

# 1 Post-LIA glacier changes along a latitudinal transect in the 2 Central Italian Alps

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## 8 9 **Abstract**

10 The variability of glacier response to atmospheric temperature rise in different topo-climatic  
11 settings is still matter of debate. To address this question in the Central Italian Alps we compile a  
12 post-LIA (Little Ice Age) multitemporal glacier inventory (1860-1954-1990-2003-2007) along a  
13 latitudinal transect that originates north of the continental divide in the Livigno mountains, and  
14 extends south through the Disgrazia and Orobie ranges, encompassing continental-to-maritime  
15 climatic settings. In these sub-regions we examine area change of 111 glaciers. Overall, total  
16 glacierized area has declined from 34.1 to 10.1 km<sup>2</sup>, with a substantial increase in the number of  
17 small glaciers due to fragmentation. Average annual decrease (AAD) in glacier area has risen of  
18 about an order of magnitude from 1860-1990 (Livigno: 0.45; Orobie: 0.42; and Disgrazia: 0.39 % a<sup>-1</sup>)  
19 to 1990-2007 (Livigno: 3.08; Orobie: 2.44; and Disgrazia: 2.27 % a<sup>-1</sup>). This ranking changes  
20 when considering glaciers < 0.5 km<sup>2</sup> only (i.e., we remove the confounding caused by large glaciers  
21 in Disgrazia), so that post-1990 AAD follows the latitudinal gradient and Orobie glaciers stand out  
22 (Livigno: 4.07; Disgrazia: 3.57; and Orobie: 2.47 % a<sup>-1</sup>). More recent (2007-2013) field-based mass  
23 balances in three selected small glaciers confirm post-1990 trends showing consistent highest retreat  
24 in continental Livigno and minimal area loss in maritime Orobie, with Disgrazia displaying a  
25 transitional behaviour. We argue that the recent resilience of glaciers in Orobie is a consequence of  
26 their decoupling from synoptic atmospheric temperature trends. A decoupling that arises from the  
27 combination of local topographic configuration (i.e., deep, north-facing cirques) and high winter  
28 precipitation, which ensures high snow-avalanche supply, as well as high summer shading and  
29 sheltering. Our hypothesis is further supported by the lack of correlations between glacier change  
30 and glacier attributes in Orobie, as well by the higher variability in ELA<sub>0</sub> positioning, post-LIA  
31 glacier change, and inter-annual mass balances, as we move southward along the transect.

1

## 2 **1 Introduction**

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

15 Composite glacier sensitivity to recent and ongoing climate changes has been reported through  
16 models based on empirical glacier mass balances from selected case studies (Oerlemans and  
17 Fortuin, 1992). Accordingly, low-elevation glaciers under maritime conditions, with high  
18 accumulation and mass turnover, would display higher sensitivity to climate fluctuations compared  
19 to their counterparts located in drier, continental settings. Similar findings have been reported by  
20 Hoelzle et al. (2003), who reconstructed the mass balance of more than fifty glaciers around the  
21 world on the basis of front retreat information during the entire 20th century. More recently, results  
22 from remotely-sensed multitemporal (2 to 5 decades) glacier inventories conducted across  
23 maritime-to-continental climatic transects have proved this question to be still open. For example,  
24 while Pan et al. (2012), when comparing six mountain systems in China, ranging from monsoonal-  
25 temperate to extreme-continental climatic conditions, could not draw a conclusive picture on glacier  
26 response in relation to climate properties, other authors in the Canadian Cordillera have even shown  
27 that maritime glaciers in the Coast Mountains retreat less than continental counterparts in the  
28 Rockies (De Beer and Sharp, 2007; Bolch et al., 2010a).

29 Within a given climatic setting, glacier dynamics are typically size dependent, with large glaciers  
30 retreating, on average, at slower pace than smaller ones (e.g., Paul et al., 2004; Bolch et al., 2010a;  
31 Diolaiuti et al., 2012a; Tennant et al., 2012; Scotti, 2013; Carturan et al., 2013b). The latter, in turn,  
32 display high variability of area change, a variability that has been related to the local topographic

1 heterogeneity of the hosting landscape (e.g., Kuhn, 1995; Paul et al., 2004; Abermann et al., 2009;  
2 DeBeer and Sharp, 2009; Hagg et al., 2012; Tennant et al., 2012; Carturan et al., 2013b). In fact,  
3 region-wide inventories have been customarily conducted from Landsat imagery (30-m grid ~ 0.001  
4 km<sup>2</sup>) with automated procedures of detection, which, if on one side allow a rapid cover of entire  
5 mountain ranges, cannot capture the area variation of very small glaciers (e.g., < 0.01 km<sup>2</sup>: Paul et  
6 al., 2004, 2011; Carturan et al., 2013b; and < 0.05 km<sup>2</sup>: Bolch et al., 2010a; Tennant et al., 2012),  
7 and most likely are less accurate than high-resolution aerial photographs (e.g., 0.5-m grid). This is a  
8 critical shortcoming since small glaciers (e.g., < 0.5 km<sup>2</sup>) in the European Alps represent more than  
9 80 % in number and 15 % in area of the whole glacier population (Paul et al., 2011), with much  
10 higher percentages in most sub-regions located south of the continental divide (e.g., Scotti, 2013  
11 and this study).

12 In this physiographic context, there is a general lack of systematic studies tracking the area change  
13 of medium-to-small sized mountain glaciers from the Little Ice Age (LIA) to the beginning of the  
14 21st century, a minimal temporal scale for constraining relevant interactions (coupling vs  
15 decoupling) between climate and glacier fluctuations (Zemp et al., 2011). In fact, most of the  
16 relevant literature on the Italian Alps is of extremely difficult access (i.e., published in Italian, e.g.,  
17 Caccianiga et al., 1994; Pelfini et al., 2002; Bonardi et al., 2012; Curtaz et al., 2013; Lucchesi et al.,  
18 2013), has examined post-LIA area change for single glaciers (Carturan et al., 2013a, 2013c), or for  
19 a limited number of case studies (e.g., seven (Federici and Pappalardo, 2010)), or has considered  
20 much shorter time intervals (e.g., Maragno et al., 2009; Diolaiuti et al., 2011, 2012a, 2012b;  
21 Carturan et al., 2013b).

22 In order to fill this research gap and improve our understanding of alpine glacier response to  
23 climatic forcing in relation to climate spatial heterogeneity, we conduct post-LIA multitemporal,  
24 high-resolution, glacier inventories in three sub-regions of the Central Italian Alps. These are home  
25 to medium-to-small glaciers, located along an idealized latitudinal transect that encompasses  
26 maritime, transitional, and continental glaciers, ranging in size from 0.002 to 2.3 km<sup>2</sup>. Along this  
27 transect, we aim to: (i) characterize glacier properties; (ii) calculate changes in glacierized area and  
28 evaluate acceleration/deceleration trends; (iii) elucidate correlations between area changes and  
29 environmental properties including glacier and terrain topographic attributes, and precipitation; and  
30 (iv) evaluate the spatial variability of glacier response to climatic forcing.

31

## 1    **2    Study area**

2    We focus on the glaciers of the Livigno, Disgrazia and Orobie sub-regions, located along a north-  
3    to-south transect within the Central Italian Alps (Fig. 1). The Livigno sub-region sits in the northern  
4    side of the Alpine continental divide (Inn-Danube River basin) and reaches 3303 m a.s.l. at Piz  
5    Paradisin. The area is dominated by a SW-NE trending valley that is chiefly underlain by ortogneiss  
6    and paragneiss of the Austroalpine basement. The Disgrazia sub-region is placed south of the  
7    Alpine continental divide and feeds the Masino and Mallero River valleys (Adda-Po River basin).  
8    The largest glaciers flow down radially from the higher peak of Monte Disgrazia massif (3678 m  
9    a.s.l.) that is built by Malenco Metaophiolites (mainly serpentinites). The Orobie are an E-W  
10    trending mountain range representing the southernmost glacierized area within Lombardy. It is  
11    located in the Southalpine tectonic domain that consists of metamorphic lithologies (paragneiss,  
12    phyllites and micaschists) covered by thick sedimentary deposits (conglomerates, marls and  
13    limestones). The highest peak is Pizzo di Coca (3052 m a.s.l.) and only two other summits exceed  
14    3000 m a.s.l.

