Measurement of the Retreat of Qori Kalis Glacier in the Tropical Andes of Peru by Terrestrial Photogrammetry

Abstract

Although the consequences of global warming in the last century may be most pronounced on glaciers of the tropics and subtropics, documentation of their recent retreat is extremely limited. The extent and volume of the largest outlet glacier from the Quelccaya Ice Cap (14° S, 71° W, 5200 m above sea level) have been measured four times between 1963 and 1991, once by aerial and three times by terrestrial photogrammetry. Drastic and accelerating rates of retreat of the terminus and of ice volume loss 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 over seven times as great. These results are consistent with the warming in this region and 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

In the last century there has been a general warming trend, with global average surface temperature on land rising about 0.6° C. The consequences of this warming may be most pronounced on glaciers of the tropics and subtropics. Mountain glaciers in these regions are very sensitive to temperature change, as they exist very close to the melting point. 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; 1992). Because documentation of the recent retreat of glaciers in the low latitudes is extremely limited, as part of these studies the largest outlet glacier from this ice cap, the Qori Kalis (Figure 1), has been mapped four times and changes in its extent and volume have been determined.

Photography and Mapping

A conventional topographic map of the glacier, with a 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 by

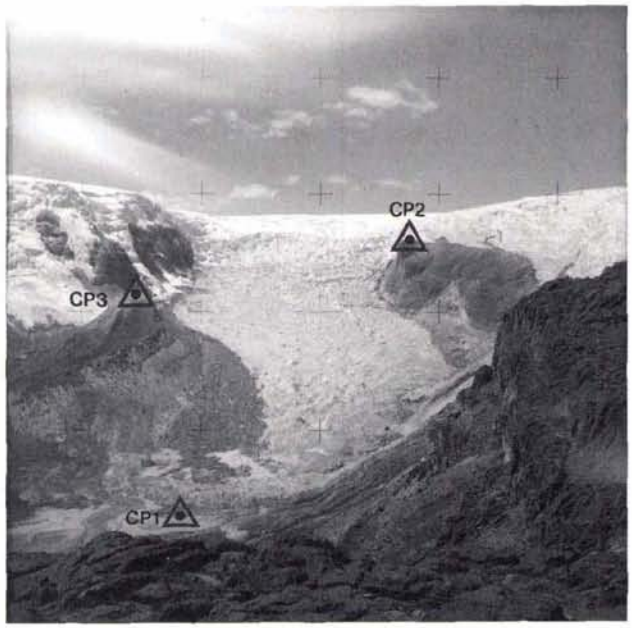

Figure 1. 1983 Hasselblad photograph of Qori Kalis from camera station PS, showing intersected control points.

reading off surface elevations to the nearest metre at every grid intersection on a 60-m grid spacing, 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, and 60-mm Zeiss Biogon lens in 1978 and 1983; Wild P32, 60- by 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). The cameras were leveled by means of a bullseye level and pointed only approximately at the center of the glacier. 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

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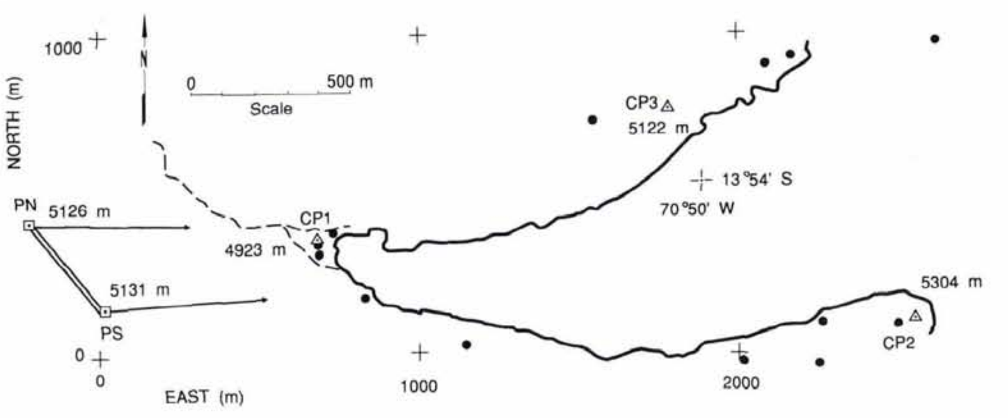

