



Post-LIA glacier changes along a latitudinal transect in the Central Italian Alps

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Abstract. The variability of glacier response to atmospheric temperature rise in different topo-climatic settings is still a matter of debate. To address this question in the Central Italian Alps, we compile a post-LIA (Little Ice Age) multitemporal glacier inventory (1860–1954–1990–2003–2007) along a latitudinal transect that originates north of the continental divide in the Livigno Mountains and extends south through the Disgrazia and Orobie ranges, encompassing continental-to-maritime climatic settings. In these sub-regions, we examine the area change of 111 glaciers. Overall, the total glacierized area has declined from 34.1 to 10.1 km², with a substantial increase in the number of small glaciers due to fragmentation. The average annual decrease (AAD) in glacier area has risen by about 1 order of magnitude from 1860–1990 (Livigno: 0.45; Orobie: 0.42; and Disgrazia: 0.39 % a⁻¹) to 1990–2007 (Livigno: 3.08; Orobie: 2.44; and Disgrazia: 2.27 % a⁻¹). This ranking changes when considering glaciers smaller than 0.5 km² only (i.e., we remove the confounding caused by large glaciers in Disgrazia), so that post-1990 AAD follows the latitudinal gradient and Orobie glaciers stand out (Livigno: 4.07; Disgrazia: 3.57; and Orobie: 2.47 % a⁻¹). More recent (2007–2013) field-based mass balances in three selected small glaciers confirm post-1990 trends showing the consistently highest retreat in continental Livigno and minimal area loss in maritime Orobie, with Disgrazia displaying transitional behavior. We argue that the recent resilience of glaciers in Orobie is a consequence of their decoupling from synoptic atmospheric temperature trends, a decoupling that arises from the combination of local topographic configuration (i.e., deep, north-facing cirques) and high winter precipitation, which ensures high snow-avalanche supply, as well as high summer shading and sheltering. Our hypothesis is further supported by the lack of correlations between glacier change and glacier

attributes in Orobie, as well as by the higher variability in ELA₀ positioning, post-LIA glacier change, and interannual mass balances, as we move southward along the transect.

1 Introduction

Mountain glaciers are prominent players in the hydrologic and geomorphic functioning of glacierized drainage basins. They are effective agents of landscape evolution (Montgomery, 2002; Brardinoni and Hassan, 2006) and modulate present hydrologic, sedimentary, and geochemical fluxes along the receiving fluvial systems. In consideration of the current generalized conditions of atmospheric temperature rise, despite the relatively small contribution of most mid-latitude mountain glaciers to sea-level change (e.g., Zemp, 2006; Radić and Hock, 2011), a quantitative appraisal of their retreat and an improved understanding of the spatial variability in relation to different climatic settings hold critical implications for (i) water supply to hydropower plants (e.g., Barnett et al., 2005; Schaefer et al., 2007; Huss, 2011) and to agricultural and civil compartments (e.g., Braun et al., 2000; Piao et al., 2010; Huss, 2011; Hagg et al., 2013), (ii) mountain tourism (e.g., Scott et al., 2007; Beniston, 2012), and (iii) the assessment of relevant natural hazards (e.g., Huggel et al., 2004; Frey et al., 2010).

Composite glacier sensitivity to recent and ongoing climate changes has been reported through models based on empirical glacier mass balances from selected case studies (Oerlemans and Fortuin, 1992). Accordingly, low-elevation glaciers under maritime conditions, with high accumulation and mass turnover, would display higher sensitivity to climate fluctuations compared to their counterparts located in drier, continental settings. Similar findings have been

reported by Hoelzle et al. (2003), who reconstructed the mass balance of more than 50 glaciers around the world on the basis of front retreat information during the entire twentieth century. More recently, results from remotely sensed multitemporal (two to five decades) glacier inventories conducted across maritime-to-continental climatic transects have proved this question to be still open. For example, while Pan et al. (2012), when comparing six mountain systems in China ranging from monsoonal-temperate to extreme-continental climatic conditions, could not draw a conclusive picture of glacier response in relation to climate properties, other authors in the Canadian Cordillera have even shown that maritime glaciers in the Coast Mountains retreat less than continental counterparts in the Rockies (DeBeer and Sharp, 2007; Bolch et al., 2010a).

Within a given climatic setting, glacier dynamics are typically size dependent, with large glaciers retreating, on average, at a slower pace than smaller ones (e.g., Paul et al., 2004; Bolch et al., 2010a; Diolaiuti et al., 2012a; Tennant et al., 2012; Scotti, 2013; Carturan et al., 2013b). The latter, in turn, display high variability in area change, a variability that has been related to the local topographic heterogeneity of the hosting landscape (e.g., Kuhn, 1995; Paul et al., 2004; Abermann et al., 2009; DeBeer and Sharp, 2009; Hagg et al., 2012; Tennant et al., 2012; Carturan et al., 2013b). In fact, region-wide inventories have been customarily conducted from Landsat imagery (30 m grid ~ 0.001 km²) with automated procedures of detection, which, if they on one side allow rapid coverage of entire mountain ranges, cannot capture the area variation of very small glaciers (e.g., < 0.01 km²; Paul et al., 2004, 2011; Carturan et al., 2013b; and < 0.05 km²; Bolch et al., 2010a; Tennant et al., 2012), and most likely are less accurate than high-resolution aerial photographs (e.g., 0.5 m grid). This is a critical shortcoming, since small glaciers (e.g., < 0.5 km²) in the European Alps represent more than 80 % in number and 15 % in area of the whole glacier population (Paul et al., 2011), with much higher percentages in most sub-regions located south of the continental divide (e.g., Scotti, 2013, and this study).

In this physiographic context, there is a general lack of systematic studies tracking the area change of medium- to small-sized mountain glaciers from the Little Ice Age (LIA) to the beginning of the twenty-first century, a minimal temporal scale for constraining relevant interactions (coupling vs. decoupling) between climate and glacier fluctuations (Zemp et al., 2011). In fact, most of the relevant literature on the Italian Alps is extremely difficult to access (i.e., published in Italian, e.g., Caccianiga et al., 1994; Pelfini et al., 2002; Bonardi et al., 2012; Curtaz et al., 2013; Lucchesi et al., 2013), has examined post-LIA area change for single glaciers (Carturan et al., 2013a, c) or for a limited number of case studies (e.g., seven; Federici and Pappalardo, 2010), or has considered much shorter time intervals (e.g., Maragno et al., 2009; Diolaiuti et al., 2011, 2012a, b; Carturan et al., 2013b).

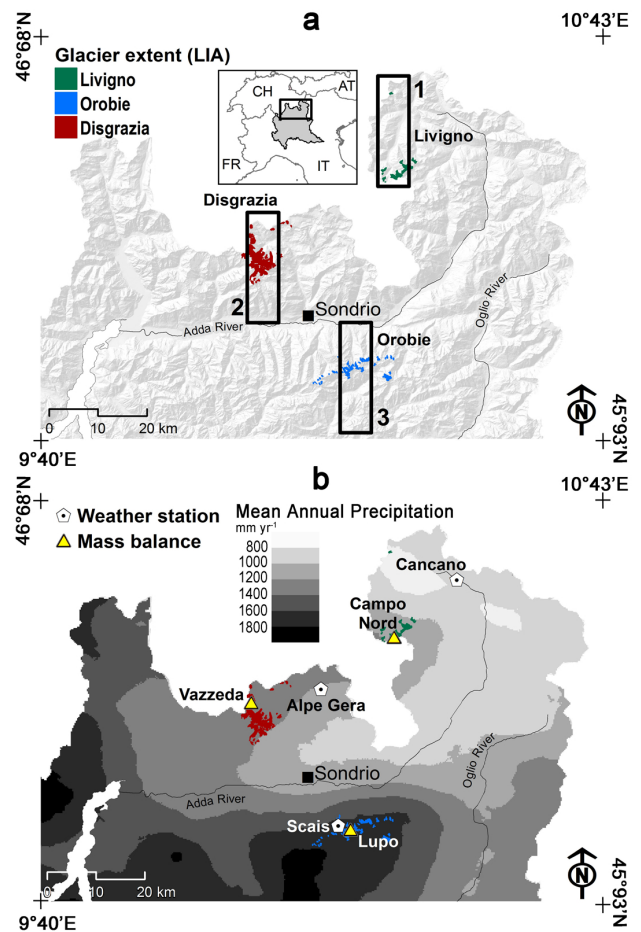


Figure 1. Maps of northern Lombardy showing (a) the three sub-region location and the transects used to create the swath profiles (see Fig. 4) and (b) spatial distribution of mean annual precipitation with sample weather stations and mass balance measured glaciers (see text for further details). Mean annual precipitation was interpolated by using ordinary co-kriging with 374 rainfall stations (1981–1990) (Ceriani and Carelli, 2000) and 50 000 elevation points randomly distributed within the region.

In order to fill this research gap and to improve our understanding of Alpine glacier response to climatic forcing in relation to climate spatial heterogeneity, we conduct post-LIA multitemporal, high-resolution glacier inventories in three sub-regions of the Central Italian Alps. These are home to medium-to-small glaciers, located along an idealized latitudinal transect that encompasses maritime, transitional, and continental glaciers, ranging in size from 0.002 to 2.3 km². Along this transect, we aim to (i) characterize glacier properties, (ii) calculate changes in glacierized area and evaluate acceleration/deceleration trends, (iii) elucidate correlations between area changes and environmental properties, including glacier and terrain topographic attributes and precipitation, and (iv) evaluate the spatial variability of glacier response to climatic forcing.

2 Study area

We focus on the glaciers of the Livigno, Disgrazia and Orobie sub-regions, located along a north-to-south transect within the Central Italian Alps (Fig. 1). The Livigno sub-region sits on the northern side of the Alpine continental divide (Inn–Danube River basin), and reaches 3303 m a.s.l. at Piz Paradisin. The area is dominated by a SW–NE trending valley that is chiefly underlain by ortogneiss and paragneiss of the Austroalpine basement. The Disgrazia sub-region is located south of the Alpine continental divide, and feeds the Masino and Mallero river valleys (Adda–Po River basin). The largest glaciers flow down radially from the higher peak of the Monte Disgrazia massif (3678 m a.s.l.) that is built of Malenco metaophiolites (mainly serpentinites). The Orobie are an E–W trending mountain range representing the southernmost glacierized area within Lombardy. They are located in the Southalpine tectonic domain that consists of metamorphic lithologies (paragneiss, phyllites and micaschists) covered by thick sedimentary deposits (conglomerates, marls and limestones). The highest peak is Pizzo di Coca (3052 m a.s.l.), and only two other summits exceed 3000 m a.s.l.

