Glacier shrinkage driven by climate change during half a century (1954–2007) in the Ortles-Cevedale group (Stelvio National Park, Lombardy, Italian Alps)

Carlo D'Agata · Daniele Bocchiola · Davide Maragno · Claudio Smiraglia · Guglielmina Adele Diolaiuti

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1 Introduction

In the recent past, glaciers have begun melting at rates that cannot be explained only by natural climate variability (Dyurgerov and Meier 2000). Glacier shrinkage is particularly severe upon the Alps, and it is likely driven by the important changes occurring in mid-tropospheric conditions, such as the widely acknowledged rapid increase in temperature during the last few decades (IPCC 2001, 2007). In the Alps, atmospheric warming was estimated to be more than double of the planet average over the last 50 years (Böhm et al. 2001), with a significant summer warming, particularly severe since 1970 (Casty et al. 2005). Between 1850 and 1980, glaciers in the European Alps lost approximately one third of their area and one half of their mass, and since 1980, another 20 to 30 % of the ice has melted (European Environment Agency (EEA) 2004).

Among possible methods to analyse the ongoing evolution of glaciers, the collection and analysis of glacier inventories (e.g. glacier area and geometry features) can be used to investigate mountain glaciers in a changing climate (Paul et al. 2004) and potential scenarios on the regional Alpine

C. D'Agata · D. Maragno · C. Smiraglia · G. A. Diolaiuti
Dipartimento di Scienze della Terra "A. Desio", Università degli Studi di Milano, Milan, Italy

D. Bocchiola (✉)
DICA Politecnico di Milano, Milan, Italy
e-mail: daniele.bocchiola@polimi.it

D. Bocchiola · C. Smiraglia · G. A. Diolaiuti
EVK2CNR Committee, Bergamo, Italy

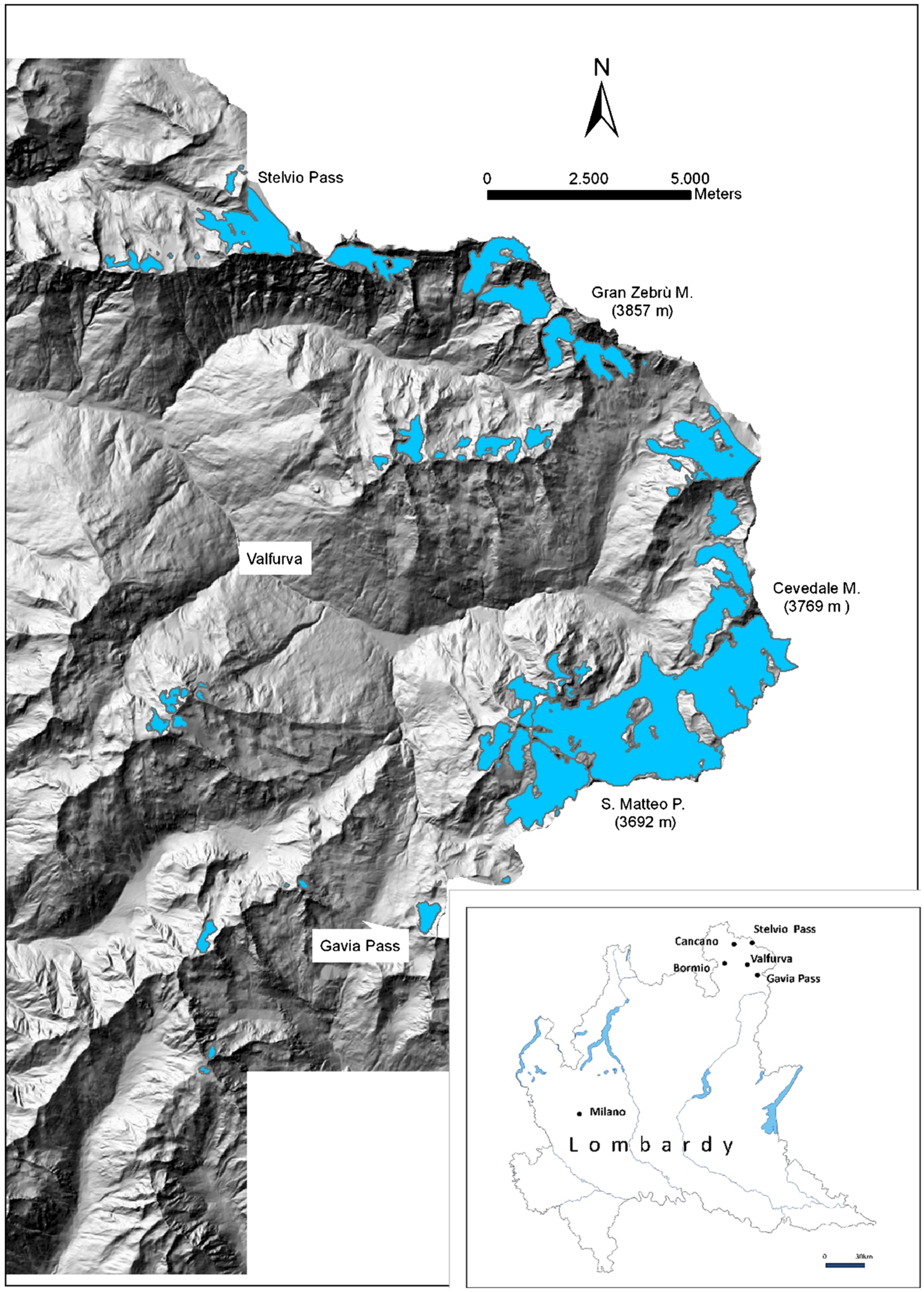
scale (Zemp et al. 2006). Glacier geometry changes are indeed key variables with respect to strategies for the early detection of enhanced greenhouse effects on climate (Kuhn 1980; Hoelzle et al. 2003). Glacier inventories should be carried out at intervals compatible with the characteristic dynamic response times of mountain glaciers (a few decades or less in the case of small glaciers), and the currently observed glacier downwasting calls for frequent updates of inventories (Paul et al. 2007). In the Alps, Maisch (2000) evaluated an overall decrease of 27 % from the mid-nineteenth century to the mid-1970s, and losses were even greater in some areas. Even more striking was the recession in the Berne–Valais area during 1973–1998 (Kääb et al. 2002). The strongest area reduction is affecting small glaciers (i.e. glaciers with surface area <1 km^2) that cover roughly 80 % of the census in the Alps and make an important contribution to water resources (Citterio et al. 2007a; Bocchiola et al. 2010; Diolaiuti et al. 2012a, b). Paul et al. (2004) compiled the Swiss Glacier Inventory 2000 and estimated that 44 % of the glacier area reduction during 1973–1998/1999 was charged to glaciers shorter than 1 km, encompassing 18 % of the total area in 1973. Lambrecht and Kuhn (2007) estimated that Austrian glacier covered area decreased of about 17 % during 1969–1998. Knoll and Kerschner (2009) reported a decrease of area of the South Tyrolean glaciers of approximately 36 % during 1983–2006, mainly due to small glaciers (0.1 km^2<area< 1 km^2), responsible for 23.8 % of the total reduction. Diolaiuti et al. (2012a, b) analysed geometry changes of several glaciers in the Italian Alps (Lombardy and Val d'Aosta regions) during 1991–2003 and 1975–2005, respectively. They found that Aosta Valley glaciers lost 44.3 km^2 during 1975–2005, i.e. approximately 27 % of the initial area, and Lombardy glaciers experienced a 21 % reduction in the period 1991–2003. In Lombardy, glaciers smaller than 1 km^2 accounted for 53 % of the total loss in area and an acceleration in the reduction rate was found (i.e. the area change rate was higher lately, during 1999–2003). A similar accelerating trend was experienced by Aosta Valley glaciers (stronger retreat in 1999–2005).

Here, we studied recent (i.e. last 50 years) changes affecting a representative Italian glacierised group (namely, Ortles-Cevedale glaciers, Stelvio National Park, Lombardy Alps) and their link to climate variability. The Lombardy sector of the Ortles-Cevedale group was chosen because (1) there is a relative abundance of high-quality aerial photos during the last 50 years and (2) it represents one of the largest and most representative sectors of the glacierised areas of Lombardy. Here, the widest Italian valley glacier (namely, Forni Glacier) is also located, where several glaciological studies have been performed in the past, claiming for continuous analysis of glacier dynamics and evolution in this Alpine sector. Moreover, this glacierised group is located in an important, naturalistically valuable and highly protected high-altitude area, the Stelvio National Park of Italy, where the impacts of climate change have to be accurately monitored and surveyed. We analysed here a number of aerial photos collected ever since 1954, until recently (i.e. 2007). Also, ad hoc targeted field campaigns were performed to evaluate the glaciological and geomorphological processes occurring in the present glacier phase. We further investigated climate variations within this area, and their possible effect upon glaciers reduction, by analysing seasonal records of temperature and precipitation (1951–2007) in Bormio station (1,225 m a.s.l.) and snow cover (1971–2007) in Cancano station (1,950 m a.s.l.), representative of the area. We perform stationarity analysis of the data by way of two different objective statistical tests, namely, (1) linear regression (LR) and (2) Mann–Kendall (MK), to assess the presence of significant non-stationarity of these variables. We analysed correlation (with different time lags) between climate variables and glacier terminus fluctuations for the two most studied glaciers to highlight the (also delayed) response of ice bodies to climate variability. We discuss the possible link between modified climate and glacier dynamics in this area.

2 Study area and previous glaciological investigations

Ortles-Cevedale is one of the most important glacierised sectors of Italy. The highest elevation peaks are Ortles (3,905 m a.s.l.) and Cevedale (3,769 m a.s.l.). The First Italian Glacier Inventory (CNR and CGI, 1961) classified 113 glaciers in the Ortles-Cevedale group. These glaciers were located in Lombardy (42 glaciers, 39 % of the area coverage), in Alto Adige (50 glaciers, 43 % of the area surface) and in Trentino (21 glaciers, 18 % of the area coverage). Here, we analysed the glacierised sector of Lombardy, which includes Forni, the largest Italian valley glacier (approximately 12 km^2 area), and several important glaciers featuring different sizes, aspects and geometries, and thus, being representative of the whole Italian glaciation. In the Lombardy sector, the main peaks are Cevedale, San Matteo (3,692 m a.s.l.), Gran Zebrù (3,857 m a.s.l.), Corno dei Tre Signori (3,360 m a.s.l.) and Punta Thurwieser (3,641 m a.s.l.). The Ortles-Cevedale glacierised region (Fig. 1) is located inside the Stelvio National Park (approximately 600 km^2 area in Lombardy), among the most important and representative protected areas of Italy. In the park area, according to the 92/43/EEC Directive, several sites of community importance are recognised. Forni Glacier, due to its scenic, scientific and naturalistic values, is also inserted in the Lombardy Region List of Geosites (Regione Lombardia 2009). The impressive shortening experienced by Ortles-Cevedale glaciers during the last century may be appreciated by visual comparison of historical pictures. In Fig. 2, we reported, as an instance, some photos of the Forni Glacier taken in 1890 (photo by V. Sella), in 1941 (photo by A.

