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RECENT (1975-2003) CHANGES IN THE MIAGE DEBRIS-COVERED GLACIER TONGUE (MONT BLANC, ITALY) FROM ANALYSIS OF AERIAL PHOTOS AND MAPS (***)

ABSTRACT: DIOLAIUTI G., D'AGATA C., MEAZZA A., ZANUTTA A. & SMIRAGLIA C., *Recent (1975-2003) changes in the Miage debris-covered glacier tongue (Mont Blanc, Italy) from analysis of aerial photos and maps*. (IT ISSN 0391-9838, 2009).

The present study aims at identifying any changes in volume and thickness of the Miage Glacier tongue (Mont Blanc Massif, Italy) during the period 1975-2003. The Miage glacier developed the largest part of its debris cover over the last century, now found mostly between the glacier terminus (about 1850 m a.s.l.) and the upper ablation tongue (c. 2400 m a.s.l.) on a surface area of c. 4 km^2. The period examined (1975-2003) addresses climate conditions which were glacier-favourable (around the 1980s), as well as glacier-unfavourable (since the early to mid-1990s), thus contributing to an understanding of the behaviour of debris covered glaciers under a changing climate.

The analysis was based on the comparison between digital elevation models (DEMs), derived from historical records, specifically maps (1975; scale 1:10,000) and photogrammetric surveys (1991 and 2003, scale 1:15,000). The results show a general glacier volume loss (-16.640×10^6 m^3) from 1975 to 2003; nevertheless if we focus on the two time sub-windows (i.e.: 1975-1991 and 1991-2003) opposite trends are found: in the period 1975-1991 the volume variation of the Miage Glacier was about $+19.25\text{x}10^6$ m^3, in the period 1991-2003, on the other hand, a volume decrease of about $-36.2\text{x}10^6$ m^3 occurred. Analysis shows that volume changes were strongly influenced by the supraglacial debris coverage which on Miage glacier tongue modulates the magnitude and rates of buried ice ablation.

KEY WORDS: Debris covered glaciers, Glacier elevation changes, Italian Alps.

INTRODUCTION

Debris-Covered glaciers are widespread in the mountains chains of Asia, such as the Karakoram, the Himalaya (Moribayashi & Higuchi, 1977) and the Tien Shan ranges. They are also particularly common in New Zealand (Kirkbride, 2000; Kirkbride & Warren, 1999), in the Andes and in Alaska. Despite their relatively common occurrence (Nakawo & *alii*, 2000), debris-covered glaciers have only become the subject of detailed studies in very recent times.

Debris covered glaciers are also becoming an important feature in the Alpine environment (Smiraglia & *alii*, 2000; Diolaiuti & *alii*, 2003; Deline, 2005; D'Agata and Zanutta, 2007; Mihalcea & *alii*, 2008a). The increasingly important role they play is probably due to intensification of macrogelivation and rock degradation processes which seem more frequent and stronger in glaciated regions during recent times (O'Connor & Costa, 1993; Evans and Clague, 1994; Marchi & Tecca, 1996; Haeberli & *alii*, 1997; Barla & *alii*, 2000; Deline, 2001; 2003; Deline & *alii*, 2004; Huggel & *alii*, 2005; Chiarle & *alii*, 2007; Gruber & Haeberli, 2007; Deline & Kirkbride, 2008; Ravanel & Deline, 2008). In addition glacier recession induced by climate warming causes an increase in supra-glacial slopes, enhancing the rate of paraglacially mobilized debris input, either from bedrock or pre-existing sediment storages on the glacier surface below. Consequently, the supra-glacial debris cover is prone to enlargement. Rates of debris input from the two adjacent supra-glacial slopes of a valley glacier may differ substantially from each other, reflecting different topography (varying debris entrainment and transport) and/or lithology (variations in weathering susceptibility) between the two sides. Moreover, the surface geometry of a supra-glacial debris cover may be influenced by the spatial distribution and nature of medial

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moraines and/or of englacial debris *septa*, which melt out of the ice in the ablation area (Benn & Evans 1998; Anderson 2000, Kellerer-Pirklbauer & *alii*, 2008).

The current literature (Deline, 2002; 2005; 2008; Mihalcea & *alii*, 2008a) considers rock falls and rock avalanches crucial factors which had driven the development of the debris coverage of the largest Italian debris-covered glacier, the Miage, on the Mont Blanc Massif. In this area rock degradation phenomena seem to be more numerous in very recent years (i.e. the last 150 years). The Miage glacier developed the largest part of its debris cover over the last century, now found mostly between the glacier terminus (about 1850 m a.s.l.) and the upper ablation tongue (c. 2400 m a.s.l.) on a surface area of c. 4 km^2 (Deline, 2005).

Supraglacial debris coverage plays a key role in determining rates and magnitudes of buried ice ablation (Østrem, 1959; Nakawo & Young, 1981; Nakawo & Takahashi, 1982; Nakawo & Rana, 1999). In fact, supraglacial debris cover, whenever thicker than the *critical value* (*sensu* Mattson & *alii*, 1989; 1993), reduces magnitude and rates of glacier ice ablation (Mihalcea & *alii*, 2006). On actual debris-covered glaciers the larger ice losses due to supraglacial ablation are mainly concentrated at the debris free areas of the ablation zone and at the surfaces of ice cliffs and crevasses, vertical ice walls where debris coverage is thinner or absent, thus exposing bare ice to fast and rapid ablation (Mihalcea & *alii*, 2008a); therefore, the climatic response of adjacent debris free and debris-covered glaciers under the same meteorological conditions may substantially differ from each other, as has been revealed by comparative studies (Pelto, 2000; Takeuchi & *alii*, 2000; Thomson & *alii*, 2000; Diolaiuti & *alii*, 2003; Kellerer-Pirklbauer & *alii*, 2008). In the Italian Alps such comparative studies are required and few attempts at evaluating magnitude and rates of buried ice ablation have been made (Smiraglia & *alii*, 2000; Diolaiuti & *alii*, 2003; Diolaiuti & *alii*, 2006; D'Agata & Zanutta, 2007).