The climate of the Central Italian Alps above 2000 m a.s.l. is classified as a tundra climate (ET) according to the Köppen–Geiger scheme (e.g., Peel et al., 2007). In the three selected sub-regions, precipitation (rainfall and snowfall) exhibits high spatial variability in terms of total annual values (Fig. 1b) and seasonal distribution (Ceriani and Carelli, 2000). In the northernmost mountain range (Livigno), annual precipitation ranges locally from 790 to 1200 mm, with a winter minimum in February and a single summer maximum in August (e.g., Cancano weather station, 1950 m a.s.l.) (Fig. 2a). The opposite extreme can be observed in the southernmost mountain range (Orobie), where two precipitation peaks in June and October (Scais weather station, 1500 m a.s.l.) contribute to annual precipitation values ranging from 1620 to 1770 mm (Figs. 1b and 2c). The Disgrazia region is located at an intermediate latitude, exhibits a transitional behavior in terms of total annual values (range 1210–1370 mm), and mimics the Orobie seasonal distribution (Alpe Gera weather station, 2125 m a.s.l.) (Figs. 1b and 2b). The foregoing high spatial variability in total annual precipitation is confirmed and enhanced by field data of glacier winter mass balances (Bonardi et al., 2014). Specifically, the Lupo glacier (Orobie), despite its 500 m lower elevation, shows more than three times (2.9 m w.eq.) the accumulation observed at the Campo Nord glacier (0.9 m w.eq.) (Livigno).

Mean annual air temperature (MAAT) is 1.7 °C at Cancano (Livigno), 1.3 °C at Alpe Gera (Disgrazia) and 6.3 °C at Scais (Orobie). December and August are, respectively, the coldest and hottest months at Cancano and Scais, while at Alpe Gera, the monthly extremes happen in January and July.

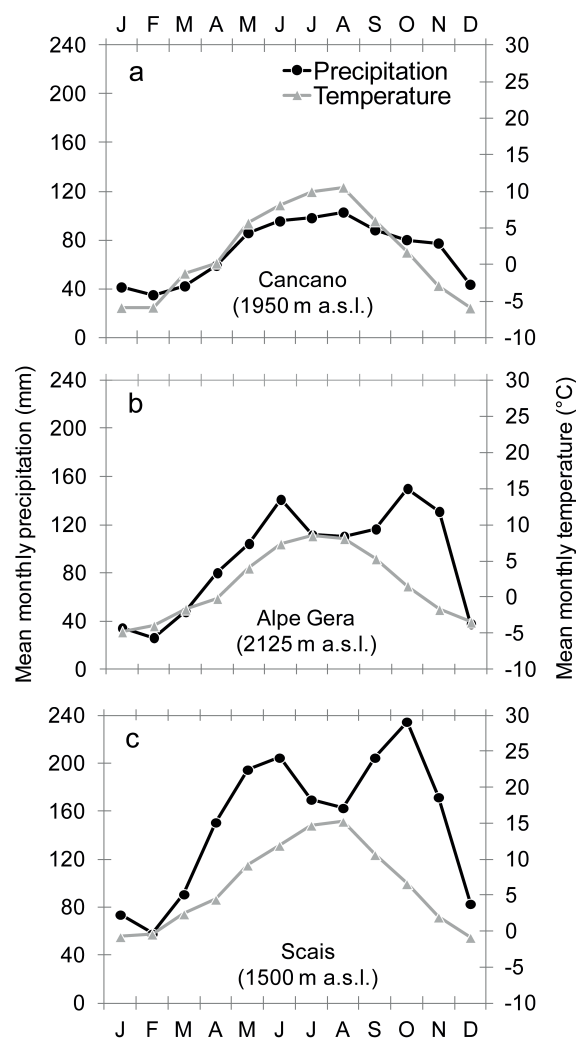


Figure 2. Climographs for the Cancano (Livigno sub-region), Alpe Gera (Disgrazia sub-region) and Scais (Orobie sub-region) weather stations. Time series: temperature (1990–2000); precipitation (1951–2000 Cancano, 1990–2000 Alpe Gera, and 1958–2000 Scais). Data sources: Servizio Idrografico e Mareografico Nazionale, Consorzio dell’Adda, ARPA Lombardia, Database OLL – Regione Lombardia D.G.S.P.U.

The progressive climatic shift from oceanic (Orobie) to continental (Disgrazia and Livigno) was detected as the main cause of the lower treeline elevation observed in the Orobie range (2260 m a.s.l. for trees ≥ 3 m) compared to the Disgrazia (2420 m) and Livigno (2480 m) areas (Lucini, 2000; Caccianiga et al., 2008). In this paper, we discuss continental and maritime climatic settings in relation to the spatial arrangement (or orographic configuration) of the three study sub-regions, making a geographic distinction between wetter, outer ranges (Orobie) and drier, inner ranges (Livigno) (e.g., Ivy-Ochs et al., 2006). Moisture-rich air masses travel from the Atlantic Ocean through the Mediterranean, and hit the Orobie first, imparting markedly higher precipitation

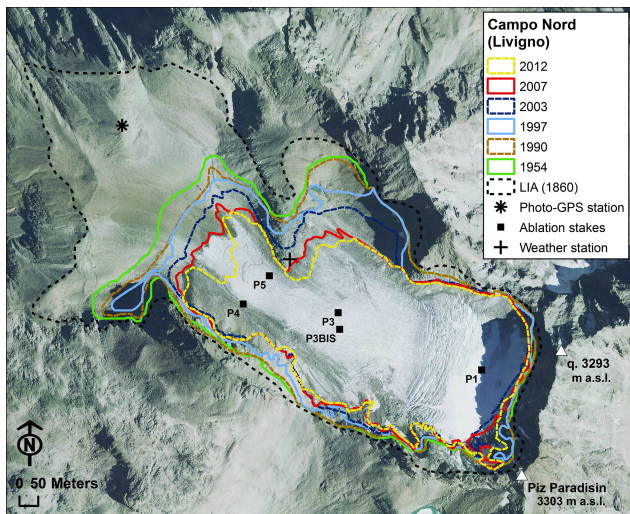


Figure 3. Example of multitemporal glacier delineation, i.e., Campo Nord glacier (Livigno sub-region), with the 2007 orthophoto in the background. The slightly larger extension of the glacier top area in 2012 compared to 2003 and 2007 is due to the presence of a snow field developed after the 2007 season that was characterized by very limited snow cover.

across this mountain range. When using the term “maritime” in the manuscript, we do not make a causal relation between the precipitation peaks in the climographs (Fig. 2) during the year and the presence of the Mediterranean Sea or the Atlantic Ocean.

3 Data collection and methods

In order to constrain the recent trend of glacier retreat, we reconstructed the extent of glacier, glacierets and perennial snowfields (here all termed “glaciers”), starting from the last maximum advance associated with the Little Ice Age (LIA), and proceeding with those from 1954, 1990, 2003 and 2007 (Fig. 3). The detection of the LIA maximum was conducted by integrating (i) field mapping of moraines and trim lines, (ii) remotely based interpretation of aerial photographs and DSM (digital surface model) shaded-relief rasters, and (iii) historical information including maps, paintings, photographs, reports and scientific literature. The LIA moraine ridges in the region are usually very well preserved but, in some glaciers, the interpretation is more challenging; therefore, in order to quantify the planimetric accuracy of the mapping, we assumed a conservative buffer of ± 10 m around the digitized glacier boundaries.

The shape and position of LIA moraines in the study areas and surrounding regions resemble those of other regions in the Alps where examples of LIA glacier reconstructions exist (e.g., Gross, 1987; Maisch, 1992; Maisch et al., 2000). Moraine ages have been determined by means of dendrochronology (e.g., Pelfini, 1999), geopedology (e.g., Cac-

cianiga et al., 1994; Trobio glacier in the Orobic), as well as lichenometry (e.g., Orbelli, 1987; Ventina glacier in Disgrazia) and a combination of these methods (e.g., Pelfini et al., 2002; Disgrazia/Sissone glaciers). These studies significantly improved the confidence of our reconstruction and helped in setting the generic date of the last LIA maximum glacial advance in the Disgrazia, Livigno, and Orobic sub-regions to AD 1860 (Pelfini and Smiraglia, 1992). This constitutes our benchmark against which we have computed historical area fluctuations.

The glaciers’ limits in 1954 have been stereographically interpreted on paper copies of black and white aerial photographs (nominal scale 1 : 45 000), then manually drawn on digital orthophotos. In this context, a careful visual inspection of available terrestrial oblique pictures was carried out in order to improve mapping consistency and accuracy that was assessed to be ± 5 m (e.g., Diolaiuti et al., 2011).

The glacial extent of the third time step (1990) relies on the Lombardy glacier inventory (Galluccio and Catasta, 1992), a data set based on detailed field surveys conducted between 1988 and 1991. Since most fieldwork was conducted in 1990, we have decided to set this year as a reference. To maximize consistency with the original data, the glacier limits, formerly on paper, have been digitized in a GIS environment and slightly revised on the basis of terrestrial and aerial oblique photos. The planimetric uncertainty of this inventory (± 2 m) is due to the reading error of the map used by the authors (scale 1 : 10 000) (Citterio et al., 2007; Diolaiuti et al., 2011, 2012a).

