Recent areal and altimetric variations of Miage Glacier (Monte Bianco massif, Italian Alps)

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Abstract Changes in ice thickness and area of the debris-covered tongue of Miage Glacier have been measured using 1975 and 1991 aerial photographs, supplemented by measurements of ice flow from the displacement of 24 supraglacial boulders. Results show an increase in surface elevation of the lower glacier of >40 m, but thinning upstream. Overall ice volume increased in the study period, with negligible detectable change to terminus position and glacier area. The pattern of thickness variation is interpreted as a response to positive mass balance sometime after *c.* 1951. The debris cover may have prevented ablation from reducing the amplitude of a kinematic wave. Thus, the downstream amplification of thickening in the zone of compressive flow has been largely preserved. Debris-covered glaciers, whose termini are often held to be unresponsive to climatic variability, may actually magnify mass balance perturbations if ice remains mobile to the terminus.

INTRODUCTION

Debris-covered glaciers are widespread in the mountain chains of Asia, such as the Karakorum, the Himalaya (Moribayashi & Higuchi, 1977) and the Tien Shan. They are also common in New Zealand (Kirkbride & Warren, 1999) and Alaska. There are few examples of such glaciers in Europe. Two of the best-known (Miage and Brenva) drain the southwest and southeast slopes of Monte Bianco in Valle d'Aosta (western Alps). Miage Glacier (45°47'N, 06°52'E), with an area of *c.* 11 km^2, is Italy's third largest glacier. Morphologically, the glacier resembles the large Asian debris-covered glaciers (Fig. 1). The accumulation zone consists of several crevassed ice-fall tributaries descending from *c.* 4000 m to 2500–2700 m. The confluent tongue descends more gently for 6 km into Val Veny, bending abruptly northeast and dividing into two large lobes terminating at 1775 m, bounded by lateral moraines. The tongue is debris-covered below *c.* 2500 m, initially by medial moraines then more uniformly across the entire surface. Near the terminus, debris thickness exceeds 0.5 m.

Valle d'Aosta has a history of military strategy and trade, and has been explored for science since the observations of De Saussure in the eighteenth century. A long record of frontal variations exists, as well as reconstructions of lateral moraine formation (Baretti, 1880; Porro, 1914; Sacco, 1917; Capello, 1959; Lesca, 1974;

Deline, 1997, 1999a). The debris cover itself has received little attention. This paper interprets thickness change in the ablation zone over a 16-year period in terms of debris-cover insulation, velocity, and glacier response to mass balance change.

AREAL AND ALTIMETRIC VARIATION BETWEEN 1975 AND 1991

Method

Digital terrain models (DTMs) were prepared from aerial photographs taken for the Regional Government of Valle d'Aosta in 1975 (1:30 000 scale) and 1991 (1:26 000 scale). Aerial slides of Miage Glacier were not available. Photographs were scanned and the images so obtained were used to construct stereoscopic models for each photograph year. DTMs were obtained using digital video plotter (DVP) software, which uses scale, focal distance, aircraft altitude and recognizable homologous control points (HCPs) on both surveys. The points used to construct the DTMs were directly measured on the stereoscopic models. A Trimble Geoexplorer Differential GPS was used to locate 20 control points well spread around the glacier to georeference the absolute orientation of the photo images. The GPS master was located in Milan. In order to improve the georeferencing, another 15 control points visible on the aerial photographs were checked and identified on the regional technical map, at 1:10 000 scale (CTR Map, Regione Valle d'Aosta). For each image, a 40-m grid was created to generate the DTM. Spot elevations were interpolated to form a triangular irregular network (TIN), a mosaic of triangles overlapping the grid, and reproducing the morphology of the glacier and adjacent ice-free ground.