15    The climate of the Central Italian Alps above 2000 m a.s.l. is classified as Tundra Climate (ET)  
16    according to the Köppen-Geiger scheme (e.g., Peel et al., 2007). In the three selected sub-regions  
17    precipitation (rainfall and snowfall) exhibits high spatial variability in terms of total annual values  
18    (Fig. 1b) and seasonal distribution (Ceriani and Carelli, 2000). In the northernmost mountain range  
19    (Livigno) annual precipitation ranges locally between 790 and 1200 mm with a winter minimum in  
20    February and a single summer maximum in August (e.g., Cancano weather station, 1950 m a.s.l.)  
21    (Fig. 2a). The opposite extreme can be observed in the southernmost mountain range (Orobie)  
22    where two precipitation peaks in June and October (Scais WS, 1500 m a.s.l.) contribute to annual  
23    precipitation values ranging between 1620 and 1770 mm (Figs. 1b and 2c). The Disgrazia region is  
24    located at an intermediate latitude, exhibits a transitional behavior in terms of total annual values (range  
25    1210-1370 mm), and mimics the Orobie seasonal distribution (Alpe Gera WS, 2125 m a.s.l.) (Figs. 1b  
26    and 2b). The foregoing high spatial variability in total annual precipitation is confirmed and  
27    enhanced by field data of glacier winter mass balances (Bonardi et al., 2014). Specifically, the Lupo  
28    glacier (Orobie) despite its 500-m lower elevation, shows more than three times (2.9 m w.eq.) the  
29    accumulation observed at the Campo Nord glacier (0.9 m w.eq.) (Livigno).

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

1 The progressive climatic shift from oceanic (Orobie) to continental (Disgrazia and Livigno) was  
2 detected as the main cause of the lower treeline elevation observed in the Orobie range (2260 m a.s.l. for  
3 trees  $\geq$  3m) compared to the Disgrazia (2420 m) and Livigno (2480 m) areas (Lucini, 2000; Caccianiga  
4 et al., 2008). In this paper we discuss about continental and maritime climatic settings in relation to the  
5 spatial arrangement (or orographic configuration) of the three study sub-regions making a geographic  
6 distinction between wetter, outer ranges (Orobie) and drier, inner ranges (Livigno) (e.g., Ivy-Ochs et al.,  
7 2006). Moist rich air masses travelling from the Atlantic Ocean, through the Mediterranean, and hit the  
8 Orobie first, imparting markedly higher precipitation across this mountain range. When using the term  
9 maritime in the manuscript we do not make a causal relation between the precipitation peaks in the  
10 climographs (Figure 2) during the year and the presence of the Mediterranean Sea or the Atlantic Ocean.

### 11 **3 Data collection and methods**

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

22 The shape and position of LIA moraines in the study areas and surrounding regions resembles that  
23 of other regions in the Alps where examples of LIA glacier reconstructions exist (e.g., 1987;  
24 Maisch, 1992; Maisch et al., 2000). Moraine ages have been determined by means of  
25 dendrochronology (e.g., Pelfini, 1999), geopedology (e.g., Caccianiga et al., 1994; Trobio glacier in  
26 the Orobie), as well as lichenometry (e.g., Orombelli, 1987; Ventina glacier in the Disgrazia) and  
27 combination of these methods (e.g., Pelfini et al., 2002; Disgrazia/Sissone glaciers). These studies  
28 significantly improved the confidence of our reconstruction and helped setting the generic date of  
29 the last LIA maximum glacial advance in the Disgrazia, Livigno, and Orobie sub-regions to 1860  
30 A.D. (Pelfini and Smiraglia, 1992). This constitutes our benchmark against which we have  
31 computed historical area fluctuations.

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

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

13 The most recent inventories of glacial extent have been reconstructed from 2003, 2007 and 2012  
14 digital orthophotos. Despite the existence of a similar 2003 regional inventory (i.e., Diolaiuti et al.,  
15 2012a), in order to minimize the degree of subjectivity due to multiple interpreters, we decided to  
16 map independently all glaciers on 2003 orthophoto mosaic (0.5-m grid). This mosaic is  
17 characterized by minimal snow cover over the glaciers and surrounding areas due to the extremely  
18 high temperatures recorded throughout that summer (i.e., García-Herrera et al., 2010). The 2007  
19 inventory was compiled via manual delineation of glacier limits on a high-resolution (0.5-m pixel)  
20 orthophoto mosaic and a 2-m gridded Digital Surface Model (DSM, 2007). Thanks to the dry and  
21 hot accumulation season, snow cover is very limited in the 2007 images too (Scotti et al., 2013).  
22 Such conditions improved substantially our ability to identify glacier limits and constituted a hard  
23 stress test for the survival of glacierets and perennial snow fields previously detected during field  
24 surveys. Manual delineation of glacier limits on summer 2012 orthophotos (0.5-m pixel) was  
25 limited to three sample glaciers (Campo Nord (Livigno), Vazzeda (Disgrazia) and Lupo (Orobie))  
26 (Fig. 1b).

27 Despite the excellent quality of the orthophoto mosaics, in order to minimize problems related to  
28 the delimitation of debris-covered glaciers, we conducted complementary GPS field surveys on  
29 three sample glaciers that provided critical ground control for data extracted from remotely-based  
30 inspection. We consider the planimetric uncertainty of the digitized 2003 and 2007 glacier limits  
31 equal to  $\pm 1$  m, that is the uncertainty associated with the orthophoto mosaic as specified by the  
32 manufacturer (e.g., Diolaiuti et al., 2012a).

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

6 In order to improve our understanding on the factors controlling the site specific variability of  
7 glacier retreat we have collected a number of environmental attributes for the 2007 dataset. These  
8 include glacier primary classification, contribution of snow avalanching to accumulation, surface  
9 area (A), maximum elevation ( $E_{max}$ ), terminus elevation ( $E_{min}$ ), glacier relative relief ( $\Delta E$ ),  
10 balanced-budget Equilibrium Line Altitude ( $ELA_0$ ), elevation of the ridgecrest upslope of the  
11 glacier ( $E_{ri}$ ), mean slope gradient (S), main aspect (MA), summer clear-sky radiation (CSR) and  
12 annual precipitation on the glacier (MAP) (Fig. 1b and Table 1).

13 The glacier primary classification and the definition of the avalanche contribution to glacier  
14 accumulation are crucial to characterize the glacier types of the three study areas. The former  
15 follows the Illustrated GLIMS Glacier Classification Manual (Rau et al., 2005); the latter, which we  
16 define as Avalanche Area Accumulation Basin Ratio (ABR), is the ratio between the area occupied  
17 by avalanche accumulation at the end of an average snowfall accumulation season and the area of  
18 the accumulation basin (above the  $ELA_0$ ). This classification scheme, which is based on decadal  
19 field observations, consists of three classes: low ( $ABR \leq 0.33$ ), moderate ( $> 0.33 ABR \leq 0.66$ ) and  
20 high ( $ABR > 0.66$ ). The main topographic attributes (i.e.,  $E_{max}$ ,  $E_{min}$ ,  $ELA_0$ ,  $E_{ri}$  and S) have been  
21 extracted from the 2-m gridded DSM using zonal statistics in ArcGIS v.9.3 (Paul et al., 2009). The  
22 terminus ( $E_{min}$ ) and the maximum glacier elevation ( $E_{max}$ ) are effective tools to define the lower and  
23 upper limit of the glacial domain and their fluctuations are usually related with surface and volume  
24 changes. The analysis of the elevation fluctuations was applied on a fixed sample of glaciers present  
25 in all the inventories. This approach minimize the errors caused by the increase (or decrease) in  
26 number of glaciers due to fragmentation (or extinction). The use of the entire dataset of each  
27 inventory would have resulted in under or overestimation of the  $E_{min}$  and  $E_{max}$  change. The  
28 maximum difference we have found comparing the two approaches is 45 % (e.g., underestimation  
29 of the  $E_{max}$  drop of Livigno glaciers from the LIA to 2007). The glacier relative relief ( $\Delta E$ ) is the  
30 arithmetical difference between  $E_{max}$  and  $E_{min}$  and depends on glacier length and slope gradient (S).

31 The Balanced-Budget Equilibrium Line Altitude ( $ELA_0$ ) (Meier and Post, 1962; Cogley et al.,  
32 2011) is a widely used parameter in glacier and paleoclimatic reconstructions (e.g., Miller et al.,

