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NEW EVIDENCE FROM ITALY (ADAMELLO GROUP, LOMBARDY) FOR ANALYSING THE ONGOING DECLINE OF ALPINE GLACIERS

ABSTRACT: MARAGNO D., DIOLAIUTI G., D'AGATA C., MIHALCEA C., BOCCHIOLA D., BIANCHI JANETTI E., RICCARDI A. & SMIRAGLIA C., *New evidence from Italy (Adamello Group, Lombardy) for analysing the ongoing decline of Alpine glaciers*. (IT ISSN 0391-9838, 2009).

Glaciers worldwide are showing overwhelming evidence of the impact of climatic change. In the Alpine region the warming experienced since the early 1980s, while synchronous with warming at the global scale, is of a far greater amplitude and exceeds 1 °C, which represents roughly a three-fold amplification of the global climate signal.

To evaluate the magnitude of climate change impacts, recent data covering large and representative areas are needed. This paper is aimed at contributing to describe the recent evolution of Alpine glaciers by analysing surface area changes in a representative subset of data (34 glaciers located in the Adamello Group, Lombardy, Italy).

Four surface area records, for the years 1983, 1991, 1999 and 2003, were analysed. The 1983, 1999 and 2003 surface area records were compiled by the authors by combining aerial photo analysis, Differential Global Positioning System (DGPS) surveys of glaciers and Geographic Information System (GIS) data processing. The analysis led to a quantification of surface reduction: c. 19% from 1983 to 2003 for glaciers in the Adamello group.

Small glaciers proved to contribute strongly to total area loss: in 2003, 31 glaciers (c. 91% of the total number) were smaller than 1 km^2, covering 2.28 km^2 (c. 10% of the total area), but accounted for 39% of the total loss in area (losing 2.05 km^2 from 1983 to 2003). The rate of area change accelerated in the later period, with surface reduction between 1999 and 2003 amounting to c. 5.5% (with respect to the 1999 total glacier coverage), equal to a mean area loss of c. 0.34 km^2/year; the mean yearly loss over the previous period (1991-1999) was found equal to 0.23 km^2/year. This acceleration coincided with a clear local warming and a small local decrease in snow cover depth and duration which resulted strongly related to North Atlantic Oscillation (NAO) winter variability.

KEY WORDS: Glacier shrinkage, Climate change impacts, Italian Alps.

RIASSUNTO: MARAGNO D., DIOLAIUTI G., D'AGATA C., MIHALCEA C., BOCCHIOLA D., BIANCHI JANETTI E., RICCARDI A. & SMIRAGLIA C., *Nuovi dati italiani (Gruppo dell'Adamello, Lombardia) per analizzare il ritiro in atto dei ghiacciai alpini*. (IT ISSN 0391-9838, 2009).

I ghiacciai dell'intero pianeta stanno mostrando ampie evidenze degli impatti del Cambiamento Climatico. Nella regione alpina il riscaldamento registrato sin dai primi anni 80 (del XX secolo), sebbene sia avvenuto in sincronia con quello manifestatosi a scala globale, è stato di maggiore intensità ed ha anche superato 1°C, valore che rappresenta un'amplificazione circa tripla del segnale climatico globale.

Al fine di valutare l'intensità degli impatti del Cambiamento Climatico sono necessari dati recenti relativi ad aree estese e rappresentative. Questo articolo è finalizzato a contribuire alla conoscenza dell'evoluzione recente dei ghiacciai alpini attraverso l'analisi delle variazioni areali di un campione rappresentativo di ghiacciai (34 apparati localizzati nel Gruppo dell'Adamello, Lombardia, Italia).

A questo scopo sono state analizzate quattro serie di dati areali (relative agli anni 1983, 1992, 1999 e 2003). Le superfici del 1983, 1999 e 2003 sono state ottenute dagli autori del presente contributo analizzando sia fotogrammi aerei che dati rilevati sul terreno con tecnica GPS differenziale (Differential Global Positioning System) ed integrando ed elaborando tutte le informazioni in ambiente GIS (Geographic Information System). L'analisi condotta ha permesso di quantificare una riduzione areale dei ghiacciai dell'Adamello di circa il 19% tra il 1983 e il 2003.

I ghiacciai di minori dimensioni sono risultati tra i maggiori responsabili della perdita areale totale: i 31 ghiacciai che nel 2003 (pari a c. il 91% del numero totale) risultavano più piccoli di 1 km^2 e si estendevano in totale per 2,28 km^2 (circa il 10% dell'area totale) hanno portato a perdite areali per circa il 39% (pari –2,05 km^2). Il ritiro areale ha visto nell'ultimo periodo un'intensa accelerazione: la riduzione di superficie glaciale tra il 1999 ed il 2003 assomma a c. il 5,5% (calcolato rispetto al-

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l'estensione glaciale del 1999), pari ad una perdita areale media di c. 0,34 km^2/anno; la perdita media annua calcolata per il periodo precedente (1992-1999) era di c. 0,26 km^2/anno. Questa accelerazione è avvenuta in coincidenza con un evidente riscaldamento climatico locale e con un modesto decremento locale nello spessore e nella durata del manto nevoso risultati in forte correlazione con la variabilità invernale della North Atlantic Oscillation (NAO).

