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Twentieth century surface elevation change of the Miage Glacier, Italian Alps

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Abstract The 5 km debris-covered tongue of Miage Glacier has been studied to explore the effect of the debris cover on patterns of thickness change over an 86-year period (1913–1999). Changes in surface elevation and volume for four intervals of eight to 44 years' duration have been calculated from comparisons of digital terrain models (DTMs) derived from cartographic and topographic surveys. Thickness changes over successive periods show that parts of the ablation zone have thickened while other parts have thinned or maintained stable elevations. Zones of thickening migrated downstream to cause small advances of the terminus on two occasions. In contrast to nearby uncovered glaciers, Miage Glacier increased in volume over the entire period. Our results indicate that decadal-scale thickness changes are forced primarily by mass flux perturbations in synchrony with uncovered glaciers, and not by debris-mantle insulation. Century-scale volume and thickness changes differ from uncovered glaciers, due to the conservation of ice beneath the debris cover during prolonged periods of thinning.

INTRODUCTION

In contrast to "clean" glaciers, the response of debris-covered glaciers to climatic variation is commonly delayed, subdued and given topographic expression by thickening and thinning rather than by terminus advance and retreat, because reduced ablation beneath the debris cover allows "extended" ablation zones to evolve (Kirkbride & Warren, 1999). Changes to debris-covered glaciers over several decades have generally been measured during negative balance periods, and have involved comparison of only two surveys from which calculated average rates of change (of thickness, ablation, velocity) suggest steady, uniform evolution and an attenuated climatic response (e.g. Kirkbride & Warren, 1999; Nakawo *et al.*, 1999).

This paper traces changes to the surface elevation of the Miage Glacier, Italian Alps, using digital terrain models (DTMs) derived from five maps produced at eight to 44 year intervals between 1913 and 1999. The aim is to compare century-scale "average" rates of change to ice thickness with approximately decadal spatial and temporal patterns measured over several mass balance cycles, as far as historical data sources permit. A more detailed understanding of the relative roles of sub-debris insulation and ice flow on the topographic expression of climatic forcing may then be ascertained.

SETTING

The Miage Glacier (45°47'30"N, 6°52'00"E) is the largest ice mass on the southern side of the Mont Blanc massif. Three steep tributaries (~24°–33°) draining the western flank of Mont Blanc converge to form the gently inclined glacier tongue (~5°), which occupies a deeply incised trough (Fig. 1). This section, which contains two prominent medial moraines, divides to form two main terminal lobes, which descend more steeply (~11°) to ~1750 m. The lower ~5 km of the ice surface is buried beneath a continuous mantle of coarse, angular debris, delivered to the glacier by frequent rockfall and avalanche events. Spot depth measurements from 1999 show that the debris mantle is generally 5–20 cm thick on the tongue, increasing to >1 m thick approximately 0.5 km upglacier from the twin terminal lobes.

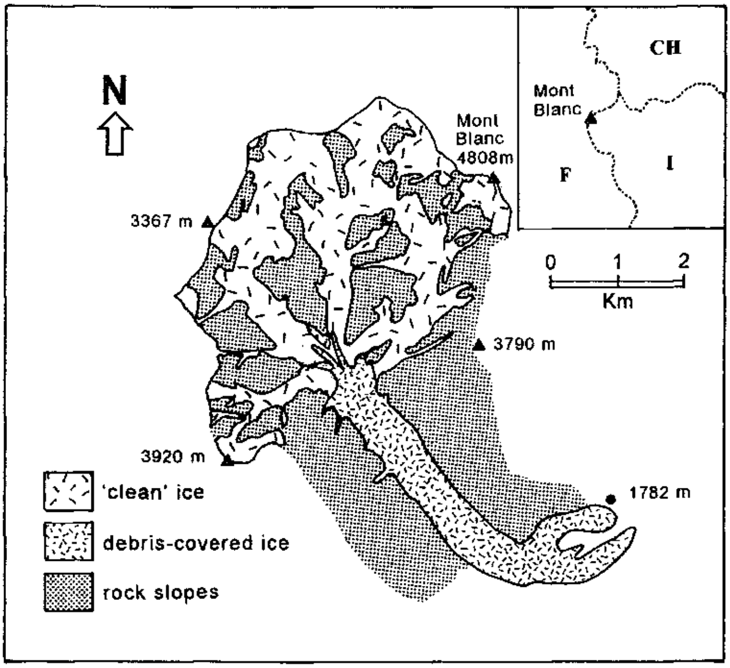


Fig. 1 Location and physical characteristics of Miage Glacier, Italian Alps. I = Italy; F = France; CH = Switzerland.

