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THE STATE OF ITALIAN GLACIERS: A SNAPSHOT OF THE 2006-2007 HYDROLOGICAL PERIOD

Abstract: Salvatore M.C., Zanoner T., Baroni C., Carton A., Banchieri F.A., Viani C., Giardino M. & Perotti L., *The state of Italian glaciers: a snapshot of the 2006-2007 hydrological period.* (IT ISSN 0391-9838, 2015).

In this study, we present a snapshot of Italian glaciers that outlines the hydrological years of 2006 and 2007 and was derived from the interpretation of high-resolution orthophotographs. The results are freely available and downloadable on the website of the Italian Glaciological Committee (http://www.glaciologia.it/).

Considering that glacial resources are suffering the effects of an extreme degree of ongoing climate warming, glacier monitoring requires homogeneous and accurate contemporary surveying approaches to realize the effective management of multi-temporal glacier inventories in GIS environments. Furthermore, the diffuse and rapid withdrawal of glaciers requires the use of multi-temporal, repeatedly updated data acquired with the same instruments during the same time interval.

In this work, the data collected were organized and processed using the orographic setting of the Alps (*International Standardized Mountain Subdivision of the Alps,* ISMSA-SOIUSA) rather than local and regional administrative boundaries within which glaciers are placed (regions and provinces).

The conducted survey allowed us to evaluate the distribution of Italian glaciers (969 including the two small Apennine glacierets of Calderone in the Gran Sasso Massif), which covered an area of 387.4 km^2 ± 2%. The most glaciated mountain group is the Ortles, with 134 glaciers covering an area of 76.5 km^2, whereas the Alpi Marittime hosts only one small glacier (0,041 km^2). New data, which until now have never been published in Italian inventories, refer to the extension of the glacial debris cover (> 46 km^2, equivalent to 12% of the whole glaciated surface in 2006-2007). Debris cover was outlined on 614 glaciers, corresponding to 63% of all surveyed glacial units.

The comparison of our data with those recorded in the first systematic glacier inventory of the Italian Alps (CGI 1959-1962) shows that in 2006-2007, 181 glaciers were completely extinct, 470 glaciers remained unitary, and 171 bodies were fractionated to generate 243 new glaciers. As a consequence of recent glacial retreat and the induced fractionation of glacial bodies, the total number of glaciers increased (+ 147 glaciers), whereas the surface decreased by ca. 140 km^2 (-27%).

This work represents a breakthrough in the availability of glaciological data from the Italian Alps collected over a very short time period. This study will also satisfy the rising demand of open source availability of environmental data pertaining to mountainous regions.

Key words: Glacier inventory, Debris cover, GIS, Aerial photographs, Italian Alps, Apennines

Riassunto: Salvatore M.C., Zanoner T., Baroni C., Carton A., Banchieri F., Viani C., Giardino M. & Perotti L., *Lo stato dei ghiacciai italiani: un'istantanea degli anni idrologici 2006-2007.* (IT ISSN 0391-9838, 2015).

In questo lavoro presentiamo l'istantanea dello stato dei ghiacciai italiani nel periodo idrologico 2006-2007, derivata dall'interpretazione di ortofotografie ad alta risoluzione. I risultati sono liberamente disponibili e scaricabili sul sito internet del Comitato Glaciologico Italiano (http://www.glaciologia.it/).

Considerando il fatto che la risorsa glaciale è fortemente sensibile agli effetti del riscaldamento climatico in corso, il monitoraggio delle variazioni glaciali richiede un approccio omogeneo, adeguata accuratezza e il contemporaneo rilevamento dei dati in periodi ristretti, al fine di realizzare catasti multitemporali dei corpi glaciali gestibili in ambiente GIS. Inoltre, il diffuso e rapido ritiro dei ghiacciai ci spinge a realizzare catasti multitemporali che aggiornino rapidamente i dati quantitativi della risorsa glaciologica disponibile, acquisendoli con le stesse metodologie, negli stessi intervalli di tempo e mantenendoli sempre aggiornati.

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In questo lavoro i dati raccolti sono stati organizzati ed elaborati con riferimento alla Suddivisione Orografica Internazionale Unificata del Sistema Alpino (SOIUSA) piuttosto che ai confini amministrativi locali e regionali all'interno dei quali i ghiacciai sono collocati (regioni, province).

L'indagine svolta ha permesso di valutare la distribuzione dei ghiacciai italiani (969 compresi i due piccoli glacionevati appenninici del Calderone nel massiccio del Gran Sasso), che coprivano una superficie di 387.4 km^2 ± 2%. Il gruppo montuoso più estesamente glacializzato è l'Ortles-Cevedale con 134 ghiacciai che coprono una superficie di 76.5 km^2, mentre le Alpi Marittime rappresentano il gruppo montuoso meno glacializzato, ospitando solo un piccolo ghiacciaio di limitate dimensioni (0.041 km^2). Nuovi dati, che fino ad ora non erano mai stati indicati nei catasti glaciologici italiani finora pubblicati, si riferiscono all'estensione della copertura detritica sui corpi glaciali (> 46 km^2 pari al 12% dell'intera superficie glaciale nel 2006-2007). La copertura detritica è stata delineata su 614 ghiacciai, corrispondenti al 63% delle unità glaciali censite.

Il confronto dei nostri dati con quelli pubblicati nel primo inventario sistematico dei ghiacciai delle Alpi italiane (CGI-CNR 1959-1962) mostra che, nel 2006-2007, 181 ghiacciai erano completamente estinti rispetto al primo inventario, 470 ghiacciai avevano continuato a rimanere apparati unitari e 171 ghiacciai si sono frazionati per generare 243 nuovi corpi glaciali. Per effetto della recente contrazione degli apparati glaciali e del conseguente frazionamento dei corpi glaciali, il numero totale dei ghiacciai nel 2006-2007 è aumentato (+147 ghiacciai) mentre la superficie è diminuita di circa 140 km^2 (-27%).

Questo lavoro rappresenta un significativo contributo alla disponibilità di dati glaciologici relativi alle Alpi italiane, fornendo un'istantanea della risorsa disponibile negli anni considerati, anche nella prospettiva di soddisfare la crescente domanda di disponibilità di dati ambientali (*open source*) nelle aree montane.

Termini chiave: Catasto dei ghiacciai, Copertura di detrito, SIT, Fotografie aeree, Alpi Italiane, Appennini

INTRODUCTION

Glaciers are among the most impressive elements of the Alpine landscape and retain a valuable freshwater resource, which is particularly precious considering its renewable nature. It is widely recognized that glaciers are very sensitive climatic indicators, and mountain glacier variations are considered among the best natural proxies for evaluating climate change (Zemp & *alii*, 2006; IPCC 2007, 2013; Haeberli & *alii*, 2007; Winkler & *alii*, 2010).

The ongoing climate warming, which has been particularly significant in the Alps since the end of the Little Ice Age (ca. 1850 AD), dramatically accelerated following the end of the 20th Century (IPCC, 2007, 2013; Brunetti & *alii*, 2009; Büntgen & *alii*, 2011). This evidence has been confirmed by multi-archive, multi-proxy summer temperature reconstructions at the scale of the entire Alpine Chain (using tree-ring and lake sediment data; Büntgen & *alii*, 2006, 2011; Trachsel & *alii*, 2012) and further verified at a regional scale in the Italian Alps by annually resolved dendroclimatic reconstruction of summer (JJA) mean temperatures (Coppola & *alii*, 2012, 2013).

As a consequence of climate warming, glacial resources are considered at risk in many regions, particularly on mid-latitude mountains (IPCC, 2007, 2013); for example, in the Italian Alps, relevant glaciers might disappear within a few decades or be halved in size by 2050 (e.g., Carturan & *alii*, 2013a, 2013b; Grossi & *alii*, 2013). Many mountain groups in the Alps have lost a significant portion of their glacierized areas over the past 150 years (Maisch, 2000; Maisch & *alii*, 2000; Lambrecht & Kuhn, 2007; Zumbühl & *alii*, 2008), with strong acceleration registered in the past two decades (e.g., Paul & *alii*, 2004b; WGMS, 1988, 1993, 1998, 2005, 2008, 2012, 2015; Zemp & *alii*, 2008, 2015). Significant evidence of a strong glacial shrinkage in terms of surface area, volume, and thickness has also been recorded for the Ghiacciaio del Calderone, the southernmost glacier in Europe located in the Gran Sasso Group (Central Apennine; Fiucci & *alii*, 1997; Pecci & *alii*, 2008; WGMS, 2012).

The accelerated retreat of glaciers recorded in all mountain systems provides some of the most striking evidence in support of current human-induced global climate change (IPCC, 2007, 2013). Also for this reason, glacier behaviour represents one of the environmental issues attracting the most attention not only from the scientific community but also from the general public. The evocative impact of the many images depicting the dramatic retreat of glacial termini, which are well appreciable over the course of a single lifetime, offers the direct perception that glacial collapse is underway (Zumbühl & *alii*, 2008). Furthermore, glacial retreat and cryosphere degradation creates new alpine landscapes (Linsbauer & *alii*, 2009, 2013) and induces new scenarios of geomorphological risk in the newly formed paraglacial environment (*sensu* Ballantyne, 2002; Harris & *alii*, 2009; Huggel & *alii*, 2010). In this rapidly changing world, glaciers as well as the integrity of mountain ecosystems and biodiversity are considered at risk (Beniston, 2003; Grabherr & *alii*, 2010; Dullinger & *alii*, 2012).

A huge amount of glaciological data on the fluctuation of glaciers has been collected thus far (e.g., FoG 1959 to 2010, available at http://www.geo.uzh.ch/microsite/wgms/fog.html; WGMS, 1988, 1989, 1993, 1998, 2005, 2008, 2012, 2015; Zemp & *alii*, 2015 and references therein) and a more accurate and multi-temporal quantification of occurred changes, even in recent times, is needed for assessing the climate warming impact on glacier areal extent, the freshwater volume stored in alpine glaciers, and the expected future runoff in mountain catchments (Huss, 2011). In fact, the comparison of data obtained using different detection techniques can produce relevant qualitative information but is frequently problematic if used for quantitative purposes. Furthermore, a modern approach in glacier monitoring necessarily requires a continuous updating of multi-temporal glacier inventories based on accurate and homogeneous contemporary surveying approaches (Serandrei-Barbero & Zanon, 1993; Haeberli, 2004; Hoelzle & *alii*, 2007; Abermann & *alii*, 2009; Huss, 2012; Gardent & *alii*, 2014; Fisher & *alii*, 2014).

In the past, morphometric data and cartographic representations of glaciers have been acquired using criteria and methods that differ substantially from those available today (Desio, 1967; Belloni & *alii*, 1985; Secchieri, 1985; Pelfini & Smiraglia, 1988; WGMS, 1989) or that refer to regional and local scales (e.g., Zanon, 1990; Comitato Glaciologico Trentino, 1994; Servizio Glaciologico Lombardo, 1992; Federici & Pappalardo, 2009, 2010; Bonardi & *alii*, 2012; Secchieri, 2012). As a consequence, comparisons of data obtained from different sources furnish meaningful qualitative information but are often quantitatively inaccurate or depict only local to regional conditions. Alternatively, quantitative information on glacier area and length need to be precisely assessed to be valuable as climate change indicators (Paul & *alii*, 2013). Modern technologies of data acquisition and processing (e.g., GIS, LIDAR, and orthophotos) allow for an extremely qualified monitoring that can be used together with data that are collected or created with the same accuracy. In a period when glacial resources are suffering to an extreme degree, the availability of data acquired using the same instruments and during the same time interval is necessary more than ever, particularly if we consider the diffuse and rapid withdrawal of glaciers.

In particular, the consistent evaluation of glacier spatio-temporal coverage represents a fundamental step for defining the status of this part of the cryosphere, which is necessary for reconstructing future scenarios in a world with a warming climate.

The Italian Glaciological Committee (CGI) has a unique, secular history of glaciological documentation that, in conjunction with a rich wealth of spatial and multi-temporal data, allows for an accurate reconstruction of recent glacier evolution, including one of the longest observation series of glacier frontal variations in the world (Porro, 1925; Porro & Labus, 1927; CGI, 1928-1977; 1978-2010; Desio, 1967; WGMS, 1988, 1993, 1998, 2005, 2008, 2012, 2015; Baroni & *alii*, 2011, 2012, 2013, 2014a, 2015; Belloni & *alii*, 1985; Secchieri, 1985; Belloni, 1992; Pelfini & Smiraglia, 1988; 1997; Citterio & *alii*, 2007; Carturan & *alii*, 2014; Santilli & *alii*; 2002; Zemp & *alii*, 2015; and references therein). Unfortunately, these data are not all organized into a database, and in several cases, the results are dispersed and/or difficult to access. The most recent glacier inventory of italian glaciers was published in 2015 (Smiraglia & Diolaiuti, 2015; Smiraglia & *alii*, 2015). Starting in 2012, this inventory has been realized by the University of Milan in the framework of a collaboration with "Levissima" and Everest-K2-CNR with the scientific support of CGI. Glacial boundaries refer to a period of seven years (from 2005 to 2011).

Our aim, which was conducted within the framework of the activities of the CGI, was to contribute in updating multi-temporal data pertaining to Italian glacial resources and to make these data available to the scientific community and stakeholders. This was achieved through the use of an integrated information management system in line with the requirements of NextData Portal, a national system for the retrieval, storage, access and diffusion of environmental and climate data from mountainous and marine areas (http://www.nextdataproject.it).

Here, we present a snapshot of Italian glaciers in 2006-2007 that was derived from high-resolution orthophotographs. The glacier boundaries and glaciological data are freely available and downloadable on the website of the Italian Glaciological Committee (http://www.glaciologia.it/).

MATERIALS AND METHODS

The study area covered the entire Italian Alps and included the Gran Sasso Group (Central Apennines), where the southernmost glacieret of the Italian Peninsula is located (figs. 1, 2, 3).

It is well known that remote sensing represents one of the most useful tools for monitoring glacial resources, furnishing several different sources of data and methods of outlining glacier boundaries (e.g., Paul & *alii*, 2004a; 2011). Here, we utilized the new generation of orthorectified aerial photos at high geometric resolution provided by the National Geoportal of the Ministry of Environment and Protection of Land and Sea, which is available through the Web Map Service (WMS, http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/raster/ortofoto_colore_06.map), to contour the glacier limits on a homogeneous base of representation and to providing a snapshot of the state of glacial bodies developing on the Italian Alps and Apennines in 2006-2007.