The present study investigates the response to recent climate changes in the tongue of the Miage glacier, the largest debris-covered glacier of the Italian Alps. The aim of this work is to assess, with indirect methods, the Miage tongue's volume variations in the period 1975-2003 and to compare the results with those calculated for the same period on debris free glaciers located in the Mont Blanc area.

The period examined (1975–2003) addresses climate conditions which were glacier-favourable (around the 1980s), as well as glacier-unfavourable (since the early to mid-1990s), thus contributing to an understanding of the behaviour of debris covered glaciers under a changing climate.

THE MIAGE DEBRIS-COVERED GLACIER

The Miage Glacier (45° 47' N, 6°52' E) is the largest debris-covered glacier in the Italian Alps (area, 11 km^2). The glacier drains the southwest slope of Mont Blanc in Valle d'Aosta (Western Italian Alps) and shows a quite continuous debris coverage on the ablation tongue. Its shape and morphology resemble the huge Asian debris-covered glaciers. The glacier snout terminates in two main lobes (the southern and northern lobes) and a smaller intermediary one (fig. 1a and b).

Until the last decade the well known and best developed debris covered glaciers of the Alps were all located on the Italian side of the Alpine chain (the Miage and the Brenva glaciers in the Mont Blanc Massif and the Belvedere glacier in the Monte Rosa Group). During recent years, important changes have affected these debris-covered glaciers which resulted, during the summers of 2004 and 2006, respectively, in the tongues of the Brenva and Belvedere debris-covered glaciers detaching from the accumulation basins (Mazza & Godone, 2008, Cerutti, 2005). The Miage glacier therefore now represents the best example of an active debris-covered glacier in Italy.

The Miage glacier boasts a long sequence of investigations. It has been explored since observation by De Saussure (18th century); many studies have been carried out on its morphologic and glaciological characteristics (Baretti 1880; Sacco 1917; Capello 1959; Cunietti, 1961; Lesca 1974; Deline1999; 2002; Deline & Orombelli, 2005; Thomson & *alii*, 2000; Smiraglia & *alii*, 2000). Some studies also addressed the developments of the supraglacial debris (Deline, 2005), others focused on the calving phenomena active at its ice-contact lake and on the lake's abrupt drainage events (Deline & *alii*, 2004; Diolaiuti & *alii*, 2005; 2006), on the thermal properties of the debris (Mihalcea & *alii*, 2008a) and on the presence of flora supported by the occurrence of a debris coverage (Richter & *alii*, 2004; Pelfini & *alii*, 2007). The debris cover, in fact, is colonized by vegetation, particularly on the lowermost part, where tree species (*Larix decidua* Mill., and *Picea abies* Karst) occur.

On the Miage glacier high rates of debris are supplied by rock falls and avalanches from the surrounding rock walls which enabled development of the present debris-covered glacier tongue. The rock debris shows thicknesses ranging from a few centimetres (in the higher glacier sector) up to 1.5 metres (close to the glacier terminus) mainly depending on the surface slope and the glacier flow magnitude (Mihalcea & *alii*, 2008a).

The Miage debris cover shows different grain sizes, from rock boulders to fine pebbles and sand and mainly consists of crystalline rocks: gneiss, micaschist and granite (Deline, 2002; 2005). The Southern (left) lobe presents a debris cover of mainly grey-coloured granite and gneiss; on the Northern (right) lobe, rusty-coloured micaschist is found. There are ice cliffs on the largest part of the Miage ablation tongue and, as mentioned above, they represent the sectors with the highest ablation rates due to the thinner debris coverage. Ice cliffs may derive from the evolution of crevasses (as is the case with most ice cliffs) or they may develop from bare ice exposure due to differential ablation on the terminal, lateral or frontal snout sectors. In the latter case the ice cliff evolution is mainly driven by backwasting and downwasting phenomena (Benn & Evans, 1999).

FIG. 1a) - Location Map of the Miage glacier.

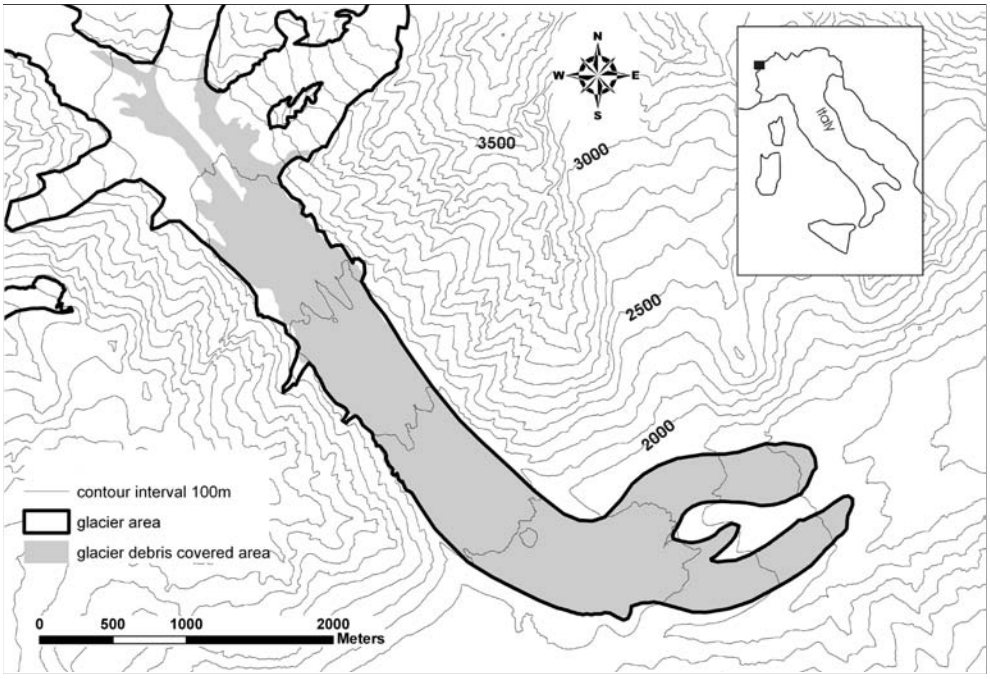


FIG. 1b) - The Miage debris covered glacier (Mont Blanc Massif, Italian Alps). The snout is shaped into three main lobes and reaches at its terminus c. 1850 m of elevation, one of the lowest of the Alps.