The most recent inventories of glacial extent have been reconstructed from 2003, 2007 and 2012 digital orthophotos. Despite the existence of a similar 2003 regional inventory (i.e., Diolaiuti et al., 2012a), in order to minimize the degree of subjectivity due to multiple interpreters, we decided to map independently all glaciers on a 2003 orthophoto mosaic (0.5 m grid). This mosaic is characterized by minimal snow cover over the glaciers and surrounding areas due to the extremely high temperatures recorded throughout that summer (i.e., García-Herrera et al., 2010). The 2007 inventory was compiled via manual delineation of glacier limits on a high-resolution (0.5 m pixel) orthophoto mosaic and a 2 m gridded digital surface model (DSM – year 2007). Thanks to the dry and hot accumulation season, snow cover is very limited in the 2007 images too (Scotti et al., 2013). Such conditions improved substantially our ability to identify glacier limits, and constituted a hard stress test for the survival of glacierets and perennial snowfields previously detected during field surveys. Manual delineation of glacier limits on summer 2012 orthophotos (0.5 m pixel) was limited to three sample glaciers: Campo Nord (Livigno), Vazzeda (Disgrazia) and Lupo (Orobic) (Fig. 1b).

Despite the excellent quality of the orthophoto mosaics, in order to minimize problems related to the delimitation of debris-covered glaciers, we conducted complementary GPS field surveys on three sample glaciers that provided critical

Table 1. Glacier variables considered.

Glacier variable	String	Unit
Size	GS	km ²
Maximum elevation	E_{\max}	m a.s.l.
Minimum elevation	E_{\min}	m a.s.l.
Balanced-budget equilibrium line altitude	ELA ₀	m a.s.l.
Ridge-crest elevation	E_{ri}	m a.s.l.
Glacier relative relief	ΔE	m
Mean slope gradient	S	°
Main aspect	MA	na
Clear-sky radiation (June–September)	CSR	W m ²
Mean annual precipitation	MAP	mm a ⁻¹
Avalanche area accumulation basin ratio	ABR	na

ground control for data extracted from remotely based inspection. We consider the planimetric uncertainty of the digitized 2003 and 2007 glacier limits equal to ± 1 m, that is the uncertainty associated with the orthophoto mosaic as specified by the manufacturer (e.g., Diolaiuti et al., 2012a).

The uncertainty associated with glacier area was evaluated for each glacier by setting buffers of ± 10 m (LIA), ± 5 m (1954), ± 2 m (1990) and ± 1 m (2003, 2007 and 2012) on the digitized glacier limits. Subsequently, to evaluate the uncertainty of estimated glacier change, we used the root of the squared sum of buffer areas along the study time series (e.g., Xu et al., 2013; Tennant and Menounos, 2013).

In order to improve our understanding of the factors controlling the site-specific variability of glacier retreat, we have collected a number of environmental attributes for the 2007 data set. These include glacier primary classification, contribution of snow avalanching to accumulation, surface area (A), maximum elevation (E_{\max}), terminus elevation (E_{\min}), glacier relative relief (ΔE), balanced-budget equilibrium line altitude (ELA₀) elevation of the ridge crest upslope of the glacier (E_{ri}), mean slope gradient (S), main aspect (MA), summer clear-sky radiation (CSR) and mean annual precipitation on the glacier (MAP) (Fig. 1b and Table 1).

The glacier primary classification and the definition of the avalanche contribution to glacier accumulation are crucial for characterizing the glacier types of the three study areas. The former follows the illustrated Global Land Ice Measurements from Space glacier classification manual (Rau et al., 2005); the latter, which we define as the avalanche area accumulation basin ratio (ABR), is the ratio between the area occupied by avalanche accumulation at the end of an average snowfall accumulation season and the area of the accumulation basin (above the ELA₀). This classification scheme, which is based on decadal field observations, consists of three classes: low ($ABR \leq 0.33$), moderate ($0.33 < ABR \leq 0.66$) and high ($ABR > 0.66$). The main topographic attributes (i.e., E_{\max} , E_{\min} , ELA₀, E_{ri} and S) have been extracted from the 2 m gridded DSM using zonal statistics in ArcGIS v.9.3 (Paul et al., 2009). The terminus (E_{\min}) and the maximum glacier elevation (E_{\max}) are effective tools for

defining the lower and upper limit of the glacial domain, and their fluctuations are usually related to surface and volume changes. The analysis of the elevation fluctuations was applied to a fixed sample of glaciers present in all the inventories. This approach minimizes the errors caused by the increase (or decrease) in the number of glaciers due to fragmentation (or extinction). The use of the entire data set of each inventory would have resulted in underestimation or overestimation of the E_{\min} and E_{\max} change. The maximum difference we have found comparing the two approaches is 45 % (e.g., underestimation of the E_{\max} drop in Livigno glaciers from the LIA to 2007). The glacier relative relief (ΔE) is the arithmetical difference between E_{\max} and E_{\min} , and depends on glacier length and slope gradient (S).

The balanced-budget equilibrium line altitude (ELA₀) (Meier and Post, 1962; Cogley et al., 2011) is a widely used parameter in glacier and paleoclimatic reconstructions (e.g., Miller et al., 1975; Benn and Lehmkühl, 2000), and it is usually defined with the balance-budget accumulation area ratio (AAR₀) method (Meier and Post, 1962; Gross et al., 1978). While the high variability of worldwide-measured AAR₀ (from 0.22 to 0.72) in mass balance data warns against a straightforward use of this parameter (WGMS, 2005; Zemp et al., 2007), we delineate ELA₀ (also termed local-topography _{lt}ELA₀) as the median surface elevation of the glacier (i.e., considering a 0.50 AAR₀, e.g., Hughes, 2009, 2010; Bolch et al., 2010b; Carturan et al., 2013b; Ignéczi and Nagy, 2013). This value appears to be particularly well suited for small glaciers (e.g., Braithwaite and Raper, 2007, 2009; Kern and László, 2010), like the ones we are studying. Indeed, the low glacier relative relief (ΔE) that is typically associated with small glacier size imparts very little change to our ELA₀ values when using AAR₀ = 0.5, as opposed to 0.67 (originally proposed by Gross et al., 1978), hence providing a reasonable justification for assuming $E_{\text{median}} = \text{ELA}_0$. Since a number of seminal paleoclimatic and landscape evolution studies have adopted an AAR₀ equal to 0.67 (e.g., Maisch et al., 2000; Kerschner et al., 2000; Bavec et al., 2004; Zemp et al., 2007; Kerschner and Ivy-Ochs, 2008), for completeness, we provide an ELA₀ based on AAR₀ 0.67 in the supplementary material. This topography-based parameter differs from the regional climatic ELA (i.e., _{rc}ELA₀), which relies on synoptic climatic data and mass balances of a limited number of selected glaciers (e.g., 14 glaciers for the European Alps, and only two belonging to the Italian portion; Zemp et al., 2007). The elevation of the ridge crest upslope of the glacier (E_{ri}) is computed as the median elevation of the 10 m wide buffer drawn along the ridge crest feeding the glacier accumulation basin. The elevation difference between E_{ri} and ELA₀ is considered to be correlated with both the degree of avalanching contribution to the glacier's mass balance and the shading effect of the rock walls upslope of the glacier. The main aspect of the glacier, divided into eight classes, was manually defined along the direction of the main flow axis or,

for snowfields, the general aspect of the mountain slope. The summer clear-sky global radiation (June to September) was calculated with ArcGIS Spatial Analyst (Dubayah and Rich, 1995) using a 20 m resampled version of the DSM. This parameter is directly affected by the glacier aspect slope and by the shading proprieties of the rock walls surrounding the glacier. Mean annual precipitation for each glacier is derived from a 250 m gridded precipitation map (Fig. 1b), and represents a proxy for snow accumulation on the glacier.

4 Results

4.1 Glacier proprieties

In the presentation of the results, we provide an overview of the glacier properties as inventoried in 2007. We proceed from the northernmost Livigno sub-region, home to 16 glaciers (total glacier area = $1.1 \text{ km}^2 \pm 0.02$), continue with the Disgrazia sub-region that hosts 37 glaciers ($7.3 \text{ km}^2 \pm 0.09$), and conclude with the Orobic sub-region, in which we identify 44 glaciers ($1.8 \text{ km}^2 \pm 0.05$). Along this transect, we observe a remarkable increase in mean annual precipitation (MAP) as we move from the interior ranges (Livigno, 790–1200 mm) towards the outer ranges (Orobic, 1620–1770 mm) (Fig. 4). Concurrently, median ELA_0 (Fig. 4) and clear-sky radiation mirror the spatial variability of local relief in that they slightly increase from the interior, plateau-like topography of Livigno (2833 m a.s.l.; 176 W m^{-2}) to the Disgrazia massif (2890 m a.s.l.; 210 W m^{-2}) and drop abruptly in the Orobic range (2517 m a.s.l.; 145 W m^{-2}). The altitudinal distribution of ELA_0 displays an increase in within-regional scatter with increasing MAP (i.e., moving from Livigno down south; Fig. 5a). This variability is imparted by the combination of two spatial patterns in which ELA_0 rises progressively: (i) from north- to south-facing glaciers within the same mountain range (i.e., Disgrazia in Fig. 5b); and (ii) for a given aspect category (e.g., N and NW in Fig. 5b) moving from the peripheral Orobic range inland to the Livigno Mountains.

In the Livigno Mountains, glacierets and cirque glaciers are the dominant typologies, and face mainly northwest to northeast (Figs. 5b and Table 2). Despite the presence of relatively high peaks across the entire sub-region, glaciers today survive almost only in the southernmost portion of the range (with one exception), where, incidentally, MAP is higher. Glacier size ranges from 0.003 to 0.37 km^2 (Val Nera Ovest glacier). The propensity for avalanche snow/ice supply (ABR) is high (11 cases) to moderate (4 cases), while slope (S) ranges from 19.6 to 33.0° (median 29.2°).

In the Disgrazia sub-region, besides the abundance of permanent snowfields, glacier types comprise, in decreasing order of frequency, cirque, niche, and simple/compound basin valley glaciers (Table 2). Glaciers face preferentially north-

Table 2. Glacier characteristics in the study sub-regions as inventoried in 2007.

