Correspondence

Recent variations of a debris-covered glacier (Brenva glacier) in the Italian Alps monitored by comparison of maps and digital orthophotos

Debris-covered glaciers are widespread in the mountain chains of Asia (e.g. the Karakoram, the Himalaya (Moribayashi and Higuchi, 1977) and the Tien Shan). They are also particularly common in New Zealand (Kirkbride and Warren, 1999), in the Andes and in Alaska. Despite their relatively common occurrence, debris-covered glaciers have not been well studied (Nakawo and others, 2000). A debris cover that partially or completely masks the glacier ablation zone significantly influences the surface energy flux, the ablation rate and the discharge of meltwater streams. By reducing ablation, a debris cover produces an alteration of the response of the glacier to climate change. It is important, therefore, with the aim of understanding how a persistent debris cover influences terminus fluctuations, to collect quantitative information on length and thickness variations.

In the European Alps, there are only a few examples of such glaciers. Miage and Brenva glaciers, which drain the south slope of Mont Blanc in Valle d'Aosta, western Italian Alps, are two of the best known (Fig. 1). Brenva glacier (8 km^2 wide and 7 km long) originates on the east side of Mont Blanc (Monte Bianco; 4810 m a.s.l.) and descends steeply to the floor of Val Veny where it terminates at 1415 m a.s.l. This is the lowest-altitude glacier front in the Italian Alps and the closest to a permanently inhabited location (the village of Entrèves and the Mont Blanc tunnel entrance are 1 km distant; Fig. 2). The terminal zone is extensively mantled with granitic debris, mainly deriving from large rock falls that were deposited in November 1920. Until that event, its terminus fluctuations were comparable with other Mont Blanc clean glaciers, such as Glacier d'Argentière or Mer de Glace (Orombelli and Porter, 1982); after the rock falls, Brenva glacier diverged from the general trend. While most alpine glaciers retreated, it continued to advance, in the 1940s almost reaching the 1818 limit. From then, it began to recede. A renewed advance commenced between 1965 and 1967, reaching a new maximum in 1991 (Cerutti, 1993). The latest measurements of terminal variation show a new reduction phase (Deline, 2002). Despite the often detected short-term terminus fluctuations of Brenva glacier, its tongue thickness and volume variations are poorly known.

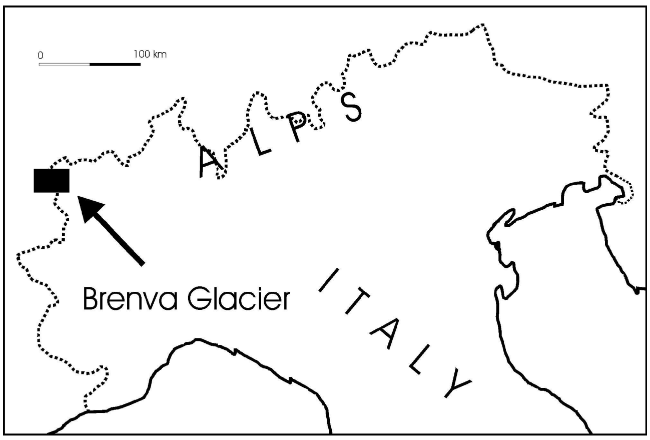

Fig. 1. Brenva glacier location.

Current work deals with processing and comparison of large-scale maps and aerial imagery of the glacier, supported by Geographical Information System (GIS)-based methodology. The maps used were: (i) EIRA (1972) (tongue only); (ii) Alifoto (1972) (tongue only); (iii) Regione Valle d'Aosta (1988); and (iv) Regione Valle d'Aosta (1999). For the same purpose, the following aerial photographs have been used: (i) CGR (Italian General Company Aerial Surveys), flight RAVDA (Regione Autonoma Valle d'Aosta), scale 1 : 17 000 image, 1991; and (ii) CGR, flight RAVDA, scale 1 : 17 000 image, 1997. The 1991 and 1997 stereo pairs were scanned using a Wheerli flatbed photogrammetric scanner at a resolution of 2116 dpi, which results in a pixel size of 12 μm, corresponding to approximately 18 cm on the ground.

A Digital Photogrammetric Workstation (Menci Software) was adopted for the generation of the digital terrain models using semi-automatic and automatic mode. The residuals from external parameter estimation were always <15 cm, demonstrating the overall good quality of the photogrammetric surveys. Ground-control points used to calculate the external orientation parameters were defined in a Universal Transverse Mercator grid (European datum 1950), and elevations measured above sea level. The adopted reference system allows comparison between maps and terrain models to detect multitemporal glacier tongue changes.