Fig. 1 Location map of Ortles-Cevedale glaciers



Desio) and in 1997 and 2007 (photos by C. Smiraglia), respectively. A noticeable shortening of the glacier tongue, together with a reduction of the glacierised area and strong morphological variations, is clearly visible. The Lombardy sector of the Ortles-Cevedale group has been the focus of considerable investigation, starting in the first half of the twentieth century, with measurements of glacier terminus fluctuations (Comitato Glaciologico Italiano (CGI) 1977, 2011). Scientists and researchers focused especially upon the Forni Glacier (Stoppani 1908; Desio 1967). Therein, several studies were performed, namely, mapping and dating the well-preserved moraine ridges (Pelfini 1987, 1996; Rossi et al. 2003), describing epiglacial (i.e. upon glaciers surface) morphology features and development (Smiraglia 1989; Smiraglia and Diolaiuti 2011), evaluating ice thicknesses and volume (by geophysical surveys, see Guglielmin et al. 1995) and developing methods of tourist promotion also based on glacier paths and trails (Smiraglia 1995; Smiraglia and Diolaiuti 2001). Most recent studies have focused on glacier micrometeorology (Citterio et al. 2007b; Diolaiuti

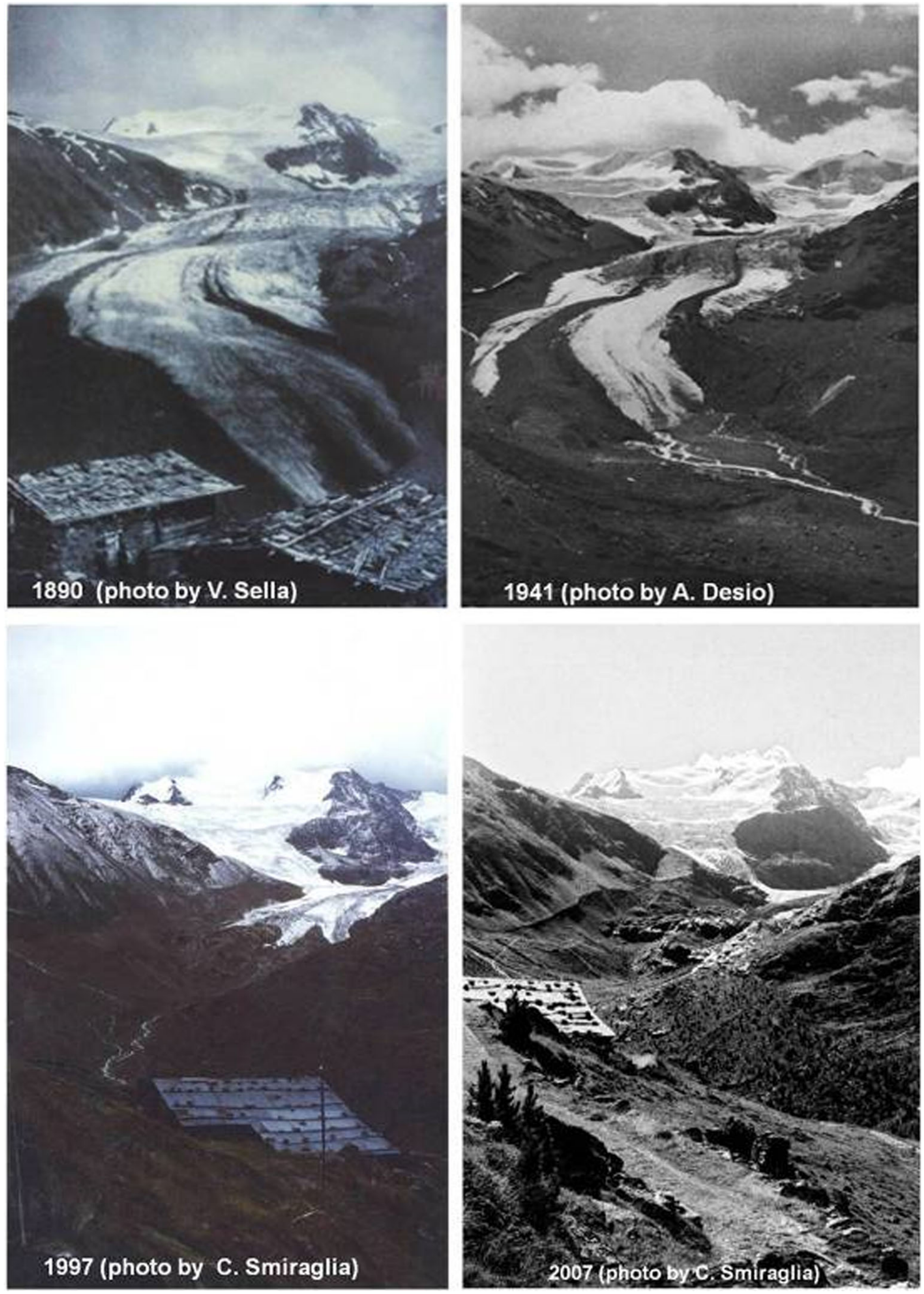


Fig. 2 Comparison of photos showing the strong retreat witnessed by Forni Glacier. The photos were taken in 1890 (by V. Sella), in 1941 (by A. Desio) and in 1997 and 2007 (by C. Smiraglia), respectively

et al. 2009a, b; Senese et al. 2010), the evaluation of glacier energy budget and mass balance (Senese et al. 2012), the relation between glacier features and mesofauna occurrence and behavior (Pelfini and Gobbi 2005) and the presence of yeasts and bacteria at the glacier forefield and inside the glacier ice and snow (Turchetti et al. 2008). The Forni Glacier was also analysed by Diolaiuti and Smiraglia (2010) as an example of a fast-changing glacierised area witnessing the ongoing climate change and being representative of the ongoing processes affecting glacier *geomorphosites* (sensu Panizza 2009). Moreover, other glaciers in the group have been analysed with further details in the recent past. The mass balance record of Sforzellina Glacier (Gavia Pass, Lombardy) was analysed by Diolaiuti et al. (2002) with respect to other series of data in Europe to find relations at both local and regional scales according to the approach introduced by Letréguilly and Reynaud (1990). Moreover, Cannone et al. (2008) analysed Sforzellina Glacier for correlating glacier retreating rates and changes witnessed by vegetation and plants at the glacier forefield, revealing that both biological and abiological environmental systems are experiencing strong climate change impacts. Last but not least, a glacier located in the park and used for summer skiing, Vedretta Piana (Stelvio Pass, Lombardy), was studied by Diolaiuti et al. (2006) to detect the impacts due to human activities on the glacier seasonal and interannual evolution. In spite of these previous studies, comprehensive assessment of the changes affecting the glaciers located in the Lombardy sector of the Ortles-Cevedale group and comprehensive long-term analysis of the evolution of all the Ortles-Cevedale glaciers were not made available yet to our knowledge.

3 Data and methods

3.1 Glaciological data

Five surface glacier area records, dating from 1954, 1981, 1990, 2003, and 2007, are available for the Ortles-Cevedale Lombardy sector. The 2003 and 2007 area records were worked out by combining glacier limits manually digitised on registered colour orthophotos (2003 and 2007 flights—Compagnia Generale Riprese Aeree [CGR], see Volo Italia 2003, 2007) and field surveys using the Differential Global Positioning System (DGPS). All data were processed and managed through a Geographic Information System (GIS) software. The orthophotos used as the base layer for delimiting the 2003 and 2007 glacier boundaries are purchasable products (distributed by CGR), featuring a planimetric resolution specified by 1 pixel (pixel size=0.5 m). The planimetric accuracy stated by the manufacturer for the 2003 and 2007 data is ±1 m. The 1954 and 1981 area records were obtained by analysing aerial photos (at a scale of approximately 1:20,000) with an optical stereoscopic system to obtain a 3D view of the glacierised 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 a raster base. The topographic data reported in the CTR are referred to the beginning of the 1980s, thus allowing the evaluation of the accuracy of our findings from the 1981 aerial photos. The planimetric accuracy of the 1954 and 1981 data is ±5 m.

The final planimetric accuracy was evaluated according to Vögtle and Schilling (1999), considering both the uncertainty due to the sources (orthophotos or DGPS surveys) and the sharpness of glacier limits. The area precision for each glacier was evaluated by buffering the glacier perimeter considering the area uncertainty. The final precision of the whole Ortles-Cevedale glacier coverage was assessed by taking the root of the squared sum of all the buffer areas. A database was also available, describing area coverage in 1990, and assembled previously by other scientists (Servizio Glaciologico Lombardo (SGL) 1992). These authors did not provide an accuracy measure, so that the final accuracy of the data was taken as the resolution of the map they produced (all the glaciers were represented on a 1:10,000 scale map, featuring a nominal map reading error of 2 m).

We also measured for each glacier elevation data (maximum and minimum values), slope, aspect and maximum glacier length. All these parameters were evaluated according to the recommendations of Paul et al. (2010). Area changes were analysed by first classifying the Ortles-Cevedale glaciers according to the following size classes: <0.10, 0.10–0.5, 0.5–1, 1–2, 2–5, 5–10 and >10 km^2. These size classes were applied in previous studies (Paul et al. 2004; Citterio et al. 2007a; Maragno et al. 2009; Diolaiuti et al. 2011, 2012a, b), thus allowing direct comparison.

3.2 Weather data

To investigate climate trends within the area and possible bearing upon glacier dynamics therein, we studied data on yearly and seasonal values of temperature T [in degrees Celsius], total daily precipitation P [in millimeters] and snow cover depth H_S [in meters]. Average daily temperature and daily precipitation series covering the period 1951–2007, overlapping our time window of glaciers' data, were retrieved for a meteo station in the city of Bormio (1,225 m a.s.l.), approximately 20 km away from Forni Glacier. Concerning snowfall, the longest (1971–2007) available series of observed daily snowpack depth we could find nearby was in Cancano (1,950 m a.s.l.; Fig. 1). For our analysis, we considered (mean) seasonal values of T, P and H_S (e.g. Bocchiola and Diolaiuti 2010, 2012; Diolaiuti et al. 2012b). We carried out two types of stationarity tests upon the mentioned variables, namely, LR and traditional and progressive MK test (Kendall 1975; Bocchiola and Diolaiuti 2010).