Digital colour RGB true-colour orthophotos with a radiometric resolution of 8 bit for channels and nominal geometric resolution of 50 cm × 50 cm were used; the planimetric accuracy stated by the manufacturers was ±1 m. The images were taken in very low or absent cloud coverage and only in particular orographic and slope aspect conditions as the glacial bodies on the northern slopes of the Orobie or Brenta groups resulted in shadows. Partial or total debris coverage on glacier surfaces has become increasingly common in recent years and often makes it difficult to correctly interpret the location of glacier boundaries, especially in the frontal area (Fischer & *alii*, 2014 and references therein). To overcome this problem, we paid particular attention to interpreting a number of clues and epiglacial landforms that helped identify the presence of ice under the debris cover (Biasini & Salvatore, 1993; Paul & *alii*, 2004a, 2009), such as anomalous darker areas due to greater melt water content, surficial ponds, *bédières*, glacial dolines, hummocky morphology, or glacier mouths. In the cases of shaded images and when glaciers were locally covered by supraglacial debris, we interpreted the limit using additional photographic documentation. In particular, we used terrestrial photographs taken during the 2006 and 2007 annual glaciological surveys (available in the archives of the Italian Glaciological Committee or in local archives of the images, see supplementary material). Furthermore, in many cases, the availability of Lidar images taken in the same temporal interval allowed us to better define the glacier limits.

Orthophotos including the Italian glaciers were acquired mostly during the end of the 2006 summer season (approximately 78%) and, to a lesser extent, during 2007 (fig. 2); overall, more than 90% of glacial bodies were captured during the end of the summer season (August and September). Only in few cases did images in the same mountain range not have a contemporary acquisition year; however, the time lag did not exceed one hydrological year.

All outlines of the glacial bodies were manually digitized from high-resolution aerial ortophotographs using an open source GIS (Q-gis®), which allowed for mapping glaciers as polygons in the vector domain as well as creating an alphanumeric attribute table associated with the glacier outlines.

Following the World Glacier Monitoring Service (WGMS) guidelines for the compilation of glacier inventory data from digital sources (Paul & *alii*, 2009), each table

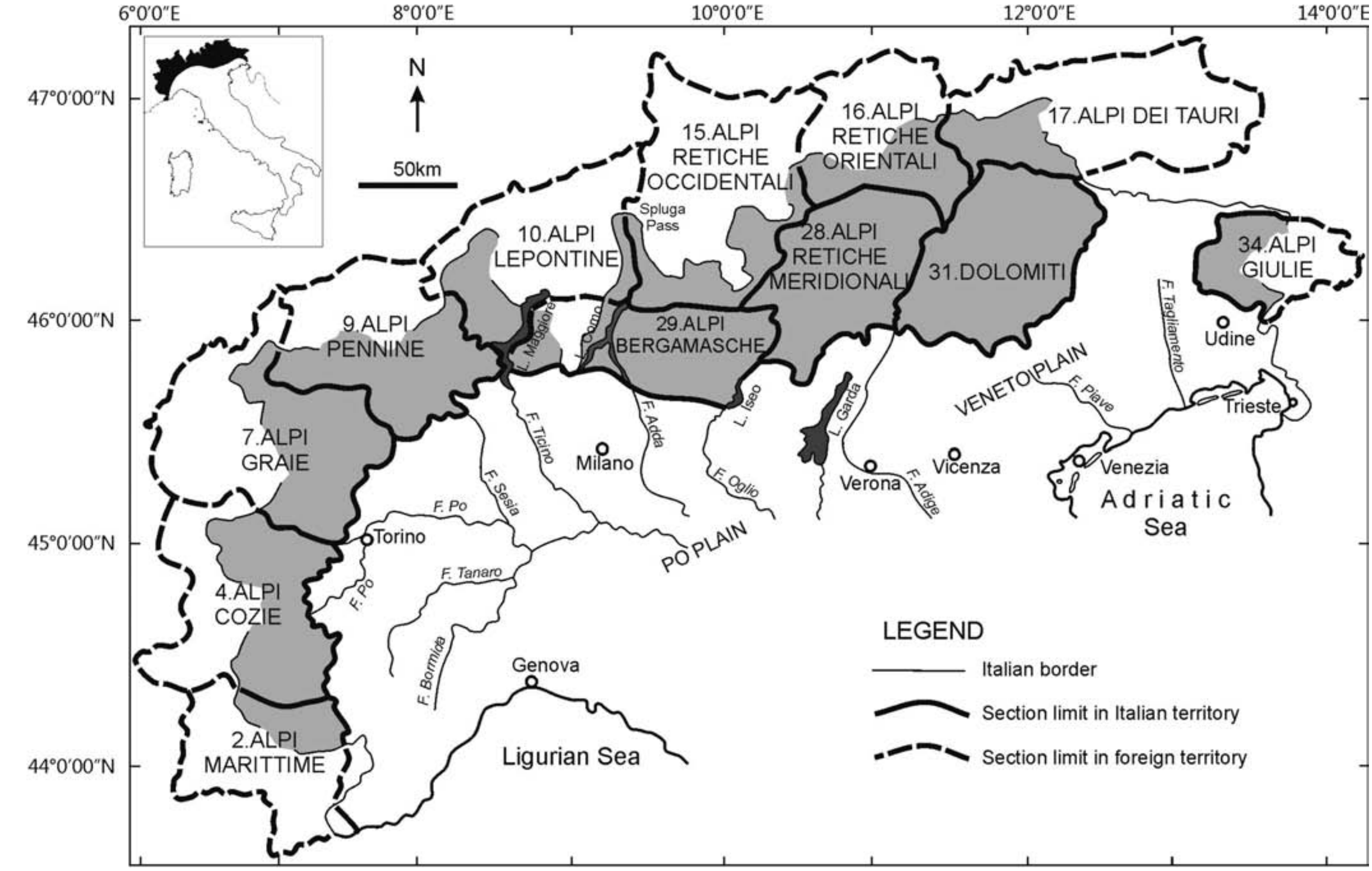


Fig. 1 - Geographical setting of the Alps according to the International Standardized Mountain Subdivision of the Alps (ISMSA). The division and toponymy of the reliefs are shown at the section level. Only sections with glaciers are represented. Light grey indicates sections partially or completely within the Italian territory.

corresponding to a glacial body contains the main morphometric parameters (area, maximum length, width, slope, max and min elevation, aspect, latitude and longitude of the glacier centroid), the cadaster number according to the previous Inventory of Italian Glacier (CGI-CNR, 1959, 1961a, 1961b, 1962), and the identification (ID) according to the hydrological coding suggested by the WGMS (1989). Although the Ghiacciaio dell'Adamello was divided into six different glacial units (n. 600, 603, 604, 608, 609, 639 in CGI-CNR, 1961b) in previous glacier inventories, here, we considered it as a single unitary body and accounted for its morphological classification as well as its glacial dynamics. In fact, the Ghiacciaio dell'Adamello is a Scandinavian-type glacier that lies on a plateau (at an average elevation of ca. 3000 m) and feeds different frontal margins descending from the top (Baroni & Carton, 1996; Ranzi & *alii*, 2010, 2013). The adjacent Ghiacciaio della Lobbia is similar to the Ghiacciaio dell'Adamello; here, we also considered it as a single glacial body, although in the past it was separated into two different glaciers (n. 637 and 615 in CGI-CNR, 1962).

To ensure data consistency, experts conducted mapping with knowledge of the assigned area and followed criteria previously planned for identifying glacier boundaries in case of problematic interpretations (e.g., debris covered glaciers, shadows).

Evaluating the accuracy of glacier outlines is a widely debated question that depends on several parameters and has not been completely solved (Paul & *alii*, 2013, Fisher & *alii*, 2014 and references therein). The accuracy of glacial limits that we present here was assessed following the approach suggested by Vögtle & Schilling (1999) and recently applied in alpine environments by Diolaiuti & *alii* (2012) and Smiraglia & *alii* (2015). Our data gave an estimated error of less than ± 2%; the only exceptions were a few cases with continuous supraglacial debris coverage, for which we estimated a maximum value of approximately ± 5%. Following Paul & *alii* (2013) and Fischer & *alii* (2014), we also applied several cross validations comparing glacier boundaries detected by different operators. The difference between the values of areal extension obtained by different operators was almost completely within the maximum values of error indicated above. A relevant point is the reliability of the previous CGI 1957-1958 Inventory of Italian Glacier area accuracy. According with previous cited references and with the old data and methods adopted (1:25,000 scale as base map without *GIS* assistance), we can estimate the area error using basic cartographic parameters such as the map reading tolerance (0.5 mm on the map). The total area accuracy estimation error on 1957-1958 CGI inventory is estimated between ± 5% to ± 10%. According to Paul & *alii* (2004b), the glaciers were divided into seven size classes following international standards, thereby allowing a better comparison between glaciological data coming from other inventories.

Unlike the geographical subdivision adopted thus far in the compilation of glacier inventories of the Italian side of the Alps, the data we collected were organized and processed using the orographic setting and not the administrative boundaries within which the glaciers were placed (regions, provinces). In fact, some cases in the past have considered the glacial bodies split by regional and national boundaries that intersect mountain groups to be distinct glaciers. Apart glaciers divided by national borders, we adopted a criterion that accounted for glacial dynamics and applied these divisions into distinct bodies in correspondence of ice divide.

The morphological setting of the Italian Alps is extremely complex and is characterized by a number of mountain ranges separated by an articulate system of valleys and saddles. Although the Italian Alps have been divided in the past according to different national geographical subdivisions, we adopted the *International Standardized Mountain Subdivision of the Alps* (ISMSA), better known by the acronym SOIUSA (Marazzi, 2005), which better allowed for connecting groups along the entire Alpine chain even if the Italian Alps were classified according to different criteria (figs. 1, 3).

ISMSA introduced the bipartition of the Alpine System (Western Alps and Eastern Alps) to replace the old tripartite division (Western Alps, Central Alps and Eastern Alps). The bipartite division follows a multilevel pyramidal hierarchy, accounting for the historical and geographical regions in the Alps, and provides higher level (5 major sectors SR; 36 sections SZ; 132 subsections STS) and lower level mountain groups (333 supergroups SPG; 870 groups GR; subgroups STG).

To sufficiently provide a detailed glacier distribution framework that was not too broad, we operated at the levels of section and subsection (figs. 1, 3). This approach enabled the synthetic processing of data (at the level of sections) while still offering sufficient detail (subsections) to allow for the appreciation of differences in glacial behaviour conditioned by geographical factors, including the energy of the relief and the different distributions with respect to latitude,

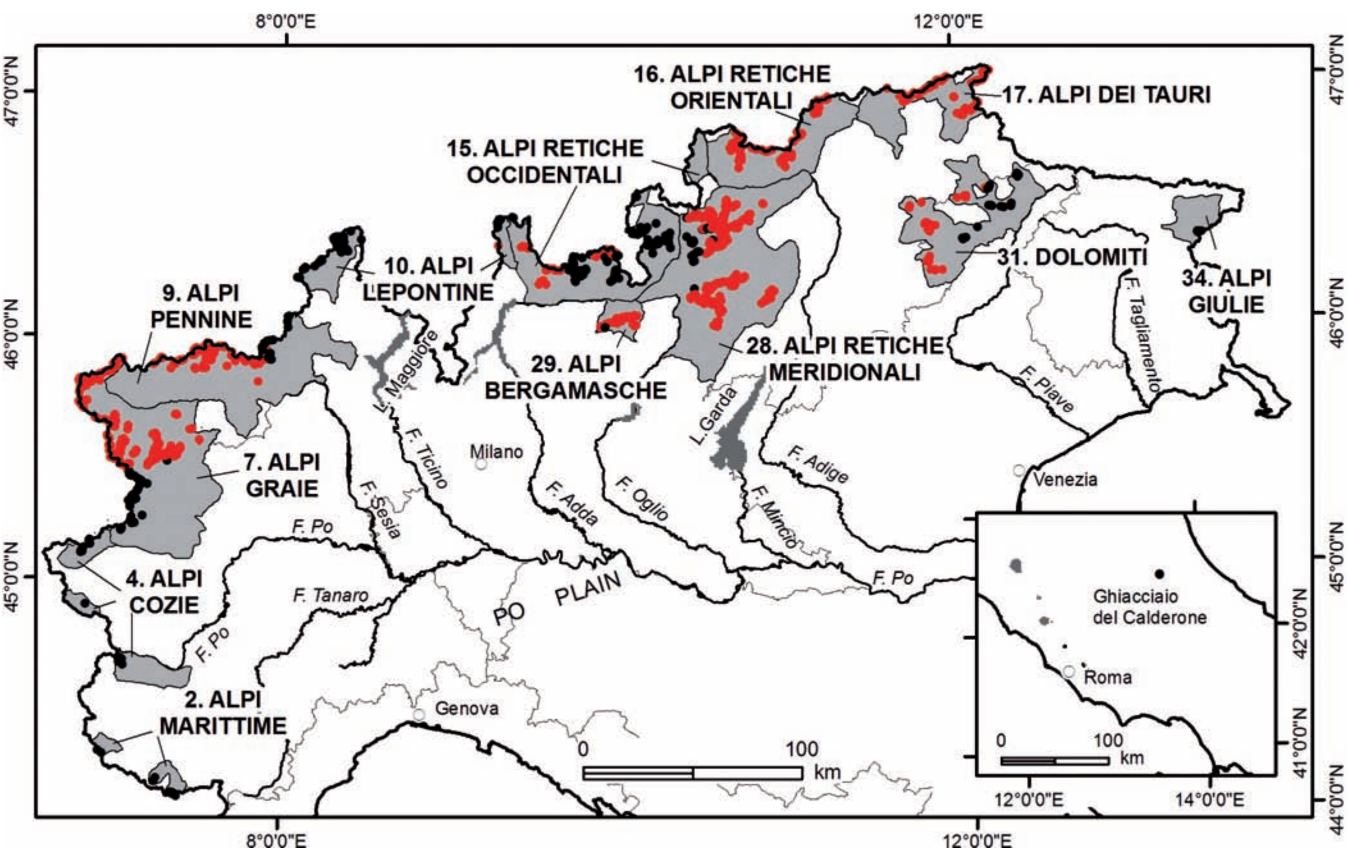
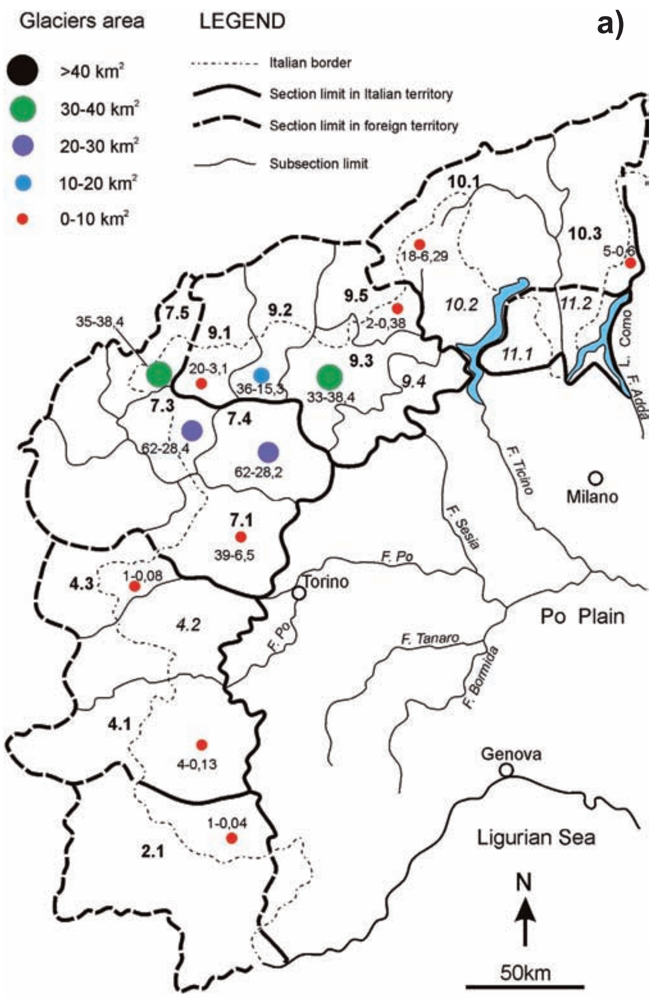


FIG. 2 - Location of Italian glaciers in 2006-2007, as detected from orthophotos provided by the National Geoportal of the Ministry of Environment and Protection of Land and Sea through the Web Map Service. Grey represents the ISMSA sections hosting glaciers in the Italian Alps. Red and black circles refer to glaciers detected in orthophotos taken in 2006 and 2007, respectively.



