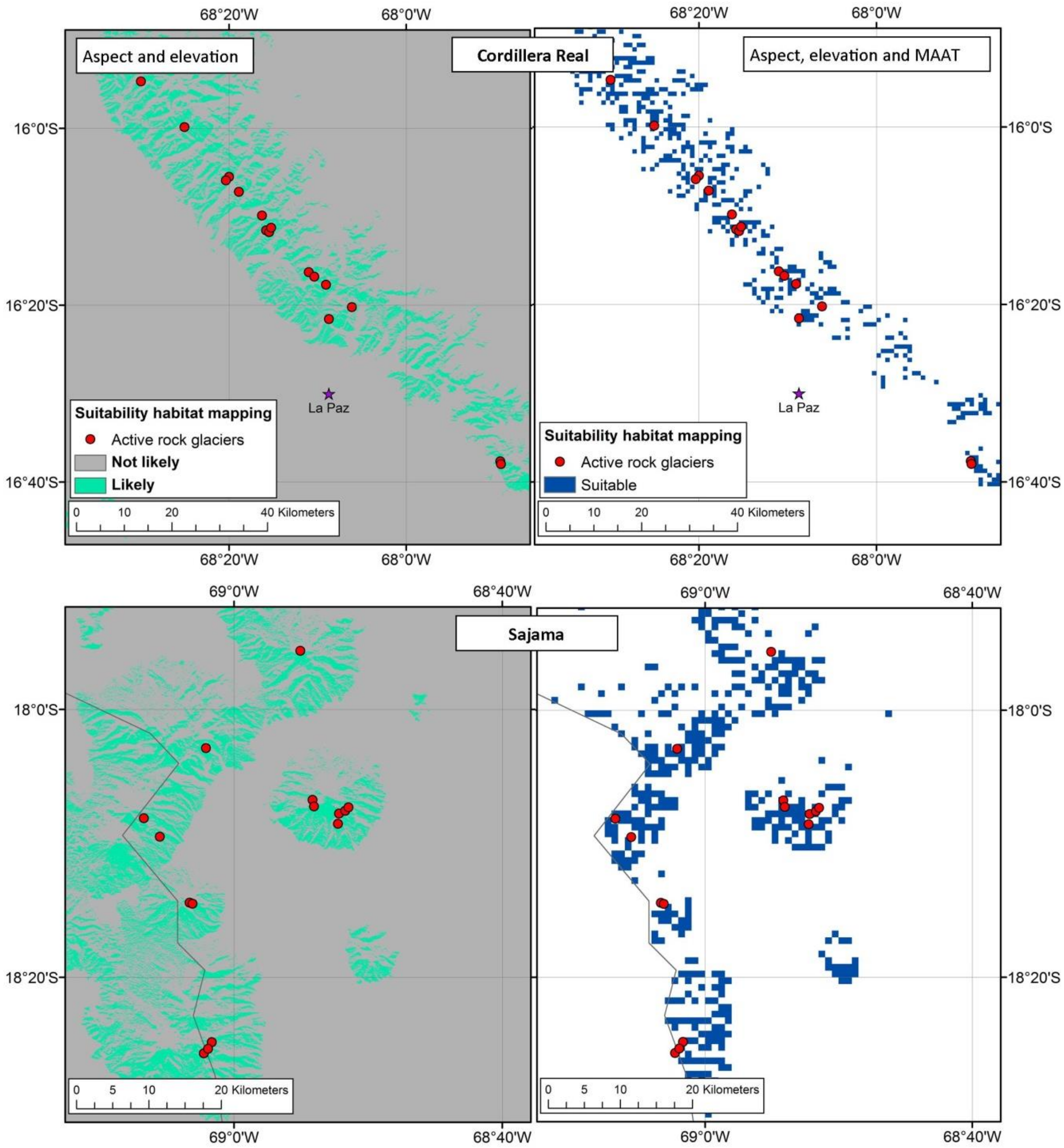


Figure 6.11 Rock glacier habitat suitability mapping Cordillera Real (top) and Sajama (bottom) regions showing two different methods: aspect and elevation (left) and aspect, elevation and MAAT (right). Red circles represent identified active rock glaciers.

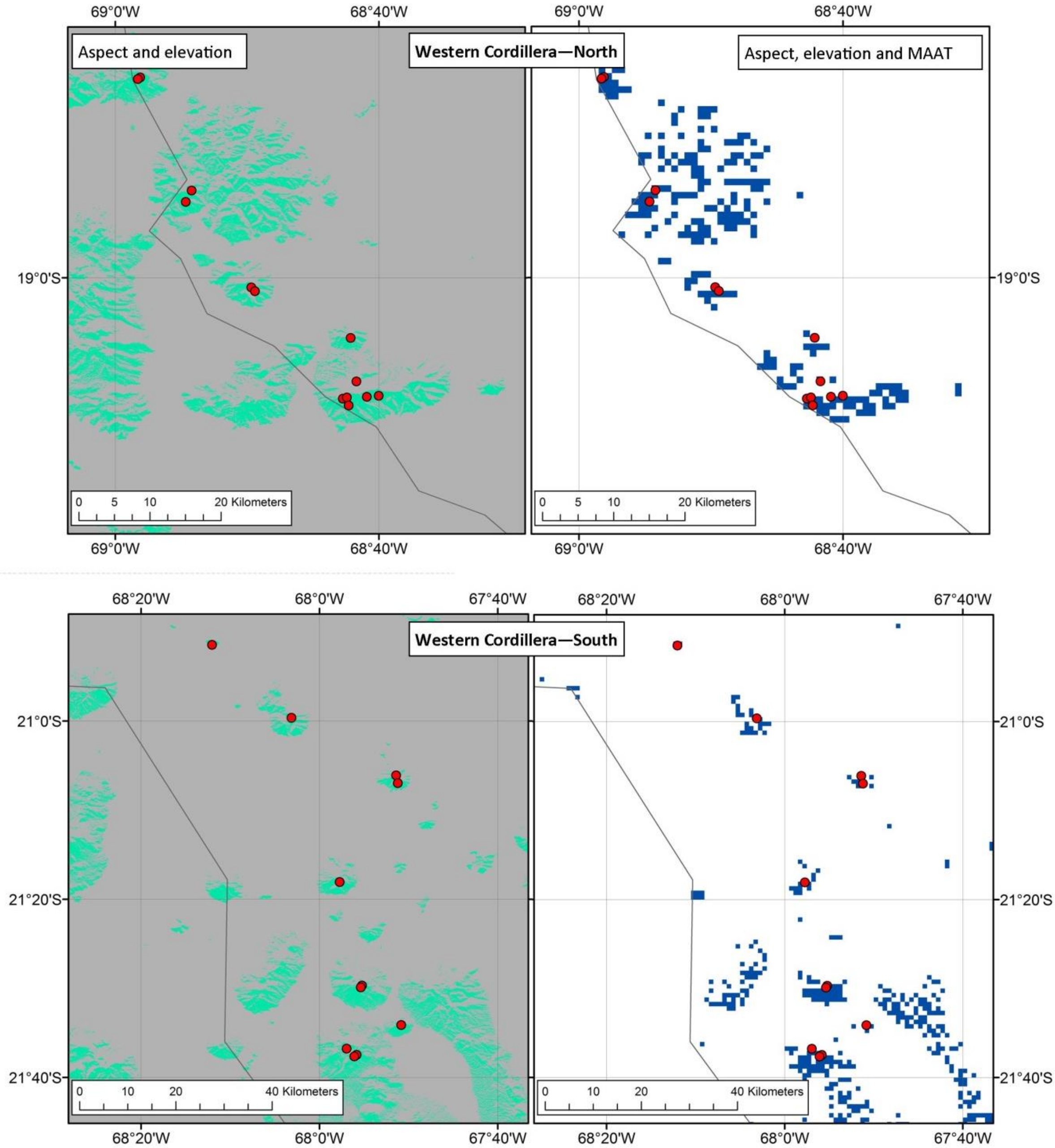


Figure 6.12 Rock glacier habitat suitability mapping Western Cordillera North (top) and South (bottom), showing the mapping of habitat suitability for two different methods: aspect and elevation (left) and aspect, elevation and MAAT (right). Red circles represent identified active rock glaciers.

This can be seen more clearly on Figure 6.13 the combination of elevation and aspect (Fig. 6.13e) retains fine pixel resolution, however the addition of the climate data (Fig. 6.13c) results in a much coarser output layer (Fig. 6.13f). However, it can be noted that using the aspect and the climate factors results in only one of the two rock glaciers being located in a ‘suitable habitat’.

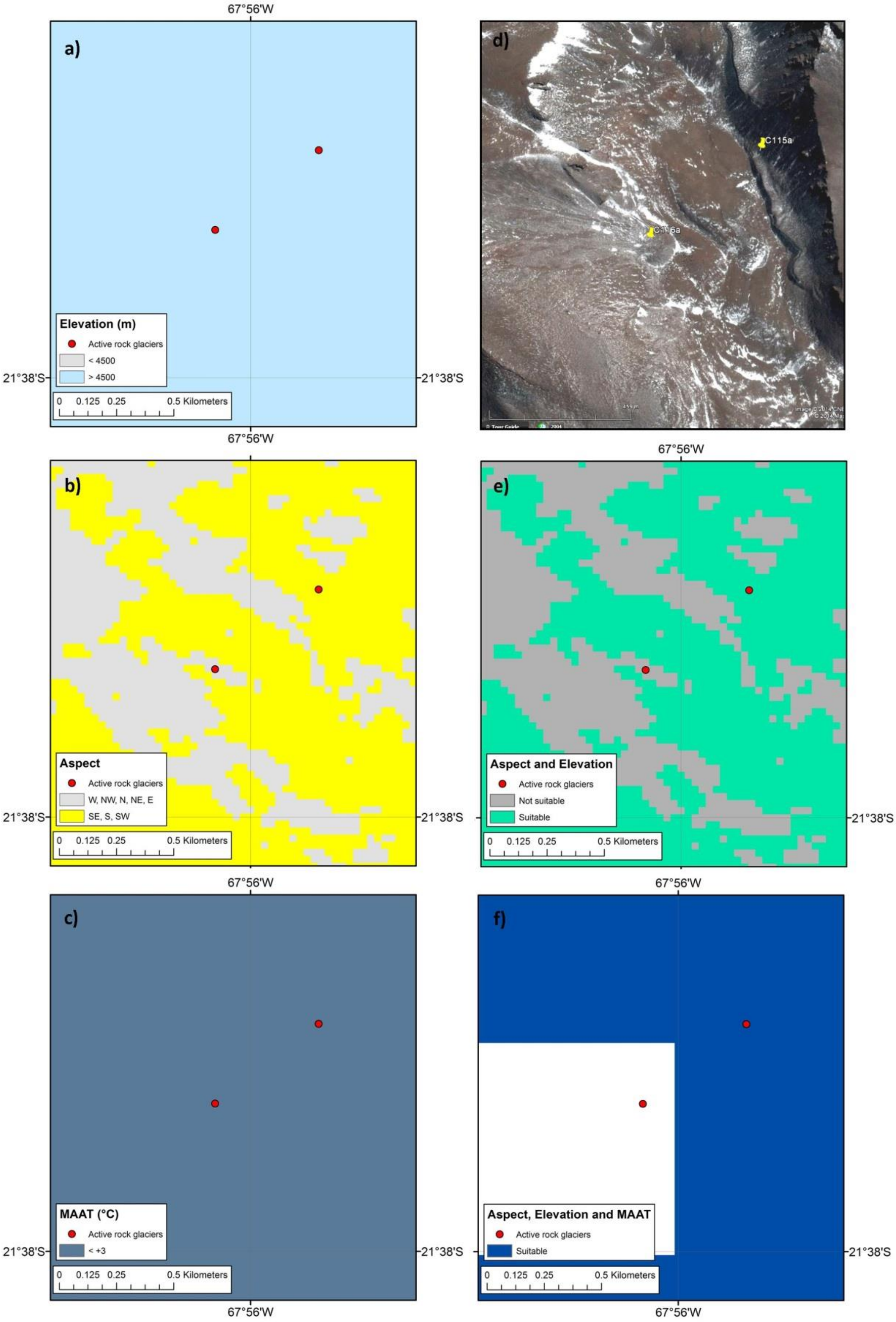


Figure 6.13 Example region hosting two rock glaciers with different GIS classifying as suitable or not for rock glaciers depending on the attribute: a) elevation only; b) aspect only; c) MAAT only; d) Google Earth screen shot of the region; e) Combined layer of aspect and elevation; f) combined layer of aspect, elevation and MAAT.

From this research it can be observed that using just terrain attributes (elevation and aspect) was more successful at mapping suitable habitat areas for rock glaciers than when these terrain attributes were combined with climate data (MAAT) (Table 6.5). It can be assumed that this is because of the difference in spatial resolution, with the climate data being a coarser resolution (1 km compared to 30 m) (illustrated in Figure 6.13). Furthermore, this shows that rock glaciers can exist in areas that do not satisfy all three parameters (mainly MAAT), which could be presumed due to local topography, glacial history and rock supply. However, it is important to understand that through the application of suitability habitat mapping, the area that is needed to be covered by the human eye for rock glacier mapping can be reduced significantly. This shows potential at highlighting the regions in which rock glaciers may exist globally, to an estimated 75% accuracy level.

Region	**Elevation and aspect**	**Elevation, aspect and MAAT**
Cordillera Real	75%	44%
Sajama	80%	40%
Western Cordillera	74%	70%
Total	**76%**	**54%**

Table 6.4 Success rate for locating rock glaciers in the suitability mapping using just terrain attributes and also using terrain attributes with MAAT data.

6.3.2 Unsupervised classification

From both classifications (Fig. 6.14) it was observed that there was no spectral discrepancy between the area on the rock glacier and the surrounding rock walls which supply the rock glacier (Fig. 6.14). The areas occurring on the rock glacier surface were also identified in numerous other surrounding areas (Fig. 6.14). This can be assumed because the rock located on the rock glacier is derived from surrounding head and side walls. Irrespective of the number of classes, the clusters of similarity are not rock glacier specific, demonstrating the lack of success at identifying rock glaciers through unsupervised classification algorithms.

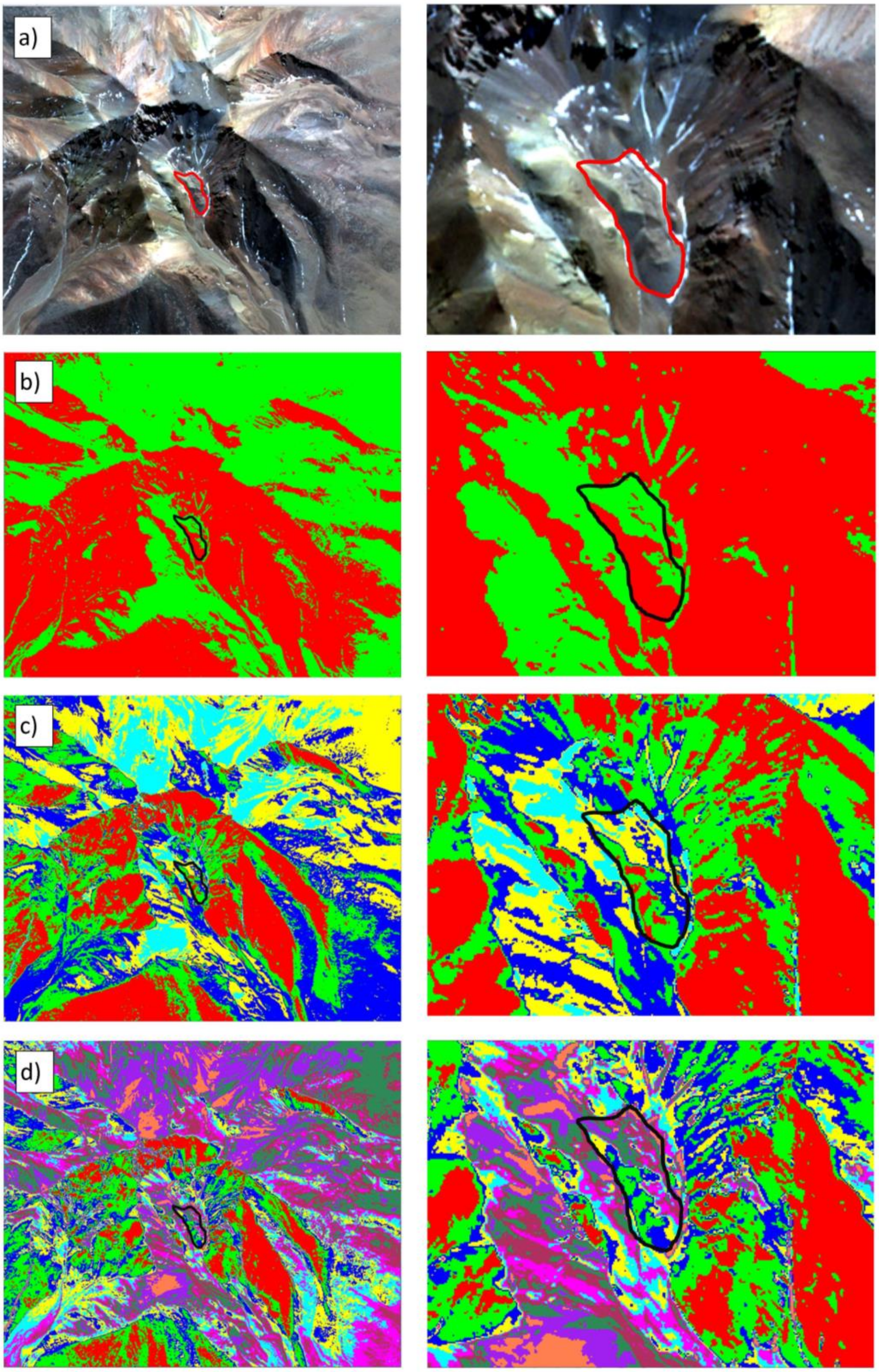


Figure 6.14 ISODATA unsupervised classification
a) original data; b) 2 classes; c) 5 classes; d) 10 classes. All classifications were produced with 10 iterations in ENVI.

6.3.3 Supervised classification

The results from the maximum likelihood classification are shown in Figure 6.15. Overall the supervised classification system identified the spectral signal across the rock glacier to be a mixture of the defined classes of rock glacier (red), head wall (blue) and melt water (green). Using a post-classification confusion matrix, the accuracy of the rock glacier identification was estimated to be at 34.7% (Table 6.6). A larger percentage of the independent test data was classified as melt water (41.55%) (Table 6.6). Equally, areas surrounding the rock glacier have been classified as 'rock glacier' (red) although they are not. Of the entire independent test ROIs, rock glaciers recieved the lowest accuracy (Table 6.6). This demonstrates the complexity of rock glacier surfaces. It was evident from Figure 6.15 that the frontal slope of the rock glacier was classified as 'head wall' (blue). Therefore, even when trained using defined ROIs, the alogrithm failed to identify the rock glacier separately from the surrounding bare rock based upon its spectral information (Fig. 6.15).

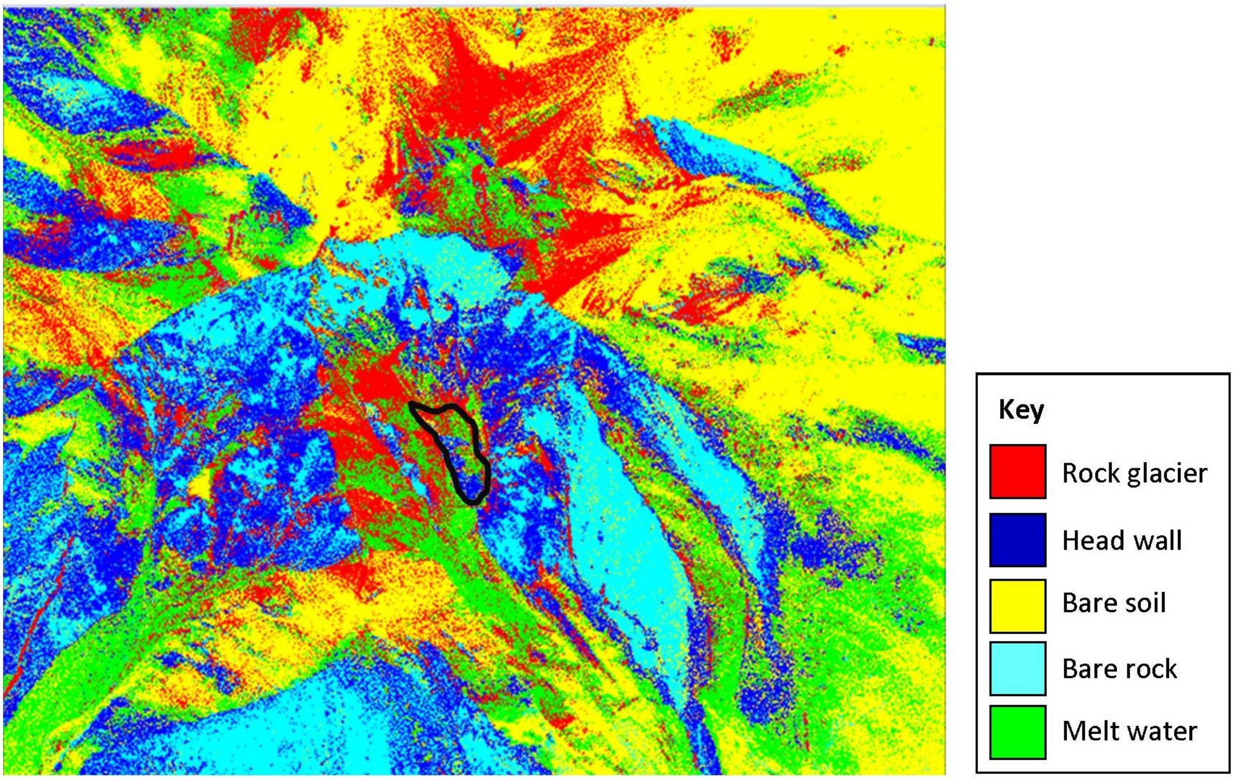


Figure 6.15 Results from Maximum Likelihood supervised classifications using 5 classes of training data (key).

		Independent testing data				
		Rock glacier	Head wall	Bare rock	Bare soil	Melt water
Classified on map	Rock glacier	**152** **(34.7)**	108 (8.17)	163 (9.74)	239 (10.84)	74 (4.49)
	Headwall	49 (11.19)	**768** **(58.09)**	242 (14.47)	435 (19.73)	51 (3.09)
	Bare rock	7 (1.60)	96 (7.26)	**1047** **(62.58)**	26 (1.18)	11 (0.67)
	Bare soil	48 (10.96)	77 (5.82)	188 (11.24)	**1177** **(53.38)**	168 (10.19)
	Melt water	182 (41.55)	273 (20.65)	33 (1.97)	328 (14.88)	**1345** **(81.56)**
	Total pixels	**438**	**1322**	**1673**	**2205**	**1649**

Table 6.5 Confusion matrix of maximum likelihood supervised classification

6.3.4 Statistical testing

Overall, significant differences were found between the mean spectral values across the ROIs for rock glacier regions and non-rock glacier regions (Fig. 6.16; Appendix 3). However, this also included the two areas selected on the rock glacier (region 9 and region 10) (Fig. 6.16). These two regions were found to be significantly different, showing that spectral values are not similar enough across the whole body of the rock glacier to allow for statistical identification. Figure 6.16 and Appendix 3 show that the 2 rock glacier ROIs (regions 9 and 10) are significantly different across all 5 bands. Furthermore, in bands 2, 3, 4 and 5 one rock glacier ROI (region 9) is statistically similar to a non-rock glacier ROI, meltwater land cover (region 6). Also in bands 3, 4 and 5 the other rock glacier ROI (region 10) is statistically similar to bare soil (region 1). This is different to expected as it was hypothesised that the source of rock supply (headwall) would be spectrally similar to the rock debris on the rock glacier. However, these results demonstrate that is it highly unlikely that analysis of spectral values can help to identify rock glacier from surrounding areas.

In summary, most regions were found to be significantly different, even when compared to the same land cover type (i.e. region 1 and 2, region 3 and 4 etc). Some exceptions to this were found.

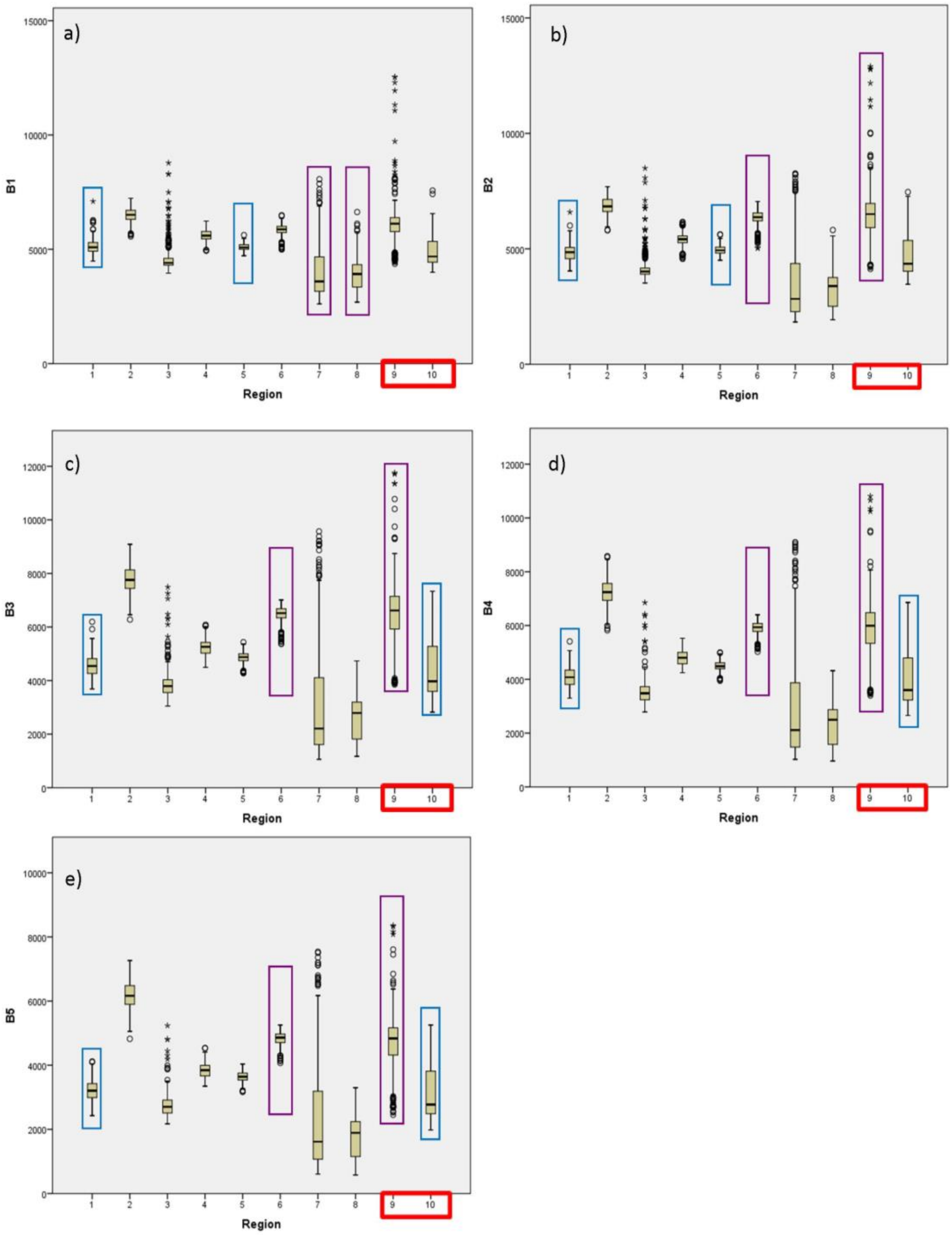


Figure 6.16 Box plots for the spectral means of ROIs from RapidEye data for all 5 bands. Rock glacier regions are shown with a red box outline. One set of significantly similar regions are highlighted with a blue box. The other set of significantly similar regions are indicated with a purple box.

6.3.5 Textural analysis

The difference in the semivariogram shapes between rock glaciers and corresponding non-rock glacier areas show that texturally the surfaces are different (Figs 6.17 – 6.23). However, as it can be seen from the semivariograms (Fig. 6.17-6.23) and the data in Table 6.6, there is no absolute pattern across the rock glaciers (Fig. 6.24). A majority of the rock glacier semivariograms have sill values which are a magnitude less than the non-rock glacier sill values (Figs. 6.17 – 6.23; Table 6.6). It can also be seen that the range values vary across the rock glaciers, from 125 to 300. Non-rock glacier semivariograms appear to have larger ranges, ranging from 180 – 600. However it can be seen that the non-rock glacier semivariograms consistently produce larger sill values than their corresponding rock glaciers (Table 6.6).

Some of the rock glaciers share similar range values, and similar semivariogram shapes. Caquella (Fig. 6.24a), Chiguana (Fig. 6.24b), Uyuni (Fig. 6.24e) and Tuni (Fig. 6.24f) all have ranges at similar distances, between 125 – 140 m (Table 6.6). Figure 6.24 shows that two different shapes of semivariogram can be observed from all the rock glaciers. Caquella, Chiguana, Chiguana 2 and Huyana Potosi (Fig. 6.24 a – d) have similar shapes. Different to these, Uyuni, Tuni and Pico (Fig. 6.24 e – g) also have similar shapes. These two different shapes indicate two different surface textures. This could be that the rock glaciers with the second shape mentioned have less pronounced ridges and furrows, which appears to be the case for all except Uyuni (C109a) (Fig. 6.10). These results suggests that Uyuni, Pico and Tuni rock glaciers have less patterns detected in their surface expression of brightness. Whereas the Caquella, Chiguana, Chiguana 2 and Huyana Potosi rock glaciers have more prominent expressesions of brightness, which can be interpreted as more well-defined ridges and furrows.

These rock glacier patterns differ from the semivariograms of the land surrounding the rock glaciers. Pico (A19a) showed the least amount of difference in the semivariograms between rock glacier and non-rock glacier ROIs, their semivariograms show very similar patterns with two sills (Fig. 6.23). But this rock glaciers surface is not as obvious on the satellite image. The same is observed for Tuni (A20a); the rock glacier is not very distinct on the RapidEye image and subsequently no pattern observed in the rock glacier semivariogram (Fig. 6.22).

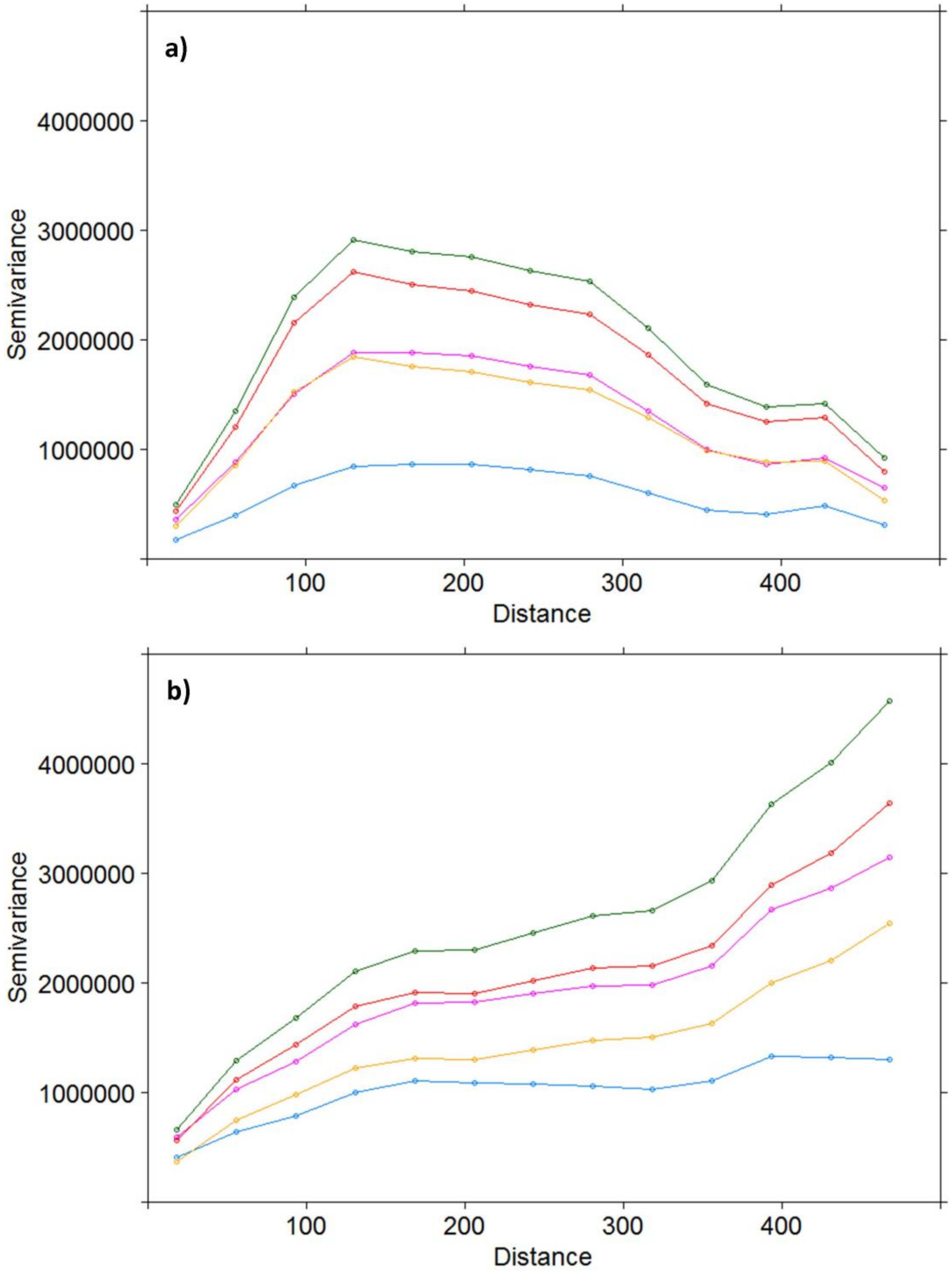


Figure 6.17 Semivariograms produced and plotted for Caquella C110a (Caquella rock glacier Fig. 6.10a). Two regions selected: a) rock glacier and; b) non-rock glacier. Band 1 (blue), band 2 (purple), band 3 (green), band 4 (red), band 5 (orange).

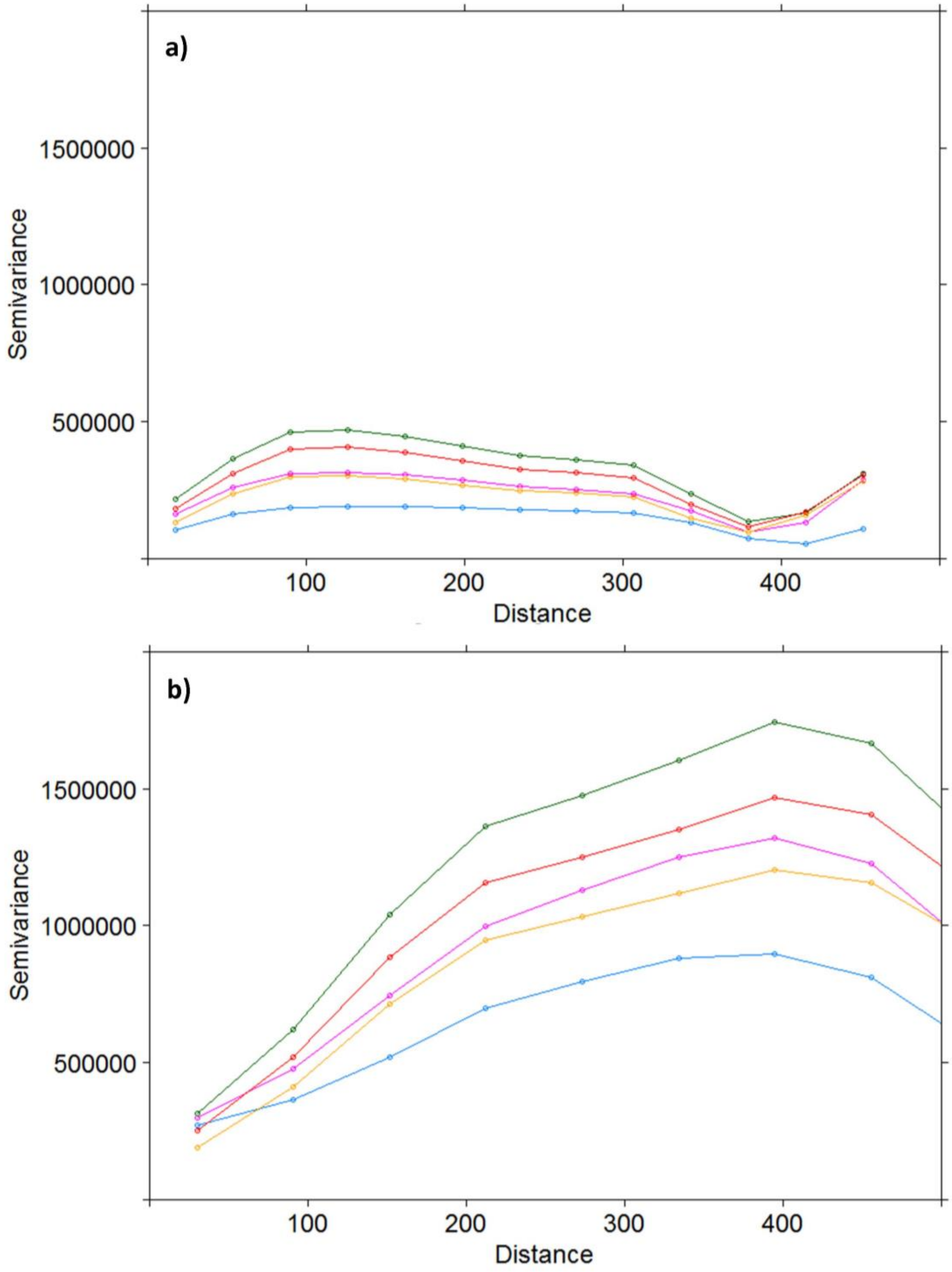


Figure 6.18 Semivariograms Chiguana C108a
(Chiguana rock glacier, Fig. 6.10b): a) rock glacier; b) non-rock glacier. Band 1 (blue), band 2 (purple), band 3 (green), band 4 (red), band 5 (orange).

