Belvedere Glacier, Monte Rosa, Italian Alps: Tongue Thickness and Volume Variations in the Second Half of the 20th Century

Authors: Diolaiuti, Guglielmina, D'Agata, Carlo, and Smiraglia, Claudio

Source: Arctic, Antarctic, and Alpine Research, 35(2) : 255-263

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2003)035[0255:BGMRIA]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 35, No. 2, 2003, pp. 255–263

Belvedere Glacier, Monte Rosa, Italian Alps: Tongue Thickness and Volume Variations in the Second Half of the 20th Century

Guglielmina Diolaiuti,
Carlo D'Agata, and
Claudio Smiraglia

Department of Earth Sciences,
University of Milan,
Via Mangiagalli 34, 20133 Milan, Italy.
claudio.smiraglia@unimi.it

Abstract

In studying the response of alpine glaciers to climate warming, the study of debris-covered glaciers is important in order to demonstrate that a negative feedback exists in the temperature-ablation relationship that is introduced by the increase in debris cover. In this paper, variations in the Belvedere Glacier tongue volume and thickness were quantified through a comparison of large-scale maps for 1957 and 1991. A volume increase of 22.7 million m^3 was revealed, and there was a mean increase of 15 m in thickness. Thickening was greatest above 1830 m, and thinning occurred at the glacier front (1830–1770 m). The glacier terminus advanced only slightly. This particular evolution of the Belvedere tongue has been attributed to positive balances of the glacier created by favorable climatic conditions (increase in winter precipitation between the early 1970s and mid-1980s and lower summer temperatures in the 1960s and 1970s). After the mid-1980s, reduced precipitation and a simultaneous increase in temperatures led to a slight retreat of the glacier front in the early 1990s. However, these climatic conditions were not sufficient to bring about a significant reduction of the thickness of the glacier, partly owing to the debris cover, which reduced the role of ablation.

Introduction

Belvedere Glacier constitutes the terminus of the glaciers descending the steep eastern slope of Monte Rosa (4633 m; Fig. 1) in the Italian Alps, which cover the gigantic face between Cima Tre Amici and Punta Nordend (Fig. 2) with their vast flows. This well-known glacier has been studied extensively since the early decades of the 20th century (Porro and Somigliana, 1918; Monterin, 1918; 1922). Important studies were also carried out in the 1950s and 1960s (Aliverti, 1950; Gili-Borghet, 1961; De Visintini, 1961) as well as in more recent times (Haeberli, 1984; VAW-ETH, 1985; Mazza, 2000). In the summer of 2001, Belvedere Glacier experienced a surge-type flow acceleration with a very active detachment zone for rock falls that affected the growing hazard potential for local infrastructures (Haeberli et al., 2002; Haeberli et al., 2002).

Belvedere Glacier is a typical debris-covered glacier like its not-too-distant neighbors, Miage and Brenva Glaciers (Monte Bianco, Valle d'Aosta). The tongue is almost completely covered with debris. The glacier virtually lacks a true accumulation basin and is fed mostly by avalanches flowing down from the eastern face of Monte Rosa, the highest face in the Alps. This glacier typology offers many interesting aspects for study.

The response of alpine glaciers to global warming has long been identified as a key factor in runoff variations and sea-level changes. However brief reductions in global warming combined in some regions with increased precipitation are factors that have brought about a limited phase characterized by glacier advances. On debris-covered glaciers, the presence of the debris and its increase modify the relations between temperature and runoff, reducing melting (Nakawo and Young, 1982). This type of glacier is undergoing a rapid increase in number in the Italian Alps as a result of the current warming phase. By reducing the snow and ice cover on the slopes, recent warming has fostered processes of slope mass-wasting owing to macrogelivation, supplying abundant debris to the surfaces of the glaciers below and thereby increasing the number of glaciers that are partially or totally debris-covered. On the larger clean valley glaciers such as Lys, Verra, and Forni Glaciers, the medial moraines have markedly widened over the past fifteen years to the point of covering the entire lower sectors of the tongues with debris. On the smaller glaciers, particularly the cirque glaciers, the entire surface, or over half of it, is covered with debris. This latter phenomenon involves almost all of the small glaciers in the Italian Alps.

Unlike debris-covered glaciers in Nepal and New Zealand that have been studied during negative-balance phases, several Italian debris-covered glaciers (Miage and Brenva) have experienced positive mass balances with increases in thickness and relatively accentuated front advances (Thomson et al., 2000; Smiraglia et al., 2000; Cerutti, 1992; Orombelli and Porter, 1982).

In this context, quantification of the variations in volume over the late 20th century for Belvedere Glacier, one of Italy's largest glaciers, could be important to establish whether a regional pattern exists in the southern Alps.

Another element of interest lies in the recent dynamics of Belvedere Glacier (surging and rock falls), which are creating hazardous situations.

Variations in Thickness and Volume

The variations in the thickness and volume of Belvedere Glacier in the second half of the 20th century were computed through a comparison of two large-scale maps

- The first, with a scale of 1:5,000 and a 5-m contour interval, was compiled by means of ground photogrammetry carried out in 1957 by the Ente Italiano Rilievi Aerofotogrammetrici—Italian aerial photography agency (EIRA) of Florence for the Comitato Glaciologico Italiano—Italian glaciological committee (EIRA, 1961).
- The second, with a scale of 1:10,000 and a 10-m contour interval, is the Carta Tecnica Regionale della Regione Piemonte—Regional technical map of the region of Piedmont (sheets

1523-0430/03 $7.00

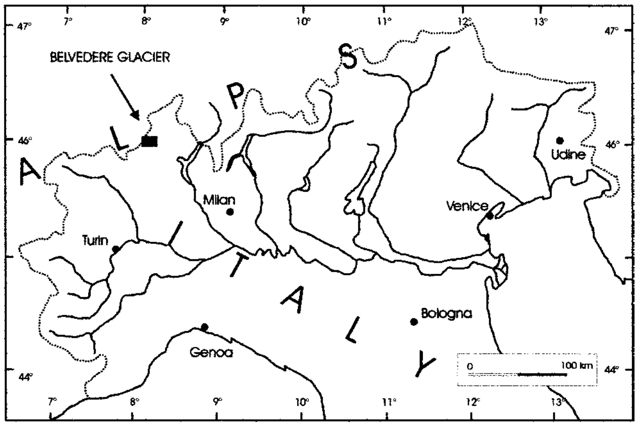

FIGURE 1. Location of Belvedere Glacier.

FIGURE 2. View of Monte Rosa east face with Belvedere Glacier at its base (photograph by G. Buscaini).