MK test is widely adopted to assess significant trends in the hydrometeorological time series. It is a non-parametric test, thus being less sensitive to extreme sample values, and independent from hypothesis about the nature of the trend, either linear or not (e.g. Wang et al. 2005), so being somewhat complementary to the LR test. The traditional MK test provides a judgment about the (non-)stationarity of a series. In case of non-stationary behavior, the progressive form of the MK test may locate the starting point of a trend, if applicable (Bocchiola and Diolaiuti 2010, 2012). We evaluated the p value statistics for LR and MK, and we labelled as significant trends those giving $p<0.05$ for both tests. We assume that, in view of the strong control of temperature, precipitation and snow cover upon glacier melting evolution, widely reported within the available literature (Ohlendorf et al. 1997; Huss et al. 2009; Nemec et al. 2009), significant trends of H_S, T and P do imply consequences upon glaciers, possibly substantiating deduction of glacier shrinkage as from observed data, within the considered regions. To evaluate linkage between the local climatic variables and drivers from general circulation, we analysed the correlation of H_S, T and P against the corresponding North Atlantic Oscillation (NAO) anomaly, ΔNAO (data by Jones et al. 1997; Osborn 2004, 2006) (yearly value−long-term average) for the period 1951–2007 (e.g. Scherrer et al. 2004; Bocchiola and Diolaiuti 2010). We then tested whether the temperature change in our target area is linked to warming at the global scale. To do so, we studied correlation between global temperature anomalies ΔT_G (as calculated by Brohan et al. 2006) and temperature in our study area. We then evaluated the presence of a (linear) correlation between our target climate variables and glaciers' dynamics, as given by glacier terminus fluctuations. We did so for two glaciers in the Ortles-Cevedale group, namely, Sforzellina (a mountain cirque glacier, 0.54 km^2 in 1954 and 0.28 km^2 in 2007) and Forni (a valley glacier, 14.08 km^2 in 1954 and 11.36 km^2 in 2007), that were more extensively studied. We evaluated the (linear) correlation coefficients between the yearly fluctuation (in meters) of the glacier terminus against climate variables (1951–2006), namely, temperature, precipitation and snow cover, for all seasons (unless snow during summer). We considered a time lag of up to 10 years, i.e. we tentatively correlated terminus fluctuation with values of the climate variables until 10 years back; in the hypothesis, the long-term persistence of the climate signal may occur. Because most of the glaciers' terminus measurements were taken in September, we considered the period OND only starting from 1 year backward. We applied this simple approach to evaluate delayed response of glacier to the dynamics of some selected climate variables, since we sought to evaluate the occurrence and magnitude of climate–glaciers relations. Clearly, accurate quantitative analysis of glaciers' dynamics against weather variables requires more accurate and physically based analysis (see Oerlemans 2007).

4 Results

4.1 The 2007 Stelvio Park (Lombardy sector) Glacier Inventory

We first focused on the description of the most recent regional glacier database, i.e. the 2007 glacier record. The estimated Ortles-Cevedale glacierised area was of 29.29 km^2±0.10 % in 2007 (67 glaciers). We considered glaciers wider than 0.1 km^2, thus neglecting *glacierets* and ice bodies with unclear evidences of ice flow and glacier dynamics. Glaciers with a surface below 0.5 km^2 are prevalent in the Ortles-Cevedale group (i.e. more than 50 % of the whole sample), highlighting how glacier resource is spread into several small ice masses (Fig. 3a). About 13 % of the sample is given by ice bodies larger than 1 km^2. The most typical maximum length (Fig. 3b) ranges between 0.51 and 0.75 km (i.e. for more than 30 % of the sample) and <5 % of the glaciers were longer than 3 km. The minimum glacier elevation (Fig. 3c), indicative of glacier terminus altitude, is between 2,801 and 2,900 m a.s.l. (more than 35 % of the whole sample). Ortles-Cevedale glaciers show a north preferred aspect (Fig. 3e). The slope frequency distribution (Fig. 3f) indicates that, on average, glaciers in this area have a gentle slope, with a mean value of 16.9°. We found negative correlation between terminus elevation (i.e. glacier minimum elevation) and glacier area (ρ=−0.6), i.e. larger glaciers tend to reach lower elevations, while smaller glaciers have higher termini. These patterns were observed in other glacier areas, namely, the Alaska Brooks Range (Manley 2008), the Swiss glaciers (Kääb et al. 2002), the Cordillera Blanca (Racoviteanu et al. 2008) and in the Piazzi–Dosdè group in the Italian Alps (Diolaiuti et al. 2011).

4.2 Glacier changes during 1954–2007

The Ortles-Cevedale glacierised area was 50.03 km^2±0.33 % in 1954 (54 glaciers), 42.84 km^2±0.38 % in 1981 (56 glaciers), 38.60 km^2±0.28 % in 1990 (57 glaciers), 32.12 km^2± 0.08 % in 2003 (63 glaciers) and 29.29 km^2±0.10 % in 2007 (67 glaciers, approximately 60 % of ice cover in 1954). The number of glaciers surveyed is different in the five data sets, either due to unreliable detection of some glaciers in the aerial photos (e.g. arising from the effects of cloud cover and/or snow cover) or to disappearance of some glaciers. Although the Ortles-Cevedale glaciers generally underwent losses in area (losing the largest part of their tongues), their number increased. This is caused by fragmentation of previous larger glaciers, which generates smaller ones, and it is typical of the ongoing deglaciation phase. A similar behavior was reported, for example, by Knoll and Kerschner (2009) for the South Tyrolean glaciers (Eastern Alps), where more than 50 smaller glaciers were derived from the disintegration of previously larger ones, and by Diolaiuti et al. (2011) for glaciers in the Dosdè–Piazzi group (Lombardy, Italy). In order to evaluate the area changes of Ortles-Cevedale glaciers, only the surface coverage of glaciers present in all the data sets were compared. The records for 1954, 1981, 1990, 2003 and 2007 were considered, which allowed evaluation of the evolution of 43 glaciers (Table 1).

To analyse in more detail the relations between glacier size and area changes, we analysed the glaciers listed in Table 1 according to size classes applied in previous studies of Lombardy glacier during 1991–1999 (Citterio et al. 2007a) and during 1991–2003 (Diolaiuti et al. 2011), of Adamello glacier during 1981–2003 (Maragno et al. 2009) and of Dosdè–Piazzi glaciers during 1954–2003 (Diolaiuti et al. 2011). The same classes were introduced by Paul et al. (2004) for Swiss glaciers and they were used by Knoll and Kerschner (2009) for analysing South Tyrol glacier changes.

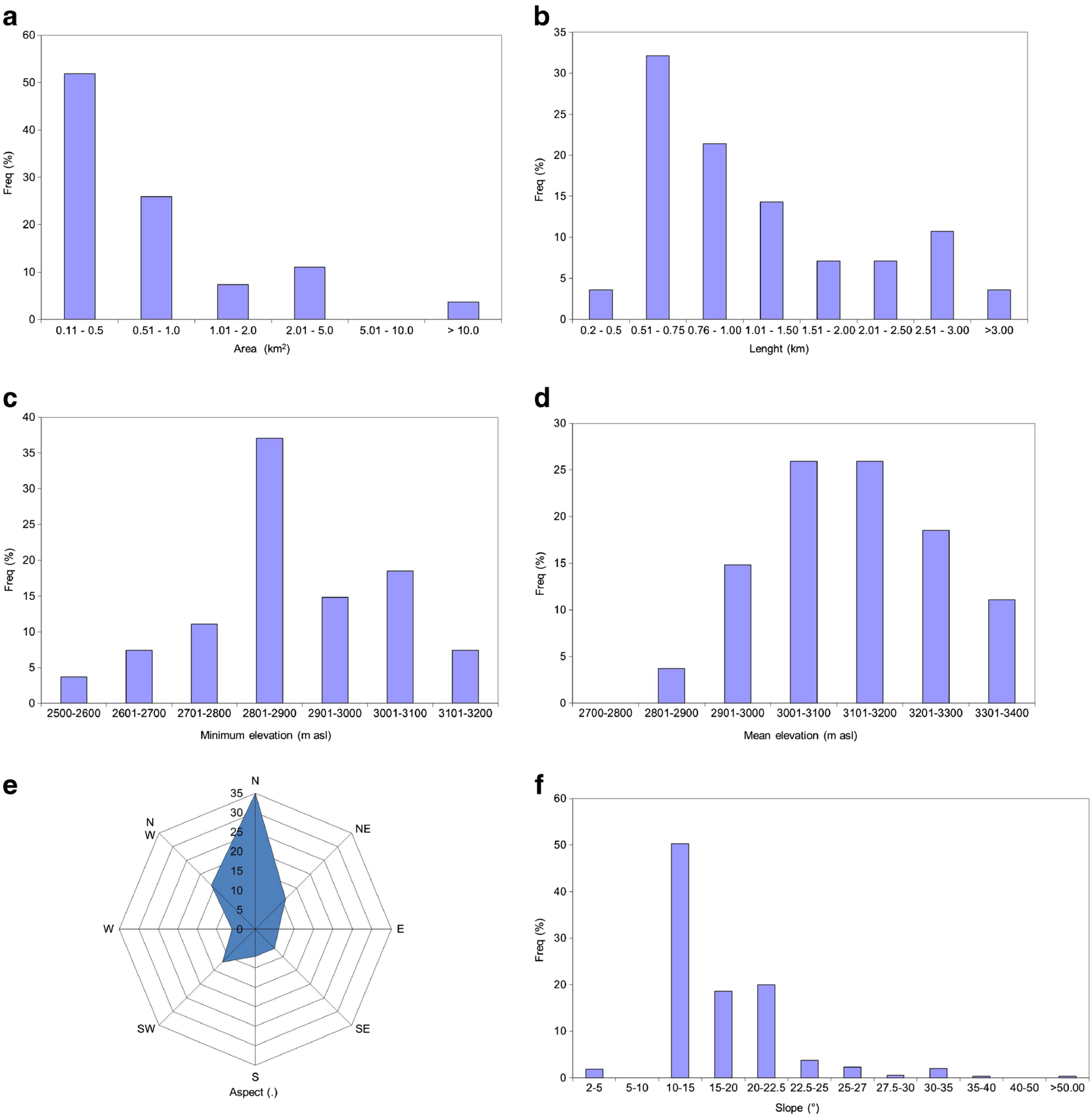


Fig. 3 Main features of the Ortles-Cevedale glaciers derived from the analysis of 2007 orthophotos. Only glaciers larger than 0.1 km^2 in area are considered. **a** Area frequency distribution. Glaciers smaller than 0.5 km^2 are prevalent. **b** Glacier maximum length frequency distribution. Glaciers 0.51–0.75 km long are prevalent. **c** Glacier minimum elevation (~terminus) frequency distribution. Glaciers with a minimum elevation between 2,801 and 2,900 m are prevalent. **d** Glacier mean elevation frequency distribution. Glaciers with a mean elevation between 3,001 and 3,200 m are prevalent. **e** Aspect frequency distribution. Numbers represent the percent of glacier area in 45° aspect bins. North is the preferred aspect. **f** Slope frequency distribution. On average, glaciers in this area have a gentle slope, with a mean value of 16.9°

Analysis of columns 2–5 of Table 2 shows that several glaciers have shifted from the largest size classes to the smallest ones. To avoid inconsistencies such as the apparent gain in area for those classes that acquired more glaciers from the larger classes than those they lost to the smaller ones, Table 3 was obtained by crediting the contribution of each glacier according to its class in 1954. Thus, the evaluations of area changes (Tables 4, 5 and 6) were not affected by class shifts. Therefore, the 43 glaciers so analysed covered an area of 48.70 km^2±0.40 % in 1954, 42.16 km^2± 0.39 % in 1981, 38.23 km^2±0.28 % in 1990, 32.05 km^2± 0.08 % in 2003 and 29.27 km^2±0.10 % in 2007 (Table 3),

Table 1 Surface coverage data of the 43 Ortles-Cevedale glaciers analysed in this study