Classification		Sub-region		
Primary	Secondary	Livigno	Disgrazia	Orobic
Valley glacier	Simple basin	–	1	–
	Compound basins	–	1	–
Mountain glacier	Cirque	3	13	24
	Niche	–	2	–
	Compound basins	–	2	–
Glacieret	Cirque	4	4	9
	Niche	1	1	–
Permanent snowfield		8	13	11
Total sample		16	37	44
Area (km^2)		$1.1(\pm 0.02)$	$7.3(\pm 0.09)$	$1.8(\pm 0.05)$

west and southeast, but thanks to the radial structure of the massif, all aspects are well represented (Fig. 5b). Compared to the other study sub-regions, ice masses are evenly distributed across the N–S transect, they are relatively larger, and they range from 0.002 to 2.31 km^2 (Disgrazia glacier). ABR is high, moderate, and low for, respectively, 24, 10, and 3 glaciers. Median slope is comparatively lower (27.1°), and we observe the largest slope variability (18.1 – 45.0°).

Glaciers in the Orobic are located exclusively within north- to northwest-facing cirques. They are clustered around a narrow latitudinal range, along the main ridge of the sub-region (Fig. 4), and are particularly small in size, ranging from 0.002 to 0.22 km^2 (Lupo glacier) (Fig. 5b). The peculiar morphometric setting made of high and steep rock walls, located immediately upslope of each glacier, is confirmed by the high elevation difference (233 m) recorded between ELA_0 and the mean ridge-crest elevation (E_{ri}). Accordingly, all Orobic glaciers exhibit a high ABR potential for avalanche snow supply. Slope range is similar to that observed in Disgrazia (18.8 – 42.2°), while median slope (29.1°) is higher, and resembles that of Livigno.

4.2 Area changes

Since the LIA, all of the 111 glaciers of the study sub-regions have gone extinct (14) or have experienced a strong net areal reduction (97), for a combined area loss of 24 km^2 (Fig. 6a–c). At the acme of LIA advance, the 15 glaciers of the Livigno cluster used to cover an area of 5.4 km^2 (Fig. 6a and Table 3). By 1954, a total of 21 glaciers (i.e., 3 of the initial 15 had fragmented into smaller ones) occupied 2.5 km^2 ($52.6 \pm 14.6\%$), for an average annual decrease (AAD) of about $0.031 \pm 0.006 \text{ km}^2 \text{ a}^{-1}$ (Table 3). In the same period, the 27 LIA glaciers of the Disgrazia Mountains increased to 36 (Fig. 6b), but with an overall area loss of $43.6 \pm 6.4\%$ and an AAD of about $0.102 \pm 0.015 \text{ km}^2 \text{ a}^{-1}$ (Table 3). Finally, in the Orobic sub-region, by 1954, we record $52.6 \pm 14.6\%$ in LIA surface reduction, which corresponds to an AAD of about $0.038 \pm 0.010 \text{ km}^2 \text{ a}^{-1}$ (Table 3).

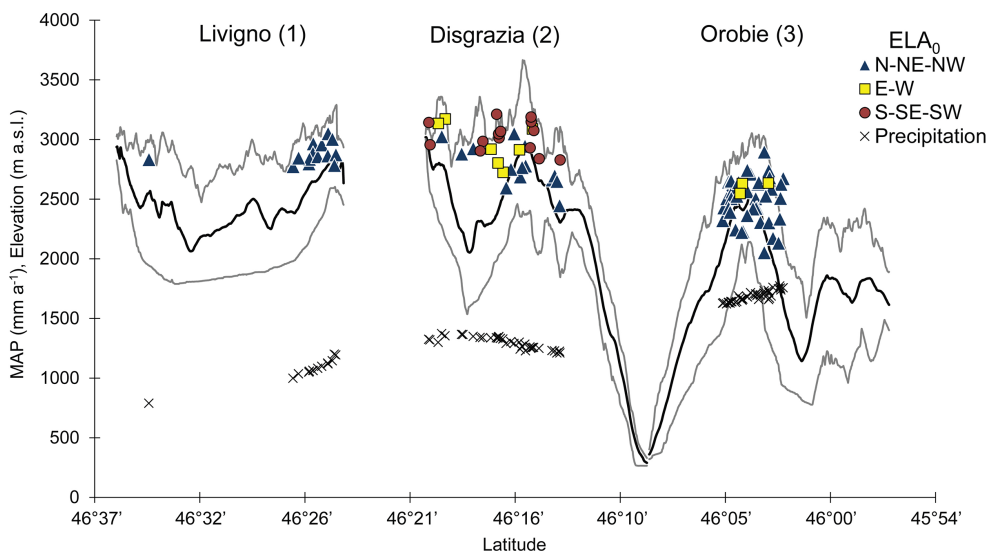


Figure 4. Latitudinal transect across the Livigno, Disgrazia, and Orobie sub-regions. Dashed lines indicate minimum and maximum elevation, and solid lines indicate mean elevation. Filled symbols and crosses refer, respectively, to the ELA_0 (stratified by dominant slope aspect) and mean annual precipitation (MAP) values associated with each study glacier.

Table 3. Variation of glacier count and glacierized area through time in the study sub-regions.

Sub-region	1860		1954		1990		2003		2007	
	Count	Area (km ²)	Count	Area (km ²)	Count	Area (km ²)	Count	Area (km ²)	Count	Area (km ²)
Livigno	15	5.4 ± 0.53	21	2.5 ± 0.20	22	2.3 ± 0.07	21	1.3 ± 0.03	16	1.1 ± 0.02
Disgrazia	27	22.0 ± 1.28	36	12.4 ± 0.59	38	11.9 ± 0.22	39	8.4 ± 0.10	37	7.3 ± 0.09
Orobie	45	6.7 ± 0.93	49	3.2 ± 0.31	49	3.1 ± 0.12	48	2.0 ± 0.06	44	1.8 ± 0.05

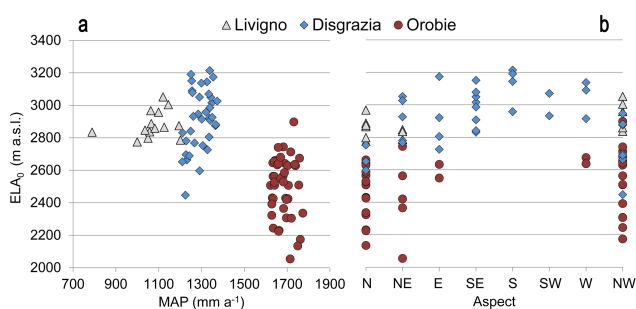


Figure 5. Balanced budget equilibrium line altitude (ELA_0) as a function of (a) mean annual precipitation (MAP) and (b) slope aspect.

The 1990 inventory depicts a much slower rate of areal contraction, with values small enough to fall within the envelope of uncertainty (Fig. 7). The glacierized area in the Livigno Mountains records the stronger relative contraction (i.e., $9.5 \pm 8.3\%$), equal to 0.23 km^2 ($AAD = 0.007 \pm 0.006 \text{ km}^2 \text{ a}^{-1}$) (Table 3). Glaciers in Disgrazia lost $3.5 \pm 5.1\%$, which corresponds to a net loss of 0.43 km^2 ($AAD = 0.012 \pm 0.017 \text{ km}^2$

a^{-1}) (Table 3). Similarly, in Orobie, we observe a $3.5 \pm 10.4\%$ decrease, corresponding to a net loss of 0.11 km^2 ($AAD = 0.003 \pm 0.009 \text{ km}^2 \text{ a}^{-1}$).

In the 1990–2003 period, glaciers exhibit consistently fast retreat throughout the three study areas (Fig. 7). In increasing order, Disgrazia witnesses a decrease of 3.5 km^2 that corresponds to a $29.5 \pm 2.0\%$ reduction ($AAD = 0.271 \pm 0.018 \text{ km}^2 \text{ a}^{-1}$), the Orobie exhibit a 1.2 km^2 decrease, which amounts to a $35.0 \pm 4.2\%$ contraction ($AAD = 0.083 \pm 0.010 \text{ km}^2 \text{ a}^{-1}$), and Livigno glaciers lost 1 km^2 , equal to a $42.7 \pm 3.3\%$ loss of the 1990 glacierized area ($AAD = 0.075 \pm 0.006 \text{ km}^2 \text{ a}^{-1}$) (Table 3). During the 2003–2007 interval, we observe for the first time that glacier area loss increases northward, with Livigno displaying the highest area loss ($16.9 \pm 2.5\%$) ($AAD = 0.063 \pm 0.009 \text{ km}^2 \text{ a}^{-1}$), followed by Disgrazia ($12.8 \pm 1.6\%$) ($AAD = 0.309 \pm 0.037 \text{ km}^2 \text{ a}^{-1}$) and Orobie ($10 \pm 3.6\%$) ($AAD = 0.057 \pm 0.020 \text{ km}^2 \text{ a}^{-1}$) (Table 3). Overall, considering the entire study period (1860–2007), glaciers of the Livigno sub-region display the largest retreat recorded amongst the three study areas, losing a total of $4.4 \pm 0.5 \text{ km}^2$ ($80.1 \pm 9.8\%$ of the initial 1860

