Using remote sensing data for monitoring rock glacier distribution in the Bolivian Andes: implications for water supply

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Abstract

Many large cities in the South American Andes are located above 2500m and rely almost entirely on high-altitude water stocks (e.g. glaciers, lakes and rock glaciers). It is now evident that warming in the tropical Andes due to climate change has had a measurable impact on ice glaciers, which are known to have receded over the past decades, affecting water supply. This research is focused on rock glaciers in the Bolivian Andes as their contribution to mountain water supplies is ambiguous and understudied. Remote sensing approaches offer an efficient method for developing an inventory of the current rock glaciers in Bolivia. Rock glacier inventories elsewhere in the world have successfully utilised remote sensing data for this purpose (e.g. aerial photos, satellite images). In this research, we exploit a range of remote sensing data sources including historic air photos, fine spatial resolution satellite data (IKONOS 5 m resolution), global-extent DEMs (e.g. ASTER 30 m) and Google Earth. Fieldwork conducted in June 2011 provided the basis for field validation of the remote sensing approach, and targeted rock glaciers visited in July 2012 provided a basis for in situ measurement and thus validation of the remote sensing datasets. These data will be used to establish a detailed spatial understanding of rock glacier physical characteristics, and when coupled with the remote sensing data will enable potential water supply questions to be answered.

1 Introduction

The importance of ice glaciers and their role in regulating hydrological processes in mountainous regions is well studied. In contrast the contribution of “rock glaciers” (debris covered periglacial features with ice cores) to mountain water supplies is ambiguous and understudied. Although rock glaciers are known to be abundant and very well developed forms of locally significant long term water storage in the semi-arid Andes (Trombotto et al., 1999; Brenning, 2005), critical gaps in present knowledge of the Andean mountain cryosphere exist (Azócar and Brenning, 2010). The effect of climate change on the behaviour of glaciers and snowpacks is a key factor for future water availability in these regions (Tromobotto et al., 1999). A decrease in water supply is projected for La Paz, Bolivia, due to glacier retreat and climate change, exacerbated by population increase (Magrath, 2011; IPCC, 2007) (Figure 1). It is becoming evident that warming in the tropical Andes is likely to be of similar magnitude as in the Arctic, but with consequences that will affect a much larger population (Vergara, 2009). With glaciers currently in retreat there is concern for future water supplies (Bradley et al., 2006), affecting economic development and increasing social, political and ecological instability. Consequently, we are now looking to other parts of the cryosphere for more resilient water supplies, including rock glaciers.

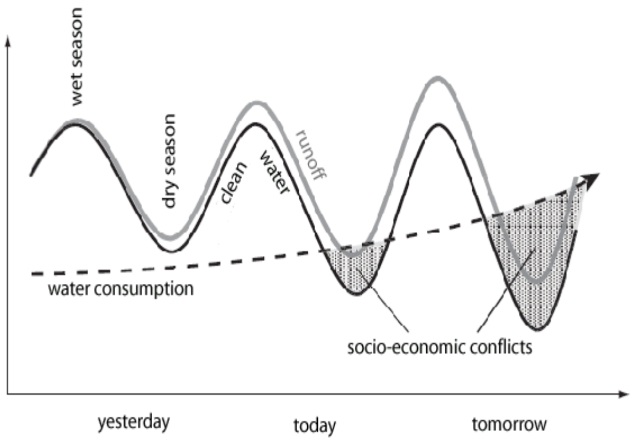

***Figure 1**: The predicted decrease in water availability and increase in consumption, resulting in increasing socio-economic conflicts (Vuille, 2006, cited in Vergara, 2009, p.62).*

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). The internal composition of a rock glacier is very variable, ranging from pure ice to an ice/rock mixture (Whalley and Azizi, 1994). It is estimated that rock glaciers contain a range of between 40-60% ice under a top layer of rock, which acts as insulation for the ice from low amplitude and high frequency temperature changes (Brenning, 2005). Due to a predominantly steady-state flow/creep over long time periods, rock glaciers display a lava flow-like landform with furrows and ridges often alternating with each at the surface, reflecting the internal deformation process of the permafrost body (Kaufmann and Ladstädter, 2003). Glaciers are absent in some arid environments of Bolivia because the equilibrium-line altitude exceeds some of the highest peaks (Francou et al., 1999), increasing the local importance of rock glaciers in the dry Andes of Bolivia. Active rock glaciers typically have a steep frontal slope (>35°), well developed flow like morphology, little or no vegetation development, and a top layer of angular rocks (Angillieri, 2009). Rock glaciers with gentler frontal and side slopes (<35°) and heavy vegetation are classified as relict (Payne, 1998; Seligman, 2009). It is understood that rock glaciers are sensitive to mean annual temperature, thus have a limited altitudinal range. They are found to exist around the 0°C isotherm (Payne, 1998), therefore elevation can be used to distinguish active rock glaciers from relict ones (Angillieri, 2009). Lichenometery can also be used to identify activity status.

