MEASUREMENT OF THE RETREAT OF QORI KALIS GLACIER IN THE TROPICAL ANDES OF PERU BY TERRESTRIAL PHOTOGRAMMETRY

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ABSTRACT

The extent and volume of the largest outlet glacier from the Quelccaya Ice Cap (14°S, 71°W, 5200 m a.s.l.) has been measured four times between 1963 and 1991, once by aerial and three times by terrestrial photogrammetry. Drastic and accelerating retreat of the terminus and decrease of ice volume have been documented. The rate of retreat was nearly three times as fast between 1983 and 1991 as between 1963 and 1978 and the rate of volume loss was about eight times as great. These results are consistent with the behavior of tropical glaciers in the Cordillera Blanca in Peru and in the Ruwenzori Mountains and on Mount Kenya in East Africa.

INTRODUCTION

The Byrd Polar Research Center has been carrying out glaciological studies for reconstructing a climatic history for tropical South America on the Quelccaya Ice Cap in the Andes of Peru since 1974 (Thompson 1991, 1992; Thompson et al. 1982, 1985, 1986, 1988, 1991). As part of these studies the extent and volume of its largest outlet glacier, the Qori Kalis (Figure 1), has been mapped four times and changes in its extent and volume have been determined.

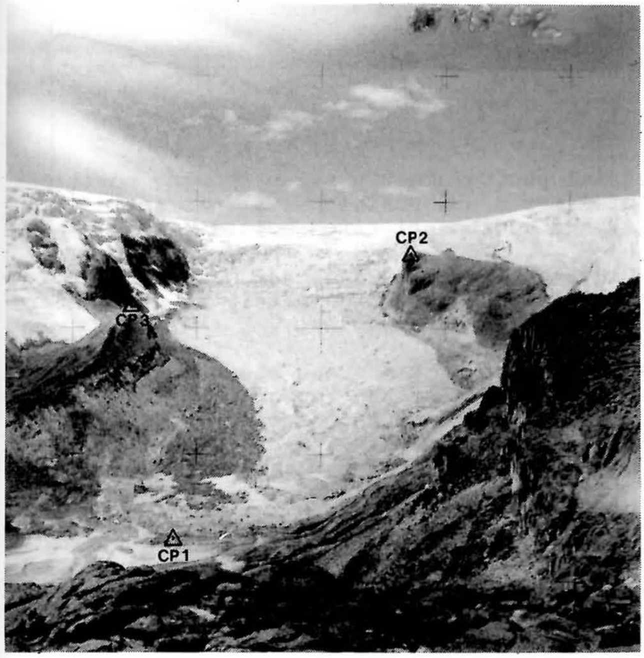

Figure 1

1983 Hasselblad photograph of Qori Kalis from station PS showing intersected control points

PHOTOGRAPHY AND MAPPING

A conventional topographic map of the glacier, with 5 m contour interval and at 1:6,000 scale, was produced on an analog (Wild B8) plotter from one stereoscopic model of 1:25,000 scale vertical aerial photography taken on 22 May 1963. The model was set up on ground control determined by aerial triangulation by Peruvian government mapping agencies for use in general topographic mapping of the area at 1:25,000 scale. This map was subsequently digitized on a 60 m grid interval by reading off surface elevations at grid intersections to the nearest meter, which yielded a point density roughly equal to that obtained from measurements on the terrestrial photography and also served to smooth the 1963 representation.

Terrestrial photographs were taken on 2 July 1978, 22 July 1983 and 17 September 1991 with metric cameras (Hasselblad 500 EL with reseau, 55 mm square format, 60 mm Zeiss Biogon lens in 1978 and 1983, Wild P32, 60 x 80 mm format, 64 mm lens in 1991) from a 370 m baseline on a bluff about 900 m from the glacier terminus (Figure 2).

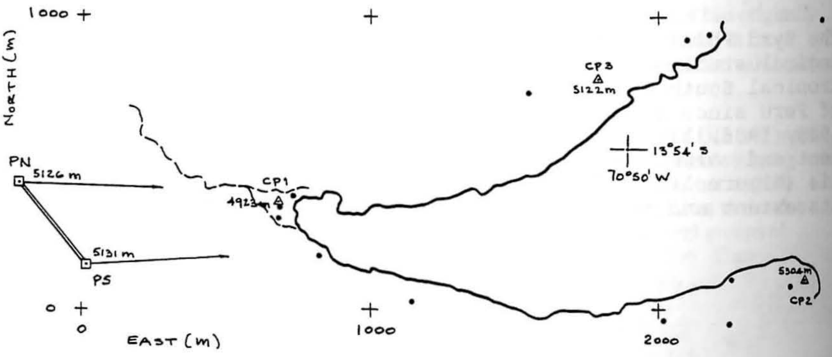

Figure 2 Terrestrial photogrammetry setup showing positions and convergence of cameras and positions of intersected control points (▲) and additional fixed points (•)

The cameras were leveled in "roll" and "yaw" by means of a bullseye level and pointed only approximately at the center of the glacier in "pitch" (convergence).