The maps and orthophotos were managed after digitization using GIS software. Digital elevation models were produced, and their comparison allowed us: (i) to quantify

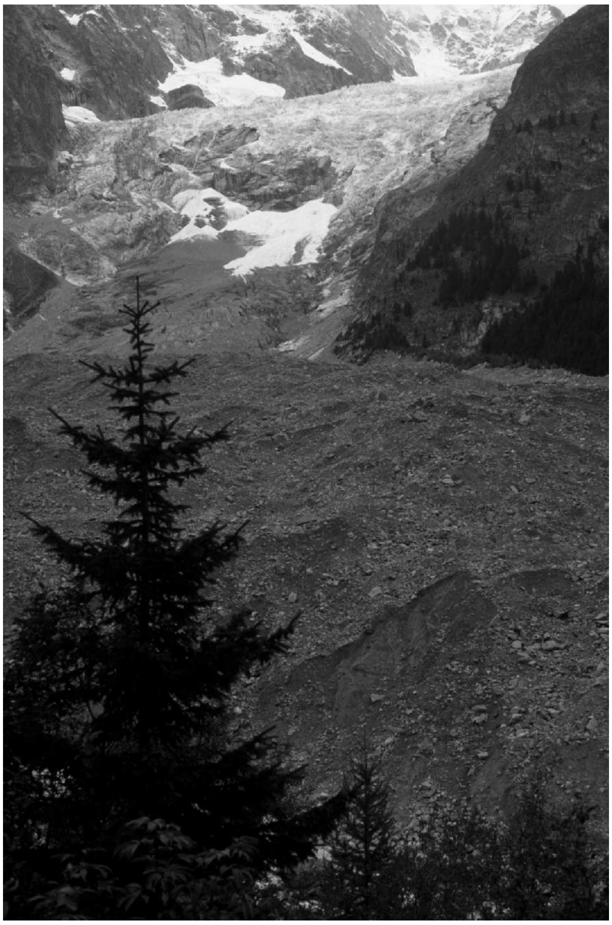

Fig. 2. A view of the east side of Mont Blanc with Brenva glacier.

v8.07j/W 21st July 2005 Article ref: 04J052 Typeset by: Sukie Proof No: 1

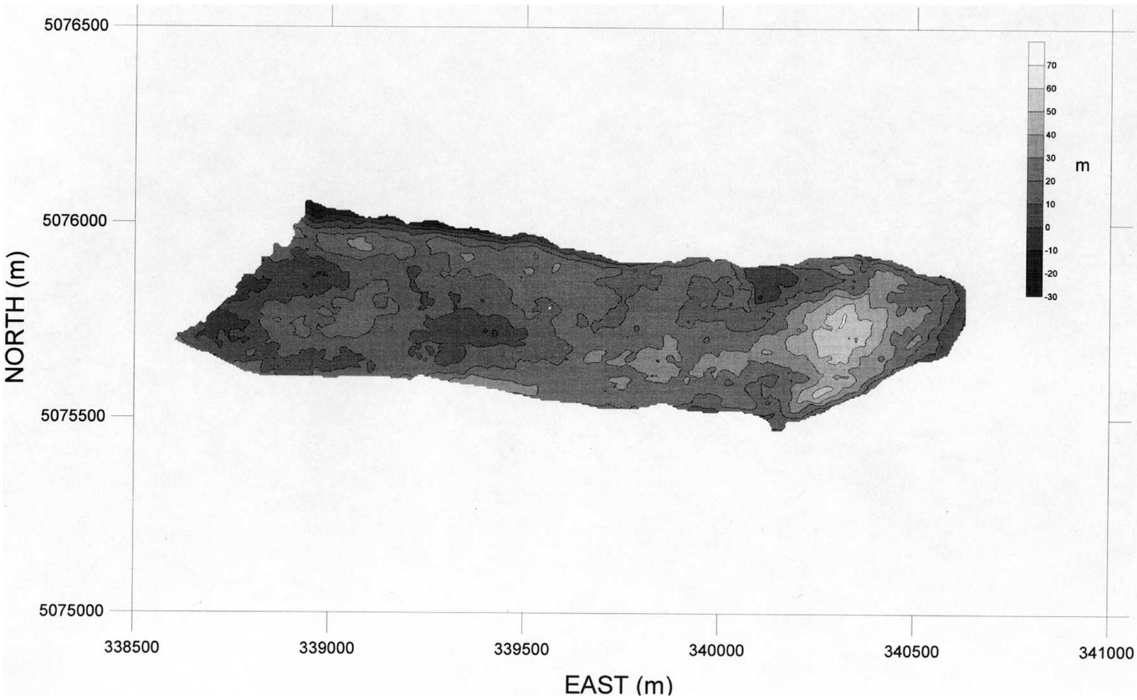

Fig. 3. Changes in surface elevation on the tongue of Brenva glacier, 1959–97.

surface, volume and thickness variations of the Brenva glacier tongue in the second half of the 20th century; (ii) to elaborate ice-thickness variation thematic maps; and (iii) to elaborate longitudinal and transverse profiles to underline thickness variations (Fox and Nuttall, 1997; Kääb, 2000; Kääb and Vollmer, 2000).