Glacier name	1954 Glacier area (km^2)	1981 Glacier area (km^2)	1990 Glacier area (km^2)	2003 Glacier area (km^2)	2007 Glacier area (km^2)
Platigliole (I+II+III+IV)	0.59	0.39	0.27	0.17	0.11
Vitelli	2.72	2.47	2.28	2.01	1.89
Crapinellin (I+II)	0.41	0.19	0.09	0.04	0.01
Cristallo Est (I+II+III)	0.88	0.70	0.49	0.21	0.16
Cristallo Centrale	0.25	0.15	0.14	0.11	0.09
Cristallo Ovest	0.40	0.31	0.28	0.14	0.09
Campo	1.43	1.10	1.00	0.91	0.84
Zebrù (I+II)	2.96	2.65	2.36	2.22	2.01
Miniera	0.80	0.74	0.65	0.60	0.60
Castelli Est (I+II)	0.55	0.46	0.39	0.31	0.24
Castelli Ovest	0.80	0.68	0.64	0.48	0.43
Montagna Vecchia I	0.08	0.06	0.04	0.03	0.03
Montagna Vecchia II	0.39	0.24	0.21	0.13	0.07
Montagna Vecchia III	0.10	0.08	0.07	0.06	0.05
Montagna Vecchia IV	0.22	0.15	0.08	0.06	0.05
Forà	0.87	0.64	0.56	0.47	0.44
Confinale Ovest	0.20	0.16	0.12	0.10	0.08
Confinale Sud (I+II)	0.17	0.11	0.06	0.02	0.01
Gran Zebrù (I+II)	1.87	1.34	1.27	0.88	0.80
Cedèc	2.94	2.67	2.63	2.15	2.07
Pasquale Nord (I+II)	0.40	0.33	0.26	0.10	0.10
Pasquale Sud	0.18	0.14	0.09	0.06	0.06
Rosole	1.53	1.07	0.90	0.64	0.61
Col de la Mare (I+II)	1.26	1.16	1.19	0.89	0.81
Palon de la Mare	1.40	1.35	1.31	1.13	1.06
Forni	14.08	13.66	12.90	12.11	11.36
San Giacomo Sud	0.12	0.10	0.08	0.05	0.05
San Giacomo Est	0.29	0.23	0.21	0.12	0.10
San Giacomo Ovest	0.35	0.26	0.24	0.18	0.17
Cerena (I+II+Pizzo Tresero Nord)	1.15	1.07	0.89	0.71	0.64
Tresero	0.99	0.79	0.77	0.62	0.53
Dosegù (+Punta Pedranzini I+II)	3.96	3.52	3.33	2.74	2.56
Passo di Dosegù I	0.28	0.17	0.12	0.03	0.02
Punta della Sforzellina Ovest	0.12	0.08	0.04	0.02	0.01
Sforzellina	0.54	0.41	0.42	0.32	0.28
Gavia	0.11	0.08	0.06	0.04	0.04
Alpe Sud (I+II)	0.71	0.47	0.45	0.27	0.09
Sobretta Nord Est (Superiore+Inferiore)	0.43	0.35	0.23	0.09	0.06
Sobretta Nord Ovest	0.60	0.45	0.36	0.26	0.22
Profa	0.67	0.44	0.32	0.20	0.17
Savoretta	0.42	0.36	0.29	0.23	0.18
Cima Monticello Sud	0.29	0.21	0.11	0.05	0.03
Pietre Rosse Nord	0.18	0.15	0.10	0.07	0.05
Total	48.70	42.16	38.23	32.05	29.27

Glacier codes are reported in parentheses for fragmented glaciers (area coverage taken as the sum of the areas of each derived/fragmented glacier)

Table 2 Number of glaciers within Ortles-Cevedale, sorted according to their area

Size class (km^2)	1954 Glacier number	1981 Glacier number	1990 Glacier number	2003 Glacier number	2007 Glacier number
<0.1	1	4	9	13	18
0.1–0.5	20	23	19	17	12
0.5–1.0	11	5	6	7	7
1.0–2.0	6	6	4	1	2
2.0–5.0	4	4	4	4	3
5.0–10.0	0	0	0	0	0
>10.0	1	1	1	1	1
Total	43	43	43	43	43

Number of glaciers reported for 5 years (1954, 1981, 1990, 2003 and 2007)

with minimal loss of area with respect to the total cover. The area change between 2007 and 1954 was −19.43 km^2±1.2 % (−40 % of the area coverage in 1954), with the fastest rate of change later (see values in Tables 4, 5 and 6). In fact, the mean estimated rate is −0.693 km^2/year during 2003–2007, against −0.48 km^2/year during 1990–2003, −0.44 km^2/year during 1981–1990 and −0.242 km^2/year during 1954–1981 (Table 6).

From Table 5, during 1954–2007, glaciers smaller than 0.1 km^2 lost approximately 61.3 % of their initial areas. However, this strong decrease accounts for only 0.2 % of the whole glacier area loss. In the same period, glaciers with their area in the range of 0.1–0.5 km^2 lost approximately 75.2 % of the surface they covered in 1954, thus contributing 20.6 % of the whole area loss. Larger glaciers, such as those in the size class 0.5–1.0 km^2, lost about 59.2 % of their surface, i.e. 24.4 % of the total glacier reduction. Finally, glaciers in the class 1.0–2.0 km^2 reduced their area by 44.8 %, or 19.9 % of the whole glacier retreat. Eventually, the contribution to the total area loss given by glaciers with areas smaller than 2 km^2 during the period 1954–2007 was 65 % (with respect to their total coverage in 1954), much more than the contribution of large glaciers (area >2 km^2, contribution of 35 %).

Considering the different time windows of the analysis (i.e. 1954–1981, 1981–1990, 1990–2003 and 2003–2007), the first class (<0.1 km^2) always decreased considerably, but still it contributed little to the total loss (0.21, 0.72, 0.005 and 0.18 %, respectively). By contrast, the size classes 0.1–0.5 and 0.5–1.0 km^2 were the most dominant in the overall reduction. The glaciers therein decreased by 24.76 % during 1954–1981, by 18.80 % during 1981–1990, by 31.16 % during 1990–2003 and by 18.25 % during 2003–2007, with a contribution to the overall loss of 50.43, 48.02, 41.04 and 36.90 %, respectively. The largest glaciers (>10 km^2) reduced their area by 2.97, 5.55, 6.09 and 6.26 %, respectively, thus yielding 6.39, 19.30, 12.71 and 27.35 % of the total loss. The area changes of the Ortles-Cevedale glaciers were compared against initial glacier areas (Fig. 4), showing that the smaller the glacier, the faster the reduction.

These results reflect findings by other authors for different Alpine glacierised sectors (Paul et al. 2004; Diolaiuti et al. 2011, 2012a, b). Diolaiuti et al. (2011) studied glaciers in the Dosdè–Piazzi area (Lombardy Alps) during 1954–2003 and found an area reduction of approximately 50 %. This retreat is stronger than that in the Ortles-Cevedale glacier during 1954–2007. This difference may be due to the smaller mean size featured by Dosdè–Piazzi glaciers than those in the Ortles-Cevedale group. In Fig. 4, a high variability in the percent area lost by small glaciers, ranging from 2 to 90 %, is seen. The wide range in the magnitude of glacier area

Table 3 Area coverage of glaciers within the Ortles-Cevedale according to aerial photos (1954, 1981), orthophotos (2003 and 2007) and a previous regional inventory (1990 data from SGL, 1992)

Size class (km^2)	1954 Area (km^2)	1981 Area (km^2)	1990 Area (km^2)	2003 Area (km^2)	2007 Area (km^2)
<0.1	0.08	0.06	0.04	0.03	0.03
0.1–0.5	5.33	3.86	2.84	1.68	1.32
0.5–1.0	8.00	6.16	5.30	3.92	3.26
1.0–2.0	8.64	7.10	6.56	5.16	4.77
2.0–5.0	12.59	11.31	10.60	9.13	8.54
5.0–10.0	0.00	0.00	0.00	0.00	0.00
>10.0	14.08	13.66	12.90	12.11	11.36
Total	48.70±0.40 %	42.16±0.39 %	38.23±0.28 %	32.05±0.08 %	29.27±0.10 %

Table 4 Surface area changes of the Ortles-Cevedale glaciers during 1954–2007, 1954–1981, 1981–1990, 1990–2003 and 2003–2007

Size class (km^2)	ΔA 1954–2007 (km^2)	ΔA 1954–1981 (km^2)	ΔA 1981–1990 (km^2)	ΔA 1990–2003 (km^2)	ΔA 2003–2007 (km^2)
<0.1	−0.05	−0.01	−0.03	0.00	0.00
0.1–0.5	−4.01	−1.46	−1.02	−1.16	−0.37
0.5–1.0	−4.74	−1.84	−0.86	−1.38	−0.66
1.0–2.0	−3.87	−1.54	−0.54	−1.40	−0.39
2.0–5.0	−4.05	−1.27	−0.72	−1.46	−0.59
5.0–10.0	0.00	0.00	0.00	0.00	0.00
>10.0	−2.72	−0.42	−0.76	−0.79	−0.76
Total	−19.43±1.20 %	−6.54±3.02 %	−3.93±5.03 %	−6.18±1.77 %	−2.77±1.38 %

changes for small glaciers (<1 km^2) can be partly explained as follows:

(a) differences in the maximum elevation of glaciers relative to their equilibrium line altitude (ELA),
(b) the elevation of the mountain ranges they are located in,
(c) the altitudinal range of the glaciers.

We found a significant negative relationship (ρ=−0.6) between the percent area change and the vertical extent of the glacier (i.e. difference between maximum and median elevation). Glaciers with small vertical extent (i.e. maximum elevation close to median) are losing more area. We also found a significant negative relationship (ρ=−0.7) between maximum elevation and percent area loss, indicating that glaciers located upon lower summits are also losing more area. In addition, we found a significant negative relationship (ρ=−0.7) of the change in area vs the altitudinal range (i.e. maximum minus minimum elevation). Correlation analysis showed that small glaciers possess both smaller altitudinal range and vertical extent (ρ=0.8). These results support the idea that small glaciers with narrow altitudinal range are losing more of their area, also highlighted in other studies (Kaser and Osmaston 2002; Mark and Seltzer 2005; Racoviteanu et al. 2008; Diolaiuti et al. 2011, 2012a, b). This may be explained because a change in local climate could have increased the ELA of those glaciers above their maximum elevation, putting their whole area in a year-round ablation zone (Kaser and Osmaston 2002). Conversely, larger glaciers display a wide altitudinal range, with ELA well below the maximum elevation. The recession trends of Ortles-Cevedale glaciers are consistent, albeit slightly more intense, with the behaviour of other mid-latitude glaciers in the last decades. In Fig. 5, following Racoviteanu et al. (2008), we compared the Ortles-Cevedale data with those from other glacierised regions worldwide, such as Coropuna data (Peruvian Andes; studied period, 1962–2000) from Racoviteanu et al. (2007); Cordillera Blanca data (Peru; analysed period, 1970–2003) from Racoviteanu et al. (2008); Qori Kails data (Eastern Peruvian Andes; time frame, 1963–2005) from Thompson et al. (2006); Kilimanjaro data (Africa; time window, 1970–1990) from Kaser (1999); Kenia data (Africa; studied period, 1963–1993) from Kaser (1999); Thien Shan data (Asia; analysed period, 1977–2001) from Khromova et al. (2006); Swiss Alps data (time window, 1973–1999) from Paul et al. (2004); Western Himalaya data (Asia; time frame, 1962–2001) from Kulkarni et al. (2007). In spite of being placed at mid-latitudes, Ortles-Cevedale glaciers are comparable in size with those at low latitudes in the case study areas reported previously and this may explain the slightly stronger area changes with respect to Swiss and Himalayan glaciers that are greater in size on average. From our analysis, glacier minimum