TERMINI CHIAVE: Riduzione dei ghiacciai, Impatti del Cambiamento Climatico, Alpi Italiane.

INTRODUCTION

The worldwide retreat of glaciers from Alpine areas (Haeberli & Beniston, 1998) to Antarctica (Rott & *alii*, 1996; Cook & *alii*, 2005), during the last few decades, is frequently mentioned as a clear and unambiguous sign of global warming (Oerlemans, 2005; IPCC, 2007).

Atmospheric warming in the Alps has been found to be stronger and clearer in comparison to other sites (Böhm & *alii,* 2001), with significant summer warming, which has been particularly severe since 1970 (Casty & *alii*, 2005).

As a result of this rapid climate evolution, many small glaciers (i.e., glaciers with a surface area < 1 km^2) located at mid elevation could disappear in the next few decades (Zemp & *alii*, 2006). These small glaciers are common in the Alps, where they represent 80% of the total glacial number and constitute an important contribution to water resources (Oerlemans & Fortuin 1992) (See also the alone Apenninic Glacier, Ghiacciaio del Calderone, Pecci & *alii*, 2008).

The rapid shrinkage of Alpine glaciers has already been noted and discussed in an analysis of the Swiss Glacier Inventory of 2000 by Paul & *alii* (2004). According to this study, 44% of the area loss between 1973 and 1998/1999 refers to glaciers with lengths of less than 1 km and covering only 18% of the total area in 1973 (Paul & *alii*, 2004). Citterio & *alii*, 2007, reported analogous results by analysing Lombardy glaciers in the 1991-1999 period. Therefore small glaciers are showing a higher sensitivity than larger ones, due to their very rapid *reaction time* (*sensu* Haeberli & Hoelzle, 1995) and are therefore suitable sites for the assessment and monitoring of climate change impacts (Dyurgerov & Meier, 2000).

Various types of studies can be performed to analyze the ongoing evolution of glaciers, including the data collection and analysis of parameters typically considered in glacier inventories (e.g. glacier area), which can be used to investigate mountain glaciers in a changing climate (Paul & *alii*, 2004), and potential scenarios on the regional Alpine scale (Zemp & *alii*, 2006). Comparison of various glacier inventories makes it possible to draw a general picture of the changes that have taken place in a glacier region in the past decades. Repeated glacier inventories should be carried out at intervals that are compatible with the characteristic dynamic response times of mountain glaciers (a few decades or less in the case of small glaciers). However, the current glacier down-wasting observed in several mountain areas probably calls for more updates of inventories at shorter time intervals (Paul & *alii*, 2007). A recent and updated glacier inventory covering the whole glacierized area of the Italian Alps is lacking; the last inventory dates back to 1989 (Biancotti & Motta, 2000) and enables comparison only with the previous one (CNR-CGI, 1961).

In this paper, in order to contribute to the knowledge of the recent changes affecting Italian glaciers, surface area changes of a representative subset of data (34 glaciers located in Adamello Group, Lombardy) were calculated and analyzed. Four area records (1983, 1991, 1999 and 2003) were available for this study, thus allowing quantification of not only glacier changes, but also variations of their rates over time so as to look for any increasing-decreasing trend.

In addition, in this contribution attention is paid to local climate trends and their relations with the global tendency in order to look for evidence of climate changes and, if any, to evaluate their magnitude.

STUDY AREA

The Adamello Group represents an important glaciarized subregion (c. 24.6% of Lombardy glacier coverage is located here) that can be considered representative of Italian glaciation (fig. 1). In fact, not only it includes Italy's largest glacier (i.e., Adamello Glacier, with an area of about 18 km^2), but also many medium and small glaciers with a wide range of settings, aspects, altitudes and surface slopes. In the Adamello group the main glacier type is the *mountain* glacier, representing 80% of the total number. The Adamello area represents an important study site and previous authors completed several studies deepening on understanding of the relations among geomorphological evidences and glacier variations (among others Baroni & Carton, 1987).

DATA SOURCES AND METHODS

Four surface area records, dated 1983, 1991, 1999 and 2003, are available for the Adamello glaciers. We compiled the 1983, 1999 and 2003 records by defining glacier outlines on colour aerial photographs (1983, 1999 and 2003 flights) and reporting them in a GIS environment. The 1991 data base, instead, was compiled by previous authors (SGL, 1992).

As regards the 1983 area record, it was obtained by analysing with an optical stereoscopic system the 1983 aerial photos (at a scale of c. 1:20,000) to obtain a 3D view of the glacierized area. Then the glacier limits observed on the photos were reported as polygons in a GIS environment. The 1:10,000 scale Technical Regional Map (CTR) of Lombardy Region was used as raster base. The topographic data reported in the CTR are referred to the same period as the aerial photos (1983), thus enabling evaluation of the reliability and accuracy of our findings. The planimetric accuracy of the 1983 source of data was found equal to ± 5 m. The 1999 and 2003 records, instead, were obtained by combining glacier outlines manually