Preliminary results obtained through differential analysis show that:

from 1959 to 1971 the Brenva glacier tongue increased in volume by about $15.3 \times 10^6\,m^3$ of ice, corresponding to a mean thickness increase of 23.0 m (20.9 m w.e.), or 1.92 m a^{-1} (1.75 m w.e. a^{-1}), the largest thickness increase (40–50 m) being in the snout zone and on the medium sector of the tongue;

a volume increase ($17.8 \times 10^6\,m^3$) of the tongue was also observed between 1971 and 1983, corresponding to a total thickness increase of 22.7 m (20.6 m w.e.), or 1.89 m a^{-1} (1.72 m!w.e. a^{-1}), the largest thickness increase (50–70 m) being in the terminus zone;

from 1983 to 1991, a volume loss ($8.2 \times 10^6\,m^3$) corresponding to a thickness reduction of 11 m (10m w.e.), or 1.37 m a^{-1} (1.25 m!w.e. a^{-1}), was observed, the largest reductions (40–50 m) being in the upper and the central zone of the tongue; and

the glacier shrinkage continued in the period 1991–97, with a volume loss of $9.3 \times 10^6\,m^3$, corresponding to a thickness decrease of 11.4 m (10.4 m w.e.), or 1.9 m a^{-1} (1.7m w.e. a^{-1}), and the largest thickness reduction, 42 m, was more evident in the lower sector of the tongue.

It should be noted that the 1997 aerial photograph was acquired in October. In January 1997, a large landslide from the upper basin of Brenva glacier covered the whole tongue. The resulting granitic deposit thickness was about 1 m (Deline, 2002), which was superimposed upon the former debris cover. The above volume and thickness calculations may therefore be a slight underestimate.

Summarizing, for Brenva glacier during the second half of the 20th century (1959–97) a net volume increase of $15.6 \times 10^6\,m^3$, i.e. a thickness change of 23.3 m, or 0.41 m a^{-1} (0.37 m w.e. a^{-1}), occurred (Fig. 3). This pattern of thickness change contrasts with recorded fluctuations of non-debris-covered Italian glaciers. For instance, Lys glacier (Monte Rosa group) and Forni glacier (Ortles group), two of the widest glaciers on the south side of the Alpine chain, experienced strong thickness reduction of their tongues: from 1953 to 1994, Lys Glacier lost 15.6 m w.e. (0.38 m w.e. a^{-1}) (Rota and others, 2001), and from 1953 to 1988 Forni Glacier lost 21.8 m w.e. (0.48 m w.e. a^{-1}) (Merli and others, 2001).

The Brenva glacier tongue exhibited two main phases during the second half of the 20th century: a strong positive pattern of volume and thickness change between 1959 and 1983, and a less strong negative pattern between 1983 and 1999. The first phase may be explained by a drop in summer temperature (between 1951 and 1960 the temperature was 0.65C lower at Courmayeur, close to the glacier, than the 1936–83 mean), accompanied by increased annual precipitation. This climatic pattern caused a reduction in the ablation of Monte Bianco glaciers, resulting in their expansion during the 1962–89 period (Cerutti, 1993). Furthermore the trend was widespread throughout the Alps (Wood, 1988). The second phase was triggered by climate warming after 1985, accompanied by reduced precipitation, causing negative glacier surface mass balance.

Earlier Brenva glacier results are comparable with the general trend of the 'clean' Italian glaciers (they also registered a phase of positive mass balance), but the recent behaviour of the glacier is very different. In fact, at the end of the 20th century, Brenva glacier and other debris-covered glaciers such as Miage and Belvedere (Smiraglia and others, 2000; Diolaiuti and others, 2003) showed a net positive balance because of the debris insulation effect, allowing more ice at the lower tongue of the glacier to be conserved.

ACKNOWLEDGEMENTS

The authors thank D. Muzzu Martis who helped collect and elaborate the data and maps. This work was conducted as part of the 2003 Ministero Istruzione, Universitá, Ricerca (MIUR) project 'The present transformations of the Italian Alps glaciers'.

Carlo D'AGATA
Claudio SMIRAGLIA
Department of Earth Sciences 'Ardito Desio',
University of Milan, Via Mangiagalli 34,
I-20133 Milan, Italy
E-mail: claudio.smiraglia@unimi.it

ANTONIO ZANUTTA
FRANCESCO MANCINI
Engineering Faculty, DISTART
University of Bologna, Viale Risorgimento 2,
I-40136 Bologna, Italy
15 January 2005

REFERENCES

Alifoto. 1972. *1:5000 map from 1971 aerial photogrammetry.* (Scale 1 : 5000.) Bollettino del Comitato Glaciologico Italiano.