DATA AND METHODS

Three different years (1975, 1991 and 2003) were analysed for volumetric changes of the glacier tongue by using surface data derived from a 1975 topographical map at scale 1:10,000 and from two stereo-pairs of aerial photographs (scale 1:17,000), dating from 1991 and 2003 respectively.

The 1975 map: it was already in digital form and it was registered in the UTM grid. Then map contour lines and the glacier boundaries were manually digitized as polylines in ESRI's ArcGIS software in order to obtain the base points building the Digital Elevation Model.

The 1991 and 2003 stereopairs: they were digitized by photogrammetric scanner (Wheerli Flatbed photogrammetric scanner, at a resolution of 2116 dpi, producing a pixel size of 12 mm, corresponding to approximately 18 cm on the ground), sufficient to guarantee a high level of detail.

A Digital Photogrammetric Workstation (StereoView Suite, Menci Software, Arezzo, Italy) was adopted to generate Digital Elevation Models using the semiautomatic and automatic mode (we adopted the method described with details by D'Agata & Zanutta, 2007). The DEMs were first generated automatically, with post-editing by the operator to correct errors deriving from the correlation procedure. In order to detect and eliminate points that can be affected by errors, the procedure was recursively applied by analyzing the residuals of the absolute orientation. The residuals from external parameters estimates, always lower than 15 cm, demonstrate the overall good quality of the photogrammetric surveys.

The data obtained by digitizing map contour lines and by the photogrammetric elaboration were managed with ArcGIS software and were used to create three DEMs describing the 1975, 1991 and 2003 Miage tongue surface and elevation distributions (elevations spaced on a 10-meter grid). By comparing the three DEMs it was possible to calculate volume and thickness changes for the period 1975-2003 and the sub-periods 1975-1991 and 1991-2003. To better analyse the results several thematic maps and glacier surface profiles were calculated as well. The length of the cross-profiles varied between 500 and 700 m and that of the longitudinal profiles between 2000 and 4000 m.

A map describing the Miage debris coverage was also considered to assess the results produced. The map was obtained by the authors of the present contributions in the context of previous research by processing a 2005 ASTER satellite image (Thermal InfraRed data, further details in Mihalcea & *alii*, 2008a). The availability of this map enabled analysis of variability in glacier thickness as a function of debris cover thickness and distribution.

RESULTS AND DISCUSSION

We calculated tongue variations in comparison to a control area which was $3.51\text{x}10^6$ km^2 (1975-2003), $3.53\text{x}10^6$ km^2 (1975-1991) and $3.45\text{x}10^6$ km^2 (1991-2003).

Our analysis showed that, from 1975 to 2003 (fig. 2), the Miage tongue experienced a volume loss of about $-16.640\text{x}10^6$ m^3. The mean thickness change was negative and equal to −4.7 m. The thickness change distribution was found varying among negative values of about –20 m in the central and upper sectors and positive variations, generally concentrated on the glacier medial moraine (where spots with thickness increase up to + 20 m occur) and on the snout lobes (with maximum values of thickness increase up to + 40 m close to the glacier terminus).

Analysing the sub-windows 1975-1991 and 1991-2003, two opposite trends are evident. In fact, from 1975 to 1991 (fig. 3) the volume change was positive, with an increase of about + $19.254\text{x}10^6$ m^3, from 1991 to 2003 (fig. 4) a volume loss of $-36.200\text{x}10^6$ m^3 occurred.

The 1975-1991 mean thickness change was positive (+ 5.5 m); the distribution of thickness variations was found to be in agreement with the 1975-2003 changes, with maximum positive values up to +20 m along the medial moraine and on the snout lobes. The negative values were found to be concentrated in some points of the medial moraine and where the tongue splits into three lobes, thus giving origin to a largely crevassed and unstable area. The 1991-2003 mean thickness change, on the other hand, was negative (–10.5 m). The thickness change map (fig. 4) reveals a pattern with maximum losses ranging from –20 m to –40 m along the medial moraine and small thickness increases concentrated on the lower sectors of the lobes, with smaller positive spots present along the medial moraine.

The elevation changes were also analysed by calculating several longitudinal and cross profiles. Figs. 5 and 6 show longitudinal and cross profiles.

The longitudinal profile (fig. 5) is about 2 km long and it describes the tongue elevation changes from 2140 m to 1860 m of altitude. The pink line describing 1991 elevation data is almost always the highest one, while the yellow line (2003 data) is generally the lowest, although in both the cases some exceptions due to differential ablation processes occur. The differences in elevation between the 1991 and 1975 lines are generally positive (i.e.: 1991>1975) and greater in the upper profile sector (from 2000 to 2140 m), diminishing in the lower part close to the lobe terminus. The single notable exception is in the area between 2025 and 2000 m where 1975 line exceeds the 1991 profile. This area corresponds to the largely crevassed sector where the tongue splits into three lobes; here the debris coverage is discontinuous due to the occurrence of crevasses and ice breaks and it is characterized by a thinner debris layer thus promoting ice ablation and/or providing a less efficient insulating effect. It is interesting to observe that also by comparing the 1991 line with the 2003 profile a similar behaviour is found: a general decrease (i.e.: 1991>2003) is appreciable, with stronger thinning at higher elevation and smaller thickness changes close to the lobe terminus. Between 2010 m and 1970 m of altitude the most pronounced thickness loss is found. This corresponds to the crevassed area we described above, which, on the 2003 line, shifted about 500 m downvalley compared to its 1975 position. These findings agree with the glacier velocity data which for the area were estimated to range from 15 to 20 m/yr (Lesca, 1974; Diolaiuti & *alii*, 2006); taking a mean value of 18 m/yr gives a displacement of c. 540 m over a time frame of 30 years.