METHODS

Published cartographic data sources of the 1913, 1957, 1967 and 1975 glacier surface were supplemented by a topographic survey of the glacier surface in July 1999, using a Sokkia (Set 5a) total station. Because some maps fail to delineate terminus positions in sufficient detail, changes in the planimetric area of the glacier were not examined. Contour lines were digitized using manual point selection, producing a series of (*x*, *y*, *z*) coordinates from each map. The density of points varied largely as a function of the complexity of relief over the glacier surface, with areas of irregular relief containing a greater number of sampled points in comparison to homogeneous areas. Data were imported into the ARC/INFO software package, for conversion into triangulated irregular networks (TINs) based on the Delauney algorithm (ESRI, 1993). TINs were converted into 50-m grids using a linear interpolation routine, giving data attached to five sets of coincident nodes, allowing quantitative comparisons of the five DTMs. The difference in elevation between equivalent nodes of successive models was computed and displayed as polygon altitude difference maps (Figs 2 and 3).

To test the accuracy of the DTMs, the elevations of 125 control points, taken directly from the 1967 contour map of the glacier surface, were compared with corresponding estimates of elevation of the same points interpolated from the final DTM. The vertical root mean square error (RMSE) was calculated as <4 m over the study area. This value equates to a volume error of 1.1×10^6 m^3, which applies to comparisons between the DTMs. Due to the similarity in relief and density of sampled points, RMSEs were assumed to be of a similar magnitude for all DTMs. Given these error estimates, together with unknown errors inherent in the construction of the original maps, all thickness changes within the ±5 m interval were regarded as areas of little or no change.

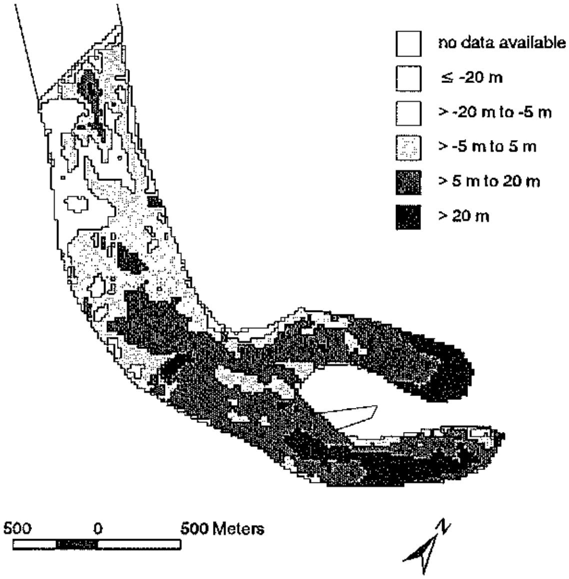
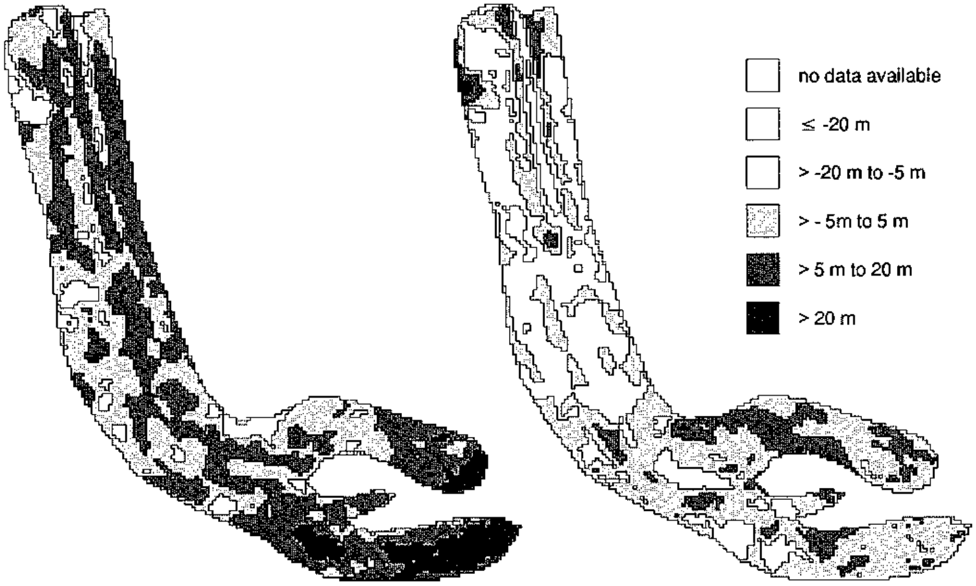