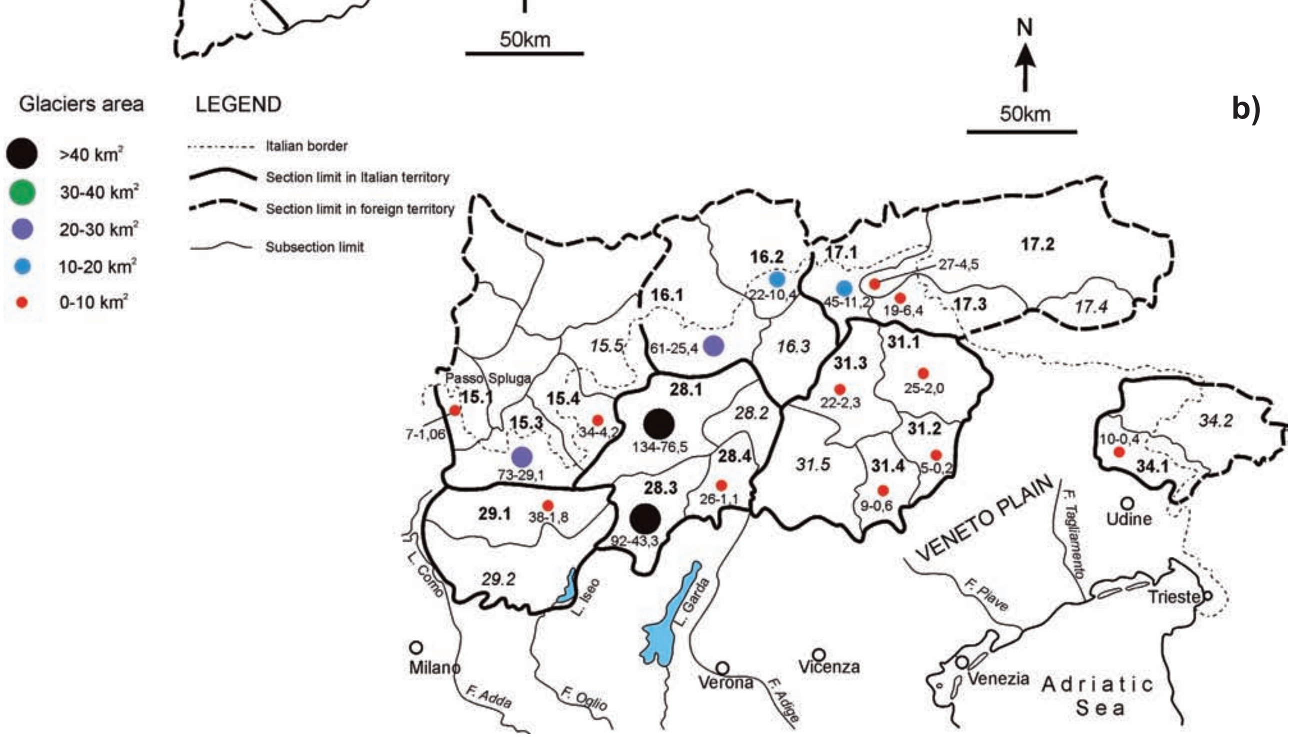


FIG. 3 - Geographical setting of the Western Alps (a) and Eastern Alps (b) according to the International Standardized Mountain Subdivision of the Alps (ISMSA) at the subsection level. Numbers in bold indicate the subsection codes where glaciers have been detected; subsections without glaciers are indicated in italics. Circles of different sizes and colour indicate the total glacierized area for each subsection, divided into five classes. The small numbers associated with circles indicate the total number and the areal extent (km^2) of glaciers in 2006-2007. Subsection codes of the Western Alps: 2.1 Alpi Marittime s.s.; 4.1 Alpi del Monviso; 4.3 Alpi del Moncenisio; 7.1 Alpi di Lanzo e dell'alta Moriana; 7.3 Alpi della Gran Sassier e del Ruitor; 7.4 Alpi del Gran Paradiso; 7.5 Catena del M. Bianco; 9.1 Alpi del Gran Combin; 9.2 Alpi del Weisshorn e del Cervino; 9.3 Alpi del M. Rosa; 9.5 Alpi Vallesane orientali; 10.1 Alpi del M. Leone e del S. Gottardo; 10.2 Alpi Ticinesi e del Verbano; 10.3 Alpi dell'Adula.
Subsection codes of Eastern Alps: 15.1 Alpi del Platta; 15.3 Alpi del Bernina; 15.4 Alpi di Livigno; 16.1 Alpi dell' Otztal, Venoste orientali e Passirie; 16.2 Alpi dello Stubai e Breonie occidentali; 17.1 Alpi Breonie orientali e Aurine; 17.2 Alti Tauri; 17.3 Alpi Pusteresi; 28.1 Alpi dell'Ortles; 28.3 Alpi dell'Adamello e della Presanella; 28.4 Dolomiti di Brenta; 29.1 Alpi Orobie; 31.1 Dolomiti di Sesto, di Braies e d'Ampezzo; 31.2 Dolomiti di Zoldo; 31.3 Dolomiti di Gardena e di Fassa; 31.4 Dolomiti Feltrine e delle Pale di S. Martino; 34.1 Alpi Giulie p.d.

longitude or other geographical parameters. The data analysis grouped at the level of single sections also allowed for a comparison between our findings and the traditional classification of the Italian Alps (adopted since 1924), with which ISMSA-SOIUSA has points of connection in this hierarchical level.

The Italian side of the Alps is well suited to an analysis of the geographic distribution of glaciers.

In fact, the western sections, which include the Marittime to Lepontine Alps, developed with a meridian trend of approximately 300 km (approximately 2.6° of latitude), whereas the rest of the sections are distributed longitudinally for more than 350 km from the western Alpi Retiche to the Alpi Giulie (distributed along almost 4.59° of longitude).

This approach also allowed us to extend the survey to the alpine sections that, for administrative reasons, are divided by the political borders between Italy and other alpine countries. Of the 16 sections in the Italian side, 12 host active glaciers (fig. 1) and were analysed in 30 subsections, 9 of which were entirely within the Italian territory (figs. 2 and 3). Therefore, only for these latter glaciers did we furnish glaciological data related to the whole alpine subsection (Tables, 1 and 2).

For management in the GIS environment, morphometric and geographical data were also reported in the 1957-1958 inventory of Italian glaciers (CGI-CNR, 1959, 1961a, 1961b, 1962). Thus, we created a vectorial point file for identifying the geographic location of both extinct and existing glaciers listed in the CGI inventory, which includes an attribute table containing both glaciological and geographical data. To compare the data of the 1957-1958 glacier inventory and the 2006-2007 snapshot of Italian glaciers and to harmonize the criteria of geographic divisions adopted in the past, we associated glacier point files through a spatial joint using the ISMSA-SOIUSA limits, which were digitized in vector format.

RESULTS

The conducted survey allowed us to evaluate the total extent of Italian glaciers in 2006-2007, which covered a surface of approximately 387.4 km^2 ± 2%. The total number of glacial bodies was 969, including the two small Apennine glacierets of Calderone (tabs. 1, 2). In the Italian Alps, the Ortles represented the mountain group with the most glaciated area (76.5 km^2) and with the highest number of glacial bodies (134), whereas the smaller glaciated surface was present in the Marittime Alps s.s. (0,04 km^2), with only one glacier. In 11 of the 30 subsections considered, the total glacierized area still exceeded 10 km^2 (tab. 2). Among these subsections, Adamello Presanella (ca 43 km^2), M. Bianco (38.4 km^2) and M. Rosa (38.4 km^2) stand out, retaining some of the largest Italian glaciers (e.g., Adamello plateau and the Miage and Belvedere glaciers).

Following Paul & *alii* (2004b), we considered seven classes of glacier extension (fig. 4), which allowed for a comparison of our data with those of other national and international inventories.

Glaciers of the smaller size classes dominated the number of Italian glaciers in 2006-2007 (Fig. 4a).

Over 54% of the Italian glaciers (526 bodies) in 2006-2007 extended less than 0.1 km^2, whereas more than 29 % of the glacial bodies ranged between 0.1 and 0.5 km^2. The remaining ca. 16 % of Italian glaciers (in number) was comprised of the wider extension classes. Although ca. 84% of the glaciers (in number) had an area smaller than 0.5 km^2, they cover a total surface of more than 82 km^2, which represents ca. 21% of the total glacierized area in the Italian Alps in 2006-2007.

Among the glaciers exceeding 0.5 km^2, only 0.3% extended more than 10 km^2. The three widest glaciers of the Italian Alps were the Adamello ice plateau in the Adamello - Presanella (16.4 km^2), the Forni Glacier in the Ortles (11.3 km^2), and the Miage Glacier (10.3 km^2) in the M. Bianco. Altogether, these three ice bodies covered approximately 38 km^2, representing approximately 10% of the total area. Among the glaciers of the intermediate class sizes (comprise between 0.5 and 5 km^2) those falling in the 2-5 km^2 class covered the widest area (> 97 km^2, ca. 25% of the total area), although the number of glaciers was markedly reduced (30 glaciers, ca 3% of the total). In addition, glaciers of the 5-10 km^2 size class covered more than 55 km^2 (ca. 14% of the total area) but consisted of only 8 glacial bodies (less than 1% of the total number). Finally, glaciers of the 0.5-1 and 1-2 km^2 size classes covered ca. 48 km^2 and ca. 66 km^2, respectively (12.5% and ca. 17% of the total, respectively). For the 0.5-1 and 1-2 km^2 size classes, the number of glaciers ranges from 69 to 47, representing ca. 7% and ca. 5% of the total number, respectively.

Accounting for this aspect (fig. 5), most of the glaciers face towards the northern quadrants: in particular, approximately 97 km^2, which corresponded to 25% of the total glacierized area, faced N, 54 km^2 (14%) faced NE, and 32 km^2 (8%) face NW.

Detecting and mapping the distribution of supraglacial debris over the entire Italian Alpine chain and the Apennine glacierets was important for evaluating glacier conditions during the 2006-2007 hydrological years. The presence of debris cover plays an important role in influencing glacier behaviour as debris can significantly influence the glacier energy budget and, consequently, the ablation rate compared to that of clean ice (Østrem, 1965; Lundstrom & *alii* 1993; Foster & *alii*, 2009; Reznichenko & *alii*, 2010).

Supraglacial debris cover is currently increasing in area and thickness on many mountain glaciers, as documented in several parts of the world, including the European Alps (Kellerer-Pirklbauer, 2008; Kellerer-Pirklbauer & *alii*, 2008; Deline & *alii*, 2012). These data refer to single glaciers or small numbers of glaciers and regional inventories (e.g., Kirkbride & Deline, 2013 and reference therein). In the Italian Alps in recent years, glaciological annual campaigns have reported an increase in the number of observed glaciers covered with debris (CGI, 1978-2010; Baroni & *alii*, 2011, 2012, 2013, 2014a, 2015).