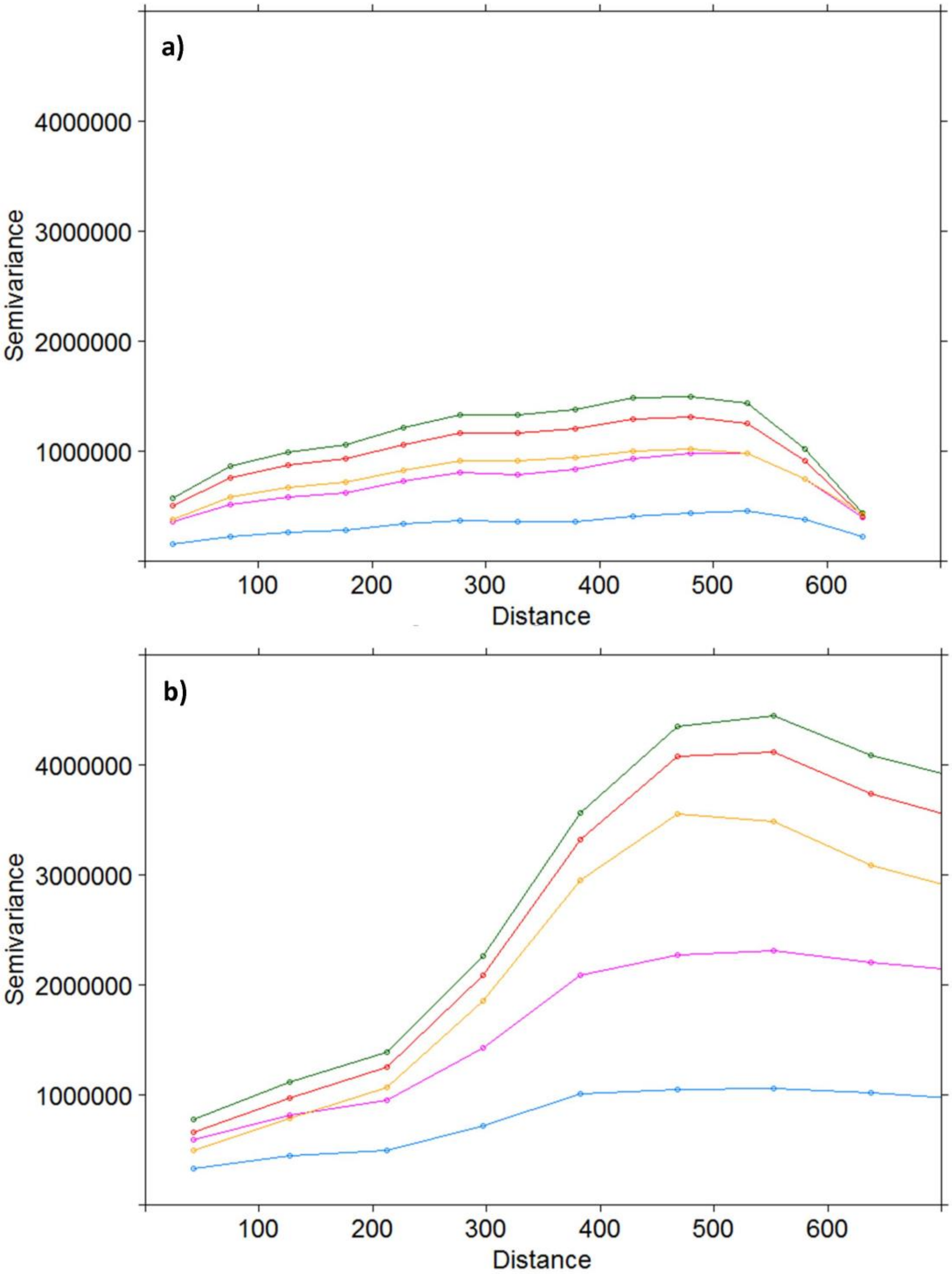


Figure 6.19 Semivariograms Chiguana 2 C107a (Chiguana 2 rock glacier, Fig. 6.10c): a) rock glacier; b) non-rock glacier. Band 1 (blue), band 2 (purple), band 3 (green), band 4 (red), band 5 (orange).

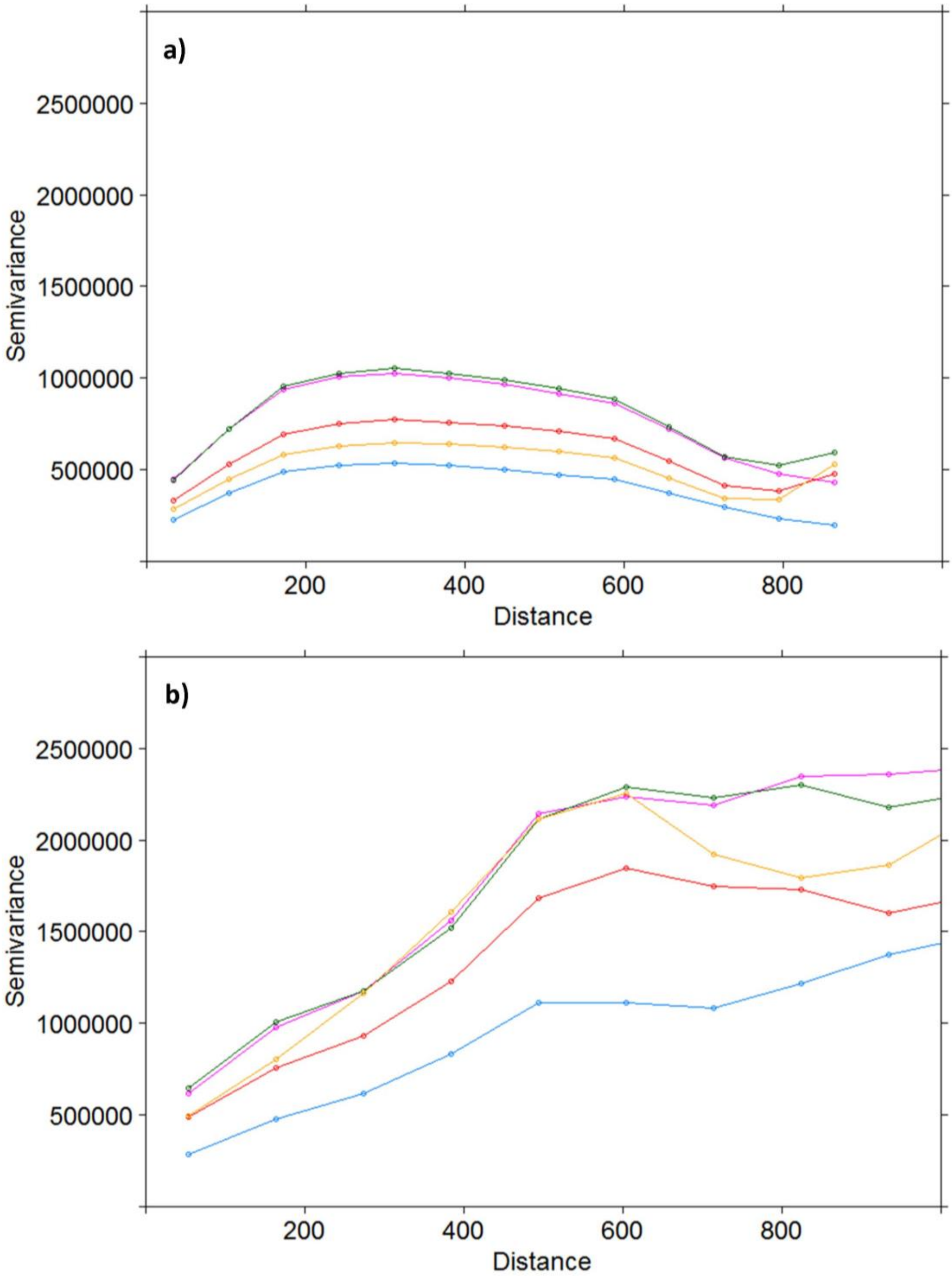


Figure 6.20 Semivariograms Huyana Potosi A39a (Huyana Potosi rock glacier, Fig. 6.10d): a) rock glacier; b) non-rock glacier. Band 1 (blue), band 2 (purple), band 3 (green), band 4 (red), band 5 (orange).

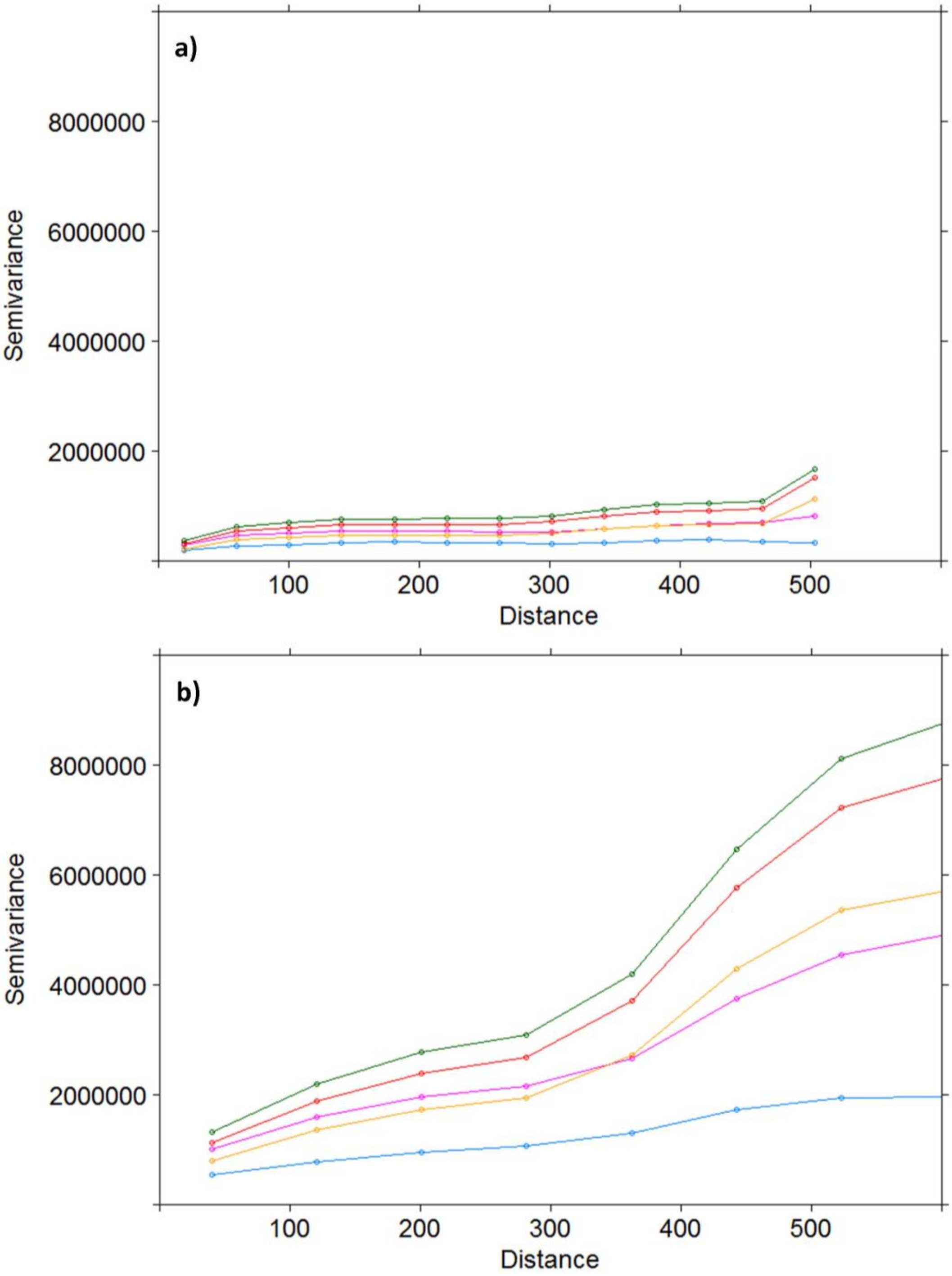


Figure 6.21 Semivariograms Uyuni C109a
(Uyuni rock glacier, Fig. 6.10e): a) rock glacier; b) non-rock glacier. Band 1 (blue), band 2 (purple), band 3 (green), band 4 (red), band 5 (orange).

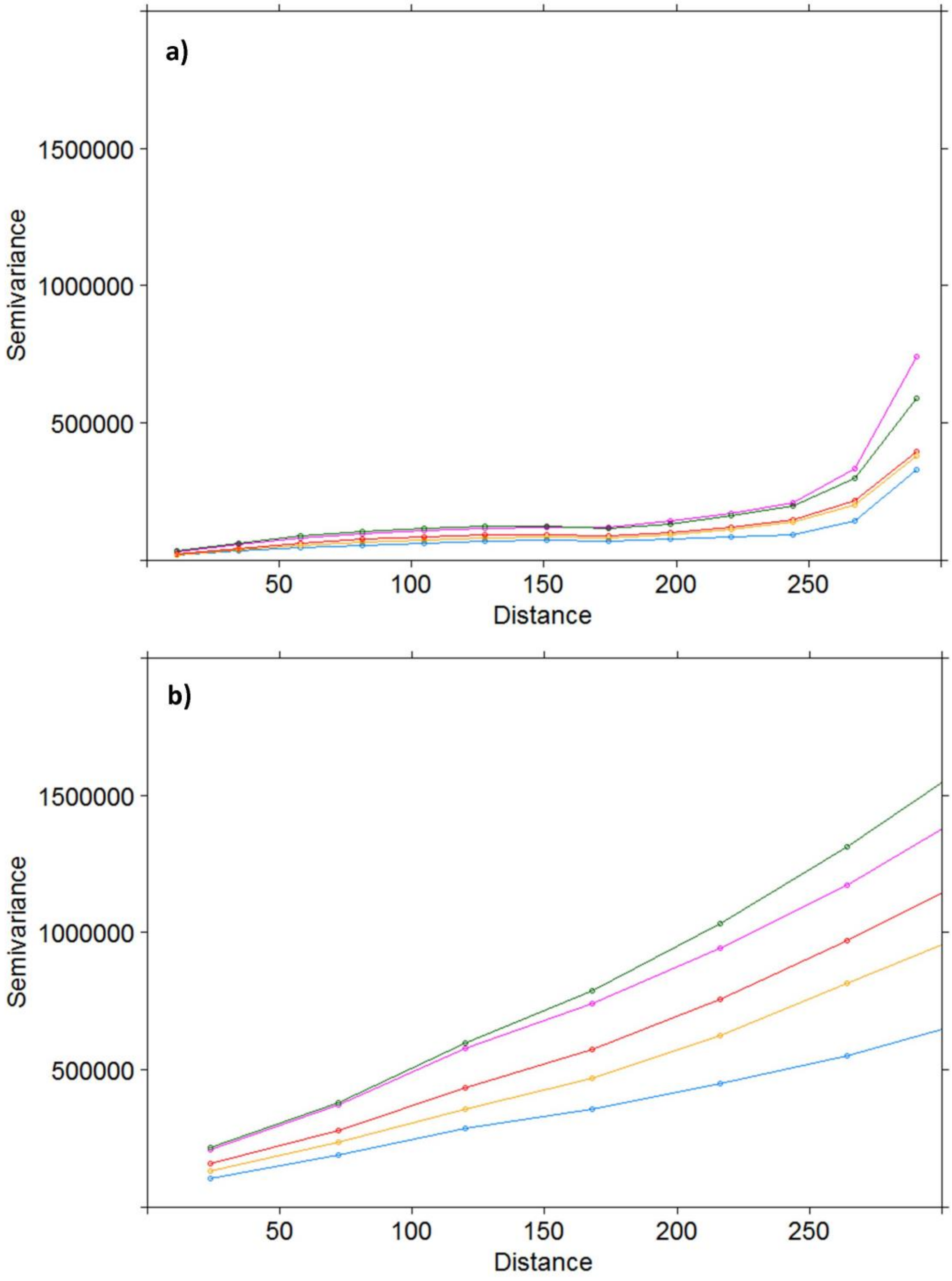


Figure 6.22 Semivariograms Tuni A20a
(Tuni rock glacier, Fig. 6.10f): a) rock glacier; b) non-rock glacier. Band 1 (blue), band 2 (purple), band 3 (green), band 4 (red), band 5 (orange).

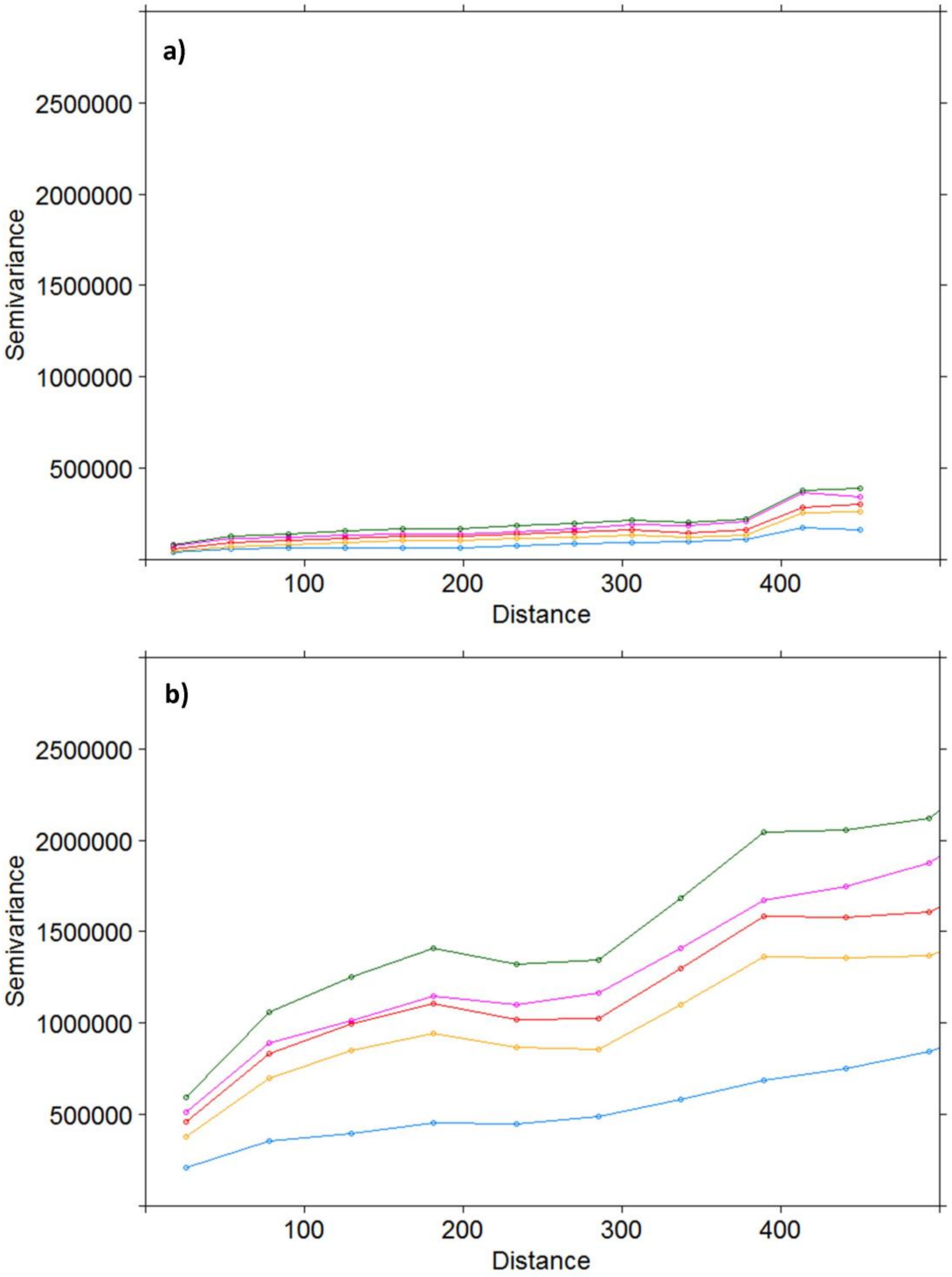


Figure 6.23 Semivariograms Pico A19a
(Pico rock glacier, Fig. 6.10g): a) rock glacier; b) non-rock glacier. Band 1 (blue), band 2 (purple), band 3 (green), band 4 (red), band 5 (orange).

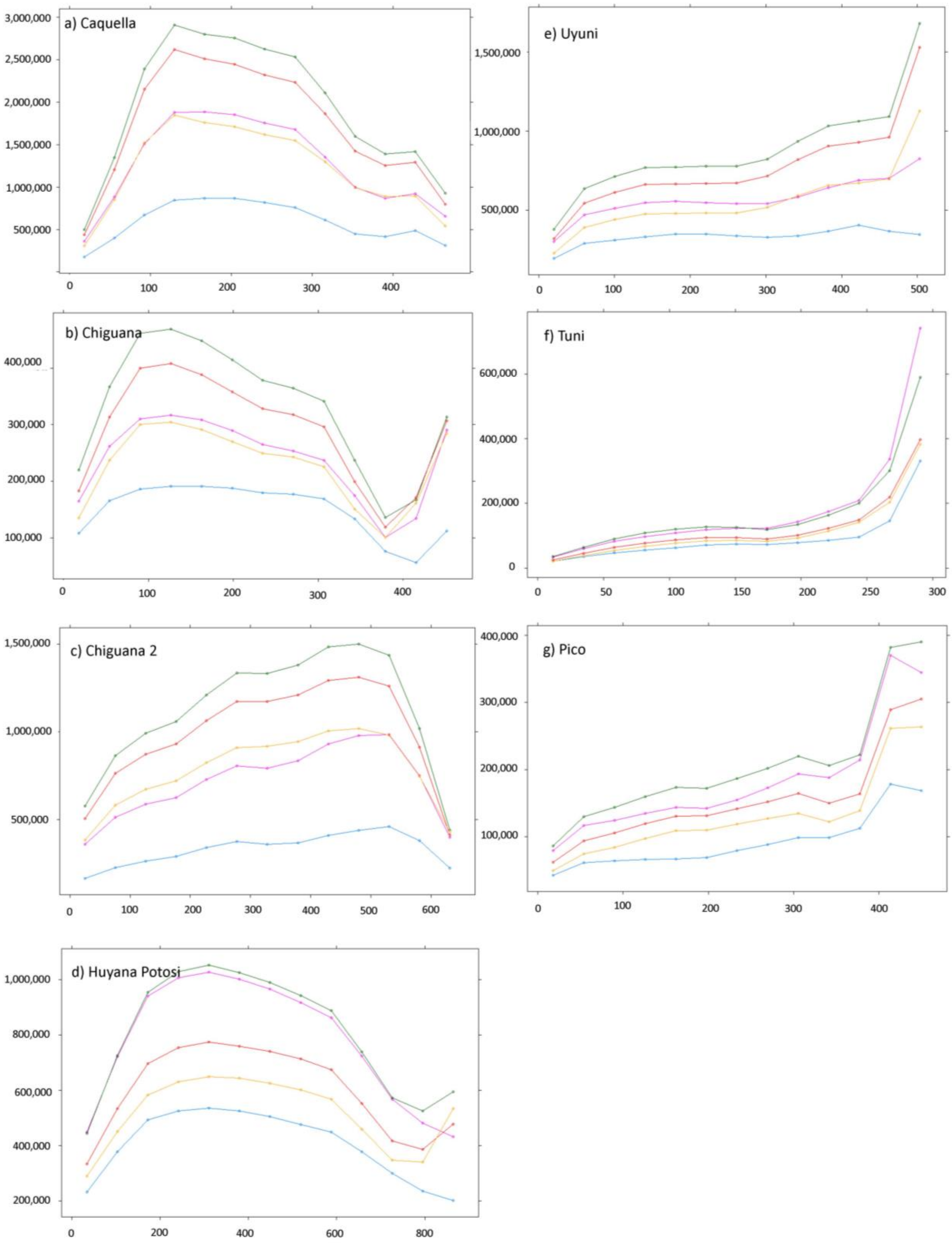


Figure 6.24 Semivariograms for rock glaciers
Range (m) on x axis and semivariance on y axis.

Region	ROI classification	Range	Sill	Nugget
C110a Caquella	Rock glacier	130	2.8×10^6	0
	Non-rock glacier	180	2.2×10^6	0.3×10^6
C108a Chiguana	Rock glacier	130	4.5×10^5	1.1×10^5
	Non-rock glacier	400	1.7×10^6	0.5×10^6
C107a Chiguana 2	Rock glacier	280	1.35×10^6	0.4×10^6
	Non-rock glacier	550	4.2×10^6	0.5×10^6
A39a Huyana Potosi	Rock glacier	300	1.5×10^6	2.2×10^5
	Non-rock glacier	600	2.3×10^6	0.5×10^6
C109a Uyuni	Rock glacier	140	7.5×10^5	2×10^5
	Non-rock glacier	-	-	0.8×10^6
A20a Tuni	Rock glacier	125	1.2×10^5	0.1×10^5
	Non-rock glacier	-	-	0.2×10^6
A19a Pico	Rock glacier	170	1.75×10^5	0.5×10^5
	Non-rock glacier	190	1.4×10^6	0.2×10^6

Table 6.6 Key values extracted from semivariograms: range, sill and nugget

6.4 Discussion

The resulting output from the rock glacier habitat suitability model can be applied as a layer in Google Earth to validate areas that have high rock glacier probability to verify the inventory. This method could also be used to limit the extent covered manually to check for rock glaciers (Fig. 6.5) or it could be used to identify areas of potential interest to explore with purchased satellite data (Fig. 6.5).

It should be noted that the characteristic attributes used here are specific to the Bolivian Andes. For example rock glacier elevations may be lower or higher in other regions, such as in the Chilean Andes where active rock glaciers are known to exist at 3,500 m a.s.l. (Brenning, 2005a). Therefore, a more suitable proxy for elevation could be to use the MAAT 0 °C isotherm. However, as evidenced in Chapter 5, some rock glaciers exist at MAATs higher than 0 °C due to local topography and proximity to ice bodies, therefore a more conservative upper threshold should be considered, as used in this mapping (Table 6.2). Yet, as these results have demonstrated (Table 6.5), current climate data is too coarse a resolution to enable accurate rock glacier habitat suitability mapping.

Multispectral analysis has shown that unsupervised and supervised classification algorithms cannot detect rock glacier regions to be statistically similar across the rock glacier and to be different from the surrounding regions to automatically detect rock glaciers. However, textural analysis showed differences in surface patterns of rock glaciers and non-rock glaciers, although there is a lack of consensus amongst these results across the rock glaciers analysed, suggesting no uniform pattern for rock glacier identification. Therefore, this prohibits the application of semivariograms to automatically 'locate' rock glaciers from their surrounding regions. However, it does demonstrate that there is a textural difference between the rock glaciers and their surroundings, which can be assumed mainly due to their ridge and furrow surface morphology, and can be further explored as future work from this PhD.

Another analysis of satellite data that could be potentially used to detect rock glaciers is thermal. The potential for thermal infrared bands to solve the reflectance ambiguity has been shown by Shukla et al. (2010) as substantial differences in temperature were found to exist between supraglacial and periglacial debris. This may not be the same for rock glaciers because the top layer of rock tends to be thick, potentially masking the ice and prohibiting its detected.

It is thought that there might be a detectable difference between the thermal data over a rock glacier when compared to the surrounding area using thermal inertia analysis, using maximum and minimum daily temperature information: thermal inertia (Toomley, 2011). The temperature of landforms could show a difference as ice is contained in the rock glacier, providing a distinctive thermal signal (Toomey, 2011). Maximum and minimum temperatures depict the response of a material to temperature changes. It is assumed that rock glaciers would heat up slower than their surroundings during the day time (Brenning *et al*., 2012b). Thermal intertia mapping of the cryosphere is a fairly novely approach; Brenning *et al.* (2012b) demonstrated the initaly possibility of using thermal imaging for thermal inertia mapping of the cryosphere, however, they state that further research is neded for a better understanding and improved interpretations. This method would require ASTER or Landsat thermal band data.

Analysing rock glacier locations and size over time would allow for an objective method of active rock glacier detection. It can be assumed that the resolution of the available data from Landsat is not fine enough to detect rock glacier detail change over time as movement is typically < 1 m annually (Kääb et al., 1998; Kaufmann, 1998; Liu et al., 2013). Therefore, temporal analysis would be better suited to much finer resolution data and accurate method, such as InSAR offset tracking (Ford, 2011). Ford (2011) has observed glacier velocity using Ultra-Fine-Beam mode InSAR offset-tracking, a methodology that might work for observing rock glacier velocities. This could provide a form of automated rock glacier identification/ or mapping, as well as reveal velocity values for the Bolivian rock glaciers.

Kaufmann (2010) has demonstrated the use of orthophotographs from virtual globes to measure flow/creep velocities in the European Alps. The work showed that rock glaciers with a mean annual flow/creep velocity greater than 10-15 cm/year can be detected successfully using multi-year high resolution orthophotos from virtual globes using Matlab-based toolbox for automatic measurement of 2D displacement vectors developed at Graz University of Technology, Austria. Therefore, conditional to access to the relevant high resolution data, temporal analysis on mountain regions could provide an objective method to detect (and quantify the movement of) active rock glaciers.

6.5 Conclusions

Overall, this research assessed the possibility of automated rock glacier detection, mainly from freely available satellite data. From the pilot studies in this chapter it can be seen that rock glaciers cannot be identified based on their spectral signal. It can also be seen that it is difficult to identify rock glaciers based on their spatial/textural signature, especially because rock glaciers vary with climate, topography, age, history and rock supply. However, the use of suitability habitat mapping can successfully narrow down the extents that need to be searched manually to identify geomorphological features by eye. The methods tested here have shown there is evidence for using textural methods for rock glacier identification, however this needs exploring in further regions and with a range of different sensors.

However, it should be noted that rock glacier characterstics vary regionally, nationally and internationally. Therefore, the criteria used for a region decision tree may be different/ very different to the relevant critera for another region. For example, no rock glaciers are found below 4000 m a.s.l. in the Bolivian Andes, however this elevation limit is a lot lower for research in the Chilean Andes, where it is considered to be 3000 m a.s.l. (Brenning, 2005a). Therefore, the importance of local knowledge and exisiting studies for informing the attributes for the suitability mapping can be considered significantly beneficial.

Furthermore, it is evident from the large difference in extent of the regions identified as suitable habitats for rock glaciers and the much smaller extents actually covered by rock glaciers, that factors other than terrain and climate play an important role in controlling rock glacier formation and persistence. These could include glacial history, rock supply.

Potentially, the technique with the most potential for automated active rock glacier detection could be InSAR offset-tracking. The application of InSAR analysis could also act as a validation for exisiting rock glacier identification and classification. However, a huge drawback to this method is requirement of expensive satellite imagery. Thus, it is important to continue in this relatively novel field of research to investigate further with freely available data sets. Current research is coming through using Google Earth to detect and measure rock glacier movement (Kaufmann, 2010) and thermal inertia (Brenning et al., 2012b).

Chapter 7 : An assessment of knowledge and perceptions on climate change and water resources in the Bolivian Andes

Questionnaire data from 34 participants was analysed to gather background information on the level of their understanding and knowledge of the topics of rock glaciers, climate change, glacier recession, and water security. Through a series of open- and closed-ended questions, information on the perceived impacts of climate change in the Bolivian Andes, the possible severity of future water security and potential solutions was gathered. The aim of this chapter was to collect and analyse quantitative and qualitative data regarding the perceptions and knowledge of an educated population in La Paz, to allow an assessment of the impact of my work and how best it can be applied and to whom. This data is to be featured in an Oxfam Research Report looking at the social implications of water scarcity in Bolivia.

7.1 Introduction

A questionnaire (Appendix 4; Appendix 5) was developed and distributed to examine the awareness and knowledge of climate change, water security and future situations in the Bolivian Andes of a well-educated Bolivian sample population. Using the attendees of a conference hosted in La Paz titled ‘Glaciers, Water and Climate Change’ on the 27th May 2014, a questionnaire was distributed and collected before the conference started to gather information from a group of participants who had knowledge and experience in similar research areas (water resources and climate change in Bolivia) such as academics, consultants and government employees. The research was designed to assess the level of knowledge, understanding and awareness of these research areas. Questionnaires were a combination of closed- and open-ended questions and answers were measured using a rating scaling (Likert scale). Quantitative data from closed-ended questions were automatically generated through responses. Quantitative data was generated through coding of the qualitative data from open-ended questions. Data was analysed descriptively, showing frequencies and trends. These trends were explored to establish a baseline of knowledge and understanding of climate change, glacier recession and water resources in the Bolivian Andes from an educated group. This then allowed for a comparison of the knowledge and understanding of the respondents regarding rock glaciers. Following the data collection from the questionnaires, results from this PhD were orally presented at the conference in La Paz (Appendix 6). Translated recordings of the questions asked after the presentation have been analysed for complementary qualitative data and validation for the need for this research.

7.2 Methodology

7.2.1 Materials

This questionnaire (Appendix 4) assessed individual perception of climate change and water resources in the Bolivian Andes. The questions addressed five different topics: (1) rock glaciers; (2) climate change; (3) glacier recession; (4) water resources and (5) future water security. The concept and conduct of this questionnaire were designed according to those of Read et al. (1994) where a questionnaire was used to examine educated laypeople’s knowledge about the possible causes and effects of global warming, as well as the likely efficacy of possible interventions.

The questionnaire was designed and piloted in the UK with University of Exeter postgraduate students and staff before then being piloted in Bolivia with a Spanish participant from Agua Sustentable in the final trial. The questionnaire was designed to make it as easy, straightforward and quick as possible for the respondent, without compromising the quality of data gathered. It is known that respondents are more willing to fill out a questionnaire if intentions are stated clearly at the start. Therefore there was a paragraph at the start of the questionnaire explaining that the data was being collected for academic research and that the questionnaire was expected to take ten minutes to complete [see Appendix 4]. It is also known that it is important to include clear instructions throughout the questionnaire to make it comprehensible and easy for the participant. The questionnaire was designed with questions grouped together according to the subject to maximise the flow.

Written in Spanish (Appendix 5), the questionnaire was distributed to 34 people in total. The questionnaires were collected before the start of the conference, thus responses were not influenced by the information disseminated at the conference. All written answers were translated from Spanish, therefore there was a risk of some concepts or answers being misunderstood or 'lost in translation'. This risk was limited by working alongside a fellow native English scientist fluent in Spanish (specifically scientific Spanish) for the translations. The conference and the question session following it were also recorded and translated/transcribed.

7.2.2 Data analysis

The data has been analysed descriptively for frequencies and trends, using tables, percentages and charts in Microsoft Excel and IBM SPSS. The questionnaire was designed with a mix of open- and closed-ended questions to gather qualitative and quantitative data, respectively. Both qualitative and quantitative approaches have their strengths and weaknesses. Quantitative methods produce factual, reliable outcome data. Qualitative methods generate rich, detailed, valid data that accurately represents the respondents' perspectives (Steckler et al., 1992).

Closed-ended questions provide answer categories (Ballou, 2008), limiting the respondent to the set of options being offered (Reja et al., 2003), providing instant quantitative data for analysis. Numerous questions were closed-ended questions using a 5 point Likert scale. Likert questions can help assess how strongly respondents agree (or disagree) to a particular statement. Advantages of using a Likert scale is that data can be gathered relatively quickly, it is self-coded making analysis relatively straightforward and it can provide highly reliable person ability estimates (Nemoto and Beglar, 2014).

Open-ended questions allow the respondent to formulate the answer in their own words (Ballou, 2008), avoiding being influenced by the research (Foddy, 1993 cited in Reja et al., 2003). Open-ended answers were coded and analysed for frequencies and trends, as well as using the raw data for quotes.

Respondents did not answer all questions of the questionnaire; therefore the analysis of each question has been treated separately and calculated with regard to the number of respondents for each specific question. The total numbers of respondents for each question are described throughout the results section.

7.3 Results

7.3.1 Social-demographic background

The questionnaire gathered a range of information on the background of the respondents, such as age, gender, profession and number of years spent living in La Paz, to build a rough understanding of their social-demographic background. Of the 34 respondents, 65% were male. Of the 33 who responded about their age, the largest age group was the 21 – 30 years (36%), followed by 31 – 40 year olds (30%) (Fig. 7.1a). Of the 31 respondents, students comprised over a quarter (29%). Overall, the respondents were well-educated. The professional spread of the 31 respondents composed of: 29% were students at universities in La Paz and El Alto, 27% were working for non-governmental organisations (NGOs), 16% were working for the government, 12% were working in the private sector, and 10% were lecturers. Based on this and the data provided throughout the questionnaire regarding their perceptions on own knowledge, the respondents were of an academic and educated background, with special interest in the topics of climate change and water resources in Bolivia.

Furthermore, by gathering information on the length of time spent living in La Paz, a deeper understanding any differences in observations and levels of knowledge of climate change in La Paz could be possibly attributed to time spent in the locale. From the questionnaires it can be assumed that 30% of the respondents have not lived in La Paz their whole life, with 20% of the respondents living in La Paz less than 10 years (Fig. 7.1b).

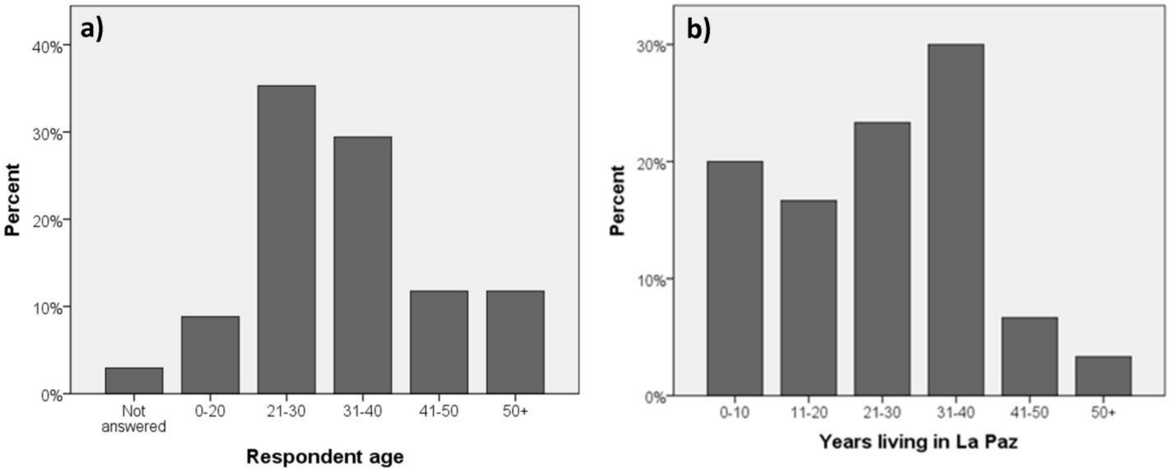


Figure 7.1 Percentage breakdown on participant's responses to a) Respondents ages; b) Number of years spent living in La Paz by respondents.

7.3.2 Rock glacier knowledge

The questionnaire opened with the topic of rock glaciers to assess the participant's current understanding and knowledge of rock glaciers and specifically rock glaciers in Bolivia. It is important to note that this data was gathered before a presentation about rock glaciers was given. Within this educated socio-demographic group, less than half (41%) stated that they had heard of rock glaciers before (Table 7.1). 3 respondents were excluded from analysis of this question because they were members of Agua Sustentable who have worked directly with this research (R11, R30, R32). The composition of the group who have heard of rock glaciers was mainly lecturers (18%), students (27%), NGO employees (18%) and those who work with the government for hydrology/environment (18%).

	Yes	*No*	*Total number of respondents*
Have you heard of a rock glacier?	*41%*	*59%*	*29*

Table 7.1 Table stating the percentage of respondents who have or have not heard of the term 'rock glacier' before

Analysis of the data regarding knowledge as rated on the Likert scale showed that from the 31 respondents only 16% of the respondents believed that they were knowledgeable about rock glaciers in Bolivia. 19% strongly disagreed, 29% disagreed; 35.5% neither agreed nor disagreed; 16% agreed; and none strongly agreed. Again, the 3 members from Agua Sustentable were excluded from this analysis.

The second part to this question was open-ended, allowing respondents to briefly describe what they thought a rock glacier was, and to explain what they knew about rock glaciers in Bolivia. Again, excluding the same 3 members of Agua Sustentable, all 11 respondents who answered that they had heard of a rock glacier wrote down their definition. From these definitions it is apparent that numerous people got confused between the term ‘rock glacier’ and what are actually ice glaciers and debris covered glaciers (although they are on this continuum, i.e. Giardino and Vitek, 1988).

Some definitions were far from correct, such as R13 who described rock glaciers to be *“through the process of atmospheric compression and by the cooling to below zero the snow is compressed until it is converted to rock”*. A limited number of the definitions were correct. One such example was R6 (who works in the field of hydrology) who correctly defined a rock glacier (*“A rock glacier refers to a landform where the rock covers the ice”*) and was aware that they exist in the Western Cordillera (IRD have worked on Caquella rock glacier), however did not express any knowledge of them elsewhere.

R25 made a good point regarding limitations in our knowledge of the cryosphere: *“There are few glacial studies in the country for lack of sufficient resources, accessibility and shared resources. Studies of Zongo glacier and Illimani recently Sajama, first Chacaltya - French IRD, IHH”.* R34 (government employee in the field of hydrology) also understands this lack of knowledge, underlying the importance of this PhD research: *“I understand that there are very few studies in Bolivia in this regard, but they are in the mountains of the Andes of Bolivia”*.

