Can the snowline be used as an indicator of the equilibrium line and mass balance for glaciers in the outer tropics?

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ABSTRACT. Because the glacier snowline is easy to identify on optical satellite images and because in certain conditions it can be used as an indicator of the equilibrium line, it may be a relevant parameter for the study of the relationships between climate and glaciers. Although several studies have shown that the snowline altitude (SLA) at the end of the hydrological year is a good indicator of the equilibrium-line altitude (ELA) for mid-latitude glaciers, such a relationship remains conjectural for tropical glaciers. Indeed, unlike in mid-latitudes, tropical climate conditions result in a distinct seasonality of accumulation/ablation processes. We examine this relationship using direct field ELA and mass-balance measurements made on Glaciar Zongo, Bolivia (−16°S), and Glaciar Artesonraju, Peru (−9°S), and the SLA retrieved from satellite images acquired in the past two decades. We show that on glaciers in the outer tropics: (1) ablation is reduced during the dry season in austral winter (May–August), the SLA does not change much, and satellite images acquired between May and August could be used to compute the SLA; and (2) the highest SLA detected on a number of satellite images acquired during the dry season provides a good estimate of the annual ELA. However, as snowfall events can occur during the dry season, the SLA detected on satellite images tends to underestimate the ELA. Thus, we recommend validating the SLA computed from satellite images with field data collected on a benchmark glacier before measuring the SLA on other glaciers in the same mountain range for which no field data are available. This study is a major step towards extending the measurement of glacier parameters (ELA and mass balance) at the scale of a whole mountain range in the outer tropics to better document the relationships between climate and glaciers.

1. INTRODUCTION

In situ measurements of glacier mass balance are rare at the global scale. The World Glacier Monitoring Service has compiled data from 110 of the ~100,000 existing glaciers listed in the World Glacier Inventory. To better understand the climate–glacier relationship at regional scale and to analyze the influences of both morphological (e.g. aspect, slope, elevation, latitude) and meteorological parameters (e.g. temperature, precipitation) on glacial changes, glaciological parameters (mass balance, equilibrium-line altitude (ELA)) at the scale of a mountain chain or a climatic region need to be measured. Remote-sensing techniques appear to be appropriate for this purpose (e.g. Rees, 2006; Bamber and Rivera, 2007).

The equilibrium line of a glacier separates the accumulation zone (where the annual mass balance is >0) from the ablation zone (where the annual mass balance is <0). Its position is determined by the climatological environment and the net budget for each individual year (Meier and Post, 1962; Kuhn, 1989). Lliboutry (1965) stated that for mid-latitude glaciers the position of the end-of-summer snowline, i.e. the snowline at the end of the hydrological year, can be considered as representative of the ELA. This assertion has since been confirmed for mid-latitude mountain glaciers (e.g. Rabatel and others, 2005). This enables variations in the ELA to be reconstructed from remote-sensing data like aerial photographs and/or satellite images on which the snowline is generally easy to discern, and consequently study of the climate–glacier relationship in remote areas for which no direct measurements are available (e.g. Chinn and others, 2005; Barcaza and others, 2009). The relationship between the end-of-summer snowline and glaciological parameters also enables reconstruction of annual mass-balance time series, assuming that: (1) the mass-balance gradient in the vicinity of the ELA is representative of the mass-balance gradient of the whole glacier and remains constant throughout the study period; and (2) the average glacier mass balance over the study period has been determined using the geodetic method, which enables changes in volume to be computed by subtracting digital elevation models (DEMs) created by photogrammetry or field topography (e.g. Braithwaite, 1984; Rabatel and others, 2005, 2008).

However, the above relationship is not valid for glaciers where superimposed ice (resulting from freeze/thaw cycles at the surface) is accreted to the glacier, which is the case for cold glaciers; in such cases, at the end of the hydrological year, the ELA is lower than the snowline altitude (SLA) (Lliboutry, 1998). For glaciers in the outer tropics, the representativeness of the snowline as an indicator of the ELA is still highly conjectural. The few studies performed in the outer tropical Andes that made use of this relationship assumed that the relationship is clear...