Continuous supraglacial debris with a minimum mappable area of approximately 1000 m^2 was identified and outlined on glaciers distributed in almost all subsections considered.

a)

b)

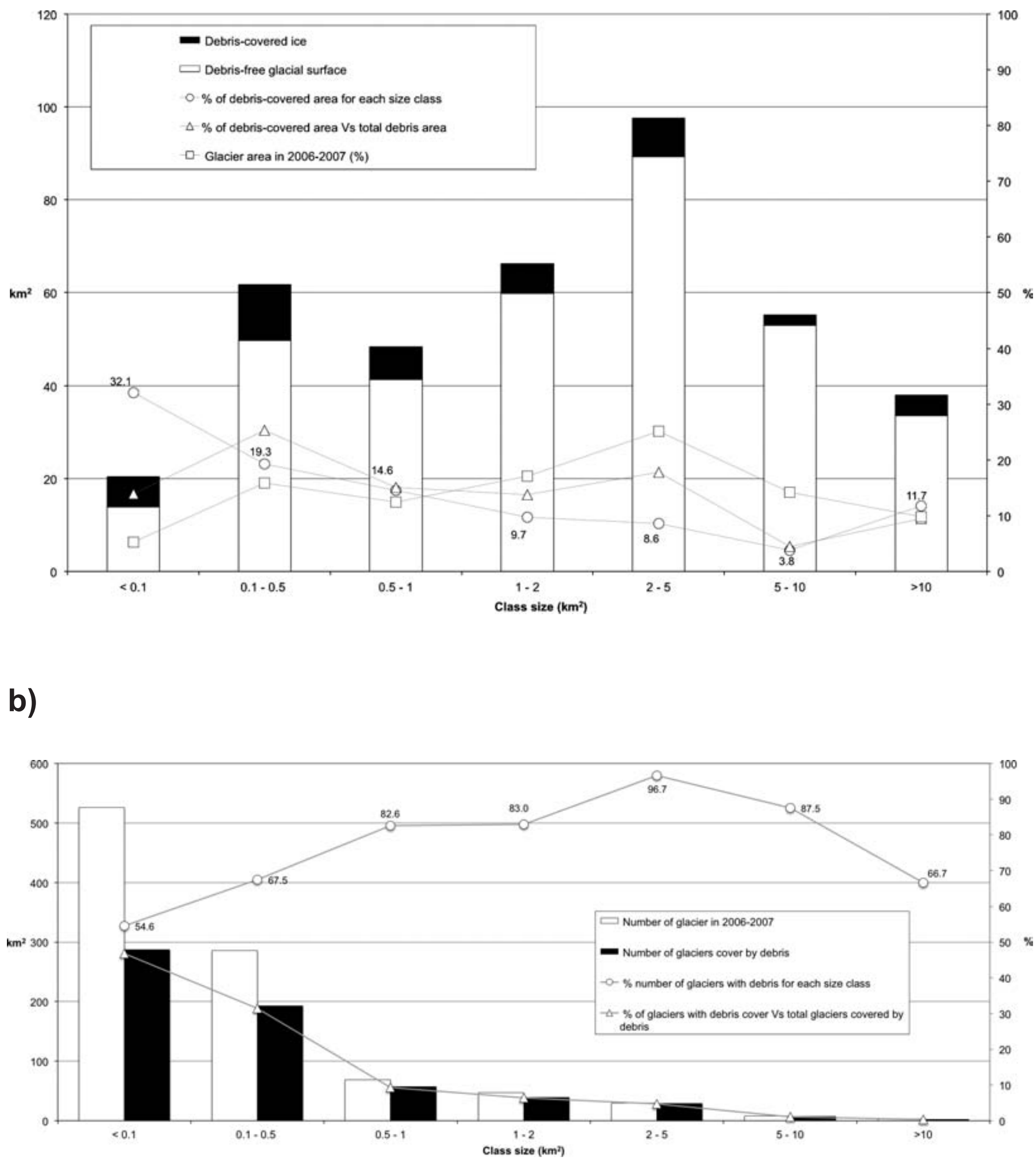


FIG. 4 - Number and areal frequency distribution of Italian glaciers in 2006-2007. Black stacks indicate the frequency of glaciers with debris cover. a) Areal extent (km^2) and percentage of glacier area for each size class (white square); percentage of debris covered area (circles) and percentage of debris covered area vs. total debris area for each class. b) Number and percentage of total glaciers and glaciers covered by debris for each size class; percentage of number of glaciers with debris cover for each class (circles) and percentage of glaciers with debris cover for class size vs. total glaciers covered by debris.

In particular, we detected continuous debris patches on 614 glaciers, which corresponded to 63% of all the surveyed glacial units and covered a total area of approximately 47 km^2 (equivalent to ca. 12% of the whole glaciated surface). The largest number of glaciers (figs. 4a and 4b) affected by supraglacial debris cover fell into the size class of <0.1 km^2 and decreased gradually in the higher size classes, in which the number of glacial bodies is decreasing. Considering the areal extent of each size class, the greatest percentage of debris coverage was found on glaciers with an area < 0.1 km^2 (approximately 30% of the total area of the class), progressively decreasing up to the class of 5-10 km^2, and finally increasing in the next larger size (> 10 km^2), in which it reached approximately 12% of the total extent of the class. This high value was due to the presence of the Miage Glacier, the widest debris-covered glacier of the Italian Alps. Considering the percentage of debris cover in a single size class with respect to the total debris coverage, we found two relative maxima in the 0.1 - 0.5 km^2 and 2- 5 km^2 size classes.

The debris cover area in each ISMSA subsection varied considerably in extent and in the number of glaciers involved (figs. 6 and 7).

Two-thirds of the subsections (21) hosted glaciers with debris cover smaller than 1 km^2 (figs. 6 and 7). A larger number of glaciers affected by debris coverage were found in the western subsections than in the eastern subsections, in the following order: Alpe Gran Paradiso, Alpe Bernina, Alpe dell'Otztal Venoste orientali and Passirie, Alpe Ortles, and in the Alpi Orobie.

Finally, the two southernmost glacierets of the Italian Peninsula, located on the Gran Sasso d'Italia, were completely covered by debris in 2006-2007.

The maximum extent of debris-covered areas was detected on the glaciers of Alpi dell'Ortles (ca 10 km^2), although these areas represented only 13% of the entire glaciated area of this subsection. Other subsections with extensive debris included the Catena del M. Bianco, Alpe dell'Otztal Venoste orientali and Passirie, and Alpi del M. Rosa (figs. 6 and 7). In particular, in the central-western subsections, from Alpi Marittime to Alpi dell'Adamello-Presanella and Orobie, the debris cover was, on average, less extensive (between 0 and 21%, mean value 11%) than in the eastern subsections (from the Dolomiti di Brenta to the Alpi Giulie), where the values ranged from 23% to 92% (mean value 48%).

The adjacent Alpi dell'Ortles and Adamello Presanella groups presented a significant difference in debris cover both in terms of areal extent (13% vs. less than 6%, respectively) and number of glaciers involved (80 in the Ortles and 48 in the Adamello Presanella, corresponding to 60% and 50% of the total glaciers, respectively). These differences seem to be justified considering the important role played by different lithological compositions of the bedrock in driving frost-weathering (metamorphic vs. intrusive rocks, respectively), although several other factors may drive the production of debris in Alpine environments in reaction to ongoing permafrost degradation (Fischer & *alii*, 2006, 2012; Krautblatter & *alii*, 2012; Deline & alii, 2015).

Finally, it is worth noting that debris-covered glaciers in the M. Bianco and M. Rosa groups descended with their fronts to the lowermost elevation of the entire southern side of the Alps, as effects of debris-coverage on glacier ablation. In 2006-2007, the Brenva and Miage glaciers (M. Bianco) reached their minimum elevations of 1420 m and 1723 m, respectively. Their frontal positions were more advanced in 2006-2007 than in the late 1950s, when their fronts reached 1550 m and 1775 m, respectively, descending in elevation for approximately 130 m in the case of the Brenva glacier and approximately 50 m in the case of the Miage glacier. Also the Belvedere glacier (M. Rosa) descended down to approximately 1770 m, with its front increasing in elevation by ca. 15 m since the late 1950s.

DISCUSSION

To assess the impacts of climate change, the data collected in this study were compared with those previously published by the Italian Glaciological Committee. The first available data furnishing a complete picture of Italian glaciers were obtained from a survey conducted during the International Geophysical Year of 1957-58, when the Italian Glaciology Committee supported by the National Research Council produced an inventory of Italian glaciers (CGI-CNR 1959, 1961a, 1961b, 1962). The glaciers are represented in older editions of IGMI (Istituto Geografico Militare Italiano, Italian Military Geographical Institute) topographic maps at the scale of 1:25,000. The data collection methodology was based primarily on mapping and field surveys conducted in 1957-1958 with integration based on older documents for extinct glaciers (CGI-CNR, 1959, 1961a, 1961b, 1962).

Tables 1 and 2 compare the data regarding the number of glaciers and their extent during the time intervals of 1957-1958 and 2006-2007. These distributions of glaciers were considered according to ISMSA-SOIUSA subsections. Table 1 summarizes the total number of glaciers and their distribution during the two time intervals. The comparison highlights i) the number and percentage of completely extinct glaciers, ii) the number and percentage of glaciers that maintained their unitariness despite being impacted by areal reduction, iii) the number and percentage of shrinking glaciers that were split into smaller glacial bodies (coded as parent and son glaciers,

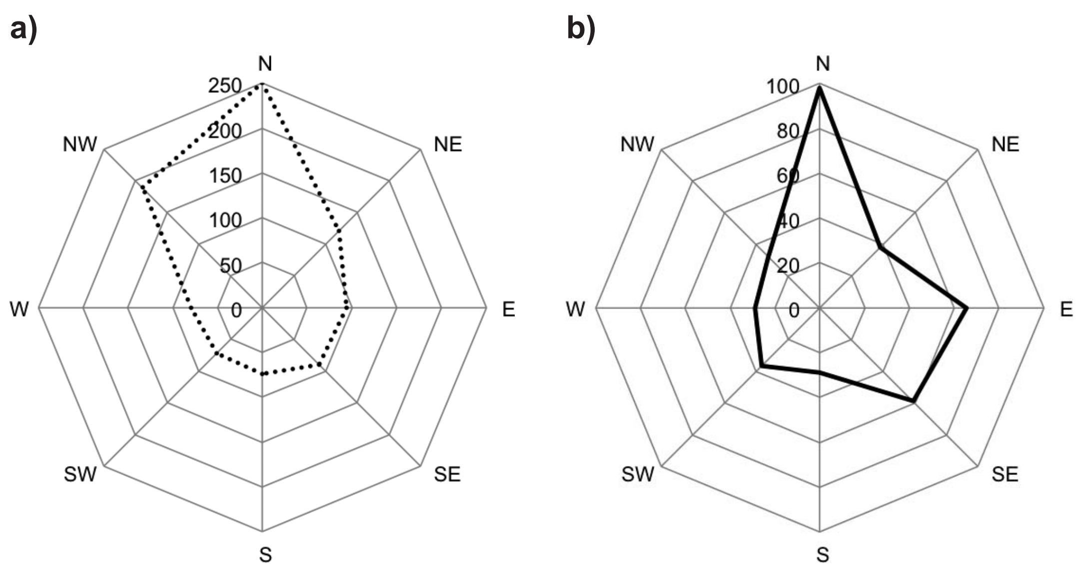


FIG. 5 - Distribution of 2006-2007 glacier number (a) and areal extent (km^2, b) vs. aspect.

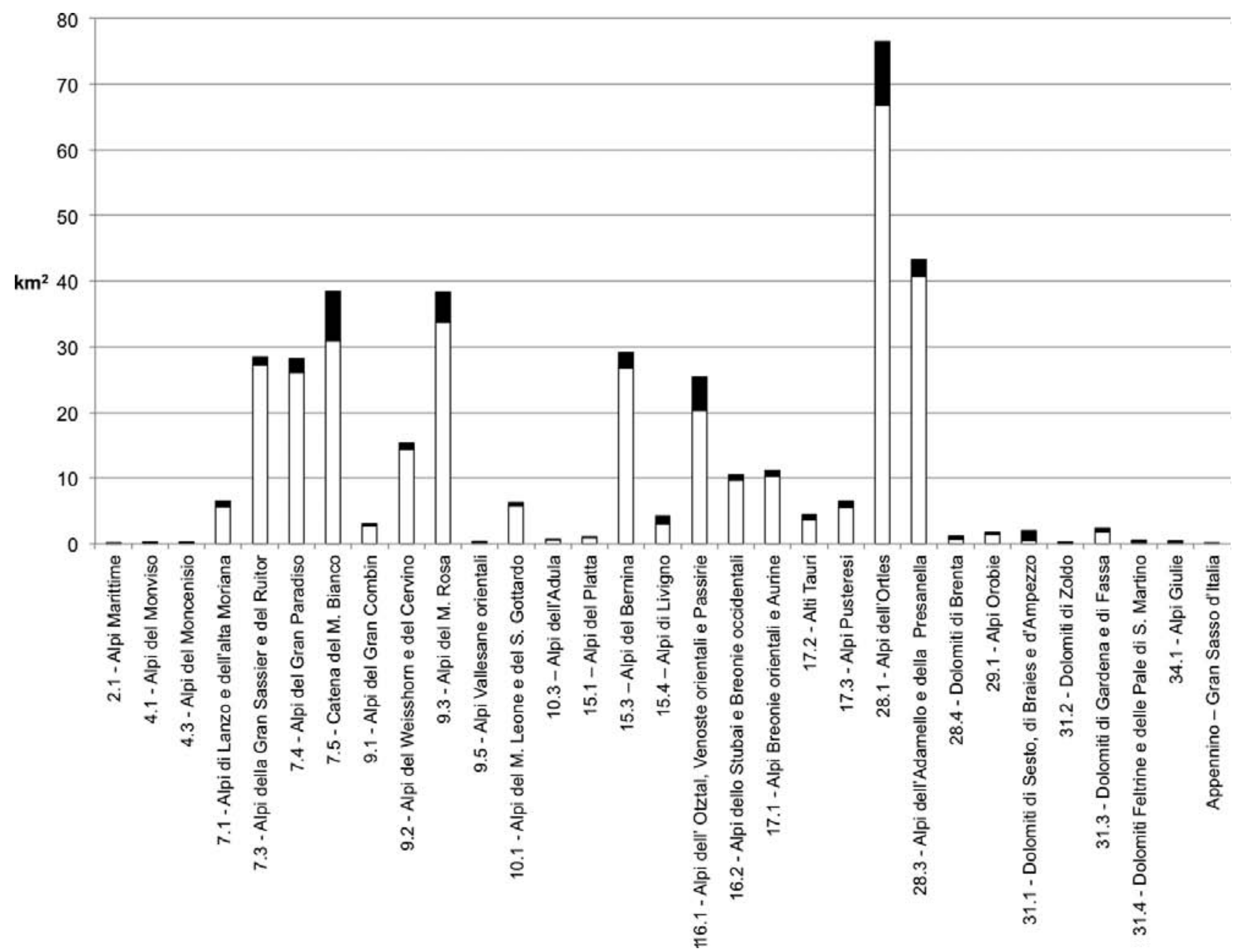


FIG. 6 - Frequency of glacier areal extent in each ISMSA subsection and in the Apennines in terms of debris-free (white) and debris-covered area (black). Values (km^2) are indicated by numbers. See fig. 3 for subsection locations.

respectively), and iv) glacial bodies that have been newly surveyed or never registered, for different reasons, in the glacier inventory published by the Italian Glaciological Committee (CGI-CNR, 1959, 1961a, 1961b, 1962).

The CGI Inventory lists 836 glaciers active in 1957-1958. This number reduces to 822 glaciers if we consider the bodies we grouped (Ghiacciaio dell'Adamello and Ghiacciaio della Lobbia) and those glaciers listed in the CGI inventory but lacking morphometric data. Among these, 181 were completely extinct in 2006-2007, 470 remained unitary, and 171 were fractionated to generate 243 new glaciers ("glacier sons").