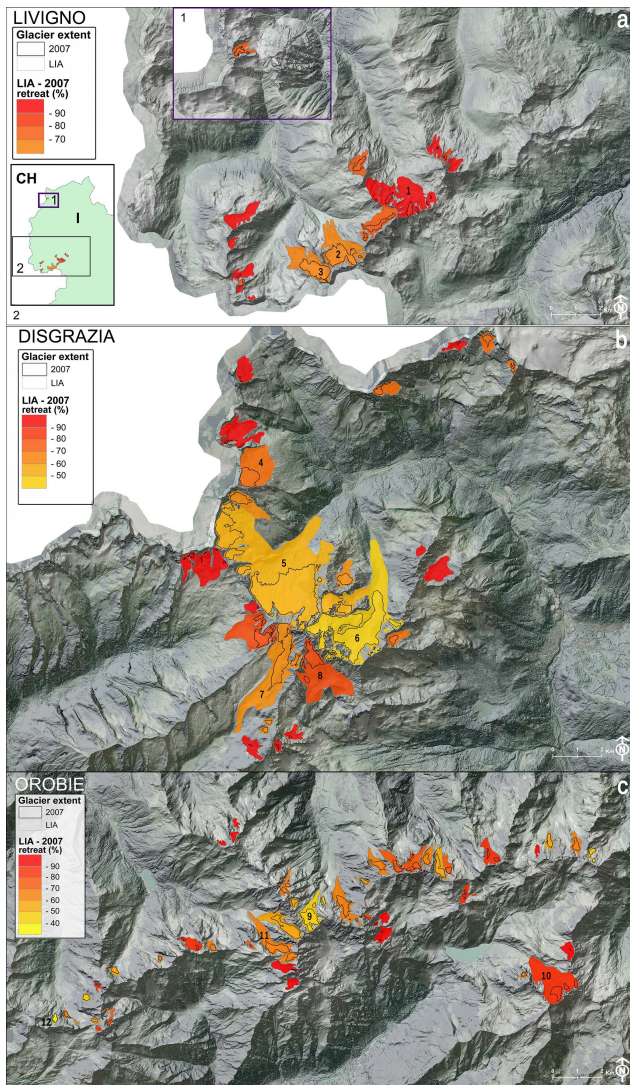


Figure 6. Maps showing the glacier extents in 1860 (LIA) and 2007, and the spatial distribution of the relative change in glacier area in (a) Livigno, (b) Disgrazia, and (c) Orobie. Numbers refer to the glaciers cited in the text. 1: Mine, 2: Campo Nord, 3: Val Nera Ovest, 4: Vazzeda, 5: Disgrazia/Sissone, 6: Ventina, 7: Predarossa, 8: Cassandra, 9: Lupo, 10: Trobio, 11: Scais, 12: Aga. The northern-facing Disgrazia–Sissone and Ventina glaciers display a smaller relative retreat (56 and 45 %, respectively) compared to the southern-facing counterparts of Predarossa (69 %) and Cassandra (83 %) that are similar in size and that flow down from the same summits (see also Fig. 11b).

extension). Glaciers in the Disgrazia cluster lost a total of $14.6 \pm 1.3 \text{ km}^2$ ($66.5 \pm 5.9 \%$) and, in the Orobie range, they lost $4.9 \pm 0.9 \text{ km}^2$ ($73.2 \pm 13.8 \%$).

Examination of AAD across size classes shows that the relative change rate in glacier area in the 1860–1954 period has been fairly low (0.46 \% a^{-1} in Disgrazia, 0.56 \% a^{-1} in Orobie and 0.57 \% a^{-1} in Livigno) and complementary among small- and large-size classes (Table 4). Subsequently

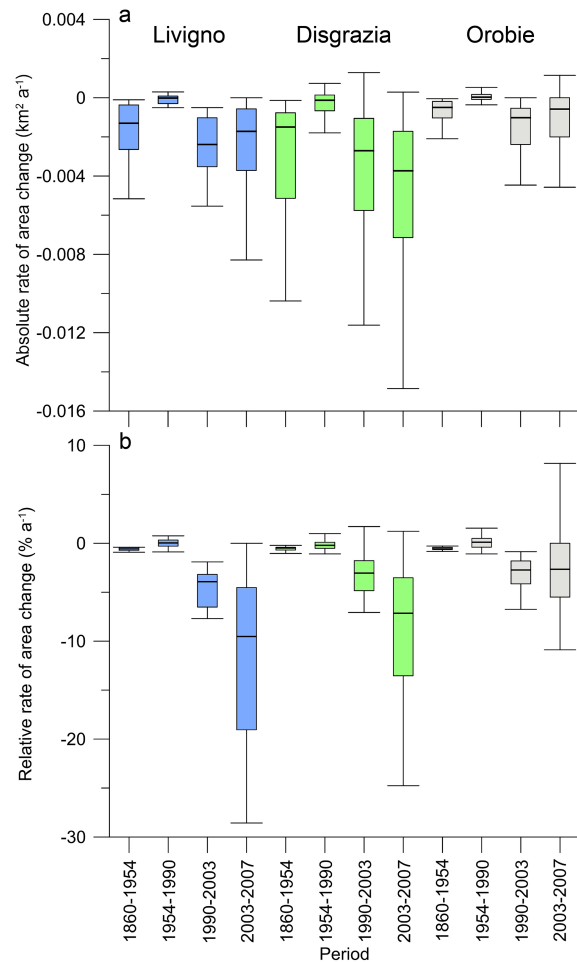


Figure 7. Boxplots showing (a) absolute rate of glacier area change and (b) relative rate of glacier area change. Horizontal lines indicate median values, boxes constrain the 25th and 75th percentiles, and whiskers mark the 10th and 90th percentiles. Outliers are not presented due to scale constraints.

(1954–1990), the $< 0.1 \text{ km}^2$ class displays the lowest reduction (Livigno: 0.02 ; Disgrazia: 0.16 \% a^{-1}) and, in the Orobie, even a modest increase (-0.09 \% a^{-1}). In Disgrazia and Livigno, the largest retreat rates are observed in the intermediate classes ($0.5\text{--}1 \text{ km}^2$ and $0.1\text{--}0.5 \text{ km}^2$, respectively), whereas larger glaciers exhibit a slight area increase (Disgrazia: -0.22 \% a^{-1} for $2\text{--}5 \text{ km}^2$; Livigno: -0.04 \% a^{-1} for $0.5\text{--}1 \text{ km}^2$) (Table 4).

The strong glacier shrinkage recorded in the two more recent periods (1990–2003 and 2003–2007) has affected especially small glaciers (i.e., $< 0.1 \text{ km}^2$ and $0.1\text{--}0.5 \text{ km}^2$), and we observe progressively slower retreat rates within the larger size classes (Table 4).

4.3 Elevation changes

The area changes detailed above correspond to changes in glacier ice elevation, both in terms of E_{\min} and E_{\max} .

Table 4. Relative change rate in glacier area, expressed as average annual decrease (AAD) across glacier size classes.

Size classes km ²	AAD (% a ⁻¹)			
	1860–1954	1954–1990	1990–2003	2003–2007
Livigno				
< 0.1	0.63	0.02	5.20	8.73*
0.1–0.5	0.68	0.62	2.88	3.17
0.5–1	0.41	−0.04	2.31	–
1.0–2.0	0.60	–	–	–
Total AAD	0.57 ± 0.11	0.26 ± 0.23	3.28 ± 0.25	4.82 ± 0.70
Median AAD	0.58	−0.04	3.92	9.52
Disgrazia				
< 0.1	0.41	0.16	3.54	11.11*
0.1–0.5	0.63	0.36	2.71	3.31
0.5–1	0.63	0.43	3.14	3.74
1.0–2.0	0.47	0.18	2.82	–
2.0–5.0	0.34	−0.22	1.52	2.17
5.0–10.0	0.43	–	–	–
Total AAD	0.46 ± 0.07	0.10 ± 0.14	2.27 ± 0.15	3.67 ± 0.44
Median AAD	0.47	0.20	3.06	7.14
Orobie				
< 0.1	0.55	−0.09	3.27	3.77*
0.1–0.5	0.55	0.25	2.21	2.04
0.5–1	0.56	–	–	–
1.0–2.0	0.60	–	–	–
Total AAD	0.56 ± 0.15	0.10 ± 0.29	2.69 ± 0.32	2.87 ± 1.02
Median AAD	0.55	−0.11	2.72	2.64

* In 2003–2007, small glaciers (< 0.1 km²) exhibit by far the highest decrease rate of the whole study period in Disgrazia and Livigno; by contrast, in Orobie, this size class shows a much slower decrease.

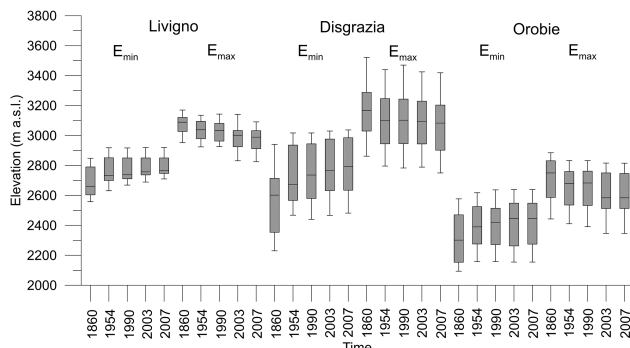


Figure 8. Change in glacier maximum (E_{max}) and minimum (E_{min}) elevations across the four study intervals. Horizontal lines indicate median values, boxes constrain the 25th and 75th percentiles, and whiskers mark the 10th and 90th percentiles. Outliers are not presented due to scale constraints.

The median E_{min} of the 111 glaciers detected at the LIA maximum lies at 2480 m a.s.l., and rises progressively throughout the twentieth century to a maximum of 2628 m in 2007, which translates to an average annual gain of 1.0 m a⁻¹. In the same period, median E_{max} drops from 2893 to 2810 m a.s.l. (−0.6 m a⁻¹). Data stratification into sub-regional domains reveals a considerable spatial variability

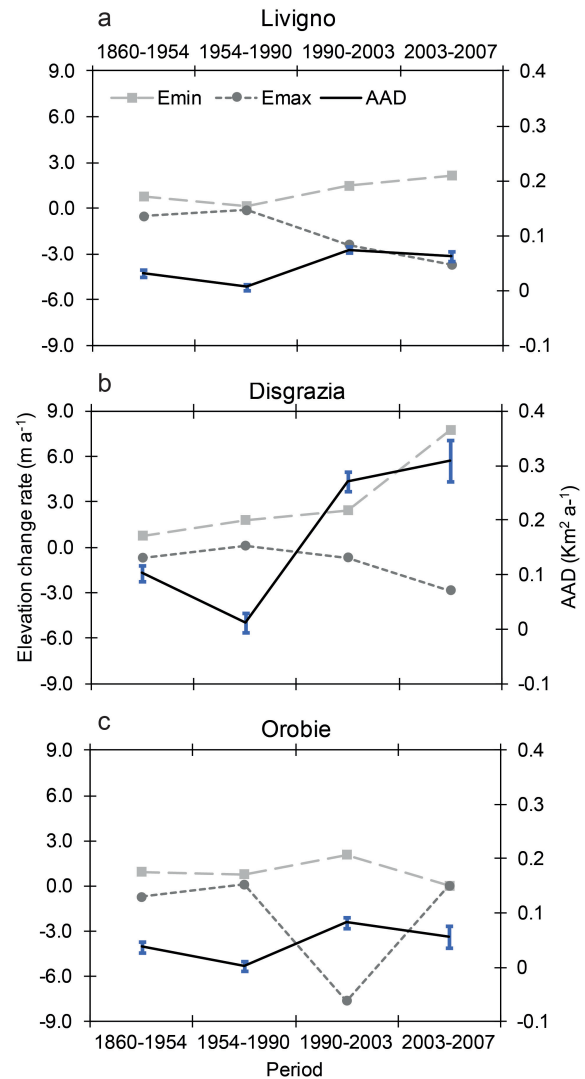


Figure 9. Mean annual elevation change rate (m a⁻¹) and average annual decrease (AAD) in glacier area (km² a⁻¹) in (a) Livigno, (b) Disgrazia, and (c) Orobie. Bars indicate uncertainty in glacier area delineation.