(Author: what is this a map of? Please supply more details.)

Cerutti, A. V. 1993. L'espansione dei ghiacciai italiani del Monte Bianco fra il 1962 e il 1989. *Geogr. Fis. Din. Quat.,* **15**(1–2), [1992], 67–74.

Deline, P. 2002. Etude géomorphologique des interations écroulements rocheux/glaciers dans la haute montagne alpine (versant sud-est du massif du Mont Blanc). (Thèsis de doctorat de gèographie, Universitè de Savoie.)

(AUTHOR: how many pages in thesis?)

Diolaiuti, G., C. D'Agata and C. Smiraglia. 2003. Belvedere Glacier, Monte Rosa, Italian Alps: tongue thickness and volume variations in the second half of the 20th century. *Arct. Antarct. Alp. Res.,* **35**(2), 255–263.

EIRA (Ente Italiano Rilievi Aerofotogrammetrici). 1972. *1:5000 map from 1959 terrestrial photogrammetric survey.* (Scale 1 : 5000.) Bollettino del Comitato Glaciologico Italiano.

(AUTHOR: What is this a map of?)

Fox, A. J. and A.-M. Nuttall. 1997. Photogrammetry as a research tool for glaciology. *Photogramm. Rec.,* **15**(89), 725–737.

Kääb, A. 2000. Photogrammetric reconstruction of glacier mass balance using a kinematic ice-flow model: a 20 year time series on Grubengletscher, Swiss Alps. *Ann. Glaciol.,* **31**, 45–52.

Kääb, A. and M. Vollmer. 2000. Surface geometry, thickness changes and flow fields on permafrost streams: automatic extraction by digital image analysis. *Permafrost and Periglacial Processes,* **11**(4), 315–326.

Kirkbride, M. P. and C. R. Warren. 1999. Tasman Glacier, New Zealand: 20th-century thinning and predicted calving retreat. *Global Planet. Change,* **22**(1–4), 11–28.

Merli, F., M. Pavan, G. C. Rossi, C. Smiraglia, A. Tamburini and G. Ubiali. 2001. Variazioni di spessore di voluma della lingua del Ghiacciaio dei Formi (Alpi Centrali, Gruppo Ortles-Cevedale) nel XX secolo. Risultati e confronti di metodologie. *Supp. Geogr. Fis. Din. Quat.,* **5**, 121–128.

(AUTHOR: please provide an English translation of the title. Please fax us a copy of the cover of the publication.)

Moribayashi, S. and K. Higuchi. 1977. Characteristics of glaciers in Khumbu region and their recent variations. *Seppyo,* **39**, Special Issue, 3–6.

Nakawo, M., C. F. Raymond and A. Fountain. 2000. Preface. *In* Nakawo, M., C. F. Raymond and A. Fountain, *eds. Debris-covered glaciers.* Seattle, IASH Press, (International Association of Hydrological Sciences Publication 264.)

Orombelli, G. and S. Porter. 1982. Late Holocene fluctuations of Brenva glacier. *Geogr. Fis. Din. Quat.,* **5**(1), 14–37.

???Regione Valle d'Aosta. 1988. *Regional Technical Map 1:10000 from 1983 aerial photogrammetric survey.* (Scale 1 : 10000.) ** name of map publisher **. (Regione Valle d'Aosta ** map number **)

(AUTHOR: please supply more details about map. Is there a proper author name we can use instead of the region mapped?)

???Regione Valle d'Aosta. 1999. *Regional Technical Map 1:10000 from 1991 aerial photogrammetric survey.* (Scale 1 : 10000.) ** name of map publisher **. (Regione Valle d'Aosta ** map number **)

(AUTHOR: please supply more details about map. Is there a proper author name?)

Rota, T., E. Bonacina, P. De Lotto, G. C. Rossi and C. Smiraglia. 2001. Variazioni volumetriche della lingua del Ghiacciaio dei Lys (Monte Rosa, Valle d'Aosta) nel XX secolo. *Supp.Geogr.Fis. Din. Quat.,* **5**, 183–185.

(AUTHOR: please provide an English translation of the title. Please fax us a copy of the cover of the publication.)

Smiraglia, C., G. Diolaiuti, D. Casati and M. P. Kirkbride. 2000. Recent areal and altimetric variations of Miage Glacier (Monte Bianco massif, Italian Alps). *IAHS Publication* 264 (Symposium at Seattle 2000 — *Debris-Covered Glaciers*), 227–233.

Wood, F. B. 1988. Global alpine glacier trends, 1960s to 1980s. *Arct. Alp. Res.,* **20**(4), 404–413.