Table 5 Surface area changes of Ortles-Cevedale glaciers with respect to their own class and to total area

Size class (km^2)	1954–2007		1954–1981		1981–1990		1990–2003		2003–2007	
	% of class area lost	% of total area lost	% of class area lost	% of total area lost	% of class area lost	% of total area lost	% of class area lost	% of total area lost	% of class area lost	% of total area lost
<0.1	−61.32	−0.24	−17.65	−0.21	−44.76	−0.72	−0.81	−0.01	−14.27	−0.18
0.1–0.5	−75.23	−20.63	−27.45	−22.35	−26.50	−26.08	−40.68	−18.68	−21.71	−13.19
0.5–1.0	−59.22	−24.39	−22.97	−28.08	−13.98	−21.94	−26.06	−22.33	−16.77	−23.71
1.0–2.0	−44.81	−19.92	−17.81	−23.50	−7.58	−13.70	−21.34	−22.63	−7.65	−14.23
2.0–5.0	−32.14	−20.83	−10.12	−19.48	−6.34	−18.26	−13.80	−23.65	−6.48	−21.35
5.0–10.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>10.0	−19.32	−14.00	−2.97	−6.39	−5.55	−19.30	−6.09	−12.71	−6.26	−27.35

Table 6 Yearly reduction rates (values in square kilometres per year) calculated for Ortles-Cevedale glaciers, by averaging the surface area changes occurring in each size class with respect to the different time windows (1954–2007, 1954–1981, 1981–1990, 1990–2003 and 2003–2007)

Size class (km^2)	1954–2007 Yearly area loss (km^2)	1954–1981 Yearly area loss (km^2)	1981–1990 Yearly area loss (km^2)	1990–2003 Yearly area loss (km^2)	2003–2007 Yearly area loss (km^2)
<0.1	−0.001	−0.001	−0.003	0.000	−0.001
0.1–0.5	−0.076	−0.054	−0.114	−0.089	−0.091
0.5–1.0	−0.089	−0.068	−0.096	−0.106	−0.164
1.0–2.0	−0.073	−0.057	−0.060	−0.108	−0.099
2.0–5.0	−0.076	−0.047	−0.080	−0.112	−0.148
5.0–10.0	0.000	0.000	0.000	0.000	0.000
>10.0	−0.051	−0.015	−0.084	−0.060	−0.190
Total	−0.367	−0.242	−0.436	−0.476	−0.693

elevation (indicative of glacier terminus altitude) of Ortles-Cevedale glaciers increased from 1954 to 2007. The mean value was 2,774 m in 1954, 2,813 m in 1981, 2,837 m in 1990, 2,890 m in 2003 and 2,914 m in 2007, displaying an increase of approximately 140 m in 53 years (mean annual value, +2.6 m). The minimum altitude increase was faster more recently, and the mean annual value was +1.4 m during 1954–1981, +2.6 m during 1981–1990, +4 m during 1990–2003 and +6 m during 2003–2007.

4.3 Geomorphological changes and impacts on Alpine landscape

As a consequence of glacier recession, several valley areas are now abandoned by ice (see the sequence of pictures in Fig. 2) and vegetation is starting to colonise the newly exposed rocks and mountain slopes, especially on the lower sectors of the deglaciated valleys. Ortles-Cevedale glaciers are also experiencing increasing rock debris cover (Fig. 6). The Forni Glacier tongue was always characterised by two main medial moraines (both ice stream interaction and ablation dominant type, see Smiraglia 1989). Now the largest Italian valley glacier shows more supraglacial rock debris, ranging from quite continuous to sparse and sporadic (Fig. 7), mainly due to the increasing macrogelivation and rock degradation processes which seem more frequent and stronger in glacierised regions during the recent times (Haeberli et al. 1997; Deline 2005; Huggel et al. 2005; Gruber and Haeberli 2007; Deline and Kirkbride 2009; Diolaiuti et al. 2009a, b). Rock debris covering mountain glaciers is a function of the ratio between debris-producing rock walls and glacier surface area (Haeberli 1996; Zemp et al. 2005). Not only the warming-induced destabilisation of surrounding rock walls plays an important role in driving glacier darkening but also the occurring glacier area reduction leads to a systematic increase in debris cover. Kellerer-Pirklbauer et al. (2008) underlined that rates of debris input from the two adjacent supraglacial slopes of a valley glacier may differ substantially from each other, reflecting different topographies (varying debris entrainment and transport) and/or lithologies (variations in weathering susceptibility) between the two sides. Moreover, the surface geometry of

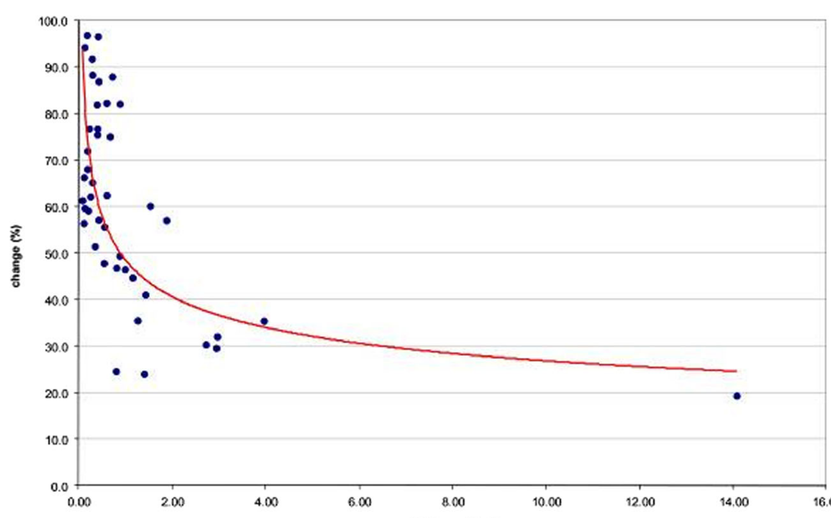


Fig. 4 The smaller, the stronger, the faster: Non-linear relationship between percent area loss from 1954 to 2007 and initial glacier size. A wide range in the magnitude of glacier area changes for small glaciers (<1 km^2) can be observed

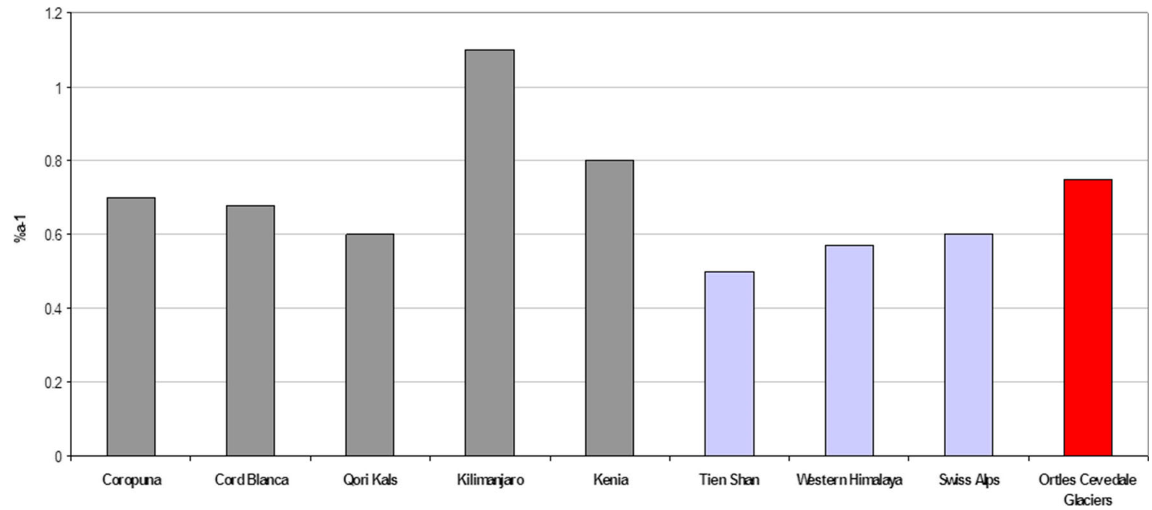
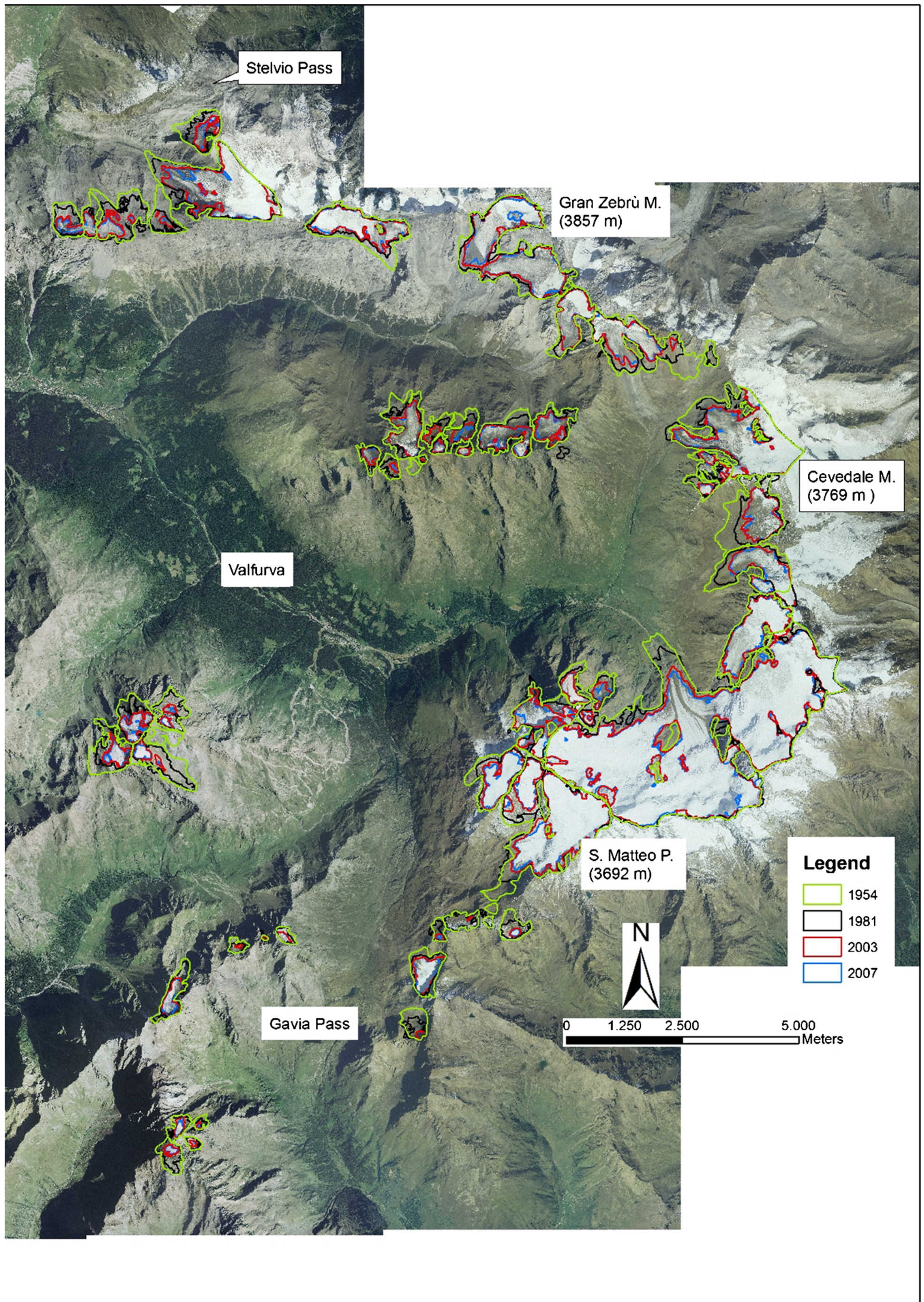