The cross profile (fig. 6) represents the elevation changes which occurred between heights of 2,040 and 2,007 m in the lower tongue sector close to the crevassed areas. It shows a complex glacier morphology, typical of a debris covered glacier, with emerging areas due to a thicker debris layer (medial moraines and large dirt cones) and a narrow valley created by differential ablation where debris coverage is thinner and/or discontinuous. By comparing the 1975 line with the 1991 profile a general thickness increase (i.e.: 1991 >1975) is found, the stronger gains are concentrated on the medial moraines where the debris is thick enough to provide an efficient insulation. The single exception is the north sector where 1975 line is higher than 1991, revealing a marked reduction (–20 m), probably due to the large crevasses and the poor debris coverage characterizing this area. The 2003 profile is always lower than the 1991 line and in addition

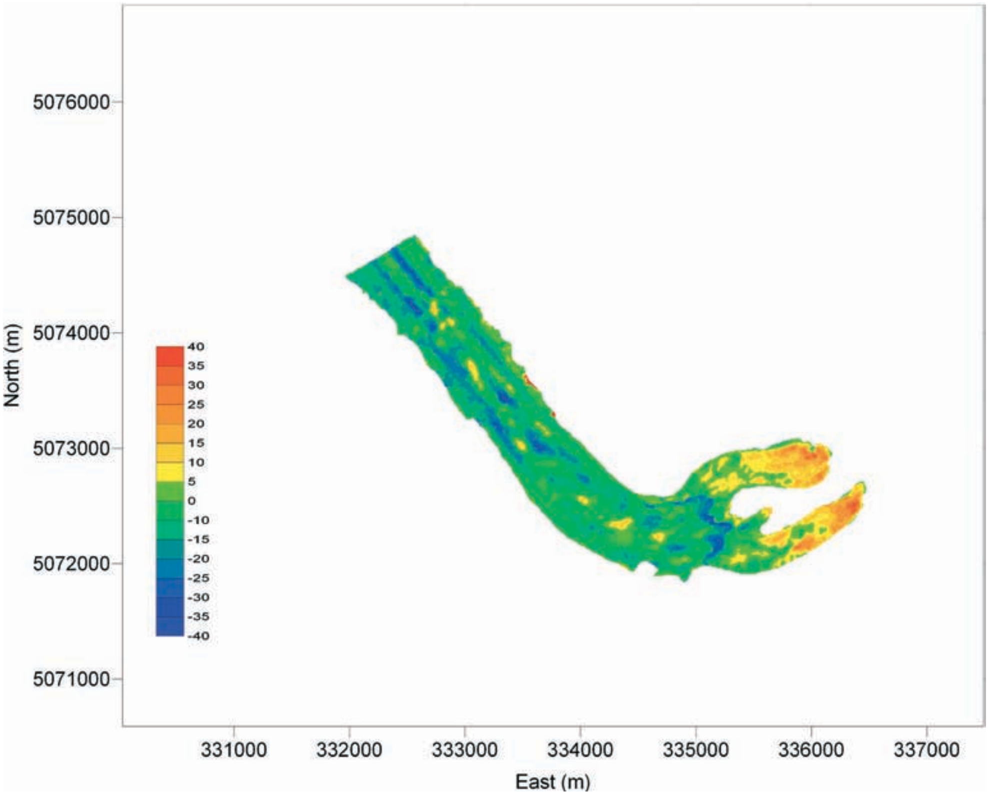


FIG. 2 - Miage tongue thickness changes from 1975 to 2003.

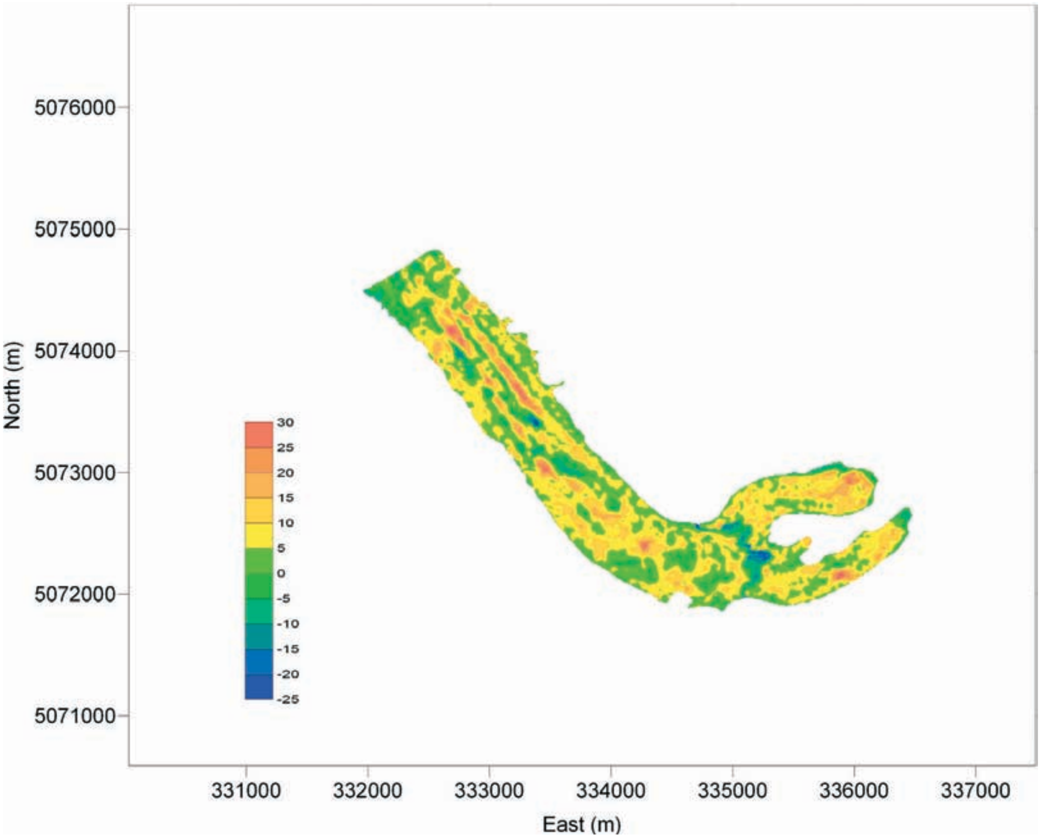


FIG. 3 - Miage tongue thickness changes from 1975 to 1991.

