

Modelling Ice Retreat on Kilimanjaro Using GIS

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1.0 INTRODUCTION

Since the late 1800's the ice fields on the top of Mt. Kilimanjaro have been retreating (Cullen *et al.*, 2006, Hastenrath, 2006). In order to document and analyse this demise, the mapping of the ice bodies has been addressed by several studies. This relied on multiple techniques such as ground photogrammetry (Klute, 1920), or more recently using satellite imaging. Recently, Cullen *et al.* (2013) revisited the mapping of glaciers and produced a set of eight outlines of ice extent over Kilimanjaro for the past 100 years. These maps are depicting the unabated retreat of the ice mass and allow the rate of retreat to be analysed.

Contrasting topographic settings such as aspect, slope, and height of glaciers have a potential influence on the retreat of glaciers (Hastenrath and Greischar, 1997, Cullen *et al.*, 2006, Racoviteanu, 2008, Thompson *et al.*, 2009). On Kilimanjaro, rates of areal retreat have been found to vary across different domains of the mountain from 2.32% to 5.23% between 2000 and 2007 (Thompson *et al.*, 2009). Alternatively, Cullen *et al.* (2013) identified three contrasting glacier zones (western, plateau, and southern regions) exhibiting areal rates of retreat of 0.043, 0.034, and 0.021 km²/yr, respectively. Under the assumption that these rates hold true since retreat started, it can be estimated that the plateau, except the Ruesch Crater, was entirely covered with ice around 1830.

The new dataset established by Cullen *et al.* (2013) provides an opportunity to further characterize the retreat of the glaciers. In particular, the complex geometry and pattern of retreat complicated the use of typical measures such as the planimetric retreat rate of the glacier terminus to characterize the demise. Thus, only the areal extent has been considered and exhibited an approximately linear retreat rate allowing projections to be made with regard to the disappearance of ice (Cullen *et al.*, 2013). This study uses geographic information systems to characterize further the disappearance of glaciers by considering the planimetric rate of retreat of the boundaries of ice bodies on Kibo. Firstly, the topographic settings of the ice boundaries were investigated as potential drivers controlling the planimetric retreat rate. Secondly, a linear model of boundary retreat was formed that allowed the glacier outlines of the plateau region to be interpolated between the documented epochs.

2.0 DATA AND METHODS

A series of eight digital outlines of Kilimanjaro glaciers from the past one hundred years was used to characterise the retreat of the glacier's boundaries and to interpolate the extent of the ice bodies between known epochs (Cullen *et al.*, 2013). A distance model was created that provided the shortest Euclidean distance from equally spaced points along each glacier outline to the outline of the previous or the next epoch. Underlying topographic variables such as elevation, slope, and aspect were retrieved for each point from the analysis of the 30m SRTM DEM. On the relatively flat plateau region, where most of the boundaries are ice cliffs, the aspect variable derived from the SRTM DEM was unreliable to represent the orientation of the cliffs. The direction of the normal vector to the outline at equally spaced points was considered as a better representation of the cliff's orientation. The correlation between the planimetric retreat rate of the boundary and each morphometric measure was investigated by considering the entire set of glacier outlines, as well as outlines from each of the three regions identified by Cullen *et al.* (2013).

Over the plateau region, the retreat rate of the ice cliffs was derived for equally spaced points along each outline and for each pair of documented epochs. This allowed the location of the cliff to be interpolated between each epoch pair by intervals of no more than 10 years. The area of the interpolated outlines was computed and its trend was compared with the trend inferred from the observation points. This process was to reveal whether the inherently complex geometry of the glacier outlines allowed both the planimetric retreat of the boundary and the corresponding glacierized area to obey linear trends simultaneously. In turn, it provided reliability to the interpolated outlines between documented epochs.

3.0 RESULTS

The analysis of the rate of retreat of the glacier boundaries with respect to topographic variables failed to reveal any clear or systematic pattern, whether considering the entire set of outlines or within each region. This contrast with the fact that the areal extent retreat rate appears clearly related to morphometric variables (Cullen *et al.*, 2013). It is hypothesized that the shortest distance model may have failed to resolve the ambiguities associated with the trajectory of the glacier outlines, especially given the complex geometry of the set of polygons. This may have been further impaired by the large time span between some of the documented epochs. Furthermore, the relatively poor quality of the SRTM DEM in this steep region, and the fact that its unique epoch (February 2000) failed to resolve the changing topography associated with the glacial retreat may have yielded uncertainties in the derived variables that could have contributed to the noisy and uncertain relationship.

The lack of any clear empirical relationship between the boundary retreat rate and topographic variables compromised the use of the morphometric measures to design an elaborated model of boundary retreat. Instead, the interpolation of glacier outlines between epochs was only attempted on the plateau region as the geometry of the ice bodies was less subject to follow the underlying topography. Winkler *et al.* (2010), who surveyed the retreat of an ice cliff between 2005 to 2008 reported retreat rates of about 1.4cm a month during the beginning of March to mid-October and 13cm a month the rest of the year (or using simple math, 69cm a year). Although it was difficult to identify precisely the exact location of the cliff, results from this study revealed retreat rates ranging from 2 to 75cm per year between 2003 and 2011. A linear retreat rate of the ice boundary was thus assumed to estimate the position of the ice cliffs between each epoch pair. The interpolated outlines are shown in Figure 1. The modelled areal extent of the plateau glaciers obtained from the interpolated outlines was compared with the retreat from the observations and shown in Figure 2. This suggests that, despite the complex geometry of the ice bodies, a linear rate of retreat of the ice cliffs between two epochs is an appropriate assumption to depict observed changes in ice extent in the plateau region. In turn, it is argued that the shape of the interpolated extents can be regarded as relevant candidates of the ice extent at the undocumented epochs.