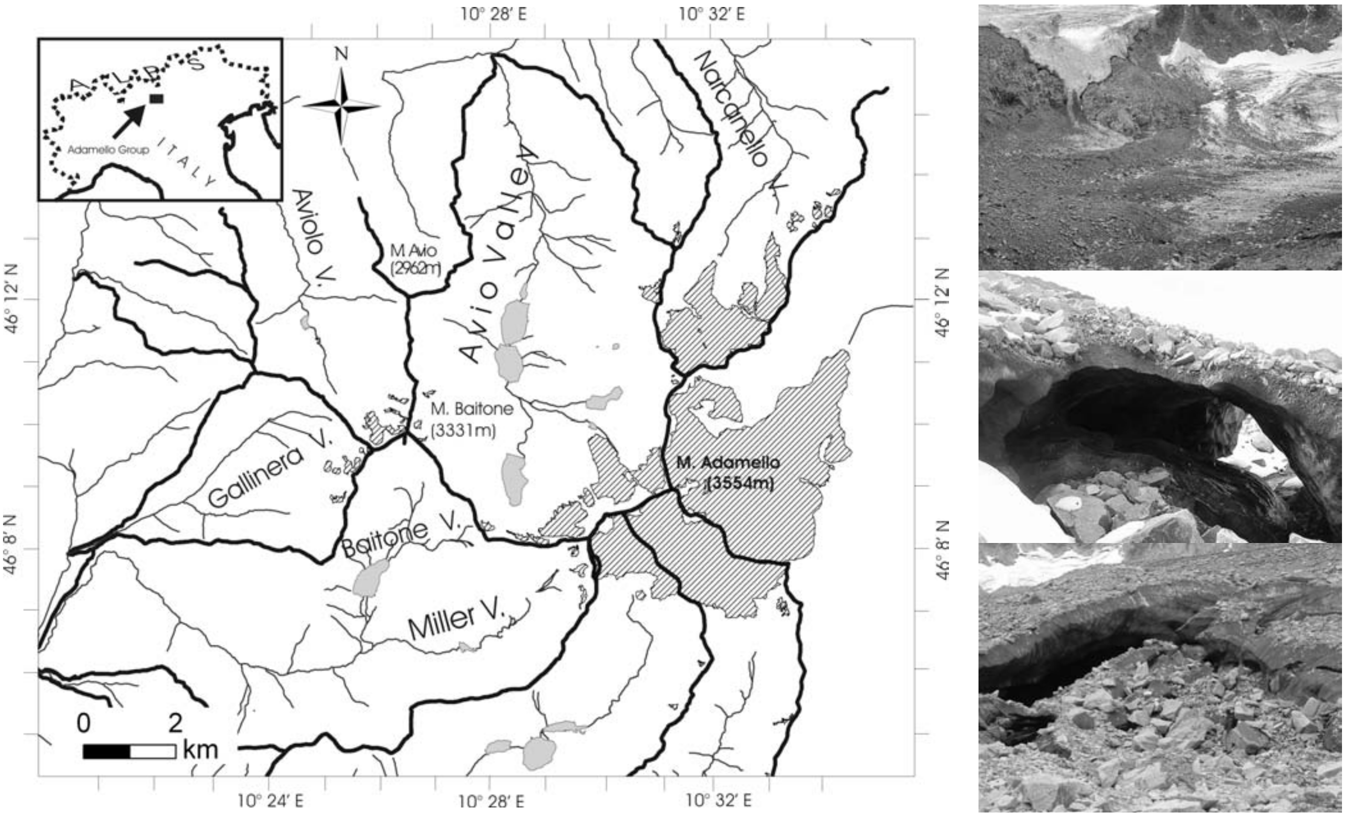

FIG.1 - Upper: location map of Adamello glaciers (shaded areas on the map). Lower: photos presenting changes in the morphology of glaciers (glacier fragmentation, ice collapses, increasing supraglacial debris).

digitized on registered colour orthophotos (1999 and 2003 flights - Compagnia Generale Riprese Aeree - CGR) and Differential Global Positioning System (DGPS) field surveys of glaciers. The orthophotos used as the base layer for delimiting the 1999 and 2003 glacier boundaries are standard commercial products (made purchasable by CGR) with a planimetric resolution specified as 1 pixel of variable size; the pixel size was equal to 1 m for the 1999 photos and equal to 0.5 m for the 2003 images. The planimetric accuracy stated by the manufacturer is equal to ± 2 m for the 1999 images and ± 1 m for the 2003 data. We delimited the 1999 and 2003 glacier boundaries as polygons by using the orthophotos as base layer in a GIS environment. Regarding the 1999 orthophotos, in several cases we also referred to glacier boundaries determined in the field through DGPS campaigns (in the manner explained by Diolaiuti & *alii*, 2004). The planimetric accuracy of the glacier limits evaluated through DGPS measurements was equal to ± 1 m. As regards the 2003 images, due to the particular weather conditions prevailing in the Alps during the summer of 2003 (i.e., almost total absence of snow cover up to the highest glacier elevations), there was no need to refer to other sources (such as DGPS field data) to mark the glacier boundaries.

The final planimetric precision value was then evaluated according to Vögtle & Schilling (1999), considering both source-related uncertainty (analysis of aerial photos by optical stereoscopic system, orthophotos and/or DGPS surveys) and the clarity of the glacier limits. The area precision for each glacier (for 1983, 1999 and 2003 data) was evaluated by buffering the glacier perimeter considering the area uncertainty. The final precision values for the whole regional glacier coverage were determined by taking the root of the squared sum of all the buffer areas. The 1991 area data were already available in a published regional inventory (Servizio Glaciologico Lombardo, SGL, 1992). As the authors of that previous inventory did not declare an accuracy value, the final accuracy of this record of data was considered equal to the resolution of the map they produced (all the glaciers were represented on a 1:10,000 scale map with a nominal map reading error of 2 m).