Enhancing our knowledge of rock glacier distribution and water equivalence at a regional scale is an important step in the assessment of the state of the cryosphere. This knowledge is required for climate impact studies and permafrost exploration for economic activities (Brenning and Azócar, 2008). Building a rock glacier inventory is of immediate importance in the high Andes of Bolivia as it will help to achieve two outcomes:

1. supporting environmental impact assessment for specific projects; and
2. helping to provide a long-term knowledge base, necessary for protecting vital water resources (Toomey, 2011).

To address water availability issues in Bolivia, water companies, governments and local policy makers require accurate projections regarding future water supplies. This requires data describing the distribution, extent and temporal dynamics of rock glaciers in this region. To improve understanding of water availability in the Bolivian dry Andes, values for glacier and rock glacier hydrological input are needed, parallel to the quantification of glacier and rock glacier response to climate change and projected climate change. This is what our study seeks to address.

2 Methodology

Remote sensing approaches offer an efficient method for inventory of the current rock glacier characteristics in the Bolivian Andes. The difficult, vast and inaccessible nature of mountainous regions lends itself to remote sensing as a practical tool for an extensive, cost-effective study (Shukla et al., 2010). Rock glacier inventories elsewhere in the world have successfully utilised remote sensing data for this purpose (e.g. aerial photos and satellite data) (Gulielmin and Smiraglia 1998; Humlum, 2000; Angillieri, 2009; Scotti et al., 2011). In this research, we exploit a range of remote data sources including historic aerial photos, fine spatial resolution satellite data (IKONOS 5 m resolution), global-extent DEMs (e.g. ASTER 30 m) and the broadly available platform of Google Earth to:

i) Establish the first Bolivian rock glacier inventory using expert photomorphic mapping from Google Earth;
ii) Determine the location, frequency and spatial distribution and extent of rock glaciers in the region;
iii) Consider temporal changes in extent and volume for targeted rock glaciers using historic data.

This short paper will comment on the results of the first and second aims. The project is still in its early stages and fieldwork conducted in July 2012 is in the process of being analysed at the time of writing. Our aim is to use this fieldwork to verify the information content of data provided by Google Earth, to gain a preliminary insight into the spatial characteristics of Bolivian rock glaciers. Despite its widespread availability, free global access and provision of fine spatial resolution data (in some areas), very few studies have commented on the viability of using Google Earth for studies of this nature. In developing countries and in projects where non-governmental (not-for-profit) organisations are working, Google Earth is one of the most useful Geographical Information Science tools available for answering questions about the spatial location of features of interest. We intend to assess how representative data provided by Google Earth are in the context of a science-based hydrological question with a clear end-user.

2.1 Fieldwork

We have identified rock glaciers in various areas in Bolivia using remote sensing data (Google Earth), however we chose to focus the main body of this research in the mountainous regions around La Paz, which include Illimani, Tuni Condoriri and mountains closer to La Paz (such as Pamplarama and Chacaltaya) (Figure 2). These areas were selected due to their importance for water supplies for the growing capital city. For the Illimani region, the indicative presence of several rock glaciers identified on Good Earth, coupled with the availability of cloud-free fine spatial resolution data from IKONOS and historic aerial photographs made this a primary fieldwork area. Accessibility is also a deciding factor for fieldwork sites, as we have identified some large rock glaciers in the Tuni Condoriri region, an important mountain range for La Paz, however they are inaccessible (Figure 3.4). Sajama (Figure 2) will also be explored as a fieldwork site as some very good examples of rock glaciers have been identified here, however the region is not in close proximity to La Paz.

During July 2011, fieldwork in this region focused on collecting data on the spatial and physical characteristics and the historic conditions of rock glaciers of the region. The high altitude nature of the field site (up to 5000 m) makes complex field measurements difficult and so we relied on field photos, GPS surveying from a handheld Garmin system, and rudimentary surveying tools (abney level measurements of slope and relief, quadrat sampling along rock glacier surface) to capture fine scale detail.