Fig. 5 Rates of area change in other glacierised areas of the world, expressed as percent per year based on various studies (see references in the text, data also reported by Racoviteanu et al. 2008). *Dark gray bars* represent glaciers situated in the tropics, *light blue bars* represent mid-latitude glaciers and *red bar* represents the Ortles-Cevedale glaciers. Glacier size seems the main factor driving glacier sensitivity

supraglacial debris cover may be influenced by the spatial distribution and nature of medial moraines and/or of englacial debris septa, which melt out of the ice in the ablation area (Benn and Evans 2010). Further, when glacier fronts become partially inactive, little shear fractures can supply the englacial sediments to the surface, shielding with debris the glacier surface in the front, possibly forming shear moraines (Smiraglia and Diolaiuti 2011). The complexity of such phenomena explains the different debris cover distribution at the surface of Ortles-Cevedale glaciers. Supraglacial debris plays a key role in controlling rates and magnitudes of ice melt (Østrem 1959; Nakawo and Young 1981, 1982; Nakawo and Rana 1999). Supraglacial debris cover, whenever thicker than a "critical value" (sensu Mattson et al. 1993), diminishes magnitude and rates of glacier ice melt (Mihalcea et al. 2006). Thus, the presence and complex distribution of supraglacial debris drives the genesis and the evolution of epiglacial morphologies due to differential ablation processes (Smiraglia and Diolaiuti 2011). On the Ortles-Cevedale glaciers' tongues, the most present and spreading epiglacial morphologies due to differential ablation are cryoconites, dirt cones and glacier tables. These morphologies are increasing their number and are becoming dominant upon the glacier surface landscape due to the major abundance of supraglacial debris following the glacier shrinkage. In addition to these morphologies, differential ablation processes also drive a strong gravitational and meltwater reworking of the former debris-covered surface. The flanks of dirt cones and of medial moraines became gradually steeper and the abundance of debris and water causes debris flows and sliding, all processes that redistribute sediments on the glacier surface, changing the pattern of differential ablation and creating in the deglaciation phases very characteristic and distinctive features. The final phase of this gravitational reworking is the development of a low-relief topography upon the very thick debris mantle that reduces strongly ice ablation rates (Smiraglia and Diolaiuti 2011). On the glacier tongue sectors covered by quite continuous debris (i.e. the lower sector of Forni Glacier or at the snout of Sforzellina Glacier and Gran Zebrù Glacier), the larger ice losses are mainly concentrated within the debris free areas, i.e. the walls of open crevasses and other holes on the glacier surface and steep marginal areas. Ablation proceeds by preferential melting and retreat of such slopes, in a process known as backwasting (Eyles 1979). This process enlarges holes and produces a chain of circular depressions filled with water, triggering the collapse of the roofs of englacial and subglacial water conduits (Kirkbride 1993). This results into a sequence of landscapes similar to the evolution of karst features on limestone terrain and thus defined as glacier karst (Clayton 1964). All these features, increasing upon the surface of Ortles-Cevedale glaciers due to enlarging supraglacial debris coverage, are temporary increasing the local *geodiversity* (sensu Eberhard 1997; Erikstad 1999; Gray 2004; Zwolinski 2004; Reynard and Coratza 2007; Serrano and Ruiz-Flano 2007; Panizza 2009). The spreading of supraglacial debris also leads to ecological effects, like an increase in the typical habitat of several vegetal species (herbaceous and shrubby plants), promoting the migration of lithophyte and microthermal species toward higher altitudes and a consequent increase in local biodiversity (Nagy et al. 1961). Other spreading morphologies due to glacier shrinkage are rounded rock outcrops and small *nunatak* outstanding from the glacier surface or enlarging their size at the glacier boundary (see Figs. 8 and 9). On Forni Glacier, several outcrops are evident on ice seracs connecting the three upper accumulation basins with the main ablation tongue (Fig. 8). Here, the steepness of the rock slopes drives ice flow, reducing ice thickness and

Fig. 6 The Ortles-Cevedale glaciers. In *light green* are the 1954 glacier boundaries. In *dark blue* are the 1981 limits. In *red* and in *light blue* are the 2003 and the 2007 glacier limits, respectively. The base layer is the 2007 orthophoto (Flight Terraitaly IT2000 surveyed in 2007 by Blom CGR)



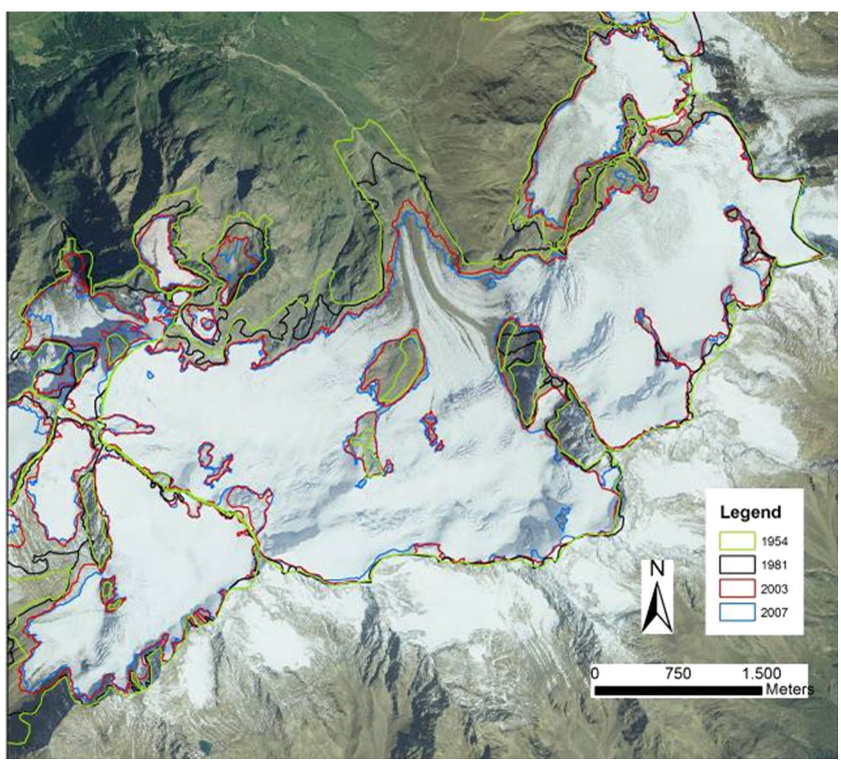
shaping the flows like actual ice falls. In particular, on the east ice fall, an outcrop has been developing in the last 3 years. This outcrop is causing separation between the upper east accumulation basin and the main glacier tongue. The result of such evolution will likely be the transformation of the east accumulation basin into an isolated cirque glacier. Generally, rock outcrops are characterised by fast evolution, and in a few years, they can cause glacier fragmentation (Fig. 10). Glacier melting leads also to the formation of glacial lakes. The newly formed lakes are located at the glacier surface, at the glacier boundary (lateral and frontal position) and in the glacier forefield. The lakes located at glacier surface are actually large water ponds which, due to their low albedo, act as heat storage increasing surface melting and accelerating glacier recession. Their evolution is fast, and generally, their lifespan is shorter than 1 year. The lakes located at the glacier boundary are ice-contact ones. These features are becoming increasingly widespread in the Ortles-Cevedale group due to the current phase of glacier shrinkage. In fact, the retreat of glacier termini has produced

Fig. 7 Forni Glacier tongue. Debris coverage from quite sparse to continuous is abundant, thus influencing the magnitude and rate of ice ablation

favourable settings for ponding of small ice-contact lakes behind moraine ridges, particularly those formed by most recent glacier advance in the late twentieth century, or less frequently, the lake dam is constituted by glacier ice. The ice-contact conditions allow calving phenomena to occur, driving the production of icebergs. In the Ortles-Cevedale group, calving events are limited and they occur at a smaller scale compared with those of calving glaciers at higher latitudes, and yet, the phenomenon is active and appreciable (Diolaiuti and Smiraglia 2010). The lifespan of ice–water contact at Alpine glaciers is, however, generally limited. Either most of the newly formed lakes disappear after a few years or the accelerating retreat of the glacier snouts lead to a rapid evolution from ice-contact to distal proglacial lakes. The persistence in time and space of such conditions seems to be longer where the glacier surface in the ice-contact zone is covered by debris that reduces ablation (i.e. a debris thickness thicker than the critical value) because of the greater stability of the ice margin. Moreover, the existence of ice-contact lakes allows water to be stored at higher elevations, even if for short and temporary periods, giving rise to local ecosystems where yeasts and bacteria adapted to extreme environments are able to survive (Buzzini et al. 2005), increasing at a local scale the biodiversity.