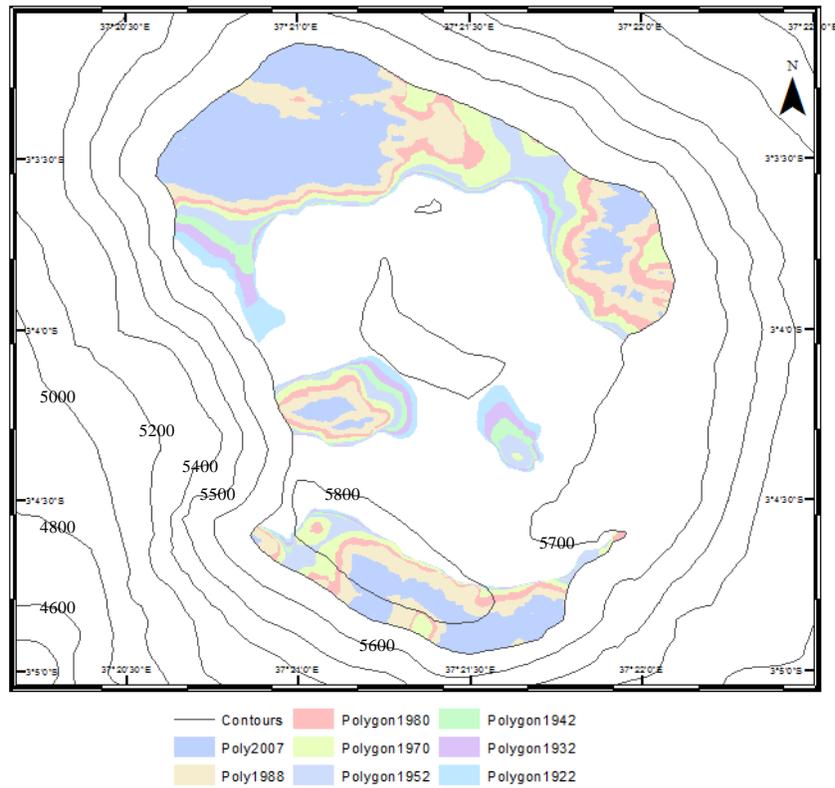


Figure 1. Interpolated ice extents between documented epochs.

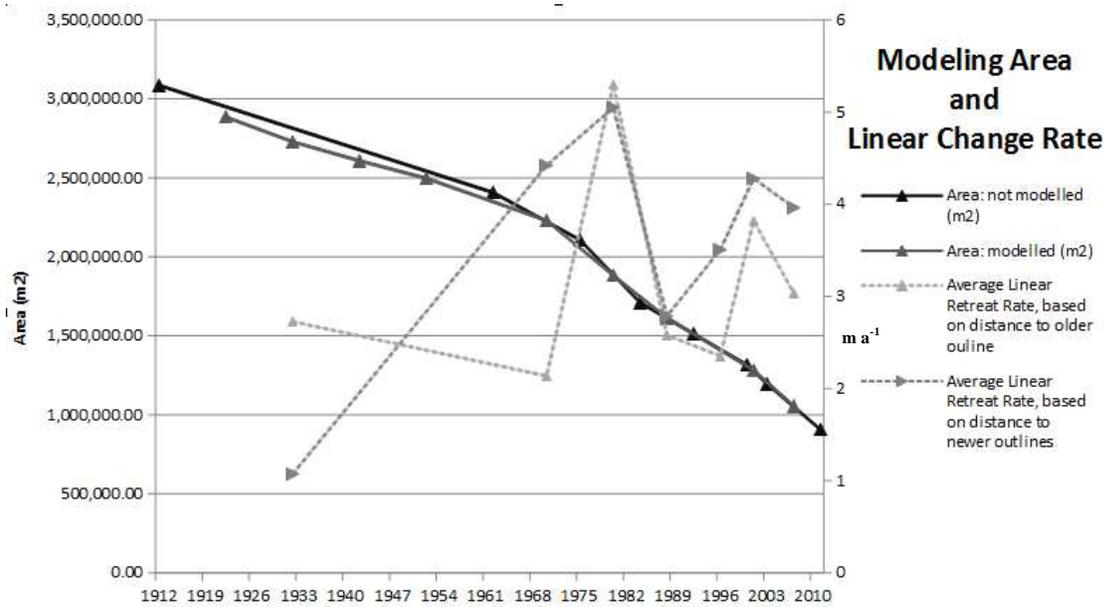


Figure 2: Area of the glaciated plateau for observed and interpolated epochs.

4.0 CONCLUSIONS

The lack of correlation between topography and distance between outlines could have been expected when considering all regions due to the large variation controlling the ablation of ice. It was however unexpected to find so little signal from the topography to govern the planimetric retreat of the ice boundaries in each region when analysed independently. Despite this, it is anticipated that a model of this kind may be used to characterize the retreat of glaciers when the geometry is not complex and clearly constrained by the underlying topography.

Interpolated outlines of the glacier extent could nonetheless be obtained for the plateau region based on a simple assumption of a linear retreat of the ice boundaries. This proved valid to generate outlines for which the areal extent matched closely to the observed trend, making the interpolated outlines credible. This approach could form the basis of extrapolations to predict the pattern of ice retreat, as well as to obtain an alternative estimate of the date at which the summit of Kilimanjaro was totally covered by glaciers.

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