071030, 071040, 071070, 071080), obtained through an aerial photograph survey conducted in 1991.

Digital elevation models (DEMs) of the maps were developed in order to determine surface, thickness, and volume variations for the period between 1957 and 1991.

Computation of the glacier variations was organized according to five main stages:

1. Digitization of the maps.
2. Georeferencing with the Gauss-Boaga projection, International Spheroid orientated to Monte Mario 1940, and vectoring of the rasters obtained.
3. Calculation of the DEM files for both maps using Surfer 7 software. The points acquired through vectoring were utilized for the calculation of the DEMs. The preliminary phase consisted of the processing (again, using Surfer) of a 10-m grid, starting from the x, y, and z data, through a linear variogram.
4. Overlaying of the DEM files thus obtained.
5. Calculation of the variations in volume, thickness, and area. This procedure was carried out automatically by computer, taking into account the differences between the two DEM meshes.

The major drawback in performing this type of calculation lies in map comparability. In the case of this study, it was not possible to consider the entire glacial basin, as the 1957 mapped representation was limited to the tongue sector alone. The boundaries of the glacier tongue (both along the perimeter and the front) were not always evident, because of the large amount of supraglacial debris. Another factor limiting the comparison concerns the map of 1957 because this map is a representation referring to a local system (not the Roma40 geographic national system or the ED50 geographic international system). Therefore, the comparison of the maps was made through the identification of homologous points (a total of 12) on the two representations. As a result of these limitations, the final accuracy in the map comparison can be estimated to amount to 5 m in the horizontal plan. This value led us to consider the overlaying of the maps as acceptable and, consequently, the data obtained from the calculation of the variations as reliable.

The digitization of the 1957 map made it possible to calculate the area of the glacier tongue (from the terminus at 1768 m to an altitude of 2205 m) as 1,484,000 m^2. The 1991 map gave a calculated area of 1,467,000 m^2, with a resulting change in area amounting to –17,000 m^2. This loss is concentrated mainly in the frontal zone and is attributable to the recent slight retreat of the glacier's terminal sector. The variation in volume for Belvedere Glacier between 1957 and 1991 (34 years) calculated by means of the comparison of the two DEM files was +22,672,000 m^3. This value includes the thickness of the superficial debris, the measurements of which (taken in the summer of 2000) yielded a mean value of 15 cm.

As no previous measurements of the debris thickness exist, this value was utilized to calculate the volume of debris (220,050 m^3) to be subtracted from the overall variation. The variation in the volume of ice would then amount to about +22,451,950 m^3, equivalent to 20,206,755 m^3 of water, utilizing a mean density of 900 kg/m^3 for the ice. The current debris thickness used in the calculations is probably greater than the thickness in previous decades, so the variation in ice thickness may have been slightly underestimated.

A map of isovariations (Fig. 3) was then calculated by the comparison of the DEM files in order to provide a better visualization of the distribution of thickness changes between 1957 and 1991. The mean variation in thickness over the entire glacier was +15 m, corresponding to an annual mean of +0.44 m. The maximum positive variations (exceeding +40 m) were found in limited zones of the central sector, whereas the maximum negative variations (exceeding –30 m) were recorded in the frontal sector in the area from where the glacier has retreated (see the Discussion section) and also in several zones along the perimeter.

Over 50% of the glacier surface has registered increases in thickness ranging between 10 and 20 m, whereas 25% of the surface shows no significant change in surface elevation. Less than 5% of the surface has thinned over the 34-yr interval.

Assessment of the Total Volume of Ice

A map of the glacier bedrock was utilized in order to obtain information on the total volume of ice contained in the tongue of Belvedere Glacier (and thus also on the water reserves represented by the glacier) as well as on the glacier's recent variations. This map was prepared by De Visintini in 1957 (De Visintini, 1961) using seismic prospecting and published in the *Bollettino del Comitato Glaciologico Italiano*. As regards the bedrock morphology, this map does not differ significantly from the results of a more recent study (VAW-ETH, 1985) carried out by using GPR techniques that in some profiles indicated a large thickness of sediments between bedrock and ice.

The map was digitalized and then georeferenced using the same points utilized for the georeferencing of the topographic map of the same year. The isohypses were then vectored and the points acquired were processed with Surfer 7 (according to the same methodology followed previously) to calculate a DEM of the bedrock. The isopach map obtained from the DEM is shown in Fig. 4, it highlights the deep