Fig. 2 Net change in surface elevation between the 1913 and 1999 topographic surveys. Negative and positive values indicate areas of thinning and thickening respectively.

RESULTS

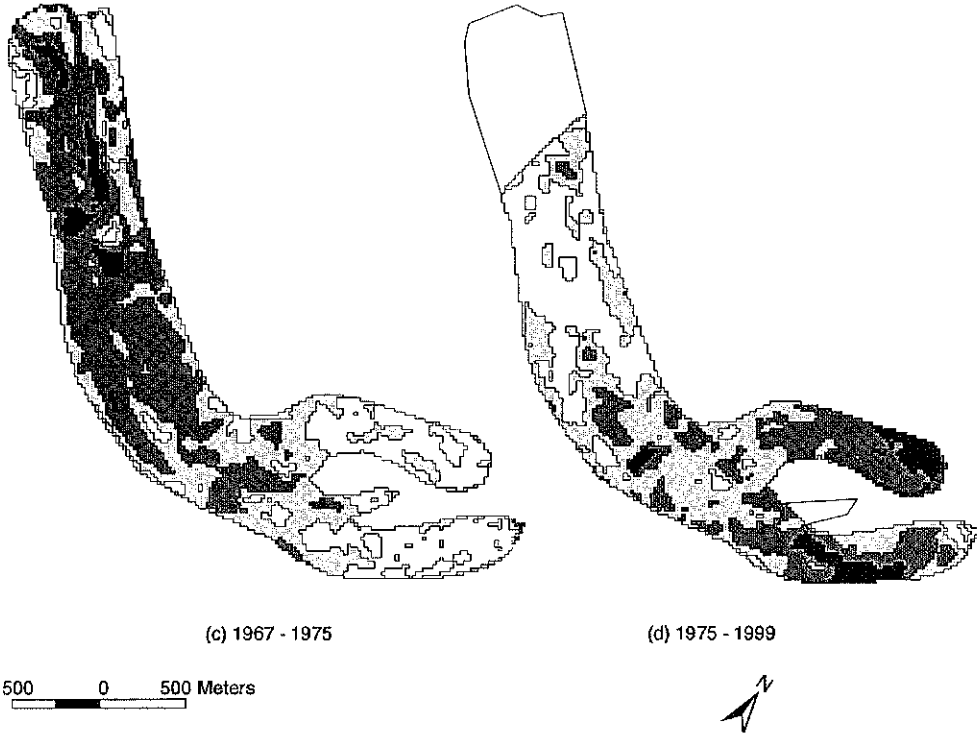
The overall change between 1913 and 1999 (Fig. 2) demonstrates a net increase in elevation on the lower parts of the glacier. On the left (northern) lobe, positive values are accentuated towards the terminus whilst a net decrease in elevation of the same magnitude has occurred over a small area at the terminus right (southern) lobe. Upglacier, large areas experienced little change (>–5 to 5 m). Net losses occur towards the upper limits of the study area, but with localized areas of thickening evident. The total change over the entire 1913–1999 period was a net volume gain of 1.3×10^6 m^3 (equivalent to a mean specific net balance of +5.7 m or +0.07 m $year^{-1}$).