The locations of the camera stations and the convergence of the camera axes were dictated by the topography, resulting in geometry which did not allow a satisfactory stereoscopic model to be formed, even on an analytical plotter. Stereo viewing was particularly difficult near the terminus due to the substantially different views from the two camera stations. It was therefore not possible to produce graphical plots directly from the terrestrial photography. Instead, point measurements of the glacier edge and elevation profiles across the glacier were made by stereocomparator. The profiles were taken at what was judged to be a reasonable

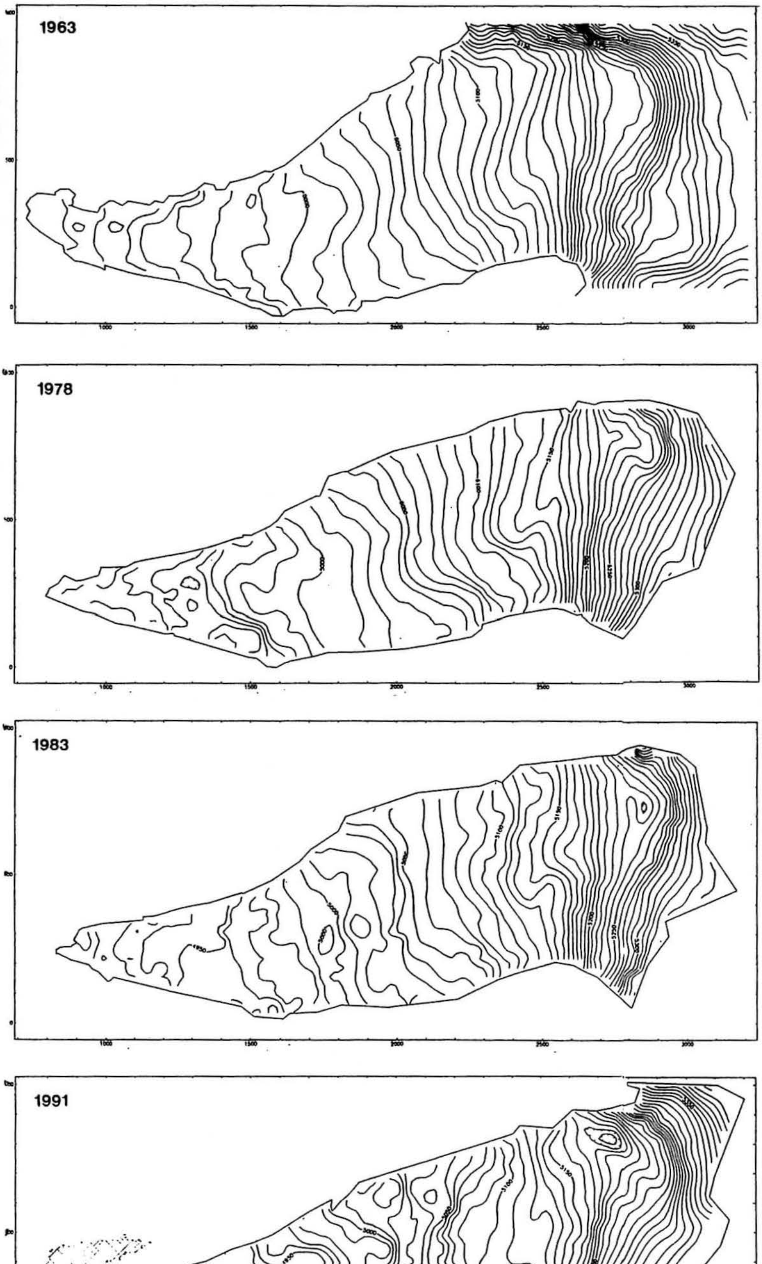

Figure 3 Maps for the four epochs, reduced to 1:25,000 scale

and practical interval on the photographs. This procedure yielded about ten profiles in the upper two-thirds of the glacier at an average spacing of about 150 m with points about 50 m apart along the profiles, and points spaced at about twice this density in the lower one-third of the glacier. Each of the mappings from terrestrial photography is based on about 400 acceptable points. Three-dimensional terrain coordinates of the points were computed with a block triangulation program (GIANT) which uses rigorous bundle adjustment procedures. Digital elevation **models** were generated from these measurements and from the digitized 1963 contour map at 30 m grid spacing with the SURFACE III graphics system package. Maps with 10 m contour interval were then plotted from these DEM's for each epoch with the SURFACE III package (Figure 3).