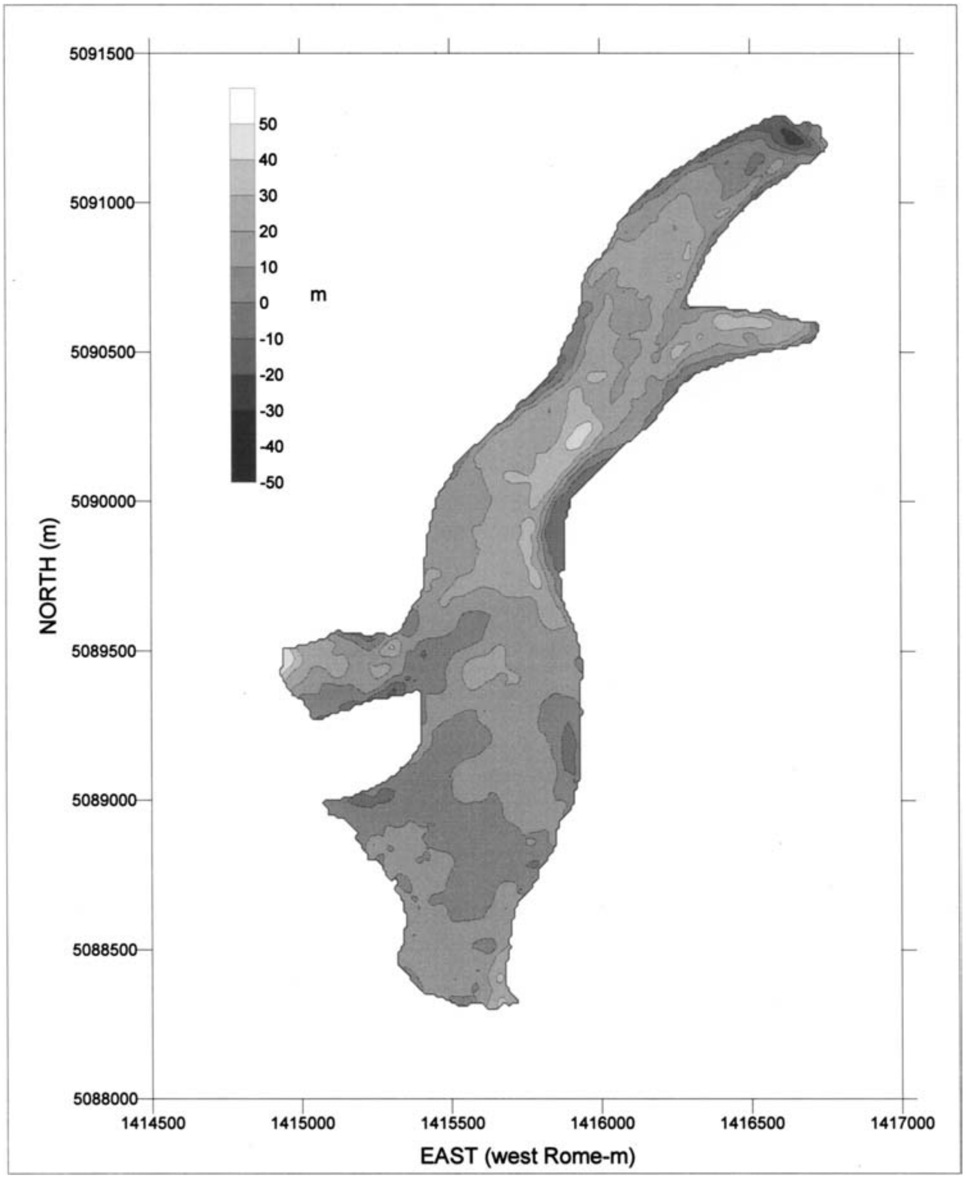

FIGURE 3. Map of 1957–1991 thickness isovariations.

excavation of the glacial valley. In fact, the central sector proves to be more than 240 m deep over a breadth of about 500 m.

The DEM thus obtained was compared with the one compiled for the glacial surface of 1957. This comparison made it possible to calculate the volume in 1957 of the glacier tongue contained between the topographic surface and the bedrock, which proved to be equal to 115.7×10^6 m^3 (this value includes the ice; the surficial debris, the thickness of which is not available for 1957; and the sediments between bedrock and ice revealed by the VAW-ETH survey but not exactly quantified).

The glacier volume calculated for 1957 was algebraically added to the 1957–1991 change in volume (ice and debris). However, there is a difference of 428,000 m^2 in the areas on which the volumes were calculated (1,482,000 m^2 on the 1991 map and 1,056,000 m^2 on the map of the bedrock). Therefore, the volumes for the same reference surface area were recalculated prior to adding up the two values in order to obtain the volume of ice and debris for 1991. It was thus possible to estimate the glacier's volume in 1991, which proved to be equal to 131.7×10^6 m^3, with an increase of 14% compared to the volume calculated for 1957.

In addition, five profiles (one longitudinal and four cross-profiles) were plotted on each DEM (the 1957 DEM and the 1991 DEM). The locations of the three profiles held to be the most representative are shown in Fig. 5 and the profiles are presented in Fig. 6. The profile of the bedrock, which was obtained as indicated above, has also been inserted.

Figure 6a presents a graph that compares the 1957 and 1991 longitudinal profiles. The y-axis scale has been enlarged with respect to the x-axis coordinates in order to highlight the variations that took place. The profiles extended for a length of about 3 km over an altitude interval between 1768 and 2205 m. The 1991 profile remains consistently above the 1957 DEM between the altitudes of 1830 and 2205 m, but between 1830 m and 1768 m in altitude it is lower than the 1957 profile. In those 34 yr, the glacier decreased in thickness (and thus also in volume) in the outermost frontal portion (where the debris cover is extremely thin), whereas it increased in thickness (and thus in volume) in the zone above the altitude of 1830 m.

Figures 6b and 6c show the cross-profiles. It shows that thickness increased between 1957 and 1991, while an almost identical surface morphology was maintained.

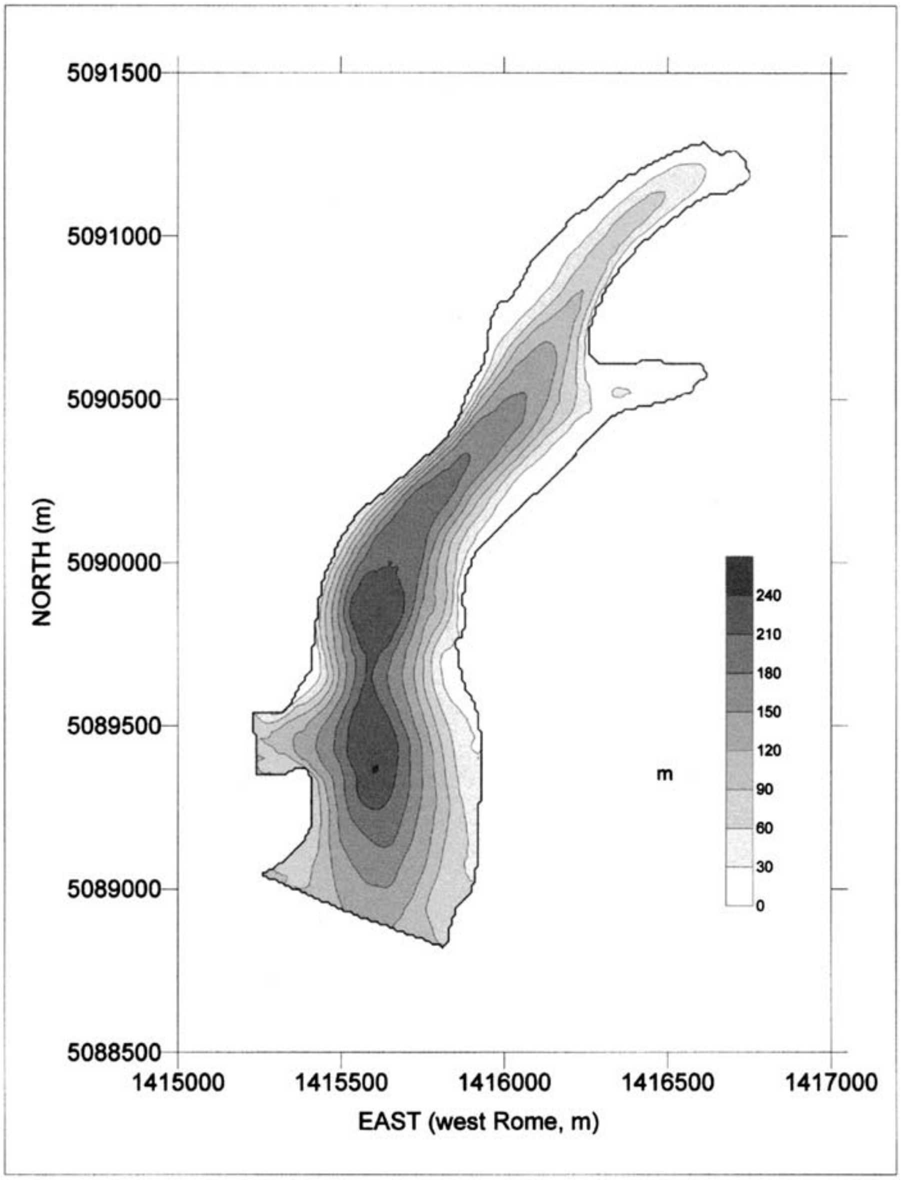

FIGURE 4. Map of glacier thicknesses.