The second fieldwork season, in Summer 2012, will target two or three of the most easily accessible rock glaciers, for a more detailed *in situ* survey, investigating the internal structure using ground-penetrating radar and other subsurface geophysical techniques. The data collected over the two field seasons will be used to establish a detailed spatial understanding of rock glacier physical characteristics, and when coupled with the remote sensing data will enable potential water supply questions to be answered.

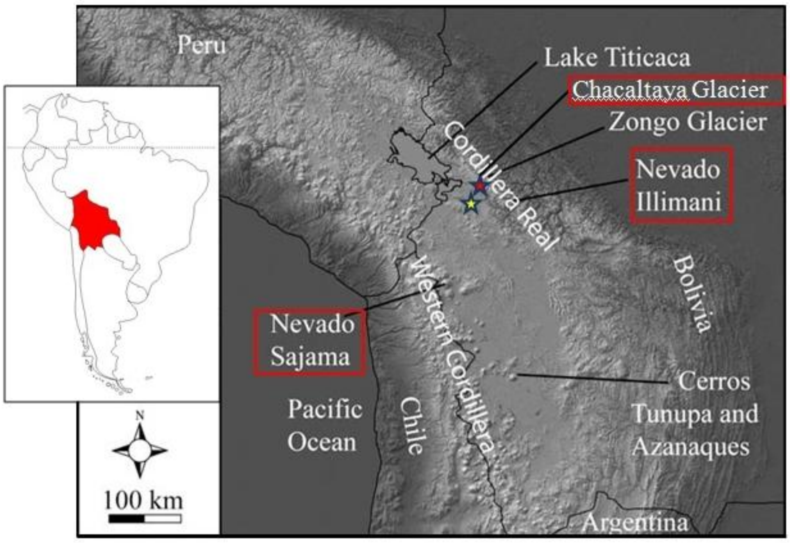

Figure 2: *Map showing the three study regions in the Bolivian Andes, and Bolivia's location within South America is illustrated with the insert. La Paz is represented with a yellow star.*

2.2 Analysis of fine spatial resolution data from IKONOS and air photos

Once field data have been analysed, and the Google Earth inventory compiled, more detailed analysis of rock glacier surface features will be assessed using aerial photos and IKONOS satellite data. These data will be of sufficiently fine spatial resolution (pixel size <5 m) such that their surface geomorphic features will be identifiable from pattern/texture analysis. Digital terrain models of the region will also be compiled from local datasets and analysed to establish slope, aspect and other topographic indicators.

2.3. Changes through time

In relation to the third research objective, our research group has already developed a novel method for describing the historic glacial extent and for reconstructing the recession of glaciers over time, using ASTER 30 m DEMs, along with accurate field data describing the location and height of trimlines and terminal moraines (Glasser et al., 2011). We intend to apply this method to understand and quantify temporal changes in Bolivian rock glaciers studies discussed here. Combining the fieldwork and remote sensing data with meteorological data will allow for an assessment of rock glaciers responses to climate change to be explored, especially in comparison to monitored glacier retreat.

3 Results

The fieldwork has enabled the verification of features that have been identified on Google Earth. We have used photographs of a rock glacier in the Illimani region (Figure 3.1; 3.2; 3.3) to verify the satellite data. Other features in this area have been explored, and other regions have been visited for similar fieldwork and verification, such as Pampalarama (Figure 3.5), Chacaltaya and Sajama.

Figure 3.1*: Photograph taken at the bottom of rock glacier in the Illimani region (13/07/2011), 16°37.946 S, 67°49.551, elevation 4880m.*

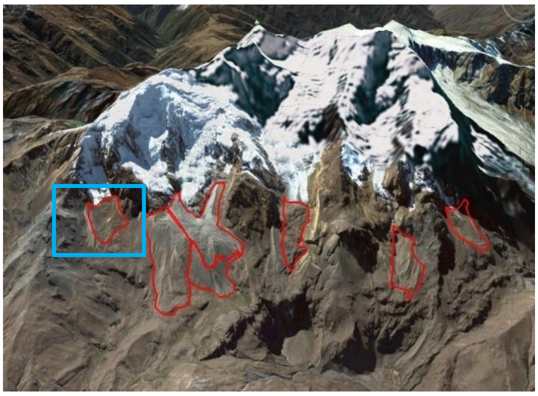

Figure 3.2*: Google Earth image of Illimani, used to preliminary identify rock glaciers (Fig. 3.1 outlined in blue).*