7.3.3 Perception of knowledge on climate change, glacier recession and water resources

Of the 33 respondents, 70% of the participants agreed or strongly agreed they were knowledgeable about climate change in the Bolivian Andes. None of the respondents strongly believed themselves to not be; 15% disagreed that they were knowledgeable, 15% neither agreed nor disagreed, whereas 55% agreed they were, and 15% strongly agreed. This demonstrated that the respondents were of a knowledgeable level regarding climate change and its impacts. This was also reflected in large number of respondents who listed the maximum number of climate change impacts (section 7.3.4); 87% of the of the 30 respondents listed 3 impacts, the maximum number requested.

Of all the respondents, over half (56%) agreed that they were knowledgeable about glacier recession in the Bolivian Andes, with a further 12% strongly agreeing. 21% of the participants disagreed or strongly disagreed (15% and 6%, respectively) that they were knowledgeable about glacier recession in the Bolivian Andes, with the remaining 12% stating that they neither agreed nor disagreed.

88% of the respondents agreed or strongly agreed (53% and 35%, respectively) that glacier recession is occurring in the Bolivian Andes, with only 6% strongly disagreeing with that statement and 6% neither agreeing nor disagreeing. Furthermore, a large majority (91%) agreed or strongly agreed that climate change is expected to affect water resources in the Bolivian Andes.

Again, over half (53.5%) agreed or strongly agreed (41% and 12.5%, respectively) that they were knowledgeable about water resources and water security in La Paz. None of the participants strongly disagreed with this statement, but 9% did ‘disagree’ and a further 37.5% neither agreed nor disagreed, demonstrating that this was a niche audience who were educated in this topic. Yet, over half of this group had never heard of a rock glacier before.

7.3.4 Impacts of climate change

Using open-ended questions, this questionnaire gathered information on individual knowledge of climate change impacts in the Bolivian Andes. The questionnaire asked respondents to list up to 3 impacts of climate change in the Bolivian Andes (if possible). Upon analysis, these impacts were coded into 9 different categories (Fig. 7.2) which covered the range of changes listed in the responses. These categories were then further coded into directional changes, if mentioned (Table 7.2). This directional coding was divided into three categories: negative change, positive change and no change mentioned. For example, a negative change for the category ‘change in glaciers’ represents a loss or reduction of glaciers (Table 7.2).

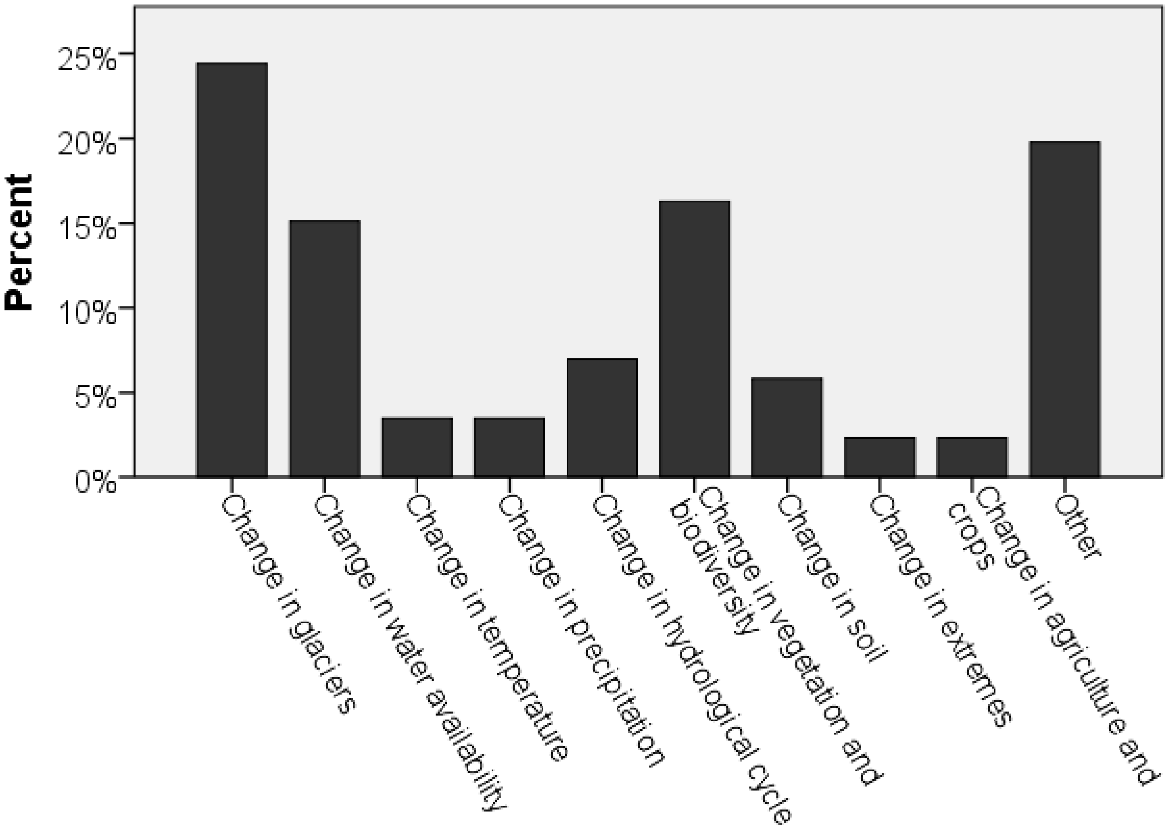


Figure 7.2 Participant responses to naming the main impacts of climate change in the Bolivian Andes

‘Change in glaciers’ was the most common response (24%). 95% of the respondents who mentioned this impact associated climate change to a negative change in glaciers (Table 7.2). 1 participant associated a positive change, glacier advance (R6), stated as a potential impact of increased rainfall. 15% of the respondents stated that changes in water availability would be an impact of climate change, with 92% of these comments being associated to a negative change in water availability (and the remaining 8% not having a directional change associated).

16% of the respondents stated a change in vegetation and biodiversity, of which 86% associated with a loss. Of the 6% who mention changes to soils, all of them state a drying out of soils. 3.5% mentioned that changes in temperature are linked to climate change, with all these respondents stating an increase in temperature. However, of the respondents who mentioned changes in precipitation (3.5%), there was no consensus of the direction of this change (Table 7.2). The category ‘other’ (20%) included erosion, wildfire, climate migration and social problems, drought and conflict over water sources.

Main impacts of climate change in the Bolivian Andes			***Direction of change***		
Impacts	% of respondents	Number of respondents	*Negative*	*Change*	*Positive*
Changes in glaciers	24%	21	*95%*	-	*5%*
Changes in water available	15%	13	*92%*	*8%*	-
Changes in temperature	3.5%	3	-	-	*100%*
Changes in precipitation	3.5%	3	*33%*	*33%*	*33%*
Changes in hydrological cycle	7%	6	-	*67%*	*33%*
Changes in vegetation and biodiversity	16%	14	*86%*	*14%*	-
Changes to soil (drying)	6%	5	-	-	*100%*
Changes in extremes	2%	2		*50%*	*50%*
Changes in agriculture and crops	2%	2	50%	50%	-
Other	20%	17	-	-	-

Table 7.2 Coded responses to the main impacts of climate change in the Bolivian Andes and their associated direction of change if stated.

Further analysis studied the frequency of the categories for just the first impact listed the questionnaire (Table 7.3) as this can be taken as the most instinctive response. It becomes even clearer in this analysis that changes in glaciers is the most commonly stated impact (43%) associated with climate change in the Bolivian Andes. Changes in water availability (17%), the hydrological cycle (13%) and agriculture and crops (7%) were other common initial responses (Table 7.3).

First listed impact of climate change in the Bolivian Andes	
Impacts	% of respondents
Changes in glaciers	43%
Changes in water available	17%
Changes in temperature	3%
Changes in precipitation	3%
Changes in hydrological cycle	13%
Changes in vegetation and biodiversity	3%
Changes to soil (drying)	0%
Changes in extremes	0%
Changes in agriculture and crops	7%
Other	10%

Table 7.3 Table showing the frequency of only the first impacts of climate change listed by respondents

7.3.5 Evidence of climate change

With a direct close-ended question regarding the witnessing of climate change in La Paz, of 32 respondents, 94% agreed that they have witnessed climate change in La Paz (Table 7.4). Of the 2 participants who said ‘no’, one was a student who has lived in La Paz for 4 months (R5), the second was an independent consultant hydrologist in the Ministry of Public Water Utilities (R25) as he states that he has not seen evidence of climate change in La Paz or Bolivia because there are too fewer facts available and a scarce coverage of monitoring and too short an observation time.

Similarly, respondents were asked the same question but for Bolivia. Of the 28 who responded, 89% believed that they have seen evidence of climate change impacts in Bolivia; whereas 11% believed that they had not (Table 7.4).

	Have you witnessed evidence of climate change		*Total number of respondents*
	Yes	*No*	
La Paz	*94%*	*8%*	*32*
Bolivia	*89%*	*11%*	*28*

Table 7.4 Frequency of responses of participants to the question ‘have you witnessed evidence of climate change in La Paz?’

The open-ended second part of this question allowed participants to describe what they have observed and why they thought it is linked to climate change. These responses were coded into 9 categories (Table 7.5) with the most common evidence as glacier recession (28%), particularly the disappearance of Chacaltaya glacier. Quotes included *“melting of mount Chacaltaya”* (R19), *“from La Paz we can see the snow cap of Illimani: over the years it has been possible to observe the extent of the glacier is rapidly decreasing”* (R1) and *“I have personally seen in La Paz that several of its mountains have lost the snowy i.e. which have retreated glaciers”* (R34).

‘Changes in precipitation’ was the second most commonly identified evidence of climate change (17%) (Table 7.5), which included *“changes to the rainy and dry season”* (R7) and *“rains out of the wet season (unseasonable rain)”* (R6). Changes in precipitation mainly regarded changes in patterns and occurrence rather than changes in quantity. Changes in temperature and flooding were both mentioned by 11% of the respondents (Table 7.5).

Observations of climate change	% of respondents	Frequency
Glacier recession	28%	15
Loss in biodiversity	2%	1
Changes in temperature	11%	6
Changes in precipitation	17%	9
Flooding	11%	6
Changes to vegetation and crops	4%	2
Drought	4%	2
Changes in extremes	6%	3
Other	17%	9

Table 7.5 Coded responses of participants to their observations of climate change in La Paz/ Bolivia

The coded category ‘other’ included observations such as: *“Four years ago you didn’t find mosquitos in the city of La Paz, in the months of heat today you do”* (R13), *“increase in acid rain”* (R27) and *“I think that the majority of environmental impacts are exacerbating more with changes in the climate. However, many of the problems are not directly caused by climate change, but rather by the activities of* *man and little planning that exists"* (R31). These comments were all important, and illustrate other changes witnessed, however did not fit the general trends observed when coding. Some responses could not be coded, but provided invaluable insight and knowledge, such as R25 (hydrologist) who pointed out*: "There are few facts available, scarce coverage of monitoring, also short observation times. We should evaluate the changes in a physio-geographical context. Wants better meterological stations to monitor climate change and longer data sets".* This is a valuable point to make regarding the lack of data on appropriate temporal and spatial scales to make confident assessments regarding a changing climate in the Bolivian Andes.

7.3.6 Water resources

The water resources section of this questionnaire asked questions which dealt with present and future water availability, specifically asking participants if they thought that water availability would be sufficient enough for societal needs of La Paz. The year 2100 was used to question about the future, based on existing scenario models and forecasts.

Data on respondents opinions regarding present day water availability in La Paz, less than half (41%) agreed or strongly agreed (29% and 12%, respectively) that it is currently sufficient for societal needs. 27% of the participants disagree or strongly disagree (21% and 6%, respectively) that current water availability is sufficient for societal needs in La Paz. Whereas, for 2100, 76% believed that water availability in La Paz will pose problems for society. None of the respondents strongly disagreed with this statement, but 12% did disagree.

With a nominal scale of insufficient, sufficient and more than sufficient, of the 33 respondents, 88% believed that the water available in 2100 will be insufficient to support La Paz's social needs (Fig. 7.3). 9% thought that levels will be sufficient/ adequate for supporting society, and only 1 respondent (3%) believed that water availability will be plentiful enough to support society's needs.

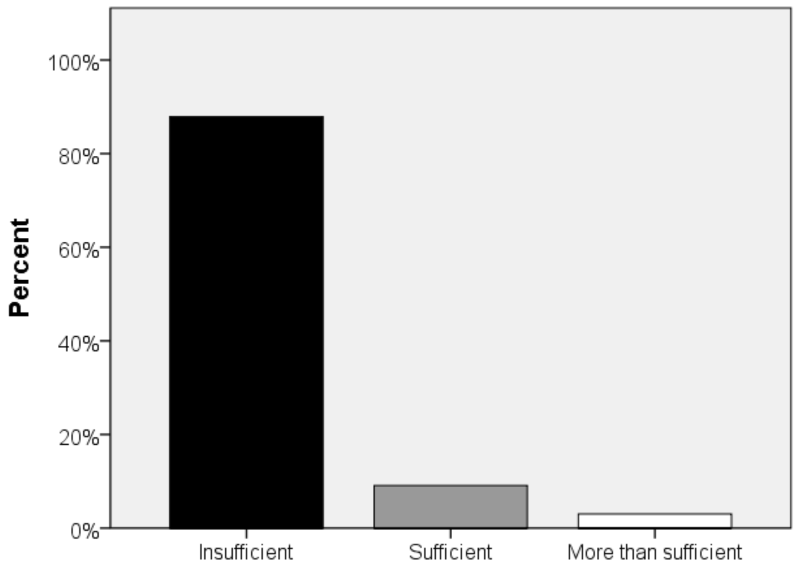


Figure 7.3 Participant responses to the closed question of 'water availability in 2100 for La Paz's societal needs'

7.3.7 Possible solutions

The final section of the questionnaire was an open-ended question allowing participants to list up to 3 ways in which they believed that the city of La Paz could address possible reduced water security in the future. These answers were coded into 15 categories (Table 7.6). Overall, promoting water conservation was the most popular suggestion (14%) (Table 7.6). A combination of 'others' (11%) was the second most common suggestion, followed by storage, dams and reservoirs (10%). Better capturing/ harvesting of water and efficient use of water both received 9%, with improving the system of cleaning water/treatment receiving 8% of the suggestions (Table 7.6).

The 'other' category included a wide range of suggestions including the suggestion to *"study and identify sources of water"* (R25), giving justification to this research. As one respondent pointed out, most suggestions deal with adaption rather than the actual problem *"I am not sure if the construction of reservoirs and other measures will be the solution"* (R11). Constructing reservoirs could help increase the hydrological buffering ability of the region, but it does not address the change in available water coming from the mountains in the first place. Another participant acknowledged this by stating that we need to *"Study possible climatic scenarios, population demand scenarios"* (R25).

Coded categories	Percentage	Frequency
Promoting water conservation	14 %	13
Improve system of cleaning water	8 %	7
Better capture/ harvesting of rain water	9 %	8
Dams/ reservoirs/storage	10 %	9
Infrastructure improvements/ distribution network	5 %	5
Try to reduce consumption of water	4 %	4
Recharging of aquifers	2 %	2
Recycling of water	5 %	5
Efficient use of water	9 %	8
Extraction of ground water	4 %	4
Agriculture/reduce deforestation/ reforestation	7 %	6
Protection of water sources	5 %	5
Implement charge for water	2 %	2
Regulate use of water	4 %	4
Other	11 %	10

Table 7.6 Coded responses of respondents to the open ended question asking of ways in which the city of La Paz could address reduced water security in the future.

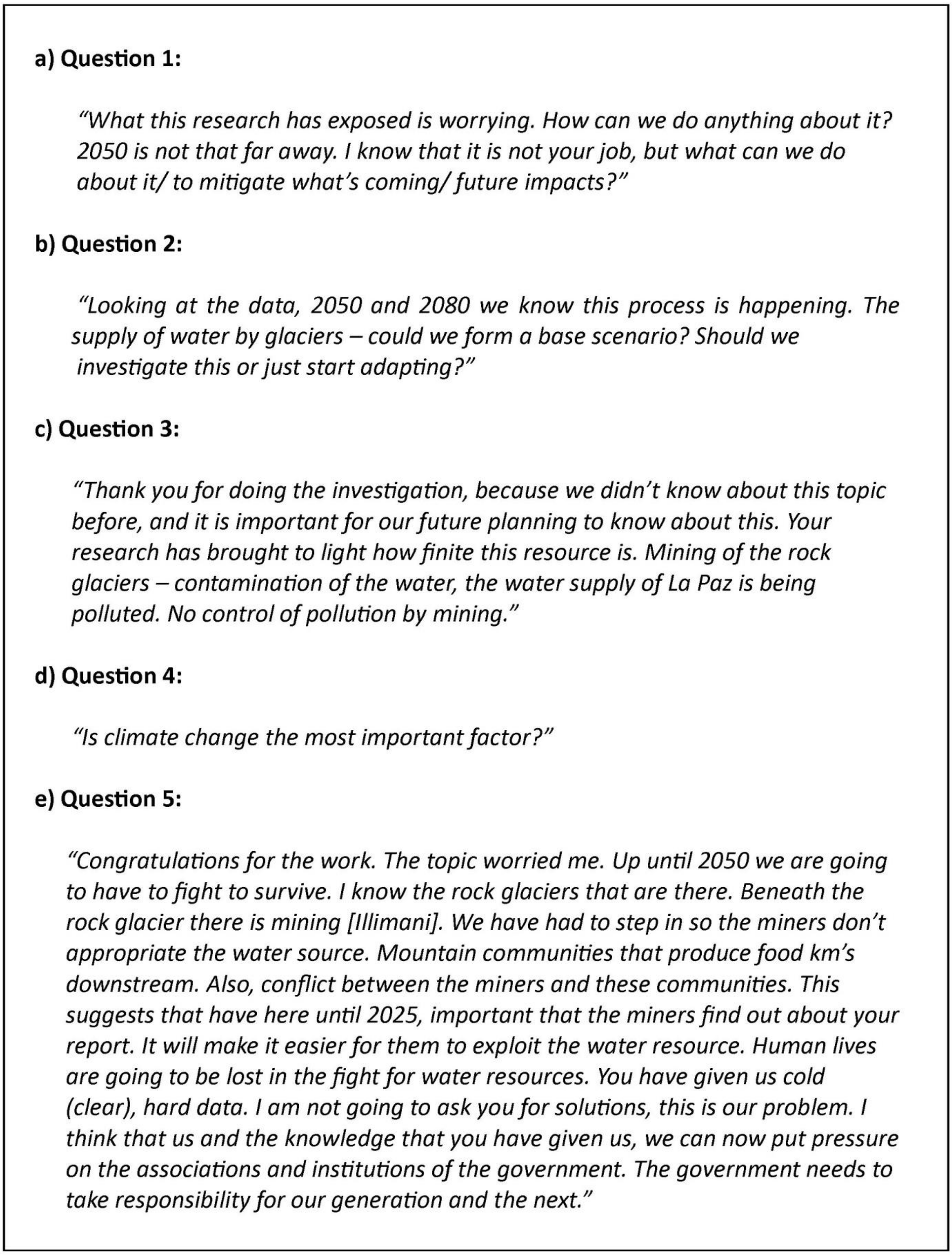
Coded categories	Percentage
Promoting water conservation	6 %
Improve system of cleaning water	6 %
Better capture/ harvesting of rain water	12 %
Dams/ reservoirs/storage	6 %
Infrastructure improvements/ distribution network	9 %
Try to reduce consumption of water	9 %
Recharging of aquifers	3 %
Recycling of water	3 %
Efficient use of water	9 %
Extraction of ground water	9 %
Agriculture/reduce deforestation/ reforestation	6 %
Protection of water sources	6 %
Implement charge for water	0 %
Regulate use of water	6 %
Other	9 %

Table 7.7 Table showing the frequency of only the first suggestion of solutions for La Paz to address future reduced water security listed by respondents.

Again, when analysing only the first of the three responses listed (Table 7.7), better capture/harvesting of rain water is the most frequent (12%). This suggests that capturing and harvesting water is seen as the most obvious and easiest solution to reduced water availability, a view common in the policy literature (UNFCCC, 2011; UNEP, 2012). Rainwater harvesting is seen as the most practical, easily implemented, sustainable and cost-effective option (UNFCCC, 2011). It is in these initial responses that the importance of improving infrastructure is hinted at (9% of response), along with trying to reduce the consumption of water, efficient use of water, and the extraction of ground water (Table 7.7). It is clear that the implementation of a water charge is not seen as an initial solution.

7.3.8 Conference questions

The questions that were raised after my oral presentation (Appendix 6) at the conference brought to light some interesting points and also helped to highlight how important the research presented in this thesis is. Furthermore, the questions and statements made at the conference demonstrated how important it is to get the information out to those who want it/ need it. Figure 7.4 is the transcript of the questions posed at the conference.



a) Question 1:

"What this research has exposed is worrying. How can we do anything about it? 2050 is not that far away. I know that it is not your job, but what can we do about it/ to mitigate what's coming/ future impacts?"

b) Question 2:

"Looking at the data, 2050 and 2080 we know this process is happening. The supply of water by glaciers – could we form a base scenario? Should we investigate this or just start adapting?"

c) Question 3:

"Thank you for doing the investigation, because we didn't know about this topic before, and it is important for our future planning to know about this. Your research has brought to light how finite this resource is. Mining of the rock glaciers – contamination of the water, the water supply of La Paz is being polluted. No control of pollution by mining."

d) Question 4:

"Is climate change the most important factor?"

e) Question 5:

"Congratulations for the work. The topic worried me. Up until 2050 we are going to have to fight to survive. I know the rock glaciers that are there. Beneath the rock glacier there is mining [Illimani]. We have had to step in so the miners don't appropriate the water source. Mountain communities that produce food km's downstream. Also, conflict between the miners and these communities. This suggests that have here until 2025, important that the miners find out about your report. It will make it easier for them to exploit the water resource. Human lives are going to be lost in the fight for water resources. You have given us cold (clear), hard data. I am not going to ask you for solutions, this is our problem. I think that us and the knowledge that you have given us, we can now put pressure on the associations and institutions of the government. The government needs to take responsibility for our generation and the next."

Figure 7.4 Transcript of questions asked at the conference following the presentations

The following quotes selected from this transcript (Fig. 7.4) showed how the audience viewed the research presented at the conference and what they believed that this data could be used for:

> *"Thank you for doing the investigation, because we didn't know about this topic before, and it is important for our future planning to know about this. Your research has brought to light how finite this resource is"*
>
> (Question 3 at the conference)

> *"What this research has exposed is worrying*"
>
> (Question 1 at the conference)

> *"Congratulations for the work. The topic worried me. Up until 2050 we are going to have to fight to survive"*
>
> (Question 5 at the conference)

> *"You have given us cold (clear), hard data. I am not going to ask you for solutions, this is our problem. I think that with the knowledge that you have given us, we can now put pressure on the associations and institutions of the government. The government needs to take responsibility for our generation and the next"*
>
> (Question 5 at the conference)

It is clear from these questions, and the questionnaire responses, that there was a lack of knowledge and understanding of rock glaciers, a gap highlighted by the information presented at the conference. From the questions asked it also became apparent that there is conflict between rock glaciers as water stores and mining. Two out of the five questions involved concerns over mining and rock glaciers:

> *"I know the rock glaciers that are there. Beneath the rock glacier there is mining [Illimani]. We have had to step in so the miners don't appropriate the water source. Mountain communities that produce food kilometres downstream. There is conflict between the miners and these communities"*
>
> (Question 5 at the conference)

> *"Mining of the rock glaciers – contamination of the water, the water supply of La Paz is being polluted. No control of pollution by mining"*
>
> (Question 3 of the conference)

This attention to mining and contamination and conflict is something explored by Brenning (2008) for rock glaciers of the Chilean Andes and has not been explored by this research yet. However, it can be linked to the idea of 'protecting sources of water', which was one of the potential solutions named by the respondents (section 7.3.7).

7.4 Discussion

Based on the data collected through the questionnaire, the respondents were predominantly of an academic and educated background, with experience in the topics of climate change and water resources in Bolivia. Over two thirds (70%) of the respondents agreed or strongly agreed they there were knowledgeable about climate change in the Bolivian Andes, and similarly, 68% of the respondents agreed or strongly agreed that they were knowledgeable about glacier recession in the Bolivian Andes. 88% of the respondents agreed or strongly agreed that glacier recession is occurring in the Bolivian Andes and 91% of the participants agreed or strongly agreed that climate change is expected to affect water resources in the Bolivian Andes. Over half (53.5%) of the respondents agreed or strongly agreed that they were knowledgeable about water resources and water security in La Paz. Despite this knowledgeable audience, over half (59%) had never heard of rock glaciers before, with only 15% of the respondents agreeing that they were knowledgeable about rock glaciers in Bolivia. This data gives justification and validation for the need for this PhD research a concept which is verified by the questions asked at the end of the conference (Fig. 7.4). It also showed the importance of disseminating the research and results, to raise awareness of other sources of water in the Bolivian Andes. It should be noted that one of the limitations of this data analysis could lie in human error; mistakes or misunderstanding of respondent's answers for open-ended questions could have arisen through translations and the misreading of hand written answers in Spanish.

Analysis of the climate change impacts identified by the respondents showed a mirroring of the current scientific observations, projections and uncertainties: that there is high confidence that glaciers will continue to shrink almost worldwide due to climate change (IPCC, 2014), that temperatures are projected to increase, but precipitation projections differ on their direction and magnitude (Magrin et al., 2007; IPCC, 2014). Glacier recession was the most common impact of climate change in the Bolivian Andes named (24%), of which 95% stated glacier recession (Table 7.2). Of the respondents mentioning changes in temperature, all stated an increase in temperature, and of the respondents who mentioned changes in precipitation, there was no consensus on the direction of this change (Table 7.2).

An Oxfam report outlines five main impacts expected as a result of climate change for Bolivia: less food security; glacier retreat affecting water availability; more frequent and more intense natural disasters; an increase in mosquito-borne diseases; and more forest fires (Oxfam, 2009). Glacier recession and water availability represented 39% of the responses in this research; however the other four main impacts were barely covered by the respondents, if mentioned at all. This could be because some of the impacts are more relevant to parts of Bolivia separate to the Andes (such as forest fires). Reduced food security is not directly mentioned by the respondents; however climate change impacting agriculture and crops was stated by 2 respondents (Table 7.2). Analysis of the impacts listed by the respondents in a network diagram (Fig. 7.5) shows that there are some direct impacts of climate change (changes in temperature, changes in precipitation) and then these impacts affect water availability (water security), agriculture (food security) which then can drive some of the impacts categorised as ‘other’ such as climate migration and conflict over water sources (Fig. 7.5). These impacts mirror some of the main points made by the network diagram in Rangecroft *et al.* (2013, Chapter 2, Fig. 2.11). However the network diagram by Rangecroft *et al.* (2013) was focused around the drivers and impacts of reduced water availability, and hence some of the impacts may not be directly connected to climate change (such decreased HEP generation) and are therefore not mentioned by any of the respondents. However, some of the secondary impacts of climate change and reduced water availability were identified by the respondents, such as climate migration (R13) and conflict over water sources (R10) (Fig. 7.5). The two network diagrams mentioned have considerable cross over, especially considering that network diagram by Rangecroft *et al.* (2013) was drawn before the questionnaire data was collected and analysed.

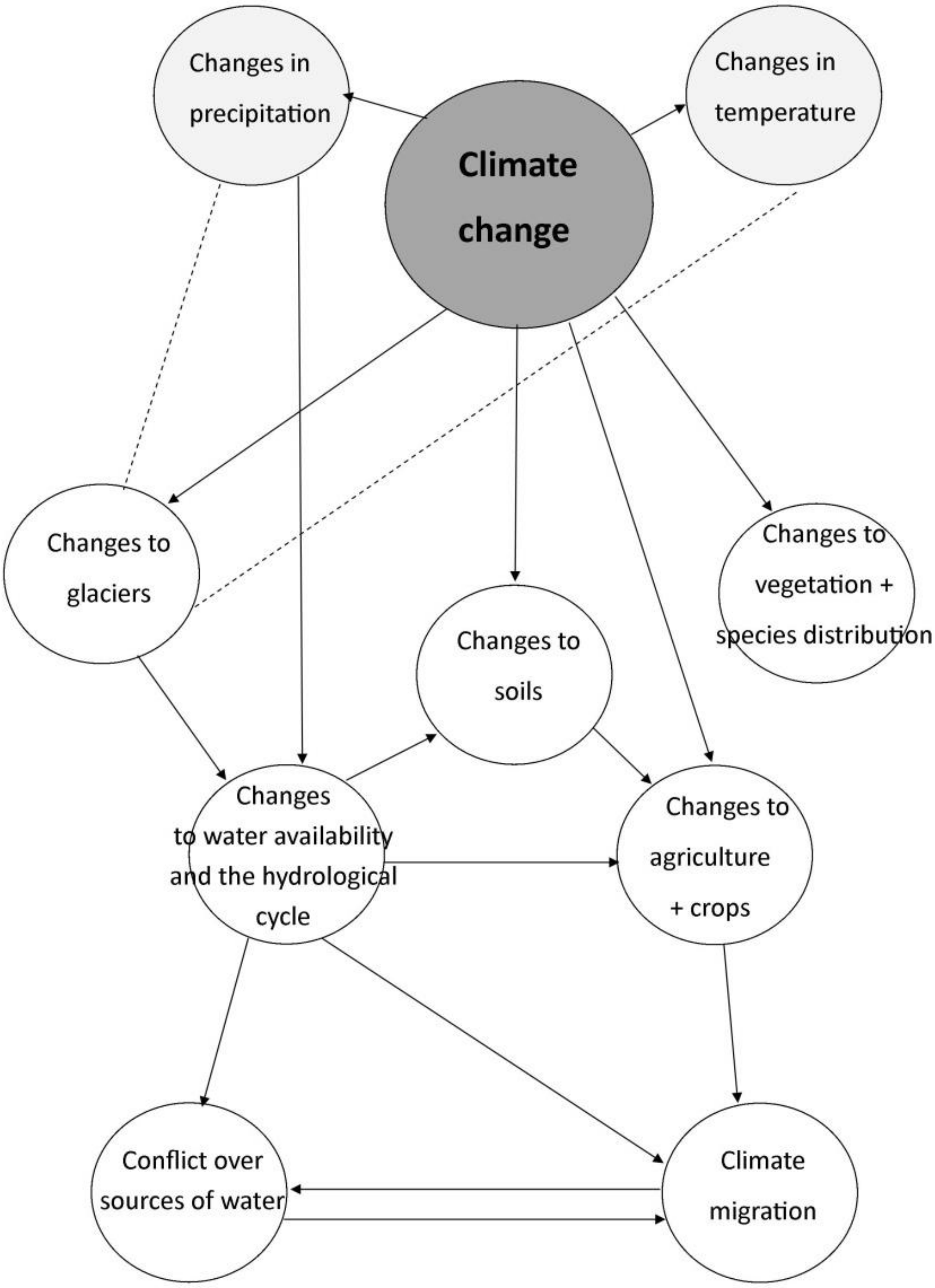


Figure 7.5 Network diagram of coded impacts of climate change listed by respondents and how they are interlinked

Despite an estimated 30% of the respondents having not lived in La Paz their whole life, and with 20% of the respondents having lived in La Paz for less than 10 years, a striking 94% of the respondents believed that they have witnessed evidence of climate change in La Paz. The most common link made between evidence and climate change was the disappearance/retreat of glaciers (29%), especially Chacaltaya. This could be media related, or education could be factor; students (29% of the respondents) learning about glacier recession and the loss of Chacaltaya as a case study. From this questionnaire it is apparent that nearly one third of the participants considered glacier recession to be a clear sign of climate change, and that this was the most common response. This is supported in the literature as glacier recession is seen as a clear visible reflection of recent climate change in mountain regions (Francou et al., 2003; Vuille et al., 2003; Vuille et al., 2008; Mark et al., 2010).

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) and 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, such as Chacaltaya. The observations/awareness of the respondents demonstrates the importance of these changes. However, it must be noted that this is an educated audience. Although, I hypothesis that local mountain communities will also have similar observations, if not, more so. This is because they are closer to the mountains and they depend directly on them for their livelihoods.

76% believed that water availability in La Paz will pose problems for society by 2100, whereas 41% agreed (or strongly agreed) that present day water availability in La Paz is currently sufficient for societal needs. Future research interviewing the respondents could help identify what factor they most attribute to this projected change: climate change, glacier recession, population increase; migration, or which factor they perceive to be the most impacting upon water availability.

A large majority of the participants, 88%, believed that the water available in 2100 will be insufficient to support La Paz's social needs. Possible solutions to future reduced water security included the promotion of water conservation (14%), better capturing/ harvesting of water (9%), improving the system of cleaning water (8%) and recycling water (5%). Other suggestions made by the participants included reforestation and the protection water sources. It is believed that increased water conservation and water use efficiency remain the most cost effective priority for supplying water (UN Israel, 2014). Williams (2000) agree that efforts at water conservation, reducing waste and improving water-efficiency are imperative, and should be supported by public education and incentive programmes for successful implementation.

Rainwater harvesting is an important option for augmenting water sources (UNFCCC, 2011), seen to be the key solution first suggested by the questionnaire respondents (Table 7.7). It is a cheap and effective method of increasing water supplies; however, it should be noted that the Bolivian Andes experience a dry season for half of the year and therefore could potentially only increase water stores during the wet season. The construction of dams to create reservoirs has also commonly been the response to growing demands for water for hydropower, irrigation, potable supplies (UN, 2006). Dams can take on the role similar to that of natural hydrological storage such as ice glaciers, especially during the dry season. Thus dams can help to increase water storage for the city, pertintent with current and projected glacier recession. However, increased water storage does not help to address the actual problem of reduced water supplies, as one respondent pointed out (R11): *"I am not sure if the construction of reservoirs and other measures will be the solution"*. Furthermore, climate change and population scenarios need to be studied for better water resource management, something which this PhD has also discovered, that we need more information on current water availability, hydrological stores and water usage, and to really accommodate for changes in population as well as changes in climate.

The aim for adaptation should be to maximize available water supplies before attempting to explore and expand new supplies at high costs (Williams, 2000). Therefore, improving infrastructure should be an essential strategy for the Bolivian government as up to ~40% of the water is lost before it gets to the tap in El Alto due to poor infrastructure (SEI, 2013). Yet 'infrastructure improvements' only received 5% of the suggestions from the questionnaire participants. Williams (2000) stress the importance of prioritising improvements to infrastructure. In cities like El Alto and La Paz, water resources are limited and wastage from leaks is high, so water conservation initiatives involving metering and leak detection work by water agencies should be implemented. This research has shown that despite the level of education and awareness of these respondents, they were unaware or apparently did not make the link between water resource issues (current and future) and poor infrastructure.

Yet it is thought that reduction of water losses in urban and agricultural areas has the best potential for addressing water security in the short term (SEI, 2013). This demonstrates that policy research and advice needs to be more obvious about the importance of improving infrastructure.

7.5 Conclusions

Based on the data provided throughout the questionnaire, the respondents were of an academic and educated background, with experience in the topics of climate change and water resources in Bolivia. Despite this knowledgeable audience, over half (59%) had never heard of rock glaciers before, highlighting the importance of my work and the need to share scientific research with the government, NGO's and public in the countries as well as the scientific community through international journals.

Glacier recession is viewed as the most common impact of climate change in the Bolivian Andes, and it is also the most common evidence of climate change witnessed by residents of La Paz. Over three quarters of the respondents agreed that water availability in La Paz will pose problems for society by 2100 and will be insufficient for societal needs. Suggested solutions included promotion of water conservation, increased storage and better capturing/ harvesting of water; however the lack of frequency for improved infrastructure demonstrates that the importance of improving infrastructure in La Paz and El Alto is significantly underestimated. Furthermore, many solutions are concerned with limiting the use/wastage of existing water rather than addressing the bigger issue of a growing demand on dwindling water resources.

Chapter 8 : Discussion

This PhD thesis has detailed several new contributions to scientific knowledge about Bolivian rock glaciers and water supply, namely establishing: i) the first rock glacier inventory for the Bolivian Andes; ii) the first estimates of the water held in Bolivian rock glaciers and ice glaciers; iii) the first assessment of the hydrological importance of Bolivian rock glaciers; and iv) the first modelling of the future Bolivian cryospheric extents with projected climate change. The research process has highlighted some significant gaps in our knowledge of the Andean cryosphere and identified key data that are still needed for effective water resource management and planning. This chapter provides a summary of key discussions from this thesis based upon the aims and research questions. The research in the Bolivian Andes summarised here employs an interdisciplinary approach, using the methods and approaches from physical and social sciences. Additionally, this research was conducted in partnership with two NGOs enabling direct end-user application of the results. This chapter highlights the key research themes, discusses the research findings in relation to other studies, and identifies future areas for research.

8.1 PhD aims

The overarching aim of the PhD stated in section 1.4 (p. 27) was: *to extend scientific knowledge and understanding on the Andean cryosphere and, more specifically, to increase knowledge of the frozen store of water in rock glaciers in the arid mountains of Bolivia.* This aim was achieved through primary research carried out using remotely sensed data, climate models and fieldwork, the publication of scientific journal articles (Rangecroft et al., 2013, 2014a, b), knowledge exchange with project partners, delivery of results at a conference in La Paz, and the production of a report for Agua Sustentable and Oxfam. These deliverables allowed the research gained from this PhD to be accessible to the scientific community, NGOs working on the topic and the study area, and the general public.

The following section discusses how the research has addressed the aims of the thesis (Section 1.4) and reflects on the research questions (Section 1.5). The aims are summarised here:

- To produce the first rock glacier inventory for the Bolivian Andes;
- To understand the importance of rock glaciers as a water source for Bolivia;
- To analyse the relationship between rock glaciers and the present 0 °C isotherm;
- To explore the implication of future warming on permafrost extent and active rock glaciers in the Bolivian Andes;
- To achieve knowledge transfer between scientific work and Bolivian communities.

8.2 Discussion of results

8.2.1 What is a rock glacier?

Although there is limited literature on rock glaciers from the Bolivian Andes, it is important to establish what is considered to be a rock glacier in the region, given the research and knowledge gained in this thesis. This is a fundamental question underpinning the established research questions (section 1.5) as it crucial for the identification and calculations for rock glacier water stores. From existing published literature, definitions of rock glaciers tend to converge on these features being cold climate landforms which are an accumulation of ice-rock debris with varied ice content which act as important water reservoirs in arid regions. These mesoscale landforms of angular rock debris have distinct ridge and furrow surface patterns and a core of ice or ice-cemented fine clasts (Potter, 1972; Degenhardt and Giardino, 2003; Brenning, 2005a). In this thesis active and relict rock glaciers have been identified across the Bolivian Andes (94 in total) using remote sensing and field observations. It has also been observed that there are a number of substantial, well-developed rock glaciers further south along the Western Cordillera (e.g. Fig. 2.16) where glaciers are absent and precipitation is minimal (Fig. 3.1). From this research it is clear that the rock glaciers of the Bolivian Andes meet this description, however, their temperature requirements appear to be different to those of the European Alps literature.

For the rock glacier inventory these rock glaciers have been identified from remote sensing image data using expert photomorphic mapping approaches, drawing on an accumulated knowledge of rock glacier surface topographic features consisting of ridges and furrows (Paul et al., 2003; Kääb and Weber, 2004). Due to their debris cover originating from surrounding valley walls, rock glaciers are not spectrally different from their surroundings (Shukla et al., 2010; Chapter 6) making it difficult to easily identify them, especially as they can be misidentified as rock avalanches, protalus lobates, and protalus ramparts (Whalley and Azizi, 2003). However, it is the surface ridges and furrows associated with rock glacier movement, as well as the characteristic shape, that aids manual identification from RS data and in the field. Field work was essential for validation of the RS approach, and it was an extremely important process to improve the understanding of what features the RS data related to. Given the difficulty of access to field sites in the Bolivian Andes due to terrain, altitude and remoteness, field work was limited to 13 sites which allowed a range of typologies (active, relict) in different regions (Cordillera Real, Sajama, Western Cordillera) to be visited and validated (Fig. 3.14; Table 3.11; Table 3.12).