The accuracy of the calculated models has been evaluated as 6 m. The difficulties in the DEM generations at high elevation due to snow cover and associated loss of parallax were solved by a slight displacement of the acquisition point where no snow cover was present. Altimetric and volumetric variations of the glacier were calculated

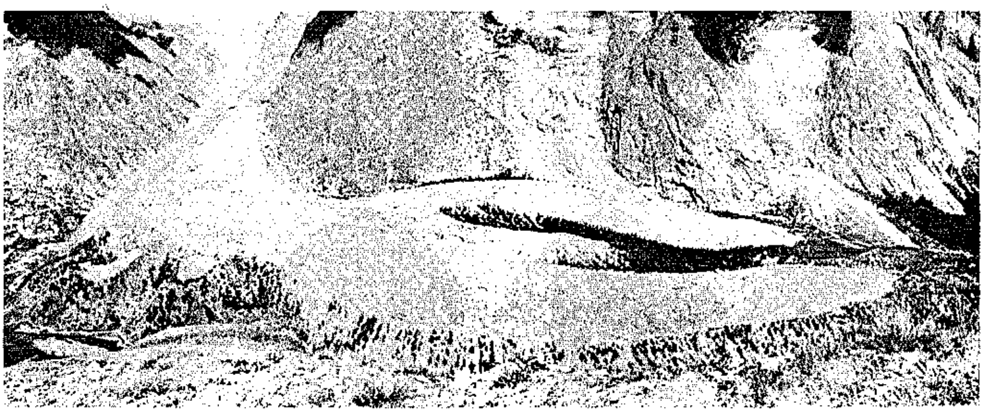

Fig. 1 Wide-angle photograph of Miage Glacier, looking northwards. The southern lobe is in the foreground, and the calving cliff at Lake Miage visible on the right (west) margin of the glacier. Note supraglacial rock avalanche debris draped over a medial moraine in the left (western) part of the debris cover, and recent slope activity on the foreground lateral moraine due to thickening of the southern lobe.

by comparison of the 1975 and 1991 DTMs. HCPs visible in both the surveys (24 control points on the glacier surface) allowed the calculation of glacier surface velocity, by computing the displacement over 16 years of point coordinates on the two surveys. The accuracy of this calculation is controlled by the same factors, and comparable to that of the DTMs.

Results

The surface morphology changed little over the 16-year period, especially in the frontal area. No significant change to the terminus position was registered and the relief of the two main medial moraines increased. The area of the glacier tongue reduced very slightly from 4 461 334 m^2 in 1975 to 4 448 752 m^2 in 1991, a change of –12 582 m^2 (–0.3%). The only differences between the 1975 and 1991 surface areas were to the termini of the two main lobes and to the calving ice wall at Lake Miage (Fig. 1). The margins overlap perfectly for the rest of the glacier tongue. Most frontal retreat is associated with the main outwash portal of the north lobe. The terminus of the right lobe has remained unchanged, but the lobe has narrowed slightly.

Based on the premise that a variation in altitude corresponds to a variation in ice thickness, an altitudinal comparison of the DTMs (Fig. 2) indicates thickening of >40 m in the lower sector, particularly on the south lobe. Only at the southern terminus, where debris cover exceeds 0.5 m, was there no variation in thickness. The DTM surfaces converge upstream, so that the 1975–1991 altitude difference becomes zero near Lake Miage. Above *c.* 2100 m thinning of >40 m was recorded. There is no thinning around 2300 m altitude, where large landslide accumulations evidently reduce ablation (Fig. 1). Debris thickness decreases upstream to become thin and discontinous in the upper part of the glacier tongue.

In summary, thickening of the lower sector contrasts with thinning in the middle–upper sector, which has created a "swelling" in the terminal part of the glacier, as shown by topographic profiles (Fig. 3). Ice melted by ablation has been more than replaced by ice transported downglacier by flow. Across the whole tongue, a volumetric increase of *c.* 310 000 m^3 indicates a marginally positive balance. Only a very small part of this increase is attributable to an increase in debris thickness due to englacial melt-out and direct deposition on the glacier surface. Thickening of the terminal sector is consistent with observations along the glacier margins. The glacier has constructed new lateral moraine crests partially burying the "Little Ice Age" moraine crest, and at a lower gradient. Recent moraine superposition has been associated with numerous boulder falls down the distal moraine slopes of the south lobe (Fig. 1), creating a hazard on the road below the moraine (Mortara & Sorzara, 1987).