in E_{min} and E_{max} fluctuations. Both glacier attributes in the Livigno cluster are characterized by a markedly lower variability compared to Orobie and Disgrazia (Fig. 8). The 1860–2007 overall rise in E_{min} is lowest in Livigno (0.7 m a⁻¹), intermediate in Orobie (1.0 m a⁻¹), and highest (1.9 m a⁻¹) in the Disgrazia sub-region, where we note a sharp increase between 1860 and 1954 (Fig. 8). Conversely, Disgrazia exhibits the lowest drop in E_{max} (−0.6 m a⁻¹), followed by Livigno (−0.7 m a⁻¹) and Orobie (−1.1 m a⁻¹), with the last characterized by two large drops in 1860–1954 and 1990–2003 (cf. the median lines in Fig. 8).

Simultaneous analysis of elevation (E_{min} and E_{max}) and area changes through time is instructive in that it allows inferring qualitatively characteristic trends of volumetric

glacier shrinkage (Fig. 9). Up until 1990, we observe a general decline in average annual decrease and a general convergence of the E_{\min} and E_{\max} trend lines in Livigno and Orobic clusters, while in Disgrazia, both E_{\min} and E_{\max} rise slightly (Fig. 9). This latter trend suggests that, on average, glacier ice lost at the terminus was nearly completely replaced (i.e., at least in terms of area) by the increase in elevation of the accumulation basin (Fig. 9b). From 1990, we start observing a progressive divergence of the E_{\min} and E_{\max} trend lines (Fig. 9), an indication of net, generalized, glacier volume loss. While such trend continue to the end of the study period in Livigno and Disgrazia, in the Orobic, we observe an opposite trend between 2003 and 2007, with E_{\min} and E_{\max} overlapping around a null elevation change rate (Fig. 9c). This stability in elevation range, in conjunction with a minor decrease in surface area, suggests volumetric shrinkage mainly caused by a reduction in glacier width.

4.4 Area change with glacier attributes

Analysis of changes in glacier area within the same sub-region allows one to detect, and possibly rank, the main environmental attributes driving glacier retreat. To this purpose, we analyze the mutual correlations among the “1860–2007 area change” in relation to glacier size (GS), main aspect (MA), mean slope gradient (S), minimum elevation (E_{\min}), maximum elevation (E_{\max}), glacier relative relief (ΔE), mean annual precipitation (MAP), ridge-crest elevation (E_{ri}), and clear-sky radiation (CSR) (Tables S3–S5 in the Supplement).

Relative area change (AC%) in Livigno exhibits strong direct correlations with E_{ri} ($r = 0.77$), E_{\max} ($r = 0.72$) and ΔE ($r = 0.65$), and moderate correlations with E_{\min} (inverse, $r = -0.46$), former glacier size (GS, $r = 0.43$), and clear-sky radiation (CSR, $r = 0.43$) (Table S3). These correlations with relative area change weaken progressively moving south to Disgrazia (i.e., E_{ri} ($r = 0.35$), E_{\max} ($r = 0.45$), ΔE ($r = 0.47$), and glacier size (GS, $r = 0.42$)) (Table S4), and virtually disappear in Orobic (i.e., E_{ri} ($r = -0.03$), E_{\max} ($r = -0.20$), ΔE ($r = 0.20$), and E_{\min} ($r = -0.40$)) (Table S5).

Despite the moderate glacier size–retreat correlations previously identified in the Livigno and Disgrazia sub-regions, representing relative area changes as a function of former glacier size does not aid in constraining an empirical envelope of variability (Fig. 10).

In order to gain further insights into the elevation–retreat correlations identified above, we have represented relative area change as a function of E_{ri} (Fig. 11). We hypothesize this variable to be a useful proxy of the local climatic conditions (e.g., snowfall available for subsequent avalanche inputs, shading effect and wind shielding) that characterize a glacier’s source basin. Although we reckon that E_{ri} is closely related to other glacier elevation attributes, i.e., E_{\max} and ΔE (Tables S3–S5), unlike these, E_{ri} does not change with time,

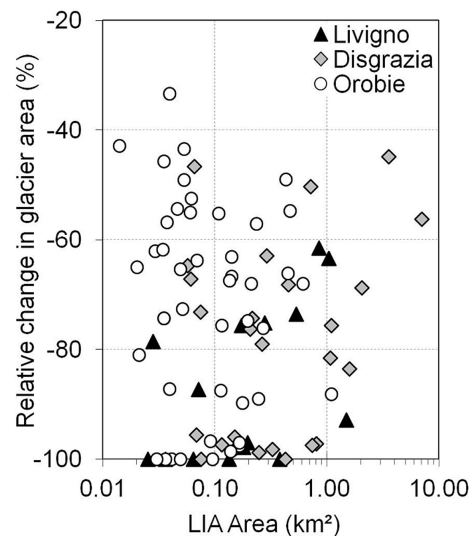


Figure 10. Relative change in glacier area (1860–2007) as a function of former glacier size.

and as such would constitute a more reliable reference across changing climate conditions. In addition, E_{ri} is a more statistically sound attribute, as it is not based on a single datum of elevation (i.e., E_{\min} and E_{\max}).

The representation presented in Fig. 11 shows that E_{ri} declines progressively along our north-to-south transect. In the Livigno and Disgrazia sub-regions, relative area change (AAD) varies inversely with E_{ri} , and this relation is well constrained for AAD up to 80%. Beyond this threshold, the degree of scatter increases. Stratification of glaciers according to south- and north-facing categories allows constraining two distinct retreat–elevation envelopes, with the former glaciers plotting about 300 m higher. Finally, in the Orobic Mountains, we see that the wide range of retreat rates is completely unrelated to E_{ri} (Fig. 11c) and glacier size (Fig. 6c), suggesting that different mechanisms must control contemporary glacier dynamics in this physiographic setting.

5 Discussion

5.1 Equilibrium line altitude

The equilibrium line of a glacier is a climate-dependent attribute that, when estimated at the regional scale using climatic data and a limited set of glacier mass balances ($_{rc}ELA_0$; e.g., Ohmura et al., 1992; Zemp et al., 2007), can mask the intrinsic spatial heterogeneity modulated by glacier aspect and other local topographic variables (Dahl and Nesje, 1992). Such topographic effects can be evaluated by comparing the local topography $ELA_0(itELA_0)$ (i.e., the ELA_0 considered in this study) with the regional climatic one ($_{rc}ELA_0$) (Dahl and Nesje, 1992; Lie et al., 2003; Zemp et al., 2007). In this respect, the distributed $_{rc}ELA_0$ map of the Central

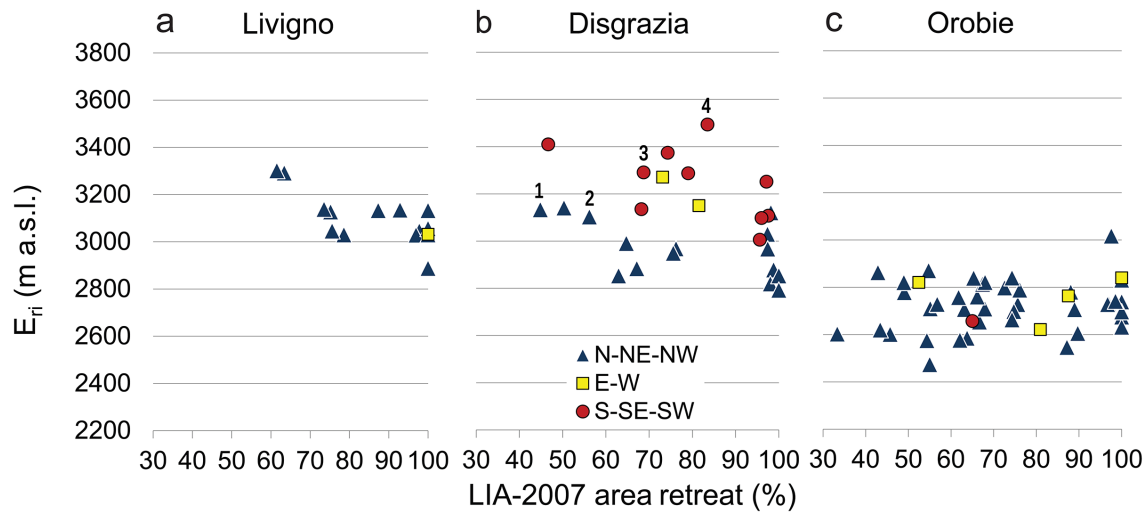


Figure 11. Relative area retreat in 1860–2007 as a function of E_{ri} (ridge-crest elevation upslope of the glacier) in (a) Livigno, (b) Disgrazia, and (c) Orobie. Glaciers are stratified by the dominant slope aspect (note the different symbols). Numbers refer to the glacier cited in the text; 1: Ventina, 2: Disgrazia/Sissone, 3: Predarossa, 4: Cassandra.

European Alps presented by Anders et al. (2010) (i.e., based on equations by Ohmura et al., 1992, and Zemp et al., 2007) reports values that are about 40, 130, and 380 m higher than the actual topography-based analogs for Disgrazia, Livigno, and Orobie, respectively, suggesting that local topography, on average, has a different weight in each sub-region.