The research presented in this thesis suggests that Bolivian rock glaciers have different climatic parameters defining their ‘habitat’ or geomorphic setting than those studied in Europe. In the European Alps active rock glaciers exist where MAAT is less than -1/-2 °C (Barsch, 1996; Baroni et al., 2004). However, in the Bolivian

Andes, where elevations are much higher, the climate is drier and the geology is different, rock glaciers exist at temperatures closer to the 0 °C isotherm (Fig. 5.3a). Similar climate constraints were observed in the Chilean Andes by Brenning (2005a). From the rock glacier inventory presented in this thesis an average rock glacier MAAT of +0.07 °C was found across the Bolivian Andes (Table 5.4; Figure 5.3a). However, it was found that the Cordillera Real hosted rock glaciers at warmer temperatures than elsewhere in the Bolivian Andes, with an average MAAT of +1.7 °C (Fig. 5.3a) with all rock glaciers in the region found at elevations with MAATs positive of 0 °C. This could be due to a number of local topographic factors such as topographic shading or proximity to glacial ice bodies, although testing these relationships was outside the scope of this thesis. Massive-ice bodies such as glaciers are known to act as sources of cold air (Brenning, 2005a) producing locally lower temperatures and preserving ice in otherwise climatically unfavourable locations, thus permitting permafrost and rock glaciers to exist at temperatures higher than the MAAT 0 °C. A large number of the rock glaciers in the Cordillera Real are located in close proximity to glaciers. However, this close proximity to glaciers could also have implications about rock glacier origin, with close proximity to glaciers implying a glacial origin, and therefore a higher percentage of ice content, with implications on water equivalent (section 8.2.2).

8.2.2 Rock glacier origins

Determining the origins of rock glaciers has not be addressed directly by this research due to the lack of data required to classify for this, however rock glacier origin will significantly determine the ice content of the rock glacier, and therefore its importance as a hydrological store. As shown in Chapter 2 (section 2.4.2), rock glaciers are usually considered to have either a glacial or permafrost origin (glacial-derived or talus-derived, respectfully) (Humlum, 2000). It has been shown that a glacial-derived rock glacier with an ice-core will contain a much higher percentage of ice to debris content than a talus-derived rock glacier (Krainer and Ribis, 2012). A talus-derived rock glacier will have internal structure which is more mixed; a debris and ice mixture also known as "ice-cement" (Whalley and Azizi, 2003).

This research has assumed that the most appropriate rock glacier model for the Bolivian Andes is of the permafrost variety, as it is the common view amongst the recent work in the Andes and in the Alps, it provided a simple analysis and ice content could be estimated from the literature. However, it does not take into account that some rock glaciers may be of glacial origin (the glacier-ice model) which would give a much higher volume of ice in these bodies to that shown in Chapter 4 and a different relationship to the 0 °C isotherm. This research used an assumption of 40 – 60% ice content for all active rock glaciers (Chapter 4). However, if the origin of a rock glacier can be established and classify into either glacial-derived, with a higher ice content, or talus-derived, with a lower ice content, a better assumption of its ice content and estimate water equivalence can be made accordingly. This would therefore help to reduce the large range of uncertainty of ice content and water equivalence (Table 4.3; Table 4.7), and is recommended as an area for future research.

One key characteristic that could help to determine rock glacier origin is rock glacier proximity to existing glaciers or glacial landforms, as this implies a glacial genesis. Based upon this, a number of rock glaciers in the Cordillera Real might be considered to be glacial-derived due to their close proximity to existing glaciers and landforms indicative of glacial retreat such as terminal moraines. While in this research rock glaciers of the Cordillera Real were estimated to contained between 0.007 – 0.0176 km^3 of water (0.01 km^3 average) (Table 4.7; Table 4.8), if a glacial-origin was established for these rock glaciers, these estimations would be higher.

To investigate the internal composition and structure of the rock glacier, and thus classify its origin, direct measurements are necessary. For example, Degenhardt Jr and Giardino (2003) demonstrated using GPR that the Yankee Boy basin rock glacier in Colorado was formed by permafrost processes rather than by covering a mass of remnant glacier ice. Increased understanding of the internal structure of a sample of talus-derived and glacial-derived rock glaciers would allow for a scaled up assessment across the region, although would require a significant field program. However, field measurements such as geophysical surveys and test pits or boreholes are essential for this step. Furthermore, the origin of rock glaciers remains a contested topic in rock glacier research and considerable disagreements exist in the literature regarding the models of permafrost genesis, a discussion outlined in Chapter 2 (section 2.4.2).

8.2.3 Rock glacier inventory and its implications

94 rock glaciers were mapped in the first rock glacier inventory for the Bolivian Andes (Rangecroft et al., 2014b), of which 54 were classified as active (containing ice). Bolivian rock glacier average length was 500 m (± 30 m) (Section 3.3.3) with an average area of 0.12 km^2 (Section 3.3.3). Bolivian rock glaciers were found to be of similar size to those of the Chilean Andes (Brenning, 2005a) and those in recent European rock glacier inventories (Krainer and Ribis, 2012; Kellerer-Pirklbauer et al., 2012) (Table 3.4). Bolivian rock glaciers covered 11 km^2 of the Bolivian Andes, of which active rock glaciers covered 7 km^2. However, the total coverage of active rock glaciers in Bolivia was much less than that of the Chilean Andes (Brenning, 2005a), Argentinean Andes (38 km^2 in the Valles Calchaquíes region) (Falaschi et al., 2014), American Rockies (70 km^2 of the San Juan mountains, Colorado) (Brenning et al., 2007) and the European Alps (167.2 km^2 in the Tyrolean Alps) (Krainer and Ribis, 2012) (Table 3.4).

One factor explaining this difference in rock glacier abundance between the Bolivian and the Chilean/Argentinean Andes could be climate. From modelling of the 0 °C isotherm across South America (Fig. 5.7, Chapter 5), it is clear that permafrost conditions are more prevalent in the Chilean/Argentinean Andes between 27° and 35° S compared to the Bolivian Andes (Chapter 5). This difference in rock glacier abundance also explains why rock glacier water equivalences were found to be lower than those of the Chilean Andes (Azócar and Brenning, 2010) and the Argentinean Andes (Perucca and Esper Angillieri, 2011) (Chapter 4, section 4.4.1). Rock glaciers of the Bolivian Andes were estimated to contain between 0.05 and 0.14 km^3 of water (Table 4.7) and the rock glacier to ice glacier water equivalence ratio for the Bolivian Andes was estimated to be ~1:40 (Table 4.8).

It can be assumed that the hydrological importance of rock glaciers in the Sajama region estimated here is an underestimation because, in line with observed glacial recession, it is expected that glacier extent is now less than that estimated by Jordan (1998). 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). This demonstrates a topic for further research, with importance on current and future water supplies.

The large range in estimated rock glacier water equivalence established here in this research stems from using varying ice contents and two methods of estimating thickness (Table 4.7), producing what can be considered as an upper and lower estimate of water content. As discussed, the origin of the rock glacier would act as a predictor of ice content. However, these results are limited by a lack of field data on permafrost thickness and ice content of Bolivian rock glaciers. Overall, this demonstrates the importance of gaining field data to establish the ice thickness, ice content and internal structure, to allow for a more accurate estimation of water equivalence and rock glacier origin.

Active rock glaciers in Sajama were located at statistically higher elevations than in the other regions (Fig. 3.7). Active rock glaciers had an average MAF of ~4980 m a.s.l. Relict rock glaciers had an average MAF of 4870 m a.s.l. (Table 3.2). The present lower boundary of permafrost was estimated to be 4,700 m in the Bolivian Andes using the lowest elevation of active rock glaciers as a proxy. Using average active rock glacier MAFs as a proxy, it is estimated that the 0 °C isotherm lies at 4,900 – 5,000 m for the Bolivian Andes (Section 3.4). This suggested elevation of the 0 °C isotherm for the Bolivian Andes (4,900 – 5,000 m) is in agreement with the limited literature that estimates this. For example, Francou *et al.* (2001) estimated the 0 °C isotherm of the Cordillera Real to be at 4,900m. Rock glaciers are known to exist between the 0 °C isotherm and the ice glacier ELA (Payne, 1998; Milana and Maturano, 1999). For the Cordillera Real it is estimated that the ELA lies between 5,200 – 5,400m depending on aspect (Ramirez et al., 2001). Indeed, no rock glaciers were found higher than 5,400 m.

This research shows that there is a strong link between rock glaciers and the MAAT 0 °C isotherm. However, the Cordillera Real shows rock glaciers with an MAAT of +1.7 °C, with highest MAATs of +3 °C. Usually rock glaciers mark the permafrost limit, however if rock glaciers exist at elevated temperatures in the Cordillera Real because of local factors (topography, proximity of ice bodies, insolation shading), it implies that the permafrost limits are actually overestimated through the use of rock glaciers in this region. This has possibly happened with this research given the mapping of the 0 °C MAAT in Figure 5.2. Here, active rock glaciers are all located at lower (warmer MAAT) sites than the present 0 °C MAAT, shown by their locations in Figure 5.2 being mapped close to, but mainly outside of the MAAT permafrost extents.

8.2.4 Mapping rock glaciers

This research discovered that manual mapping is still the most effective method of rock glacier identification. Freely available satellite data through Google Earth data proved to be highly valuable to this research due to its fine spatial resolution, which was similar to most RS data which was considered for purchasing (IKONOS, SPOT, RapidEye), at no cost or restrictions on data extents. This was specifically important for working with NGO's such as Agua Sustentable, to be able to utilise freely available and licence free data. Given the reliance on manual mapping, Google Earth remains the most suitable data choice for rock glacier identification and inventory building, especially for such large regions as the Bolivian Andes. The increasing availability and access of other fine resolution RS data that would allow for rock glacier monitoring (and therefore, identification of active rock glaciers), such as InSAR could help improve rock glacier research significantly by providing an automated method to identifying active rock glaciers through assessment of their movement.

Rock glaciers were found to have a textural/spatial pattern different from their surroundings, but with no consistent signal across different rock glaciers (Fig. 6.17 – 6.24) which was probably due to differences in ice content, rock debris, slope and movement rate between rock glaciers and sites. Further research is needed to investigate automated identification and classification of rock glaciers from RS data. There may be methods emerging over the next few years where filters can be applied to help automatically or semi-automatically identify rock glaciers. However, these would need to be applied with local knowledge and data to help with accuracy, and then the method should be assessed for its success rate. To take this research further a comparison between the Gabor filter used by Brenning (2012a) and the semiovariogram research explored in Chapter 6 is necessary.

Using 'habitat' suitability mapping, areas most likely to host rock glaciers were mapped from freely accessible satellite data (ASTER DEM, WorldClim climate data and Google Earth) (Chapter 6). The key characteristics used here were elevation, aspect and MAAT; however, due to differences in spatial resolution, rock glacier habitat was more successfully identified using just the terrain attributes of elevation and aspect. The potential which this method has to reduce significantly the extent of manual analysis has huge benefits, especially considering the input of free satellite data. The ecological concept of habitat suitability models has not been used to investigate permafrost features before, and given the results of this research, it appears to be an approach which could be developed further. However, the habitat modelling could be expanded with finer resolution DEMs and DTMs and further knowledge of rock glacier origin. This would also allow for improved information on rock glacier characteristics and texture analysis. In conclusion to this thesis, automation of rock glacier identification is still very difficult; however with increasing technology and access to improved RS data, the potential to automatically identify rock glaciers and their suitable habitats could increase accordingly.

8.2.5 Rock glaciers and projected climate change

Using a multi-model ensemble, projected temperature changes for the Bolivian Andes (> 3,500 m a.s.l.) are estimated to range between 2.7 - 3.2 °C by 2050 and 4.2 – 4.9 °C by 2080 (Table 5.3; Fig. 5.5). These projected temperature increases are in agreement with those projected for Bolivia by Mitchell and Hume (2000) by the end of the 21st century, which range from 3.5 - 5.9 °C. The projections for the Bolivian Andes from this research lie at the higher end of this range.

This warming is projected to decrease permafrost extent by up to 95% by 2050 and 99% by 2080 from present day extents (Fig 5.2). Research modelling 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 impacts of climate change on mountain permafrost are very limited (Bonnaventure and Lewkowicz, 2011). This research addresses the current lack of knowledge through the modelling of permafrost extents in the Bolivian Andes in response to projected climate change using future projections of temperature based on a downscaled multi-model ensemble of seven IPCC GCMs (driven by the A1B emissions scenario) (Chapter 5).

Accordingly, it is estimated that by 2050 34% of Bolivian active rock glaciers will remain within MAATs that are suggested to sustain active status (< +2 °C) (Table

5.2; Fig. 5.3b). By 2080 only one rock glacier is modelled to remain within this MAAT threshold (Table 5.2; Fig. 5.3b). However, it is important to remember that rock glaciers respond slowly to changes in climate (on decadal or centennial scales), and therefore the responses modelled here will lag climate forcing. Nevertheless, the key message from the results remains that permafrost in rock glaciers (and elsewhere) is vulnerable to continued warming.

8.3 Implications of the results of the thesis

The research conducted during the course of this PhD programme has broad application within Bolivian NGOs concerned with water security (e.g. Agua Sustentable, Oxfam) and has utility within science as it addresses gaps of knowledge in the Bolivian cryosphere for water resource management. These results are important for Agua Sustentable as they are currently conducting research programmes across the Bolivian Andes, and these include mapping current water resources, assessing the impacts of climate change on these and making future climate projections for mitigation and adaptation. It is known that successful adaptation to climate change and water availability will require the development of links between the knowledge systems of producers and scientists (Valdivia et al., 2013), and this emphasises the importance of scientists working directly with local NGOs and local populations, and thus the importance of this PhD. As Xu *et al.* (2009) have argued, challenges for water resource management and climate change adaptation should be addressed through increased regional collaboration in scientific research and policy making.

8.3.1 Validation of impact

Firstly, it can be seen that this research was important due to the lack of existing knowledge of rock glaciers in the Bolivian Andes and understanding their importance on water supplies. This was shown by the lack of previous scientific data and publications (Rangecroft et al., 2013) and reinforced by the results from the questionnaire: over half (59%) of the respondents had never heard of rock glaciers before, with only 15% of the respondents agreeing that they were knowledgeable about rock glaciers in Bolivia (Chapter 7). These data help justify the need for this PhD research and the importance of communicating it to policymakers and other groups. Furthermore, the comments and questions made after my presentation at the conference (27/05/14) illustrated that this information was not previously known but it was regarded as important:

> *“Thank you for doing the investigation, because we didn’t know about this topic before, and it is important for our future planning to know about this. Your research has brought to light how finite this resource is”*
>
> (Question 3 at the conference)

Not only has this research contributed to existing knowledge of the Bolivian water stores, it has also produced model projections and assessed the implications of a forecasted warming climate in the Bolivian Andes. In particular, this research has shown the vulnerability of water security in La Paz and the Andes, which the audience of the conference detected:

> *“What this research has exposed is worrying*”
>
> (Question 1 at the conference)

Therefore, it is important to explore further the potential impacts of reduced water security, given the projections for this in the Bolivian Andes and this will support policy making and adaptation (Marengo et al., 2010; Viviroli et al., 2011; Rangecroft et al., 2013).

8.4 Reduced water security

The simplified network diagram (Fig. 2.11, Chapter 2) of the four main drivers of reduced water availability in the Bolivian Andes (glacier recession, climate change, poor infrastructure and population increase) illustrates some of the main impacts of projected water scarcity (Fig. 2.11). Buytaert and De Bièvre (2012) acknowledge that managing water resources in a dynamic society is challenging, and climate change will add to this complexity. Although this PhD focuses on climate change and the Bolivian Andes, it is important to remember that these other pressures (population increase, poor infrastructure) will affect water supply and demand, and thus water availability (Fig. 2.11). One of the questions from the conference stressed this:

> *"Is climate change/temperature increase the most important factor affecting water supplies?"*
>
> (Question 4 at the conference)

Consequently, the following sections discuss the importance of population increase and poor infrastructure on water availability, as well as climate change. Furthermore, it is important to acknowledge the stress on water security that each adds independently. For example, an increasing population places increased stress on water supplies through increasing demand for water without the added interaction of climate change and glacier melt affecting water availability.

8.4.1 Climate change

Climate change is expected to have a major impact on water resources worldwide (Buytaert and De Bièvre, 2012) both directly and indirectly. Buytaert and De Bièvre (2012) outline the two-fold impact of climate change on water availability: 1) changes in precipitation will directly affect water availability through changes in water fluxes: 2) increases in temperature will impact evapotranspiration rates and reduce the recharge of groundwater resources, indirectly affecting water availability. However, for the Bolivian Andes, this is likely to be four-fold as: 3) changes in climate affect glaciers which impacts water availability and 4) climate change can lead to climate change migration, thus increasing demand on specific water supplies. The changes that have already been observed in the Bolivian Andes and further changes that are projected can be used as an exemplar for other mountain regions.

8.4.2 Population increase

It is projected that population growth will be the main driver of increased stress on water resources in major Andean cities, a pressure greater than climate change (Buytaert and De Bièvre, 2012). Population growth, which includes changes with urbanisation and migration, is expected to increase water demand by up to 50% by 2050 in Andean cities (Rossing 2010; Buytaert and De Bièvre, 2012), exacerbating the problems of poverty and hunger as competition over limited resources is increased (Akin, 2012). Subsequently, Buytaert and De Bièvre (2012) argue that demographic changes should be the priority for local policy making.

8.4.3 Poor infrastructure

The impact of poor infrastructure on water supply provision is a factor which is often overlooked in the literature and yet is where some of the biggest changes can be made for improving existing water supplies. It is estimated that El Alto's water system loses ~40% of its water through inadequate water infrastructure (Farley and Liemberger, 2005; Lee and Schwab, 2005; SEI, 2013). Thus, reduction of water losses in urban areas has the best potential for increasing water resilience in the short term (SEI, 2013) through repairing leaking pipes, reducing wastage, and rehabilitating and updating existing water facilities. However, these changes are an expensive, time-consuming endeavour (Hays, 2011) that can be impeded by rapid urbanisation and need to be supported by an effective implementation of governance policies and democratic involvement (Mejia, 2012). Improvements to the existing poor infrastructure could make a large impact to water availability and the importance of this should be better highlighted as the ability to maximise existing water supplies through infrastructure improvements was not fully understood by the respondents to the questionnaire.

8.4.4 Impacts of reduced water security

The interaction between these drivers (climate change, population increase, poor infrastructure) will reduce water security in the Bolivian Andes. Reduced water availability will affect agriculture, drinking water and power generation, adding stresses on livelihoods, which in turn can contribute towards migration and further increase in water demands in concentrated regions (Fig. 2.11). Future water conflicts are predicted to be more likely with decreased water security (IPCC, 2007a; Vuille, 2007), especially in glacier-fed areas during the dry season (Painter, 2007). Increased conflicts over water have already been observed in the Middle East and the Nile Basin (FAO, 2011).

Moreover, these discussions do not consider a number of the implications of reduced water availability, such as reduced food security and reduced HEP generation potential (Fig. 2.11). HEP is the major source of energy for numerous Andean cities (Bradley et al., 2006) and accounts for a third of Bolivia’s electricity production (World Bank data, 2011). La Paz depends even more so on HEP for its electricity, powered by glacier melt water mainly from two glacier ranges of the Cordillera Real, Zongo valley and Charquiri (Painter, 2007) (Fig. 2.7, Chapter 2). Given the importance of glacier melt for HEP, it is necessary to produce forecasts of future meltwater.

It is anticipated that the volume of melt water will initially increase with the recession of glaciers (Immerzeel et al., 2013), and from the discussion at the conference this is currently being observed by the Bolivian population (Chapter 7). However, once glaciers have disappeared, the lack of glacier melt water will have a negative impact on HEP production in Bolivia (Fig. 2.11), and this will be magnified by likely increases in river sediment load characteristic of rivers draining rapidly deglaciating catchments (Vuille, 2013). Furthermore, an increasing population will create an increasing demand for energy.

Currently, renewable sources other than HEP are barely exploited in Bolivia; HEP is currently 98% of Bolivia’s installed renewable capacity (Renewable facts, 2014). Accordingly, adaptation should incorporate methods to reduce Bolivia’s dependence on HEP and investment into other renewable energies to increase resilience, these being necessary to adapt for future glacier recession and ultimate disappearance. However, this can be costly and might result in an increased dependence on fossil fuels, causing an increase in emissions (Bradley et al., 2006; Vergara, 2009).

8.5 Further research questions

This research has highlighted the need for improved data sets to improve current understanding on cryospheric water stores and their likely responses to projected climate change and implications. Given the crucial importance of water resources and the need for effective management, these gaps in knowledge can be used to direct further research and policy. 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 (Marengo et al., 2010). This will allow the anticipation of water shortages and creation of physical and political infrastructure that could help compensate for reduced water availability (Magrath, 2005). To aid this knowledge base, research is needed on various key areas, with focus on local and regional scale implementation. Listed below are the key further research areas for the Bolivian Andes needed for improve knowledge for water resource management:

- Longer and more consistent data sets on climate and water discharge to address questions about future water availability and security;
- Data on all water sources (not just glaciers) for more accurate information on water supplies and future projections;
- Data on current extents of ice glaciers in Bolivia for a comprehensive assessment of current water stocks;
- Data on glacier and rock glacier discharge are needed for an understanding of current melting and contribute to water supplies;
- Field data on ice content of Bolivian rock glaciers for improved estimates of rock glacier water equivalents;
- Improved spatial and temporal resolutions of climate projections for decision making;
- The inclusion of population increases in future scenarios for more accurate predictions on water demands;
- The inclusion of permafrost feedback processes in climate models for improved climate projections.

8.5.1 Observational data

The identification and understanding of water sources other than ice glaciers, such as permafrost, in Bolivia and data on their importance is currently very limited. Field studies investigating and quantifying ice content of Bolivian rock glaciers are still required, and could be considered essential in order to take this research further. Whilst we can make estimates based upon existing research for a similar region, ultimately, data from the specific study region is required for validation and improved accuracy. Furthermore, research and data on rock glacier and ice glacier discharge are crucial for improving scientific understanding of local cryospheric reserves and their importance to the hydrological cycle and for future water resources management. It is also clear from this thesis that more recent data on ice glaciers across the whole of the Bolivian Andes are needed, including information on their thickness and ice content and water flow. Casassa et al. (2007) stated that very little is known about ice volumetric changes in the Andes except for frontal and areal changes. Whilst a limited number of publications have sought to address this (e.g. Soruco et al., 2009), one noticeable data set that remains missing is a full assessment of the current extent of Bolivian ice glaciers. Focus has remained on the Cordillera Real; however the Western Cordillera and Cordillera Apolobamba need to be assessed too. This is prohibiting a more accurate hydrological assessment of rock glacier importance in comparison to existing ice glaciers (Chapter 4).

For Bolivia, one of the first steps towards improving water management is to gather data on all water sources contributing to the mountain hydrological cycle in order to increase the accuracy of water availability projections as good decision making and policy development are dependent upon good information (WHO, 2012). 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 is known to limit the effectiveness of adaptation (IPCC, 2007b) due to the lack of information upon which to base modelling and projections. Therefore, longer and more consistent time series of climate data are needed for improved models and projections. The data currently available from the Bolivian national meteorological service (SENAMHI) are extremely broken and unreliable. 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 standardised collection of basic data on water levels and flow. Improvements can also be made by finding a better way to collate existing records.

8.5.2 Climate projections

This research uses climate projections to provide information regarding future climates and their possible implications. However, these results could be investigated further by using finer spatial resolution data, different time scales, different emission scenarios, more climate parameters and the inclusion of more feedback loops. Whilst these arguments are discussed below, it is important to note that current research is limited by the availability of these data.

A major limiting factor for water resource planning and management is the current spatial resolution of data used for climate modelling. Climate models run at too coarse a resolution produce a smoothing out of local precipitation and temperature gradients which are important for modelling many local hydrology processes (Buytaert et al., 2010; Rangecroft et al., 2013). Therefore, the downscaling of climate projections is necessary to provide data needed for water resource management (Vergara, 2009; Buytaert et al., 2010; Marengo et al., 2010). This PhD begins to address this requirement by analysing downscaled outputs for the Bolivian Andes.

However, in this research only the IPCC A1B emissions scenario was used. This is a medium emissions scenario that represents a future world of rapid economic and population growth, peaking mid-century with balanced emphasis on all energy sources (IPCC, 2000) (Fig. 8.1). Understandably, the magnitude of temperature results depends on the emissions scenario used (Loarie et al. 2009), therefore, future research should explore how results vary with different emissions scenarios. Furthermore, future research should look to use CMIP5 models when the data is available.

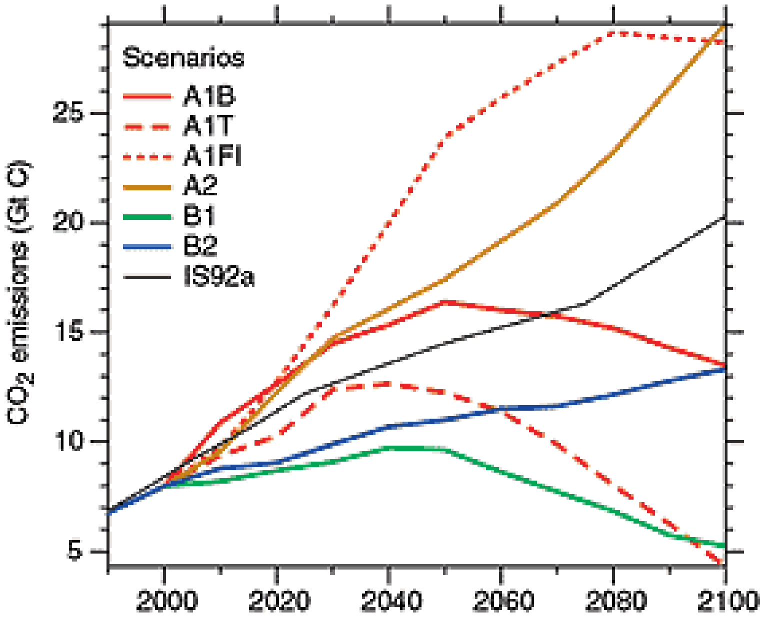


Figure 8.1 IPCC SRES Simulated Carbon Dioxide Emissions from 1990 to 2100 (IPCC 2007a).

Furthermore, Thibeault *et al.* (2010) argue that it is climate change projections for the next 20 to 30 years that are most relevant for decision makers and planners who are developing adaptation strategies now. Therefore, regional climate projections and the modelled implications are needed for the imminent decades, as well as the long term future.

Additionally, this climate modelling only used one climate parameter, temperature. This is because there is a clear consensus regarding the direction of projected temperature change (IPCC, 2013). However, other climatic changes, such as the spatial and temporal distribution of precipitation (including snowfall), are likely to influence permafrost extent and could affect rock glacier development and persistence (Haeberli et al., 1993). Yet precipitation projections were not included in this analysis due to the large uncertainties surrounding the direction and magnitude of future change (IPCC, 2013). Therefore, when uncertainties can be reduced, future research should aim to include precipitation projections as well as temperature changes. Furthermore, given the importance of population growth on water demand it is important to focus on improving scenarios and water availability modelling including climate change and population growth inputs.

Permafrost changes and feedbacks are currently missing from climate projection models (Schaefer et al., 2012). It is acknowledged that permafrost carbon feedback is not incorporated into the newest IPCC 5th Assessment Report, yet permafrost is a large carbon and methane sink, and therefore, changes to permafrost extent will have implications on greenhouse gas emissions and subsequent warming. Warming of permafrost accelerates climate warming through increased greenhouse gas emissions, known as a positive feedback loop. Permafrost is estimated to cover 24% of the Northern Hemisphere land (Schaefer et al., 2012), storing ~1.5 trillion tons of carbon (twice the amount of carbon currently in the atmosphere). Decreases in the extent of permafrost have been widely observed (IPCC, 2014) and the IPCC (2013) has high confidence that permafrost temperatures have increased in most regions since the early 1980s. Yet, given the projected thawing of permafrost with forecasted temperature increase, it can be assumed that the climate projections from the IPCC 5th Assessment Report are underestimates because the models did not include the permafrost carbon feedback (Schaefer et al., 2012).

8.6 Potential Solutions

Although this research has identified some water sources that were previously unknown and unaccounted for, the reality of future pressures and changes to water availability appear to be negative. Furthermore, although rock glaciers are long-term stores of frozen water, the water equivalent stored in the rock glaciers calculated in this research does not represent water readily available for release for human consumption. Whilst this final section will discuss some of the key actions for adaptation and mitigation, the underlying message from this research is that these strategies need to start sooner rather than later.

Ultimately, the root of the problem of reduced water security needs to be addressed. That is, the imbalance between reduced water supplies and increasing demands (Fig. 2.10, Chapter 2). For vulnerable countries such as Bolivia, climate change is already impacting the environment and livelihoods. However, climate change is not a country specific problem; it is a global issue and thus requires a global solution (EU insight, 2009; Longden et al., 2012). Adaptation will be necessary to address impacts resulting from the warming which is already unavoidable due to past emissions (IPCC, 2007a), without the added pressures of population increase and the associated stresses of reduced water security, reduced food security and increased demand for energy.

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 which restrict adaptation (Magrath, 2005; IPCC, 2007b; Viviroli et al., 2011) especially for developing countries (UNFCCC, 2007). A large range of adaptive responses to water security suggested by the IPCC (2007b) includes technological (e.g. dams, infrastructure), policy (e.g. planning regulations), managerial (e.g. altered farming practices), and behavioural (e.g. altered food choices, changes in water use and waste) adaptations.

Technological adaptation will help to increase water storage and supplies. Increasing ‘natural’ storage through the creation of dams, reservoirs, water tanks etc, will help replace the lost hydrological buffers of the ice glaciers. Infrastructure change will significantly reduce the water lost from the mountains to the tap, increasing the amount of water available. Behavioural adaptation could help to decrease the demand on water supplies. This can include promoting water conservation and changing the behaviour in domestic and industrial contexts. This will require significant changes in agriculture, industry and lifestyle (Barnett et al., 2005). Agriculture is the largest user of water globally and in Bolivia (~70%) (World Bank, 2010), and therefore is a key sector for making changes. Furthermore, agriculture production will increase with population increase; therefore reductions in the water use of this sector will be beneficial. It is a combination of these changes that is required for the most resilient solution to climate change (IIED, 2013). For Bolivia, a holistic and country-specific approach can be recommended. For example, the IIED (2013) suggest four approaches in the Andes that are perceived as highly resilient due to their diversity: 1) climate proofing: 2) water storage in the wet season: 3) water management and water conservation: 4) research, monitoring and risk management.

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 ranging from engineering, climate, population, politics, economics, ecology, farming, the community and local cultures (Viviroli et al., 2011) and local level resource management. Successful 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 to understand their water resources and usage and therefore manage them both directly (ICE, 2011). Working at 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 Andean communities and self-run through community organisation 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) potentially decreasing the risk of conflict.

The relevance of this research particularly in highlighting the issues and potential impacts has been acknowledged by the Bolivian conference attendees and their desire to use the results as evidence in arguing for action with the government and policy makers. The vulnerability and sensitivity of the Bolivian Andes has produced an early warning ecosystem for mountain regions worldwide. Adaption to climate change and reduced water security is important, especially given the sensitivity and vulnerability of the Bolivian Andean population. However, this does not address the main pressures of reduced water availability identified in this research. Action is needed to address anthropogenic climate change, population pressures and poor infrastructure for a long term solution to reduce the pressures on water security in arid regions such as the Bolivian Andes.

Chapter 9 : Conclusions

Rock glaciers distribution, characteristics and water content have not been explored in the Bolivian Andes before. This lack of data and knowledge was subsequently addressed through the publication of scientific manuscripts, knowledge exchange with the project partners and the delivery of results at a conference in La Paz. This research identified, mapped and assessed these features in the Bolivian Andes, with focus on their hydrological importance and the implications of a projected warmer climate on rock glaciers and permafrost. This research linked the results and knowledge found here with the implications on future water resources in the Bolivian Andes.

Across the Bolivian Andes 94 rock glaciers were identified, of which 54 were classified active, containing an estimated 0.05 and 0.14 km^3 of water. This coverage and estimated water store was seen to be much smaller than that of the Chilean and Argentinean Andes. The limited distribution of areas across the Bolivian Andes with MAATs below 0 °C could explain the difference observed in rock glacier abundance. Overall, it can be seen that rock glaciers in the Bolivian Andes are small stores of frozen water unequally distributed along the mountain ranges, where they potentially act as local sources of water in the most arid, ice-free regions along the Cordillera Occidental (19° - 22° S). However, in regions such as the Cordillera Real where populations greatly rely on the cryosphere for water supplies to La Paz and El Alto, ice glaciers still dominate as water stores. This rock glacier inventory was a fundamental step in assessing the hydrological importance of rock glaciers in the Bolivian Andes and modelling of permafrost extent and decrease with projected temperature increase.

Using the 0 °C isotherm as a proxy for permafrost extent, modelling of current and future permafrost extent and rock glacier activity projected a major loss in permafrost extent. Results suggest that by 2050 there will be a 95% loss and by 2080 a 99% loss from present day extent. This represents a loss in the Bolivian cryosphere, including ice glaciers, permafrost and rock glaciers. Although, it can be noted that rock glaciers have a longer response lag than ice glaciers to changes in climate.

Ultimately, given the estimates of water in rock glaciers in the Cordillera Real, and with a backdrop of continued glacier recession, climate change and population growth, reduced water security and availability are projected for La Paz and its surrounding communities. This research has shown that despite the literature emphasizing climate change negatively affecting water security, population increase is projected to be a larger stress on water availability, especially in the Bolivian Andes. This research has highlighted a number of sections for further work with the aim of improving data for water resource management. The changes in climate, glacier recession and water security being felt in the Bolivian Andes are a sign of future realities for mountain regions worldwide.

References

Aggarwal, S. 2003. Principles of Remote Sensing. In *Satellite Remote Sensing and GIS Applications in Agricultural Meteorology*. (eds) Sivakumar, M. V. K., Roy, P. S., Harmsen, K. and Saha, S. K. Proceedings of a training workshop, 7-11 July 2003, Dehra Dun, India. AGM-8, WMO/ TD-No. 1182. pp. 23 – 38. http://www.wmo.int/pages/prog/wcp/agm/publications/AGM8_en.php

Agua Sustentable, 2011. Impact of climate change in Andean Bolivian communities that depend from tropical glaciers. http://glaciares.org.bo/illimani/publicaciones/Cartilla_CC_Ingles.pdf

Akin, J. 2012. Civil Justice in the Mountains: The Bolivian Andes. Colorado Journal of International Environmental Law and Policy, 23: 433 – 471.
http://www.colorado.edu/law/sites/default/files/AKIN%20_corrected_%20v2.pdf

Anderson, K. and Croft, H. 2009. Remote sensing of soil surface properties. *Progress in Physical Geography*, 33: 457–473.

Anderson, K. and Kuhn, N. J 2007. Variations in soil structure and reflectance during a controlled crusting experiment. *International Journal of Remote Sensing*, 29 (12): 1 - 9.

Anderson, K., Bennie, J. J., Milton, E. J., Hughes, P. D. M., Lindsay, R. and Maede, R. 2010. Combining LiDAR and IKONOS Data for Eco-Hydrological Classifcation of an Ombrotrophic Peatland. *Journal of Environmental Quality*, 39: 260 – 273.

Arbona, J. M. and Kohl, B. 2004. City profile La Paz-El Alto. *Cities*, 21 (3): 255 – 265.

Arenson, L. U. and Jakob, M. 2010. Short Communication: The Significance of Rock Glaciers in the Dry Andes – A Discussion of Azócar and Brenning (2010) and Brenning and Azócar (2010). *Permafrost and Periglacial Processes,* 21 (3): 282 – 285.

Arenson, L., Hoelzle, M. and Springman, S. 2002. Borehole Deformation Measurements and Internal Structure of Some Rock Glaciers in Switzerland. *Permafrost and Periglacial Processes,* 13: 117 – 135.

Arenson, L. U., Pastore, S., Trombotto, D., Bolling, S., Quiroz, M. A. and Ochoa, X. L. 2010. Characteristics of two Rock Glaciers in the Dry Argentinean Andes based on initial surface investigations. *Geo2010*, Calgary, http://pubs.aina.ucalgary.ca/cpc/CPC6-1501.pdf

Avian, M. and Kellerer-Pirklbauer, A. 2012. Modelling of potential permafrost distribution during the Younger Dryas, the Little Ice Age and at present in the Reisseck Mountains, Hohe Tauern Range, Austria. *Austrian Journal of Earth Sciences,* 105: 140 – 153.

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

Balaguer, A., Ruiz, L. A., Hermosilla, T. and Recio, J.A., 2010. Definition of a comprehensive set of texture semivariogram features and their evaluation for object-oriented image classification. *Computers and Geosciences* 36 (2): 231-240.

Ballagh, L. M., Parsons, M. A. and Swick, R. 2007. Visualising cryopsheric images in a virtual environment: present challenges and future implications. *Polar Record,* 43(4): 305 – 310.

Ballagh, L. M., Raup, B. H., Duerr, R. E., Khalsa, S. J. S., Helm, C., Fowler, D., Gupte, A. 2011. Representing scientific data sets in KML: Methods and challenges. *Computers and Geosciences,* 37(1): 57 – 64.

Ballou, J. 2008. Open-ended question. Encyclopedia of Survey Research Methods, 2008. SAGE Publications, p.547- 549.
http://www.uk.sagepub.com/chambliss4e/study/chapter/encyc_pdfs/4.1_Open-Ended%20Questions.pdf

Baltsavias, E., Zhang, L., Holland, D., Srivastava, P. K., Gopala Krishna, B. and Srinivasan, T. P. 2006. Extraction of geospatial information from high spatial resolution optical satellite sensors. ISPRS Technical Commission IV Symposium "Geospatial Databases for Sustainable Development", Goa, India, 27 – 30 September 2006.
http://www.isprs.org/education/PDF/GOA_David_HR_mapping_Section8.pdf

Barbosa, R. I. and Campos, C. 2011. Detection and geographical distribution of clearning areas in the savannas ('lavrado') of Roraima using Google Earth web tool. *Journal of Geography and Regional Planning*, 4(3): 122 – 136.

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

Baroni, C., Carton, A. and Seppi, R. 2004. Distribution and behaviour of rock glaciers in the Adamello-Presanella Massif (Italian Alps). *Permafrost and Periglacial processes,* 15: 243 – 259.

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. pp 1 – 4.

Barsch, D. 1996. *Rockglaciers – indicator for the present and former Geoecology in high mountain environments*. Springer, Berlin.

Becker, A. and Bugmann, H. 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.

Benn, D. and Evans, D. J. A. 1998. *Glaciers & Glaciation*. Hodder Arnold Publication, London.

Berthling, I. 2011. Beyond confusion: Rock glaciers are cryo-conditioned landforms. *Geomorphology*, 131: 98 – 106.

Bigas. H., Morris, T., Sandford, B., Adeel, Z. 2012. The Global Water Crisis: Addressing an Urgent Security Issue. Papers for the InterAction Council, 2011 – 2012. Hamilton, Canada: UNU-INWEH.

Bishop, M. P., Shroder Jr., J. F. and Ward, L. J., 1995. SPOT multispectral analysis for producing supraglacial debris-load estimates for BaturaGlacier, Pakistan. *Geocarto International*, 10: 81– 90.

Bodin, X., Rojas, F. and Brenning, A. 2010a. Status and evolution of the cryosphere in the Andes of Santiago (Chile, 33.5°S). *Geomorphology* 118: 453 – 464.