1 1975; Benn and Lehmkuhl, 2000) and it is usually defined with the Balance-Budget Accumulation  
2 Area Ratio ( $AAR_0$ ) method (Meier and Post, 1962; Gross et al., 1978). While the high variability of  
3 worldwide measured  $AAR_0$  (from 0.22 to 0.72) in mass balance data warns about a straight forward  
4 use of this parameter (WGMS, 2005; Zemp et al., 2007), we delineate  $ELA_0$  (also termed local-  
5 topography  $_{lt}ELA_0$ ) as the median surface elevation of the glacier (i.e., considering a 0.50  $AAR_0$   
6 (e.g., Hughes, 2009; Bolch et al., 2010b; Hughes, 2010; Carturan et al., 2013; Igneczi and Nagy,  
7 2013)). This value appears to be particularly well suited for small glaciers (e.g., Braithwaite and  
8 Raper, 2007, 2009; Kern and Laszlo, 2010) like the ones we are studying. Indeed, low glacier  
9 relative relief ( $\Delta E$ ) that is typically associated with small glacier size, imparts very little change to  
10 our  $ELA_0$  values when using  $AAR_0 = 0.5$ , as opposed to 0.67 (originally proposed by Gross et al.  
11 (1978)), hence providing a reasonable justification for assuming  $E_{median} = ELA_0$ . Since a number of  
12 seminal paleoclimatic and landscape evolution studies have adopted an  $AAR_0$  equal to 0.67 (e.g.,  
13 Maisch et al., 2000; Kerschner et al., 2000; Bavec et al., 2004; Zemp et al., 2007 and Kerschner  
14 and Ivy-Ochs., 2008), for completeness, we provide  $ELA_0$  based on  $AAR_0$  0.67 in the  
15 supplementary material. This topography-based parameter, differs from the regional-climatic ELA  
16 (i.e.,  $_{rc}ELA_0$ ), which relies on synoptic climatic data and on mass balances of a limited number of  
17 selected glaciers (e.g., 14 glaciers for the European Alps, and only two belonging to the Italian  
18 portion (Zemp et al., 2007)). The elevation of the ridgecrest upslope of the glacier ( $E_{ri}$ ) is computed  
19 as the median elevation of the 10 m-wide buffer drawn along the ridgecrest feeding the glacier  
20 accumulation basin. The elevation difference between the  $E_{ri}$  and the  $ELA_0$  is considered to be  
21 correlated to both the degree of avalanching contribution to the glacier's mass balance and the  
22 shading effect of the rock walls upslope of the glacier. The main aspect of the glacier, divided in 8  
23 classes, was manually defined along the direction of the main flow axis, or for snow fields, the  
24 general aspect of the mountain slope. The summer clear sky global radiation (June to September)  
25 was calculated with ArcGIS Spatial Analyst (Dubayah and Rich, 1995) using a 20m resampled  
26 version of the DSM. This parameter is directly affected by glacier aspect slope and by the shading  
27 properties of the rock walls surrounding the glacier. Mean annual precipitation for each glacier is  
28 derived from a 250-m gridded precipitation map (Fig. 1b) and represents a proxy snow  
29 accumulation on the glacier.

30

## 1 4 Results

### 2 4.1 Glacier properties

3 In the presentation of the results we provide an overview of the glacier properties, as inventoried in  
4 2007. We proceed from the northernmost Livigno sub-region, home to 16 glaciers (total glacier area  
5 = 1.1 km<sup>2</sup> +/- 0.02), continue with the Disgrazia sub-region that hosts 37 glaciers (7.3 km<sup>2</sup> +/- 0.09),  
6 and conclude with the Orobie sub-region in which we identify 44 glaciers (1.8 km<sup>2</sup> +/- 0.05). Along  
7 this transect, we observe a remarkable increase in mean annual precipitation (MAP) as we move  
8 from the interior ranges (Livigno; 790-1200 mm) towards the outer ranges (Orobie; 1620-1770 mm)  
9 (Fig. 4). Concurrently, median ELA<sub>0</sub> (Fig. 4) and clear-sky radiation mirror the spatial variability of  
10 local relief in that they slightly increase from the interior, plateau-like topography of Livigno (2833  
11 m a.s.l.; 176 W m<sup>-2</sup>), to the Disgrazia Massif (2890 m a.s.l.; 210 W m<sup>-2</sup>), and drop abruptly in the  
12 Orobie Range (2517 m a.s.l.; 145 W m<sup>-2</sup>). The altitudinal distribution of ELA<sub>0</sub> displays an increase  
13 in within-regional scatter with increasing MAP (i.e., moving from Livigno down south; Fig. 5a).  
14 This variability is imparted by the combination of two spatial patterns in which ELA<sub>0</sub> rises  
15 progressively: (i) from north- to south-facing glaciers, within the same mountain range (i.e.,  
16 Disgrazia in Fig. 5b)); and (ii) for a given aspect category (e.g., N and NW in Fig 5b) moving from  
17 the peripheral Orobie range inland to the Livigno mountains.

18 In the Livigno mountains, glacierets and cirque glaciers are dominant typologies, and face mainly  
19 northwest to northeast (Figs. 5b and Table 2). Despite the presence of relatively high peaks across  
20 the entire sub-region, glaciers today survive almost only in the southernmost portion of the range  
21 (with one exception), where incidentally MAP is higher. Glacier size ranges between 0.003 and  
22 0.37 km<sup>2</sup> (Val Nera Ovest glacier). Propensity to avalanche snow/ice supply (ABR) is high (11  
23 cases) to moderate (4 cases), while slope (S) ranges between 19.6° and 33.0° (median 29.2°).

24 In the Disgrazia sub-region, besides the abundance of permanent snowfields, glacier types comprise  
25 in decreasing order of frequency: cirque, niche, and simple/compound basin valley glaciers (Table  
26 2). Glaciers face preferentially northwest and southeast, but thanks to the radial structure of the  
27 massif, all aspects are well represented (Fig. 5b). Compared to the other study sub-regions, ice  
28 masses are evenly distributed across the N-S transect, they are relatively larger, and range from  
29 0.002 to the 2.31 km<sup>2</sup> (Disgrazia glacier). ABR is high, moderate, and low for respectively 24, 10,  
30 and 3 glaciers. Median slope is comparatively lower (27.1°), and we observe the largest slope  
31 variability (18.1 - 45.0°).

1 Glaciers in the Orobic are located exclusively within north-to-northwest facing cirques. They are  
2 clustered around a narrow latitudinal range, along the main ridge of the sub-region (Fig. 4), and are  
3 particularly small in size, ranging between 0.002 and 0.22 km<sup>2</sup> (Lupo glacier) (Fig. 5b). The  
4 peculiar morphometric setting made of high and steep rock walls, located immediately upslope of  
5 each glacier, is confirmed by the high elevation difference (233 m) recorded between ELA<sub>0</sub> and  
6 mean ridgecrest elevation (E<sub>ri</sub>). Accordingly, all of Orobic glaciers exhibit a high ABR potential of  
7 avalanche snow supply. Slope range is similar to that observed in Disgrazia (18.8 - 42.2°), while  
8 median slope (29.1°) is higher and resembles that of Livigno.

## 9 **4.2 Area changes**

10 Since the LIA all of the 111 glaciers of the study sub-regions have gone extinct (14) or have  
11 experienced a strong net areal reduction (97) for a combined area loss of 24 km<sup>2</sup> (Fig. 6a-c). At the  
12 acme of LIA advance, the 15 glaciers of the Livigno cluster used to cover an area of 5.4 km<sup>2</sup> (Fig.  
13 6a and Table 3). By 1954 a total of 21 glaciers (i.e., 3 of the initial 15 had fragmented into smaller  
14 ones) occupy 2.5 km<sup>2</sup> (52.6 ± 14.6 %) for an average annual decrease (AAD) of about 0.031 ±  
15 0.006 km<sup>2</sup> a<sup>-1</sup> (Table 3). In the same period, the 27 LIA glaciers of the Disgrazia Mountains  
16 increased to 36 (Fig. 6b), but with an overall area loss of 43.6 ± 6.4 % and an AAD of about 0.102  
17 ± 0.015 km<sup>2</sup> a<sup>-1</sup> (Table 3). Finally, in the Orobic sub-region by 1954 we record a 52.6 ± 14.6 % of  
18 LIA surface reduction, which corresponds to an AAD of about 0.038 ± 0.010 km<sup>2</sup> a<sup>-1</sup> (Table 3).

19 The 1990 inventory depicts a much slower rate of areal contraction with values small enough to fall  
20 within the envelope of uncertainty (Fig. 7). The glacierized area in the Livigno Mountains records  
21 the stronger relative contraction (i.e., 9.5 ± 8.3 %) equal to 0.23 km<sup>2</sup> (AAD = 0.007 ± 0.006 km<sup>2</sup> a<sup>-1</sup>)  
22 (Table 3). Glaciers in the Disgrazia lost 3.5 ± 5.1 %, which corresponds to a net loss of 0.43 km<sup>2</sup>  
23 (AAD = 0.012 ± 0.017 km<sup>2</sup> a<sup>-1</sup>) (Table 3). Similarly, in the Orobic we observe a 3.5 ± 10.4 %  
24 decrease, corresponding to a net loss of 0.11 km<sup>2</sup> (AAD = 0.003 ± 0.009 km<sup>2</sup> a<sup>-1</sup>).