The terrestrial photography was brought into the 1963 map coordinate system (UTM zone 19) by identifying the camera stations and three widely-spaced control points, located by intersection and trigonometric leveling from the two terrestrial camera stations (Figures 1 and 2), in the aerial photographs. The distance and elevation difference between the camera stations were determined by electronic distance measurement and trigonometric leveling, their relative positions were determined with high precision (on the order of 1 cm) and they were reliably identified on the 1963 aerial photographs. The distance and elevation difference between camera stations measured on the aerial photographs agreed very well (within 0.6 m and 0.5 m, respectively) with the determinations made on the ground. There was some uncertainty in identifying one intersected control point (CP 3, Figure 2) and the accuracy of positions of the intersected control points in relation to the baseline was about 1 to 3 m in the along-glacier direction. Also, point CP 3 could not be used with the 1991 photography because the top of the moraine had slumped away. In a "first pass" in the adjustments, camera positions and leveling were therefore tightly constrained while control point positions and camera convergence were held loosely by appropriate weighting. This approach enforces the best available control on the scale of the terrestrial solutions and insures that all are on the same datum. In order to secure a good fit of all three terrestrial solutions to each other twenty additional common points just off the ice along the glacier margin were measured. In the final adjustments the "best" mean values for the control points and thirteen of these additional points which proved to be acceptable (Figure 2), were held relatively tightly.

PRECISION AND ACCURACY

Repeatability of measurements on the terrestrial photographs was generally good in the regions of good stereoscopic perception; 10 µm is thought to be a reasonable estimate of precision. But results varied considerably from place to place and are estimated to be as much as 30 µm in some "difficult" regions and in a few extreme cases photo residuals in the adjustments were even larger. Although such low precision would normally be unacceptable, it was decided to accept even some poorly determined points on the basis of the "reasonableness" of their positions and elevations.

Accuracy of positions and elevations, of course, varies with position relative to the camera stations. Table 1 gives approximate means of standard errors to be expected with 10 µm measurement error on the photographs for three regions of the glacier. Note that the along-glacier direction is away from the baseline and thus, although elevations are determined with reasonable accuracy, their along-glacier positions can be appreciably in error.

TABLE 1

Errors in positions and elevations on glacier

Region	Across-glacier (m)	Along-glacier (m)	Elevation (m)
Lower one-third	0.4	1.7	0.3
Middle one-third	0.5	3.2	0.4
Upper one-third	0.6	7.0	0.8

A least-squares fit of the four acceptable common points on the 1963 map and in the terrestrial determinations (the two camera stations and control points CP 1 and CP 2, Figure 2) yielded RMS of residuals of 3.9 m in easting and 3.6 m in northing. RMS of differences in elevations of these four points is 6.7 m. This relatively large value is due to the unreasonably large difference at CP 2, which is attributed to an identification error.

RESULTS

Retreat of terminus

The outlines of the glacier terminus for all four determinations are shown superimposed in Figure 4. A "mean" posi-

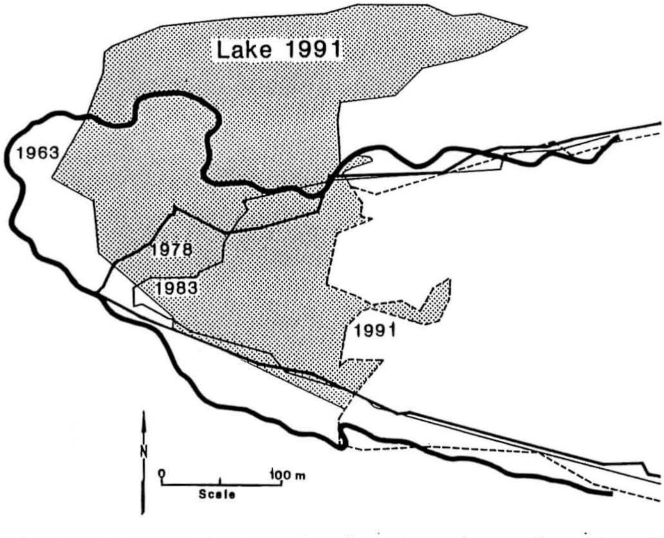

Figure 4 Outlines of the glacier terminus for the four determinations

tion of the terminus of the glacier with respect to an arbitrary origin was determined for each epoch by measuring the positions of enough points along the glacier edge in each case to represent its position adequately. The results, with respect to the 1963 position as origin, are shown in Figure 5 together with the displacements of several elevation contours determined in a similar manner. The "mean" positions of every fifth contour line between 4950 m and 5300 m were determined and the positions of two consecutive contours were then averaged to smooth the results. The displacement increases systematically with time and decreases with elevation. This result is presented in a different manner in Figure 6, where the displacements for the three time periods are plotted as rates of displacement versus elevation. The values for the terminus are shown with different symbols in these figures because the rate of retreat of the terminus is "less than it should be" for its elevation. This is attributed to the fact that melting stops because the glacier bed has been reached. That is, there is less ice thickness here than could be melted.