In the Ortles-Cevedale group, the most important ice-contact lake is developed at the margin of Forni Glacier. This lake is now experiencing its growing phase, and in the last 4 years, it passed from being a simple small water pond to its present maximum length, exceeding 150 m. Also, lateral moraines are experiencing deep changes due to ongoing climate change. This is the case of lateral moraines affected by ice core melting with subsequent collapse and genesis of mud and debris flows. In the Ortles-Cevedale group, the moraine ridges built by glaciers during the last advancing phase (1970s–1980s of the twentieth century) are now showing such evidence. In fact, starting from the 1990s,

Fig. 8 Forni Glacier's boundaries from 1954 (*green line*) to 2007 (*blue line*). In *dark blue* are the 1981 limits and in *red* are the 2003 boundaries. The image permits detecting not only the glacier retreat but also the enlargement of *nunatak* and rock outcrops. The base layer is the 2007 orthophoto (Flight Terraitaly IT2000 surveyed in 2007 by Blom CGR)



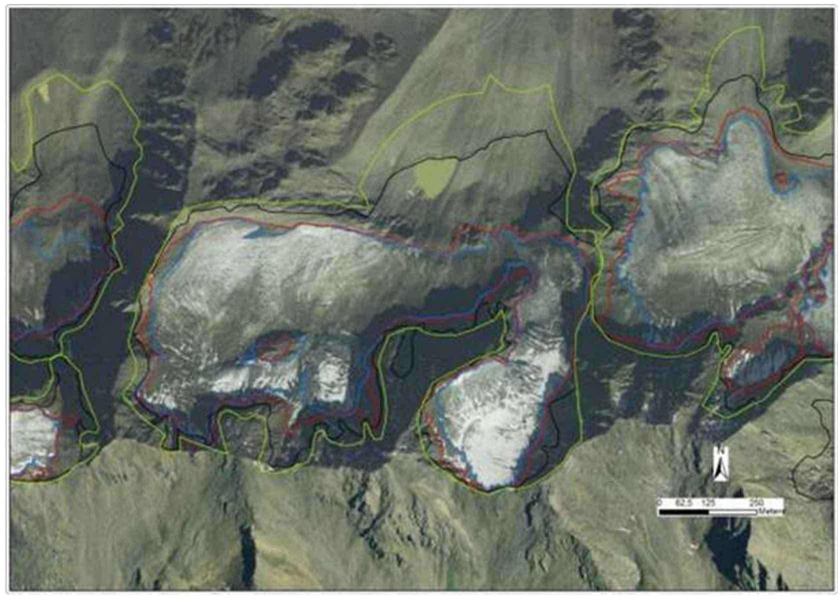


Fig. 9 The Castelli West Glacier. The *green line* is marking the 1954 boundary, the *black one* the 1981 limit and the *blue* and the *red lines* the 2003 and 2007 boundaries, respectively. In this image, a proglacial lake, which developed after 1981, and an outcrop rock emerging in the left glacier sector (west), which was detected in the recent time (2003 and 2007 orthophotos), are visible. The base layer is the 2007 orthophoto (Flight Terraitaly IT2000 surveyed in 2007 by Blom CGR)

several phenomena of fast slope evolution occurred (mainly mud and debris flow events) due to moraine ice core melting, causing deep changing in moraine morphology and suggesting the modification of some tourist trails. Summarising, all the previously reported evidence seem to indicate that, from a geodynamical point of view, the transition from a glacial system to a paraglacial one is now occurring (sensu Ballantyne and Benn 1996; Curry and Ballantyne 1999). The areas where in the recent past the main shaping and driving factors were glaciers are now subject to the action of melting water, slope evolution and dynamics and periglacial processes. The next step will be the transition from a paraglacial environment, where ice patches or glacierets are present, to a periglacial environment where cold and snow are dominant without ice glacier or ice melt water.

4.4 Climate trends

In Table 7, the findings concerning climate analysis are reported, and in Table 8, the correlation analysis of glaciers' terminus fluctuations against weather variables is shown. For trend analysis of temperature and precipitation, we considered three time windows, namely, the full period 1951–2007 and the two subperiods 1951–1984 and 1981–2007, covering approximately 30 years each (34 and 27 years, respectively) and overlapping substantially the two longest time windows for ice cover assessment considered here (1951–1981 and 1981–2007). Snow cover H_S was only available

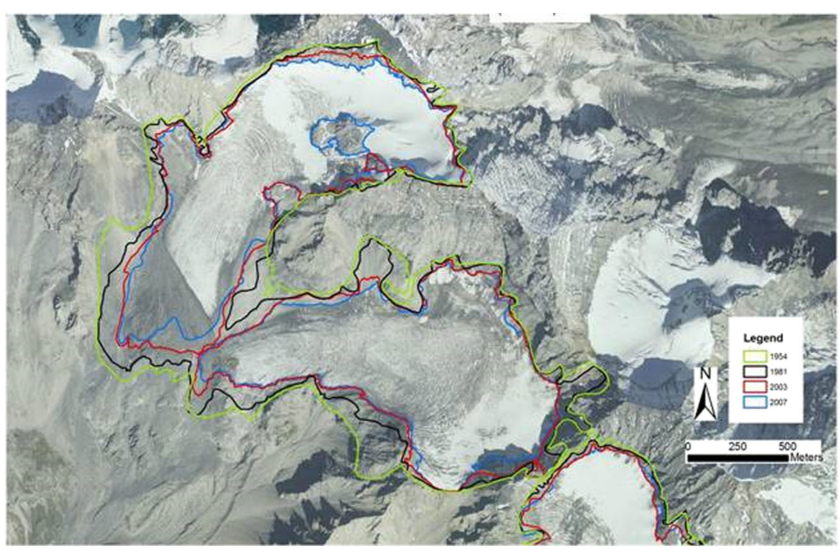


Fig. 10 The Zebrù glaciers. The unique glacier detected on 1954 photos (*green line*) gave rise to two separate glaciers visible in the 1981 photos (*black line*). The rock debris deposits due to the large landslide from Thurwieser which occurred in September 2004 are also appreciable. The base layer is the 2007 orthophoto (Flight Terraitaly IT2000 surveyed in 2007 by Blom CGR)

Table 7 Seasonal and yearly stationarity analysis of temperature T, precipitation P and snow depth H_S

Season/variable test	T MK	T LR coef	T LR pval	P MK	P LR coef	P LR pval	H_S MK	H_S LR coef	H_S LR pval
Y 1951–1984	0.28	−0.02	0.16	0.15	0.30	0.17	–	–	–
JFM 1951–1984	0.49	−0.02	0.50	0.92	0.26	0.52	–	–	–
AMJ 1951–1984	0.01	−0.07	0.00	0.06	0.67	0.08	–	–	–
JAS 1951–1984	0.63	−0.02	0.36	0.85	0.19	0.71	–	–	–
OND 1951–1984	0.54	0.01	0.73	0.92	0.12	0.80	–	–	–
Y 1981–2007	0.63	0.01	0.65	0.44	−0.18	0.59	–	–	–
JFM 1981–2007	0.98	0.01	0.76	0.33	−0.10	0.77	–	–	–
AMJ 1981–2007	0.00	0.11	0.00	0.06	−1.26	0.04	–	–	–
JAS 1981–2007	0.95	−0.01	0.82	0.72	−0.31	0.64	–	–	–
OND 1981–2007	0.07	−0.07	0.04	0.29	0.89	0.31	–	–	–
Y 1951–2007	0.16	0.01	0.21	0.27	1.05	0.31	0.01	−0.53	0.01
JFM 1951–2007	0.33	0.02	0.14	0.19	−0.15	0.36	0.01	−1.16	0.03
AMJ 1951–2007	0.42	0.01	0.32	0.28	0.14	0.41	0.01	−0.77	0.03
JAS 1951–2007	0.31	0.01	0.55	0.63	0.10	0.66	–	–	–
OND 1951–2007	0.74	0.00	0.82	0.45	0.31	0.22	0.22	−0.18	0.27
Var/season	Ty	TJFM	TAMJ	TJAS	TOND	Py	PJFM	PAMJ	–
ΔNAO 1951–2007	0.28	0.64	0.10	0.23	0.07	0.00	−0.26	−0.12	–
Var/season	PJAS	POND	HSY	HSJFM	HSAMJ	HSJAS	HSOND	–	–
ΔNAO 1951–2007	−0.33	−0.15	0.11	−0.35	−0.03	0.05	−0.12	–	–

LR coefficient is in units per year. Period for H_S is always 1971–2007. Significant values are in italics (α=5 %). Void cells (–) indicate periods non-suitable for stationarity analysis of snow cover (i.e. unchanged continuous snow coverage during winter or unchanged null snow coverage during summer). Correlation with ΔNAO is also reported

during 1971–2007, so we only considered this time window. During 1951–1984, temperature T decreased always and significantly during spring, but increased (not significantly) during fall. Precipitation P increased always, but not significantly. During 1981–2007, T increased yearly in winter (not significantly) and in spring (significantly), while it decreased in summer (not significantly) and in fall (significantly according to the LR test). Precipitation P always decreased significantly in spring, but did not significantly increase in fall. As a net result, during 1951–2007, T increased, but not significantly. P always increased (not significantly) during 1951–2007, but in winter, it did not decrease significantly. H_S during 1971–2007 significantly decreased yearly in winter and spring and not significantly in fall. Also, in Table 7, we report the correlation analysis of the considered weather variables against ΔNAO anomaly (1951–2007). Temperature T is positively (significantly) correlated against ΔNAO yearly and during winter and positively correlated (not significantly) always. Precipitation P is anti-correlated always and significantly in summer. Snow cover H_S is significantly negatively correlated to ΔNAO during winter and very slightly (not significantly, either positively or negatively) correlated elsewhere. We did not find significant correlation between T in Bormio and global anomaly ΔT_G. In Table 8, the correlation analysis between glaciers' terminus fluctuation (Forni and Sforzellina glaciers) and weather variables is reported. Upon the small Sforzellina glacier (0.54 km^2 in 1954 and 0.28 km^2 in 2007), the yearly fluctuation displayed anti-correlation against temperature during spring, TAMJ, in the same year. The greater Forni Glacier (14.08 km^2 in 1954 and 11.36 km^2 in 2007) displayed a more complicated response structure to weather. Significant positive correlation of Forni's terminus shift was found against H_S during spring of same year, and anti-correlation was found against T during winter, spring and summer in the same year. Also, significant anti-correlation was found against temperature during winter until 2 years earlier. In Fig. 11, the glaciers snout modification for Forni and Sforzellina is reported, together with the climatic variables significantly correlated.

Table 8 Terminus fluctuation correlation coefficient r against seasonal weather variables

Glacier/variable/delay	JFM	AMJ	JAS	OND
Sforz/T/0	–	−0.49	–	–
Forni/H_S/0	–	0.33	–	–
Forni/T/0	−0.39	−0.40	−0.39	
Forni/T/−1	−0.44	–	–	–
Forni/T/−2	−0.52	–	–	–

Only significant values reported (α=5 %). Delay is in years (0 is same years, −1 year before, etc.)

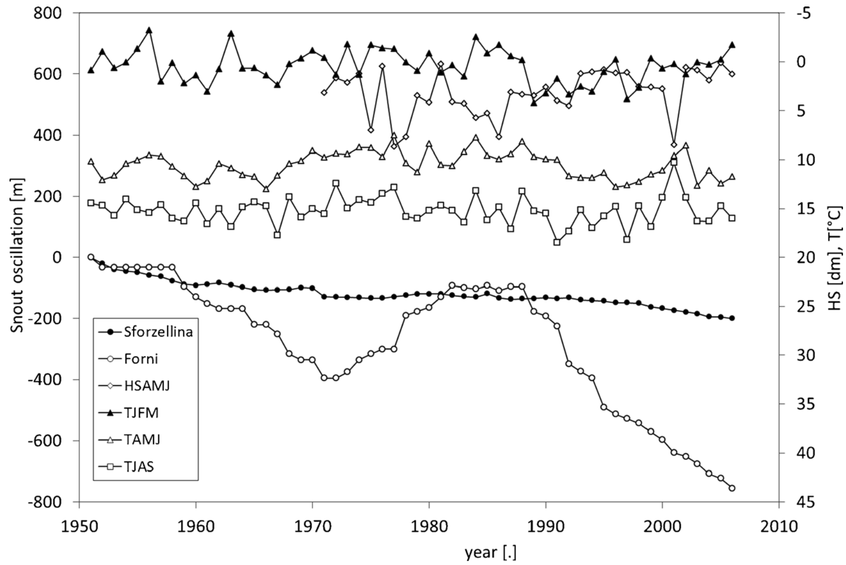


Fig. 11 Cumulated glacier terminus fluctuations of Sforzellina and Forni. We report the weather variables that are correlated with glacier snouts' variations (Table 8)

5 Discussion

The surface area changes we found point towards strong glacier reduction, which is generally interpreted as an indicator of the impact of climate change. If we compare the mean area loss witnessed by the Ortles-Cevedale glaciers over the 1954–2007 period (approximately −40 %, roughly −7 % per decade, slightly minor than Maragno et al. 2009 for the Adamello group and Diolaiuti et al. 2011 for the Dosdè–Piazzi group, northern Italy) with the area loss experienced by Alpine glaciers in the 1850–1973 period at 10-year intervals (−2.2 % reported by Paul et al. 2007), the former is about threefold the latter. This stronger reduction rate could be partially explained considering the smaller size featured by the Ortles-Cevedale glaciers (see also Lombardy glaciers analysed by Diolaiuti et al. 2012a, Dosdè–Piazzi glaciers studied by Diolaiuti et al. 2011 and Adamello glaciers investigated by Maragno et al. 2009); on the other hand, our data also evidence an acceleration in glacier retreat with the fastest rates in the most recent period (i.e. 2003–2007).