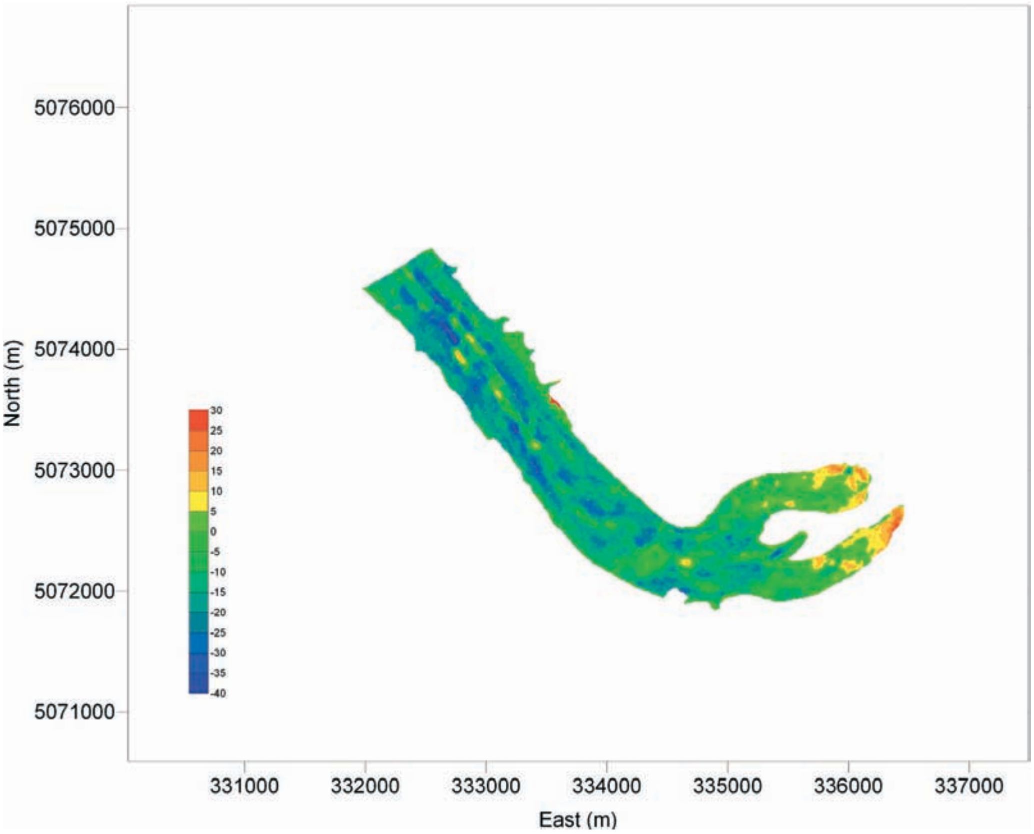


FIG. 4 - Miage tongue thickness changes from 1991 to 2003.

it shows the increase in surface morphological complexity due to the enlargement of the crevassed areas (which also featured in the collection of aerial photos reported by Giardino & *alii*, 2001).

To better understand the role played by supraglacial debris on the tongue volume and thickness changes we analysed our data compared to tongue elevation values (i.e.: 2003 DEM) and to the ASTER-derived debris thick-