CALCULATION OF SURFACE VELOCITY

Displacement of 24 boulders visible on both aerial photographs allows surface velocity to be determined for the debris-covered area. Movement between 1975 and 1991 was calculated from coordinates using the DTMs. The results (Fig. 4) show a steady downstream decrease in mean annual velocity. In the middle–upper sector of the tongue,

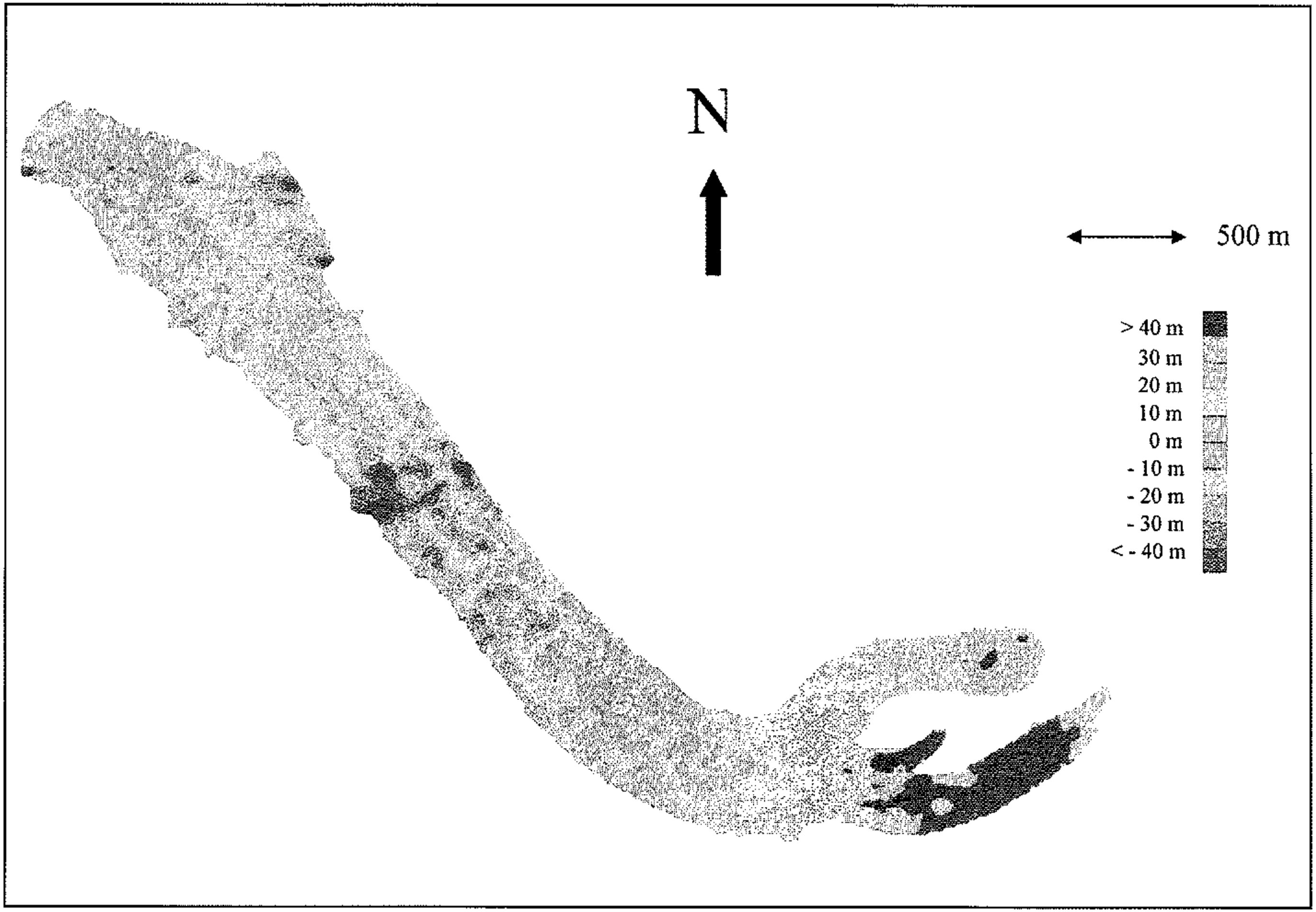

Fig. 2 Map of altitude differences on the surface of the Miage Glacier between 1975 and 1991.