25 In the 1990-2003 period, glaciers exhibit consistent fast retreat throughout the three study areas  
26 (Fig. 7). In increasing order, Disgrazia witnesses a decrease of 3.5 km<sup>2</sup> that corresponds to a 29.5 ±  
27 2.0 % reduction (AAD = 0.271 ± 0.018 km<sup>2</sup> a<sup>-1</sup>); Orobic exhibit a 1.2 km<sup>2</sup> decrease, which amounts  
28 to a 35.0 ± 4.2 % contraction (AAD = 0.083 ± 0.010 km<sup>2</sup> a<sup>-1</sup>); and Livigno glaciers lost 1 km<sup>2</sup>, equal  
29 to a 42.7 ± 3.3 % loss of the 1990 glacierized area (AAD = 0.075 ± 0.006 km<sup>2</sup> a<sup>-1</sup>) (Table 3). During  
30 the 2003-2007 interval we observe for the first time that glacier area loss increases northward, with  
31 Livigno displaying highest area loss (16.9 ± 2.5 %) (AAD = 0.063 ± 0.009 km<sup>2</sup> a<sup>-1</sup>), followed by

1 Disgrazia ( $12.8 \pm 1.6$  %) (AAD =  $0.309 \pm 0.037$  km<sup>2</sup> a<sup>-1</sup>), and Orobie ( $10 \pm 3.6$  %) (AAD =  $0.057 \pm$   
2  $0.020$  km<sup>2</sup> a<sup>-1</sup>) (Table 3). Overall, considering the entire study period (1860-2007), glaciers of the  
3 Livigno sub-region display the largest retreat recorded amongst the three study areas, losing a total  
4 of  $4.4 \pm 0.5$  km<sup>2</sup> ( $80.1 \pm 9.8$  % of the initial 1860 extension). Glaciers in the Disgrazia cluster lost a  
5 total of  $14.6 \pm 1.3$  km<sup>2</sup>, ( $66.5 \pm 5.9$  %) and in the Orobie range they lost  $4.9 \pm 0.9$  km<sup>2</sup> ( $73.2 \pm 13.8$   
6 %).

7 Examination of AAD across size classes shows that relative change rate in glacier area in the 1860-  
8 1954 period has been fairly low ( $0.46$  % a<sup>-1</sup> in Disgrazia,  $0.56$  % a<sup>-1</sup> in Orobie and  $0.57$  % a<sup>-1</sup> in  
9 Livigno) and complementary among small- and large-size classes (Table 4). Subsequently (1954-  
10 1990), the  $<0.1$  km<sup>2</sup> class displays the lowest reduction (Livigno:  $0.02$ ; Disgrazia:  $0.16$  % a<sup>-1</sup>), and  
11 in the Orobie even a modest increase ( $-0.09$  % a<sup>-1</sup>). In Disgrazia and Livigno the largest retreat rates  
12 are observed in the intermediate classes ( $0.5$ -to- $1$  km<sup>2</sup> and  $0.1$ -to- $0.5$  km<sup>2</sup> respectively), whereas  
13 larger glaciers exhibit a slight area increase (Disgrazia:  $-0.22$  % a<sup>-1</sup> for the  $2$ -to- $5$  km<sup>2</sup>; Livigno: -  
14  $0.04$  % a<sup>-1</sup> for the  $0.5$ -to- $1$  km<sup>2</sup>) (Table 4).

15 The strong glacier shrinkage recorded in the two more recent periods (1990-2003 and 2003-2007)  
16 has affected especially small glaciers (i.e.,  $<0.1$  km<sup>2</sup> and  $0.1$ -to- $0.5$  km<sup>2</sup>) and we observe  
17 progressively slower retreat rates within the larger size classes (Table 4).

### 18 **4.3 Elevation changes**

19 The area changes detailed above correspond to changes in glacier ice elevation, both in terms of  
20  $E_{\min}$  and  $E_{\max}$ . The median  $E_{\min}$  of the 111 glaciers detected at the LIA maximum lies at 2480 m a.s.l  
21 and rises progressively throughout the 20<sup>th</sup> century to a maximum of 2628 m in 2007, which  
22 translates to an average annual gain of  $1.0$  m a<sup>-1</sup>. In the same period, median  $E_{\max}$  drops from 2893  
23 to 2810 m a.s.l. ( $-0.6$  m a<sup>-1</sup>). Data stratification into sub-regional domains reveals a considerable  
24 spatial variability in  $E_{\min}$  and  $E_{\max}$  fluctuations. Both glacier attributes in the Livigno cluster are  
25 characterized by a markedly lower variability compared to the Orobie and Disgrazia (Fig. 8). The  
26 1860-2007 overall rise in  $E_{\min}$  is lowest in Livigno ( $0.7$  m a<sup>-1</sup>), intermediate in Orobie ( $1.0$  m a<sup>-1</sup>),  
27 and highest ( $1.9$  m a<sup>-1</sup>) in the Disgrazia sub-region, where we note a sharp increase between 1860  
28 and 1954 (Fig. 8). Conversely, Disgrazia exhibits the lowest drop in  $E_{\max}$  ( $-0.6$  m a<sup>-1</sup>), followed by  
29 Livigno ( $-0.7$  m a<sup>-1</sup>), and Orobie ( $-1.1$  m a<sup>-1</sup>), with the last characterized by two large drops in  
30 1860-1954 and 1990-2003 (cf. median lines in Fig. 8).

1 Simultaneous analysis of elevation ( $E_{\min}$  and  $E_{\max}$ ) and area changes through time is instructive in  
2 that it allows inferring qualitatively characteristic trends of volumetric glacier shrinkage (Fig. 9).  
3 Up until 1990 we observe a general decline in average annual decrease and a general convergence  
4 of the  $E_{\min}$  and  $E_{\max}$  trend lines in Livigno and Orobic clusters, while in the Disgrazia both  $E_{\min}$  and  
5  $E_{\max}$  rise slightly (Fig. 9). This latter trend suggests that, on average, glacier ice lost at the terminus  
6 was nearly completely replaced (i.e., at least in terms of area) by the increase in elevation of the  
7 accumulation basin (Fig. 9b). From 1990 we start observing a progressive divergence of the  $E_{\min}$   
8 and  $E_{\max}$  trend lines (Fig. 9), an indication of net, generalized, glacier volume loss. While such trend  
9 continues to the end of the study period in Livigno and Disgrazia, in the Orobic we observe an  
10 opposite trend between 2003 and 2007, with  $E_{\min}$  and  $E_{\max}$  overlapping around a null elevation  
11 change rate (Fig. 9c). This stability in elevation range, in conjunction with a minor decrease in  
12 surface area, suggests volumetric shrinkage mainly caused by a reduction in glacier width.

#### 13 **4.4 Area change with glacier attributes**

14 Analysis of changes in glacier area within the same sub-region allows to detect, and possibly rank,  
15 the main environmental attributes driving glacier retreat. To this purpose, we analyze the mutual  
16 correlations among the "1860-2007 area change" in relation to glacier size (GS), main aspect (MA),  
17 mean slope gradient (S), minimum elevation ( $E_{\min}$ ), maximum elevation ( $E_{\max}$ ), glacier relative  
18 relief ( $\Delta E$ ), mean annual precipitation (MAP), ridgecrest elevation ( $E_{ri}$ ), and clear-sky radiation  
19 (CSR) (Tables S3-S5).

20 Relative area change (AC %) in Livigno exhibits strong direct correlation with  $E_{ri}$  ( $r = 0.77$ ),  $E_{\max}$  ( $r$   
21  $= 0.72$ ) and  $\Delta E$  ( $r = 0.65$ ), and moderate correlation with  $E_{\min}$  (inverse,  $r = -0.46$ ), former glacier  
22 size (GS,  $r = 0.43$ ), and clear-sky radiation (CSR,  $r = 0.43$ ) (Table S3). These correlations with  
23 relative area change weaken progressively moving south to Disgrazia (i.e.,  $E_{ri}$  ( $r = 0.35$ ),  $E_{\max}$  ( $r =$   
24  $0.45$ ),  $\Delta E$  ( $r = 0.47$ ), and glacier size (GS,  $r = 0.42$ )) (Table S4), and virtually disappear in the  
25 Orobic (i.e.,  $E_{ri}$  ( $r = -0.03$ );  $E_{\max}$  ( $r = -0.20$ );  $\Delta E$  ( $r = 0.20$ ); and  $E_{\min}$  ( $r = -0.40$ )) (Table S5).

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

29 In order to gain further insights on the elevation-retreat correlations identified above, we have  
30 represented relative area change as a function of  $E_{ri}$  (Fig. 11). We hypothesize this variable to be a  
31 useful proxy of the local climatic conditions (e.g., snowfall available for subsequent avalanche

1 inputs, shading effect and wind shielding) that characterize a glacier's source basin. Although we  
2 reckon that  $E_{ri}$  is tightly related to other glacier elevation attributes i.e.,  $E_{max}$  and  $\Delta E$  (Tables S3-S5),  
3 unlike these,  $E_{ri}$  does not change with time, and as such would constitute a more reliable reference  
4 across changing climate conditions. In addition,  $E_{ri}$  is a more statistically sound attribute, as it is not  
5 based on a single datum of elevation (i.e.,  $E_{min}$  and  $E_{max}$ ).