Figure 2. Terrestrial photogrammetry setup showing positions of camera stations, PN and PS, intersected control points, CP 1, CP 2 and CP 3, and additional fixed points (●).

to be formed. Stereo viewing was particularly difficult near the terminus due to the large convergence angle and, thus, 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 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 the GIANT block triangulation program (Elassal and Malhotra, 1987) which uses rigorous bundle adjustment procedures. Digital elevation models (DEMs) were generated from these measurements and from the digitized 1963 contour map at a 30-m spacing with the SURFACE III graphics system package (Sampson, 1988). Maps at 1:5,000 scale and with a 10-m contour interval were then plotted from these DEMs for each epoch with the SURFACE III package (Figure 3).

The terrestrial photography was brought into the 1963 map coordinate system (UTM zone 19, translated −8,462,000 m in northing and −300,000 m in easting to obtain a convenient local origin) by identifying the two terrestrial camera stations and three widely-spaced control points, whose positions were determined by intersection and trigonometric leveling from the two camera stations (Figures 1 and 2), on 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 from 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 triangulation 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 ensures that all are on the same datum. To secure a good fit of all three terrestrial solutions to each other, 20 additional common points just off the ice along the glacier margins were measured. In the final adjustments the "best" mean values for the control points and 13 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; from experience, 10 μm is a reasonable estimate of precision. Expected errors from estimates of photo measurement precision are a better representation of overall results than errors from propagation of individual residuals for each point from each adjustment, which are highly variable and depend mostly on quality of stereo perception. Residuals were as much as 30 μm in some "difficult" regions and in a few extreme cases they were even larger. Although such low precision would normally be unacceptable, it was decided to accept even some apparently poorly determined ice surface points on the basis of the "reasonableness" of their positions and elevations. It should also be noted that the measuring mark can be positioned at a clearly defined image for delineation of the ice edge, monoscopically if necessary; it is not entirely dependent on stereoscopic perception of a more or less uniform surface, as is the case for points on the ice in many cases. Thus, the points which define the position of the ice edge are likely to be determined more accurately than points on the ice surface, in general. Accuracy of positions and elevations, of course, varies with position relative to the camera stations. Table 1 gives approximate mean 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.

A least-squares fit of the four acceptable common points on the 1963 map and in the terrestrial determinations (the two camera stations, PN and PS, and control points CP 1 and