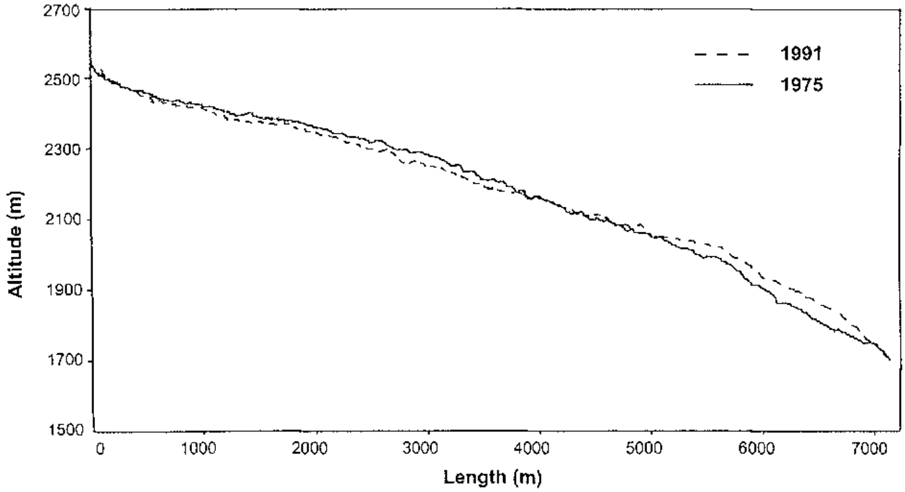

Fig. 3 Long profiles of the lower 7 km of Miage Glacier, showing the pattern of upstream thinning and downstream thickening between 1975 and 1991.

the velocity was *c.* 70 m year^{-1} (maximum of 78 m year^{-1}), slightly greater than the 61 m year^{-1} calculated by Cunietti (1961) using terrestrial photogrammetry. At 2100 m altitude the velocity is 60 m year^{-1}, decreasing to 30–40 m year^{-1} where the flow deviates eastward (2000 m), and to 15 m year^{-1} near the terminus. Velocity was less (6 m year^{-1}) on the outer edge of the south lobe, and there was no movement at a point on the right lateral moraine, employed as a control point.

GLACIER RESPONSE TO MASS BALANCE CHANGE

The unusual pattern of thickness change observed between 1975 and 1991 can be explained in terms of the expression of regional mass balance change by a debris-covered glacier with reversed ablation gradient. The observed upstream thinning and remarkable downstream thickening probably records the passage and amplification of a kinematic wave through the debris-covered tongue. The reversal of the ablation gradient would accentuate the effects of mass transfer from the accumulation basins to the ablation zone.

The Monte Bianco glaciers expanded during the 1962–1989 period (Cerutti, 1992). Since the late 1980s there has been a steady reduction in glacier lengths accompanied by a decrease in thickness that is more accentuated in the terminal sectors of the glaciers. Terminus changes at Miage Glacier indicate a slower, later response and lesser amplitude of frontal oscillation than at uncovered glaciers nearby (Deline, 1999b). Between 1954 and 1991, the Lex Blanche Glacier advanced by 740 m and the debris-covered Brenva Glacier advanced by 490 m, with an increase in volume of >57 million m^3. A 1977–1988 advance of 220 m of the north lobe is mentioned by Deline (1999b), consistent with the 1975–1991 thickening of the lobe (Fig. 2) but not with the retreat indicated by the photogrammetrically-based DTMs. Evidence for the extent of this advance is uncertain (Deline, 1999b, p. 8). Observations of frontal positions do not indicate such an advance in spite of the thickening, perhaps reflecting