Area changes were analyzed by first classifying the Lombardy glaciers according to the following size classes: < 0.10 km^2, 0.10-0.5 km^2, 0.5-1 km^2, 1-2 km^2, 2-5 km^2, 5-10 km^2 and >10 km^2. These size classes are the same as those applied in a previous study (Citterio & *alii*, 2007) that dealt with Lombardy glacier changes in the 1991-1999 period; in addition, the same classes were initially introduced by Paul & *alii*, 2004 for Swiss glaciers, thus also permitting a comparison of the results of both studies.

In addition, the meteorological data from the closest weather stations (WSs) were analyzed to look for rela-

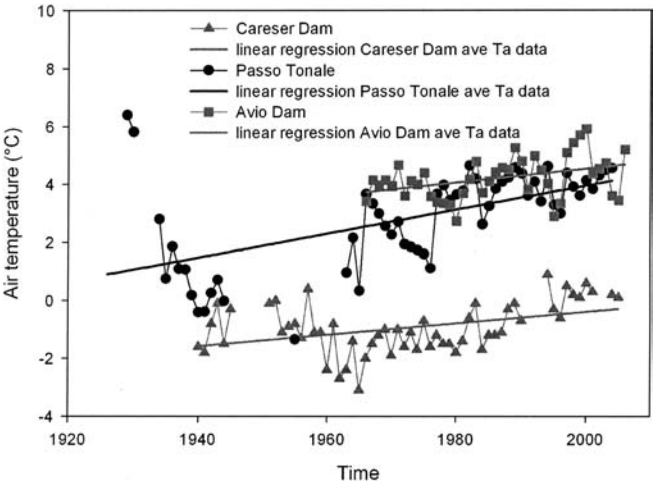

FIG. 2 - Air temperature trends at the three analysed WSs. Yearly average values are plotted.

TABLE 1 - Numerical distribution of the 34 analysed glaciers respect to the 7 size-classes

Size class (km^2)	1983 Glacier number	1991 Glacier number	1999 Glacier number	2003 Glacier number
< 0.1	21	25	27	27
0.1 - 0.5	8	4	2	3
0.5 - 1.0	2	2	2	1
1.0 - 2.0	1	1	1	1
2.0 - 5.0	1	1	1	1
5.0 - 10	0	0	0	0
> 10	1	1	1	1
Total	34	34	34	34

tions with the glaciological results. Then precipitation and temperature data from one Lombardy WS (Avio Dam, 1860 m a.s.l.), and from two WSs in Trentino (Passo Tonale, 1795 m a.s.l. and Careser Dam, 2600 m a.sl.) were considered.

Avio Dam WS has been running since 1966; Careser Dam from 1930 for precipitation and from 1940 for air temperature; Passo Tonale from 1923 for precipitation and from 1926 for air temperature.

We processed the data to detect any trends and the occurrence of minima and/or maxima. In addition, comparisons among our data and a global index (i.e.: North Atlantic Oscillation - NAO Index) were performed.

RESULTS

The Adamello glacier records describe 48 glaciers in 1983, 44 glaciers in 1991 (4 resulted to be extinct), 38 in 1999 (6 glaciers disappeared) and 44 in 2003. This numerical increase is due to fragmentation of previous larger glaciers which gave origin to newly formed smaller ones. In 2003, in fact, all the glaciers mapped on 1999 orthophotos were surveyed and, in addition, 4 glaciers showed fragmentation evidences: Pisgana Occidentale, Avio Centrale and Cima Laste Nord were divided each into two ice bodies, while Buciaga glacier was separated into 4 smaller glacier areas, and then from these fragmentations 6 new glaciers were mapped.

Thirty-four (34) glaciers were recorded in all four data series (1983, 1991, 1999 and 2003), representing 97.9% of the 2003 sample, and the respective data were analyzed with respect to the 1983-1991, 1991-1999, 1999-2003 and 1983-2003 time windows. The changes were calculated by comparing the area coverage for each area class (e.g. 2003 area coverage for the <0.1 km^2 size class minus 1983 area coverage for the <0.1 km^2 size class).

As can be noted from columns 2, 3, 4 and 5 in tab. 1, several glaciers have shifted from the larger size classes to the smaller ones. In order to avoid inconsistencies such as the apparent area gain for those classes that acquired more glaciers from the larger classes than they lost to smaller classes, columns 2-9 of tab. 2 were obtained by crediting the contribution of each glacier according to the class it belonged to in 1983. Thus the evaluations of area changes were not affected by class shifts.

In 2003, considering the 34 glaciers common to the four inventories, the Adamello glacier resource covered an area of 22.99 km^2 (± 0.02 km^2). In 1999 the same 34 glaciers covered 24.34 km^2 (± 0.04 km^2), in 1991 they were spread over a surface of 26.17 km^2 (±0.10 km^2). Instead in 1983 they covered 28.28 km^2 (±0.12 km^2). The area change over the period 1983-2003 was found equal to -5.29 km^2 (±0.12 km^2), which corresponds to a loss of 18.7% of the 1983 glacier coverage.