Bodin, X., Francou, B., Arnaud, Y., Fabre, D. and Wagnon, P. 2010b. State and dynamics of a tropical rock glacier on the Altiplano (Bolivia, 21.5°S),
http://www.cambioclimatico-bolivia.org/archivos/20130131171930_0.pdf

Bohling, 2005. Introduction to geostatistics and variogram analysis.
http://gismyanmar.org/geofocus/wp-content/uploads/2013/01/Variograms.pdf

Bolch, T., Kamp, U. and Olsenholler, J. 2005. Using ASTER and SRTM DEMs for studying geomorphology and glaciation in high mountain areas. New Strategies for European Remote Sensing, Oluić (ed). Millpress, Rotterdam. ISBN 90 5966 003 X

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

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

Bonnaventure, P. P. and Lewkowicz, A. G. 2011. Modelling climate change effects on the spatial distribution of mountain permafrost at three sites in northwest Canada. *Climatic Change*, 105: 293 – 312.

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

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

Brenning, A. 2005b. Climatic and geomorphological controls of rock glaciers in the Andes of Central Chile: Combining statistical modelling and field mapping. *PhD thesis.* Humboldt-Universität zu Berlin.

Brenning, A. 2008. The impact of mining on rock glaciers and glaciers: examples from central Chile. In Orlove, B. S., Wiegandt, E. and Luckman, B. (eds) *Darkening peaks: glacier retreat, science, and society*. University of California Press, Berkeley, Chapter 14: 196 – 205.

Brenning, A. 2009. Benchmarking classifiers to optimally integrate terrain analysis and multispectral remote sensing in automatic rock glacier detection. *Remote Sensing of Environment,* 113: 239 – 247.

Brenning, A. 2010. Land Cover Classification by Multisource Remote Sensing: Comparing Classifiers for Spatial Data, in Locarek-Junge, H. and Weihs, C. (eds), *Classification as a Tool for Research Studies in Classification, Data Analysis, and Knowledge Organization,* Part 3: 435 - 443.

Brenning, A. and Azócar, G. F. 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.

Brenning, A. and Trombotto, D. 2006. Logistic regression modeling of rock glacier and glacier distribution: Topographic and climatic controls in the semi-arid Andes. *Geomorphology*, 81: 141 – 154.

Brenning, A, Grasser, M. and Friend, D. A. 2007. Statistical estimation and generalized additive modeling of rock glacier distribution in the San Juan Mountains, Colorado, United States. *Journal of Geophysical Research* 112(F2), DOI: 10.1029/2006JF000528

Brenning, A., Long, S. and Fieguth, P. 2012a. Detecting rock glacier flow structures using Gabor filters and IKONOS imagery. *Remote Sensing of Environment*, 125: 227 – 237.

Brenning, A., Peña, M. A., Long, S. and Soliman, A. 2012b. Thermal remote sensing of ice-debris landforms using ASTER: an example from the Chilean Andes. *The Cryosphere*, 6: 367 – 382.

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

Buchroithner, M. F. 1995. Problems of mountain hazard mapping using spaceborne remote sensing techniques. *Advances in Space Research,* 15 (11): 57 – 66.

Bucki, A. K., Echelmeyer, K. A. and MacInnes, S. 2004. The thickness and internal structure of Fireweed rock glacier, Alaska, U.S.A., as determined by geophysical methods. *Journal of Glaciology*, 50 (168): 67 – 75.

Burger, K. C., Degenhardt, J.J. and Giardino, J.R. 1999. Engineering geomorphology of rock glaciers. *Geomorphology*, 31: 93 – 132.

Butler, D., 2006. Virtual globes: The web-wide world. *Nature,* 439: 776 – 778.

Buxton, N., Escobar, M., Purkey, D. and Lima, N. 2013. Water scarcity, climate change and Bolivia: Planning for climate uncertainties. Stockholm Environment Institute, http://www.sei-international.org/mediamanager/documents/Publications/SEI-DiscussionBrief-Escobar-Spanish-BoliviaWaterClimate.pdf

Buytaert, W. and De Bièvre, B. 2012. Water for cities: The impact of climate change and demographic growth in the tropical Andes. *Water Resources Research*, 48

Buytaert, W., Vuille, M., Dewulf, A., Urrutia, R., Karmalkar, A. and Célleri, R. 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, Casassa, G. and Quintana, J. 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 (6): 933–948.

Carrasco, J. F, Casassa, G. and Quintana, J. 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 (6): 933–948.

Casassa, G., Smith, K., Rivera, A., Araos, J., Schnirch, M. and Schneider, C. 2002. Inventory of glaciers in isla Riesco, Patagonia, Chile, based on aerial photography and satellite imagery. *Annals of Glaciology,* 34: 373-378.

Casassa, G., Haeberli, W., Jones, G., Kaser, G., Ribstein, P., Rivera, A., Schneider, C. 2007. Editorial: Current status of Andean glaciers. *Global and Planetary Change,* 59 (1-4): 1 – 9.

CCAFS, 2014. Statistical Dowscaling: Delta Method CMIP3 Data. http://www.ccafs-climate.org/statistical_downscaling_delta/

Cecil, D., Green, J., Vogt, S., Michel, R. & Cottrell, G. 1998. Isotopic composition of ice cores and melwater from upper Fremont glacier and Galena Creek rock glacier, Wyoming. *Geografiska Annaler* 80(A), 3-4.

Chang, A. Y., Parrales, M. E., Jimenez, J., Sobieszczyk, M. E., Hammer, S. M., Copenhaver, D. J. and Kulkarni, R. P. 2009. Combining Google Earth and GIS mapping technologies in a dengue surveillance system for developing countries. *International Journal of Health Geographics,* 8(49). DOI:10.1186/1476-072X-8-49

Chen, J. and Ohmura, A. 1990. Estimation of Alpine glacier water resources and their change since the 1870s. In Hydrology in Lang, H. and Musy, A. (eds). *Mountainous Regions, I – Hydrological Measurements*, IAHS Press, Oxfordshire, UK 193: 127–135.

Chevallier, P., Pouyaud, B., Suarez, W., Condom, T. 2011. Climate change threats to environment in the tropical Andes: glaciers and water resources*. Regional Environmental Change,* 11(1): 179 – 187.

Christian Aid, 2012. World Water Day 2012: water for crops. http://www.christianaid.org.uk/whatwedo/eyewitness/americas/bolivia-water-food-security.aspx

Clark, D. H., Steig, E. J., Potter, Jr, N., Gillespie, A. R. 1998. Genetic variability of rock glaciers. *Geografiska Annaler*, 80 A (3–4): 175 – 182.

Conese, C. and Maselli, F. 1992. Use of error matrices to improve area estimates with maximum likelihood classification procedures. *Remote Sensing of Environment*, 40 (2): 113 – 124.

Corte, A. E. 1999. Rock glaciers. In *Satellite Image Atlas of the World, South America*. USGS. Professional Paper 1386-1, April 1999. http://pubs.usgs.gov/pp/p1386i/

Corte A. E., Trombotto D. T. A. and Ahumada A. L. 1982. Relevamiento de la geomorfología criogénica del NW Argentino. IANIGLA-CRICYT, Mendoza.

Coudrain, A., Francou, B. and Kundzewicz, Z. W. 2005. Glacier shrinkage in the Andes and consequences for water resources – Editorial. *Hydrological Sciences,* 50(6): 925 – 932.

Croce, F. A. and Milana, J. P., 2002. Internal structure and behaviour of a rock glacier in the Arid Andes of Argentina. *Permafrost and Periglacial Processes*, 13(4): 289 – 299.

Croft, H., Anderson, K. and Kuhn, N. J. 2009. Characterizing soil surface roughness using a combined structural and spectral approach. *European Journal of Soil Science*, 60: 431–442.

Curran, P. J. and Atkinson, P. M. 1998. Geostatistics and remote sensing. *Progress in Physical Geography*, 22(1): 61 – 78.

Curtaz, M., Vagliasindi, M., Letey, S., Morra di Cella, U. and Pogliotti, P. 2011. A new rock glaciers inventory in the North-Western Alps. *Geophysical Research Abstracts,* 13.

Degenhardt, J. J. Jr., and Giardino, J. R. 2003. Subsurface investigation of a rock glacier using ground-penetrating radar: Implications for locating stored water on Mars, *Journal of Geophysical Research*, 108 (4), 8036

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

Durrieu, M., Ruiz, L. A. and Balaguer, A. 2005. Analysis of geostatistical parameters for texture classification of satetllite images. http://cgat.webs.upv.es/bigfiles/LARuiz_et_al%28Earsel05%29.pdf

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

Esper Angillieri, M. Y. 2010. Application of frequency ratio and logistic regression to active rock glacier occurrence in the Andes of San Juan, Argentina. *Geomorphology,* 114: 396 – 405.

Estrada, D. 2009. Scientist Warns of Threats to Rock Glaciers. Last accessed: 09/05/11, http://ipsnews.net/news.asp?idnews=46619

EU insight, 2009. Delegation of the European Commission to Australia and New Zealand. Climate Change: a global problem requiring a global solution. October 2009. http://eeas.europa.eu/delegations/australia/documents/eu_australia/eu_insight_climate_change2009_en.pdf

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

EXELIS, 2014. ENVI Classic Tutorial: Classification Methods http://www.exelisvis.com/portals/0/pdfs/envi/Classification_Methods.pdf

Falaschi, D., Castro, M., Masiokas, M., Tadono, T. and Ahumada, A. L. 2014. Rock glacier inventory of the Valles Calchaquíes region (~25°S), Salta, Argentina, derived from ALOS data. *Permafrost and Periglacial Processes,* 25(1): 69 – 75.

FAO, 2011. Highlands and Drylands: Mountains, a source of resilience in arid regions. FAO, Mountain Partnership Secretariat, UNCCD, SDC, CDE. Rome. http://www.fao.org/docrep/014/i2248e/i2248e00.pdf

Farley, M. and Liemberger, R. 2005. Developing a non-revenue water reduction strategy: planning and implementing the strategy. *Water Science and Technology: Water Supply,* 5 (1): 41 – 50.

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

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

Francou, B., Ramirez, E., Cáceres, B. and Mendoza, J. 2000. Glacier evolution in the tropical Andes during the last decades of the 20th century : Chacaltaya, Bolivia, and Antizana, Ecuador. AMBIO, 29(7) : 416 – 422.

Francou, B., Vuille, M., Wagnon, P., Mendoza, J. and Sicart, J. E. 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 (0): 1 – 12.

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

Ford, A. 2011. Remote Sensing and Photogrammetry Conference, 2011, Bournemouth.

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

Geospatial World, 2011. GIS application for mountain terrains: some considerations and options. Last accessed: 30/09/11, http://www.geospatialworld.net/index.php?option=com_content&view=article&id=16227%3Agis-application-for-mountain-terrains-some-considerations-and-options&catid=153%3Anatural-resource-management-mountain&Itemid=41&limitstart=1

Giardino, J. R. and Vitek, J. D. 1988. The significance of rock glaciers in the glacial-periglacial landscape continuum. *Journal of Quaternary Science,* 3(1): 97 – 103.

Giardino, J. R., Shroder, J. F. and Vitek, J. D. 1987. *Rock glaciers*. Allen & Unwin, Boston.

Giardino, J. R., Vitek, J. D. and Demorett, J. L. 1992. A model of water movement in rock glaciers and associated water characteristics. In J. Dixon, and A. Abrahams (Eds.). *Periglacial Geomorphology.* Chichester: John Wiley & Sons, 159–184.

Goshorn-Maroney, J. 2012. Thermal conditions and movement of rock glaciers in the North Cascades, Washington. Masters thesis, Western Washington University.

Guglielmin, M. and Smiraglia, C. 1998. The rock glacier inventory of the Italian Alps. *Permafrost – Seventh International Conference (Proceedings), Yellowknife (Canada), Collection Nordicana.* No. 55: 375 – 382.

Guodong, C. and Dramis. F. 1992. Distribution of mountain permafrost and climate. *Permafrost and Periglacial Processe*s, 3(2), 83–91.

Gusmeroli, A. 2010. Polythermal glacier dynamics at Storglaciären, Arctic Sweden, inferred using in situ geophysical techniques. PhD thesis. Swansea University.

Haeberli, W. 1985. Creep of mountain permafrost. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, 77, p. 142.

Haeberli, W. 2000. Modern research perspectives relating to permafrost creep and rock glaciers: A discussion. *Permafrost & Periglacial Processes,* 11(4): 290-293.

Haeberli, W. and Vonder Mühll, D. 1996. On the characteristics and possible origins of ice in rock glacier permafrost. Zeitschrift für Geomorphologie, Neue Folge, Supplement-Band, 104: 43 – 57.

Haeberli, W., Guodong, C., Gorbunov, A. P. and Harris, S. A. 1993. Mountain permafrost and climate change. *Permafrost and Periglacial Processes,* 4: 165–174.

Haeberli, W., Hoelzle, M., Kääb, A., Keller, F., Vonder Mühll, D. and Wagner, S. 1998. Ten years after drilling through the permafrost of the active rock glacier Murtèl, eastern Swiss Alps: Answered questions and new perspectives. *Proceedings of the 7th International Conference on Permafrost, Yellowknife*: 403 – 410.

Haeberli, W., Hallet, B., Arenson, L., Elconin, R., Humlum, O., Kääb, A., Kaufmann, V., Ladanyi, B., Matsuoka, N., Springman, S. and Vonder Mühll, D. 2006. Permafrost creep and rock glacier dynamics. *Permafrost and Periglacial Processes,* 17(3): 189 – 214.

Hamilton, S. J. and Whalley, B. W. 1995. Rock glacier nomenclature: A re-assessment. *Geomorphology,* 14: 73 – 80.

Harrison S, Whalley B and Anderson E. 2008. Relict rock glaciers and protalus lobes in the British Isles: implications for Late Pleistocene mountain geomorphology and palaeoclimate. *Journal of Quaternary Science,* 23(3): 287 – 304.

Hausmann, H., Krainer, K., Brückl, E., Mostler, W. 2007. Internal structure and ice content of Reichenkar rock glacier (Stubai Alps, Austria) assessed by geophysical investigations. *Permafrost and Periglacial Processes*, 18 (4): 351–367.

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,* (eds.) B. Orlove, E. Wiegandt and B. H. Luckman, 185pp. London: University of California Press.

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

Henry, A. 2009. Using Google Earth for Internet GIS. MSc thesis. University of Edinburgh. http://www.nabohome.org/visque/HenryThesis-ResearchPaper.pdf

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., Jarvis, A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology.* 25: 1965 – 1978.

Hirzel, A. H., Hausser, J., Chessel, D. and Perrin, N. 2002. Ecological-niche factor analysis: how to compute habitat-suitability maps without absence data? *Ecology*, 83(7): 2027 – 2036.

Hole, D. G., Willis, S. G., Pain, D. J., Fishpool, L. D., Butchart, S. H. M., Rahbek, C. and Huntley, B. 2009. Projected impacts of climate change on a continent wide protected area network. *Ecology Letters*. 12: 420 – 431.

Humlum, O. 1997. Origin of Rock Glaciers: Observations from Mellemfjord, Disko Island, central West Greenland. *Permafrost and Periglacial Processes*, 7: 1-20.

Humlum, O., 2000. The geomorphic significance of rock glaciers: estimates of rock glacier debris volumes and headwall recession rates in West Greenland, *Geomorphology*, 35: 41 – 67

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

IIED, 2013. Multistakeholder cost-benefit analysis of climate change adaptation measures and options: the case of urban water provision in the context of melting glaciers in Bolivia. http://pubs.iied.org/pdfs/G03521.pdf

Immerzeel, W. W., Pellicciotti, F. and Bierkens, M. F. P. 2013. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature Geoscience*, 6: 742 – 745.

SRES. 2000. Special Report on Emissions Scenarios: Summary for Policymakers, Working Group III. Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Yong Jung, T., Kram, T., Lebre La Rovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H. H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (eds.) Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L.. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2007b. Climate Change 2007: Impacts, Adaptation and Vulnerability, contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (eds.) Parry, M. L., Canziani, O. F., Palutikof, J. P., Van der Linder, P. J., Hanson, C. E. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (eds) Stocker, T. F., Qin, D., Plattner, G. K., Tignore, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M. Cambridge University Press, Cambridge, United Knigdom and New York, USA.

IPCC. 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (eds) Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D., Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., White, L. L. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Ishikawa, M., Watanabe, T. and Nakamura, N. 2001. Genetic Differences of Rock Glaciers and the Discontinuous Mountain Permafrost Zone in Kanchanjunga Himal, Eastern Nepal. *Permafrost and Periglacial Processes,* 12: 243–253.

Janke, J. R. 2005. Modeling past and future alpine permafrost distribution in the Colorado Front Range. *Earth Surface Processes and Landforms*. 30, 1495 – 1508.

Jansen, F. and Hergarten, S. 2006. Rock glacier dynamics: Stick-slip motion coupled to hydrology. *Geophysical Research Letters,* 33(10).

Jarman, D., Wilson, P. and Harrison, S. 2013. Are there any relict rock glaciers in the British mountains? *Journal of Quaternary Science,* 28: 131–143. DOI: 10.1002/jqs.2574.

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., Popp, A. and Lotze-Campen, H. 2012. Adaptation Options to Climate-Induced Glacier Retreat in Bolivia. In *Climate Change, Justice and Sustainability: Linking Climate and Development Policy*, (eds.) O. Edenhofer, J. Wallacher, H. Lotze-Campen, M., Reder, B. Knopf, J. Müller, 195 pp. New York: Springer.

Johnson, P. G. 1974. Mass movement of ablation complexes and their relationship to rock glaciers. *Geografiska Annaler*, 56: 93 – 101.

Johnson, P.G. 1984. Rock glacier formation by high-magnitude low-frequency slope processes in the Southwest Yukon. *Annals of the Association of American Geographers*, 74(3): 408 – 419.

Johnson, B. G., Thackray, G. D. and Van Kirk, R. 2007. The effect of topography, latitude, and lithology on rock glacier distribution in the Lemhi Range, central Idaho, USA. *Geomorphology,* 91: 38 – 50.

Jones, P. G., Thornton, P. K. and Heinke, J. 2009. Generating characteristic daily weather data using downscaled climate model data from the IPCC's Fourth Assessment. Project Report http://www.ccafs-climate.org/downloads/docs/Generating_Characteristic_Daily_Weather_Data_using_Downscaled_Climate_Model_Data_Jones_Thornton_Heinke_2009.pdf

Jordan, E. 1998. Glaciers of South America: Glaciers of Bolivia. In Williams, R. S. Jr. and Ferrigno, J. G. (eds) *Satellite Image Atlas of Glaciers of the World*. United States Geological Survey Professional Paper 1386-I, p. I 81 – 108, http://pubs.usgs.gov/pp/p1386i/bolivia/intro.html

Jordan, E., Brockman, C., Fernandez, A., Alvarez, R. and Jacobsen, K. 1980. The glacier inventory of Bolivia. *World Glacier Inventory – Inventaire mondial des Glaciers, Proceedings of the Riederalp Workshop*, September 1978.

Kääb, A. and Weber, M. 2004. Development of transverse ridges on rock glaciers: field measurements and laboratory experiments. *Permafrost and Periglacial Processes*, 15(4): 379 – 391.

Kääb, A., Haeberli, W. and Hilmar Gudmundsson, G. 1997. Analysing the Creep of Mountain Permafrost using High Precision Aerial Photogrammetry: 25 years of Monitoring Gruben Rock Glacier, Swiss Alps. *Permafrost and Periglacial Processes*, 8: 409 – 426.

Kääb, A., Gudmundsson, G. H. and Hoelzle, M. 1998. Surface Deformation of Creeping Mountain Permafrost.Photogrammetric Investigations on Rock Glacier Murtèl, Swiss Alps. *Proceedings the 7th International Conference on Permafrost*, 531-537.

Kääb, A., Haeberli, W., Huggel, C., Paul, F. 2000. Glacier- and permafrost-related hazards in high mountains: Integrative assessment in the Swiss Alps based on remote sensing and geo-information systems. Proceedings of X Congresso Peruano de Geologia. Lima.

Kääb, A., Paul, F., Maisch, M., Hoelzle, M., Haeberli, W., 2002: The new remote-sensing-derived Swiss glacier inventory: II, First results. *Annals of Glaciology*, 34: 362 - 366

Kääb, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., Salzmann, N., Schlaefli, S., Schmutz, K., Schneider, D., Strozzi, T., Weidmann, Y. 2005. Remote sensing of glacier- and permafrost-related hazards in high mountains: An overview. *Natural Hazards and Earth System Sciences* 5: 527-554.

Kääb, A., Huggel, C. and Fischer, L. 2006. Remote sensing technologies for monitoring climate change impacts on glacier- and permafrost-related hazards. *ECI Conference on Geohazards.* Last accessed: 19/09/11, http://folk.uio.no/kaeaeb/publications/kaeaeb_eci.pdf

Kaenzig, R. 2013. The circulation of people: A critical discussion on the impact of glacier shrinkage upon population mobility in the Bolivian Andes. MAPS Working Paper 7 2013/E.

Kamp, U., Bolch, T. and Olsenholler, J. 2005. DEM generation from ASTER satellite data for geomorphometric analysis of Cerro Sillajhuay, Chile/Bolivia. *Geocarto International*, 20(1): 23 – 33.

Kaufmann, V. 1998. Deformation analysis of the Doesen rock glacier (Austria). *Permafrost – Seventh International Conference Proceedings, Yellowknife, Canada, Collection Nordicana* No 55, p. 551 – 556.

Kaufmann, V. 2010. Detection and quantification of rock glacier creep using high-resolution orthoimages of virtual globes. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXIX-B5, 2012, XXII ISPRS Congress, 25 August – 01 September 2012, Melbourne, Australia.

Kellerer-Pirklbauer A., Lieb, G. K. and Kleinferchner, H. 2012. A new rock glacier inventory of the Eastern European Alps. *Austrian journal of Earth Sciences,* 105(2): 78 – 93.

Kelly, R. E., Drake, N. A. and Barr, S. L. 2004. Spatial modelling of the terrestrial environment: Outlook, in De Jong, C., Collins, D. and Ranzi, R., (eds) 2005. *Climate & hydrology in mountain areas,* p. 263 – 266.

Kirkbride, M. and Brazier, V. 1995. On the sensitivity of Holocene talus-derived rock glaciers to climate change in the Ben Ohau Range, New Zealand. *Journal of Quaternary Science*, 10: 353 – 365.

Krainer, K. and Ribis, M. 2012. A rock glacier inventory of the Tyrolean Alps (Austria). *Austrian Journal of Earth Sciences*, 105(2): 32 – 47.

LAB. 2012. Latin America Bureau, Bolivia: Landslide prevention and warning for La Paz http://lab.org.uk/bolivia-la-paz-and-landslide-prevention

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

Lee, J. Y. and Warner, T. A. 2004. Image classification with a region based approach in high spatial resolution imagery. *Proceedings XXth International Scoiety for Photogrammetry and Remote Sensing Congress Technical Commission III.* http://www.isprs.org/proceedings/XXXV/congress/comm3/papers/438.pdf

Lee, G., Tachikawa, Y. and Takara, K. 2009. Interactions between topographic and process parameters due to the spatial resolution of DEMs in distributed rainfall-runoff modelling. *Journal of Hydrological Engineering*, 14 (10): 1059 – 1069.

Lieb, G. K. 1998. High-mountain permafrost in the Austrian Alps (Europe). *Permafrost – Seventh International Conference (Proceedings), Yellowknife (Canada), Collection Nordicana*, No. 55: 663 – 668.

Lillerorren, K. S. and Etzelmuller, B. 2011. A regional inventory of rock glaciers and ice-cored moraines in Norway. *Geografiska Annaler: Series A, Physical Geography*, 93: 175 – 191.

Liu, L., Millar, C. I., Westfall, R. D. and Zebker, H. A. 2013. Surface motion of active rock glaciers in the Sierra Nevada, California, USA: inventory and a case study using InSAR. *The Cryosphere*, 7: 1109 – 1119.

Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., and Ackerly, D. D. 2009. The velocity of climate change. *Nature* 462: 1052 – 1055.

Longden, K., Pabari, R., Hassan, M. and Majumder-Russel, D. 2012. Climate change: mitigation and adaptation. Advocates for International Development, Lawyers Eradicating Poverty. http://a4id.org/sites/default/files/files/%5BA4ID%5D%20Climate%20change%20Mitigation%20and%20Adaptation.pdf

Lui, T., Kinouchi, T. and Ledezma, F. 2013 Characterization of recent glacier decline in the Cordillera Real by LANDSAT, ALOS and ASTER data. *Remote Sensing of Environment*. 137: 158 – 172.

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

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

Magrin, G., Gay García, C., Cruz Choque, D., Giménez, J. C., Moreno, A. R., Nagy, G. J., Nobre, C., and Villamizar, A. 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*. In (ed) Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, C. E. Hanson. Cambridge University Press, Cambridge, UK: 581-615.

Magrin, G., Marengo, J., Boulanger, J. P., Buckeridge, M. S., Castellanos, E., Poveda, G., Scarano, F. R., Vicuña, S. 2014. Chapter 27: Central and South America. IPCC WGII AR5. In Climate Change 2014: Impacts, Adaptation and Vulnerability

Marchesi, A., Colombo, R. and Valentini, P. 2011. Application of high spatial resolution satellite imagery for urban environment mapping. Last accessed: 04/06/11, http://www.isprs.org/proceedings/XXXVI/4-C42/Papers/16_Automated%20classification%20IC%20II%20-%20Settlements%20&%20Infrastructure/OBIA2006_Marchesi_Colombo_Valentini.pdf

Marengo, J. A., Ambrizzi, T., da Rocha, R. P., Alves, L. M., Cuadra, S. V., Valverde, M. C., Torres, R. R., Santos, D. C., Ferraz, S. E. 2010. Future change of climate in South America in the late twenty-first century: intercomparison of scenarios from three regional climate models. *Climate Dynamics,* 35:1073 – 1097.

Mark, B. G., Bury, J., McKenzie, J. M., French, A., Baraer, M. 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(4): 794 – 805.

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

Milana, J. P. and Maturano, A. 1999. Application of Radio Echo Sounding at the arid Andes of Argentina: the Agua Negra Glacier. *Global and Planetary Change*, 22 (1-4): 179 – 191.

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

Mitchell, T. D. and Hume, M. 2000. A country-by-country analysis of past and future warming rates. Tyndall Centre Working Paper, UEA, Norwich, UK.

Mitchell, T. D. and Osborn, T. J. 2005 ClimGen: a flexible tool for generating monthly climate data sets and scenarios. Tyndall Centre for Climate Change Research Working Paper. Tyndall Centre for Climate Change (2005). http://www.ccafs-climate.org/downloads/docs/Climgen-Downscaling-Tyndall.pdf. Date of access: 17/07/2014

Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M. and New, M. 2004. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901 – 2000) and 16 scenarios (2001 – 2100). Tyndall Centre for Climate Change Research, Working Paper 55. http://www.tyndall.ac.uk/sites/default/files/wp55.pdf

Mölg, T., Hardy, D. R., Cullen, N. J. and Kaser, G. 2008. Chapter 12: Tropical Glaciers, Climate Change and Society (East Africa). In *Darkening Peaks: Glacier Retreat, Science, and Society,* (eds.) B. Orlove, E. Wiegandt and B. H. Luckman, 3pp. London: University of California Press, p. 168.

Monnier, S. and Kinnard, C. 2013. Internal structure and composition of a rock glacier in the Andes (upper Choapa valley, Chile) using borehole information and ground-penetrating radar. *Annals of Glaciology* vol 54 (64): 61 – 72.

Monnier, S., Kinnard, C., Saéz, R., Garrido, R., Camerlynck, C. and Rejiba, F. 2011. The internal structure and the cryologic importance of the rock glaciers of the Los Pelambres mine (Upper Choapa Valley, Semi-arid Andes of Chile). Geophysical Research Abstracts, 13.

Morén, B., Heyman, J. and Stroeven, A. P. 2011. Glacial geomorphology of the central Tibetan Plateau. *Journal of Maps,* 7(1): 115 – 125. DOI:10.4113/jom.2011.1161.

Nemoto, T. and Beglar, D. 2014. Developing Likert-scale questionnaires. In Sonda, N. and Krause, A. (eds) JALT2013 Conference Proceedings. Tokyo.

Nourbakhsh, I., Sargent, R., Wright, A., Cramer, K., McClendon, B. and Jones, M. 2006. Mapping disaster zones. *Nature,* 439: 787 -788.

Orlove, B., Wiegandt E. and Luckman, B. H. 2008. The Place of Glaciers in Natural and Cultural Landscapes. In *Darkening Peaks: Glacier Retreat, Science, and Society,* (eds.) B. Orlove, E. Wiegandt and B. H. Luckman, 3pp. London: University of California Press

Osborn, T.J. 2009. A user guide for ClimGen: A flexible tool for generating monthly data sets and scenarios. Climatic Research Unit, University of East Anglia, Norwich, 17pp.
http://www.cru.uea.ac.uk/~timo/climgen/ClimGen_v1-02_userguide_2feb2009.pdf
Date of access: 17/07/2014

Osborn, T.J. 2014. The CLIMGEN model.
http://www.ccafs-climate.org/downloads/docs/Climgen-Downscaling-Tyndall.pdf

Oxfam. 2009. Bolivia: Climate change, poverty and adapatation: Executive summary. Oxfam International, 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.

Patterson, T. C. 2007. Google Earth as a (Not Just) Geography Education Tool. *Journal of Geography*, 106: 145-152.

Paul, F., Huggel, C. and Kääb, A., 2004. Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers. *Remote Sensing of Environment*, 89 (4): 510 – 518.

Paul, F. Kääb, A. and Haeberli, W. 2003. Mapping of rock glaciers with optical satellite imagery. 8th International Conference on Permafrost Extended Abstracts on Current Research and Newly Available Information. http://wp.cedha.net/wp-content/uploads/2011/10/Paul-et-al-2003-rgl-mapping-satellite-imagery.pdf

Paul, F., Kääb, A. and Haeberli, W. 2007. Recent glacier changes in the Alps observed by satellite: Consequences for future monitoring strategies, *Global and Planetary Change,* 56 (1-2): 111 – 122.

Payne, D.1998. Climatic implications of rock glaciers in the arid Western Cordillera of the Centra Andes. *Glacial Geology and Geomorphology*.

Perucca, L. and Esper Angillieri, M. Y. 2008. A preliminary inventory of periglacial landforms in the Andes of La Rioja and San Juan, Argentina, at about 28°S. *Quaternary International* 190 (1): 171 – 179.

Perucca, L. and Esper Angillieri, M. Y. 2011. Glaciers and rock glaciers' distribution at 28° SL, Dry Andes of Argentina, and some considerations about their hydrological significance. *Environmental Earth Sciences,* 64(8): 2079 – 2089.

Piatek, J. L., Hardgrove, C. and Moersch, J. E. 2013. Ground-based thermal analysis of a terrestrial rock glacier as an analog to martian lovate debris aprons. 44th Lunar and Planetary Science Conference 2013. http://www.lpi.usra.edu/meetings/lpsc2013/pdf/2936.pdf

Potter, N. Jr. 1972. Ice-cored rock glacier, Galena Creek, northern Absaroka Mountains, Wyoming. *Geological Society of America Bulletin,* 83: 3025 – 3058.

Quincey, D. J., Lucas, R. M., Richardson, S. D., Glasser, N. F., Hambrey, M. J., Reynolds, J. M. 2005. Optical remote sensing techniques in high-mountain environments: application to glacial hazards. *Progress in Physical Geography,* 29 (4): 475 – 505.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Cebellos, J. L., Basantes, R., Vuille, M., Sicart, J. E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Ménégoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M., Wagnon, P. 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. *The Cyrosphere,* 7: 81 – 102.

Racoviteanu, A. and Williams, M. W. 2012. Decision Tree and Texture Analysis and Mapping Debris-Covered Glaciers in the Kangchenjunga Area, Eastern Himalaya. *Remote Sensing*, 4(1): 3078 - 3109

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

Ramirez, E., Olmos, C. and Román, D. 2007. Deshielo de la Cuenca Tuni Condoriri y su impacto sobre los Recursos Hídricos de las Cuidades La Paz y El Alto. Programa de Investigación. Financiamiento Países Bajos – Plan Quinquenal PNCC. GRANT – GREAT ICE, IHH-IRD.

Ramirez, E., Ribeiro, R., Machaca, A., Fuertes, R. and Simões, J. 2012. Glacier Inventory of the Cordillera Real – Bolivia using high resolution satellite images ALOS and CBERS-2B. *Geophysical Research Abstracts, EGU General Assembly* 2012, vol 14.

Rangecroft, S., Harrison, S., Anderson, K., Magrath, J., Castel, A. P., Pacheco, P. 2013. Climate change and water resources in arid mountains: an example from the Bolivian Andes. *AMBIO*. 42: 852 – 863.

Rangecroft, S., Harrison, S. and Anderson, K. 2014a. Rock glaciers as water stores in the Bolivian Andes: an assessment of their hydrological importance. *Arctic, Antarctic and Alpine Research.* Accepted.

Rangecroft, S., Harrison, S., Anderson, K., Magrath, J., Castel, A. P. and Pacheco, P. 2014b. A first rock glacier inventory for the Bolivian Andes. *Permafrost and Periglacial Processes.* DOI:10.1002/ppp.1816

Rango, A., Laliberte, A., Steele, C., Herrick, J. E., Bestelmeyer, B., Schmugge, T., Roanhorse, A., Jenkins, V. 2006. Using Unmanned Aerial Vehicles for Rangelands: Current Applications and Future Potentials. *Environmental Practice*, 8(3): 159 – 168.

Rasemann, S., J. Schmidt, L. Schrott, R. Dikau. 2004. Geomorphometry in mountain terrain. Pp. 101 – 137. In M. P. Bishop and J. F. Shroder Jr (eds) Geographic Information Science and Mountain Geomorphology. Springer. Praxis Publishing Ltd, Chichester, UK.

Read, D., Bostrom, A., Morgan, M. G., Fischhoff, B. and Smuts, T. 1994. What do people know about global climate change? 2. Survey studies of educated laypeople. *Risk Analysis*, 14(6): 971 – 982.

Reja, U., Manfreda, K. L., Hlebec, V. and Vehovar, V. 2003. Open-ended vs. Close-ended Questions in Web Questionnaires. *Developments in Applied Statistics*. http://www.stat-d.si/mz/mz19/reja.pdf

Renewable facts, 2014, http://www.renewablefacts.com/country/bolivia/hydro

Roer, I. and Nyenhuis, M. 2007. Rockglacier activity studies on a regional scale: comparison of geomorphological mapping and photogrammetric monitoring. *Earth Surface Processes and Landforms*. 32(12): 1747 – 1758.

Rosenthal, E. 2009. In Bolivia, Water and Ice Tell of Climate Change. *New York Times*, http://www.nytimes.com/2009/12/14/science/earth/14bolivia.html?pagewanted=all

Ruiz, L. A., Fdez-sarría, A. and Recio, J. A.. 2004. Texture feature extraction for classification of remote sensing data using wavelet decomposition: a comparative study. International Archived of Photogrammetry and Remote Sensing, vol XXXV.

Sandeman, A. F. and Ballantyne, C. K. 1996. Talus rock glaciers in Scotland: Characteristics and controls on formation. *Scottish Geographical Magazine*, 112: 138 – 146.

SEI, 2013. Water scarcity, climate change and Bolivia: Planning for climate uncertainties. Discussion brief. Stockholm Environment Institute. http://sei-us.org/Publications_PDF/SEI-DB-2013-Bolivia-La-Paz-El-Alto-water.pdf

Schaefer, K., Lantuit, H., Romanovsky, V. E. and Schuur, E. A. G. 2012. Policy Implications of Warming Permafrost. http://www.unep.org/pdf/permafrost.pdf

Schrott, L. 1996. Some geomorphological-hydrological aspects of rock glaciers in the Andes (San Juan, Argentina). *Zeitschrift für Geomorphologie,* 104: 161 – 173.

Scotti, R., Brardinoni, F., Alberti, S., Frattini, P., Crosta, G. B. 2013. A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps. *Geomorphology,* 186: 136 – 149.

Seiler, C., Hutjes, R. W. A and Kabat, P. 2013. Climate variability and trends in Bolivia. 2013. *Journal of Applied Meteorology and Climatology*, 52: 130 – 146.

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

Seth, A., Thibeault, J., Garcia, M. and Valdivia, C. 2010. Making sense of 21st century climate change in the Altiplano: Observed trends and CMIP3 projections. *Annals of the Association of American Geographers*. *Special Issue: Climate Change*, 100: 835 – 865.

Shahriari, S. 2012. Pollution threatens South America's Lake Titicaca. Pulitzer Centre on crisis reporting. http://pulitzercenter.org/reporting/lake-titicaca-peru-bolivia-pollution-urbanization-tourism-agriculture-water-indigenous-population

Sheppard, S. R. J. and Cizek, P. 2009. The ethics of Google Earth: Crossing thresholds from spatial data to landscape visualisation. *Journal of Environmental Management,* 90: 2102 – 2117.

Shukla, A., Gupta, R. P. and Arora, M. K. 2010. Delineation of debris-covered glacier boundaries using optical and thermal remote sensing data. *Remote Sensing Letters,* 1(1): 11 — 17.

Sicart, J. E., Ribstein, P., Chazarin, J. P. and Berthier, E. 2002. Solid precipitation on a tropical glacier in Bolivia measured with an ultrasonic depth gauge. *Water Resources Research,* 38(10).

Silverio, W. and Jaquet, J. M., 2005. Glacial cover mapping (1987–1996) of the Cordillera Blanca (Peru) using satellite imagery. *Remote Sensing of Environment,* 95(3): 342 – 350.

Singh, V. K., Ray, P. K. C. and Jeyaseelan, A. P. T. 2010. Orthorectification and digital elevation model (DEM) generation using cartosat-1 satellite stereo pair in Himalayan terrain, *Journal of Geographic Information System,* 2(2): 85 – 92.

Slaymaker, O. 2001. The role of remote sensing in geomorphology and terrain analysis in the Canadian Cordillera. *International Journal of Applied Earth Observation and Geoinformation*, 3(1): 11 – 17.

Smiraglia, C., 1992. Observations on the Rock Glaciers of Monte Emilius (Valle d'Aosta, Italy). Short communication. *Permafrost and Periglacial Processes*, 3(2): 163-168

Smith, G. R., Woodward, J. C., Heywood, D. I., Gibbard, P. L. 2000. Interpreting Pleistocene glacial features from SPOT HRV data using fuzzy techniques. *Computers and Geosciences*, 26: 479 – 490.

Souvignet, M. and Heinrich, J. 2011. Statistical downscaling in the arid central Andes: uncertainty analysis of multi-model simulated temperature and precipitation. *Theoretical and Applied Climatology*. 106: 229 – 244.

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

Soruco, A., Vincent, C., Francou, B. and Gonzalez, J. F. 2009. Glacier decline between 1963 and 2006 in the Cordillera Real, Bolivia. *Geophysical Research Letters,* 36(6).

Steckler, A., McLeroy, K. R., Goodman, R. M., Bird, S. T. and McCormick, L. 1992. Toward integrating qualitative and quantitative methods: an introduction. *Health education quarterly* 19.1: 1-8.

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

Strozzi, T., Kääb, A. and Frauenfelder, R. 2004. Detecting and quantifying mountain permafrost creep from in situ inventory, space-borne radar interferometry and airborne digital photogrammetry. International Jounral of Remote Sensing, 25(15): 2919 – 2931.

Summerfield, M. A. 1991. *Global geomorphology*. Pearson Education Limited, Essex.