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

14

## 15 **5 Discussion**

### 16 **5.1 Equilibrium line altitude**

17 The equilibrium line of a glacier is a climate-dependent attribute that, when estimated at the  
18 regional scale using climatic data and a limited set of glacier mass balances ( $_{rc}ELA_0$ ; e.g., Ohmura  
19 et al., 1992, Zemp et al., 2007), can mask the intrinsic spatial heterogeneity modulated by glacier  
20 aspect and other local topographic variables (Dahl and Nesje, 1992). Such topographic effects can  
21 be evaluated by comparing the local topography  $ELA_0$  ( $_{lt}ELA_0$ ) (i.e., the  $ELA_0$  considered in this  
22 study) with the regional climatic one ( $_{rc}ELA_0$ ) (Dahl and Nesje, 1992; Lie et al., 2003; Zemp et al.,  
23 2007). In this respect, the distributed  $_{rc}ELA_0$  map of the Central European Alps presented by Anders  
24 et al. (2010) (i.e., based on equations by Ohmura et al. (1992) and Zemp et al. (2007)) reports  
25 values that are about 40, 130, and 380 m higher than the actual topography-based analogues for the  
26 Disgrazia, Livigno, and Orobic respectively, suggesting that local topography, on average, has a  
27 different weight in each sub-region.

28 Since the  $_{rc}ELA_0$  approach typically tends to respectively underestimate and overestimate southerly  
29 and northerly aspects (Zemp et al., 2007), the relatively small "climate-topography" mismatch in the  
30 Disgrazia cluster should not surprise, given that in this area glaciers are distributed on all aspect  
31 categories (Fig. 5b) and so aspect effects tend to cancel out. Following this logic, from a synoptic

1 climatic standpoint Orobic glaciers should not exist, as the  $r_c ELA_0$  in this sub-region (~2900 m  
2 a.s.l.) plots some 180 m above the median ridgecrest, hence confirming the characteristic topo-  
3 climatic adjustment of these glaciers (on average). In this context, the comparison between Orobic  
4 and Livigno (both characterized by dominantly north-facing glaciers) is instructive, as it removes  
5 any potential confounding associated with slope aspect. In the Orobic, we observe a four-fold  
6 increase in  $ELA_0$  variability (> 800m) compared to Livigno (~300m) (Fig. 5b), a variability that  
7 reinforces prior hints (section 4.4) on the potential decoupling between Orobic glaciers and synoptic  
8 climatic conditions, and that we interpret as the effect of local morphometric properties of the  
9 hosting cirques and niches. At these locations, peculiar conditions of snow avalanching, shading  
10 and wind accumulation would be able to sustain glaciers but not significant ice flow, as this latter  
11 would imply the existence of larger glaciers, characterized by higher glacier relative reliefs ( $\Delta E$ ).

## 12 **5.2 Area change of small glaciers**

13 Considering the characteristic limited size of our study glaciers, the high sensitivity of mid-to-small  
14 glaciers (even though associated with high scatter) to climate change (i.e., Haeberli and Beniston,  
15 1998; Paul et al., 2004; Jiskoot and Mueller, 2012; Tennant et al., 2012), and the relatively low  
16 elevation of the study terrain (Fig. 4), it is not surprising that, at first glance, post-LIA Annual  
17 Average Decrease (AAD) in Livigno (0.55 % a<sup>-1</sup>), Disgrazia (0.45 % a<sup>-1</sup>), and Orobic (0.50 % a<sup>-1</sup>)  
18 plot well above the estimated average of 0.33 % a<sup>-1</sup> for the European Alps (1850-2000, Zemp et al.,  
19 2008). However, since this regional estimate relies chiefly on satellite imagery, it is likely to carry  
20 high uncertainties on the area change of small glaciers, and therefore a direct comparison with our  
21 sub-regional glacier inventories seems inappropriate. Comparisons with other sub-regions within  
22 the Alps characterized by larger glacier and higher mountains, and where inventories of comparable  
23 temporal and spatial resolution are available, highlight lower retreat rates in: (i) Les Ecrins (AAD =  
24 0.38 % a<sup>-1</sup>; MAP ~1200-1400 mm a<sup>-1</sup>), the French side of the Mont Blanc (AAD = 0.15 % a<sup>-1</sup>; MAP  
25 ~1400-2000 mm a<sup>-1</sup>), and the Vanoise (AAD = 0.39 % a<sup>-1</sup>; MAP ~900-1400 mm a<sup>-1</sup>) (1820/50-  
26 2006/09, Gardent and Deline, 2013); (ii) Val d'Aosta (0.39 % a<sup>-1</sup>; MAP ~800-2000 mm a<sup>-1</sup>)  
27 (1820/50-2005, Curtaz et al., 2012), and (iii) the Swiss Alps (AAD = 0.26 % a<sup>-1</sup>; MAP ~600-2600  
28 mm a<sup>-1</sup>) (1850-2000, Zemp et al., 2008). Elsewhere, post-LIA retreat rates are higher (0.78 % a<sup>-1</sup>) in  
29 the Spanish Pyrenees (MAP ~1600-2000 mm a<sup>-1</sup>) (1894-2001, Gonzales Trueba et al., 2008), about  
30 the same (0.50 % a<sup>-1</sup>) in the Canadian Rocky Mountains (MAP ~730-1970 mm a<sup>-1</sup>) (1919-2006,  
31 Tennant et al., 2012), and substantially lower (0.13 % a<sup>-1</sup>) in the Jotunheimen (Southern Norway,  
32 MAP ~1300-1650 mm a<sup>-1</sup>) (1750-2003, Baumann et al., 2009).

1 In order to remove the possible confounding exerted by glacier size and conduct a more appropriate  
2 evaluation of glacier area change at the local (i.e., three sub-regions comparison) and regional (e.g.,  
3 against the alpine average) scales, we now consider the two smaller glacier size classes only i.e.,  
4  $<0.1$  and  $0.1-0.5 \text{ km}^2$ ) (DeBeer and Sharp, 2007). This adjustment yields a 1860-2007 AAD that  
5 decreases progressively moving southward, from Livigno ( $0.62 \text{ \% a}^{-1}$ ) to Disgrazia ( $0.58 \text{ \% a}^{-1}$ ) to  
6 Orobic ( $0.48 \text{ \% a}^{-1}$ ). These retreat rates are similar to: (i) data by Lucchesi et al. (2013), who report  
7 an average AAD (1860-2006) of  $0.50 \text{ \% a}^{-1}$  for the Western Italian Alps, starting from LIA glaciers  
8 of  $0.5 \text{ km}^2$  (average size), a value similar to the combined average size of our study glaciers (i.e.,  
9  $0.4 \text{ km}^2$ ); and (ii) the estimated average of the European Alps (1850-2000,  $0.51 \text{ \% a}^{-1}$ ) for the same  
10 size class (Zemp et al., 2008). It is worth highlighting that this latter figure would have risen  
11 significantly if post-2000 data were to be added, given that the 2001-2007 period was characterized  
12 by intense glacier retreat (WGMS, 2009).

### 13 **5.3 Glacier retreat and temporal variability**

14 The availability in this study of 4 different periods (1860-1954-1990-2003-2007) in 3 sub-regions  
15 allows us to detect the temporal and spatial variability of glacier change. Glaciers in the study area  
16 underwent a low relative area decrease in the 1860-1954 period, remained almost stable up until  
17 1990, and then started retreating at progressively faster rates in the 1990-2003 and 2003-2007  
18 intervals (Figure 7), with greater retreat acceleration of the very small glaciers ( $\leq 0.1 \text{ km}^2$ ). In this  
19 temporal context, the Orobic sub-region represents the exception, in that the retreat rate across  
20 1990-2003 and 2003-2007 stays constant with, in the latter period, an AAD value for glaciers  $\leq 0.1$   
21  $\text{km}^2$  that is much lower than in Livigno and Disgrazia sub-regions (Table 4). The gradual increase  
22 with time of the spread of the relative change in glacier area (Fig. 7b) is a warning that these results  
23 need to be used with caution since the study intervals differ significantly in length. In particular,  
24 potential decadal fluctuations in glacier area within the 1860-1954 and 1954-1990 periods would  
25 have gone undetected (i.e., the re-advance phase of alpine glaciers in the 1970s and 1980s (Patzelt,  
26 1985; Hoelzle et al., 2003; Citterio et al., 2007)).

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

1 our latitudinal transect, indicating that glaciers in the most continental sub-region (Livigno) not only  
2 depict a higher total post-LIA retreat, but also that such retreat has been much faster in recent years  
3 compared to more maritime environments (i.e., Orobic mountains). Similar rates (i.e., 7.1) have  
4 been reported only in the Spanish Pyrenees between 1894-1991 and 1991-2001 (Gonzales Trueba et  
5 al., 2008), whereas in many other alpine regions the acceleration is still detectable but less intense  
6 (i.e., 2.2 times in France between LIA and the 70's to 2006-09 (Gardent and Deline, 2013), and 2.9  
7 times in Swiss Alps between LIA and 1973 to 1999 (Paul et al., 2004)).