Oerlemans (2005) underlined that the transfer function between climate changes and glacier variations does not change in time and that stronger glacier changes suggest a similar climatic behaviour. As regards the climate, we can refer to the analysis of Beniston (2000). This author summarised the twentieth century trends of climate in the Alps. He reports that, in the twentieth century, climate change in the Alpine region was characterised 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 smaller trends in the average precipitation.

Casty et al. (2005) reconstructed Alpine temperatures ever since 1500, finding that 1994, 2000, 2002 and 2003 were the warmest years ever since then. Summer warming was particularly severe after 1970, reaching in 2003 the highest temperature ever. Begert et al. (2005) investigated temperature and total precipitation at 12 stations in Switzerland during 1864–2000. At Sils Maria, 1,802 m a.s.l., they found a significant increase of the yearly mean of daily temperature (+0.006 °C/year) and of fall and spring temperature (fall, + 0.008 °C/year; spring, +0.007 °C/year), the latter showing a speeding up in the late 1980s. Their findings concerning temperature in Sils Maria are in agreement with observations in Northern Italy (see Brunetti et al. 2000). As far as Lombardy region and the Stelvio National Park area are concerned, Cannone et al. (2008) analysed climate series of mean daily temperature and total precipitation for three weather stations (Uzza, 1,250 m a.s.l.; Santa Caterina Valfurva, 1,730 m a.s.l.; Forni dam, 2,180 m a.s.l.) nearby the Ortles-Cevedale glacierised group. They found a slight decrease of mean summer temperature during 1970–1980, experienced by the whole Alpine region (Wood 1988), and a subsequent increase of +0.5 °C during 1988–2006. They also detected a decrease of total precipitation during 1970–2006 (up to −10 % at 2,180 m a.s.l.). Bocchiola and Diolaiuti (2010) report climate trends for the Adamello glacierised area (Lombardy Alps, Italy) approximately 10–15 km south of Ortles-Cevedale. Total precipitation seems in practice unchanged, whereas rainfall is significantly increasing, ever since 1980–1990. Snow cover depth decreases with time, again starting since the early 1980s and consistently within the Southern Alps. The air temperature increase occurring in the Alpine areas since the end of the LIA activated a positive feedback, with a consequent increase in both the downward sensible heat flux and the longwave radiation balance (Oerlemans et al. 1998). Furthermore, during the last decades, the Ortles-Cevedale glaciers have experienced a strong decrease in surface albedo due to increasing debris coverage. The parallel reduction of the altitude range of Lombardy glaciers (Citterio et al. 2007a), together with the generalised rise in the ELA, confirmed by negative mass balances of glaciers in Lombardy over the last decade (Diolaiuti 2001; Cannone et al. 2008), point towards a scenario with many glaciers almost completely below the ELA. The analysis of the most recent orthophotos (2003 and 2007) allowed the observation and mapping of changes affecting glacier 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 they start (Paul et al. 2004; Pelto 2010). The climate trends highlighted here provide some matter for discussion. During 1951–1984, temperatures decreased in every season but in fall (and increased significantly during spring). Analysis of H_S during 1971–1984 indicates a slight increase during spring and a slight decrease during winter and fall (not shown given the short period), with no snow cover during summer. Given that H_S in winter is an indication of potential snow feeding and it is always much greater than H_S in spring (thus likely indicating not substantial snow feeding during spring), one may infer that, during 1971–1984, glaciers' feeding by snow was decreasing, although some more snow persisted until spring, disappearing in summer. During 1951–1984, precipitation always increased (not significantly) and most notably in spring and summer. Precipitation during spring and especially summer is most likely rainfall upon the glaciers' surface, thus possibly providing increased ice melting through direct heat exchange (e.g. Purdie and Fitzharris 1999). Notice that, during 1951–1984, most of precipitation falls in the considered area during summer (on average during JAS 248 mm, out of 708 yearly, i.e. 35 % of total annual rainfall). During 1954–1981, all our glaciers' size classes here lost area (Table 6), which we may thus explain by decreased snow feeding and increased summer precipitation, in spite of a slight temperature decrease. Analysis of terminus fluctuation against weather variables would provide for Forni Glacier anti-correlation (albeit not significant, $\rho=-0.197$) against summer rainfall PJAS, possibly supporting such hypothesis.

Analysis of glacier terminus fluctuations for Sforzellina and Forni glaciers in Fig. 11 display general retreat. Obviously, the magnitude of glacier's snout retreat depends upon glacier size, shape and geometry (e.g. Oerlemans 2007), and Forni experienced a stronger retreat than Sforzellina. The latter lost approximately 130 m during the last 50 years, and its average retreat rate was approximately −2.5 m/year, reaching −5.5 m/year in the last decade (2000–2011). Forni Glacier's snout lost approximately 700 m in length in the last 50 years, with an annual average of approximately −13.5 m/year, reaching −23 m/year, considering only the last decade (2000–2011). Notice (Table 8) that the Sforzellina terminus seems to vary synchronously with temperature in spring TAMJ during 1951–1984, and slower retreat (in some years, advance) is seen when TAMJ displays a decrease (1966–1976, with greater shift later on). Forni Glacier displays rapid retreat during 1951–1971. Notice that, from Fig. 11, TJFM, TAMJ and TJAS, all influencing terminus variation, increase for 15 years or so, during 1951–1966 (also confirmed by LR analysis in that period, not shown given the short period). Since then, all these temperatures decrease, and they start increasing again after 1981 or so, until 2007 (Table 7). As a result, Forni Glacier shrinks until 1972 (notice from Table 7 that Forni snout displays significant correlation against TJFM with a delay of 2 years at least). Since then, and until 1988, Forni Glacier snout is advancing and stable lately. Afterwards, Forni terminus retires fast, synchronous with temperature increase, especially in winter and spring, and with decreasing snow cover, again in winter and spring. During 1981–2007, glaciers' shrinkage in the Ortles-Cevedale group accelerates strongly with respect to 1954–1981 (Table 7). This is consistent with temperature increase, especially in spring (Table 8), and decrease of snow cover always (1971–2007, Table 8).

Evaluation of glaciers' response time (i.e. lag time of a first-order linear response equation, e.g. Oerlemans 2007) with respect to changes in climate variables may be carried out more exhaustively, pending availability of data specifically concerning ice dynamics and climate. Here, our statistically based analysis highlights the presence of a link between climate variability and glaciers' fluctuations in the area and depicts the length of the time window over which climate influences significantly the dynamics of ice bodies.

6 Conclusions

The analysis of Ortles-Cevedale glaciers here reported underlines a strong reduction of glacier coverage during the last half century. The area change between 2007 and 1954 was -19.43 km^2±1.20 % (−40 % of the area coverage in 1954). The surface reduction is enhanced more recently; the area change during 2007–2003 was -2.77 km^2±1.38 % (-0.693 km^2/year), compared to -6.18 km^2±1.77 % in the period 1991–2003 (-0.476 km^2/year), to -3.93 km^2±5.03 % in the period 1981–1990 (-0.436 km^2/year) and to -6.54 km^2± 3.02 % for the interval 1954–1981 (-0.242 km^2/year). Moreover, our data show that glacier minimum elevation (indicative of glacier terminus altitude) of Ortles-Cevedale glaciers increased from 1954 to 2007 of about 140 m (mean annual value, +2.6 m). Our results are consistent with glacier retreat observed in the Alps in the last decades (Kääb et al. 2002; Paul et al. 2004, 2007; Citterio et al. 2007a; Knoll and Kerschner 2009; Maragno et al. 2009; Bocchiola and Diolaiuti 2010; Diolaiuti et al. 2011, 2012a, b). The results here support the idea that small glaciers with narrow altitudinal range are losing more of their area, also noted in other studies (Kaser and

Osmaston 2002; Mark and Seltzer 2005; Racoviteanu et al. 2008; Diolaiuti et al. 2012a, b). Extrapolations of developments documented by repeated glacier inventories (Kääb et al. 2002; Paul et al. 2004) and provided by numerical models (Oerlemans et al. 1998) suggest that the disappearance of several mountain glaciers is quite likely a matter of few decades (Haeberli 2008). Also, Ortles-Cevedale glaciers could experience such scenario if no meaningful changes will occur in the climate trend. The ongoing glacier shrinkage is changing deeply the mountain landscape of Lombardy Alps, which are expected first to show features and forms now visible, e.g. within the Pyrenees (where the actual glaciation is the relic of the previous one and is formed by small cirque glaciers, see González Trueba et al. 2008) and, in a second phase, to resemble, e.g. the Apennines (where only the Calderone Glacier can be found, actually classified as a debris covered glacieret together with small snow fields, see Branda et al. 2010). The glaciers of Ortles-Cevedale are undergoing the transition from a glacial system to a paraglacial one (Ballantyne and Benn 1996; Curry and Ballantyne 1999). The areas where in the recent past the main shaping and driving factors were glaciers are now subject to the action of melting water, slope evolution and dynamics and periglacial processes. In this context, our study can contribute to evaluating the impacts of glacier decrease on fragile glacierised areas as the Ortles-Cevedale group in the Stelvio National Park. Here, in fact, the ongoing glacial changes are also affecting the geodiversity of the nesting glacierised basins. In a first stage, glacier shrinkage gives rise to the development of several minor morphologies. These smaller morphologies, although characterised by a short lifespan, increase the geodiversity of the glacierised site at a local scale. On a longer timescale, on the other hand, the effect of glacier recession is a general decrease of geodiversity due to the complete disappearance of glaciers and of the supraglacial and paraglacial morphologies (Diolaiuti and Smiraglia 2010). The climate patterns we evidenced here for the Ortles-Cevedale area during 1951–2007 display some complexity, cascading into diverse glaciers' response within the considered time window. However, on average along the considered period, we found a consistent signal of warming climate, especially recently, and decreased snow coverage, i.e. of nourishing and protection (via albedo) for glaciers, with subsequent loss of area and mass of the ice bodies. Eventually, the glacierised mountains of Ortles-Cevedale group (Lombardy Sector), like many others in the world, are becoming the primary witnesses of the global human impacts on the planet (Watson and Haeberli 2004).

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