Between 1913 and 1957 (Fig. 3(a)) the glacier shows a general thickening, which is more pronounced towards the termini of all lobes. Over this period the studied area



(a) 1913 - 1957

(b) 1957 - 1967



(c) 1967 - 1975

(d) 1975 - 1999

Fig. 3 Surface elevation change for selected intervals of the twentieth century, derived from the following published maps: Porro (1913), 1:10 000 scale, 5-m contour interval; Comitato Glaciologico Italiano (1957), 1:5000, 5 m; Institute Geographique National (1967), 1:25 000, 10 m; Regione Autonoma della Valle d'Aosta (1975), 1:10 000, 10 m. The 1999 surface topography is from the authors' own survey. Negative and positive values indicate areas of thinning and thickening respectively.

underwent a net increase in volume of 1.73 × 10^6 m^3 (+5.98 m or +0.07 m $year^{-1}$). Upglacier, elevation increases are principally confined to the glacier centreline and to the crests of medial moraines.

During the period 1957–1967, the study area experienced a net loss of 1.11 × 10^6 m^3 (–3.83 m or –0.38 m $year^{-1}$). On the lower half of the glacier little net change in surface elevation occurred, although areas of increase of over 20 m occur, in particular on the left lobe (Fig. 3(b)). The majority of loss occurred over the tongue, although smaller scale changes are also apparent, such as the reversal in trend of medial moraine growth.

A general reversal in the pattern of thickness change occurred between 1967 and 1975, with a net loss in elevation of over 20 m on the glacier lobes (Fig. 3(c)). A striking increase in surface elevation is evident over almost the entire area of the tongue resulting in a net gain in volume of 0.54 × 10^6 m^3 (+1.9 m or +0.23 m $year^{-1}$) for the study area.

A further net increase in volumetric change of 0.25 × 10^6 m^3 (+1 m or +0.04 m $year^{-1}$) occurred between 1975 and 1999. Again, the general pattern shows a reversal of trend with positive values now concentrated on the lobes and a trend of decreasing thickness change farther upglacier.

DISCUSSION

The observed volume increase in the debris-covered tongue between 1913 and 1999 (Fig. 2) contrasts with recorded fluctuations of nearby glaciers, whose minor advances have punctuated a general twentieth-century volume decrease (Grove, 1988; Deline, 1999). The most plausible explanation is that the debris cover has reduced surface melting to conserve ice mass in the ablation zone. At shorter (decadal) time scales, the pattern of thickness change suggests that the debris cover is not the primary control on the distribution of thickness change (assuming the current spatial pattern of debris thickness has been similar throughout the study periods). Rather, zones of thickening appear to have migrated downstream on at least two occasions between measurement periods, indicating increased mass fluxes propagated to the terminus. The first "wave" probably resulted from a sustained increase in winter precipitation and lower mean annual temperatures between 1890 and 1940 (Orombelli & Porter, 1982), culminating in an advance of Miage Glacier around 1930 which deposited a prominent lateral and terminal moraine. The second was probably triggered by increased snowfall in the 1950s and 1960s, causing an advance culminating in the late 1980s (Deline, 1999).

In the 1913–1957 interval, most of the glacier experienced thickening, interpreted as the net effect of increased mass flux early in the period followed by a slow decrease in ice surface elevation after the *c.* 1930 highstand. The 44-year interval between surveys has been sufficient to mask any downstream propagation of the zone of greater flux, which instead shows as a general thickening throughout the tongue (Fig. 3(a)). The downstream transfer of a zone of thicker ice becomes apparent over shorter measurement intervals covering the subsequent positive balance perturbation. The leading edge of a zone of thickening, first apparent in the 1957–1967 period (Fig. 3(b)), migrated *c.* 2.5 km downstream by 1975 (Fig. 3(c)), to reach the terminus sometime between 1975 and 1999. By 1999 thinning had recommenced over most of