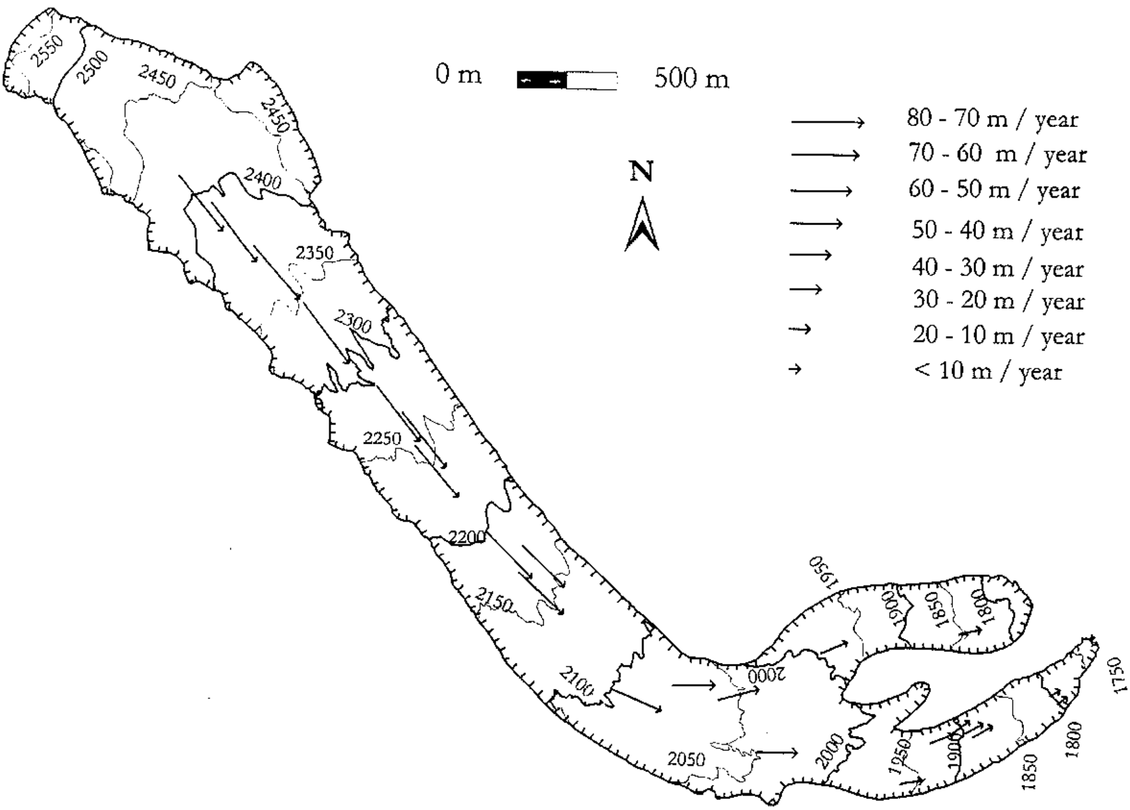

Fig. 4 Map of mean annual centre-line velocities of 24 boulders between 1975 and 1991.

thermal erosion and collapse around the main outwash portal. Significant thickening has not caused an advance of the southern terminus, because the zone of greatest thickening had not reached this terminus by 1991 due to the lower ice velocity (Fig. 4) and longer flow path of the south lobe.

The 1962–1989 advances were probably initiated by a drop in summer temperature. Between 1951 and 1960, mean summer temperature at Courmayeur was 0.65°C lower than the 1936–1983 mean, and 0.2°C cooler between 1961 and 1970. Cooling was accompanied by increased annual precipitation, which peaked between 1976 and 1980 (+303 mm compared to the 1936–1983 mean). Increased net accumulation probably generated the thickening above the equilibrium line initially during the 1950s, which has since propagated downstream. Theoretically, it is well known that the thickening generated in any cross-section is magnified downstream in a zone of longitudinal compression (Nye, 1968; Paterson, 1994). Normally the thickening would be partly offset by ablational loss of ice. On Miage Glacier, ablation decreases towards the terminus, therefore the downstream amplification of the wave has not been damped and the effect is manifested as the observed increase in surface elevation. If the mass redistribution was by passage of a kinematic wave travelling at about four to five times the ice velocity, a response time of *c*. 30–40 years is estimated, consistent with the timing of the observed thickening, and with a slightly faster response of the north lobe. Thomson *et al.* (2000) use map-based reconstructions since 1913 to demonstrate similar behaviour of the lower Miage Glacier on other earlier occasions. Thus, debris-covered glaciers which are commonly held to be unresponsive to climate change may, in fact, amplify a climatically-induced mass balance perturbation due to the insulation and preservation of ice transported into the lower ablation zone.

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