Debris Thickness Measurement

Measurement of the debris thickness was made because of its importance in terms of reducing ablation and in terms of energy exchange at the atmosphere-debris interface.

Debris thickness was measured in September 2000 at 260 points, across the glacier tongue from the terminus to an altitude of 2150 m. Thickness was measured by means of direct field surveying, with removal of the debris cover down to the underlying ice.

The points were selected on the basis of geomorphologic criteria (inclination of the glacier surface, debris distribution, presence of crevasses and other morphological structures). Three measurements were taken for each point over a square meter of surface, and the mean value was used. Each point was represented on CTR maps (1:10,000), as the survey was conducted with the aid of GPS equipment (Trimble 4600 Series in fast static mode with postprocessing of data). It was observed that the thicknesses are a direct function of glacier surface inclination, and they varied between 4–5 cm in the uppermost sector of the tongue (where the inclination is greater) and 20–30 cm on the two frontal lobes, with peak levels of 80 cm in depressions (glacier karst). It was also noted that vegetation is present mainly where there is a greater amount of debris and inclination is lower. The points acquired through GPS were processed (with GPS Survey 2.35 software) to obtain a DEM that would be representative of the debris distribution and thickness (using Surfer 7 software) and to prepare a thematic map (Fig. 7).

Discussion

As revealed by the comparison of the maps, Belvedere Glacier registered a 15m increase in mean thickness between 1957 and 1991, with a maximum increase of 50m in the central sector. The frontal variation data indicate an almost uninterrupted phase of sharp reduction lasting until 1967 (950 m, including a retreat of 200 m, as estimated by Mazza, 2000, between 1943 and 1952, when measurements were not taken); a limited advance between 1968 and 1970;

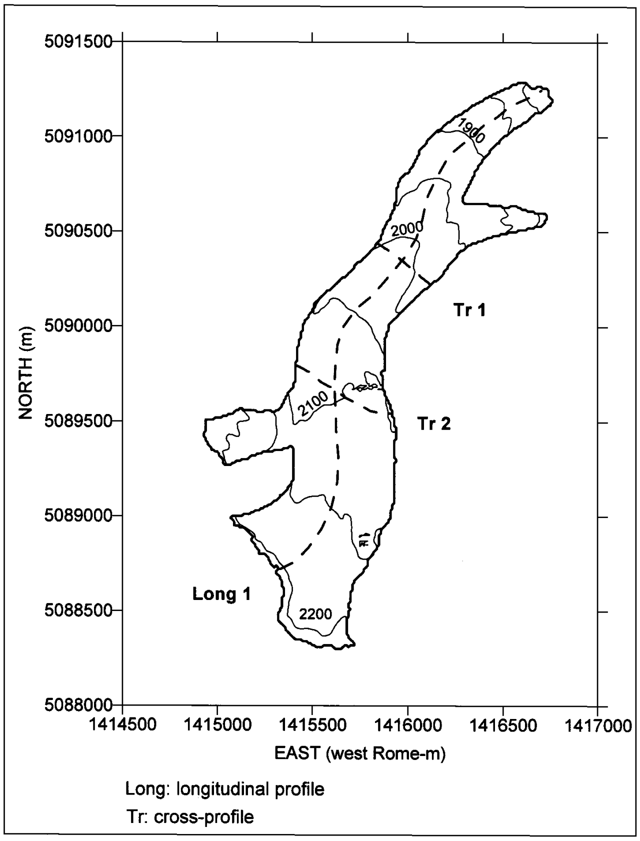

FIGURE 5. Longitudinal and cross-profile locations.

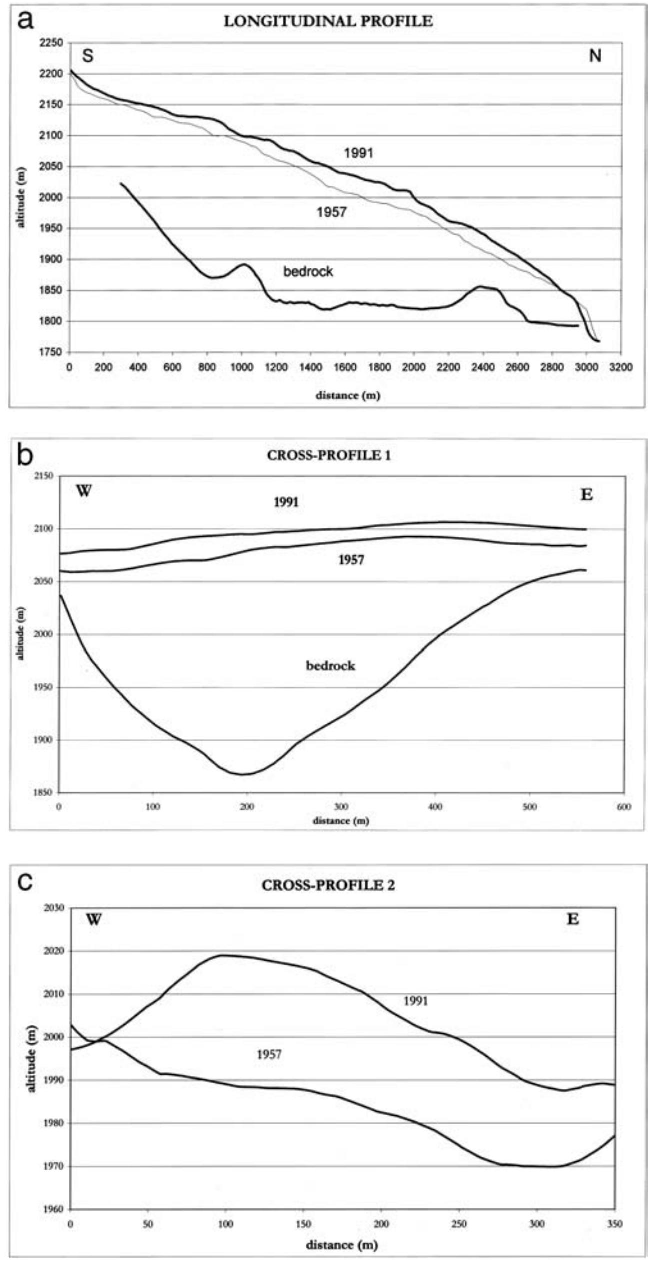

FIGURE 6. (a) Longitudinal profile; (b) and (c) cross-profile.

a limited renewal of the retreat until 1977; and alternating steady states, limited advances, and retreats of the same order from 1978 to the present (Fig. 8).