8 The previously disclosed differences in glacier retreat pattern along our latitudinal transect are even  
9 more apparent when increasing the temporal resolution to an inter-annual basis. To this end, we  
10 present unpublished data from multiple GPS field surveys and glaciological mass balance  
11 campaigns (2007-2013) on three sample glaciers: Campo Nord (GS = 0.30 km<sup>2</sup>; Livigno), Vazzeda  
12 (GS = 0.23 km<sup>2</sup>; Disgrazia), and Lupo (GS = 0.22 km<sup>2</sup>; Orobic) glaciers (Table 5 and Figs. 1b and  
13 3). Mass balances are combined with glacier limits updated to summer 2012 (Table 5 and Figs. 1b,  
14 3, 12 and 13). In particular, the relevant winter and summer point mass balances, measured  
15 averaging the data of two ablation stakes across the ELA<sub>0</sub> (Figs. 3, 12 and 13), even though referred  
16 to three glaciers only, are useful to infer the mechanisms responsible for the differences in glacier  
17 retreat observed along our transect (Table 4 and Figure 7). Since 2007, Campo Nord glacier depicts  
18 an uninterrupted series of negative net balances for a total loss of 12.9 m w.eq and an area loss of  
19 0.02 km<sup>2</sup>. Lower mass losses are recorded at Vazzeda and Lupo glaciers (6.3 and 5.6 m w.eq), with  
20 the former losing 0.03 km<sup>2</sup> and the latter showing no significant changes in glacier area (Figs. 12  
21 and 13). Despite the small latitudinal difference from Campo Nord to Lupo glacier (about 40 km),  
22 the mass balance turnover increases dramatically along the transect. At Lupo, years with high  
23 winter accumulation are able to compensate for more consistent rates summer ablation  
24 throughout the 2007-2013 period. This trend suggests a higher sensitivity of Orobic glaciers to  
25 winter precipitation, as 2009, 2010, and 2011 were characterized by both above-average winter  
26 precipitation and summer temperatures, which resulted in negative mass balances across most of the  
27 European Alps (WGMS, 2011, 2013).

#### 28 **5.4 Small, avalanche-dominated glaciers**

29 The tendency of small avalanche-dominated glaciers to be poorly coupled to synoptic temperature  
30 changes has been reported in different studies. Kuhn (1995) discusses a conceptual model to explain  
31 the mass balance of "very small" glaciers (i.e., glacier area < 10 ha, or 0.1 km<sup>2</sup>), suggesting that

1 snow drifted by wind and accumulated by avalanching activity would be crucial to sustain glaciers  
2 below the  $r_c\text{ELA}_0$ . Furthermore, he suggests that glaciers in small cirques are partly de-coupled  
3 from precipitation as in winters with heavy snow falls once the cirque is completely filled with  
4 snow, this surplus would be conveyed below the glacier terminus via avalanching and thus lost to  
5 accumulation. More recently, DeBeer and Sharp (2009) have shown that a sample of very small  
6 glaciers ( $<0.4 \text{ km}^2$ ) in the Monashee Mountains (British Columbia) displayed no observable change  
7 in area during the 1951-2004 period, while the neighboring larger glaciers suffered a generalized  
8 retreat. Accordingly, these small glaciers after an initial post-LIA retreat are now placed in locations  
9 that would favor their preservation (i.e., in sheltered sites surrounded by high and steep rock walls).  
10 The authors suggest that the enhanced mass inputs at these particular sites can compensate for the  
11 decline in winter precipitation observed in the region.

12 Dahl and Nesje (1992), while reconstructing the paleo-ELA of a small glacier in western Norway,  
13 attribute the resilience of small avalanche-dominated glaciers to patterns of winter precipitation, as  
14 opposed to summer temperature. More recently, Carturan et al. (2013a) provide empirical data  
15 supporting this explanation for the Montasio glacier ( $GS = 0.07 \text{ km}^2$ ;  $E_{\text{median}} = 1903 \text{ m a.s.l.}$ ), in the  
16 Eastern Italian Alps. Accordingly, during the 2009-2011 period years with heavy winter snow-falls  
17 (and related high snow avalanche inputs) would be able to generate a positive mass balance  
18 sufficient to compensate one or more subsequent negative years. This interpretation is further  
19 supported by the limited post-LIA area loss, which the authors estimate to be about 30%.

20 Even though most of the glaciers in our study sub-regions are small and avalanche fed (Table S 1),  
21 only those of the Orobie cluster appear to be poorly coupled to the contemporary synoptic climatic  
22 conditions and deviate from the other two (Fig. 7), hence from the average alpine trend (Zemp et  
23 al., 2008). In consideration of the progressively lower decoupling inferred moving northward along  
24 the study transect, we hypothesize that snow avalanching activity is efficiently increasing glacier  
25 accumulation, hence dampening glacier retreat, only where precipitation is relatively high, as in the  
26 Orobie case. In other words, we propose that the dynamics of these glaciers are (snow) *supply-*  
27 *limited*, rather than limited by summer ablation.

28 Despite the lack of reliable long-term climatic series for each sub-region, the progressive north-to-  
29 south decoupling of glacier change with respect to synoptic climatic conditions is supported by the  
30 southward increase in variability of  $\text{ELA}_0$  (Fig. 5a), post-LIA glacier change (Fig. 7), and inter-  
31 annual mass balances of the monitored sample glaciers (Figs. 12 and 13). Further to this, the below  
32 alpine average post-LIA retreat (for the same glacier size) and the lack of relations between glacier

1 change and glacier attributes found in the Orobic sub-region (Fig. 11c and Table S 5) are evidences  
2 of enhanced glacier-climate decoupling.

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

13

## 14 **6 Summary and conclusion**

15 With a multitemporal, airphoto-based glacier inventory, combined with inter-annual, field-based  
16 mass balances of selected small glaciers we can link glacier and terrain morphometric attributes,  
17 climatic characteristics, and glacier response to climatic forcing. In particular, we examine post-LIA  
18 glacier area and elevation changes, along a latitudinal transect, and across a 150-year time window.  
19 Within a latitudinal distance of less than 60 km we move from small continental-like glaciers  
20 surviving between 2800-3200 m a.s.l. with as little precipitation as 790 mm a<sup>-1</sup> (Livigno sub-region)  
21 to maritime ones located between 2100-2500 m a.s.l. with as much as 1770 mm a<sup>-1</sup> (Orobic sub-  
22 region). As one moves southward, this physiographic set up corresponds to: (i) a progressive  
23 depression of ELA<sub>0</sub> values with a concurrent increase (doubling) of ELA<sub>0</sub> within-subregional  
24 variability; and (ii) a weakening and/or disappearance of correlations between basic altitudinal  
25 glacier attributes and 1860-2007 glacier area change.

26 We further show that post-1990 glacier area change is about an order of magnitude faster than  
27 before, and that this trend accelerates even more in Livigno and Disgrazia between 2003-2007, in  
28 line with the European Alps trend. By contrast, Orobic glaciers, which have been retreating  
29 comparatively less since 1990, are basically stationary in the post-2003 period. This behaviour is  
30 further confirmed and extended through 2013 by an overall (2007-2013) equilibrium mass balance  
31 at Lupo glacier (Orobic), as opposed to persistent net deficits observed in Campo Nord (Livigno)

1 and Vazzeda (Disgrazia) glaciers. This equilibrium is achieved thanks to heavy accumulation  
2 seasons that, during the seven years of monitoring, have been able to compensate for consistent  
3 summer ablation losses and relevant dry winters. Therefore, we argue that the dynamics of Orobie  
4 glaciers are currently supply-limited (i.e., their survival depends on the magnitude-frequency of  
5 winter accumulations) rather than controlled by ablation. In other words, we hypothesize that the  
6 recent resilience of glaciers in Orobie is a consequence of their decoupling from synoptic  
7 atmospheric temperature trends (i.e., rise). A decoupling that originates from local topographic  
8 conditions (i.e., deep, north-facing cirques), but most importantly from high winter precipitation,  
9 which represents the distinctive attribute of the Orobie cluster. This combination of topo-climatic  
10 conditions ensures high snow-avalanche supply, as well as high summer shading and sheltering. In  
11 this context, we introduce the parameter  $E_{ri}$  (i.e., the elevation of the ridgecrest located upslope of a  
12 given study glacier), which, when represented as a function of relative glacier area change, proves  
13 to be an efficient proxy for discriminating climatically-coupled from decoupled settings.

14 The case of the Orobie, in which for the first time we identify a population of maritime,  
15 climatically-decoupled small glaciers (i.e., beyond the documentation of a single glacier behaving  
16 as an outlier), is in contrast with empirically-based mass balance models and comparative studies  
17 according to which low-elevation glaciers under maritime conditions, with high accumulation and  
18 mass turnover, would display higher sensitivity to climate fluctuations compared to their  
19 counterparts located in drier, continental settings (e.g., Oerlemans and Fortuin, 1992; Hoelzle et al.,  
20 2003, Benn and Evans, 2010). Interestingly, since winter precipitation is expected to rise by 15 to  
21 30% in the future decades across the Central European Alps (e.g., CH2011, 2011; Beniston, 2012),  
22 Orobie glaciers may continue to find favourable conditions for surviving much longer than  
23 previously thought.