Thibeault, J. M., Seth, A., and Garcia, M. 2010. Changing climate in the Bolivian Altiplano: CMIP3 projections for temperature and precipitation extremes. *Journal of Geophyscial Research: Atmopsheres (1984 – 2012)*, 115 (D8)

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

Toutin, T. and Chénier, R. 2011. GCP Requirement for high-resolution satellite mapping. Last accessed: 01/10/11, http://www.isprs.org/proceedings/XXXV/congress/comm3/papers/385.pdf

Travassos, J. M., Stael, G. C. and Liaudat, D. T. 2008. A GPR survey on degraded permafrost at Mesón San Juan, Mendonza, Argentina. *Revista Brasileria de Geoffsica,* 26(4): 519 – 526.

Trombotto, D., Buk, E. and Hernández, J. 1997. Monitoring of Mountain Permafrost in the Central Andes, Cordon del Plata, Mendoza, Argentina. *Permafrost and Periglacial Processes*, 8 (1): 123 – 129.

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

UN, 2006. World Water Development Report 2. www.unesco.org/water/wwap/wwdr2/pdf/wwdr2_ch_4.pdf

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

UN Israel, 2014. Drought and arid land water management, http://www.un.org/esa/agenda21/natlinfo/countr/israel/drought.pdf

UNEP, 2012. Fresh water for the future: A synopsis of UNEP activities in water. http://www.unep.org/pdf/Water_Report_2012.pdf

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

UNFCCC, 2011. Assessing the costs and benefites of adaptation options: an overview of approaches. The Nairobi work programme on impacts, vulnerability and adaptation to climate change. http://unfccc.int/resource/docs/publications/pub_nwp_costs_benefits_adaptation.pdf

Valdivia, C., Seth, A., Gilles, J., Garcia, M., Jimenez, E., Yucra, E., Cusicanqui, J., Navia, F. 2010. Adapting to climate change in Andean ecosystems: Landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems. *Annals of the Association American Geographers*, 100: 818 – 834.

Valdivia, C., Thibeault, J., Gilles, J. L., García, M. and Seth, A. 2013. Climate trends and projections for the Andean Altiplano and strategies for adaption. *Advances in Geosciences*, 33: 69 – 77.

Vanham, D. and Rauch, W. 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., American Water Works Association, p. 21 – 40.

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. and Rios, A. R. 2013. The impact of black carbon in Andean glacier melting: an opportunity for linking local action with local climate effects. Summer 2013 Climate Alert, Climate Institute, http://www.climate.org/publications/Climate%20Alerts/2013-summer/black-carbon-andean-glacier-melting.html

Vergara, W., Kondo, H., Pérez, E. P., Pérez, J. M. M. Rueda, V. M., Arango, M. C. M., Murcia, J. F. R., Roldán, G. J. A., Palcios, E. 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., Deeb, A. M., Valencia, A. M. Bradley, R. S., Francou, B., Zarzar, A., Grünwaldt, A., Haeussling S. M. 2007b. Economic Impacts of Rapid Glacier Retreat in the Andes. *EOS, Transactions, American Geophysical Union,* 88(25): 261 – 268.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, H. I., Lorentz, S., Schädler, B., Schwaiger, K., Vuille, M. and Woods, R. 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 tropocal Andes – Impacts and consequences for glaciation and water resources, Part 1: The scientific basis', report for CONAM and the World Bank.

Vuille, M. 2013. Climate change and water resources in the Tropical Andes. Inter-American Development Bank, Technical note. March 2013. http://idbdocs.iadb.org/wsdocs/getdocument.aspx?docnum=37571430

Vuille, M. and Amman, C., 1997. Regional snowfall patterns in the high, arid Andes. *Climatic Change,* 36: 413 – 423.

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

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

Wahrhaftig, C. and Cox, A. 1959. Rock glaciers in the Alaska Range. *Bulletin of the Geological Society of America,* 70(4): 383 – 436.

WaterAid, 2007. Climate change and water resources. http://www.bvsde.paho.org/bvsacd/cd68/WaterAidClim.pdf

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

Whalley, W. B. 2009, On the interpretation of discrete debris accumulations associated with glaciers with special reference to the British Isles in Periglacial and Paraglacial Processes and Environments, edited by J. Knight and S. Harrison, Geological Society, London, Special Publications, 320,pp. 85-102.

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

Whalley, W. B. and Azizi, F. 2003. Rock glaciers and protalus landforms: Analogous forms and ice sources on Earth and Mars. *Journal of Geophysical Research*, 108(4)

Whalley, W. B. and Martin, W. E. 1992. Rock glaciers: II models and mechanisms. *Progress in Physical Geography*, 16: 127 – 186.

Whalley, W. B., Martin, E. H. and Gellatly, A. F. 1986. The problem of "hidden" ice in glacier mapping. *Annals of Glaciology,* 8: 181 – 183.

Whalley, B. W. and Palmer, C. F. 1998. A glacial interpretation for the origin and formation of the Marinet rock glacier, Alpes Maritimes, France. *Geografiska Annaler* 80 A (3-4): 221 - 236

White, S. E.1976. Rock glaciers and block fields, review and new data. *Quaternary Research,* 6: 77 – 97.

WHO. 2012. Linking poverty reduction and water management. http://www.who.int/water_sanitation_health/resources/povertyreduc2.pdf

Williams, R. A. 2000. Environmnetal planning for sustainable urban development. For Caribbean Water and Wastewater Association 9th Annual Conference & Exhibition at Chaguaramas, Trinidad, 2-6 October 2000. http://www.bvsde.paho.org/bvsaidis/cwwa9/will.pdf

Williams, M., Knauf, M., Caine, N., Liu, F. and Verplanck, P. 2006. Geochemistry and Source Waters of Rock Glacier Outflow, Colorado Front Range*. Permafrost and Periglacial Processes* 17: 13-33.

Winters, C. 2012. Impact of Climate Change on the Poor in Bolivia. *Global Majority E-Journal,* 3(1): 33 – 43.

WMO. 2011. Climate information and water management: Story from the Andes [Online]. World Meteorological Organization. Retrieved 12 June, 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 12 June, 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.

World Bank data, 2011. Electricity production from hydroelectric sources (% of total). http://data.worldbank.org/indicator/EG.ELC.HYRO.ZS

World Bank. 2014. Data: Bolivia, http://data.worldbank.org/country/bolivia

WorldClim, 2013, http://www.worldclim.org/

Xu, B., Cao, J., Hansen, J., Yao, Joswia, D. R., Wang, N., Wu, G., Wang, M., Zhao, H., Yang, W., Lui, X. and He, J. 2009. Black soot and the survival of Tibetan glaciers. *Proceedings of the National Academy of Sciences of the United States of America*, 106 (52): 22114 – 22118.

Yale, 2014. Unsupervised Classification algorithms. http://www.yale.edu/ceo/Projects/swap/landcover/Unsupervised_classification.htm

Yu, L. and Gong, P. 2012. Google Earth as a virtual globe tool for Earth science applications at the global scale: progress and perspectives. *International Journal of Remote Sensing,* 33(12): 3966-3986.

Zasadni, J. 2007. The Little Ice Age in the Alps: Its record in glacial deposits and rock glacier formation. *Studia Geomorphologica Carpatho-Balcanica*, XLI: 117 – 137.

Zemp, M., Hoelzle, M. and Haeberli, W. 2007. Distributed modelling of the regional climatic equilibrium line altitude of glaciers in the European Alps. *Global and Planetary Change,* 56(1-2): 83 – 100.

Appendices

Appendix 1: Rangecroft et al. 2013 publication in AMBIO

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REVIEW

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

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John Magrath, Ana Paola Castel, Paula Pacheco

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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

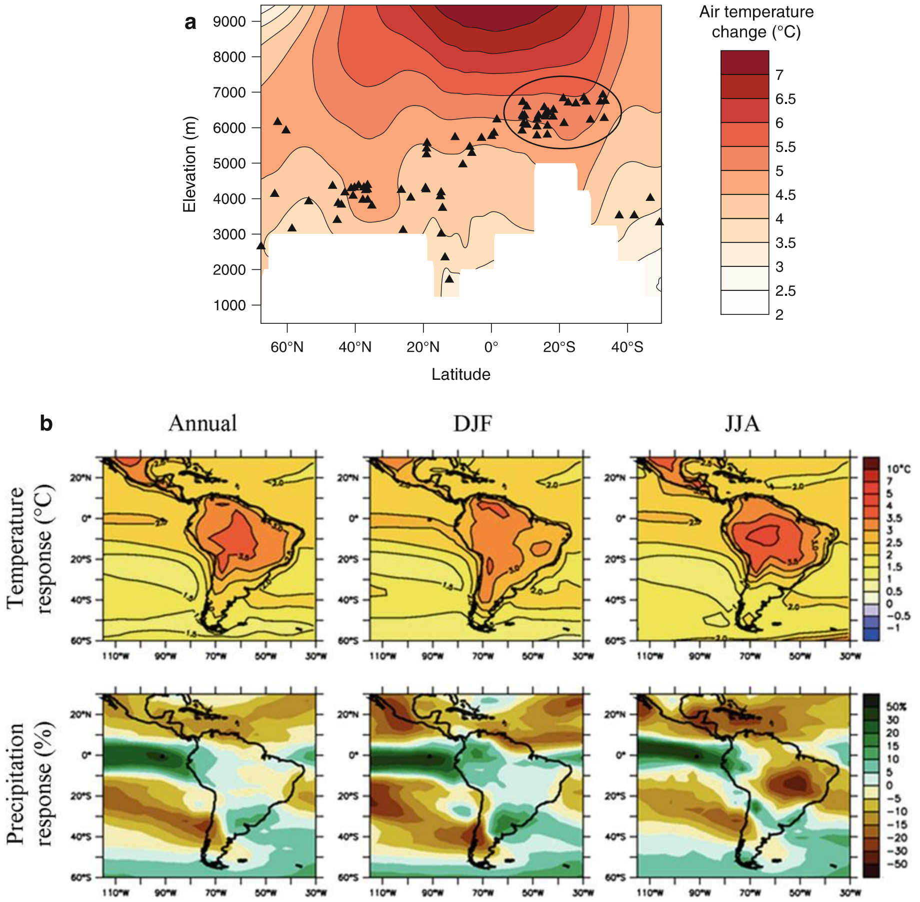


Fig. 1 **a** Visual representation of predicted global warming (adapted from Bradley et al. 2006, p. 1755). Projected changes in mean annual free-air temperatures between (1990–1999) and (2090–2099) along transect from Alaska (68°N) to southern Chile (50°S) using the mean of eight different Global Climate 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

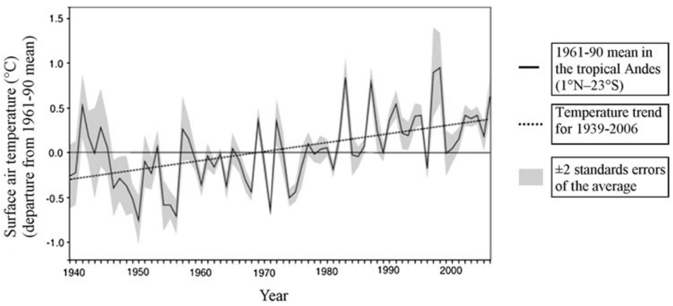


Fig. 2 Annual temperature deviation from the 1961–1990 average in the tropical Andes (1°N–23°S) between 1939 and 2006 based on a compilation of 279 station records (adapted from Vuille et al. 2008, p. 84). *Black line* shows long-term warming trend (0.10 °C/decade) based on ordinary least square regression

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).

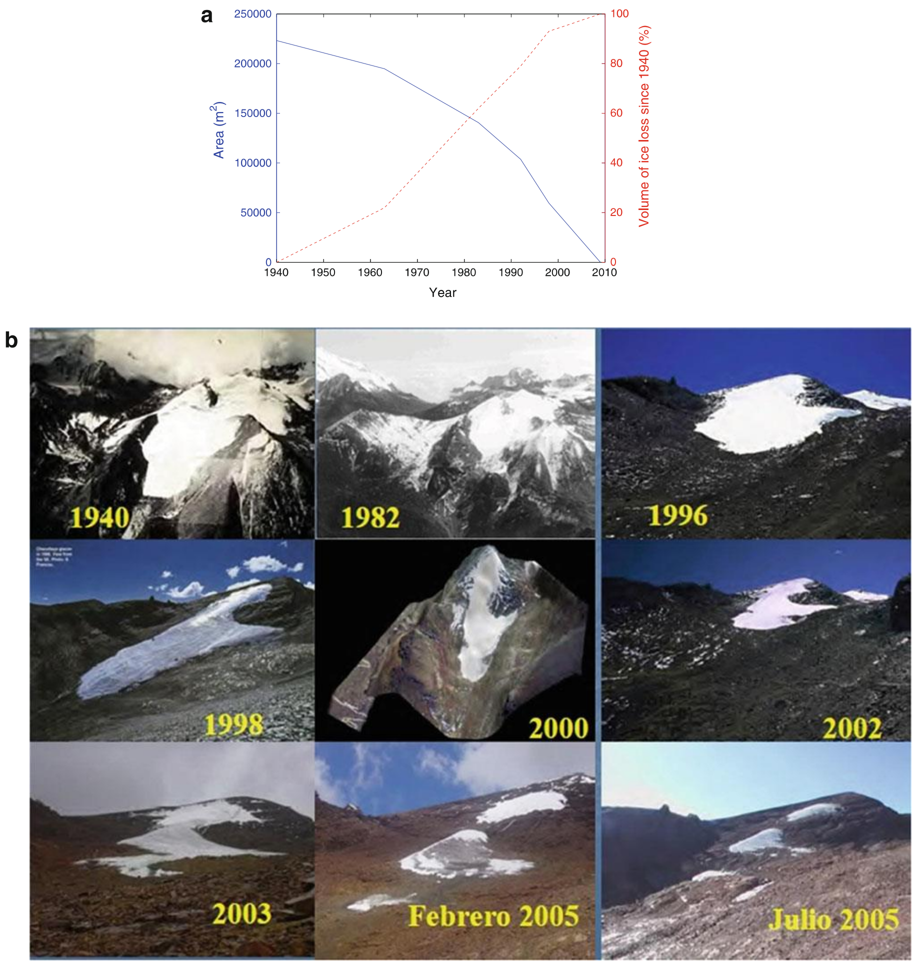


Fig. 3 **a** Graph showing the mass loss of ice from Chacaltaya during 1940–2009 in units of area and volume with its recession (data taken from Francou et al. 2000, p. 418). **b** Visual documented disappearance of the Chacaltaya glacier in Bolivia since 1940 through photography and modeling (taken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

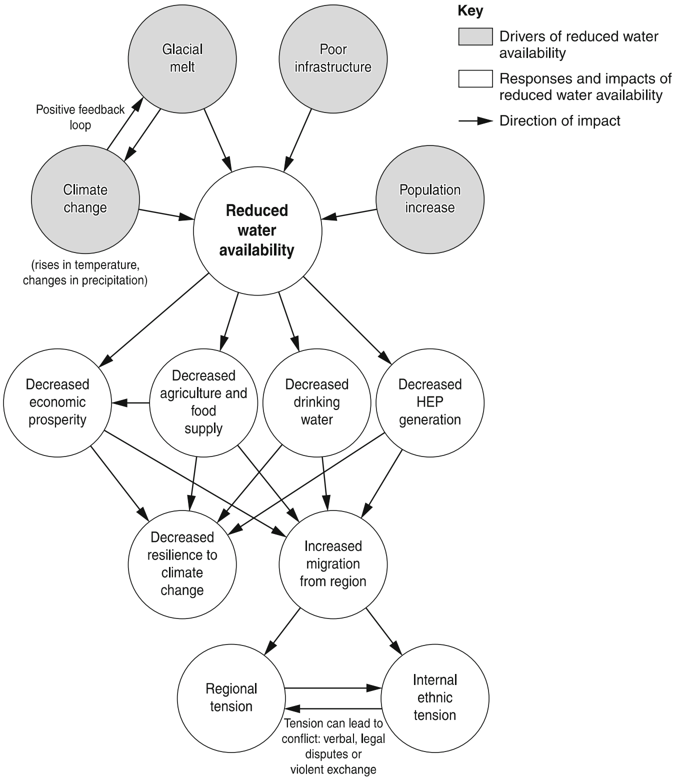


Fig. 4 Network diagram outlining the drivers of Bolivian water scarcity and impact relationships (adapted from Stewart 2010). *Gray circles* represent drivers of reduced water availability and *white circles* represent the responses of reduced water availability and further impacts

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

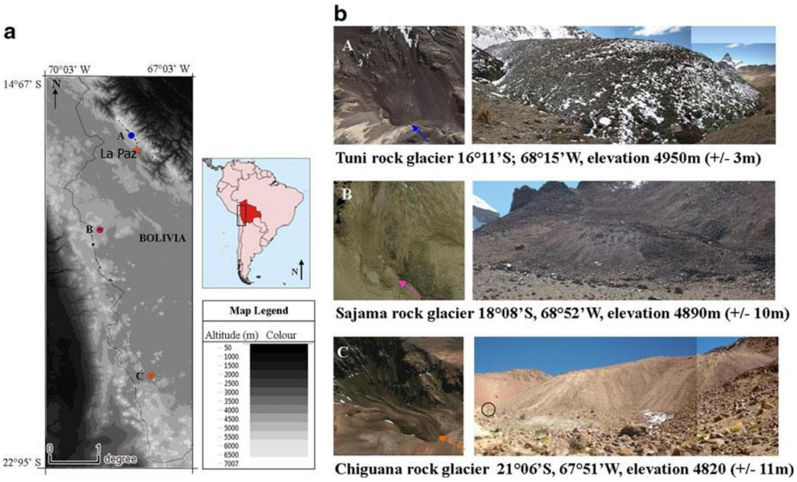
To address the growing issue of water security in arid mountain regions, water companies, governments and policy makers need better knowledge and information on current and future projections for water supplies and at finer spatial resolutions than existing models can provide. This will allow them to 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



Tuni rock glacier 16°11'S; 68°15'W, elevation 4950m (+/- 3m)

Sajama rock glacier 18°08'S, 68°52'W, elevation 4890m (+/- 10m)

Chiguana rock glacier 21°06'S, 67°51'W, elevation 4820 (+/- 11m)

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.

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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.

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Appendix 2: Rangecroft et al. 2014 publication in PPP

PERMAFROST AND PERIGLACIAL PROCESSES
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Short Communication
A First Rock Glacier Inventory for the Bolivian Andes

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ABSTRACT

Rock glaciers in the arid Bolivian Andes are potentially important water sources, but little is known about their spatial distribution and characteristics. We provide the first rock glacier inventory for the region (15–22°S), based on mapping using remote sensing data in Google Earth, supported by field validation. Of the 94 rock glaciers identified, 57 per cent were classified as active (containing ice) and the remaining as relict (not containing ice). The majority (87%) have a southerly aspect (SE, S and SW), and the rock glacier length and area averages were 500 m and 0.12 km^2, respectively. We approximate the lower limit of permafrost to be at 4700 m in the Bolivian Andes, with the mean minimum altitude of rock glacier fronts estimated to be 4980 m for active rock glaciers, and about 100 m lower for relict rock glaciers. The inventory provides an important first step towards assessing the spatial distribution of regional permafrost as well as information to allow permafrost-based water resources in the Bolivian Andes to be understood against a backdrop of severe glacier recession. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: rock glacier; inventory; Bolivia

INTRODUCTION

Rock glaciers are key stores of frozen water in arid mountains (Francou *et al*., 1999; Brenning, 2005; Azócar and Brenning, 2010; Kellerer-Pirklbauer *et al*., 2012; Rangecroft *et al*., 2013). In the dry Andes, glaciers are small and limited in their distribution (Esper Angillieri, 2009) because the equilibrium line altitude (ELA), where glacier accumulation balances with ablation (Zemp *et al*., 2007), exceeds some of the highest peaks (>6000 m) (Francou *et al*., 1999), and precipitation is scarce. Research on alternative stores of water at high elevations is needed in many regions of the world (Brenning *et al*., 2007) because of the projected scarcity of water if glacier recession continues (Bradley *et al*., 2006). Bolivian glaciers have lost roughly half of their volume in the past 60 years (Soruco *et al*., 2009) yet they 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 per cent of potable water for La Paz (Vergara, 2009; Soruco, 2012). In view of current and projected glacier recession, the contribution to water supplies from glaciers is expected to reduce (UNFCCC, 2007), whereas that from rock glaciers is likely to increase (Schrott, 1996; Millar and Westfall, 2008).

Rock glaciers have been inventoried in various mountain regions, with the highest density of research in the European Alps (e.g. Guglielmin and Smiraglia, 1998; Curtaz *et al*., 2011; Kellerer-Pirklbauer *et al*., 2012; Krainer and Ribis, 2012; Scotti *et al*., 2013), with increasing research activity in the South American Andes (Brenning, 2005; Esper Angillieri, 2009; Falaschi *et al*., 2014). Although rock glaciers are abundant and locally important to long-term water storage in the semi-arid Chilean Andes (Trombotto *et al*., 1999; Brenning, 2005), their contribution to mountain water supplies in other parts of the Andes, such as Bolivia, is uncertain. To mitigate the impacts of climate change, it is important to understand all inputs to the mountain hydrological cycle, including rock glaciers.

The primary aim of this study was to map the distribution of rock glaciers across Bolivia, and summarise the results of

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this new inventory. This work represents an important first step towards addressing water resource issues in the region, and by undertaking a survey of the current permafrost-based water resources, their hydrological contribution and importance at local, regional and national scales can be better understood. Rock glacier genesis is beyond the scope of this study.

STUDY AREA

Bolivia is situated in the central, dry part of the South American Andes (Payne, 1998). Its distinctive climate has a wet season (Dec–Feb) and a dry season (May–Aug) (Francou *et al*., 2003), with aridity increasing southwards (Figure 1). The rock glacier inventory encompasses the two Cordillera mountain ranges between 15°S and 22°S (Figure 1), home to 20 per cent of the world's tropical glaciers (Rabatel *et al*., 2013). It divides the Bolivian Andes into three regions based on location, climate and topography where rock glaciers occur (Figure 1): (i) the Cordillera Real; (ii) Sajama; and (iii) the Western Cordillera.

The 'Cordillera Real' is a glaciated fold mountain range (15–17°S) close to La Paz. With the wettest climate of the Bolivian Andes (Figure 1), this region contains the highest density of glaciers, and these are currently receding (Francou *et al*., 2003; Vergara *et al*., 2007). The bedrock comprises mainly resistant rocks of early Palaeozoic age that form prominent massifs. The 'Sajama' and 'Western Cordillera' regions are located along the Bolivia-Chile border in the mountain chain of the Cordillera Occidental, which is composed of Cretaceous-Tertiary volcanoes surrounded by Quaternary age deposits; all the high peaks there are volcanic cones. Sajama (17–18°S) is centred around the isolated ice-capped volcanic mountains in the Sajama National Park (Figure 1). The Western Cordillera extends south of Sajama, along the dry, barren mountain range of the Cordillera Occidental (18–22°S) (Figure 1). Almost no glaciers exist in this region (Francou *et al*., 1999) as rainfall is very low (Figure 1); annual precipitation is estimated to be less than 250–300 mm on the summits (Vuille and Amman, 1997). This area is the best example of arid high mountains in the inner tropics (Francou *et al*., 1999).

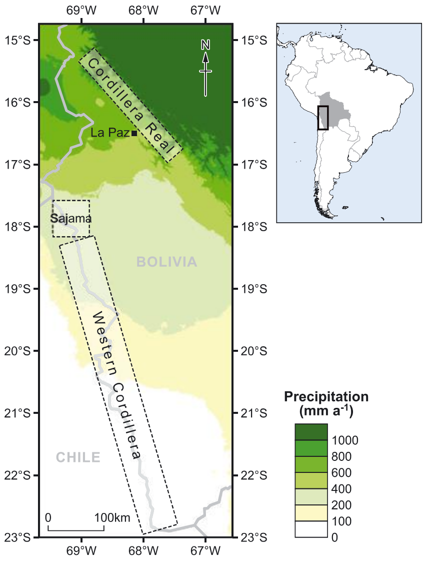

Figure 1 Map of the study area showing mean annual precipitation rates along the Bolivian Andes using WorldClim (http://www.worldclim.org/) 0.5° resolution data for 1950–2000. Three study regions have been identified and are subsequently used in this research: the Cordillera Real, Sajama and the Western Cordillera. Country boundaries are represented with a solid grey line. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

METHODS

Unlike glaciers, rock glaciers cannot easily be mapped automatically from remotely sensed data because they are spectrally similar to their surroundings (Brenning, 2009; Shukla *et al*., 2010). The optimal approach for generating this inventory was therefore to manually identify rock glaciers (Casassa *et al*., 2002) (Table 1) and digitise them. This inventory was achieved using expert photomorphic mapping from Google Earth and a 30 m global digital elevation model derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer sensor (ASTER).

Remote Sensing

Initial rock glacier mapping and evaluation used high-resolution (5 to 30 m) remote sensing data available through Google Earth (version 7.1.1.18888, Google Inc., California, USA), applying the criteria identified in Table 1, and supported with field validation. Google Earth provides a user-friendly GIS tool that facilitates the exploration of satellite data that are freely available and is well suited for assisting a developing world non-governmental organisation (NGO) (e.g. the Bolivian NGO 'Agua Sustentable'). Additionally, such data are particularly useful in large-scale geomorphological surveys (Slaymaker, 2001; Shukla *et al*., 2010) and where field access is difficult and/or limited (Kääb *et al*., 2005). Google Earth data have been applied across a range of research areas (Butler, 2006; Nourbakhsh *et al*., 2006; Ballagh *et al*., 2007, 2011; Chang *et al*., 2009; Sheppard and Cizek, 2009; Yu and Gong, 2012) and complement other satellite data or aerial photographs for geomorphological mapping (e.g. Brenning, 2005; Morén *et al*., 2011). Uncertainties to consider with this approach relate to the acquisition of remotely sensed data over

Table 1 Characteristics used to identify active and relict rock glaciers.

Characteristic features used for identification	Active	Relict	Notes
Frontal ramp	Steep (typically ≥ 30°)	Gently sloping (typically < 30°)	Frontal slope indicating the presence of ice (Baroni *et al*., 2004, p. 251). An angle exceeding the angle of repose indicates the presence of ice; however, the angle of repose depends on the lithology
Rock glacier body	Swollen body, indicating ice presence	A flattened body, result of ice disappearing	Possible swollen body indicating the presence of ice (Baroni *et al*., 2004, p. 251)
Surface texture	Signs of flow (e.g. ridges and furrows)	Less defined flow lines	Well-developed longitudinal and transversal ridges and furrows which act as signs of flow (Kääb and Weber, 2004, p. 379)

mountainous terrain subject to unfavourable meteorological conditions, topographic distortions and geometric uncertainties (e.g. differences in scale, horizontal displacements and shadows; Buchroithner, 1995).

Digitising Landform Characteristics

Planimetric landform characteristics extracted and recorded for each rock glacier (Figure 2) included geographic coordinates, elevation (minimum and maximum), length (parallel to flow), width (perpendicular to flow), aspect (main aspect of flow), and surface texture and features. The minimum altitude at the front (MAF) of each rock glacier was determined by locating the elevation of the lowest point on the rock glacier snout where it meets the slope beneath it. The maximum elevation at the head of the rock glacier was similarly recorded; however, it is acknowledged that defining the upper boundary of a rock glacier is difficult (Krainer and Ribis, 2012). Consistent judgement was made on where the upper boundary of the rock glacier meets the input accumulation zone above it. Measurements of rock glacier length and width used the ruler tool on Google Earth (Figure 2). Aspect was divided into eight classes and manually defined along the main direction of the flow of the rock glacier (Figure 2). Rock glacier surface area (km^2) of the digitised polygons was calculated using Google Earth Pro.

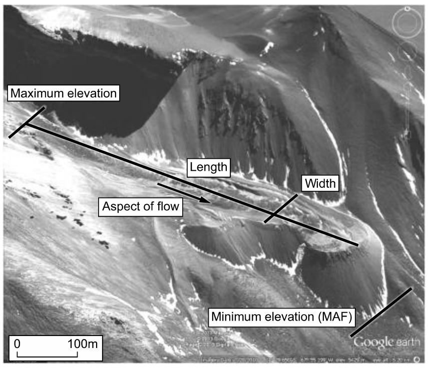

Figure 2 Annotated diagram of rock glacier parameters on the Caquella rock glacier (C110a), Bolivia (21°05'S, 67°92' W). Source: Google Earth; imagery date 20 July 2010.

Although rock glaciers are difficult to identify due to their composition of rock debris supplied from surrounding slopes (Shukla *et al*., 2010), morphological analysis can help to distinguish them from protalus lobes, debris-covered glaciers, rock slope failures and rock avalanches (Hamilton and Whalley, 1995; Seligman, 2009; Jarman *et al*., 2013). The length:width ratio distinguishes rock glaciers from other periglacial features (Harrison *et al*., 2008) such as protalus lobes and ramparts. A length:width ratio greater than 1 represents a tongue-shaped rock glacier (Guglielmin and Smiraglia, 1998; Harrison *et al*., 2008) and a ratio of less than 1 implies a lobate rock glacier or a protalus lobe or rampart. Although other permafrost features were identified (e.g. detachment failures), only active and relict rock glaciers meeting the identification criteria in Table 1 were analysed.

The activity status of rock glaciers was determined according to their assumed ice content and flow behaviour using morphological and geomorphological criteria from satellite image interpretation (Table 1) and/or field surveying. We sub-divided them as active/inactive (containing ice) or relict (no ice content) (Barsch, 1996; Baroni *et al*., 2004). Key features for identification include: surface micro-relief such as ridges and furrows, representing decelerating flow (Barsch, 1996); steep well-defined lateral margins; and a steep frontal snout, if ice is present (Payne, 1998; Harrison *et al*., 2008). Frontal slopes, with an angle usually greater than that of repose (~30–35°, depending on the material), indicate ice within the rock glacier mass (Barsch, 1996). Active rock glaciers are known to contain 40–60 per cent ice (Barsch, 1996; Brenning, 2005). Inactive rock glaciers also contain an ice core protected by sediment but are no longer mobile due to melting of most of the upper layers within the frontal slope (Barsch, 1996; Scotti *et al.*, 2013). Relict rock glaciers no longer contain ice and are characterised by collapse structures on their surface, more subtle surface relief and shallower frontal and lateral slope angles (<30°, depending on the material) (Barsch, 1996; Scotti *et al.*, 2013) than active features, and often have vegetated surfaces (Scotti *et al.*, 2013). Relict rock glaciers are usually found at lower elevations than active rock glaciers (Baroni *et al.*, 2004). Active rock glaciers typically occur between the 0 °C isotherm and the snow line, whereas relict rock glaciers generally occur just below the permafrost level/0 °C isotherm.

Mean rock glacier parameters were statistically compared between regions using SPSS (version 19, IBM Corp, Armonk, NY, USA). ANOVA, general linear models and Tukey post hoc tests were used to investigate regional differences in rock glacier parameters according to their activity. All statistical significance was tested at the 0.05 level. ArcGIS (version 10.1, ESRI, Redlands, CA, USA) and R (version 3.0.0, R Core Team, Vienna, Austria) were used to assess the relationship between mountain slope aspect and rock glacier orientation.

Field Validation

Field surveys were conducted during July–August 2011 and July - August 2012 in order to assess the reliability of the photomorphic mapping and rock glacier classification. Rock glaciers surveyed are identified in Tables S1–S6 in the Supplementary Data. Surveys validated rock glacier identification and activity classification by observing their features and measuring their frontal slope angle using an inclinometer. In existing rock glacier inventories, vegetation has been used as a further characteristic for determining rock glacier activity (e.g. Seligman, 2009; Scotti *et al.*, 2013); however, here we refrained from relying on this proxy without further information on the ecology and plant types. Furthermore, in Bolivia's arid environment, vegetation is sparse and with a lack of other studies from the region, it was not a critical factor in classifying rock glacier activity.

RESULTS

A total of 94 rock glaciers were identified in the Bolivian Andes (Table 2; Figures 3 and 4), of which 54 (57%) were

Table 2 Key mean characteristics for active and relict rock glaciers.

	Number of features	(%)	MAF (m)	MaxE (m)	Length (m)	Width (m)	Area (km^2)	Aspect
Active	54	(57)	4983	5162	552	239	0.132	SE
Relict	40	(43)	4870	5009	432	253	0.108	S

MAF = Minimum altitude at the front; MaxE = maximum elevation of rock glacier.

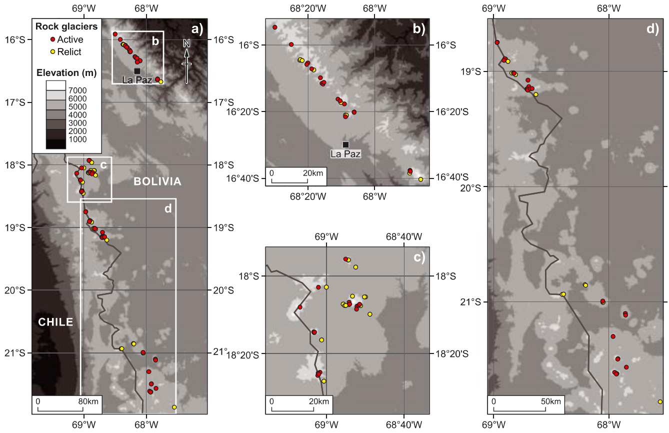

Figure 3 National and regional rock glacier inventories for the Bolivian Andes using an ASTER global digital elevation model (30 m resolution): (a) Nationally (15–22°S) with regions outlined in boxes: (b) the Cordillera Real (15–16°S); (c) Sajama region (17–18°S); (d) the Western Cordillera region (18–22°S). This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

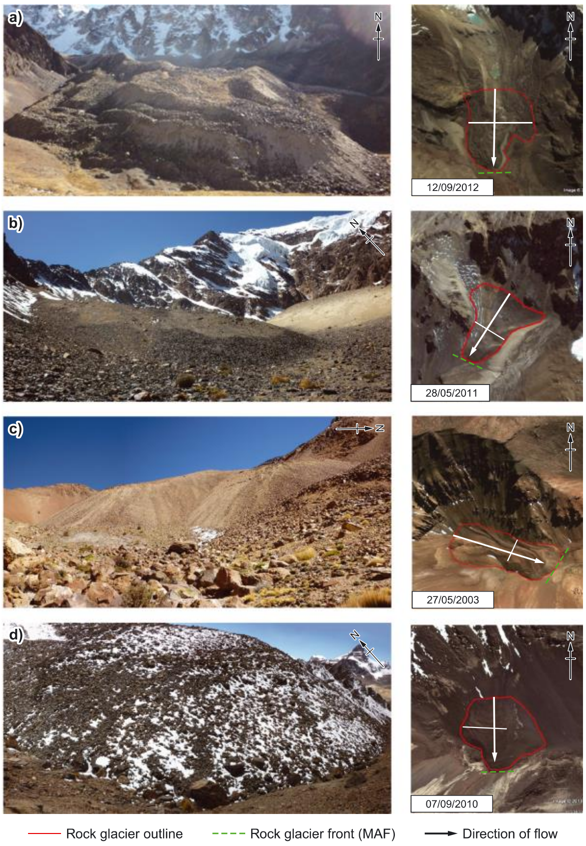

Figure 4 Rock glaciers visited during fieldwork 2011 and 2012 with corresponding Google Earth screen shots with imagery dates: (a) Huayna Potosi rock glacier (A39a) 16°17’55S, 68°09’05 W; (b) Illimani rock glacier (A40a) 16°37’44S, 67°49’25 W; (c) Chiguana rock glacier (C107a) 21°06’09S, 67°51’13 W; (d) Tuni rock glacier (A20a) 16°11’48S, 68°15’28 W. Rock glacier outlines and fronts are highlighted on the Google Earth images. Approximate orientations of the rock glaciers and the photographs are indicated. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

designated as active and the remaining as relict (43%). Eighty-nine per cent of the rock glaciers were classified as tongue-shaped. Eighty-seven per cent were developed with a southward flow direction. Ninety per cent of the rock glaciers were situated between 4700 and 5200 m altitude, with 6 per cent occurring above 5200 m and 4 per cent below 4700 m. The calculated mean MAF for active rock glaciers was 4983 m (±30 m), and 4870 m (±30 m) for relict ones (Table 2). Rock glacier characteristics were analysed at a national and a regional level. Tables S1–S6 in the Supplementary Data detail the information for each rock glacier recorded.

Rock Glacier Elevation and Range

Rock glaciers occurred within an elevation range of 4475 to 5345 m (Figures 5 and 6a, b). On average, active ones occurred at higher elevations than relict ones. Nationally, the mean MAF for all active rock glaciers was ~4985 m (±30 m) (Table 2), with a range of 4709 to 5345 m (Figures 5 and 6a), while the most frequent elevation band was 4900–5000 m (28%). Over half of the active rock glaciers (52%) were situated in the elevation bands 4900–5100 m (Figure 5). The highest active rock glacier was located in

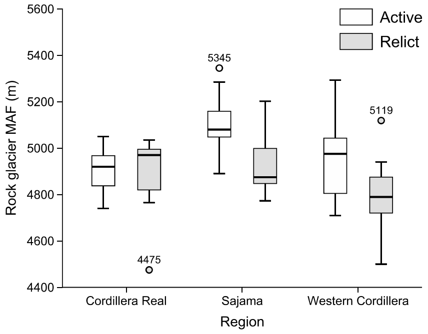

Figure 5 Box plot illustrating the regional analysis of rock glacier minimum altitude at fronts (MAFs).

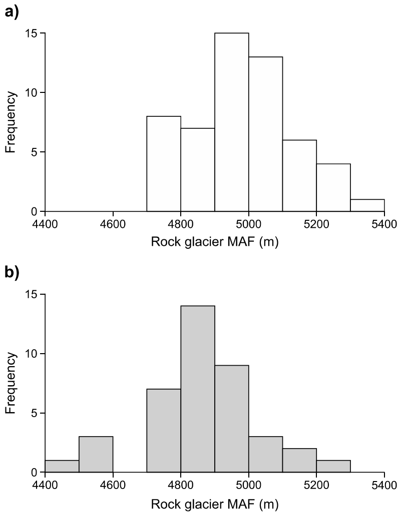

Figure 6 National rock glacier minimum altitude at the front (MAF) analysis: histograms for (a) active (white) and (b) relict (grey) rock glacier MAF elevations.

the Sajama region (B124a). The mean MAF for relict rock glaciers was roughly 100 m lower, at 4870 m (±30 m) (Table 2), with a range of 4475 to 5202 m (Figures 5 and 6b). The highest relict rock glacier was also situated in the Sajama region (B118b). Over a third of the relict rock glaciers were situated in the elevation band 4800–4900 m (35%), with 58 per cent of them between 4800 and 5000 m (Figure 6b). The box plots of Figure 5 show that the Western Cordillera had the largest elevation spread of both active and relict rock glacier elevations, whereas the Cordillera Real had the smallest range of active rock glacier MAFs (Figure 5).

Regionally, larger differences were observed between active and relict rock glacier elevations (MAFs) than on the national scale, although no significant difference was found (ANOVA: F-value = 5.756, *df* within groups = 1, between groups = 88, $p = 0.138$), presumably because of similar MAFs in the Cordillera Real (see Figure 8). Active rock glaciers in Sajama were on average at 175 m higher elevations than relict ones. Equally, active rock glaciers in the Western Cordillera were 173 m higher than relict ones there (Table 3). Across the regions, combined active and relict rock glaciers of Sajama were found at significantly different elevations compared to those in the Western Cordillera region ($p = 0.007$) and also the Cordillera Real ($p = 0.001$) (linear model: F-value: 3.697, *df* within groups = 2, between groups = 88). However, those in the Cordillera Real and Western Cordillera were not of significantly different elevations ($p = 0.949$).

Tukey post hoc testing (ANOVA: F-value: 8.161, *df* within groups = 5, between groups = 88, $p = < 0.001$) showed that active rock glacier MAFs in Sajama were statistically at higher elevations than in the other regions (Figure 7): the Cordillera Real ($p = 0.002$) and Western Cordillera ($p = 0.018$). Sajama's relict rock glacier MAFs were also found at significantly higher elevations than relict MAFs in the Western Cordillera ($p = 0.048$).