The increase in thickness revealed by the comparison of the maps of 1957 and 1991 could be linked to the positive mass balances resulting for several years. In fact, drops in the mean summer temperatures were registered at the Monte Rosa meteorological stations from 1953 to 1977 (Fig. 9a) as well as increases in snowfall between 1972 and 1985 (Fig. 9b). These positive balances gave rise to the terminus steady state and the small advances in the 1968–1970 and 1978–1992 periods.

A comparison can be made with Lys Glacier, a large clean glacier on the southern slope of Monte Rosa. The comparison of the maps revealed a reduction in thickness amounting to 17 m between 1953 and 1994 for Lys Glacier (Rota et al., 2001). As regards front variations of Lys Glacier, a rapid retreat (about 700 m) lasted until 1972. Then there was an evident expansion until 1985 (+93 m), and from 1986 to 2000 the front retreated by over 130 m. Even taking into account that several years of data are lacking for Belvedere Glacier, it is observable that the dynamics of the two glaciers were markedly different over the 1970–1990 period (Fig. 10), when the clean glacier registered a more evident expansion phase.

The positive 1973–1985 phase for Lys Glacier could be linked to the same climatic event affecting the Belvedere, but on the debris-covered glacier the passage of the kinematic wave was slowed down and the tongue thickness increase was preserved, with only a very limited advance of the terminus. On Lys Glacier the reaction to the climatic cooling period has been rapid with a real advancing phase, as well as the response to the nowdays warming period was immediate and the front retreat phase deleted all the last glacier increasing.

Miage and Brenva Glaciers are two debris-covered glaciers in the Monte Bianco Group. Between 1975 and 1991, Miage Glacier registered increases in thickness, with peaks of 40 m in the lower sector and reductions in the upper sector, with limited variations of the position of the front (Smiraglia et al., 2000; Thomson et al., 2000). Between 1959 and 1991, Brenva Glacier's increase in thickness amounted to about 40 m (Smiraglia et al., 2001), whereas the frontal variations indicate a strong advance phase until 1941 derived from the giant rock fall of the 1920s, which covered the entire tongue with a considerable thickness of debris, followed by a reduction phase from 1953 to 1966. Then the glacier underwent a strong positive phase (Lesca, 1972), with an increase in thickness and a terminus advance until 1991 (+490 m) (Cerutti, 1992). From 1992 to 1996, the glacier was in a retreat phase (–30 m).

In short, we can observe that as their response time proves to be longer, Italian debris-covered glaciers underwent an advance period from 1967 to 1991. The advance was limited for Belvedere and Miage

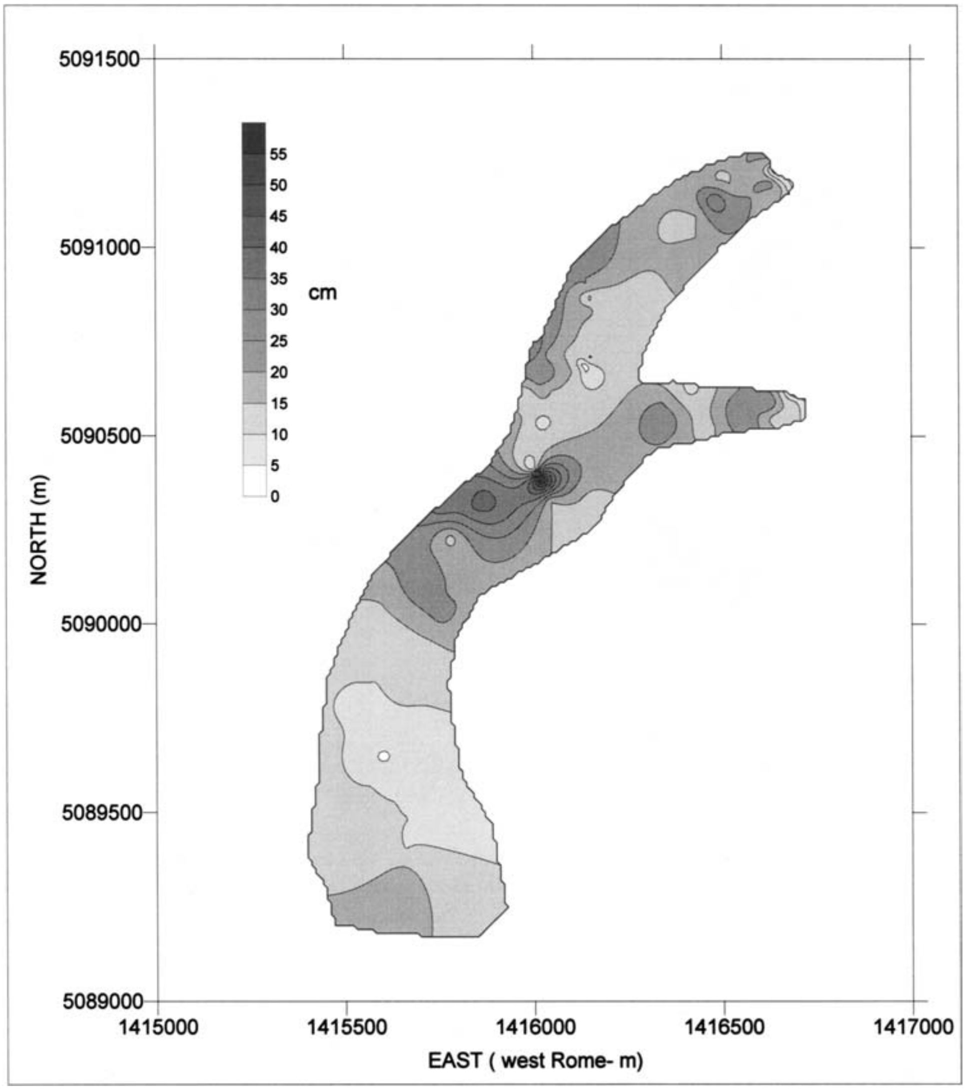

FIGURE 7. Map of the surface debris thickness.