From tab. 3 it resulted that in the period 1983-2003 glaciers smaller than 0.1 km^2 were reduced by c. 57.9% of the area they covered in 1983. On the other hand this strong decrease contributed by only 12.7% to the whole glacier area loss. The Adamello Glacier, the largest Italian one and the only glacier of the Adamello Group belonging to the size class «>10 km^2» had lost in the 1983-2003 period 11.6% of its initial area although it contributed to 41.4% of the total area loss. The contribution to the total area loss given by glaciers belonging to the size classes minor than 1 km^2 during the period 1983-1991 resulted major than the one due to glaciers classified into the two largest classes (i.e.: 5-10 and >10 km^2); in the last period (1999-2003), instead, the larger part of the glacier area loss was mainly due to the area changes of the largest glacier (i.e.: Adamello, >10 km^2 of area).

Initially the smallest glaciers resulted to be the most rapid in starting the decreasing phase. Nevertheless, after some years also the largest glaciers showed strong climate change impacts and at the present time they are the major contributors to the total glacier area loss. This evidence is surely due to the different *reaction times* characterizing each glacier size-class. In addition the ongoing glacier morphological evolution (e.g. growing rock outcrops, tongue separa-

TABLE 2 - Area coverage and area changes of the 34 analysed glaciers with respect to the 7 size- classes

Size Class (km^2)	Area 1983 (km^2)	Area 1991 (km^2)	Area 1999 (km^2)	Area 2003 (km^2)	ΔA '83-'91 (km^2)	ΔA '91-'99 (km^2)	ΔA '99-'03 (km^2)	ΔA '83-'03 (km^2)	Mean reduction (km^2/year) '83 - '91	Mean reduction (km^2/year) '91 - '99	Mean reduction (km^2/year) '99 - '03	Mean reduction (km^2/year) '83 - '03
< 0.1	1.16	0.73	0.54	0.49	-0.43	-0.18	-0.05	-0.67	-0.05	-0.02	-0.01	-0.03
0.1-0.5	1.55	1.08	0.71	0.61	-0.47	-0.37	-0.10	-0.94	-0.06	-0.05	-0.03	-0.05
0.5-1.0	1.63	1.58	1.36	1.18	-0.05	-0.22	-0.18	-0.44	-0.01	-0.03	-0.05	-0.02
1.0-2.0	1.68	1.43	1.34	1.25	-0.25	-0.08	-0.09	-0.42	-0.03	-0.01	-0.02	-0.02
2.0-5.0	3.41	3.23	3.03	2.80	-0.18	-0.20	-0.23	-0.62	-0.02	-0.03	-0.06	-0.03
5.0-10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
> 10	18.85	18.13	17.36	16.66	-0.72	-0.77	-0.69	-2.19	-0.09	-0.10	-0.17	-0.11
Total	28.28	26.17	24.34	22.99	-2.11	-1.83	-1.35	-5.29	-0.26	-0.23	-0.34	-0.26

TABLE 3 - Area changes of the 34 analysed glaciers sorted by the 7 size- classes calculated as percentage with respect to the initial size class coverage (columns 2,4,6,8) and as a percentage with respect to the total area loss occurring in the whole glacier sample (columns 3,5,7 and 9)

Size Class (km^2)	1983-2003 ΔA (%) respect to size class coverage	1983-2003 ΔA (%) respect to total area loss	1983-1991 ΔA (%) respect to size class coverage	1983-1991 ΔA (%) respect to total area loss	1991-1999 ΔA (%) respect to size class coverage	1991-1999 ΔA (%) respect to total area loss	1999-2003 ΔA (%) respect to size class coverage	1999-2003 ΔA (%) respect to total area loss
< 0.1	-57.9	12.7	-37.4	20.5	-25.3	10.1	-10	4.0
0.1 - 0.5	-60.7	17.8	-30.5	22.5	-34.1	20.2	-14.1	7.4
0.5 - 1.0	-27.2	8.4	-2.8	2.2	-13.7	11.8	-13.2	13.4
1.0 - 2.0	-25.3	8.0	-15.0	11.9	-5.8	4.5	-6.8	6.8
2.0 - 5.0	-18.1	11.7	-5.4	8.7	-6.2	11.0	-7.7	17.3
5.0 - 10	0	0	0	0	0	0	0	0
> 10	-11.6	41.4	-3.8	34.2	-4.3	42.4	-4.0	51.1
Total	-18.7	100	-7.5	100	-7	100	-5.6	100

tions, formation of pro-glacial lakes, increasing supraglacial debris and collapse structures, downwasting processes) and the subsequent positive feedbacks (albedo lowering, increasing long wave radiation from rock outcrops, heat storage due to supraglacial water ponds) affecting most alpine glaciers have been driving the strong shrinkage of recent years.

In order to improve our understanding of the glacier changes and to look for relations with local and global climate, a meteorological analysis was performed.

In this study we chose to evaluate the magnitude of local climate changes. For this purpose we considered meteo data collected at the closest weather stations running for long periods.

The air temperature data registered at the three WSs show a clear increasing trend; Careser WS presents the lowest temperature due to its highest elevation while Passo Tonale WS registered cooler values than Avio Dam despite its lower position and this is probably due to the different geographical locations (i.e.: aspect and expositions).