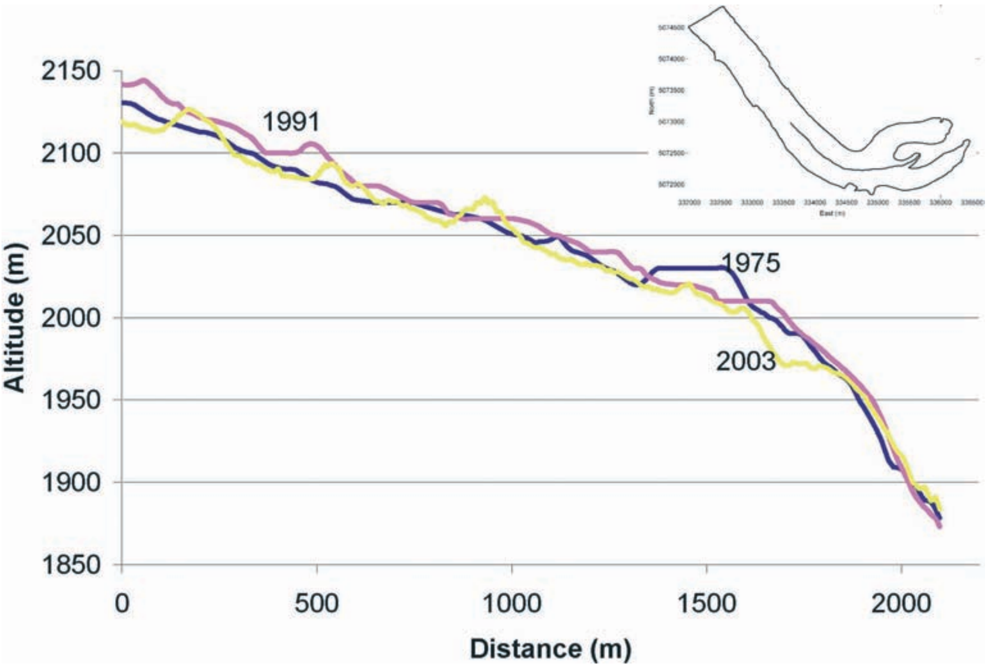
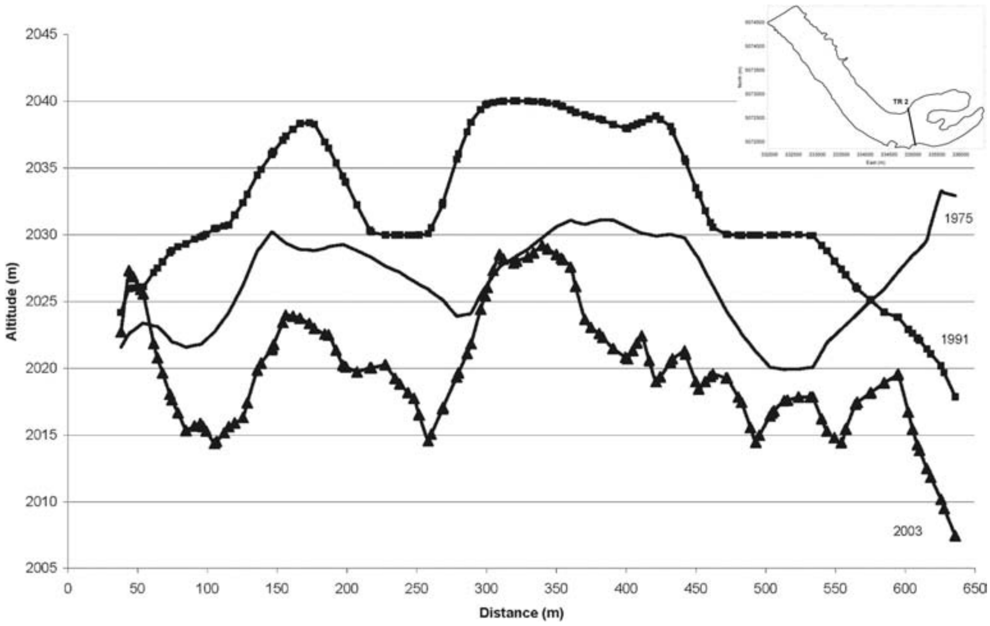


FIG. 5 - Miage tongue longitudinal profile.

FIG. 6 - Miage tongue cross profile.



ness map (Mihalcea & *alii*, 2008a). The Miage tongue debris thickness map showed a clear inverse relation between debris depth and elevation, with maximum debris thicknesses exceeding 60 cm close to the terminus and minima up to 0.5-5 cm at approx. 2500 m of altitude. The authors of the map pointed out that the mean debris thickness along a longitudinal profile at Miage Glacier seems to follow a power function, with a single exception found by the authors for the 2,101-2,200 m elevation band which corresponds to an area of the glacier affected by a large rock slide, with correspondingly thicker debris. Considering debris distribution and that a debris cover exceeding the critical thickness (*sensu* Mattson & *alii*, 1993) causes a reduction in the amount of ablation, higher surface lowering rates can be expected at the upper tongue sector where debris cover depth is close to its critical value, which for the Miage tongue was calculated to be ~3 cm (Mihalcea & *alii*, 2008a). Figs. 2, 4 and 5 above show a lowering pattern with stronger losses at higher tongue elevations; this trend is more visible in fig. 7 where the 1975-2003 elevation change evaluated for each glacier tongue pixel (total pixel number: 40,000, pixel size: 10 m) was analysed in relation to the pixel elevation (from 2003 DEM). The diagram shows a clear and meaningful inverse relation (r = –0.7) between elevation changes and elevations. Moreover the point distribution also reveals an anomaly with stronger glacier losses (also exceeding –30 m) between 2000 and 2050 m, where there is a large crevassed area with thinner and discontinuous debris cover. On the lower glacier sector (the snout and its three lobes), positive elevations changes were found. Further information derives from fig. 8 where the 1975-2003 elevation change for each glacier pixel was analysed in relation to the pixel debris depth (derived from the 2005 ASTER image). The point distrib-

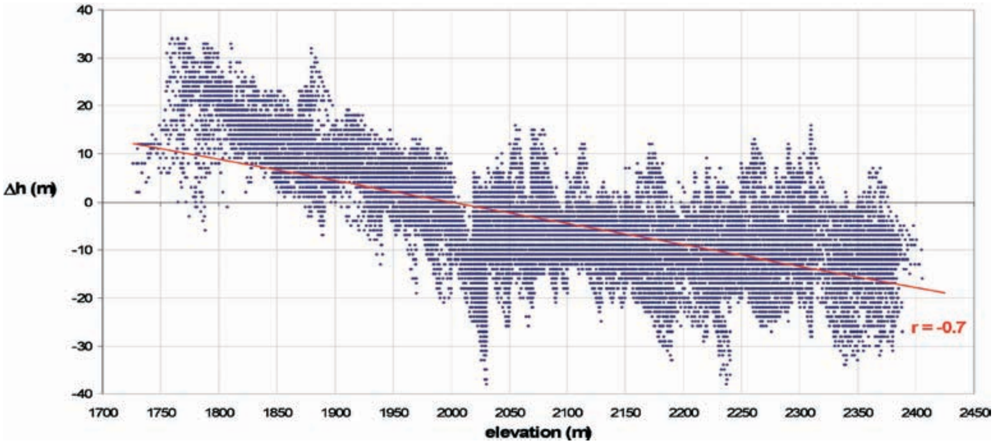


FIG. 7 - Elevation changes in the 1975-2003 time window vs elevations (from 2003 DEM). The data describes 40,000 pixel (10 x 10 m) of the Miage tongue.