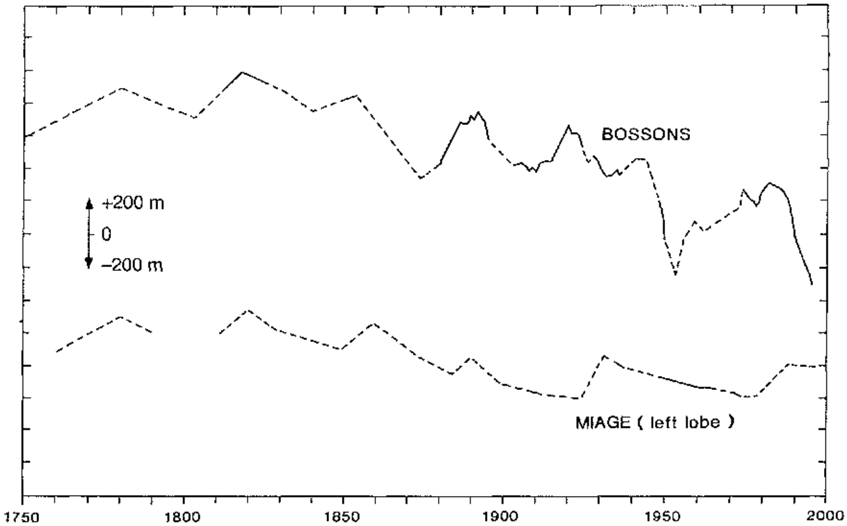


Fig. 4 Comparison of length changes of Miage Glacier and the uncovered Bossons Glacier, which shares an ice divide but flows north from Mont Blanc. Adapted from a synthesis by Deline (1999) from various sources. Solid lines indicate documented accounts of terminal advance/retreat. Dashed lines represent inferred terminal advance/retreat.

the ablation zone upstream of the "wave" (Fig. 3(d)). This spatial and temporal pattern is consistent with length changes synthesized by Deline (1999) (Fig. 4), if it is assumed that most thickening in the 1913–1957 interval occurred prior to the highstand and lateral moraine deposition in the early 1930s. Slow retreat of the left terminus between *c.* 1930 and *c.* 1976 corresponds to stable or decreasing surface elevations. The advance commencing in the mid 1970s, sustained throughout the 1980s, corresponds to the arrival of a zone of increased mass flux at the terminus evident from the comparison of Fig. 3(c) and (d). Accepting that Deline's length record can be interpreted as pulses of increased mass flux (kinematic waves) causing periodic advances, the passage of six waves between 1750 and the 1913 survey can be inferred in addition to the two identified from Fig. 3. The length record is broadly synchronous with fluctuations of nearby uncovered glaciers (Fig. 4), indicating a common climatic forcing.

In conclusion, the study has demonstrated the value of higher temporal resolution sampling of debris-covered glaciers, providing evidence of a more detailed picture of the interaction between the debris insulation effect and changes in ice flux. Detailed spatial patterns of thickness change for successive intervals show that waves of changing ice flux override any differential ablation associated with spatial variations in debris thickness. In addition, there exists a fundamental asymmetry of Miage Glacier and neighbouring uncovered glaciers during periods of advance and retreat. Both show a broadly synchronous response to positive mass balance perturbations imposed from upglacier. However, during periods of negative mass balance, terminus retreat of uncovered glaciers is more pronounced. The cumulative effect of this becomes more apparent at increasingly longer time scales. Whereas neighbouring uncovered glaciers in the Mont Blanc Range experienced a net decrease in volume over the twentieth century (Grove, 1988), the Miage sustained a net increase in volume. The difference is interpreted as the insulation of ice beneath the Miage debris cover, allowing more of the ice transported to the lower tongue of the glacier to be conserved, especially during warm summers. Thus, although detailed variations in thickness change are weakly related to differential ablation, this study has confirmed the overall importance of the debris insulation effect most strongly manifested at longer time scales.

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