Fig. 8 depicts the snapshot of 2006-2007 Italian glaciers including both existing (in grey) and extincts (in black) at the date of survey. The extinguished glaciers are distributed along the whole Italian Alps, with an evident reduction in the number of extinct glacial bodies in the easternmost sector of the Eastern. More than 97 % of the extinct glaciers had small size in 1957-1958 (<0.5 km^2) and, among these, more then 50 % had an area smaller then 0.1 km^2. Only few glaciers (slightly more than 2 %) had size comprised between 0.5 and 1 km^2.

We also identified 85 new glacial bodies (covering a total area of about 3 km^2), 27 of which were considered extinct in 1957-1958 and 58 are real new glacial bodies outlined in 2006-2007.

The new glaciers have not been taken into account when compared to data coming from the CGI Inventory.

The comparison between the number of extinct glaciers and those bodies generated by the fractionation ("parent" + "sons") plus those newly surveyed indicated an apparent incongruent increase of 147 glacier units between 1957-1958 and 2006-2007, bringing the total number of glaciers from 822 to 969.

The largest number and percentage of extinct glaciers is recognizable in the Alpi dell'Otztal, Venoste orientali and Passirie (2.8%). Similar values were also recorded in the Gran Paradiso, Otztal and Ortles.

The Alpi dell'Ortles and the Adamello Presanella contained the largest number of fractionated glaciers (25 and

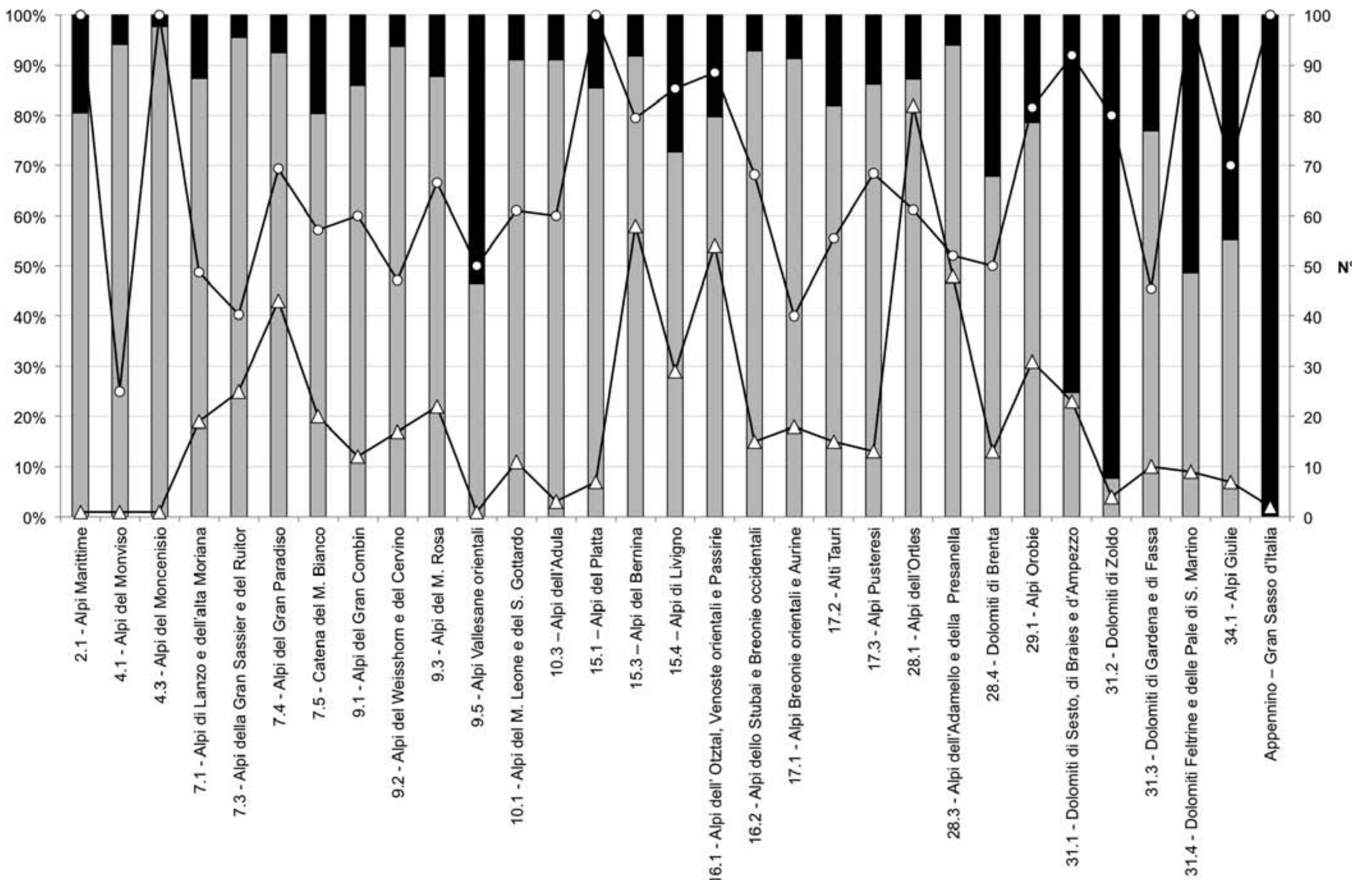


FIG. 7 - Frequency of number and percentage of glaciers in each ISMSA subsection and in the Apennine. Numbers and percentages of glaciers with debris cover are indicated by triangles and circles, respectively. Grey and black represent the percentage of debris-free and debris-covered area, respectively. See fig. 3 for subsection locations.

22, respectively), from which 37 and 27 new individuals were generated. The subsections containing glaciers that have maintained a total unitariness are the Dolomiti di Sesto, Feltrine, the Alpi Giulie and the Gran Sasso d'Italia.

Table 2 summarizes the data related to the number and areal extents of glaciers in the considered time intervals. To compare our data with the CGI Inventory, in cases of splitting glaciers, we considered the total area in 2006-2007 by adding the area of glaciers originated by fragmentation.

Our analysis indicates a total areal loss of approximately 140 km^2 between 1957-1958 and 2006-2007, which was equal to a reduction of approximately 27% for the entire Italian Alps after all the surveyed glaciers were considered. In both time periods, the widest glacierized area was found in the Alpi dell'Ortles (100.28 km^2 in the CGI Inventory and 76.5 km^2 in 2006-2007). On the contrary, the subsection with the least glaciation in the CGI Inventory was the Alpi Ticinesi del Verbano (0.14 km^2), where the glaciers had completely disappeared in 2006-2007. Considering the entire Italian territory, the Gran Sasso d'Italia had fewer glacierized areas during both time intervals (0.062 km^2 in CGI and 0.041 km^2 in 2006-2007).

Considering all the subsections separately, the mean percentage of reduction was approximately 42% and ranged from 10% to 60% (fig. 9). A dramatic glacial decrease occurred in Alpi Marittime and Alpi del Moncenisio, where we recorded an areal reduction of -96% and -95%, respectively. By contrast, a low percentage of reduction was recorded in Alti Tauri (-1%), Alpi del M. Bianco (-6%) and Orobie (-7%). Alpi dell'Ortles, Alpi dell'Adamello Presanella and Alpi del Monte Rosa, the three most extensively glacierized mountain groups in the Italian Alps, lost 24%, 11% and 25% of their glacial surfaces, respectively.

Only the Alpi Giulie subsection seemed to have undergone a slight surface increase during the considered time interval (+ 15%). This finding is opposite to the general trend of glaciers in the Italian Alps and can be explained by an underestimation of the areal extension reported by the CGI inventory, which used different measuring techniques. However, these avalanche-fed maritime glaciers, which are widely covered by debris, show higher sensitivity to precipitation than to air temperature (Carturan & *alii*, 2013c; Colucci & Guglielmin, 2015). This positive trend is consistent with the results by Colucci & *alii*

Table 1 - Total number of 2006-2007 time step glaciers compared with those listed in the CGI Inventory for each subsection. Columns refer to: 1) active glaciers listed in CGI Inventory the numbers in parentheses indicate the glacial units surveyed but not considered because quantitative data were not reported. Regarding subsection 28.3, the number in parentheses refers to six glaciers treated as separate in the CGI Inventory and then considered as a single glacial unit (the Adamello and Lobbia glaciers); 2) number and percentage of extinct glaciers in 2006-2007 respect to 1957-1958; 3) number and percentage of glaciers preserved integer in 2006-2007; 4) number and percentage of fractionated glacier (parent glaciers); 5) number of minors glacial units generated following the fractionation (son glaciers); 6) number of newly surveyed glaciers in 2006-2007 and glaciers active in 2006-2007 but considered extinct in 1957-1958; 7) total number of glaciers outlined in 2006-2007. The line in light gray highlight subsections entirely within the Italian territory.

SOIUSA SUBSECTION	1) n° of glaciers in CGI	2) n° and % of extinct glaciers in 2006-2007	3) n° and % in 2006 - 2007 (unfractionated)	4) n° and % of fractionated glaciers in 2006-2007 (parents glaciers)	5) n° of glaciers resulting from fractio-nation (sons glaciers)	6) n° of glaciers surveyed only in 2006-2007	7) n° of glaciers in 2006 - 2007
2.1 - Alpi Marittime	7	6 – 0.6%	1 – 0.1%	0 – 0.0%	0	0	1
4.1 - Alpi del Monviso	10 (+1)	6 – 0.6%	4 – 0.4%	0 – 0.0%	0	0	4
4.3 - Alpi del Moncenisio	4 (+1)	3 – 0.3%	1 – 0.1%	0 – 0.0%	0	0	1
7.1 - Alpi di Lanzo e dell'alta Moriana	26 (+2)	6 – 0.6%	13 – 1.3%	7 – 0.7%	12	7	39
7.3 - Alpi della Gran Sassier e del Ruitor	60	13 – 1.3%	38 – 3.9%	9 – 0.9%	10	5	62
7.4 - Alpi del Gran Paradiso	64	20 – 2%	32 – 3.3%	12 – 1.2%	16	2	62
7.5 - Catena del M. Bianco	30	1 – 0.1%	24 – 2.5%	5 – 0.5%	6	0	35
9.1 - Alpi del Gran Combin	18	6 – 0.6%	7 – 0.7%	5 - 0.5%	6	2	20
9.2 - Alpi del Weisshorn e del Cervino	29 (+2)	6 – 0.6%	16 – 1.6%	7 – 0.7%	12	1	36
9.3 - Alpi del M. Rosa	42	15 – 1.5%	23 – 2.4%	4 – 0.4%	5	1	33
9.5 - Alpi Vallesane orientali	4	2 – 0.2%	2 – 0.2%	0 – 0.0%	0	0	2
10.1 - Alpi del M. Leone e del S. Gottardo	20 (+2)	6 – 0.6%	11 – 1.1%	3 – 0.3%	3	1	18
10.2 - Alpi Ticinesi e del Verbano	1	1 – 0.1%	0 – 0.0%	0 – 0.0%	0	0	0
10.3 - Alpi dell'Adula	5	1 – 0.1%	3 – 0.3%	1 – 0.1%	1	0	5
15.1 - Alpi del Platta	8	1 – 0.1%	7 – 0.7%	0 – 0.0%	0	0	7
15.3 - Alpi del Bernina	51	6 – 0.6%	30 – 3.1%	15 – 1.5%	19	9	73
15.4 - Alpi di Livigno	26	4 – 0.4%	17 – 1.7%	5 – 0.5%	8	4	34
16.1 - Alpi dell' Otztal, Venoste orientali e Passirie	79	27 – 2.8%	45 – 4.6%	7 – 0.7%	8	1	61
16.2 - Alpi dello Stubai e Breonie occidentali	18	4 – 0.4%	11 – 1.1%	3 – 0.3%	8	0	22
17.1 - Alpi Breonie orientali e Aurine	31	3 – 0.3%	16 – 1.6%	12 – 1.2%	16	1	45
17.2 - Alti Tauri	18	3 – 0.3%	6 – 0.6%	9 – 0.9%	12	0	27
17.3 - Alpi Pusteresi	8	1 – 0.1%	2 – 0.2%	5 – 0.5%	8	4	19
28.1 - Alpi dell'Ortles	112	21 – 2.2%	66 – 6.8%	25 – 2.6%	37	6	134
28.3 - Alpi dell'Adamello e della Presanella	73 (+6)	12 – 1.2%	39 – 4.0%	22 – 2.3%	27	4	92
28.4 - Dolomiti di Brenta	16	2 – 0.2%	10 – 1.0%	4 – 0.4%	12	0	26
29.1 - Alpi Orobie	20	2 – 0.2%	14 – 1.4%	4 – 0.4%	4	16	38
31.1 - Dolomiti di Sesto, di Braies e d'Ampezzo	19	0 – 0.0%	19 – 1.9%	0 – 0.0%	0	6	25
31.2 - Dolomiti di Zoldo	6	2 – 0.2%	4 – 0.4%	0 – 0.0%	0	1	5
31.3 - Dolomiti di Gardena e di Fassa	7	1 – 0.1%	2 – 0.2%	4 – 0.4%	8	8	22
31.4 - Dolomiti Feltrine e delle Pale di S. Martino	2	0 – 0.0%	1 – 0.1%	1 – 0.1%	1	6	9
34.1 - Alpi Giulie	7	0 – 0.0%	6 – 0.6%	1 - 0.1%	3	0	10
Appennino - Gran Sasso d'Italia	1	0 – 0.0%	0 – 0.0%	1 – 0.1%	1	0	2
TOTAL	822 (836)	181 - 19%	470 – 49%	171 – 18%	243	85	969

TABLE 2 - Total area and number of glaciers in 2006-2007 compared to those recorded in the CGI Inventory for each subsection. In parentheses the area and number of newly surveyed glaciers in 2006-2007 and glaciers active in 2006-2007 but considered extinct in 1957-1958). The lines in light gray highlight subsections entirely within the Italian territory.

