State and dynamics of a tropical rock glacier on the Altiplano (Bolivia, 21.5°S)

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1 - Introduction

On the Southern Bolivian Altiplano, active rock glaciers are found on the flanks of volcanoes above 4800-5000 m asl. (Payne et al., 1998). Due to aridity, glaciers are quasi absent in the region, and rock glaciers hence represent a climatic indicator as well as a water reservoir. In this context, the study of the Caquella rock glacier, initiated in 1996 by IRD, intends to bring insights on the present state and the recent dynamics of a rock glacier at low (21°S) latitude.

Results from geomorphological analysis and geophysical investigations are first presented. Then we used climatic datasets, including a 5-days surface energy balance assessment, ground temperature measurements during one year and a 2-year topoclimatic monitoring, to precise the characteristics and controls of the permafrost thermal regime in this context. Repeated geodetic measurements of blocks at the surface of the rock glacier finally allow to discuss the relationship between climate and kinematics of the rock glacier under present warming conditions.

Overview of the Cerro Caquella Eastern face and the (circled) rock glacier (photo X. Bodin, avril 2009).

The Caquella rock glacier at the end of the wet season (photo IRD, avril 2008).

2 - State of the Caquella rock glacier

2.1 - Geomorphological and topoclimatic contexts

Glacial deposits on the Eastern flank of the Cerro Caquella are marked by widespread Quaternary moraines, until 4500 m asl., and a very reduced LIA moraine at 5675 m asl.

Below this latter, the 20-ha rock glacier develops until 5250 m asl. (approx. altitude of the present 0°C isotherm) in a moderately sunny context and displays a typical morphology of transverse ridges and furrow and a 80-m high front.

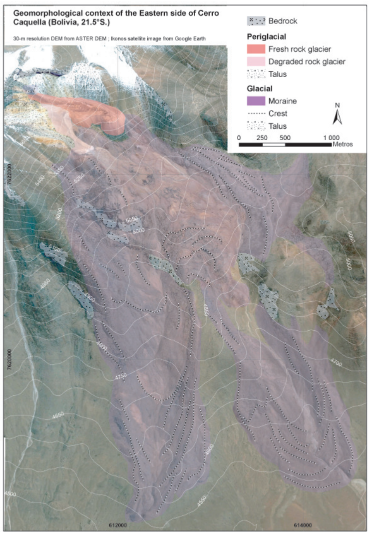
2.2 - Internal structure of the rock glacier

As already described by Francou et al. (1999) and Fabre et al. (2001), the vertical electrical soundings (VES) reveal relatively low resistivities of the 2nd layer (between 4300 and 44000 Ohm.m), which would generally correspond to mainly sandy material with low interstitial ice content and/or temperature close to 0°C. Those results are in good agreement with observations made in a crevasse in 1996.

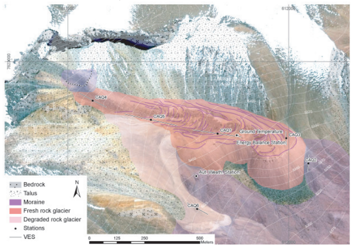
Strong spatial variations of the internal structure of the rock glacier appear, and three zones can be distinguished:

1) the root, with a thick active layer above a thin frozen level;
2) the median part, with a 40-m thick frozen layer below an active layer of 4m;
3) the terminal part, with very few or no ice.

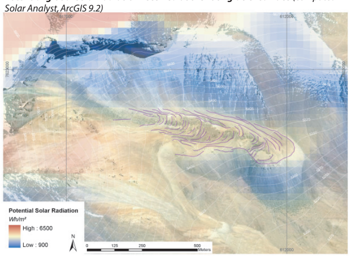
Geomorphological and topoclimatic context



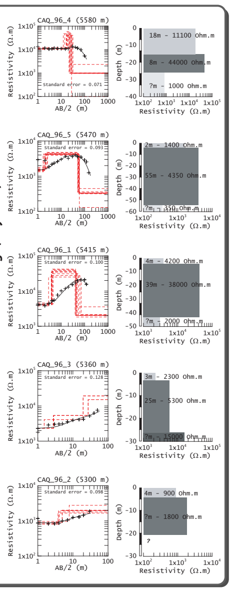
Morphologic characteristics of the rock glacier and location of the datasets (VES = vertical electrical sounding)



Potential global solar radiation received at the rock glacier surface (computed in Solar Analyst, ArcGIS 9.2)



Results of vertical electrical soundings (July 1997)



3 - Dynamics of the rock glacier

3.1 - Characteristics of the surface energy balance and the ground thermal regime

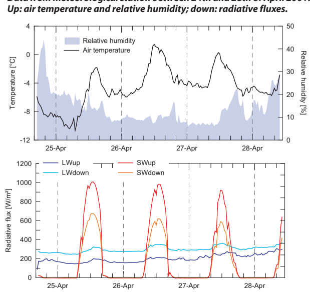
The computation of the different energy fluxes above a 40-cm thick snow cover, during a 5-day period entering the austral dry winter of 2001, indicates a negative balance (approx. -85 W/m²) and a cooling of the ground.