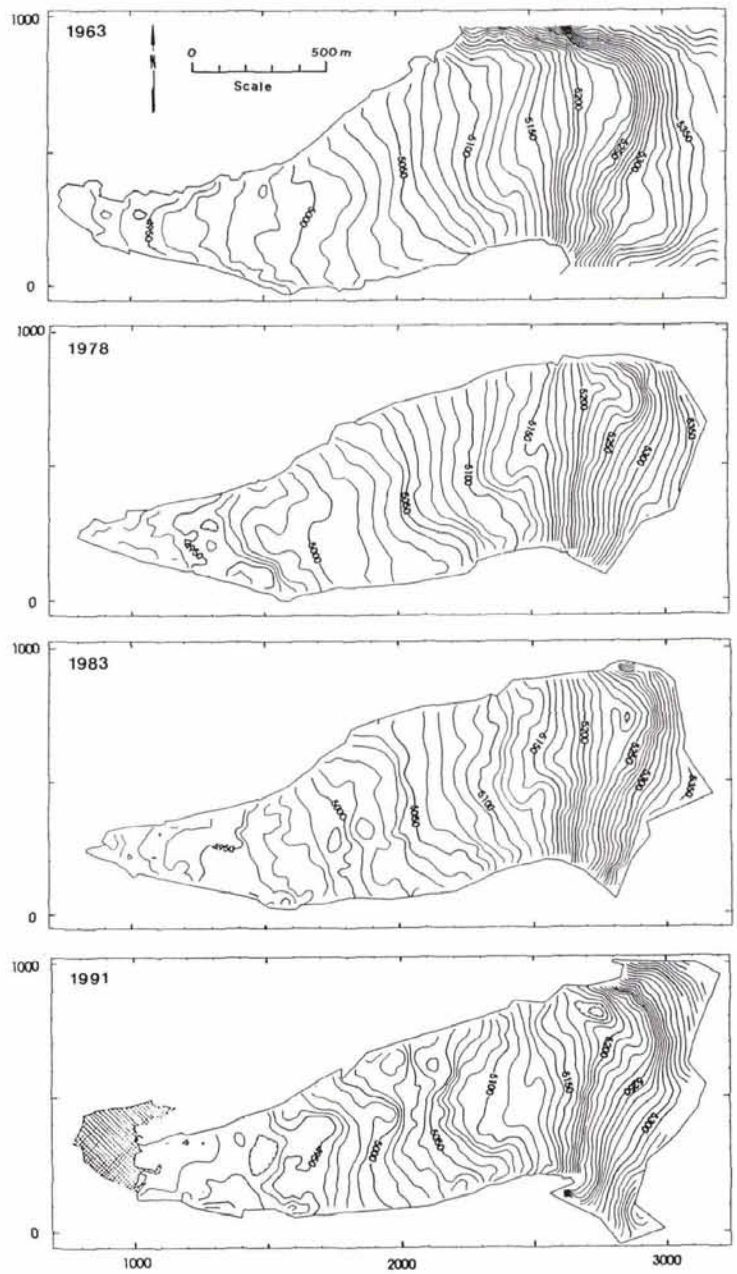

Figure 3. Maps for the four epochs, reduced for publication.

Table 1. Expected Approximate Mean Standard Errors of Positions and Elevations on Glacier (m)

Region	Across-glacier	Along-glacier	Elevation
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

CP 2, Figure 2) yielded an RMS of residuals of 3.9 m in easting and 3.6 m in northing. The 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" position 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 5a together

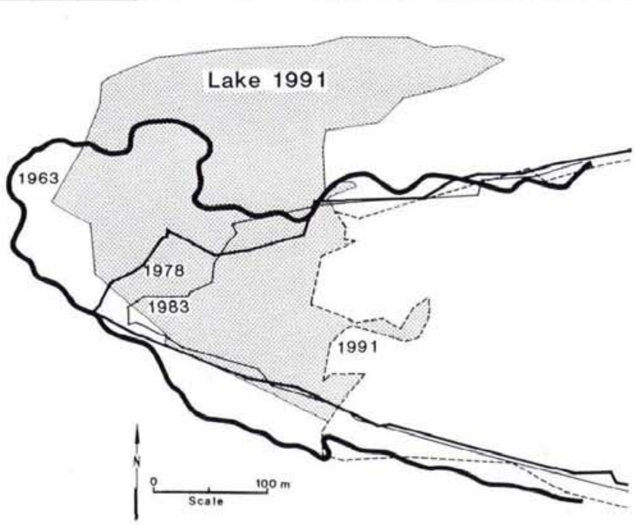

Figure 4. Outlines of the glacier terminus for the four determinations.

with the displacements of several elevation contours determined in a similar manner. The "mean" positions of every fifth contour between 4950 m and 5300 m were determined and the positions of two of these consecutive contours were 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 5b, 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 was less ice thickness here than could have been melted. 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.