Mean annual air temperature at the Avio Dam WS in the period 1966-2006 was +4.18 °C. Considering the time window of our glacier analysis, 1983-2003, the yearly average proved to be higher, i.e. +4.53°C, thus highlighting a mean increase of c. 0.34°C.

During the period 1940-2005 Careser WS acquired a mean annual air temperature of –0.95 °C; while in the period 1983-2003 the mean annual air temperature was –0.30 °C, this also outlining a mean increase of 0.65 °C.

Analysing the Passo Tonale WS data for the period 1929-2004, a mean annual air temperature of 2.8 °C was calculated. The mean annual air temperature for the time spam of our glacier analysis, 1983-2003, resulted of 3.88 °C and therefore the mean increase is of 1.08 °C.

Considering the most recent period we analysed regarding glacier surface changes, the time frame from 1999 to 2003, the temperature average at the Avio WS proved to be +5.04°C (mean increase respect to 1966-2006 average, +0.85°C). For the same period, Careser WS and Passo Tonale WS data were analysed and the mean annual air temperatures were 0.31 °C (mean increase of +1.26 °C) for Careser and 4.06 °C (mean increase of 1.25 °C) for Passo Tonale WSs. This warming registered at all three WSs, while synchronous with the one at the global scale, is of far greater amplitude and represents roughly a three-fold amplification of the global climate signal. This is in agreement with the general temperature increase affecting the Alps reported by other authors (Böhm & *alii*, 2001; Diaz & Bradley, 1997).

Concerning precipitation, the winter data (obtained by adding the DJF mean values reported as mm water equivalent, w.e.) from the Careser Dam and the Passo del Tonale WSs were considered. For Avio Dam snow depth data (reported in m w.e.) were collected by the dam surveyors, so that for this station snow depth values were analysed.

The winter precipitation data from Careser Dam and Passo del Tonale WSs showed no trends over the whole period (1930-2005 for Careser Dam and 1924-2004 for Passo del Tonale), differently a clear decreasing trend is found by analyzing the last 30 years data of both the WSs (see the linear regressions in fig. 3). Regarding the snow depth measurements performed at Avio Dam WS (fig. 4) there has been a marked decrease in total depth of winter snow (about –11.4% in the period 1999-2003 with respect to the 1966-2006 average). This decrease showed higher magnitude if we consider the most recent data (1999-2006) which are characterized by a snow depth decline of c. –16% (respect to the 1966-2006 mean). The decrease in

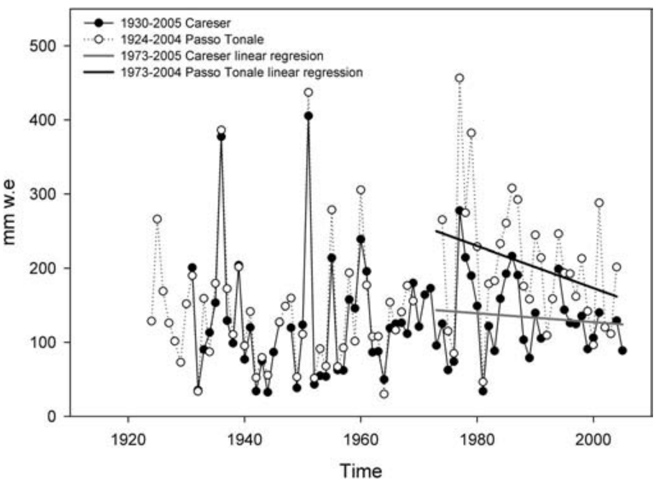

FIG. 3 - Winter precipitation trends and their regression lines (these latter calculated over the last 30 years) at the Careser Dam and the Passo Tonale WSs.

winter precipitations and in snow depth may be partially due to North Atlantic Oscillation (NAO) variability. During the last decade of the 20th century, in fact, persistently positive values of the NAO index were observed. The NAO index is based on the pressure difference between the Azores and Iceland and it is an indirect measure of the intensity of the general atmospheric circulation over the North Atlantic; its behavior can account for over 60% of the variability of climate in both the eastern third of North America and a large part of western and central Europe (Hurrell, 1995). When the NAO index is high, the alpine climate tends to respond through lower-than-average precipitation and higher-than-average temperatures. Concerning snow accumulation, the NAO effect is appreciable in fig. 5 where the NAO Index calculated for the January - February - March (JFM, black line, data by Jones & *alii*, 1997; Osborn, 2004; 2006) period during the time frame 1966-2006 is compared with the snow depth data (grey bars, values in m w.e.) displaying a clear relationship (r=–0.51): positive JFM NAO values match with lower snow depths, negative JFM NAO data match with higher snow values.

The NAO data are correlated (r=+0.52) also with the temperature of the snow period (JFM as we considered for snow data) as shown in fig. 6. There, we analysed the JFM NAO Index (black line, data by Jones & *alii*, 1997; Osborn, 2004; 2006) and the Avio Dam temperature anomalies during JFM computed as the difference between JFM yearly mean temperatures and the yearly average of these three months for the 1966-2006 period. It appears that during periods of high NAO index there resulted generally higher values of JFM anomalies, thus enhancing the potential for early snowmelt. The frequency of higher positive temperature anomalies in the period JFM increased during the nineties of the 20th century and the 1998-2002 period with a possible contribution of early snow melt to the acceleration of glacier decline.