Since the $r_{c}ELA_0$ approach typically tends, respectively, to underestimate and overestimate southerly and northerly aspects (Zemp et al., 2007), the relatively small “climate–topography” mismatch in the Disgrazia cluster should not surprise, given that, in this area, glaciers are distributed in all aspect categories (Fig. 5b) and, so, aspect effects tend to cancel out. Following this logic, from a synoptic climatic standpoint, Orobie glaciers should not exist, as the $r_{c}ELA_0$ in this sub-region (~ 2900 m a.s.l.) plots some 180 m above the median ridge crest, hence confirming the characteristic topo-climatic adjustment of these glaciers (on average). In this context, the comparison between Orobie and Livigno (both characterized by dominantly north-facing glaciers) is instructive, as it removes any potential confounding associated with slope aspect. In the Orobie, we observe a fourfold increase in ELA_0 variability (> 800 m) compared to Livigno (~ 300 m) (Fig. 5b), a variability that reinforces prior hints (Sect. 4.4) at the potential decoupling between Orobie glaciers and synoptic climatic conditions, and that we interpret as the effect of local morphometric properties of the hosting cirques and niches. At these locations, peculiar conditions of snow avalanching, shading and wind accumulation would be able to sustain glaciers, but not significant ice flow, as this latter would imply the existence of larger glaciers, characterized by higher glacier relative reliefs (ΔE).

5.2 Area change of small glaciers

Considering the characteristic limited size of our study glaciers, the high sensitivity of mid-to-small glaciers (even though associated with high scatter) to climate change (i.e., Haeberli and Beniston, 1998; Paul et al., 2004; Jiskoot and Mueller, 2012; Tennant et al., 2012), and the relatively low elevation of the study terrain (Fig. 4), it is not surprising that, at first glance, post-LIA annual average decrease (AAD) in Livigno ($0.55\% \text{ a}^{-1}$), Disgrazia ($0.45\% \text{ a}^{-1}$), and Orobie ($0.50\% \text{ a}^{-1}$) plot well above the estimated average of $0.33\% \text{ a}^{-1}$ for the European Alps (1850–2000, Zemp et al., 2008). However, since this regional estimate relies chiefly on satellite imagery, it is likely to carry high uncertainties in the area change of small glaciers, and therefore a direct comparison with our sub-regional glacier inventories seems inappropriate. Comparisons with other sub-regions within the Alps characterized by larger glacier and higher mountains, and where inventories of comparable temporal and spatial resolution are available, highlight lower retreat rates in (i) Les Ecrins ($AAD = 0.38\% \text{ a}^{-1}$; MAP ~ 1200 – 1400 mm a^{-1}), the French side of Mont Blanc ($AAD = 0.15\% \text{ a}^{-1}$; MAP ~ 1400 – 2000 mm a^{-1}), and the Vanoise ($AAD = 0.39\% \text{ a}^{-1}$; MAP ~ 900 – 1400 mm a^{-1}) (1820/50–2006/09, Gardent and Deline, 2013), (ii) Val d’Aosta ($0.39\% \text{ a}^{-1}$; MAP ~ 800 – 2000 mm a^{-1}) (1820/50–2005, Curtaz et al., 2013), and (iii) the Swiss Alps ($AAD = 0.26\% \text{ a}^{-1}$; MAP ~ 600 – 2600 mm a^{-1}) (1850–2000, Zemp et al., 2008). Elsewhere, post-LIA retreat rates are higher ($0.78\% \text{ a}^{-1}$) in the Spanish Pyrenees (MAP ~ 1600 – 2000 mm a^{-1}) (1894–2001, González Trueba et al., 2008), about the same ($0.50\% \text{ a}^{-1}$) in the Canadian Rocky Mountains (MAP ~ 730 – 1970 mm a^{-1}) (1919–2006,

Tennant et al., 2012), and substantially lower ($0.13\% \text{ a}^{-1}$) in the Jotunheimen (southern Norway, MAP $\sim 1300\text{--}1650 \text{ mm a}^{-1}$) (1750–2003, Baumann et al., 2009).

In order to remove the possible confounding exerted by glacier size and to conduct a more appropriate evaluation of glacier area change at the local (i.e., three sub-region comparison) and regional (e.g., against the Alpine average) scales, we now consider the two smaller glacier size classes only, i.e., less than 0.1 and $0.1\text{--}0.5 \text{ km}^2$ (DeBeer and Sharp, 2007). This adjustment yields an 1860–2007 AAD that decreases progressively moving southward, from Livigno ($0.62\% \text{ a}^{-1}$) to Disgrazia ($0.58\% \text{ a}^{-1}$) and Orobic ($0.48\% \text{ a}^{-1}$). These retreat rates are similar to (i) data by Lucchesi et al. (2013), who report an average AAD (1860–2006) of $0.50\% \text{ a}^{-1}$ for the Western Italian Alps, starting from LIA glaciers of 0.5 km^2 (average size), a value similar to the combined average size of our study glaciers (i.e., 0.4 km^2), and (ii) the estimated average of the European Alps (1850–2000, $0.51\% \text{ a}^{-1}$) for the same size class (Zemp et al., 2008). It is worth highlighting the fact that this latter figure would rise significantly if post-2000 data were to be added, given that the 2001–2007 period was characterized by intense glacier retreat (WGMS, 2009).

5.3 Glacier retreat and temporal variability

The availability in this study of four different periods (1860–1954–1990–2003–2007) in three sub-regions allows us to detect the temporal and spatial variability of glacier change. Glaciers in the study area underwent a low relative area decrease in the 1860–1954 period, remained almost stable up until 1990, and then started retreating at progressively faster rates in the 1990–2003 and 2003–2007 intervals (Fig. 7), with greater retreat acceleration of the very small glaciers ($\leq 0.1 \text{ km}^2$). In this temporal context, the Orobic sub-region represents the exception, in that the retreat rate across 1990–2003 and 2003–2007 stays constant with, in the latter period, an AAD value for glaciers ($\leq 0.1 \text{ km}^2$) that is much lower than in the Livigno and Disgrazia sub-regions (Table 4). The gradual increase with time in the spread of the relative change in glacier area (Fig. 7b) is a warning that these results need to be used with caution, since the study intervals differ significantly in length. In particular, potential decadal fluctuations in glacier area within the 1860–1954 and 1954–1990 periods would have gone undetected (i.e., the re-advance phase of Alpine glaciers in the 1970s and 1980s; Patzelt, 1985; Hoelzle et al., 2003; Citterio et al., 2007).

In order partly to solve this issue and conduct a more sound comparison of our results with other inventories, we consider the AAD values associated with the 1860–1990 and 1990–2007 periods. One of the most striking results is the significant increase in AAD that one observes after 1990. In particular, post-1990 AAD in Livigno, Disgrazia and Orobic is, respectively, 4.07, 3.57 and $2.47\% \text{ a}^{-1}$, equal to 7.2, 6.6, and 6.1 times the pre-1990 rate. These values gradually de-

crease along our latitudinal transect, indicating that glaciers in the most continental sub-region (Livigno) not only depict a higher total post-LIA retreat, but also that such retreat has been much faster in recent years compared to more maritime environments (i.e., the Orobic mountains). Similar rates (i.e., 7.1) have been reported only in the Spanish Pyrenees between 1894–1991 and 1991–2001 (González Trueba et al., 2008), whereas in many other Alpine regions, the acceleration is still detectable but less intense (i.e., 2.2 times in France between LIA and the 1970s to 2006–2009 (Gardent and Deligne, 2013), and 2.9 times in the Swiss Alps between LIA and 1973–1999 (Paul et al., 2004)).

The previously disclosed differences in glacier retreat patterns along our latitudinal transect are even more apparent when increasing the temporal resolution to an interannual basis. To this end, we present unpublished data from multiple GPS field surveys and glaciological mass balance campaigns (2007–2013) on three sample glaciers: Campo Nord (GS = 0.30 km^2 ; Livigno), Vazzeda (GS = 0.23 km^2 ; Disgrazia), and Lupo (GS = 0.22 km^2 ; Orobic) glaciers (Table 5 and Figs. 1b and 3). Mass balances are combined with glacier limits updated to the summer of 2012 (Table 5 and Figs. 1b, 3, 12 and 13). In particular, the relevant winter and summer point mass balances, measured averaging the data of two ablation stakes across the ELA₀ (Figs. 3, 12 and 13), even though referring to three glaciers only, are useful for inferring the mechanisms responsible for the differences in glacier retreat observed along our transect (Table 4 and Fig. 7). Since 2007, Campo Nord glacier has depicted an uninterrupted series of negative net balances, for a total loss of 12.9 m w.eq. and an area loss of 0.02 km^2 . Lower mass losses are recorded at Vazzeda and Lupo glaciers (6.3 and 5.6 m w.eq.), with the former losing 0.03 km^2 and the latter showing no significant changes in glacier area (Figs. 12 and 13). Despite the small latitudinal difference from the Campo Nord to Lupo glaciers (about 40 km), the mass balance turnover increases dramatically along the transect. At Lupo, years with high winter accumulation are able to compensate for more consistent rates of summer ablation throughout the 2007–2013 period. This trend suggests a higher sensitivity of Orobic glaciers to winter precipitation, as 2009, 2010, and 2011 were characterized by both above-average winter precipitation and summer temperatures, which resulted in negative mass balances across most of the European Alps (WGMS, 2011, 2013).