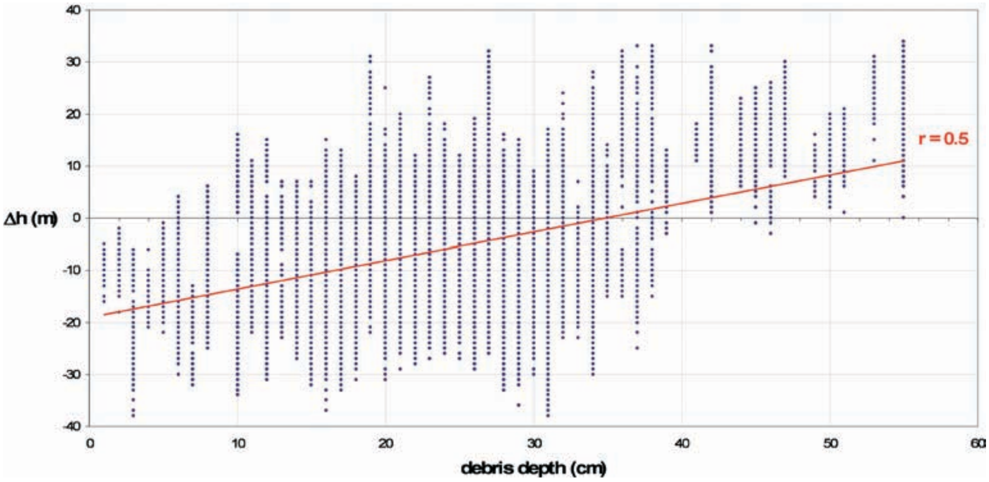


FIG. 8 - Elevation changes in the 1975-2003 time window vs debris depth (from 2005 ASTER). The data describes 40,000 pixel (10 x 10 m) of the Miage tongue.

ution shows a direct meaningful (r = 0.5) relation between glacier elevation changes and debris layer thickness (i.e.: positive or slightly negative variations with thick debris depth and glacier lowering with thin debris cover).

The main limitations of such comparisons are due to the different temporal and spatial resolutions of the sources. The space resolution elevation changes were computed by DEM comparison and they have DEM resolution (pixel size 10x10 m), while the debris thickness map was derived by Mihalcea & *alii* (2008a) from ASTER surface temperature (90x90 m pixel size), so in order to compare these data the debris map was resampled in accordance with the 1975 and 2003 DEM resolution to obtain a new map, spaced 10x10 m. The original poor resolution of the debris map is reflected by the point alignment appreciable in fig. 8, nevertheless a clear trend of increasing debris depth, decreasing glacier lowering was found. In terms of the time frame, the debris map is derived from a 2005 ASTER, while the elevation changes were computed for the period 1975-2003. Certainly during the 30 year period the supraglacial coverage experienced changes and was subject to glacier flow and this could have slightly narrowed the relation among the data compared. Nevertheless these findings are supported by studies from the Baltoro debris covered glacier, Pakistan, where the lowermost 50 km of the glacier forms a long, narrow debris-mantled ablation area (Mihalcea & *alii*, 2008b); according to Inoue (1977) and as reported in Benn & Lehmkuhl (2000) for other debris-covered glaciers (e.g. Ama Dablam Glacier, Nepal; Batura Glacier, Pakistan), ablation decreases with decreasing altitude due to increasing thicknesses of supra-glacial debris. Ablation rates at the Baltoro Glacier are at their maximum in the upper part of the ablation area where a thin and patchy debris cover increases ablation, whereas further down-glacier ice is insulated by thicker debris. This insulating effect had reduced magnitude and rates of ablation on actual debris covered glaciers and had preserved longer in time the mass gains due to cooler climatic periods as reported for the Italian glaciers Belvedere (Diolaiuti & *alii*, 2003) and Brenva (D'Agata & Zanutta, 2007).

To contribute to understanding the behaviour of debris-covered glaciers under a changing climate a comparison among the elevation changes we evaluated on Miage and the ones calculated by other authors on debris free glaciers of the Italian Alps was made. The debris free glaciers of Mont Blanc experienced an acceleration in the magnitude of negative mass balances since the mid nineteen eighties (Cerutti, 2001); this was in contrast to the Miage behaviour, which due to its debris cover preserved the positive phase up to the second half of the 1990s. An interesting comparison is possible between the Miage glacier variations and those of the Lex Blanche Glacier, a debris free glacier located in the same glaciarized basin (Veny Valley, Mont Blanc). The changes of Lex Blanche in the period 1975-1991 were documented by D'Agata & *alii* (2003) and they proved slightly negative in contrast with the positive phase experienced by Miage in the same period. Villa & *alii* (2007) computed volume and surface variations of the Rutor Glacier, in Aosta Valley like the Miage, and they found strong negative changes in the period 1975-1991. Similar findings by Carnielli (2005) computed volume and thickness variations of Verra Grande Glacier, a debris free glacier located in the Monte Rosa Group (Aosta Valley) which showed an important volume loss in the 1975-1991 period in contrast to the Miage behaviour. It is notable that Lex Blanche, Rutor and Verra Grande glaciers have their termini reaching higher elevations than the Miage snout thus suggesting the efficiency of the insulation effect played by Miage debris cover to be able not only to reduce ablation but also to preserve the volume and thickness gains up to 1800 m of elevation.

For the very recent time sub-window (1991-2003) data are not available on volume and thickness changes in Italian debris-free glaciers, but we can compare the mean annual thickness change of the Miage debris-covered tongue with the annual ablation rates of some debris-free benchmark Italian glaciers (Diolaiuti, 2001; Cannone & *alii*, 2008; Bertoglio & *alii*, 2005) and the Miage thickness change proved to be up to 30% minor than these. This is in agreement with the findings by Kellerer-Pirklbauer & *alii* (2008) who compared the debris free and the debris covered ablation area of Pasterze Glacier.