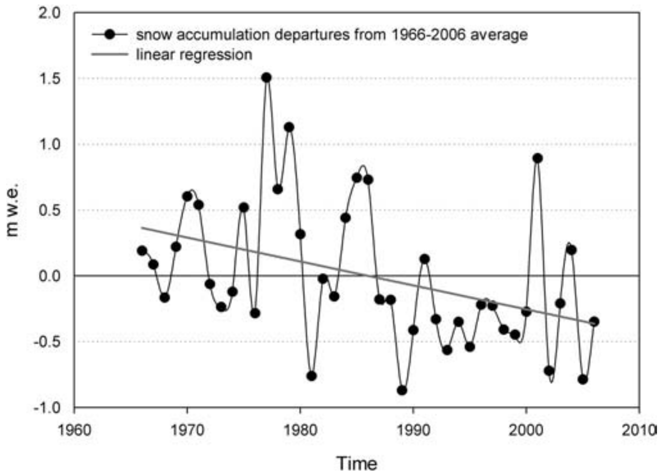

FIG.4 - Snow depth departures (m w.e.) from the 1966-2006 mean value in Avio Dam. The grey line shows the linear regression.

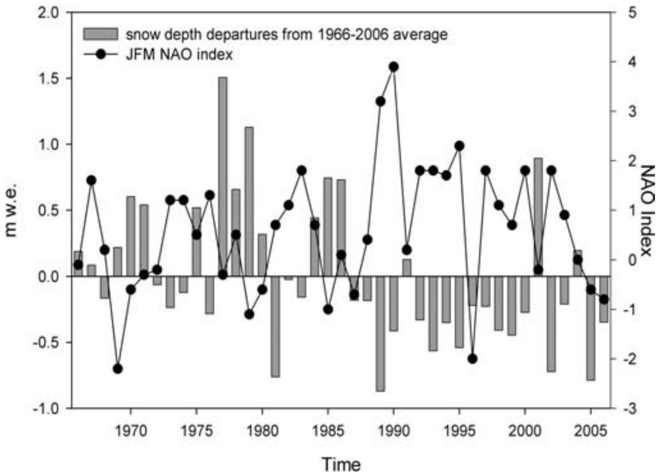

FIG. 5 - Snow data from Avio Dam WS (values in m w.e., grey bars) and NAO Index values calculated for the JFM period (black line).

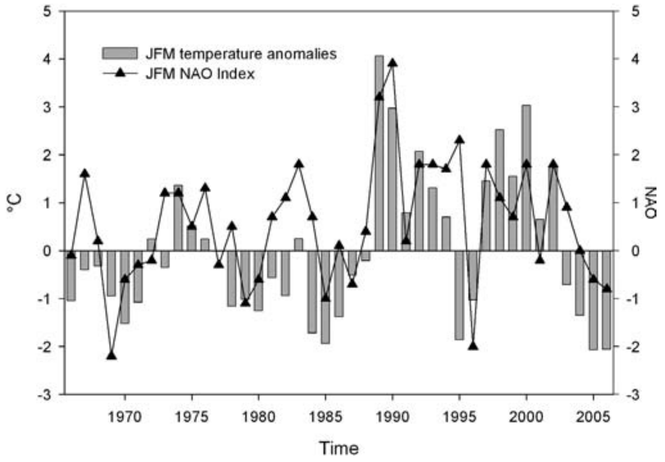

FIG. 6 - JFM temperature anomalies from Avio Dam WS (values in °C, grey bars) and NAO Index calculated for the period JFM (black line).

According to Beniston & Jungo (2002) the bias imposed by the highly positive NAO index on temperatures has been shown to exceed 1°C for minimum temperatures, then our findings agree with the general Alpine trend

DISCUSSION

The strong surface reduction we found indicates an accelerated shrinkage of the glacier-covered area. In fact, the analysis of the most recent orthophotos, which were acquired during the summer of 2003 under exceptional conditions (i.e., total absence of snow cover thus permitting a better analysis of the glacier surface), allowed observation and mapping of glacier changes affecting not only their size, but also their shape and morphology, including growing rock outcrops, tongue separations, formation of proglacial lakes, increasing supraglacial debris and collapse structures. These phenomena are related to positive feedbacks that accelerate further glacier disintegration once it is initiated (fig. 1). Paul & *alii*, 2007 report a similar trend for Swiss glaciers. Moreover, if we compare the mean area loss witnessed by the Adamello glaciers over the 1983-2003 period (c. –19%, roughly –10% per decade) with the area loss experienced by Alpine glaciers in the 1850-1973 period at ten-year intervals (–2.2% reported by Paul & *alii*, 2007), the former show a loss that is five times greater than the latter.

The surface area changes point towards strong glacier reduction, which is generally interpreted as a truthful indicator of the impact of climate change. In addition, as the transfer function among climate changes and glacier variations does not change in time (Oerlemans, 2005), stronger glacier changes suggest a similar climatic behaviour.