SOIUSA SUBSECTION	Glaciers area in CGI (km^2)	n° of Glaciers in CGI	Glaciers area in 2006–2007 (km^2)	n° of glaciers in 2006 - 2007	Δ area (km^2)	Δ area (%)	Δ n°	Δ n° (%)
2.1 - Alpi Marittime	1.050	7	0.041	1	-1.009	-96	-6	-86
4.1 - Alpi del Monviso	1.644	10	0.136	4	-1.508	-92	-6	-60
4.3 - Alpi del Moncenisio	1.750	4	0.088	1	-1.662	-95	-3	-75
7.1 - Alpi di Lanzo e dell'alta Moriana	12.440	26	6.361 (+0.191)	32 (+7)	-6.079	-49	6	19
7.3 - Alpi della Gran Sassier e del Ruitor	42.712	60	28.110 (+0.377)	57 (+5)	-14.602	-34	-3	-5
7.4 - Alpi del Gran Paradiso	40.470	64	28.183 (+0.045)	61 (+1)	-12.287	-30	-3	-5
7.5 - Catena del M. Bianco	41.030	30	38.458	35	-2.572	-6	5	14
9.1 - Alpi del Gran Combin	6.670	18	3.070 (+0.054)	18 (+2)	-3.600	-54	0	0
9.2 - Alpi del Weisshorn e del Cervino	25.330	29	15.368 (+0.018)	35 (+1)	-9.962	-39	6	17
9.3 - Alpi del M. Rosa	51.110	42	38.386 (+0.026)	32 (+1)	-12.724	-25	-10	-24
9.5 - Alpi Vallesane orientali	0.810	4	0.387	2	-0.423	-52	-2	-50
10.1 - Alpi del M. Leone e del S. Gottardo	12.650	20	6.280 (+0.017)	17 (+1)	-6.370	-50	-3	-15
10.2 - Alpi Ticinesi e del Verbano	0.140	1	0.000	0	-0.140	-100	-1	-100
10.3 - Alpi dell'Adula	1.565	5	0.671	5	-0.894	-57	0	0
15.1 - Alpi del Platta	2.285	8	1.061	7	-1.224	-54	-1	-13
15.3 - Alpi del Bernina	36.356	51	29.139 (+0.04)	71 (+2)	-7.217	-20	20	28
15.4 - Alpi di Livigno	7.075	26	4.234 (+0.025)	32 (+2)	-2.841	-40	6	19
16.1 - Alpi dell' Otztal, Venoste orientali e Passirie	39.038	79	25.350 (+0.068)	60 (+1)	-13.688	-35	-19	-24
16.2 - Alpi dello Stubai e Breonie occidentali	14.215	18	10.460	22	-3.755	-26	4	18
17.1 - Alpi Breonie orientali e Aurine	14.920	31	11.164 (+0.092)	44 (+1)	-3.756	-25	13	30
17.2 - Alti Tauri	4.608	18	4.539	27	-0.069	-1	9	33
17.3 - Alpi Pusteresi	6.985	8	5.471 (+0.978)	15 (+4)	-1.514	-22	7	47
28.1 - Alpi dell'Ortles	100.280	112	76.531 (+0.008)	133 (+1)	-23.749	-24	22	17
28.3 - Alpi dell'Adamello e della Presanella	48.734	73	43.293 (+0.085)	89 (+3)	-5.441	-11	16	18
28.4 - Dolomiti di Brenta	3.227	16	1.125	26	-2.102	-65	10	38
29.1 - Alpi Orobie	1.845	20	1.719 (+0.082)	33 (+5)	-0.126	-7	13	39
31.1 - Dolomiti di Sesto, di Braies e d'Ampezzo	3.150	19	1.899 (+0.133)	19 (+6)	-1.251	-40	0	0
31.2 - Dolomiti di Zoldo	0.520	6	0.272 (+0.012)	4 (+1)	-0.248	-48	-2	-33
31.3 - Dolomiti di Gardena e di Fassa	3.920	7	1.862 (+0.446)	14 (+8)	-2.058	-53	7	50
31.4 - Dolomiti Feltrine e delle Pale di S. Martino	0.790	2	0.305 (+0.298)	3 (+6)	-0.485	-61	1	33
34.1 - Alpi Giulie	0.377	7	0.444	10	0.067	15	3	30
Appennino - Gran Sasso d'Italia	0.062	1	0.041	2	-0.021	-34	1	50
TOTAL	527.758	822	384.448 (387.443)	911 (969)	-140.315	-27	147	15

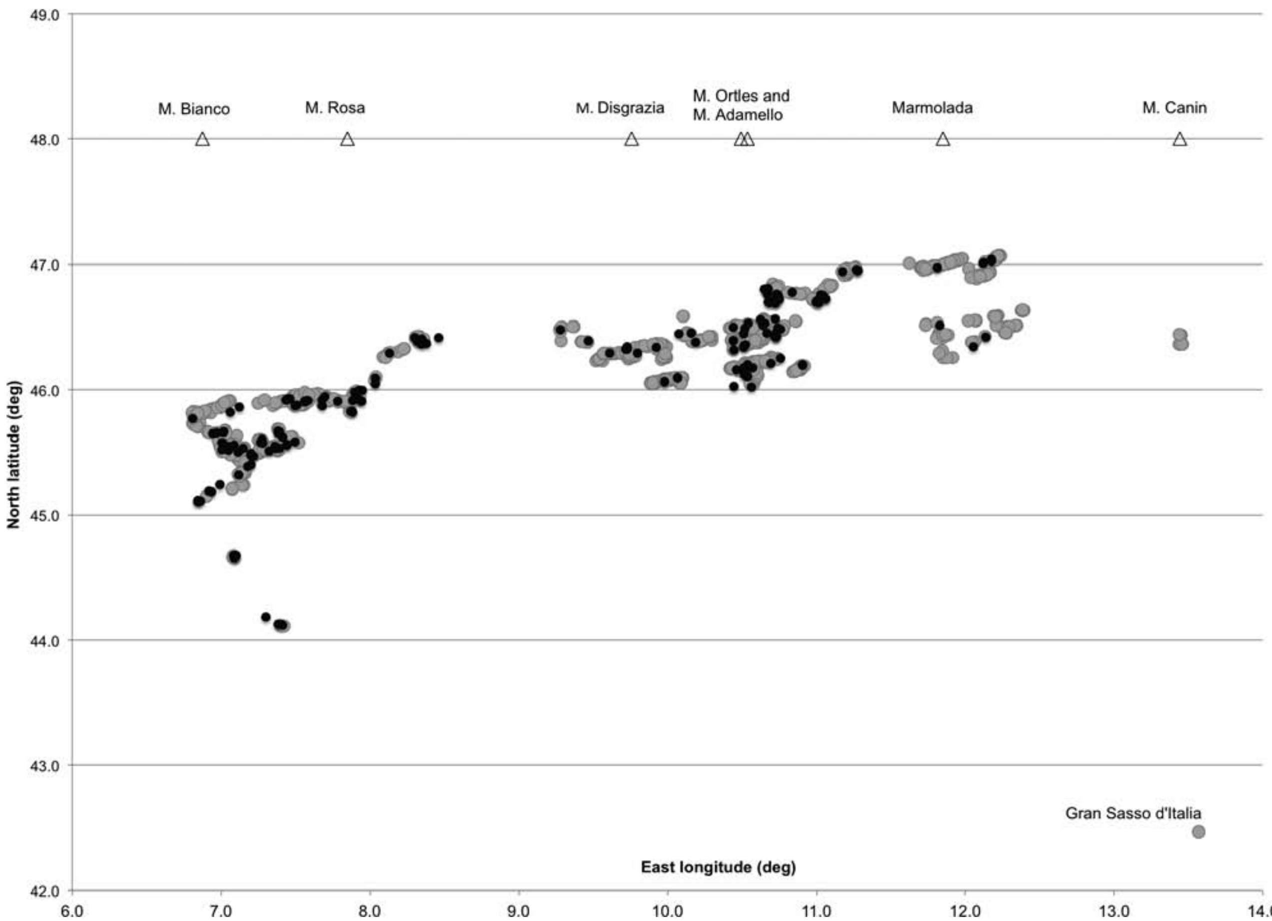


FIG. 8 - Snapshot of existing (in gray) and extinct (in black) Italian glaciers in 2006-2007 hydrological period.

(2015) indicating a doubling in the areal extension of the Ghiacciaio del Canin Orientale between 2006 and 2011.

The number of glaciers increased from 822 glaciers in the CGI Inventory (836, considering the bodies we grouped and those glaciers listed in the CGI Inventory but lack morphometric data) to 969 in 2006-2007. Considering the entire Italian Alps, the percentage increase in the number of glaciers was more significant in the eastern sector (Table 1 and fig. 10) starting from Alpi del Bernina.

In particular, an increase occurred in 17 subsections, whereas only 3 subsections showed the same number of glaciers. In 12 subsections, despite fragmentation, the number of glaciers decreased (fig. 10).

Excluding the subsections containing few glaciers in 1957-1958, the largest reductions in the number of glacial bodies are recorded in Alpi del M. Rosa and Alpi dell'Otztal (-24%), Alpi del M Leone e S. Gottardo (-15%) and Alpi del Gran Paradiso (-5%).

Some relevant considerations of the glacier distribution in the Italian Alps include the elevation of fronts and the mean elevation of each glacier of the Italian Alps as a function of latitude and longitude. From the western to the eastern margins, the Italian Alps encompasses approximately 7° of longitude and approximately 2.6° of latitude.

The data from both time intervals indicated that the positions of the fronts considerably varied by altitude at different longitudes (fig. 11). The variance of front elevation exhibited a wide range, showing slight fluctuations from mean elevations in the West, stronger fluctuations from 8° to 13° E, and a minimum fluctuation at the easternmost margin. The linear regression function indicated that in general, the fronts tended to descend in elevation from the West towards the East. The slight convergence to the right of the two linear regressions showed that the increased elevations of the fronts from 1957-1958 to 2006-07 was higher in the western sector than in the eastern sector, where glaciers in Alpi Giulie showed substantial stability despite the warming climate in recent years (Carturan & *alii*, 2013c; Colucci & *alii*, 2015; Colucci & Guglielmin, 2015).

The same trend is also evident in fig. 12 which depicts the mean elevation of the glaciers as a function of longitude. The general trend displayed similar behaviour to the previous trend, but the variation of the average altitudes of the glaciers (indicated by the linear regression) was lower with respect to the frontal elevation data.

The comparison between the 2006-2007 data and the CGI Inventory (CGI-CNR, 1959, 1961a, 1961b, 1962) data showed a significant increase in the number of glaciers within the <0.1 km^2 size class (fig. 13), changing from 224 glaciers (27.3%) to 475 (52.1%). This also suggested an increase in the areal extent of glaciers in this class (from 12.2 km^2 in the CGI Inventory to 18.8 km^2 in 2006-2007, corresponding to 2.3% and 4.9% of the total area, respectively). By contrast, all the other classes showed decreased numbers and areas of glaciers, with area losses varying from 20 km^2 to more than 30 km^2 in each class. The maximum area loss was registered for the 0.1 - 0.5 km^2 class size, which corresponded to a total reduction of 34 km^2.

As it concerns the size classes > 1 km^2, the areal reduction exceeded 20 km^2 in each class. However, the strong area loss was not followed by an increased reduction in the number of glaciers in each class.

The aspect of glacier bodies over the entire Italian Alps shows that the greatest glacier area and number of glaciers were mainly concentrated in the northern sectors (NW, N and NE). Comparing the CGI data and those of 2006-2007, we observed a general increase in the number of glaciers with N and NW aspects (fig. 14). A slight but limited increase in the apparatus number was also observed for both the E and SW aspects. By contrast, a slight decrease was detected in the sectors facing NE, SE and W. The S-facing sector (with 5% of glaciers) remained constant.

In the comparison of aspect and areal variation (fig. 15), there was a relative increase of glacierized surfaces

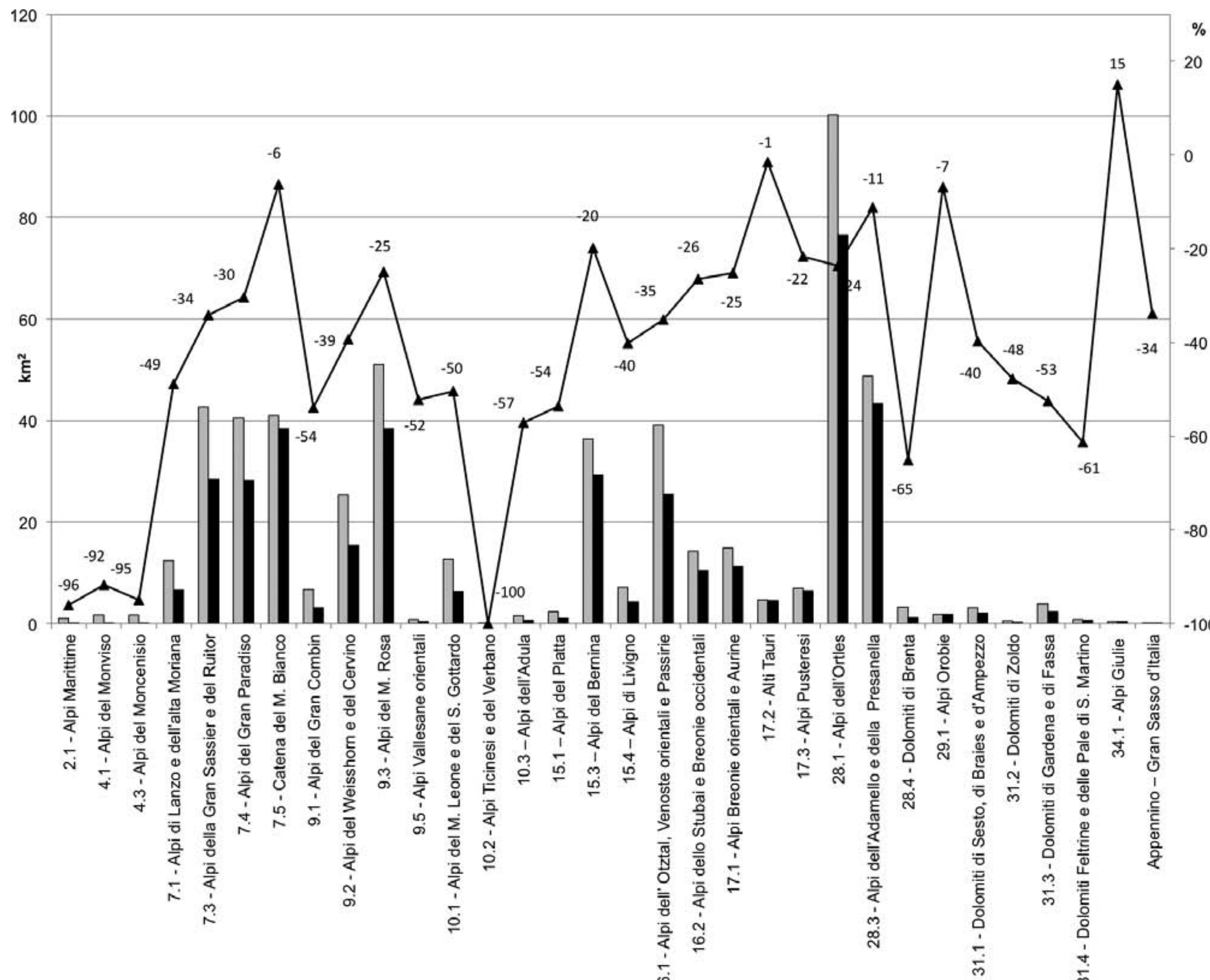


FIG. 9 - Comparison between glacier area in each subsection in 2006-2007 (in black) and in 1957-1958 (in grey, CGI Inventory). Numbers with black triangles indicate the percentage of areal variation in each ISMSA subsection and in the Apennines (excluding glaciers newly identified in 2006-2007). See fig. 3 for ISMSA subsection locations.