Aspect

South-facing slopes are the most suitable for rock glacier development and formation. Eighty-seven per cent of rock glaciers in the inventory have developed on south-facing aspects (SE, S and SW) (Figure 8), with SE being the predominant aspect (34%). Eighty-eight per cent of the active rock glaciers had a main flow direction to the south, and 86 per cent of the relict ones also had south-facing aspects. Such aspects have allowed rock glaciers to exist at lower elevations (Figure 8a), in varying sizes, including the largest rock glaciers in the country (Figure 8b). Figure 9a shows that the frequency of hillslope aspects in the Bolivian Andes is relatively uniform, whereas Figure 9b shows a strong clustering of active rock glaciers on southerly facing slopes. Further analysis of these data sought to determine rock glacier density at each aspect for all pixels above the lowest MAF (4709 m; Figure 9c); this figure also indicates that south-facing slopes have a much greater propensity for rock glacier formation and persistence.

Rock Glacier Morphology

Eighty-nine per cent of the rock glaciers in the study area are tongue-shaped, and this proportion is similar between active and relict forms (91% and 87%, respectively). Each

Table 3 Regional rock glacier characteristics.

Region	Area of region (km^2)	Activity status	Number of features	Mean MAF (m)	Mean MaxE (m)	Mean feature length (m)	Mean feature width (m)	Mean area (km^2)	Modal aspect
Cordillera Real	~ 7050	Active	16	4906	5033	380	212	0.07	SW
		Relict	10	4891	5036	378	150	0.08	S
Sajama	~ 4000	Active	15	5110	5307	753	242	0.20	SE
		Relict	16	4934	5073	519	252	0.13	S
Western Cordillera	~ 25 000	Active	23	4954	5158	541	253	0.13	SE
		Relict	14	4781	4915	373	328	0.09	SW
Total	36 050		94						

MAF = Minimum altitude at the front; MaxE = maximum elevation of rock glacier.

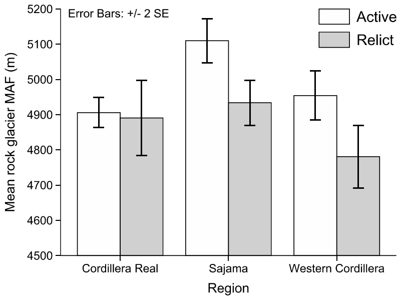

Figure 7 Regional analysis of active and relict rock glacier elevation represented by average minimum altitude at fronts (MAFs) with ± 2 standard error bars.

region had at least one rock glacier longer than 1 km, but overall 93 per cent of the rock glaciers were less than 1 km long, with an overall average length of 500 m. On average, Sajama had the longest active ($\overline{X} = 753\,\text{m} \pm 30\,\text{m}$) and relict ($\overline{X} = 519\,\text{m} \pm 30\,\text{m}$) rock glaciers in Bolivia (Figure 10a) and the Cordillera Real had the smallest active ($\overline{X} = 380\,\text{m} \pm 30\,\text{m}$) and relict ($\overline{X} = 378\,\text{m} \pm 30\,\text{m}$) ones (Table 3; Figure 10a). However, rock glacier length did not differ significantly between regions (ANOVA: F-value = 5.18, *df* within groups = 2, between groups = 88, $p = 0.162$).

In total, it is estimated that rock glaciers cover 11 km^2 of the Bolivian Andes (Table 4). Individually, rock glacier area varies between 0.006 and 0.789 km^2, a similar range to that in the Chilean Andes (Brenning, 2005, p. 234). Mean rock glacier area was 0.12 km^2, with a median area of 0.08 km^2 (Table 4). In total, 56 per cent of the rock glaciers were smaller than 0.1 km^2. The largest rock glaciers were found in Sajama, with active ones averaging 0.2 km^2 (Table 3). No correlation was observed between rock glacier length and elevation (linear model: $r = 0.07$, $df = 92$, $p = 0.501$) (Figure 10b), and between rock glacier area and elevation ($r = 0.01$, $df = 92$, $p = 0.929$). Similarly, no significant correlation was seen between latitude and both rock glacier length ($r = 0.056$, $df = 92$, $p = 0.591$) and area ($r = 0.052$, $df = 92$, $p = 0.616$). Bolivian rock glaciers are of similar size or slightly larger than rock glaciers elsewhere (e.g. Colorado, Austria) (Table 4), but their abundance in Bolivia is much lower.

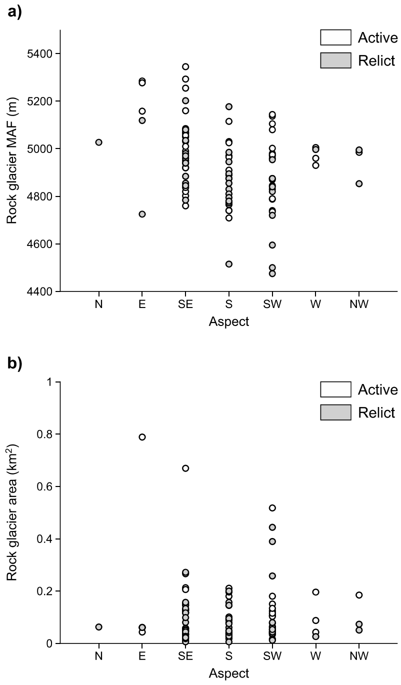

Figure 8 (a) Scatter plot of all minimum altitude at the front (MAF) elevations against categorised rock glacier aspect; (b) aspect plotted against rock glacier area.

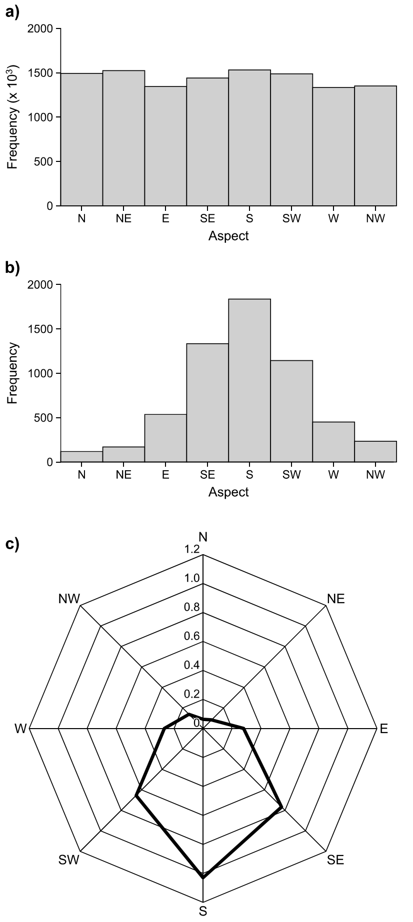

Figure 9 Analysis of hillslope aspect for rock glacier sites: (a) histogram of aspect for all mountain slopes in the Bolivian Andes showing a uniform frequency distribution; (b) histogram of aspect for rock glacier sites in the Bolivian Andes; (c) radar plot showing the active rock glacier densities for each aspect for all data in the Bolivian Andes above the lowest minimum altitude at the front (4709 m). All data are from an ASTER global digital elevation model (30 m resolution).

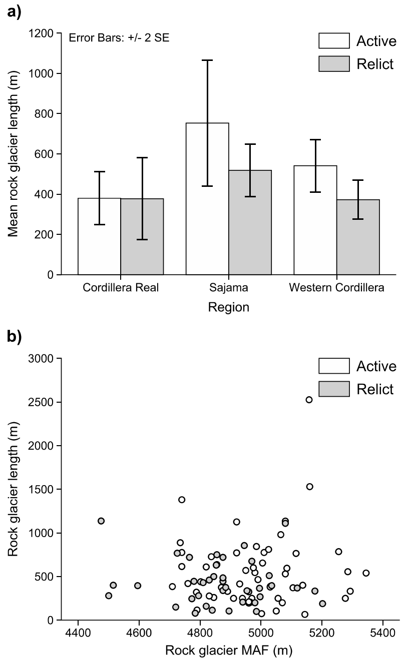

Figure 10 (a) Regional analysis of average rock glacier length with error bars representing ± 2 standard errors; (b) elevation, represented by rock glacier minimum altitude at fronts (MAFs), plotted against length (m).

DISCUSSION

This Bolivian rock glacier inventory has identified 54 active (and 40 relict) rock glaciers in the high arid mountains. Along the Cordillera Occidental, rock glaciers cluster around a few isolated mountain peaks (e.g. Sajama 18°S, 68°W). This is recognised as 'island permafrost', common across other parts of the Central Andes (Travassos *et al.*, 2008). The MAF for rock glaciers is often considered a good approximation of the lower limit of discontinuous permafrost (Scotti *et al.*, 2013). No active rock glaciers are found below 4700 m, implying that this is the lower limit of permafrost in the Bolivian Andes. This value is slightly higher but broadly consistent with that of 4500 m for the lower limit of active rock glaciers in the Argentinian Andes at 22°30'S (Corte *et al.*, 1982). Bolivian rock glaciers occur at higher elevations (>4400 m) than of those in the Chilean Andes, where Brenning (2005) identified rock glaciers at 3000 m and higher. Rock glacier size appears to be similar to those in recent European rock glacier inventories (Krainer and Ribis, 2012; Kellerer-Pirklbauer *et al.*, 2012), yet their frequency is lower, and thus their total surface area is less than those in the European Alps (Table 4).

Optimum conditions for rock glaciers occur in areas with high elevation, cold temperatures and low precipitation

Table 4 Rock glacier size (area) from this inventory compared to other rock glacier inventories.

	Number of rock glaciers	Average rock glacier area (km^2)	Median rock glaciers area (km^2)	Total rock glacier surface area (km^2)	Reference
Bolivia	94	0.12	0.08	11	—
San Juan Mountains, Colorado	756	0.064	0.051	70	Brenning *et al.* (2007)
Tyrolean Alps, Austria	3145	0.088	—	167.2	Krainer and Ribis (2012)
Eastern European Alps	347	0.061	—	21.3	Kellerer-Pirklbauer *et al.* (2012)

(Baroni *et al*., 2004): conditions characteristic of the Bolivian Andes. The key controls on rock glacier characteristics and formation are thought to be climatic conditions, glacial history and rock supply (Johnson *et al*., 2007; Guglielmin and Smiraglia, 1998). On a regional scale, rock glacier distribution is climatically controlled by precipitation and temperature, the latter dependent on elevation and aspect. Despite the availability of appropriate climatic conditions for rock glacier formation and persistence in the Bolivian Andes, the distribution of these landforms there is limited. This suggests that other factors such as rock supply, lithology, glacial history, competition with glaciers and geothermal fluxes (Brenning, 2005; Johnson *et al*., 2007) ultimately determine the locations where they form and persist. Unfortunately, high-quality lithological data were not available for use in this study.

Even though temperature is a key control on rock glacier activity, no correlation was observed between elevation and rock glacier length ($r = 0.07$) or area ($r = 0.01$), also suggesting the importance of other factors such as debris supply. However, the inventory did show that aspect is an important parameter for rock glacier formation (Figure 9b). In the southern hemisphere, south-facing slopes are more likely to host glaciers and rock glaciers (Esper Angillieri, 2010) in association with reduced insolation and increased accumulation of snow, ice and rock debris (Esper Angillieri, 2009). This inventory also suggests that southerly aspects, with their reduced insolation, allow rock glaciers to exist at lower elevations than at other aspects (Figure 8a).

Rock glaciers develop between the 0 °C isotherm and the regional snow line (e.g. Payne, 1998; Milana and Maturano, 1999). The elevation at the front of active rock glaciers, the MAF, corresponds closely to the 0 °C isotherm, which this inventory suggests lies at 4900–5000 m. Relict features interpreted as former rock glaciers reflect a change in the 0 °C isotherm elevation, associated with changes in climate and/or debris supply (Esper Angillieri, 2010). The mean difference of 100 m that we observed between active and relict rock glaciers (Table 2) represents this upward shift in the isotherm over time. The modern 0 °C isotherm descends from north to south along the Western Cordillera (Payne, 1998) but the ELA increases with aridity, leading to a bigger niche for rock glaciers. This is demonstrated by the larger range of rock glacier MAFs in this region (Figure 5). However, with rising regional temperatures there will be smaller niches for active rock glaciers to occupy as the 0 °C isotherm moves closer to, or above, mountain summits. Therefore a warming climate will decrease the number of active rock glaciers and increase the number of relict ones (Krainer and Ribis, 2012). Equally, it can also be hypothesised that rock glaciers may become more frequent in the Cordillera Real as glaciers retreat and increased debris supply buries their surfaces, producing glacial-derived rock glaciers.

In the wetter climate of the Cordillera Real, conditions favour glaciers. This smaller niche for rock glaciers was confirmed by our analyses, which determined that the Cordillera Real had the smallest elevation range of active rock glaciers (4740–5050 m) of the three regions in Bolivia (Figure 5). The drier Western Cordillera had a larger total area of rock glaciers, a surface area of 2.88 km^2 for active rock glaciers and the largest range of elevations of all regions (4500–5255 m). From the remotely sensed data, we observed that rock glaciers were also better developed in the Western Cordillera. Collectively, these observations suggest that conditions in the Western Cordillera region are the most conducive for active rock glaciers in the Bolivian Andes.

Given the lack of glaciers in the Western Cordillera, this rock glacier inventory indicates that rock glaciers there could be considered as hydrologically important features to mountain communities (18–22°S). Similarly, in Sajama where glacier ice is also limited, rock glaciers may be important for local mountain communities and the Sajama National Park. However, glaciers dominate in the Cordillera Real, with a recent estimated coverage of 185.5 km^2 (Ramirez *et al*., 2012), while rock glaciers are less abundant and smaller (Table 3). Here, we estimated that rock glaciers cover 1.07 km^2 and hence we argue that they are not an important source of water (in comparison to glaciers) for the La Paz region. However, unlike glacier ice, the ice within rock glaciers is protected from small thermal changes by the insulating rock layer, resulting in a longer lag time in their response to climate change, responding on the decadal timescale (Haeberli *et al*., 2006). Therefore, rock glaciers are likely to become increasingly important in mountain regions for water reservoirs given climate warming (Schrott, 1996; Millar and Westfall, 2008). Hence, there is a need to understand current controls on rock glacier development and explore the impact of climate change on rock glaciers.

CONCLUSIONS

This new inventory of rock glaciers in the Bolivian Andes has identified 94 such landforms, covering an estimated 11 km^2, of which 57 per cent were classified as active and the remaining as relict. The majority (87%) of rock glaciers had a southerly aspect (SE, S and SW), suggesting the importance of reduced solar input for their development. The lower limit of permafrost is thought to be at 4700 m in the Bolivian Andes, an estimation which is in agreement with those of surrounding regions. Regional differences in rock glacier elevation, distribution and size were found between the Cordillera Real, Sajama and Western Cordillera and result from variations in aridity, rock supply and direct competition with ice glaciers. The Western Cordillera has the largest niche zone for rock glacier formation and development, which has led to some of the largest and most developed rock glaciers in the Bolivian Andes. Rock glaciers in Bolivia are important sources of water in the Western Cordillera, and may become increasingly important in the Cordillera Real region, where there is growing evidence of severe ice glacier recession.

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REFERENCES

Azócar GF, Brenning A. 2010. Hydrological and geomorphological significance of rock glaciers in the Dry Andes, Chile (27°-33°S). *Permafrost and Periglacial Processes* **21**: 42–53. DOI: 10.1002/ppp.669

Ballagh LM, Parsons MA, Swick R. 2007. Visualising cryopsheric images in a virtual environment: present challenges and future implications. *Polar Record* **43**(4): 305–310.

Ballagh LM, Raup BH, Duerr RE, Khalsa SJS, Helm C, Fowler D, Gupte A. 2011. Representing scientific data sets in KML: Methods and challenges. *Computers and Geosciences* **37**(1): 57–64.

Baroni C, Carton A, Seppi R. 2004. Distribution and behaviour of rock glaciers in the Adamello-Presanella Massif (Italian Alps). *Permafrost and Periglacial Processes* **15**: 243–259. DOI: 10.1002/ppp.497

Barsch D. 1996. Rockglaciers – Indicator for the Present and Former Geoecology in High Mountain Environments. Springer: Berlin.

Bradley RS, Vuille M, Diaz HF, Vergara W. 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 and Periglacial Processes* **16**: 231–240. DOI: 10.1002/ppp.528

Brenning A. 2009. Benchmarking classifiers to optimally integrate terrain analysis and multispectral remote sensing in automatic rock glacier detection. *Remote Sensing of Environment* **113**: 239–247.

Brenning A, Grasser M, Friend DA. 2007. Statistical estimation and generalized additive modeling of rock glacier distribution in the San Juan Mountains, Colorado, United States. *Journal of Geophysical Research* **112**(F2). DOI: 10.1029/2006JF000528

Buchroithner MF. 1995. Problems of mountain hazard mapping using spaceborne remote sensing techniques. *Advances in Space Research* **15**(11): 57–66.

Butler D. 2006. Virtual globes: The web-wide world. *Nature* **439**: 776–778.

Casassa G, Smith K, Rivera A, Araos J, Schnirch M, Schneider C. 2002. Inventory of glaciers in isla Riesco, Patagonia, Chile, based on aerial photography and satellite imagery. *Annals of Glaciology* **34**: 373–378.

Chang AY, Parrales ME, Jimenez J, Sobieszczyk ME, Hammer SM, Copenhaver DJ, Kulkarni RP. 2009. Combining Google Earth and GIS mapping technologies in a dengue surveillance system for developing countries. *International Journal of Health Geographics* **8**(49). DOI: 10.1186/1476-072X-8-49

Chevallier P, Pouyaud B, Suarez W, Condom T. 2011. Climate change threats to environment in the tropical Andes: glaciers and water resources. *Regional Environmental Change* **11**(1): 179–187.

Corte AE, Trombotto DTA, Ahumada AL. 1982. Relevamiento de la geomorfología criogénica del NW Argentino. *IANIGLA-CRICYT, Mendoza.*

Curtaz M, Vagliasindi M, Letey S, Morra di Cella U, Pogliotti P. 2011. A new rock glaciers inventory in the North-Western Alps. *Geophysical Research Abstracts* **13**.

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

Esper Angillieri MY. 2010. Application of frequency ratio and logistic regression to active rock glacier occurrence in the Andes of San Juan, Argentina. *Geomorphology* **114**: 396–405.

Falaschi D, Castro M, Masiokas M, Tadono T, Ahumada A L. 2014. Rock glacier inventory of the Valles Calchaquíes region (~25°S), Salta, Argentina, derived from ALOS data. *Permafrost and Periglacial Processes* **25**(1): 69–75. DOI: 10.1002/ppp.1801

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

Francou B, Vuille M, Wagnon P, Mendoza J, Sicart JE. 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**: 1–12.

Guglielmin M, Smiraglia C. 1998. The rock glacier inventory of the Italian Alps. In *Permafrost – Seventh International Conference* (*Proceedings*), Yellowknife (Canada). Collection Nordicana No. 55: 375–382.

Haeberli W, Hallet B, Arenson L, Elconin R, Humlum O, Kääb A, Kaufmann V, Ladanyi B, Matsuoka N, Springman S, Mühll DV. 2006. Permafrost creep and rock glacier dynamics. *Permafrost and Periglacial Processes* **17**: 189–214. DOI: 10.1002/ppp.561

Hamilton SJ, Whalley B. 1995. Rock glacier nomenclature: A re-assessment. *Geomorphology* **14**(1): 73–80.

Harrison S, Whalley B, Anderson E. 2008. Relict rock glaciers and protalus lobes in the British Isles: implications for Late Pleistocene mountain geomorphology and palaeoclimate. *Journal of Quaternary Science* **23**(3): 287–304.

Jarman D, Wilson P, Harrison S. 2013. Are there any relict rock glaciers in the British mountains? *Journal of Quaternary Science* **28**: 131–143. DOI: 10.1002/jqs.2574

Johnson BG, Thackray GD, Van Kirk R. 2007. The effect of topography, latitude, and lithology on rock glacier distribution in the Lemhi Range, central Idaho, USA. *Geomorphology* **91**: 38–50. DOI: 10.1002/ppp.506

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

Kääb A, Weber M. 2004. Development of transverse ridges on rock glaciers: field measurements and laboratory experiments. *Permafrost and Periglacial Processes* **15**(4): 379–391. DOI: 10.1002/ppp.506

Kääb A, Huggel C, Fischer L, Guex S, Paul F, Roer I, Salzmann N, Schlaefli S, Schmutz K, Schneider D, Strozzi T, Weidmann Y. 2005. Remote sensing of glacier- and permafrost-related hazards in high mountains: An overview. *Natural Hazards and Earth System Sciences* **5**: 527–554.

Kellerer-Pirklbauer A, Lieb GK, Kleinferchner H. 2012. A new rock glacier inventory of the Eastern European Alps. *Austrian journal of Earth Sciences* **105**(2): 78–93.

Krainer K, Ribis M. 2012. A rock glacier inventory of the Tyrolean Alps (Austria). *Austrian Journal of Earth Sciences* **105**(2): 32–47.

Milana JP, Maturano A. 1999. Application of radio echo sounding at the arid Andes of Argentina: the Agua Negra Glacier. *Global and Planetary Change* **22**: 179–191.

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

Morén B, Heyman J, Stroeven AP. 2011. Glacial geomorphology of the central Tibetan Plateau. *Journal of Maps* **7**(1): 115–125. DOI: 10.4113/jom.2011.1161

Nourbakhsh I, Sargent R, Wright A, Cramer K, McClendon B, Jones M. 2006. Mapping disaster zones. *Nature* **439**: 787–788.

Payne D. 1998. Climatic implications of rock glaciers in the arid Western Cordillera of the Centra Andes. *Glacial Geology & Geomorphology* rp03.

Rabatel A, Francou B, Soruco A, Gomez J, Cáceres B, Ceballos JL, Basantes R, Vuille M, Sicart JE, Huggel C, Scheel M, Lejeune Y, Arnaud Y, Collet M, Condom T, Consoli G, Favier V, Jomelli V, Galarraga R, Ginot P, Maisincho L, Mendoza J, Ménégoz M, Ramirez E, Ribstein P, Suarez W, Villacis M, Wagnon P. 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, Ribeiro R, Machaca A, Fuertes R, Simões J. 2012. Glacier inventory of the Cordillera Real – Bolivia using high resolution satellite images ALOS and CBERS-2B. *Geophysical Research Abstracts*, EGU General Assembly 2012, vol. 14.

Rangecroft S, Harrison S, Anderson K, Magrath J, Castel AP, Pacheco P. 2013. Climate change and water resources in arid mountains: an example from the Bolivian Andes. *AMBIO* **42**(7): 852–863.

Schrott L. 1996. Some geomorphological-hydrological aspects of rock glaciers in the Andes (San Juan, Argentina). *Zeitschrift für Geomorphologie* **104**: 161–173.

Scotti R, Brardinoni F, Alberti S, Frattini P, Crosta GB. 2013. A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps. *Geomorphology* **186**: 136–149.

Seligman ZM. 2009. Rock glacier distribution, activity, and movement, Northern Absaroka and Beartooth Ranges, MT, USA. MSc thesis, University of Colorado, Boulder, Colorado, USA.

Sheppard SRJ, Cizek P. 2009. The ethics of Google Earth: Crossing thresholds from spatial data to landscape visualisation. *Journal of Environmental Management* **90**: 2102–2117.

Shukla A, Gupta RP, Arora MK. 2010. Delineation of debris-covered glacier boundaries using optical and thermal remote sensing data. *Remote Sensing Letters* **1**(1): 11–17.

Slaymaker O. 2001. The role of remote sensing in geomorphology and terrain analysis in the Canadian Cordillera. *International Journal of Applied Earth Observation and Geoinformation* **3**(1): 11–17.

Soruco A, Vincent C, Francou B, Gonzalez JF. 2009. Glacier decline between 1963 and 2006 in the Cordillera Real, Bolivia. *Geophysical Research Letters* **36**(6). DOI: 10.1029/2008GL036238

Soruco AS. 2012. Medio siglo de fluctuaciones glaciares en la Cordillera Real y sus efectos hidrológicos en la ciudad de La Paz. IRD, Bolivia. ISBN 9789995455620 (Spanish).

Travassos JM, Stael GC, Liaudat DT. 2008. A GPR survey on degraded permafrost at Mesón San Juan, Mendonza, Argentina. *Revista Brasileria de Geoffsica* **26**(4): 519–526.

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

UNFCCC. 2007. Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries. United Nations Framework Convention on Climate Change. http://unfccc.int/resource/docs/publications/impacts.pdf [12 June 2013].

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, Kondo H, Pérez EP, Pérez JMM, Rueda VM, Arango MCM, Murcia JFR, Roldán GJA, Palcios E. 2007. 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.

Vuille M, Amman C. 1997. Regional snowfall patterns in the high, arid Andes. *Climatic Change* **36**: 413–423.

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

Yu L, Gong P. 2012. Google Earth as a virtual globe tool for Earth science applications at the global scale: progress and perspectives. *International Journal of Remote Sensing* **33**(12): 3966–3986.

Zemp M, Hoelzle M, Haeberli W. 2007. Distributed modelling of the regional climatic equilibrium line altitude of glaciers in the European Alps. *Global and Planetary Change* **56**(1–2): 83–100.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site.

Appendix 3: ANOVA Post-hoc results for statistical testing

Tukey post-hoc results for RapidEye satellite data bands 1 – 5 across the 10 ROIs (listed in Table 6.5). All results not shown indicated that their ‘Mean difference’ results were significantly different to the 0.05 level. Results that are significantly similar have been extracted from the SPSS output and are shown in the following table:

Multiple Comparisons

Dependent variable: B1
Tukey HSD

(I) Region	(J) Region	Mean difference (I-J)	Std Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	5	16.203	41.372	1.000	-114.75	147.16
5	1	-16.203	41.372	1.000	-147.16	114.75
7	8	68.301	41.372	.823	-62.66	199.26
8	7	-68.301	41.372	.823	-199.26	62.66

Dependent variable: B2
Tukey HSD

(I) Region	(J) Region	Mean difference (I-J)	Std Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	5	-109.501	51.913	.521	-273.83	54.82
5	1	109.501	51.913	.521	-54.82	273.83
6	9	-151.462	51.913	.101	-315.79	12.86
9	6	151.462	51.913	.101	-12.86	315.79

Dependent variable: B3
Tukey HSD

(I) Region	(J) Region	Mean difference (I-J)	Std Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	10	178.497	60.874	.097	-14.19	371.19
6	9	-34.601	60.874	1.000	-227.29	158.09
9	6	34.601	60.874	1.000	-158.09	227.29
10	1	-178.497	60.874	.097	-371.19	14.19

Dependent variable: B4
Tukey HSD

(I) Region	(J) Region	Mean difference (I-J)	Std Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	10	98.769	58.001	.794	-84.82	282.36
6	9	22.247	58.001	1.000	-161.35	205.84
9	6	-22.247	58.001	1.000	-205.84	161.35
10	1	-98.769	58.001	.794	-282.36	84.82

Dependent variable: B5
Tukey HSD

(I) Region	(J) Region	Mean difference (I-J)	Std Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	10	86.650	48.835	.752	-67.93	241.23
6	9	118.068	48.835	.315	-36.51	272.65
9	6	-118.068	48.835	.315	-272.65	36.51
10	1	-86.650	48.835	.752	-241.23	67.93

Appendix 4: Questionnaire (English)

The aim of this questionnaire is to collect data for my PhD research with the University of Exeter, UK. No personal data will be used and questionnaires will remain anonymous. Thank you for participating.

Sally Rangecroft

sr332@exeter.ac.uk

<u>Your understanding of the topic</u>

<u>Rock glaciers</u>

1. Have you heard of a 'rock glacier' before?
   - ☐ Yes
   - ☐ No (if no, please move onto question 2)

   a. If 'yes', please describe a rock glacier in the space below

   ……………………………………………………………………………………

   ……………………………………………………………………………………

   ……………………………………………………………………………………..

   b. If 'yes', what is your current knowledge of rock glaciers in Bolivia?

   ……………………………………………………………………………………

   ……………………………………………………………………………………

   ……………………………………………………………………………………

Please circle the answers below that you feel are most accurate for you

2. I am knowledgeable about rock glaciers, specifically rock glaciers in Bolivia:

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Climate change

3. I am knowledgeable about climate change in the Bolivian Andes

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

4. Climate change is expected to affect water resources in the Bolivian Andes

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

5. If possible, list 3 impacts of climate change in the Bolivian Andes:

1.……………………………………………………………………………………..
2.………………………………………………………………………………………
3.………………………………………………………………………………………

6. Have you seen evidence of climate change impacts in La Paz or elsewhere in Bolivia?

La Paz	Bolivia
☐ Yes	☐ Yes
☐ No	☐ No

b. If 'yes', please briefly describe what you have observed and why you think it is linked to climate change:

………………………………………………………………………………………
………………………………………………………………………………………
………………………………………………………………………………………

Glacier recession

7. I am knowledgeable about glacier recession in the Bolivian Andes

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

8. Glacier recession is occurring in the Bolivian Andes

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Water resources

9. I am knowledgeable about water resources and water security in La Paz?

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

10. Present day water availability is sufficient for societal needs in La Paz

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

11. Water availability in La Paz will pose problems for society by 2100

Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

12. Please rate what you think water availability will be like by 2100 in La Paz

☐ Poor, not enough for supporting society’s needs
☐ Adequate for supporting society
☐ Plentiful enough to support society’s needs

13. If possible, list up to 3 ways in which the city of La Paz could address reduced water security in the future

1…………………………………………………………………………………………
2…………………………………………………………………………………………
3…………………………………………………………………………………………

About you

1. Gender

☐ Male
☐ Female

2. Age

☐ 0 - 20
☐ 21 - 30
☐ 31 - 40
☐ 41 - 50
☐ 50+

3. What is your job title and for what organisation do you work for?

…………………………………………………………………………………………

4. How many years experience do you have working in this sector?

…………………………………………………………………………………………

5. How long have you live in La Paz/El Alto for?

…………………………………………………………………………………………

Appendix 5: Questionnaire (Spanish)

El objetivo de este cuestionario es obtener datos para una investigación que forma una parte de mi doctorado con la Universidad de Exeter, Reino Unido. Los datos personales no serán utilizados y los cuestionarios permanecerán anónimos.

Muchas gracias por su ayuda.

Sally Rangecroft

sr332@exeter.ac.uk

Entendimiento del tema

Glaciares de roca

1. Sabe usted que significa el término 'glaciares de roca'?
   ☐ Si
   ☐ No (si no, por favor vaya directamente a la pregunta numero 2)

   a. Si seleccionó 'si', por favor de una descripción de un glaciar de roca:

   ………………………………………………………………………………………

   ………………………………………………………………………………………

   ………………………………………………………………………………………

   b. Por favor describa que sabe usted sobre glaciares de roca en Bolivia:

   ………………………………………………………………………………………

   ………………………………………………………………………………………

   ………………………………………………………………………………………

Por favor, encierre en un circulo la repuesta que usted considera mas adecuada:

2. Estoy bien informado sobre los glaciares de roca, especialmente sobre los glaciares de roca en Bolivia.

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

Cambio Climático

3. Estoy bien informado sobre los efectos de cambio climático en los Andes bolivianos.

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

4. Se prevé que el cambio climático afectará a los recursos hídricos en los Andes bolivianos

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

5. De ser posible, indique hasta 3 impactos del cambio climático en los Andes bolivianos:

1.……………………………………………………………………………………..
2.………………………………………………………………………………………
3.………………………………………………………………………………………

6. ¿Ha visto usted impactos del cambio climático en La Paz o en otras partes de Bolivia?

La Paz	Bolivia
☐ Si	☐ Si
☐ No	☐ No

b. Si su respuesta es ‘si’, por favor describa brevemente lo que ha observado y por qué le parece que está vinculado con el cambio climático:

…………………………………………………………………………………………………
…………………………………………………………………………………………………
…..……………………………………………………………………………………………..

Retroceso de glaciares

7. Estoy bien informado sobre el retroceso de los glaciares en los Andes bolivianos

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

8. En este momento los glaciares de los Andes bolivianos están retrocediendo.

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

Recursos hídricos

9. Estoy bien informado sobre los recursos hídricos y la seguridad del agua en La Paz

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

10. Hoy en día la disponibilidad de agua en La Paz es suficiente para las necesidades de la sociedad

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

11. Para el año 2100, la disponibilidad de agua en La Paz será un problema para la sociedad:

Totalmente en desacuerdo	En desacuerdo	Ni de acuerdo ni en desacuerdo	De acuerdo	Totalmente de acuerdo

12. Por favor indique su opinión sobre cómo piensa usted que será la disponibilidad de agua en La Paz en el año 2100:

☐ Insuficiente para las necesidades de la sociedad
☐ Suficiente para las necesidades de la sociedad
☐ Más que suficiente para las necesidades de la sociedad

13. De ser posible, indique 3 maneras en que la ciudad de La Paz podría combatir la escasez de agua en el futuro

1……………………………………………………………………………………
2……………………………………………………………………………………
3……………………………………………………………………………………

<u>Datos Personales</u>

1. Sexo

☐ Masculino
☐ Femenino

2. Edad

☐ 0 - 20
☐ 21 - 30
☐ 31 – 40
☐ 41 – 50
☐ 50+

3. ¿Cuál es su posición en su empresa y para qué de organización trabaja?

…………………………………………………………………………………………

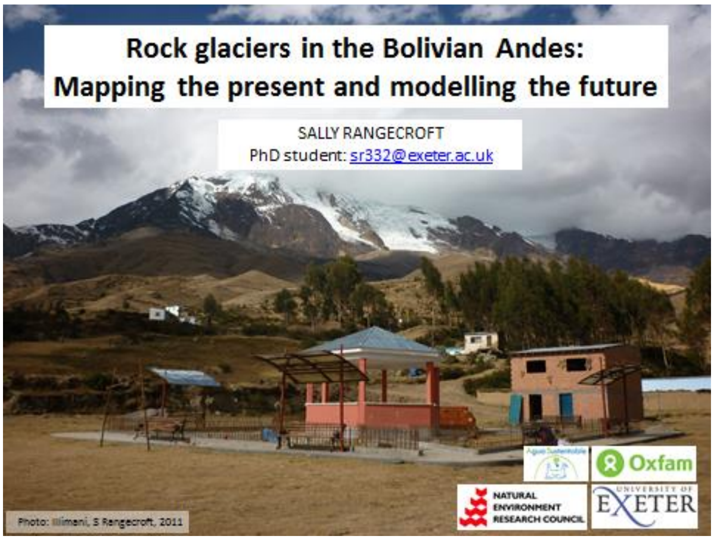
4. ¿Cuántos años de experiencia lleva trabajando en este sector?

……………………………………………………………………………………….

5. ¿Cuántos años lleva viviendo en La Paz/El Alto?

……………………………………………………………………………………

Appendix 6: Presentation transcript



Rock glaciers in the Bolivian Andes:
Mapping the present and modelling the future

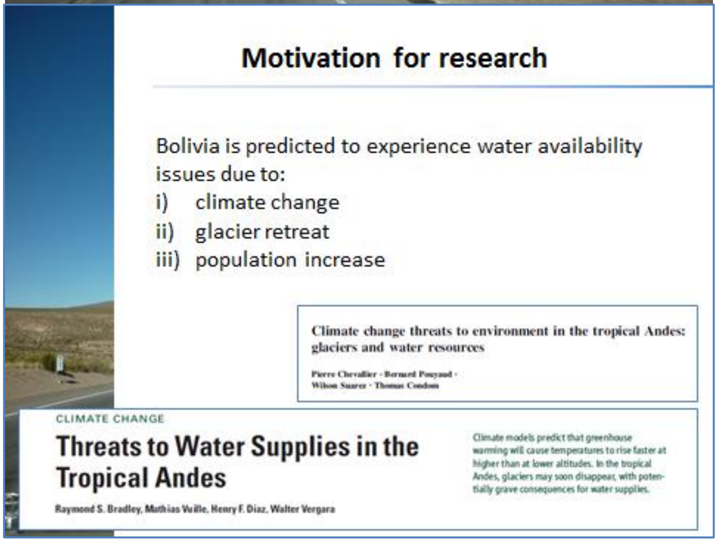
SALLY RANGECROFT
PhD student: sr332@exeter.ac.uk

Photo: Illimani, S Rangecroft, 2011

Script slide 1: Hello and good evening. I will be presenting about my PhD research tonight. I will introduce myself and my topic, the motivation behind my research and the main results from my research. Hopefully this will provide you with more information about climate change and water resources in the Bolivian Andes and introduce the feature 'rock glaciers' to those of you who have not heard of them before.

Introducción

Script slide 2: I am a PhD student from England studying at the University of Exeter. My PhD is based around 'rock glaciers in the dry Andes of Bolivia: implications for future water resources'.



Motivation for research

Bolivia is predicted to experience water availability issues due to:

i) climate change
ii) glacier retreat
iii) population increase

Climate change threats to environment in the tropical Andes: glaciers and water resources

Pierre Chevallier · Bernard Pouyaud · Wilson Suarez · Thomas Condom

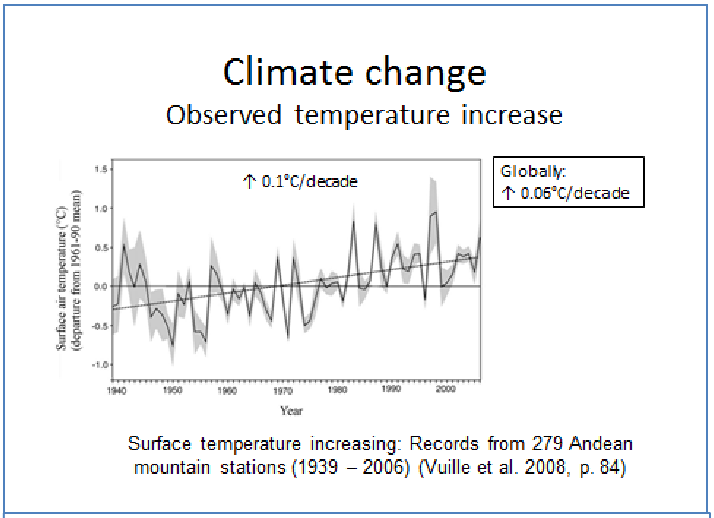
CLIMATE CHANGE

Threats to Water Supplies in the Tropical Andes

Raymond S. Bradley, Mathias Vuille, Henry F. Diaz, Walter Vergara

Climate models predict that greenhouse warming will cause temperatures to rise faster at higher than at lower altitudes. In the tropical Andes, glaciers may soon disappear, with potentially grave consequences for water supplies.

Script slide 3: Bolivia, specifically La Paz, is expected to experience water stress due to: Glacier recession and climate change reducing water supplies and population growth and westernization increasing the demand on the water. Therefore we are looking to other part of the cryosphere to assess their input into the hydrological cycle. Changes in water availability will have direct impacts. Impacts of reduced water availability can include: negative impacts on agriculture and food security, decreased water for drinking, decreased potential for hydroloelectricity power generation (Zongo).