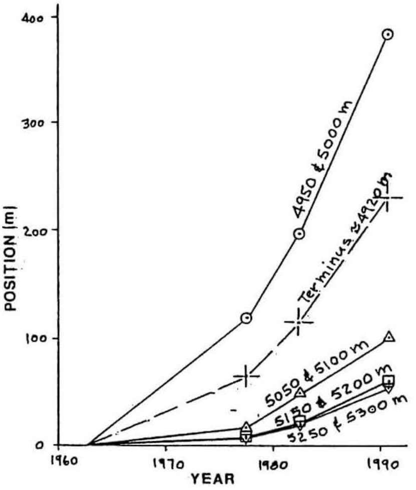

Figure 5 Retreat of terminus and displacements of selected elevation contours with time

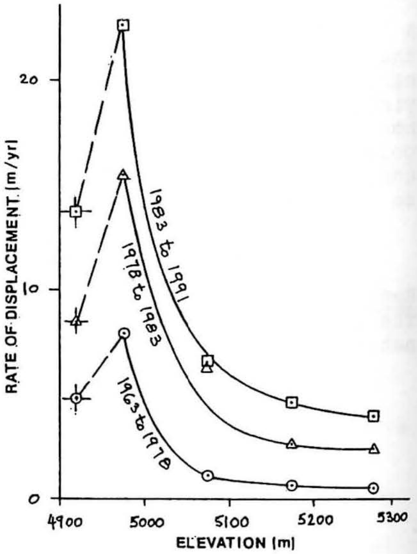

Figure 6 Rates of retreat of terminus and displacement of selected elevation contours for three periods

Table 2 presents the results numerically. The accelerating retreat with time is evident, the rate of retreat having nearly doubled from 1963-1978 to 1978-1983 and nearly tripled to 1983-1991.

Decrease in ice volume

Changes in volume for the three time intervals were computed from the differences in ice surface elevations by means of the SURFACE III package. The procedure first takes elevation differences at each grid node and then computes the change in volume by summing the differences for all grid

TABLE 2

Retreat of terminus

Period	Time interval (yr)	Mean retreat (m)	Rate of retreat (m/yr)	Ratio
1963-1978	15.09	73.5	4.87	1.00
1978-1983	5.06	41.6	8.22	1.69
1983-1991	8.17	112.9	13.82	2.84

cells within a specified boundary. For each case, the boundary of the smaller of the two areas being compared was used, and the loss of volume at the terminus, using estimated elevations at the bed, was then added. Since this neglects the volume loss at the lateral margins of the glacier, the values represent minimum volume losses. Since the neglected area is a small fraction of the total area and the ice thickness is small at the margins, the underestimation of ice loss is small.

As is the case with the retreat of the terminus, the volume loss is accelerating with time. The rate of volume loss per unit area (or rate of mean surface lowering; they are numerically equal) is nearly five times as large in 1978-1983 as in 1963-1978 and over eight times as large in 1983-1991. Table 3 summarizes the volume loss results. Using 3 m as the estimated error in surface elevations yields an error of about 0.012×10^6 m^3 for each volume difference determination, or proportional errors between about 0.1 and 0.3 %.

TABLE 3

Volume loss

Period	Area ($m^2 \times 10^6$)	Volume loss ($m^3 \times 10^6$)	Mean surface lowering(m)	Loss rate(m/yr)	Ratio
1963-1978	1.096	4.024	3.67	0.243	1.00
1978-1983	1.059	6.311	5.96	1.178	4.84
1983-1991	1.011	16.649	16.47	2.016	8.30

CONCLUSIONS

A 1500-year ice core record of climate extracted in 1983 from the Quelccaya Ice Cap was updated by the analysis of a new core drilled in October 1991. This new record indicates a 2 o/oo enrichment of $\delta^{18}O$ values (warming) for the decade of the 1980's compared to that of the 1970's, while precipitation in the region over this period has been average to above average (Thompson et al. in press). The drastic and accelerating retreat of the terminus and decrease of ice volume of this largest outlet glacier from the ice cap since 1963 and recent changes along the margin of the ice cap are consistent with this warming. Moreover, recent retreat of the Quelccaya Ice Cap is mirrored in all other tropical glaciers where measurements exist; the Cordillera Blanca in Peru, the Ruwenzori Mountains (Kaser and Noggler 1991) and Mount Kenya (Hastenrath and Kruss 1992) in East Africa as well as recent changes in higher latitude glaciers in Iceland and Austria (Hall et al. 1992). If the current warming trend persists, then many of these glaciers and the tropical and subtropical archives of climate and environmental histories which they contain will be lost to humanity.

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