Concerning the climate, Beniston (2000) summarized the 20th century trends. He concludes that, during the 20th century, climate change in the Alpine region was characterized by increases in minimum temperatures of over 2°C in some locations, by a more modest increase in maximum temperatures, with the exception of the sudden jump in maxima resulting from the 2003 heat wave that affected much of western and central Europe, and by little trends in the average precipitation data. Several periods of warming are observed during the instrumental record, with the 1940s exhibiting a particularly strong warming and then a cooling in the 1950s, probably associated with changes of solar energy fluxes (Friis-Christensen & Lassen, 1991). The most intense warming occurs in the 1990s; however this behavior can be explained in part by the influence of the NAO (Jungo & Beniston, 2001; Beniston & Jungo, 2002). In their reconstruction of temperature in the Alps since 1500, Casty & *alii*, 2005 found that 1994, 2000, 2002 and 2003 were the warmest years since 1500. Moreover, they found that summer warming was particularly severe after 1970, reaching, in 2003, the highest summer temperature peak since 1500.

The climate data we analyzed resulted in agreement with the findings of the above reported authors and permitted the quantification of the local air temperature increase which reached at Avio Dam c. 0.8 °C over the very recent time (1999-2003 period), when the strongest glacier decrease was found, and at Careser and Passo del Tonale WSs was found ranging between 0.65 and 1 °C in the period 1983-2003. Our climate data agree with the general warming trend of the last two decades, and the occurrence of the warmest Alpine years in the time frame of our analysis (1992-2003) suggests a strong influence of these years on the acceleration of glacier reduction.

Nevertheless, is the magnitude of the retreat of the Adamello glaciers (–19% of total area in two decades) in proportion with the temperature increase?

There is no doubt that Alpine glaciers are sensitive to climate change. Previous authors have shown that records of glacier fluctuations contain many examples of changes in glacier length, amounting to several kilometres within the last century. Most likely, such changes are associated with secular temperature fluctuations within the range of 1 °C (Grove, 1988; Oerlemans, 1994, Oerlemans & *alii*, 1998). The reason for this marked sensitivity lies in the nature of the melting process. Because the melting point is fixed, both the downward sensible heat flux and the longwave radiation balance increase when the air temperature rises. There are no compensating effects like increasing longwave emission (which would occur with the energy balance of a soil layer, for instance).

The air temperature increase occurring in the Alpine areas since the end of the LIA activated positive feedback, with a consequent increase in both the downward sensible heat flux and the longwave radiation balance (Oerlemans & *alii*, 1998). Furthermore, during the last two decades the Adamello glaciers have experienced a strong decrease in surface albedo due to increasing debris coverage. The latter, whenever thinner than the critical value, CV, (Mattson & *alii*, 1993) has surely played a key role in increasing glacier absorption of incoming energy fluxes, thus making a larger quantity of energy available for ice melting (Paul & *alii*, 2007, Oerlemans & *alii*, 1998). Supraglacial debris on Alpine glaciers, in fact, resulted generally of just few cm on large areas thus causing differential ablation (more precisely in the case debris thinner than CV higher magnitude of ablation occurs). Only if debris is thicker than CV (deposits of larger debris avalanches and rock falls which develop medial moraines and actual debris covered glaciers) the insulating effect prevails thus reducing buried ice ablation rates.

The contemporaneous reduction of the altitude range of Lombardy glaciers (Citterio & *alii*, 2007), together with the generalized rise in the Equilibrium Line Altitude (ELA), confirmed by negative mass balances of glaciers in Lombardy over the last decade (Diolaiuti, 2001; Cannone & *alii*, 2008), points towards a scenario with many glaciers almost completely below the ELA.

Changes in precipitation should also be considered. The Avio Dam WS snow depth data revealed a decrease dominating the recent years. Moreover, the relation between JFM temperature anomalies and the NAO index suggested early snowmelt (then reduced snow cover duration) with stronger negative effects on glacier evolution.

CONCLUSIONS

The analysis led to a quantification of surface reduction: c. 19% from 1983 to 2003 for the Adamello glaciers. The area change rate accelerated over the last (1999-2003) period: there was an area reduction of c. –1.35 km^2 between 1999 and 2003, equal to a mean area loss of c. –0.34 km^2/year; the mean yearly loss over the previous period (1991-1999) amounted to –0.23 km^2/year.

Glacier morphology changes, including growing rock outcrops (for example, Adamello, Pisgana Occidentale, Avio Centrale), tongue separation (Pisgana Occidentale, Avio Centrale, Buciaga, Cima Laste, Venerocolo), formation of pro-glacial lakes (Pisgana Occidentale, Venerocolo), increasing supraglacial debris and related albedo lowering (Aviolo) and collapse structures, were detected by analysing the 2003 orthophotos. These changes all underline down wasting rather than a dynamic response to a changed climate, as already shown by Paul & *alii*, 2007.

These phenomena are related to positive feedback, which, once initiated, accelerates further glacier shrinkage. Similar observations have been reported by Paul & *alii* (2007) for Swiss glaciers. This impressive acceleration in Lombardy coincided with clear local warming (c.+0.85°C), which represents roughly a three-fold amplification of the global climate signal, and a marked local decrease in total winter depth (about –11.4% at 1860 m a.s.l.). This decrease is even greater if we consider the most recent data (1999-2006) characterized by a snow depth decline of c. –16% (with respect to the 1966-2006 mean). This clear snow decrease may be partially due to North Atlantic Oscillation (NAO) variability. According to Beniston & Jungo (2002) the bias imposed by the highly positive NAO index on temperatures has been shown to exceed 1°C for minimum temperatures, and therefore our findings agree with the general Alpine trend.

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