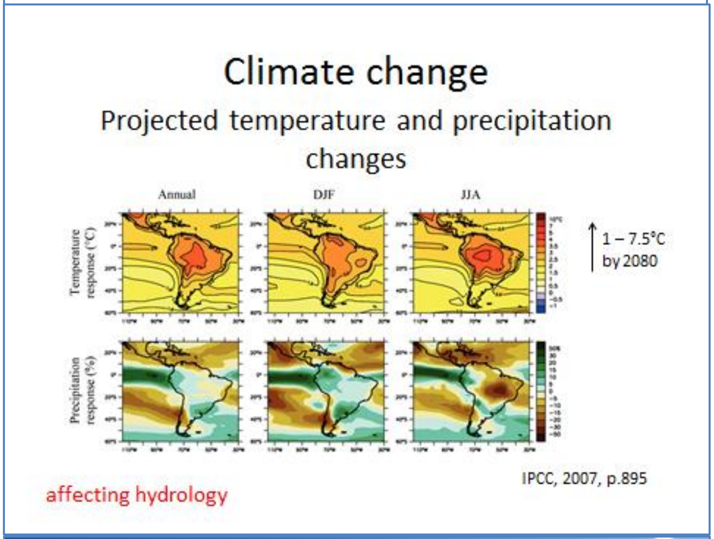


Climate change

Observed temperature increase

Surface temperature increasing: Records from 279 Andean mountain stations (1939 – 2006) (Vuille et al. 2008, p. 84)

Script slide 4: Observed climate change: annual average temperatures have increased by 0.1°C per decade between 1939 and 1998. This is higher than the global average of 0.06°C per decade. Limited work on recent observed temperature increase – I would be very interested if anyone knows of any research/ studies published with recent temperature changes observed in the Andes.



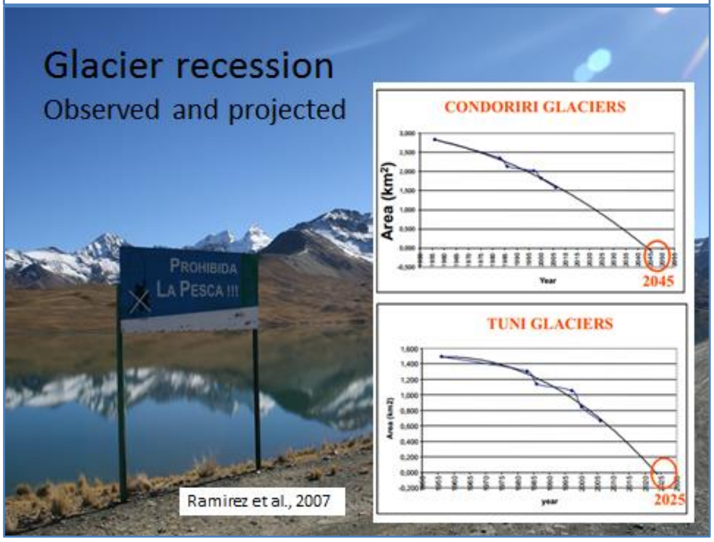
Climate change

Projected temperature and precipitation changes

IPCC, 2007, p.895

affecting hydrology

Script slide 5: Projected climate change: changes in temperature and precipitation. Continued warming is projected across much of Latin America; IPCC model projections suggest warming 1.0 – 7.5°C by 2080 (IPCC, 2007). Precipitation changes are less unimous – models disagree on the extent and direction of changes, but number of them predict a drying in the region. These changes will affect hydrology.

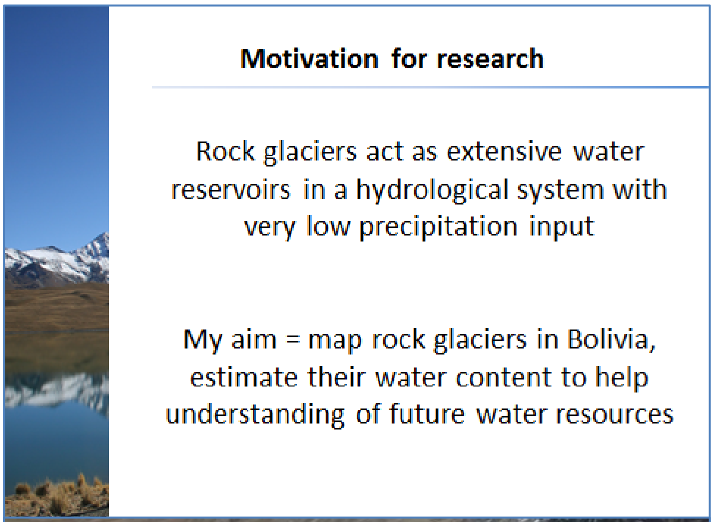


Glacier recession

Observed and projected

Ramirez et al., 2007

Script slide 6: Glacier recession is a clear visible reflection of recent climate change in mountain regions. Glacier recession is occurring worldwide, and over the past 30 years Bolivian glacier recession has accelerated in line with regional and global warming trends. Bolivian glaciologist, Alvaro, has estimated that glaciers along the Cordillera Real range have lost ~48% of their ice between 1963 and 2006, leading to the disappearance of many small glaciers already. This is illustrated by the well documented retreat and disappearance of Chacaltaya. Modelling based on observation data by Ramirez predicts that the glaciers of the Tuni Condoriri range will disappear by 2025 for Tuni and 2045 for Condoriri. These glaciers are important for water for drinking and agriculture in La Paz, El Alto and the altiplano. While glacier retreat results in a temporary increase in runoff, once glaciers disappear, there will be a loss of the hydrological buffer. Long term this will lead to water supply issues

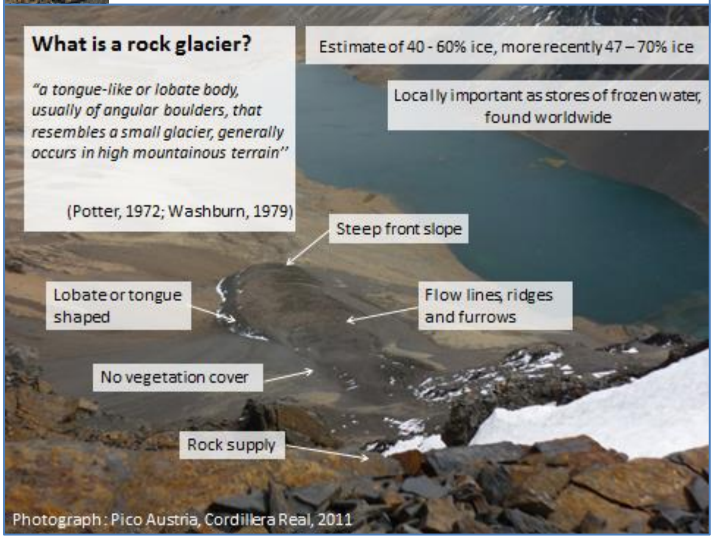


Motivation for research

Rock glaciers act as extensive water reservoirs in a hydrological system with very low precipitation input

My aim = map rock glaciers in Bolivia, estimate their water content to help understanding of future water resources

Script slide 7: In mountain regions – solid water is not only stored in glaciers, but also within the ice-rich permafrost of rock glaciers. Rock glaciers are known to be "hidden" water stores in arid mountain regions. Research from Chilean and Argentinean Andes have shown the importance of rock glaciers for water supplies/stores. Rock glaciers have not been looked at in the Bolivian Andes (with the exception of Caquella rock glacier in the very south by Francou). Therefore my PhD aim is to map the rock glaciers of the Bolivian Andes, estimate their water content and project the implications of future warming on rock glaciers and the cryosphere.



What is a rock glacier?

"a tongue-like or lobate body, usually of angular boulders, that resembles a small glacier, generally occurs in high mountainous terrain"

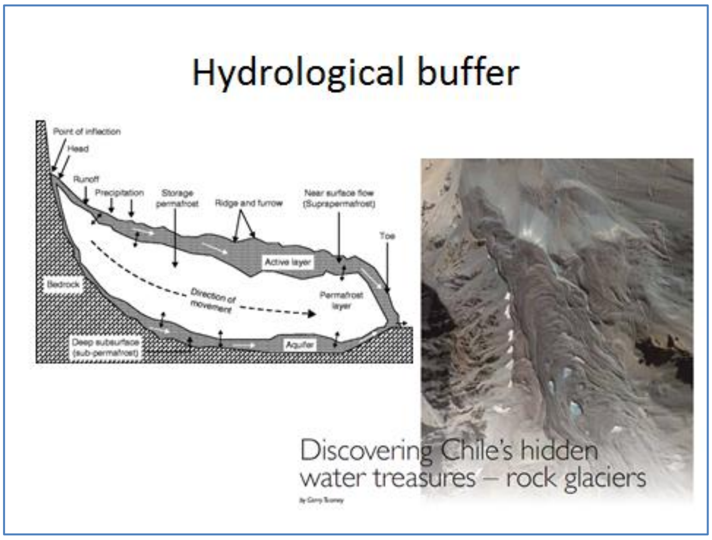
(Potter, 1972; Washburn, 1979)

Estimate of 40 - 60% ice, more recently 47 – 70% ice

Locally important as stores of frozen water, found worldwide

Photograph: Pico Austria, Cordillera Real, 2011

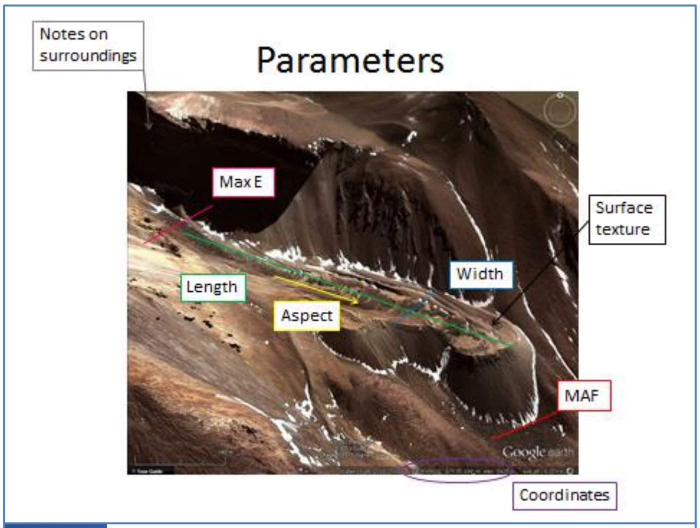
Script slide 8: So, I have mentioned the feature 'rock glacier' but I have not shown you what a rock glacier is. A rock glacier resembles a small glacier covered in rocks, found in mountainous terrain. This rock glacier protects the ice underneath from small changes in the climate, therefore rock glaciers move slower than ice glaciers. The ice content of rock glaciers is thought to be between 40 – 60%, with a more recent estimate of 47 – 70% ice. This is for active rock glaciers. Active rock glaciers contain ice, relict rock glaciers do not. There are different ways to categorise rock glaciers by origin or appearance, but the easiest way is by activity status. Features evident on a rock glacier for identification: well defined flow lines, Ridges and furrows, steep frontal slope, shape, and surrounding rock supply. A lack of vegetation on a rock glacier implies that it is active, that it is moving. This photo is taken from Pico Austria, Tuni Condoriri, Cordillera Real.



Hydrological buffer

Discovering Chile's hidden water treasures – rock glaciers

Slide 9: Similar to ice glaciers, rock glaciers are hydrological buffers which release water throughout the dry season when there is very limited rainfall. The best way to investigate the ice within a rock glacier is by using geophysics.



Parameters

Notes on surroundings

Max E

Surface texture

Width

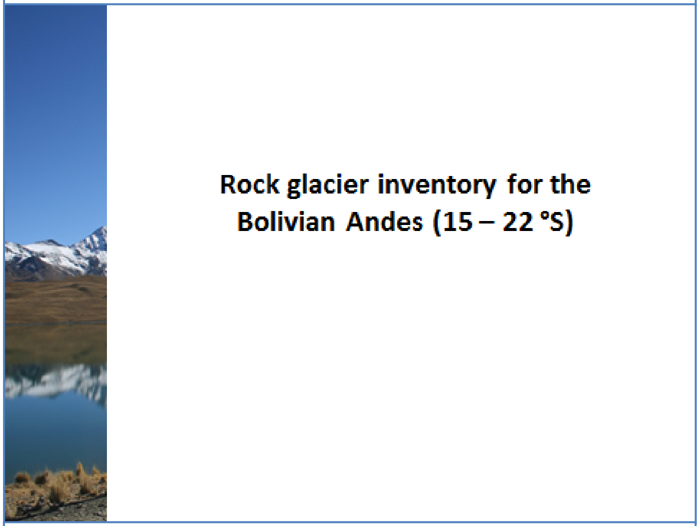
Length

Aspect

MAF

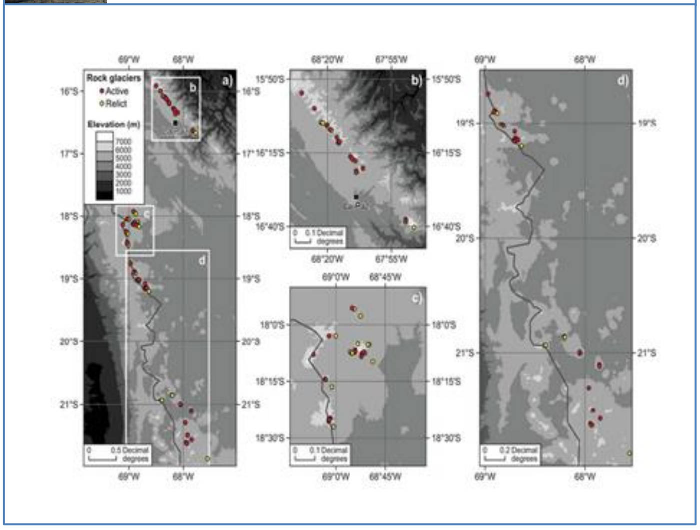
Coordinates

Slide 10: Using a set criteria to identify rock glaciers remotely, from Google Earth, a source of free high resolution satellite imagery, a RG inventory was created. Parameters were extracted from Google Earth and recorded for each rock glacier. Coordinates, Minimum Altitude at Front (known as the MAF), Maximum Elevation, Length and Width using the ruler tool in Google Earth: most representative width and length being used, Aspect: direct of flow and notes on Surface texture (including the possible presence of vegetation). This is a Google Earth image of Caquella rock glacier in the very south of Bolivia. It is the only rock glacier in Bolivia to have been studied until this inventory. And it is a very beautiful rock glacier.

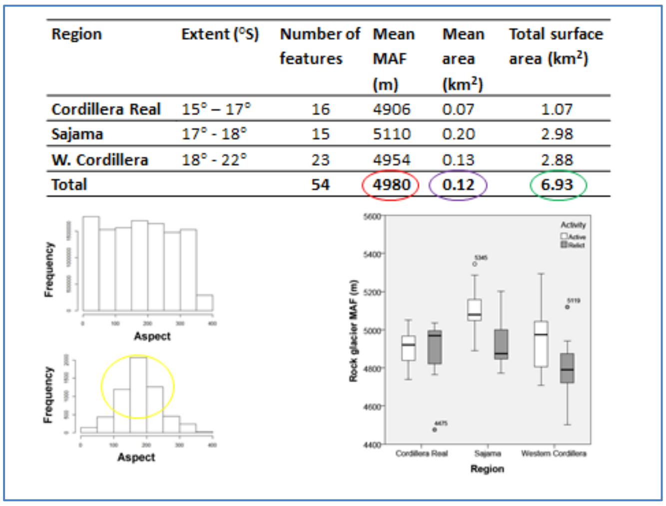


Rock glacier inventory for the Bolivian Andes (15 – 22 °S)

Slide 11: Results of the rock glacier inventory. I have identified 94 rock glaciers along the Bolivian Andes (between 15 and 22 degrees S). 54 are classified as active (containing ice) and 40 relict (containing no ice).

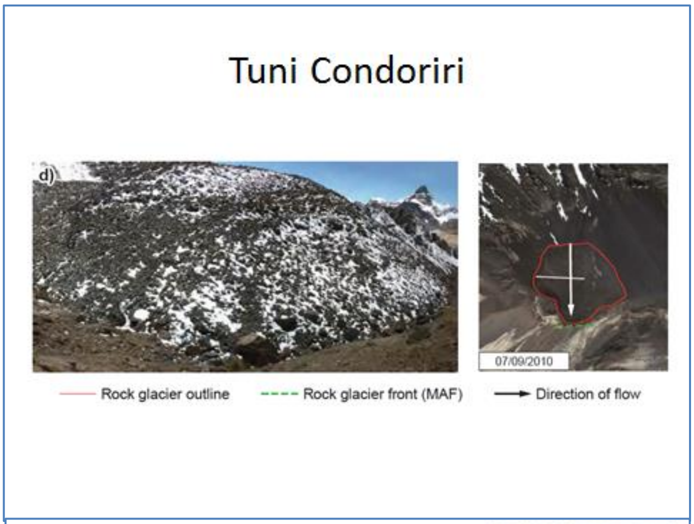


Slide 12: Bolivian active rock glaciers are shown in red: The Bolivian Andes have been split into 3 different regions for regional analysis: Cordillera Real with 16 active rock glaciers, Sajama with 15 active rock glaciers and Western Cordillera with 23 active rock glaciers.



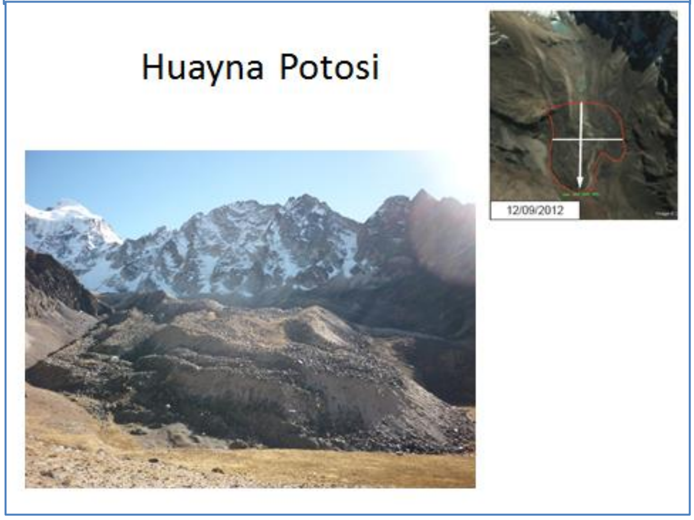
Region	Extent (°S)	Number of features	Mean MAF (m)	Mean area (km²)	Total surface area (km²)
Cordillera Real	15° – 17°	16	4906	0.07	1.07
Sajama	17° - 18°	15	5110	0.20	2.98
W. Cordillera	18° - 22°	23	4954	0.13	2.88
Total		54	4980	0.12	6.93

Slide 13: Mapping the mean elevation at the front of rock glaciers, it can be seen that active rock glaciers have an average elevation of 4980m.This tells us the lower limit of permafrost, something which is not documented or estimated for the Bolivian Andes. On average, active Bolivian rock glaciers are 0.12 km^2 in area, and in total cover nearly 7km^2. There aspects are predominately southerly (South East, South and South West). By comparing these to the aspects found across the whole of the Bolivian Andes, it was confirmed that rock glacier have preferred southerly aspects when all aspects are available. It can be presumed that this is because southerly aspects here have reduced solar radiation input. Rock glacier size are similar to those in recent European rock glacier inventories, yet their frequency is not as high, and thus their total surface area is not as great as those of inventories in the European Alps. Rock glaciers were found at higher elevations than of those in the Chilean Andes; Brenning (2005) identified rock glaciers at 3000 m and higher, whereas in the Bolivian Andes no rock glaciers were found lower than 4400 m.



Tuni Condoriri

Slide 14: The Tuni Condoriri region in the Cordiller Real. Here is an example of a rock glacier, NE of La Paz.

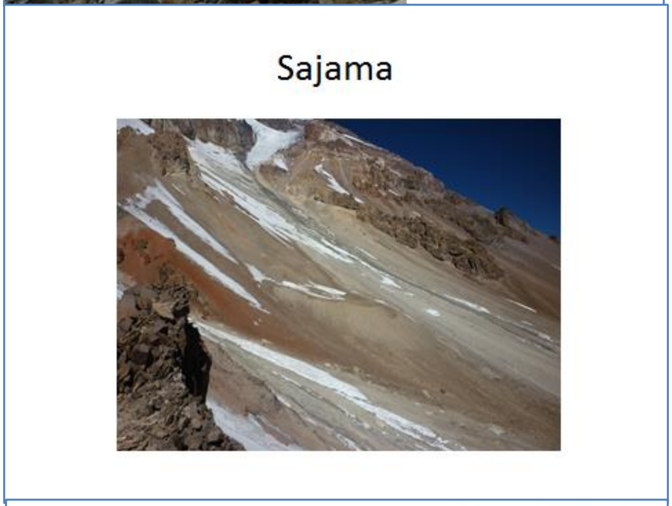


Huayna Potosi

Slide 15: and a rock glacier infront of the retreating glacier of Huayna Potosi

Illimani

Slide 16: In Illimani, rock glaciers were visited and sources of water were observed.

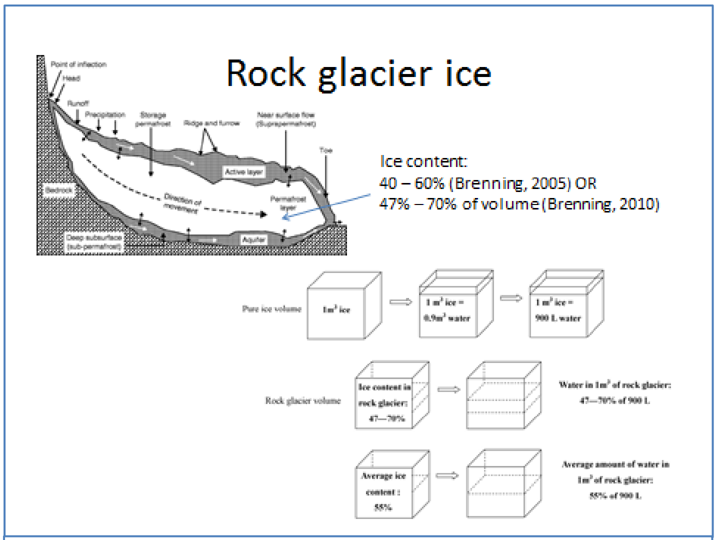


Sajama

Slide 17: and in Sajama, ice underneath debris, rock glaciers and detachment failures were observed.

Chiguana, Uyuni

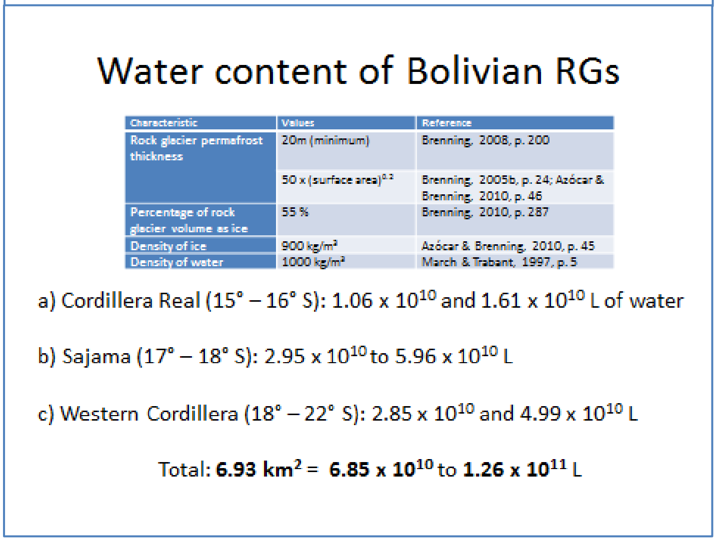
Slide 18: and in the very south of Bolivia, a rock glacier was visited near Salar de Uyuni.



Rock glacier ice

Ice content:
40 – 60% (Brenning, 2005) OR
47% – 70% of volume (Brenning, 2010)

Slide 19: So, now we know where the rock glaciers are, we can estimate how much water the hold. Estimating ice content of rock glaciers remotely is not easy. To calculate the amount of water contained in the ice held in a rock glacier I have assumed that: 1 cubic meter of ice is 0.9 m3 of water, which is 900 litres of water. It is estimated that rock glaciers contain between 47% and 70% ice, with a middle value of 55%. This average value of 55%.



Water content of Bolivian RGs

Characteristic	Values	Reference
Rock glacier permafrost thickness	20m (minimum)	Brenning, 2008, p. 200
	50 x (surface area)$^{0.2}$	Brenning, 2005b, p. 24; Azócar & Brenning, 2010, p. 46
Percentage of rock glacier volume as ice	55 %	Brenning, 2010, p. 287
Density of ice	900 kg/m^2	Azócar & Brenning, 2010, p. 45
Density of water	1000 kg/m^2	March & Trabant, 1997, p. 5

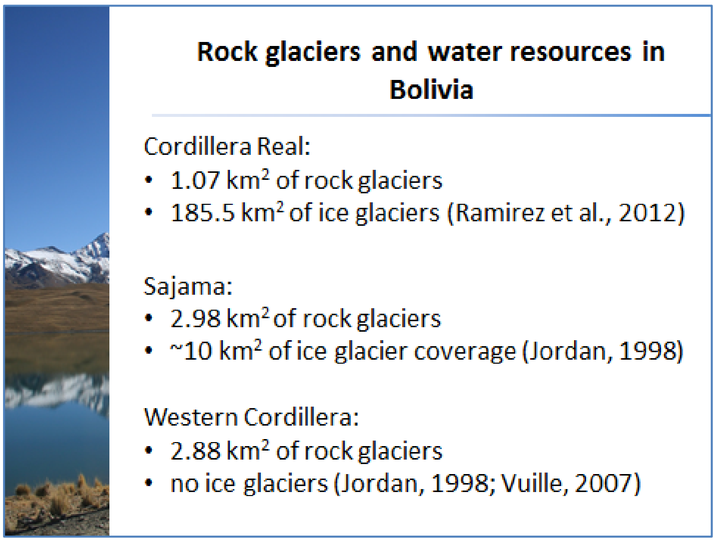
a) Cordillera Real (15° – 16° S): 1.06 x 10^{10} and 1.61 x 10^{10} L of water

b) Sajama (17° – 18° S): 2.95 x 10^{10} to 5.96 x 10^{10} L

c) Western Cordillera (18° – 22° S): 2.85 x 10^{10} and 4.99 x 10^{10} L

Total: **6.93 km^2** = **6.85 x 10^{10}** to **1.26 x 10^{11}** L

Script slide 20: I used 2 different methods of estimating rock glacier ice content: 1st) assume a minimum thickness of permafrost in all rock glaciers, which is 20m from Brenning's work in Chile. 2nd) using Brenning's equation to estimate permafrost thickness based on rock glacier size. Using this equation all rock glaciers had a permafrost thickness greater than 20m. Using both these methods, with an assumed percentage of rock glacier volume as ice of 55%, gave a lower estimate and a higher estimate of water content. Rock glaciers of the Cordillera Real are estimated to hold between 10.6 and 16.1 thousand million litres of water. Rock glaciers in Sajama are estimated to contain between 29.5 and 59.6 thousand million litres of water. Rock glaciers along the Western Cordillera are estimated to hold between 28.5 and 49.9 thousand million litres of water. In total – Bolivian rock glaciers are estimated to hold 68.5 to 126 thousand million litres of water. This is not readily available water, it is stored in the rock glaciers.



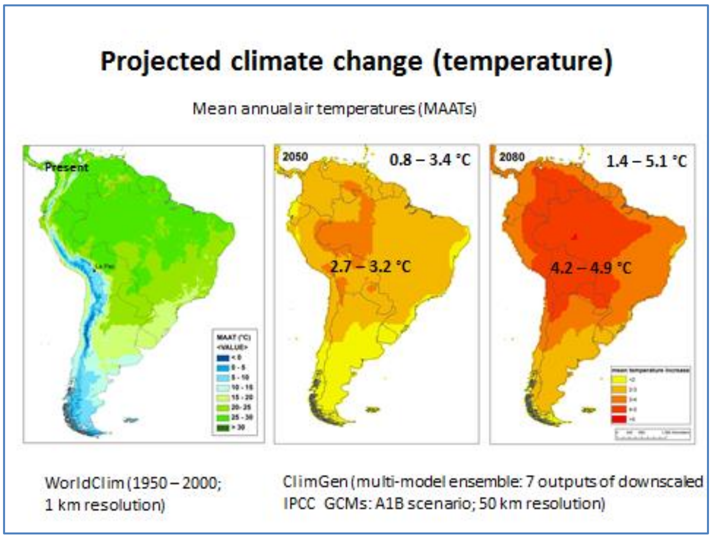
Rock glaciers and water resources in Bolivia

Cordillera Real:
- 1.07 km^2 of rock glaciers
- 185.5 km^2 of ice glaciers (Ramirez et al., 2012)

Sajama:
- 2.98 km^2 of rock glaciers
- ~10 km^2 of ice glacier coverage (Jordan, 1998)

Western Cordillera:
- 2.88 km^2 of rock glaciers
- no ice glaciers (Jordan, 1998; Vuille, 2007)

Slide 21: In the Cordillera Real, rock glaciers are not abundant where ice glaciers dominate. It is estimated that there is 185.5 m^2 of ice glaciers currently in the Cordillera Real. However, in Sajama rock glaciers could be locally important to the mountain communities of Sajama as ice glacier coverage is now estimated to be ~4 km^2. And along the Western Cordillera where there are no ice glaciers due to limited precipitation, rock glaciers can be assumed to be local water sources to mountain communities. It should also be noted too that rock glacier importance may increase with glacier recession.



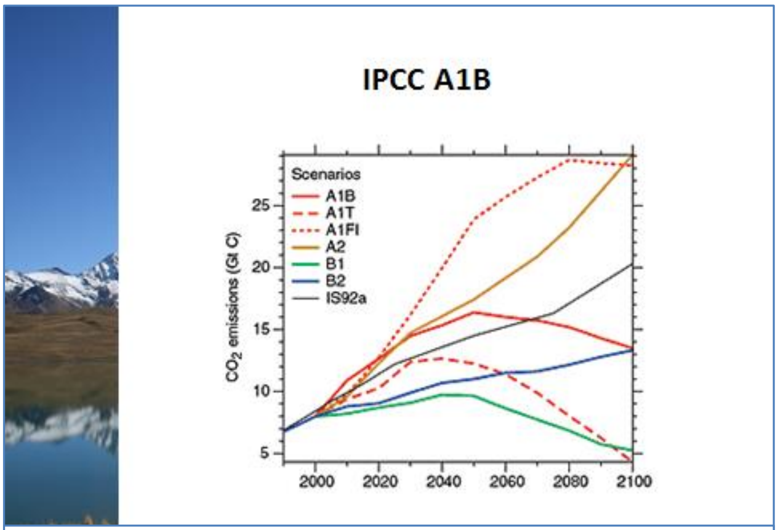
Projected climate change (temperature)

Mean annual air temperatures (MAATs)

WorldClim (1950 – 2000; 1 km resolution)

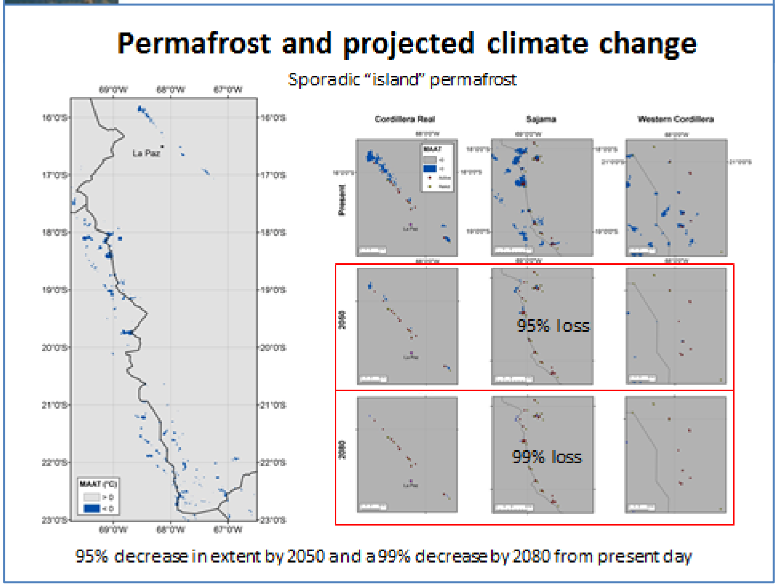
ClimGen (multi-model ensemble: 7 outputs of downscaled IPCC GCMs: A1B scenario; 50 km resolution)

Slide 22: The next step in my research: to look at future climate projections and model the response of permafrost and rock glaciers to this. Although climate projection is very difficult in the Andes, this is a preliminary assessment. I used WorldClim climate data at a resolution of 1 km for the time period 1950 – 2000 to create a baseline present temperature. For projected climate change, I just used temperature projections due to the uncertainty surrounding the direction and magnitude of future change for precipitation. I used the ClimGen data which is downscaled outputs from the 7 IPCC global circulation models driven by the A1B emissions scenario. This produced a multi-model ensemble with a resolution of 50km. From this modelling, we determined that mean annual air temperatures across South America will have increased by 0.8 – 3.4 °C in 2050, and 1.4 – 5.1 °C in 2080. Specifically for the Bolivian Andes these temperature increases are in the ranges of 2.7 – 3.2 °C by 2050, and 4.2 – 4.9 °C by 2080.



IPCC A1B

Slide 23: The A1B emissions scenario medium emission scenario. This represents a future world of rapid economic and population growth, peaking mid-century.

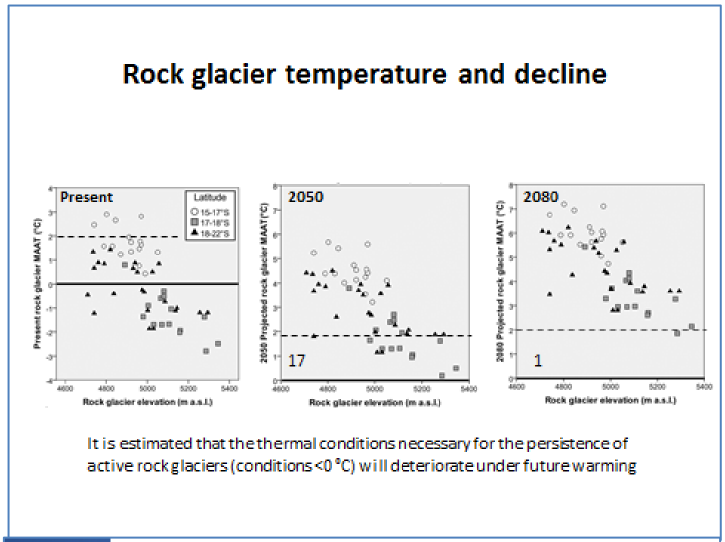


Permafrost and projected climate change

Sporadic "island" permafrost

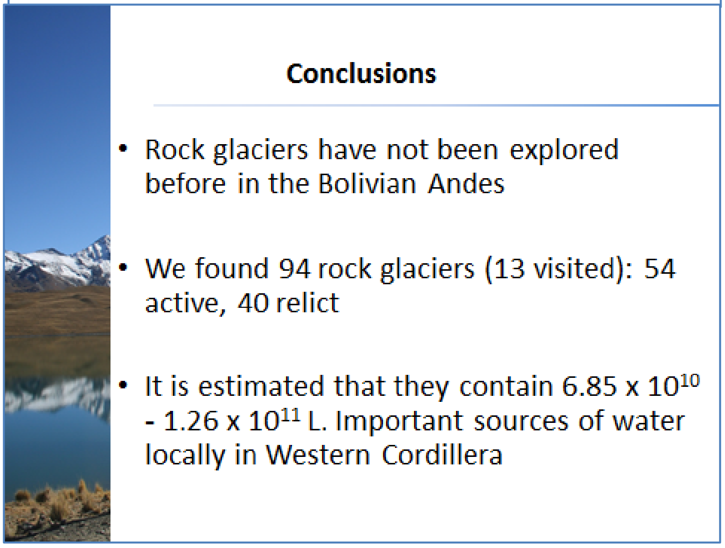
95% decrease in extent by 2050 and a 99% decrease by 2080 from present day

Slide 24: Although it is "virtually certain" that Northern Hemisphere permafrost will continue to decline during the first half of the 21st century, according to the new IPCC report, similar assessments for Southern Hemisphere permafrost are not available. Using an MAAT of below 0 °C as a proxy of permafrost, we mapped the area of the Bolivian Andes that is currently underlain by permafrost (left). We modelled the spatial extent of this isotherm for future climates, finding significantly large reductions in its present day extent of approximately 95% by 2050 and 99% by 2080.



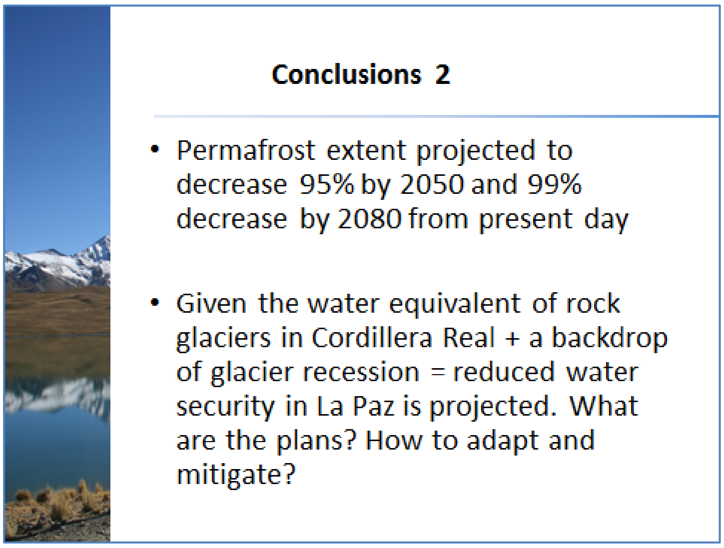
Rock glacier temperature and decline

It is estimated that the thermal conditions necessary for the persistence of active rock glaciers (conditions <0 °C) will deteriorate under future warming



Conclusions

- Rock glaciers have not been explored before in the Bolivian Andes
- We found 94 rock glaciers (13 visited): 54 active, 40 relict
- It is estimated that they contain 6.85×10^{10} - 1.26×10^{11} L. Important sources of water locally in Western Cordillera



Conclusions 2

- Permafrost extent projected to decrease 95% by 2050 and 99% decrease by 2080 from present day
- Given the water equivalent of rock glaciers in Cordillera Real + a backdrop of glacier recession = reduced water security in La Paz is projected. What are the plans? How to adapt and mitigate?

Slide 25: It is estimated that the thermal conditions necessary for the persistence of active rock glaciers, which is conditions below 0 °C, will deteriorate under future warming. Using future temperature projections at the 54 rock glacier sites, we found that all currently active rock glaciers in Bolivia are projected to have a MAAT above 0 °C by 2050. We also tested a more conservative threshold of rock glacier activity of +2 °C. This resulted in 17 of 50 rock glaciers estimated as still active by 2050, and only 1 rock glacier by 2080.

Slide 26: Rock glaciers have not been explored in the Bolivian Andes before. It is important that we know about all features contributing to the mountain hydrological cycle. This PhD aimed to fill the gap in knowledge regarding rock glaciers in Bolivia, and has done so through the creation of a rock glacier inventory. 94 rock glaciers were identified, of which 54 were active. It is estimated that these active rock glaciers contain between 68.5 to 126 thousand million litres of water. They are not considered to be important sources of water in the Cordillera Real where ice glaciers dominate, but are retreating. However, they could be important local sources of water in the Western Cordillera where ice glaciers are absent.

Slide 27: Using downscaled temperature projections for the A1B IPCC emissions scenario, we predict that permafrost extent will decrease by 95% by 2050 and by 99% by 2080 from present day. Given the estimates of water in rock glaciers in the Cordillera Real, and with a back drop of continued glacier recession, reduced water security and availability are projected for La Paz. So what are the plans and how should the city adapt and mitigate? Most importantly, actions should start now to be ready for this reality.

Gracias por escucharme

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Rangecroft et al. 2013. ‘Climate change and water resources in arid mountains: An Example from the Bolivian Andes’ *AMBIO*, **vol 42**, p. 852 – 863

Slide 28: Thank you very much for listening. Please note my email address if you have any questions after tonight, or if you would like to request a copy of my publication ‘Climate Change and water resources in arid mountains: an example from the Bolivian Andes’. I would like to thank my funders NERC, Exeter University, Oxfam and Agua Sustentable. And a big thank you to Agua Sustentable and BMI for organising tonight’s event.