Glaciers but strong for Brenva Glacier. The retreat phase from 1992 to the present was also limited for Belvedere and Miage (which alternated limited advances with limited retreats and stationary periods) but strong for Brenva Glacier. In contrast the clean Lys Glacier (like other alpine clean glaciers) advanced during the years 1973–1985, with a stronger advance than that of Belvedere Glacier. Its current retreat phase, which started in 1985, is stronger than that of the debris-covered glaciers.

The different response to the same climatic effects could be attributed to the effects of the debris cover (Nakawo and Young, 1982). In fact, the debris cover tends to reduce ablation, as demonstrated in the literature (Drewry, 1972; Humlum, 1981) and by the data collected directly on Italian glaciers. In particular, we can note that on Miage Glacier, areas with a 10 cm thick debris cover lost 0.54 m in ice thickness in the course of about one month, whereas the clean ice in that same period lost just over 1 m of w.e. (Casati, 1998). If all other factors remain constant, the ablation rate decreases exponentially with the increase in the debris thickness (Benn and Evans, 1998).

More favorable mass balances, or at least less negative ones, for debris-covered glaciers compared to neighboring clean glaciers are a direct result of the reduced ablation caused by the debris cover (Casati, 1998). This could explain the greater inertia of debris-covered glaciers in reversing the positive trend of the frontal variations compared to the clean glaciers. The Belvedere, Miage, and Brenva Glaciers continued to advance to remain steady until the early 1990s, whereas the neighboring clean glaciers began retreating five years earlier.

Conclusions

The study made it possible to quantify variations in the volume and thicknesses of Belvedere Glacier, revealing an increase in both which took place in the second half of the 20th century, thus also confirming previous data concerning the 1977–1985 period (VAW-ETH, 1985). Measurements were also taken of the thickness of the glacier's debris cover, which has certainly influenced its energy balance (Ranzi and Grossi, 2000; Ranzi et al., 2001) and dynamics. The increase in thickness is attributed to positive mass balances resulting from the increase in yearly snowfall that took place between the beginning of the 1970s and the mid-1980s and from a reduction in summer temperatures from 1953 to 1977, as recorded by numerous meteorological stations in the regions of Piedmont and Valle d'Aosta (Mazza and Mercalli, 1992; Mazza, 1998; Biancotti et al.,1998a; Biancotti et al. 1998b; Cortemiglia,1999). After the mid-1980s, the reduction in precipitation and the simultaneous increase in temperatures led to very negative mass balances for the clean glaciers, with marked retreats of the fronts, and to steady or less negative mass

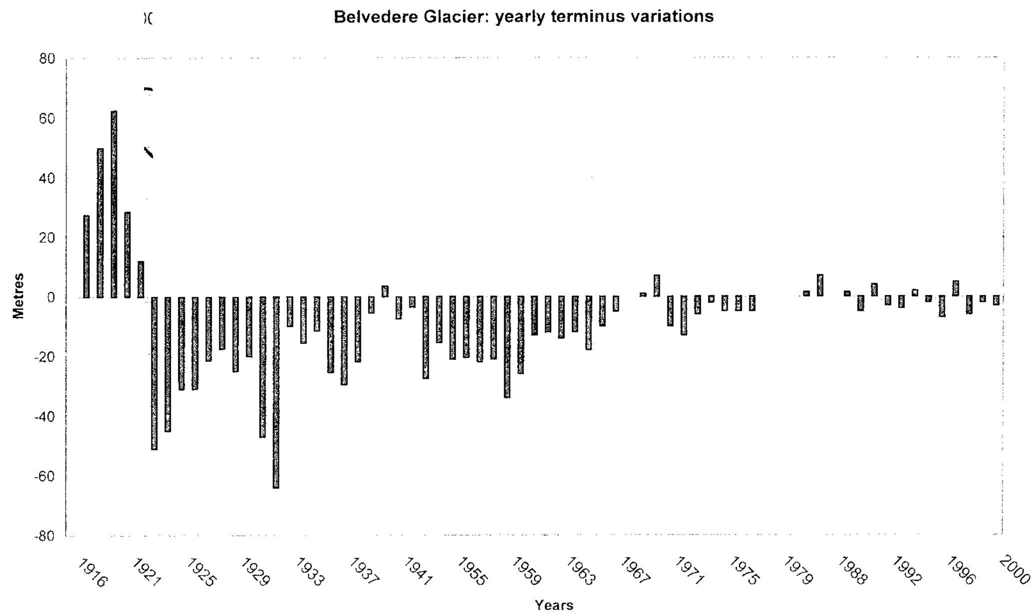

FIGURE 8. Yearly terminus variations in m (CGI data from 1917 to 1965 and IUGG data from 1965 to 2000) (in the period 1943–1952 the glacier was not surveyed).

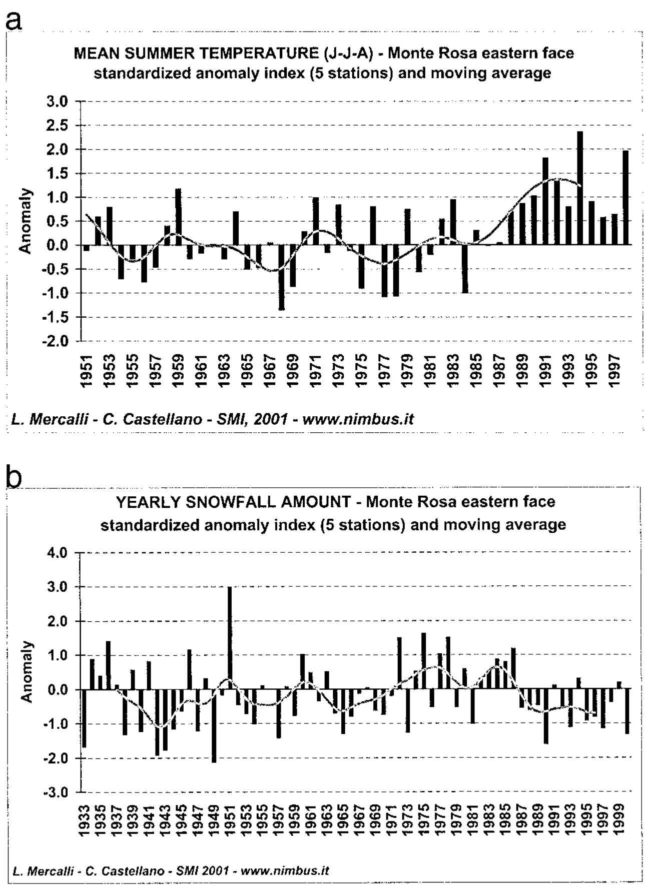

FIGURE 9. (a) Mean summer temperature—Monte Rosa group (SMI—Italian Meteorological Society data). (b) Yearly snowfall—Monte Rosa group (SMI—Italian Meteorological Society data).

balances for the debris-covered glaciers, resulting in slight retreats of the glacier fronts. The retreat phase, which started in the 1990s for the debris-covered glaciers studied, was not sufficient to determine a marked reduction of the thickness of the glacier (from the 1991 map, it proves to be greater than the thickness in 1957).