5.4 Small, avalanche-dominated glaciers

The tendency of small avalanche-dominated glaciers to be poorly coupled to synoptic temperature changes has been reported in different studies. Kuhn (1995) discusses a conceptual model to explain the mass balance of “very small” glaciers (i.e., glacier area $< 10 \text{ ha}$, or 0.1 km^2), suggesting that snow drifted by wind and accumulated by avalanching activity would be crucial to sustain glaciers below the $r_c \text{ ELA}_0$. Furthermore, he suggests that glaciers in small

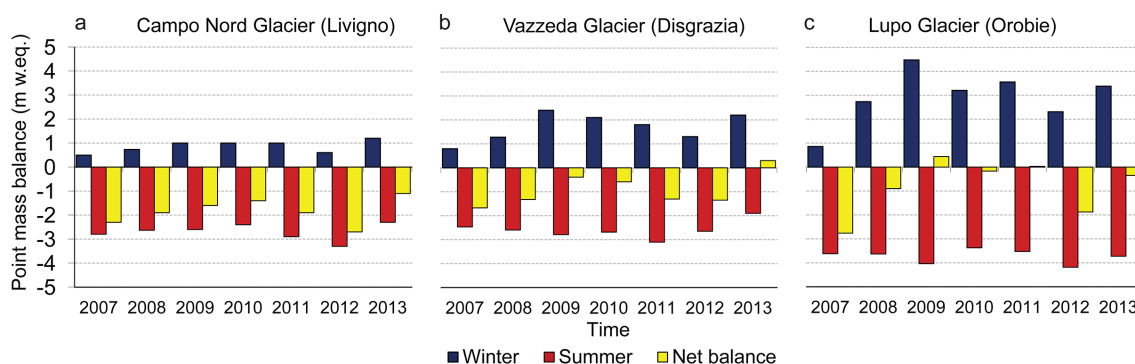


Figure 12. Histogram showing winter, summer, and net point mass balance at (a) Campo Nord glacier (Livigno), (b) Vazzeda glacier (Disgrazia), and (c) Lupo glacier (Orobie) from 2007 to 2013. Point mass balance data are measured with two ablation stakes placed across the ELA₀ of each glacier (see Table 5 for further details).

Table 5. Topo-climatic attributes of the glaciers selected for interannual mass balance analysis.

Glacier*	Sub-region	LIA area (km ²)	2012 area (km ²)	MA	ABR	<i>S</i> (°)	CSR (w m ²)	MAP (mm a ⁻¹)	<i>E</i> _{ri} (m a.s.l.)	<i>E</i> _{min} (m a.s.l.)	<i>E</i> _{max} (m a.s.l.)	ELA ₀ (m a.s.l.)	Ablation stakes (m a.s.l.)
Campo Nord	Livigno	0.84	0.30	NW	Moderate	19.1	134	1140	3137	2837–3178		3004	2970–2972
Vazzeda	Disgrazia	1.09	0.23	NE	Low	25.3	133	1350	2978	2732–3081		2926	2908–2914
Lupo	Orobie	0.42	0.22	N	High	25.1	96	1680	2844	2435–2760		2565	2555–2564

* Glacier attributes refer to the year 2007. The location of the glaciers is reported in Fig. 1b.

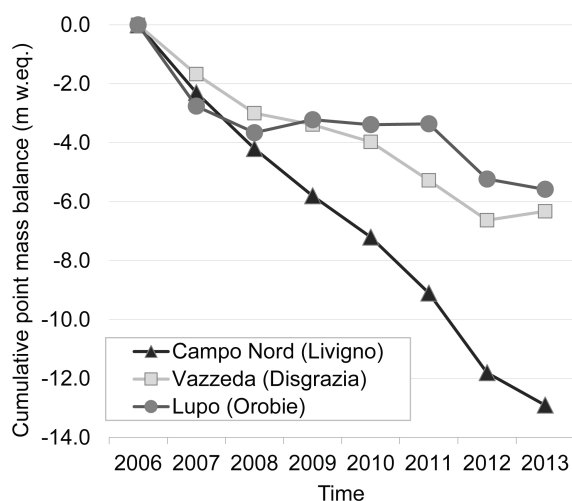


Figure 13. Cumulative point net mass balance in the Campo Nord (Livigno), Vazzeda (Disgrazia), and Lupo (Orobie) glaciers from 2007 to 2013 (see Table 5 for further details).

cirques are partly decoupled from precipitation as in winters with heavy snowfalls once the cirque is completely filled with snow; this surplus would be conveyed below the glacier terminus via avalanching, and would thus be lost to accumulation. More recently, DeBeer and Sharp (2009) have shown that a sample of very small glaciers (< 0.4 km²) in the Monashee Mountains (British Columbia) displayed no ob-

servable change in area during the 1951–2004 period, while the neighboring larger glaciers suffered a generalized retreat. Accordingly, these small glaciers after an initial post-LIA retreat are now placed in locations that would favor their preservation (i.e., in sheltered sites surrounded by high and steep rock walls). The authors suggest that the enhanced mass inputs at these particular sites can compensate for the decline in winter precipitation observed in the region.

Dahl and Nesje (1992), while reconstructing the paleo-ELA of a small glacier in western Norway, attribute the resilience of small avalanche-dominated glaciers to patterns of winter precipitation, as opposed to summer temperatures. More recently, Carturan et al. (2013a) provide empirical data supporting this explanation for the Montasio glacier ($GS = 0.07$ km²; $E_{\text{median}} = 1903$ m a.s.l.) in the Eastern Italian Alps. Accordingly, during the 2009–2011 period, years with heavy winter snowfalls (and related high snow avalanche inputs) would be able to generate a positive mass balance sufficient to compensate one or more subsequent negative years. This interpretation is further supported by the limited post-LIA area loss, which the authors estimate to be about 30 %.

Even though most of the glaciers in our study sub-regions are small and avalanche fed (Table S1 in the Supplement), only those of the Orobie cluster appear to be poorly coupled to the contemporary synoptic climatic conditions, and deviate from the other two (Fig. 7) and hence from the average Alpine trend (Zemp et al., 2008). In consideration of the

progressively lower decoupling inferred moving northward along the study transect, we hypothesize that snow avalanching activity is efficiently increasing glacier accumulation, hence dampening glacier retreat only where precipitation is relatively high, as in the Orobie case. In other words, we propose that the dynamics of these glaciers are (snow) *supply limited*, rather than limited by summer ablation.

Despite the lack of reliable long-term climatic series for each sub-region, the progressive north-to-south decoupling of glacier change with respect to synoptic climatic conditions is supported by the southward increase in variability of ELA_0 (Fig. 5a), post-LIA glacier change (Fig. 7), and interannual mass balances of the monitored sample glaciers (Figs. 12 and 13). In addition to this, the below-Alpine average post-LIA retreat (for the same glacier size) and the lack of relations between glacier change and glacier attributes found in the Orobie sub-region (Fig. 11c and Table S5) form evidence of enhanced glacier–climate decoupling.

It should be highlighted, however, that such decoupling exhibits a high degree of variability, as exemplified by post-LIA area losses of the initial Orobie 45 ice bodies, ranging from as little as 33 % (Aga glacier, comparable to the area shrinkage reported in Montasio), including, respectively, 6 and 12 glaciers that have recorded area losses of lower than 50 and 60 %, and up to 5 cases that have reached extinction (Fig. 11c). It follows that generalizations and extrapolations from small, avalanche-fed glaciers to other regions, based on a single glacier mass balance, should be conducted and evaluated with caution. Further work in Orobie is presently ongoing to investigate causal linkages between climatic forcing, landscape (i.e., hosting cirques and niches) structure, and glacier dynamics to better constrain the environmental conditions and the feedback mechanisms promoting glacier survival in temperate, maritime mountain settings.

6 Summary and conclusion

With a multitemporal, airphoto-based glacier inventory, combined with interannual, field-based mass balances of selected small glaciers, we can link glacier and terrain morphometric attributes, climatic characteristics, and glacier response to climatic forcing. In particular, we examine post-LIA glacier area and elevation changes, along a latitudinal transect, and across a 150-year time window. Within a latitudinal distance of less than 60 km, we move from small continental-like glaciers surviving between 2800 and 3200 m a.s.l. with as little precipitation as 790 mm a^{-1} (Livigno sub-region), to maritime ones located between 2100 and 2500 m a.s.l. with as much as 1770 mm a^{-1} (Orobie sub-region). As one moves southward, this physiographic setup corresponds to (i) a progressive depression of ELA_0 values with a concurrent increase (doubling) of ELA_0 within-subregional variability; and (ii) a weakening and/or disappearance of correlations

between basic altitudinal glacier attributes and 1860–2007 glacier area change.

We furthermore show that post-1990 glacier area change is about 1 order of magnitude faster than before, and that this trend accelerates even more in Livigno and Disgrazia between 2003 and 2007, in line with the European Alps trend. By contrast, Orobie glaciers, which have been retreating comparatively less since 1990, are basically stationary in the post-2003 period. This behavior is further confirmed and extended through 2013 by an overall (2007–2013) equilibrium mass balance at Lupo glacier (Orobie), as opposed to persistent net deficits observed in Campo Nord (Livigno) and Vazzeda (Disgrazia) glaciers. This equilibrium is achieved thanks to heavy accumulation seasons that, during the 7 years of monitoring, have been able to compensate for consistent summer ablation losses and relevant dry winters. Therefore, we argue that the dynamics of Orobie glaciers are currently supply limited (i.e., their survival depends on the magnitude frequency of winter accumulations) rather than controlled by ablation. In other words, we hypothesize that the recent resilience of glaciers in Orobie is a consequence of their decoupling from synoptic atmospheric temperature trends (i.e., rise), a decoupling that originates from local topographic conditions (i.e., deep, north-facing cirques), but most importantly from high winter precipitation, which represents the distinctive attribute of the Orobie cluster. This combination of topo-climatic conditions ensures high snow-avalanche supply, as well as high summer shading and sheltering. In this context, we introduce the parameter E_{ri} (i.e., the elevation of the ridge crest located upslope of a given study glacier), which, when represented as a function of relative glacier area change, proves to be an efficient proxy for discriminating climatically coupled settings from decoupled settings.

The case of Orobie, in which for the first time we identify a population of maritime, climatically decoupled small glaciers (i.e., beyond the documentation of a single glacier behaving as an outlier), is in contrast with empirically based mass balance models and comparative studies according to which low-elevation glaciers under maritime conditions, with high accumulation and mass turnover, would display higher sensitivity to climate fluctuations compared to their counterparts located in drier, continental settings (e.g., Oerlemans and Fortuin, 1992; Hoelzle et al., 2003; Benn and Evans, 2010). Interestingly, since winter precipitation is expected to rise by 15 to 30 % in the future decades across the Central European Alps (e.g., CH2011, 2011; Beniston, 2012), Orobie glaciers may continue to find favorable conditions for surviving much longer than previously thought.

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