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Environmental forcings that enable penitente development on glaciers in the high, arid Andes of Chile

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Predicting the amount and timing of water delivery is vitally important in semi-arid regions, as any changes from the norm can increase stress in an already strained environment. In the Norte Chico region of Chile, both water availability changes caused by El Niño Southern Oscillation precipitation variations, and added water demand due to the growth of the agricultural and mining sectors cause the hydrological system to be consistently placed in a precarious position. In addition, due to relatively low rainfall amounts over the year (averaging 90 mm at the coast and 300 mm in the Cordillera each year), productivity depends on meltwater delivered from snow and ice in upper catchment regions. Glacier melt is thought to provide up to 30% of runoff in glaciated catchments, however the contribution is related to the presence of penitentes on the glacier surface. It has been estimated that penitente-covered glaciers can experience up to seven times more melt than their non-penitente covered counterparts. Hence it is important to understand not only how and why penitente-covered glaciers produce more meltwater, but also why they only form on certain glaciers. This paper aims to understand the environmental forcings that enable the development of ice penitentes on glaciers.

To understand the conditions that encourage penitente development, a comparison of environmental conditions is performed between two adjacent glaciers (Guanaco vs. Toro 1). The Guanaco Glacier is a cold glacier (29.34ºS, 70.01ºW, 5355 m asl, 1.8 km2) that glacier is largely planar with little penitente development. Comparatively, on Toro 1 Glacier (29.32ºS, 70.01ºW, 5055-5235 m asl, 0.06 km2) penitentes develop during summertime across the glacier surface.

The comparison of environmental conditions consists of a comparison of: i) meteorological data collected from the surfaces of the Guanaco and Toro 1 glaciers between October 2008 and 2010; ii) terrain conditions such as slope, aspect, sediment availability and shading between glaciers; iii) model based energy balance estimations derived from i) and ii). Together these determine the conditions that control the rate and form of surface ablation and underpin the mechanisms that cause penitente development.

Results of the meteorological comparison show that that Guanaco Glacier experienced consistently higher wind speeds than Toro 1, which probably prevent the windspread development of penitentes on Guanaco. The terrain comparison shows that Toro 1 receives, and stores more sediment. The differences in albedo caused by sediment addition help to drive a melt enhancement on Toro 1 Glacier, such that melt on Guanaco accounts for less than 20% of annual ablation, whereas on Toro 1 it equates to more than 70% of annual ablation.

This study highlights how the underlying physical properties of two glaciers in semi-arid Chile impact penitente development. Specifically, spatially variability in terrain and meteorological conditions help to drive different ablation mechanisms between the study glaciers, which in turn promote disparate penitente development. These results will help to constrain distributed energy balance models, as well as to enable the extrapolation of glacier-scale datasets to the wider catchment in order to better quantify glacier contribution to streamflow in semi-arid regions.