If the results thus obtained are compared with the data on the variations that took place between 1975 and 1991 on another alpine debris-covered glacier, Miage Glacier (Monte Bianco, Valle d'Aosta), obtained using the same methodologies (map comparison for an assessment of changes in area, volume, and thickness; geophysical surveys to determine the thickness of the ice; and direct measurements of debris thickness) (Smiraglia et al., 2000), it is possible to detect dynamics that closely resemble the dynamics of Belvedere Glacier. The expansion phase took place as a consequence of an increase in glacier mass balances between 1960 and 1985 on numerous other alpine glaciers (Patzelt, 1985; Wood, 1988)—an increase that has also been confirmed for many other glaciers in North America, Iceland, Scandinavia, and the Himalayas (IAHS-UNEP-UNESCO, 1988). This

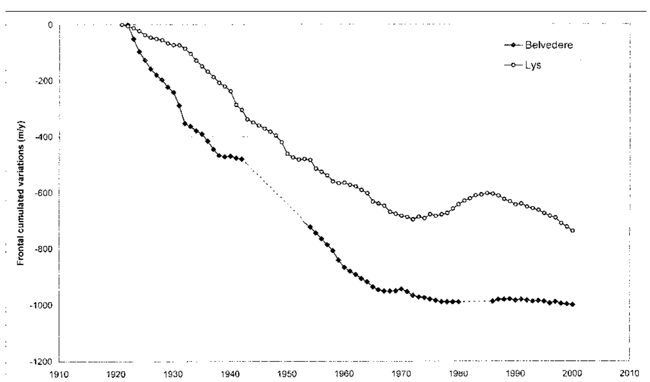

FIGURE 10. Cumulated terminus variations in m for Belvedere Glacier and Lys Glacier (CGI and IUGG data; the not surveyed period, 1943–1952, was filled by using cartographic estimations by Mazza, 2000).

expansion phase was followed by a phase marked by intensive ablation after the mid-1980s that triggered the generalized return of negative balances and retreats of glacier fronts that are still in progress but that have barely affected debris-covered glaciers. Compared to clean glaciers, the lower and nonlinear mass balance gradients (Inoue, 1977) in the debris-covered glaciers and the lengths of the tongues that reach the lowest altitudes in the Italian Alps (1775 m for Miage Glacier and 1375 m for Brenva Glacier) can justify the longer time scale of adjustment to mass balance changes and therefore both the minimal 1977–1992 advance and slow retreat thereafter.

The future evolution of Belvedere Glacier within the current framework of global warming does not depend as much upon the increase in temperature as upon the increase in the thickness of the debris. In fact, the increase in temperatures (of a few tenths of a degree, as predicted by International Climate Change Panel (ICCP) scenarios) will increase instability on the east face of Monte Rosa and the growing rockfall activity with destabilization of a larger rock mass, which could trigger an event comparable to the rock fall and powder-snow avalanche at Brenva, Mont Blanc, in 1997 (Haeberli et al., 2002).

Thus, there will be an increase in the thickness of the debris, which will further reduce ablation, compensating for the effects of increased temperatures.

The debris cover increased by macrogelivation as a consequence of nowdays warming climatic conditions can influence glacier dynamics and aid complex phenomena such as the surge-type movement that is taking place at Belvedere Glacier (Haeberli et al., 2002). These events, on soft bed conditions glaciers like Belvedere (VAW-ETH, 1985), are linked to deformation of subglacial till and were observed in young mountain range subject to rapid erosion (Paterson, 1994) as the east face of Monte Rosa.

Acknowledgments

This work was conducted as part of contract no. P1211 between the Department of Earth Sciences of the University of Milan and Centro Elettrotecnico Sperimentale Italiano = italian experimental electro-technical center (CESI), Segrate (Milan), and the 2001 40% MIUR Project "Glacial retreat in the Italian Alps and the climatic change since deglaciation to the present phase"—national coordinator: Prof. R. Federici, local coordinator: Prof. C. Smiraglia.

G. Diolaiuti processed data during her university grant Fondazione Confalonieri. The authors thank G. Stella for consulting assistance for the processing of the DEMs, L. Mercalli for the meteorological data, and M. Belò for assistance with the survey work. The authors also wish to thank the reviewers M. Kirkbride and M. Pelto for their strong improvement of this manuscript and W. Haeberli for the useful suggestions.

References Cited

Aliverti, G., 1950: Relazione su una visita ai ghiacciai del Monte Rosa versante nord-ovest. *Bollettino del Comitato Glaciologico Italiano,* serie II, 1: 31–38.

Benn, D. I., and Evans, D. J. A., 1998: *Glaciers and Glaciation.* London: Arnold. 734 pp.

Biancotti, A., Bellardone, G., Bovo, S., Cagnazzi, B., Giacomelli, L., and Marchisio, C., 1998a: Distribuzione regionale di piogge e temperature. *Collana Studi Climatologici in Piemonte*, Vol. 1 Turin, Regione Piemonte—Università degli Studi 80 pp.

Biancotti, A., Carotta, M., Motta L., and Turroni, E., 1998b: Le precipitazioni nevose sulle Alpi Piemontesi. *Collana Studi Climatologici in Piemonte*, Vol. 2 Turin, Regione Piemonte—Università degli Studi 80 pp.

Biancotti, A., Cerutti, A. V., and Mercalli, L., 1991: La montagna di ghiacci: storia dei ghiacciai italiani del Monte Rosa. Walser Kulturzentrum-Comitato Glaciologico Italiano, Torino, 79 pp.

Casati, D., 1998: *Studio della dinamica di un debris-covered glacier: il Ghiacciaio del Miage.* Unpublished first-degree thesis in Geological Sciences, University of Milan.

Cerutti, A. V., 1992: L'espansione dei ghiacciai italiani del Monte Bianco fra il 1962 e il 1989. *Geografia Fisica e Dinamica Quaternaria,* 15: 67–74.

Cortemiglia, G. C., 1999: Serie climatiche ultracentenarie. *Collana Studi Climatologici in Piemonte*, Vol. 3 Turin, Regione Piemonte—Università degli Studi 92 pp.