A fundamental point to be discussed is the reliability of our evaluations, and the accuracy and errors to be assigned to our sources and results respectively. For evaluating accuracy and error to assign to the map-derived DEM, the model proposed by Pilouk (1992) and Li (1994), already adopted by D'Agata & Zanutta (2007) was applied. This model assesses the errors using basic cartographic and photogrammetric parameters; nevertheless it is the scale which mainly influences the accuracy. The accuracy of elevation measurements in DEMs derived from contour data can be estimated by means of the equation (1)

$$\sigma_h = b \cdot CI + \sigma_r \cdot tg\,(\alpha) \tag{1}$$

where σ_r is the map reading error (0.2 mm on the map); σ_h is the root mean square error in elevation h; b is an empirical number commonly within the 0.16÷0.33 range; CI means Contour Interval; α is the mean slope of the DEM; the error affecting the 1975 DEM then proves to be between 2 and 4 m.

For DEMs derived from stereoscopic imagery we applied Kraus' model (1994) according to equation (2)

$$\sigma_h = a \cdot \frac{h}{1000} \tag{2}$$

where a is an empirical constant within the 0.1-0.15 range and h is the relative flight height. Errors obtained from photogrammetric surveys were about 0.36 m.

Differences in volume were calculated comparing the most recent surface to the oldest one. As result, the net volumes were calculated as the mean value of three numerical models generally adopted to estimate volume (Extended Trapezoidal Rule, Extended Simpson's Rule, Extended Simpson's 3/8 Rule).

Thus, the errors in volume differences were estimated by means of equation (3)

$$\sigma^2_{vs} = \sum_{i=1}^{n} (\sigma_i A)^2 \tag{3}$$

where: i = 1….n, we adopted n = 3, as we analysed 3 DEMs (1=1975; 2=1991; 3=2003)

σ^2_{vs} = variance of the Vs

σ_i = root mean square error in each DEM

A = surface area

TABLE 1 - Estimation of errors affecting DEMs

Time windows	**1975-2003**	**1975-1991**	**1991-2003**
Volumetric variation (m^3)	-16.640×10^6 m^3	$+19.254 \times 10^6$ m^3	-36.200×10^6 m^3
σ_{vs} (m^3)	b=0.16:±7.139x10^6 m^3 b=0.33:±12.99x10^6 m^3	b=0.16:±7.18x10^6 m^3 b=0.33:±13.06 m^3	±1.805x10^6 m^3
σ_{vs} (%)	b=0.16:43% b=0.33:78%	b = 0.16: 37% b = 0.33: 67%	5%

Analysis of TAB.1 shows that the better sources are the aerial photos (stereo pairs) which gave DEMs with high accuracy values. The volume change then estimated by comparing aerial photo-derived DEMs (i.e.: 1991 and 2003) is affected by a small error (±5%). On the other hand, the map-derived DEM (i.e.: 1975) is characterized by higher error values which make the errors affecting the volume changes calculated for periods 1975-1991 and 1975-2003 not negligible; more precisely in the best case the error is close to ±40% and in the worst, it may be up to ±80%. Some considerations must be made on this range of error: on one hand, it is not negligible and it underlines the reliance on the use of aerial photo-derived DEMs (or high resolution satellite image-derived DEMs) for calculating variations of debris-covered glaciers, which due to the debris coverage are characterized by thickness and volume changes with lower magnitude and rates than debris free glaciers. In fact, an error of ±7.18x10^6 m^3 found for the 1975-1991 time sub window would not be so important on debris free glaciers, which in the same time frame were affected by changes from 3 to 10 times stronger. On the other hand the errors are not sufficiently high to make our estimations meaningless and the glacier trends we found (i.e.: positive from 1975 to 1991 and negative from 1975 to 2003) are consistent and expressive of the glacier's variations tendencies.

CONCLUSIONS

The evaluation of the changes in the geometry of the Miage Glacier tongue showed a net decrease in volume (–16.640 x 10^6 m^3) between 1975 and 2003. Analysis of two time sub-windows detected two opposing trends: a strong positive increase in both volume and thickness (1975-1991) and a negative variation in the 1991-2003 period. Both the trends contrast with variations of Italian debris-free glaciers which at the beginning of the 1990s had lower thicknesses and volumes and which in very recent times (up to 2003) have been subject to lowering three times that experienced by the Miage tongue. The elevation changes were inversely related to supraglacial debris coverage (i.e.: positive or slightly negative variations with thick debris depth and glacier lowering with thin debris cover) which for the Miage Glacier is known due to a remote sensing analysis performed in very recent years (Mihalcea & *alii*, 2008a). Similar findings are reported in a paper dealing with the Baltoro debris-covered glacier, Pakistan (Mihalcea & *alii*, 2008b) and by previous authors (Inoue, 1977; Benn & Lehmkuhl, 2000) for other debris-covered glaciers (e.g. Ama Dablam Glacier, Nepal; Batura Glacier, Pakistan), where ablation was found to decrease with decreasing altitude due to increasing thicknesses of supra-glacial debris. Also previous studies on the Italian glaciers Belvedere (Diolaiuti & *alii*, 2003) and Brenva (D'Agata & Zanutta, 2007) showed the debris insulating effect to be able not only to reduce magnitude and rates of ablation on actual debris covered glaciers but also to preserve for a longer time the mass gains due to cooler climatic periods. From our evaluations on accuracy and errors affecting sources and results of this study it seems that the best sources are the aerial photos (stereo pairs), which gave DEMs with high accuracy values - the volume change then estimated by comparing aerial photo-derived DEMs (i.e.: 1991 and 2003) is affected by a small error (±5%). In contrast, the map-derived DEM (i.e.: 1975) is characterized by higher error values which make the errors affecting the volume changes calculated for the 1975-1991 and the 1975-2003 time frames not negligible. Nevertheless the errors are not high enough to make our estimations meaningless and the glacier trends we found (i.e.: positive from 1975 to 1991 and negative from 1975 to 2003) are consistent and expressive of the glacier's variations tendencies.

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