24

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3

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5 2011.

14 Table 1. Glacier variables considered.

Glacier variable	String	Unit
Size	GS	km <sup>2</sup>
Maximum elevation	E <sub>max</sub>	m a.s.l.
Minimum elevation	E <sub>min</sub>	m a.s.l.
Balanced-budget Equilibrium Line Altitude	ELA <sub>0</sub>	m a.s.l.
Ridgecrest elevation	E <sub>ri</sub>	m a.s.l.
Glacier relative relief	ΔE	m
Mean slope gradient	S	degrees
Main Aspect	MA	na
Clear-Sky Radiation (June-September)	CSR	W m <sup>2</sup>
Mean Annual Precipitation	MAP	mm a <sup>-1</sup>
Avalanche Area Accumulation Basin Ratio	ABR	na

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

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

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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 <sup>2</sup> )								
<b>Livigno</b>	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
<b>Disgrazia</b>	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
<b>Orobie</b>	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

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

Size Classes km <sup>2</sup>	AAD (% a <sup>-1</sup> )			
	1860-1954	1954-1990	1990-2003	2003-2007
<b>Livigno</b>				
<0.1	0.63	0.02	5.20	8.73 <sup>1</sup>
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
<b>Disgrazia</b>				
<0.1	0.41	0.16	3.54	11.11 <sup>1</sup>
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
<b>Orobie</b>				
<0.1	0.55	-0.09	3.27	3.77 <sup>1</sup>
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	<b>0.55</b>	<b>-0.11</b>	<b>2.72</b>	<b>2.64</b>

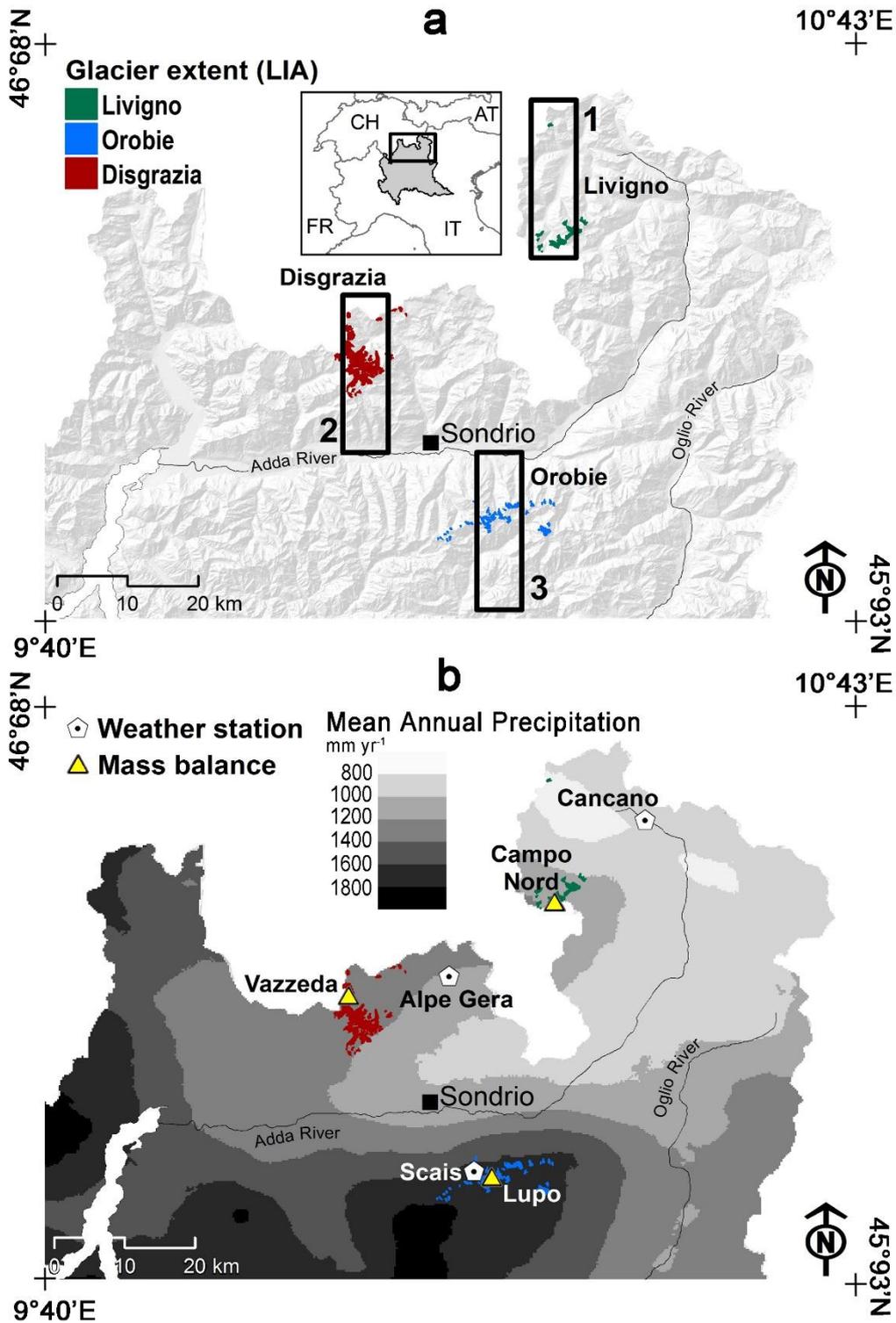
<sup>1</sup>In 2003-2007 small glaciers (<0.1 km<sup>2</sup>) exhibit by far the highest decrease rate of the whole study period in Disgrazia and Livigno by contrast, in Orobie this size class shows much slower decrease.

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

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

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



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2 Figure 1. Maps of northern Lombardy showing (a) the three sub-region location and the transects  
3 used to create the swath profiles (see Fig. 4) and (b) spatial distribution of mean annual  
4 precipitation with sample weather stations and mass balance measured glaciers (see text for further  
5 details). Mean annual precipitation was interpolated by using ordinary co-kriging with 374 rainfall

1 stations (1981-1990) (Ceriani and Carelli, 2000) and 50,000 elevation points randomly distributed  
2 within the Region.