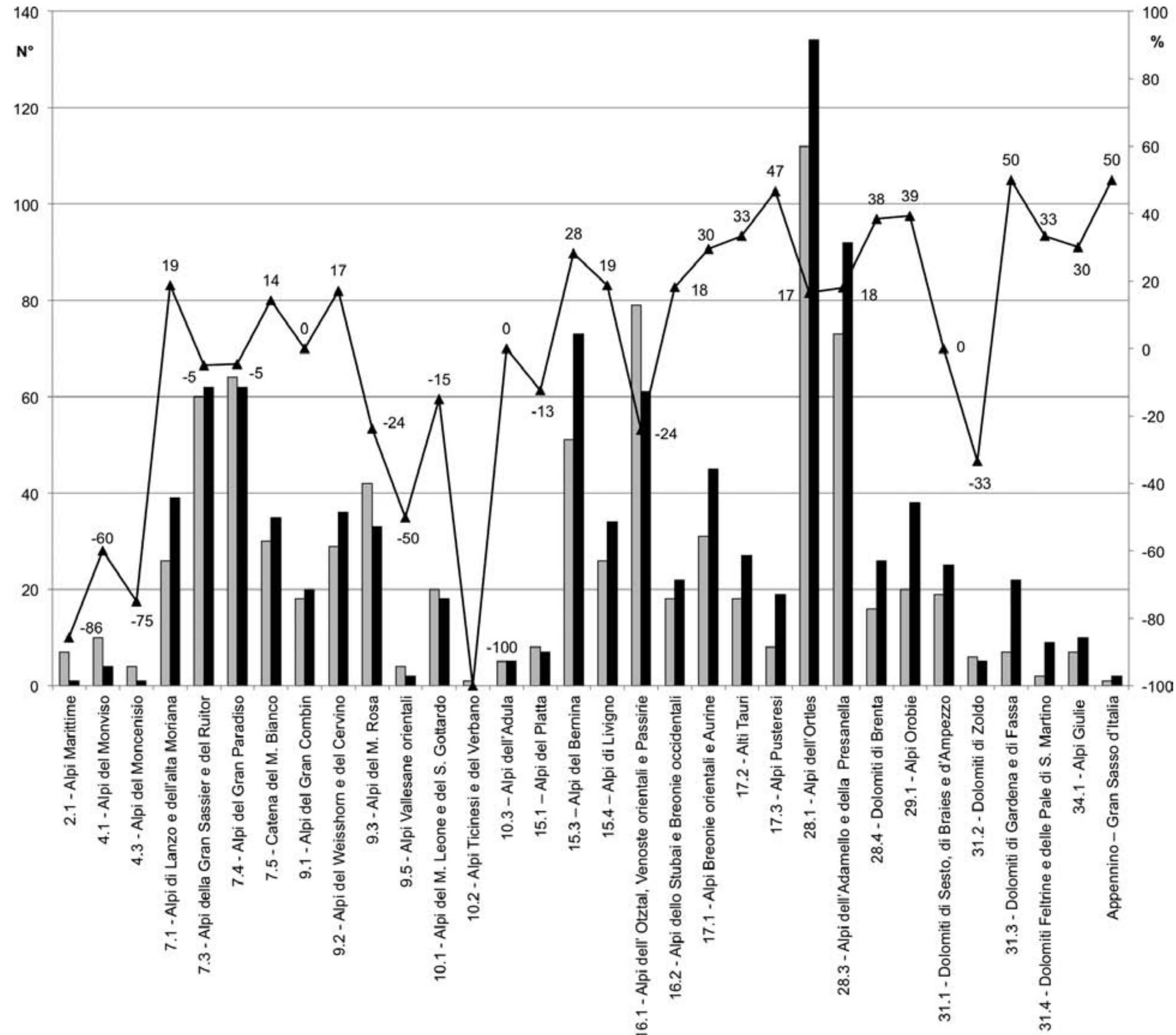


FIG. 10 - Comparison between glacier number in each subsection in 2006-2007 (in black) and in 1957-1958 (in grey, CGI Inventory). Numbers with black triangles indicate the percentage of variation in the number of glacial bodies in each ISMSA subsection and in the Apennine (excluding glaciers newly identified in 2006-2007). See fig. 3 for ISMSA subsection locations.

facing the N and E despite a generally decreasing trend. The areal reduction was concentrated both in the NW- and NE- facing sectors and in the S- and SE-facing sectors. Glaciers with aspects towards W and SW remained constant or registered slight increases.

Figure 16 depicts in detail the aspects of the complete set of Italian glaciers within the different sections of the Italian Alps in 2006-2007. In Alpi Graie (Section 7), there was prevalent SE exposure, whereas in Alpi Pennine (Section 9) there was prevalent SW exposure. In Alpi Retiche (Sections 15 and 16), the glaciers were oriented more or less with similar N, E and SW facing extensions. In the remaining sections, the glaciers were mainly distributed towards the northern quadrants.

Glacier exposure in some alpine sections was the same in 2006-2007 as in the CGI Inventory despite decreased surface areas, with only weak variations. This was the case for Alpi Pennine (9), Lepontine (10), Retiche orientali (16), Alpi e prealpi bergamasche (29), Dolomiti (31), and Giulie (34). In the other sections, the areal increase or reduction was slightly higher in different quadrants: in Alpi Graie (7), there was an increase to the N and a decrease to the NE and NW; in Alpi Retiche occidentali (15), the decrease was concentrated in the N, E and S sectors, whereas an increase was registered in the SE sector; in Alpi dei Tauri occidentali (17), there was a strong decrease to the NW and SE, with an increase to the W; and in Alpi Retiche meridionali (28), there was a reduction in the NW sector and an increase in the E sector.

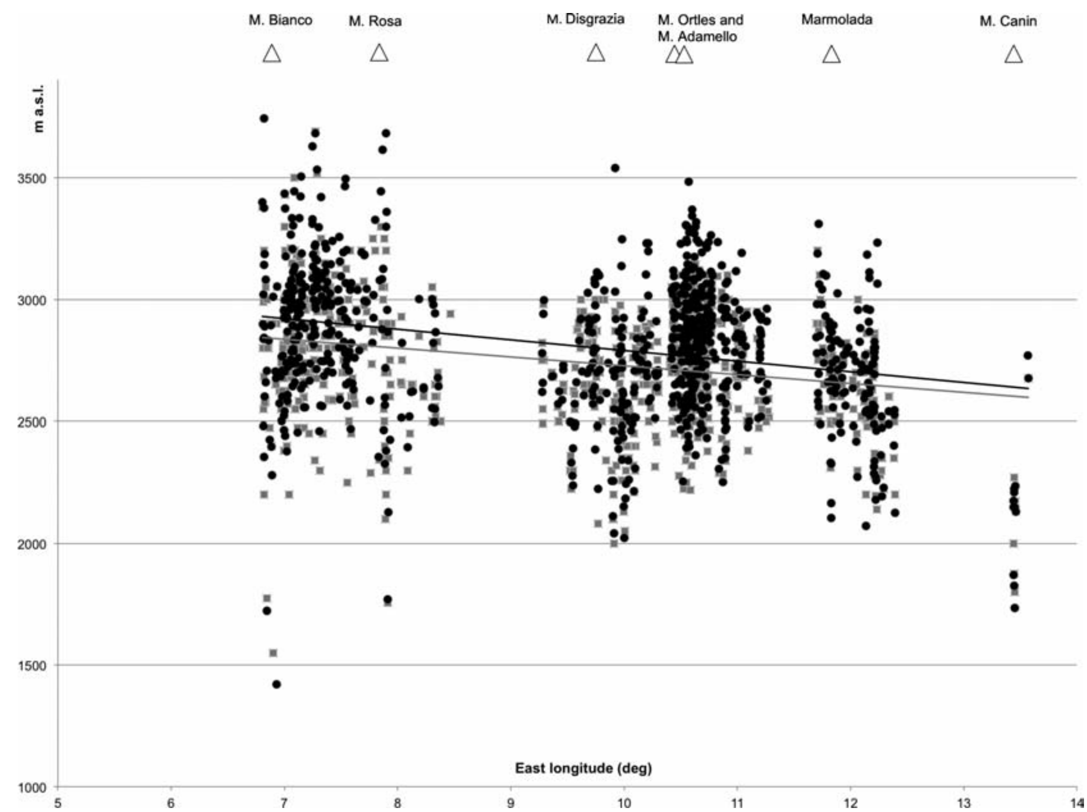


FIG. 11 - Altimetric distribution of Italian glacier fronts with respect to longitude in 2006-2007 (black) and in the CGI Inventory (grey). The linear regression of frontal elevation of the two considered time intervals is shown. Triangles indicate the geographical position of the main peaks of the Italian Alps.

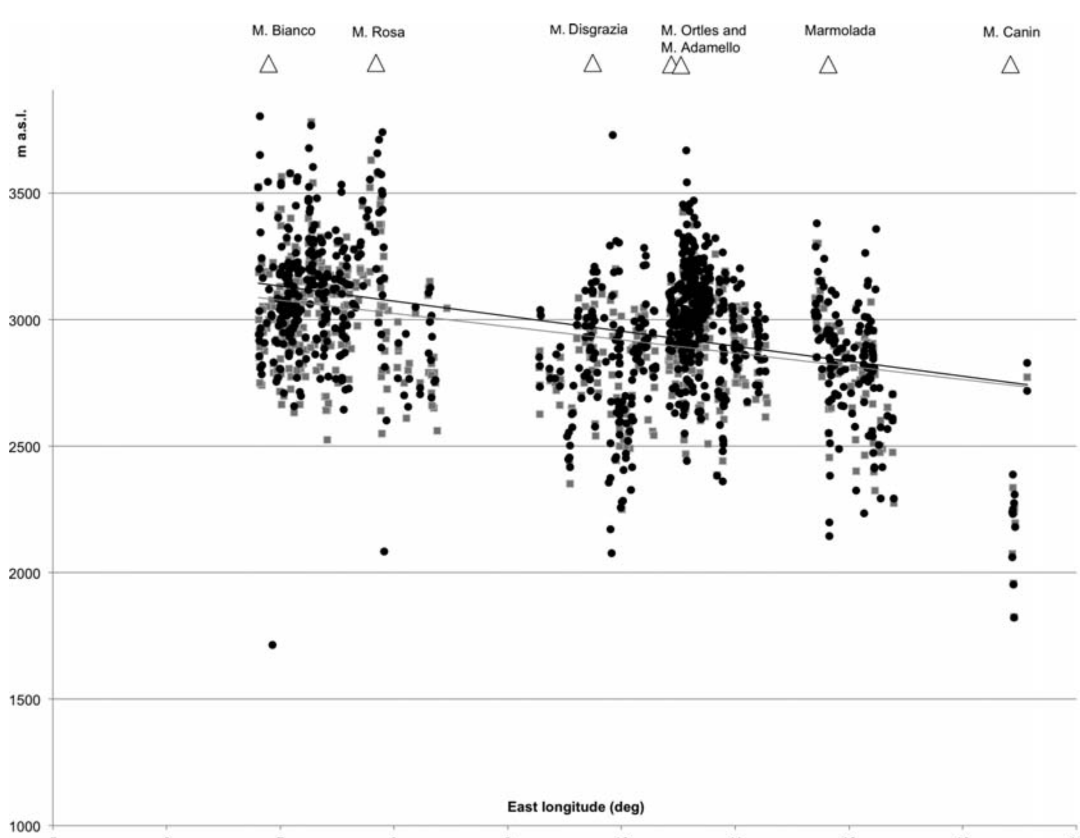


FIG. 12 - Altimetric distribution of mean elevation of Italian glaciers with respect to longitude in 2006-2007 (black) and in the CGI Inventory (grey). The linear regression of frontal elevation of the two considered time intervals are shown. Triangles indicate the geographical position of the main peaks of the Italian Alps.

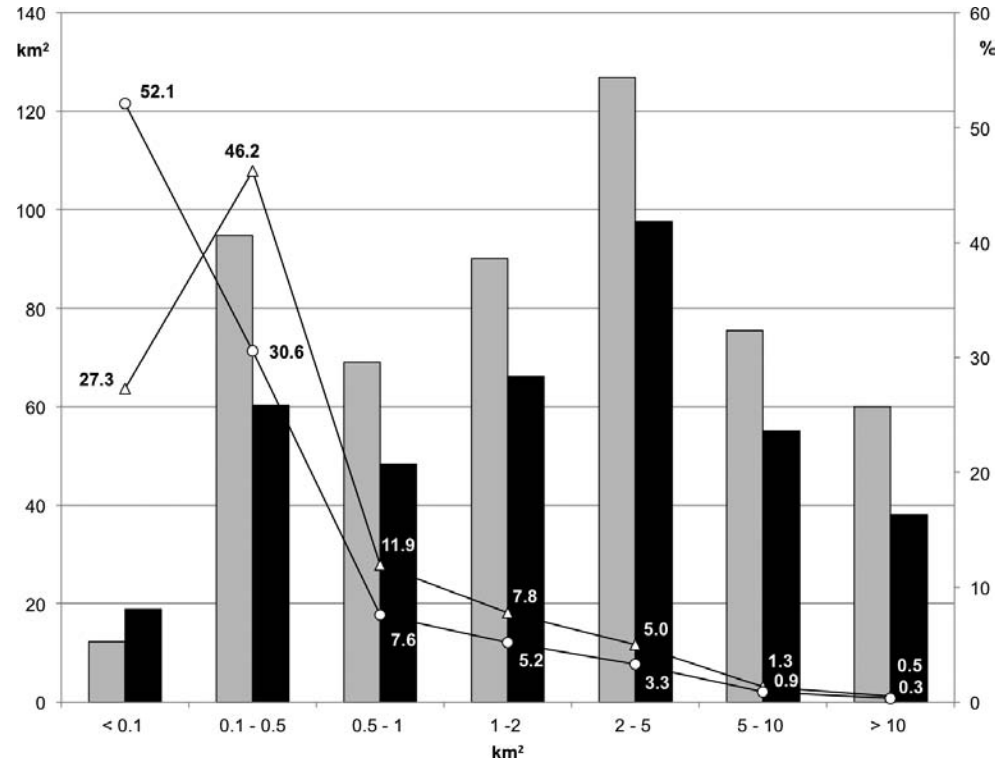


FIG. 13 - Comparison of areal frequency distribution and percentage of Italian glaciers in the 2006-2007 (black and circles, respectively) and 1957-1958 data (CGI Inventory, grey and triangles, respectively). Different size classes are considered.