De Visintini, G., 1961: Rilievo sismico a riflessione sul Ghiacciaio del Belvedere (Monte Rosa). *Bollettino del Comitato Glaciologico Italiano,* serie II, 10: 65–70.

Drewry, D. J., 1972: A quantitative assessment of dirt-cone dynamics. *Journal of Glaciology,* 11: 431–446.

EIRA (Ente Italiano Rilievi Aerofotogrammetrici), 1961: Il rilievo topografico. *Bollettino del Comitato Glaciologico Italiano,* serie II, 10: 58–64.

Gili-Borghet, A., 1961: Il Ghiacciaio del Belvedere e gli studi compiuti sino all'anno 1957. *Bollettino del Comitato Glaciologico Italiano,* serie II, 10: 33–57.

Haeberli, W., 1984: Gletschervorstoss am Ghiacciaio del Belvedere (Macugnaga, Italien) und seine Auswirkungen. *Wasser, Energie, Luft,* 76, 11–12: 262.

Haeberli, W., Chiarle, M., Mortara, G., and Mazza, A., 2002: Assessing glacier hazards at Ghiacciaio del Belvedere, Macugnaga, Italian Alps. EGS, Nice, April 2002, OA28.1: *Glaciers and Ice Sheets,* Abstract.

Haeberli, W., Kääb, A., Paul, F., Chiarle, M., Mortara, G., Mazza, A., Deline, P., and Richardson, S., 2002: A surge-type movement at Ghiacciaio del Belvedere and a developing slope instability in the east face of Monte Rosa, Macugnaga, Italian Alps. *Norwegian Journal of Geography,* 56: 104–111.

Humlum, O., 1981: Observations on debris basal transport zone of Myrdalsjøkull, Iceland. *Annals of Glaciology,* 2: 71–77.

IAHS-UNEP-UNESCO, 1988: *Fluctuations of glaciers* 1980–1985, 5 Zürich: World Glacier Monitoring Service 288 pp.

Inoue, J., 1977: Mass budget of Kumbu Glacier. *Seppyo,* 39 (special issue): 15–19.

Lesca, C., 1972: L'espansione della lingua terminale del Ghiacciaio della Brenva in base ai rilievi fotogrammetrici del 1959, 1970 e 1971. *Bollettino del Comitato Glaciologico Italiano,* serie II, 20: 93–100.

Mazza, A., 1998: Evolution and dynamics of Ghiacciaio Nord delle Locce (Valle Anzasca, Western Alps) from 1854 to the present. *Geografia Fisica e Dinamica Quaternaria,* 21: 233–243.

Mazza, A., 2000: Some results of recent investigations on Ghiacciaio del Belvedere (Anzasca Valley, Western Alps) taking into account the glacier mechanism. *Geografia Fisica e Dinamica Quaternaria,* 23: 59–71.

Mazza, A., and Mercalli, L., 1992: Il Ghiacciaio Meridionale dell'Hohsand (Alta Val Formazza): un secolo di evoluzione climatica. Rapporti con la produzione idroelettrica. *Oscellana,* 22,1: 30–44.

Monterin, U., 1918: Introduzione allo studio dei ghiacciai italiani del Monte Rosa. *Bollettino del Comitato Glaciologico Italiano,* serie I, 3: 105–194.

Monterin, U., 1922: Il Ghiacciaio di Macugnaga dal 1870 al 1922. *Bollettino del Comitato Glaciologico Italiano,* serie I, 5: 12–40.

Nakawo, M., and Young, G. J., 1982: Estimate of glacier ablation under debris layer from surface temperature and meteorological variables. *Journal of Glaciology,* 28: 29–34.

Orombelli, G., and Porter, S. C., 1982: Late Olocene fluctuations of Brenva Glacier. *Geografia Fisica e Dinamica Quaternaria,* 5: 14–37.

Paterson, W. S. B., 1994: *The physics of glaciers.* Oxford: Pergamon, 480 pp.

Patzelt, G., 1985: Die Gletscher der Österreichischen Alpen 1985–1986. *Zeitschrift für Gletscherkunde und. Glazialgeologie*, Universitätsverlag Wagner, Innsbruck, 21:403–407.

Porro, F., and Somigliana, C., 1918: Ghiacciaio di Macugnaga. *Bollettino del Comitato Glaciologico Italiano,* serie I, 3: 187–190.

Ranzi, R., and Grossi, G., 2000: Energy balance of the Belvedere Glacier (Monte Rosa—Italian Alps), *IVth Alpine Glaciological Meeting*, Trento (Italy), abstracts: 24–25.

Ranzi, R., Grossi, G., Smiraglia, C., Diolaiuti, G., D'Agata, C., and Apadula, F., 2001: Runoff, debris cover and Tritium concentration measurements for icemelt simulations at the Belvedere Glacier (Monte Rosa—Italian Alps). *IAHS Maastricht, W4: High-Mountain Regions: Hydrological Processes and Cryospheric Processes, Models and the Variability of Available Water Resources, abstract.*

Rota, T., Bonacina, E., De Lotto, P., Rossi, G. C., and Smiraglia, C., 2001: Variazioni volumetriche della lingua del Ghiacciaio del Lys (Monte Rosa, Valle d'Aosta) nel XX secolo. *Supplementi Geografia Fisica e Dinamica Quaternaria,* 5: 183–185.

Smiraglia, C., Diolaiuti, G., Casati, D., and Kirkbride, M., 2000: Recent areal and altimetric variations of Miage Glacier (Monte Bianco Massif, Italian Alps). In Nakawo, M., Raymond, C. F., and Fountain, A. (eds), *Debris-Covered Glaciers* IAHS Publ. 264: 227–233.

Smiraglia, C., Diolaiuti, G., and D'Agata, C., 2001: I ghiacciai delle Alpi italiane: variazioni areali e volumetriche e dinamica geomorfologia recente. *Relazione contratto di ricerca* n° R1877 Milano: CESI.

Thomson, M. H., Kirkbride, M. P., and Brock, B. W., 2000: Twentieth century surface elevation change of the Miage Glacier, Italian Alps. In Nakawo, M., Raymond, C. F., and Fountain, A. (eds), Debris-Covered Glaciers IAHS Publ. 264:219–226.

VAW-ETH, 1985: Studi sul comportamento del Ghiacciaio del Belvedere, Macugnaga, Italia. *Relazione* 97,3.

Wood, F., 1988: Global alpine glacier trends 1960s to 1980s. *Arctic and Alpine Research.,* 20: 404–413.

Ms submitted April 2002