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

Ice Volume Loss

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 cells within a specified boundary. Because the SURFACE III program works with whole cells, cells which are even partly outside a boundary are ignored, resulting in systematic underestimation of areas (and therefore volumes). The underestimation is about 1 percent in the present case. For each case, the boundary of the inner (smaller) of the two areas being compared was used because elevations of the newly exposed bed surface were unknown, and the loss of volume at the terminus, using estimated elevations at the bed, was then added. Because this neglects the volume loss at the lateral margins of the glacier, losses there were estimated by applying the mean surface lowering computed from the volume loss obtained with the inner boundaries. The additional area averages about 6 percent.

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. The

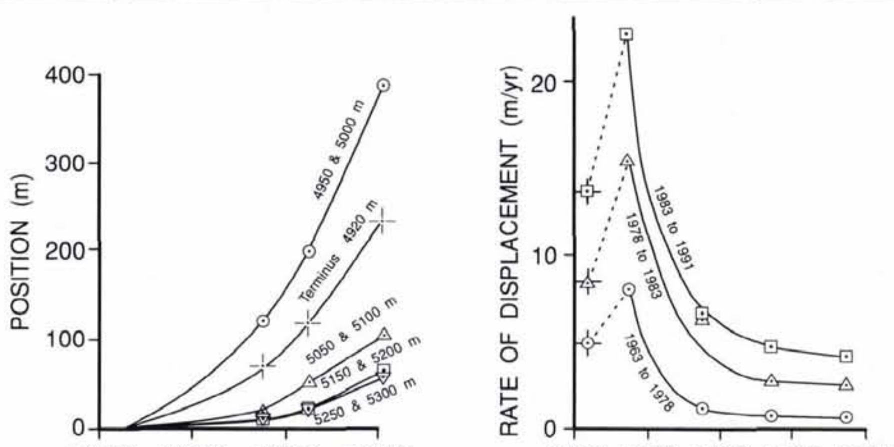

Figure 5. (a) Retreat of terminus and displacements of selected elevation contours with time. (b) Rates of retreat of terminus and displacements of selected elevation contours for three periods.

TABLE 3. VOLUME LOSS

Period	Area ($m^2 \times 10^6$)	Volume loss ($m^3 \times 10^6$)	Volume loss rate ($m^3/yr \times 10^6$)	Ratio	Mean surface lowering (m)	Surface lowering rate (m/yr)	Ratio
1963-1978	1.192	4.376	0.290	1.00	3.67	0.243	1.00
1978-1983	1.108	6.603	1.305	4.50	5.96	1.178	4.84
1983-1991	1.069	17.604	2.155	7.43	16.47	2.016	8.30

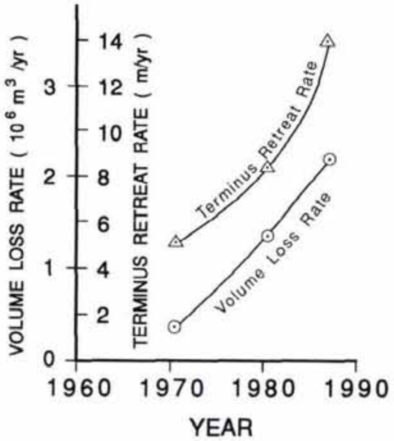

Figure 6. Rates of volume loss and retreat of terminus.

rate of volume loss is four and one-half time as large in 1978-1983 as in 1963-1978 and nearly seven and one-half 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 0.013×10^6 m^3 for each volume difference determination, or proportional errors between about 0.1 and 0.3 percent. Volume loss and terminus retreat rates are shown in Figure 6. Note that change in position of the terminus, which is far easier to measure than volume change, appears to be a good indicator of the trend in volume change, at least in this case.

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 warming of about 1° C for the decade of the 1980s compared to that of the 1970s, 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 elsewhere 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 in recent changes in higher latitude glaciers, for example, in Iceland and Austria (Hall et al., 1992). If the current warming trend persists, then many of these glaciers and the archives of tropical and subtropical climate and environmental histories which they contain will be lost.

Acknowledgments

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