The remaining sections were slightly changed in overall appearance, as in the case of Alpi Marittime (2) and Cozie (4), which displayed a total migration to the North.

CONCLUSIONS

Italian glaciers have experienced a phase of generalized retreat since the end of the maximum Holocene advance, which occurred during the Little Ice Age (LIA). Evidence indicates that a number of Italian glaciers registered their maximum Holocene position during the first decades of the 17^{th} century (Baroni & Carton, 1990, 1996;; Deline, 1999; Pelfini, 1999; Baroni & *alii*, 2014b; Carturan & *alii*, 2014), but most glaciers reached their maximum position in the first half of the 19^{th} century (Orombelli & Porter, 1982; Orombelli, 2011). The glacial retreat, which followed the end of the LIA and was accentuated in the 1950s, was interrupted by a slight advancing stage that occurred in the late 1970s and early 1980s; annual glaciological surveys of the Italian Glaciological Committee have demonstrated a general withdrawal of almost all the Italian glaciers since the 1990s (CGI, 1928-1977; CGI 1978-2010; Pelfini & Smiraglia, 1997; Santilli & *alii*, 2002; Baroni & *alii*, 2011, 2012, 2013, 2014a, 2015; Zemp & *alii*, 2015).

Therefore, the snapshot of the state of Italian glaciers supplied for 2006-2007 depicts a significant glacial retreat following the slight advance that registered for less than a decade during the late 1970s and early 1980s, which is still underway.

Although the data reported in the CGI inventory (CGI-CNR, 1959, 1961a, 1961b, 1962) were surveyed using different techniques, the comparison of the two datasets allowed for two snapshots of glaciers hosted on the entire Italian alpine chain. Of the 836 glaciers surveyed in the late 1950s (822 considering the bodies we grouped and those glaciers that lacked morphometric data), many were fractionated as a consequence of the strong shrinkage, thus generating new, smaller glacial bodies and giving rise to 969 glacial units in 2006-2007. Between 1957-1958 and 2006-2007, the initial glacierized area of approximately 527 km^2 ± 5-10% was reduced to 387.4 km^2 ± 2%, a reduction of approximately 140 km^2 (ca. -27%). Worthy of attention is the trend of maritime glaciers hosted in Alpi Giulie that have undergone a slight surface increase in recent times; these glaciers show higher sensitivity to changes in precipitation rates rather than increasing air temperatures (Carturan & *alii*, 2013c; Colucci & Guglielmin, 2015; Colucci & *alii*, 2015).

In the snapshot of Italian glaciers in 2006-2007, we also considered and outlined the supraglacial debris, taking into account that the presence of debris on a glacier's surface plays an important role in mass balance and glacier dynamics as debris thickness affects the rate of ice melt and glacial hydrology (Mattson, 2000; Scherler & *alii*, 2011; Nicholson & Benn, 2013; Juen & *alii*, 2014; Pratap & *alii*, 2015). In fact, the diffuse and increasing presence of supraglacial debris is a consequence of the recent climate warming; as demonstrated in several glacierized areas, supraglacial debris can significantly attenuate subglacial ice melting (Foster & *alii*, 2009; Lambrecht & *alii*, 2011; Collier & *alii*, 2015; Rowan & *alii*, 2015).

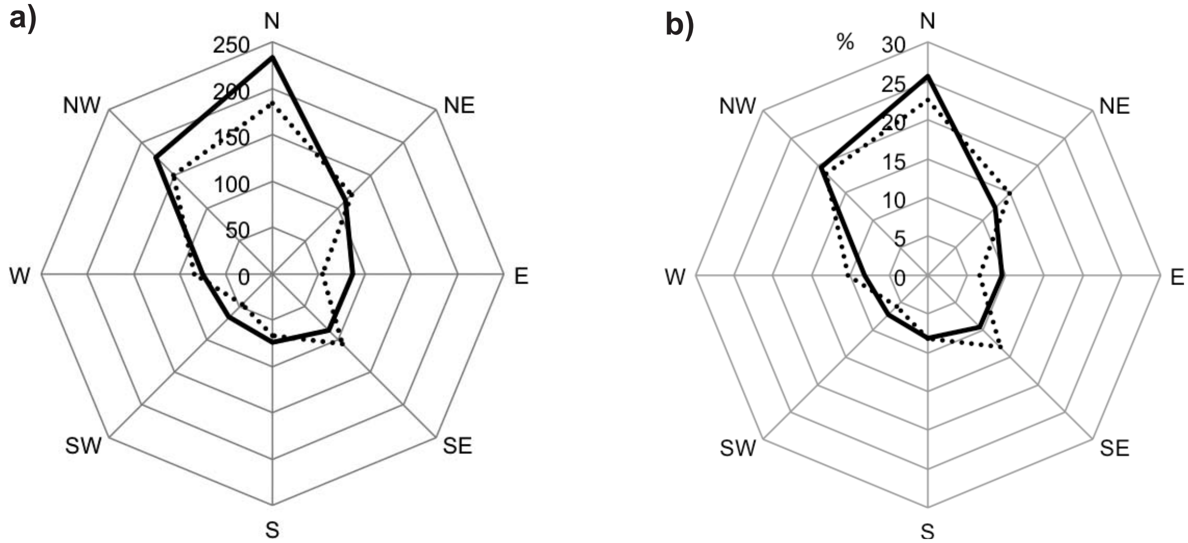


FIG. 14 - Frequency distribution of glacier number (a) and percentage (b) with respect to aspect in the Italian Alps. The black line represents the 2006-2007 time step (excluding glaciers newly identified in 2006-2007) and the dotted line represents the CGI Inventory.

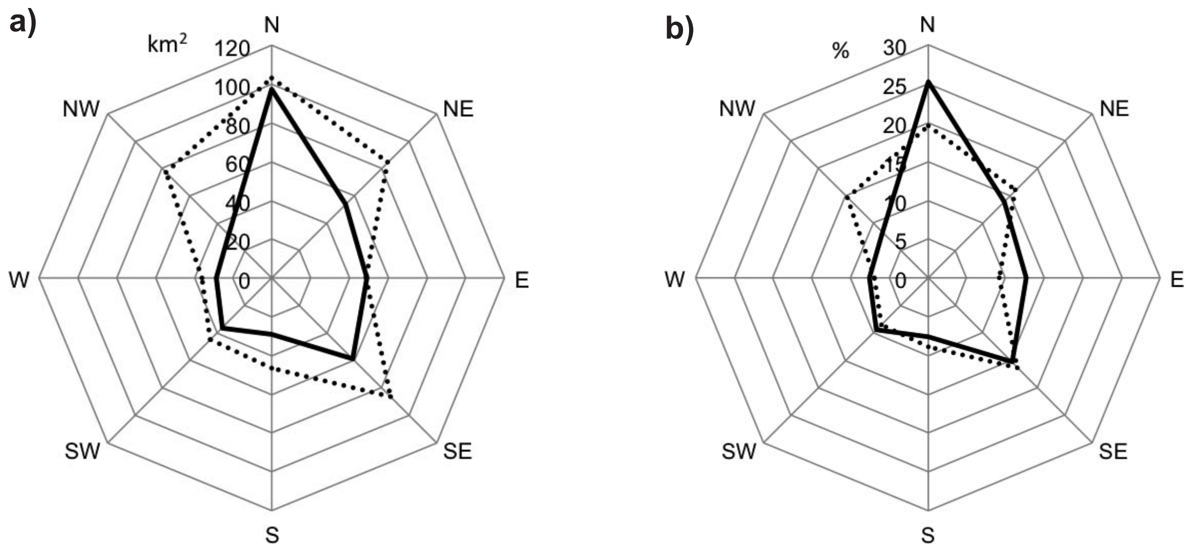


FIG. 15 - Frequency distribution of glacier areal extension (a) and percentage (b) of glacierized surface with respect to aspect in the Italian Alps. The black line represents the 2006-2007 time interval (excluding glaciers newly identified in 2006-2007) and the dotted line represents the CGI Inventory.

Our data provide the first complete inventory of a very short time interval of both glacier and debris coverage, representing the first step for monitoring the evolution of glaciers along the entire Alpine chain. The comparison of our data with those derived from annual glaciological surveys performed by CGI highlights a gradual increase in debris cover, which induces an apparent slowdown in the withdrawal of fronts in the ablation zone and a progressive decline and contraction of the accumulation basins.

The original data on single glacial bodies used in the WGI (WGMS, 1989) are not available or validated. Furthermore, the dates of the aerial photographs used for the inventory spans from 1975 to 1984 encompass a long time interval (ten years). Therefore, our data and the WGI data are not completely comparable for quantitative purposes; nevertheless, they supply very significant qualitative information about recent glacial shrinkage. In the early 1980s, following the last slight glacial advance phase registered in the Alps, the glacial extension reported by the WGI was 607 km^2 (WGMS, 1989). These findings indicated that the glaciers of the Italian Alps lost approximately 120 km^2 of their area in less than 30 years, which corresponded to a reduction of approximately 20%.

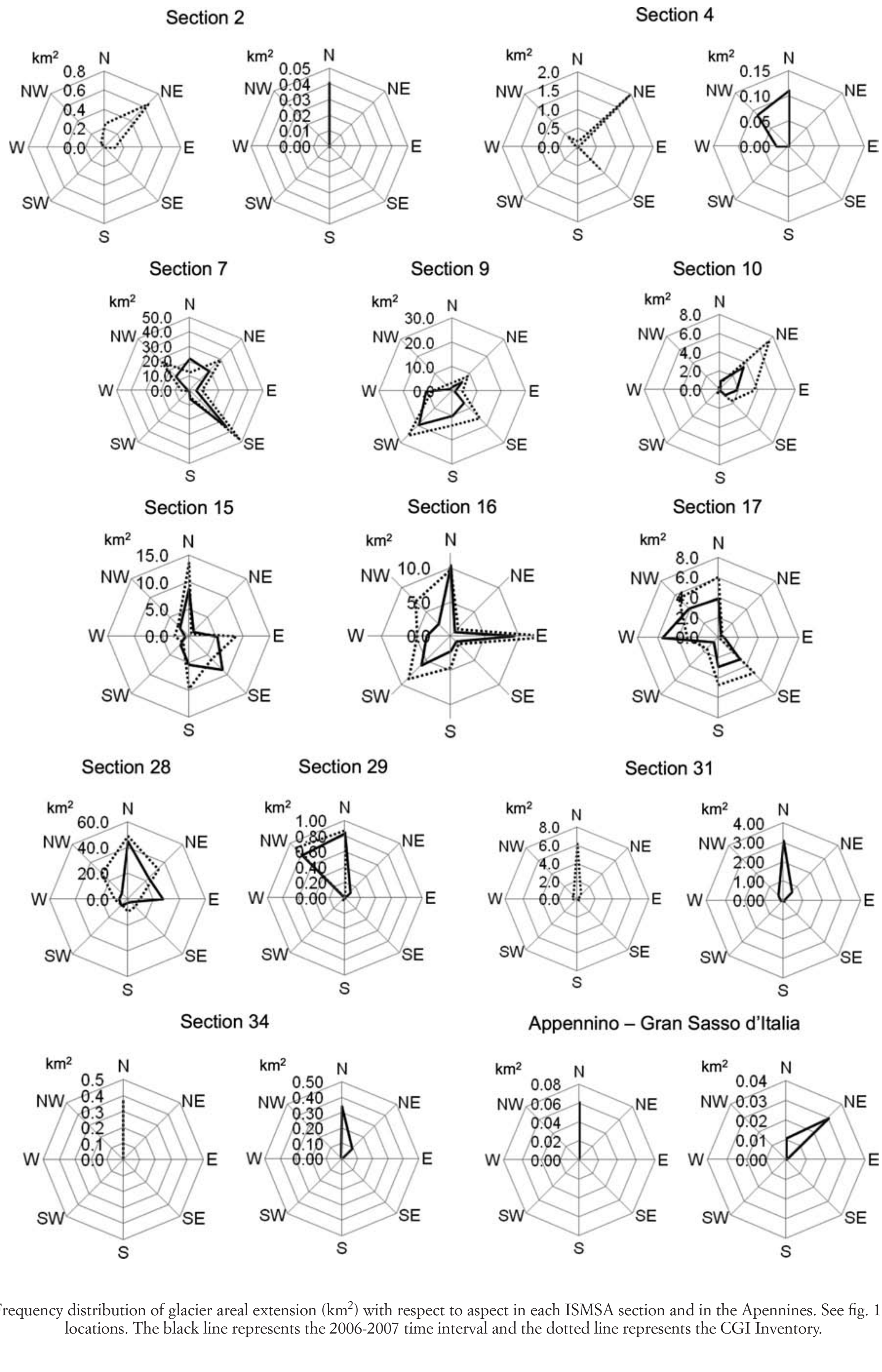


FIG. 16 - Frequency distribution of glacier areal extension (km^2) with respect to aspect in each ISMSA section and in the Apennines. See fig. 1 for section locations. The black line represents the 2006-2007 time interval and the dotted line represents the CGI Inventory.

Considering a shorter time interval, the comparison with preliminary data on the extent of the glaciers in the Italian Alps during the 1988-89 (Ajassa & *alii*, 1997), in which only glaciers larger than 5 ha were counted, underlines a reduction of approximately 90 km^2 in 2006-2007 (corresponding to an area loss of approximately 20%). Finally, data supplied by Smiraglia & *alii* (2015) report 903 glaciers covering 368.9 ± 2% km^2 but refer to a wider temporal window embracing seven years (from 2005 to 2011).

During recent decades, almost 100% of the monitored Italian glaciers have retreated, and numerous alpine glaciers have repeatedly been found entirely below the snowline. Moreover, significant contractions of the accumulation basins as well as thinning of glacial bodies and tongues have been recorded.

Only the inertia of the ice has allowed most of the Italian glaciers to overcome recent critical withdrawal: the strong imbalance that seems to characterize the glaciers compared to current climatic conditions suggests that if this situation continues, further dramatic areal and volume reductions must be expected.

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