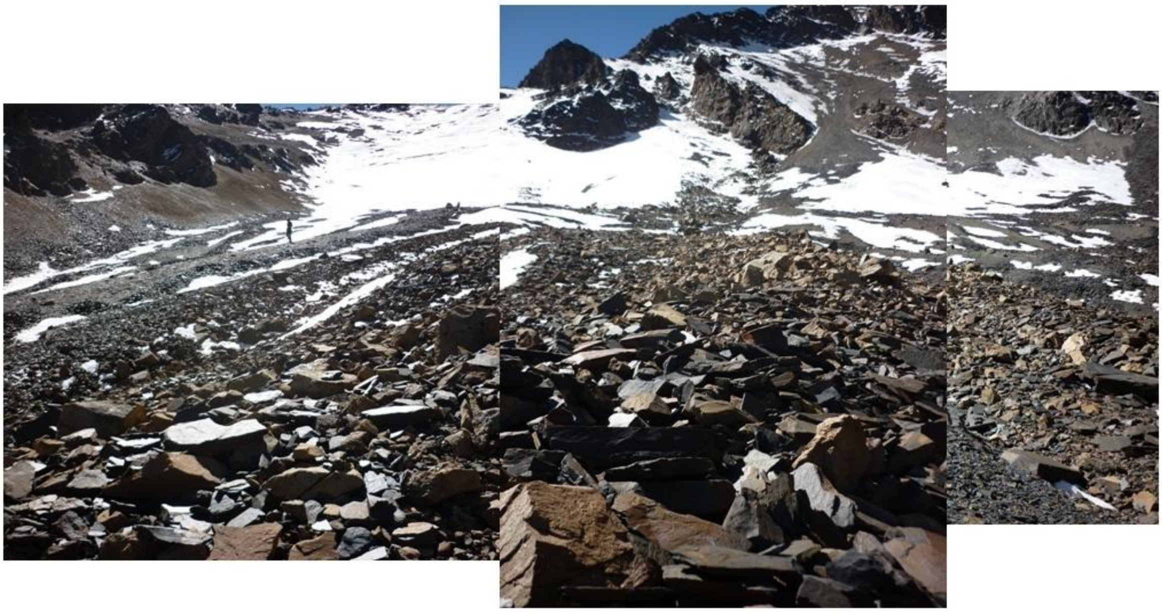

Figure 3.3*: Photo montage on the rock glacier featured in Figure 3.1, Illimani. Longitudinal furrows on the left suggest extension flow of the rearmost section of the rock glacier. The ridge in the centre comprises of rockfall debris from the cliffs behind, and shows further evidence for compression of the rock/ice mass. The remnant glacier can be seen in the background.*

Observations on the rock glacier in Illimani lead to the assumption that it is an active rock glacier. Primarily, the angularity of the rocks, the lack of weathering and the lack of lichens on the rocks, are indicative of this active status. This assumption is also supported by the existence of retreating glacier ice in close proximity behind the rock glacier (Figure 3.3).

Other areas with identified rock glaciers on Google Earth will be visited for further verification, and to allow for a collection of data on various different types of rock glaciers across the Bolivian Andes. Some rock glaciers have been identified on Google Earth, but cannot be accessed due to the nature of the landscape and limited roads, such as areas in the Tuni Condoriri region (Figure 3.4).

Figure 3.4*: Google Earth image of a rock glacier in the Tuni Condoriri region, 16°09’52” S, 68°16’22” W, elevation 4971.*

Figure 3.5*: Google Earth image of a rock glacier in the Pampalarama area, 16°20’18” S, 68°06’05” W, elevation 4796m.*

4 Summary

The contribution to water supplies from rock glaciers in the Bolivian Andes is unknown and understudied, but potentially locally and regionally important. This research will establish the first inventory of Bolivian rock glaciers using remote sensing approach to recording their spatial extent and assess temporal changes. Verification of this approach is achieved in the field with *in situ* data collection. The aim of the project is for the outputs to be used by local non-government organisations (Agua Sustentable) and international charities (Oxfam) contributing towards water resource management in Bolivia. The remote sensing techniques used are relatively simple, but offer the most appropriate methods and present the potential success in establishing a low cost remote sensing method for water resource management.

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