As it typically occurs on high mountain at very high altitude, the energy balance measurements show high sublimation rates (2-3 mm we/day) of the snow, which would generally lead to the disappearance of the snow cover in 2 to 3 months.

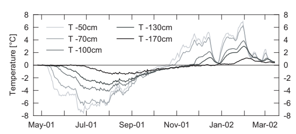
The ground thermal monitoring between April 2001 and March 2002 shows that:

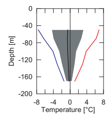
- the mean annual temperatures of that upper part of the active layer were comprised between -0.6 (-50 cm) and -0.2°C (-170 cm);
- the quasi absence of snow cover during the winter allows a strong coupling with the atmosphere and a deep freezing of the ground;
- the timelag of the minimum temperature is shifted by quasi 2 months at -170 cm compared to the surface
- the near-0°C curtain effect observed at -170 cm attests the progressive freezing of ground moisture.

Data from meteorological station between 24th and 28th of April 2001. Up: air temperature and relative humidity; down: radiative fluxes.



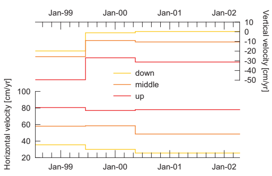
Daily ground temperatures at 5 depths between April 2001 and March 2002.





Vertical profile of ground temperature: mean, minimum, maximum and +/- 1SD envelop (April 2001 - March 2002).

3.2 - Seasonal and annual surface kinematics between 1998 and 2002

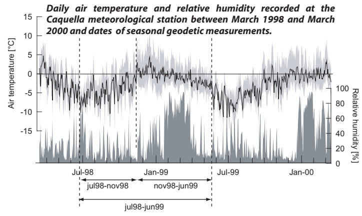


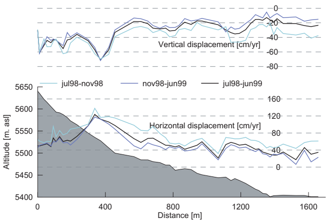
Annual vertical and horizontal velocities between 1998 and 2002 of the three main morphologic parts of the Caquella rock glacier.

Between 1998 and 2002, the measured horizontal velocities (campaigns on 07/98, 06/99, 05/00, 04/02) range from 124 to 17 cm/yr, and the vertical velocities from -61 to 5 cm/yr .

The 1998-1999 year shows a mean *vertical velocity / 3D velocity* ratio of -0.49 whereas it is only of -0.17 and -0.15 during 1999-2000 and 2000-2002 years, indicating a higher vertical component in the total movement during the first year than during the 3 next ones.

Daily air temperature and relative humidity recorded at the Caquella meteorological station between March 1998 and March 2000 and dates of seasonal geodetic measurements.





Fluctuations of vertical and horizontal displacements along the longitudinal profil of the Caquella rock glacier during the dry 1998 season, the wet 1998-1999 and the whole 1998-1999 year.

On a seasonal scale, it appears that, on average for the whole rock glacier, both vertical and horizontal velocities (absolute values) measured during the dry 1998 season (jul.98-nov.98) where lower than those during the wet 1998-1999 season (nov.98-jun.99). The amount of movement during the wet season reaches about 52 to 61% of the total annual movement, except for the lowest points on the front where the wet part is only of 38%.

4 - Discussion

4.1 - Present state of a tropical rock glacier

Results of others studies on temperate mountains (Kääb et al., 2006; Ikeda et al., 2009) suggest that the combination of low resistivity and relatively high surface velocity recorded on the Caquella rock glacier may be explained by the presence of warm permafrost (temperature close to 0°C and presence of liquid water). According to the same authors, the relatively high annual and seasonal variability of surface kinematics might also result from that specific thermal state of the ground.

As already pointed out by Francou et al (1999), this tropical rock glacier, although still located above the 0°C isotherm may therefore be experiencing degradation of its permafrost. Additional geophysical data (like electrical resistivity tomography) and thermal monitoring are nevertheless required to determine more accurately the internal structure of the rock glacier and its physical and thermal state.

4.2 - Permafrost / climate relationship at intertropical latitude

The asynchronous combination of the air temperature and snow thickness seasonal cycles lets us thinking that the thermal response of the ground is probably not as highly influenced by the snow cover here as it is under temperate climate. Furthermore, in spite of their short duration, the high sublimation rates of snow measured on the rock glacier suggest that meltwater from the snowpack would be a small contributor to the hydric state of the ground. It is possible that the water alimentation of the permafrost body results from the burying of snow under debris, as well as is probable that past nivo-meterological conditions, as attested by the (probably) LIA moraine, were significantly different from those of today.

The long-term continuation of the monitoring is therefore required, as well as the acquisition of new datasets on other intertropical Andean rock glaciers (Trombotto et al., submitted).

5 - Conclusion

This study was the first of this kind to provide a detailled panorama of the state and the dynamics of a tropical rock glacier thanks to various complementary datasets. A partial confirmation of the degrading state of the rock glacier arises from the high surface velocity recorded between 1998 and 2002 and from the interpretation of geoelectrical soundings. Meteorological measurements reveal a complex surface energy balance, strongly influenced by latent heat fluxes and rise the question of the hydric functioning of the permafrost.

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