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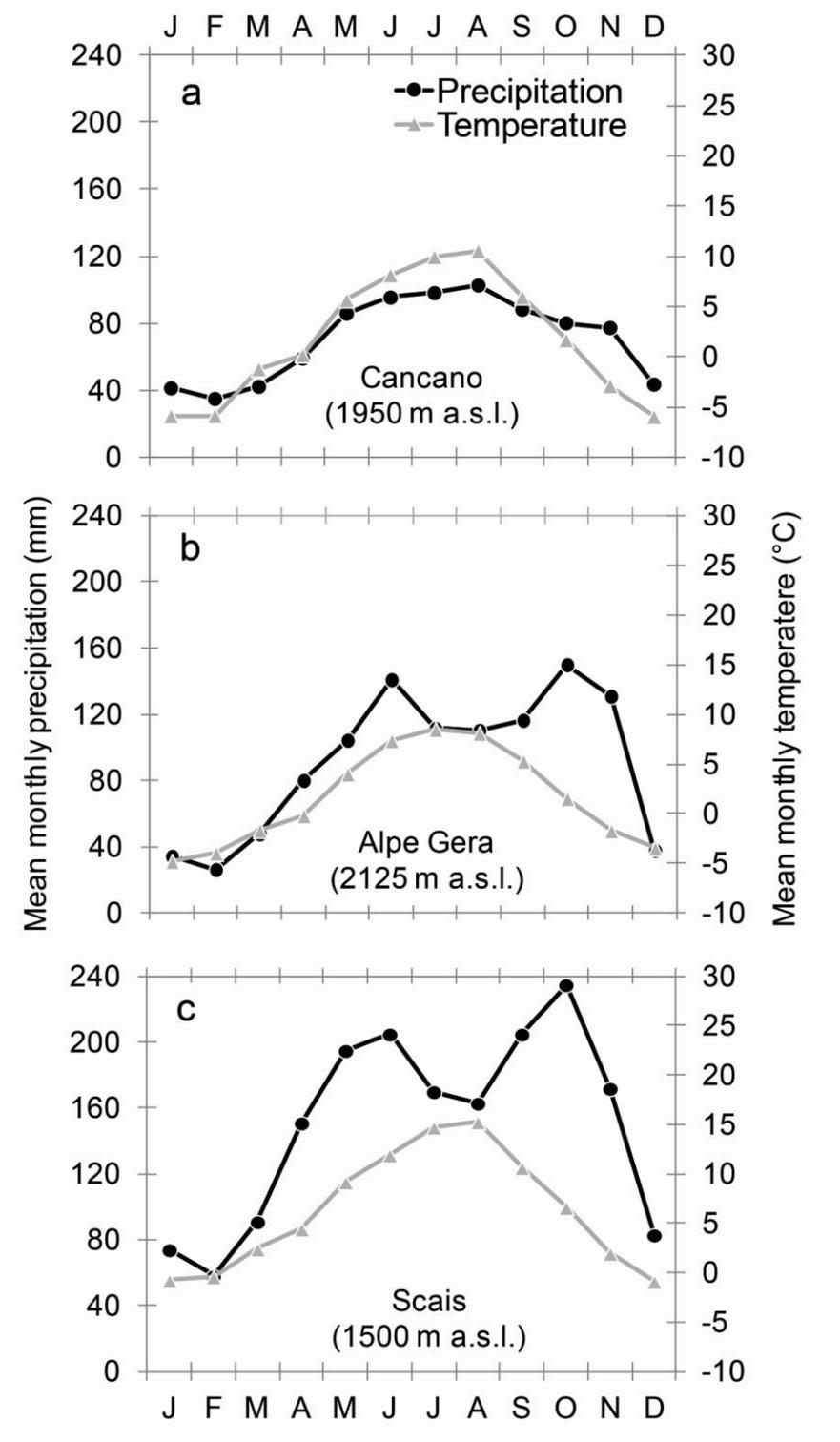
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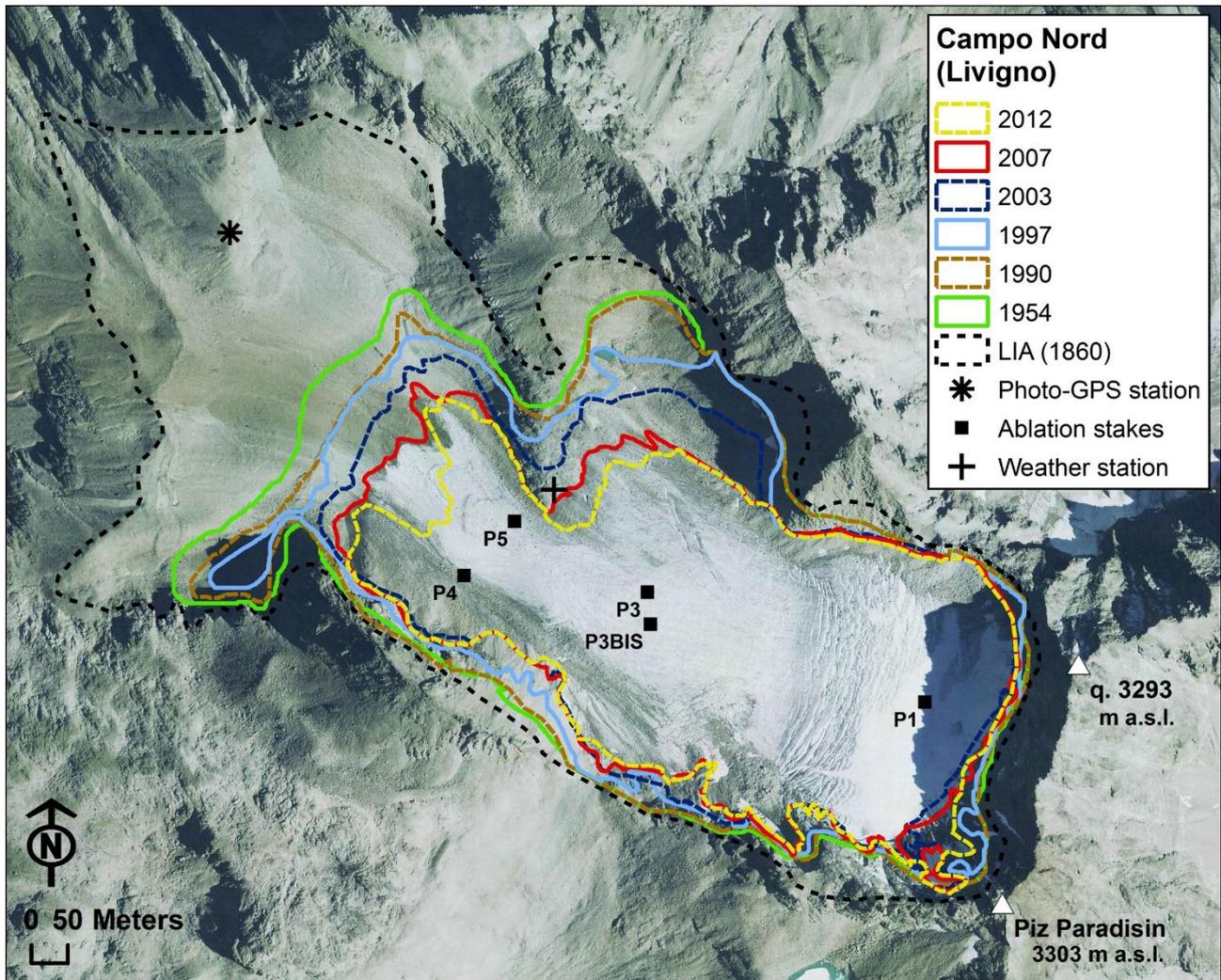
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2 Figure 2. Climographs for Cancano (Livigno sub-region), Alpe Gera (Disgrazia sub-region) and  
 3 Scais (Orobic sub-region) weather stations. Time series: temperature (1990-2000); precipitation  
 4 (1951-2000 Cancano, 1990-2000 Alpe Gera and 1958-2000 Scais.). Data sources: Servizio  
 5 Idrografico e Mareografico Nazionale, Consorzio dell'Adda, ARPA Lombardia, Database OLL –  
 6 Regione Lombardia D.G.S.P.U.



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2 Figure 3. Example of multitemporal glacier delineation i.e., Campo Nord glacier (Livigno sub-  
 3 region) with 2007 orthophoto in the background. The slightly larger extension of the glacier top  
 4 area in 2012 compared to 2003 and 2007 is due to the presence of a snow-field developed after the  
 5 2007 season that was characterized by very limited snow cover.

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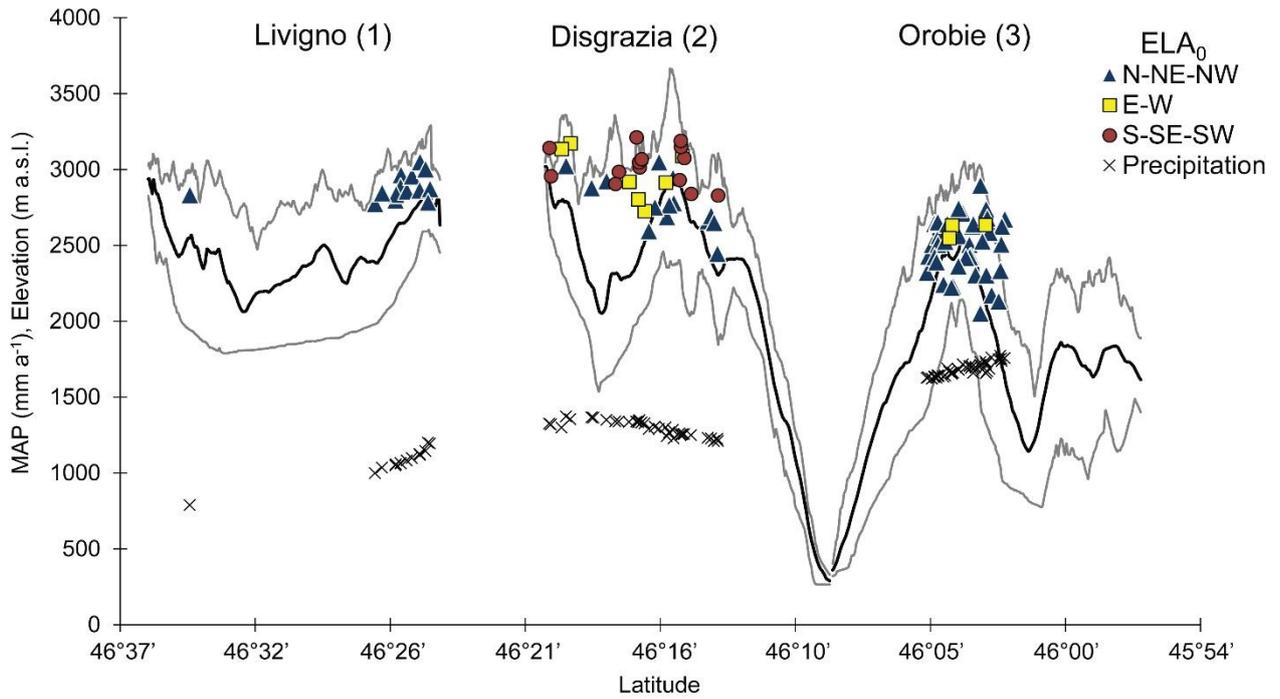
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2 Figure 4. Latitudinal transect across Livigno, Disgrazia, and Orobie sub-regions. Dashed lines  
 3 indicate minimum and maximum elevation, solid line indicate mean elevation. Filled symbols and  
 4 crosses refer respectively to ELA<sub>0</sub> (stratified by dominant slope aspect) and Mean Annual  
 5 Precipitation (MAP) values associated to each study glacier.

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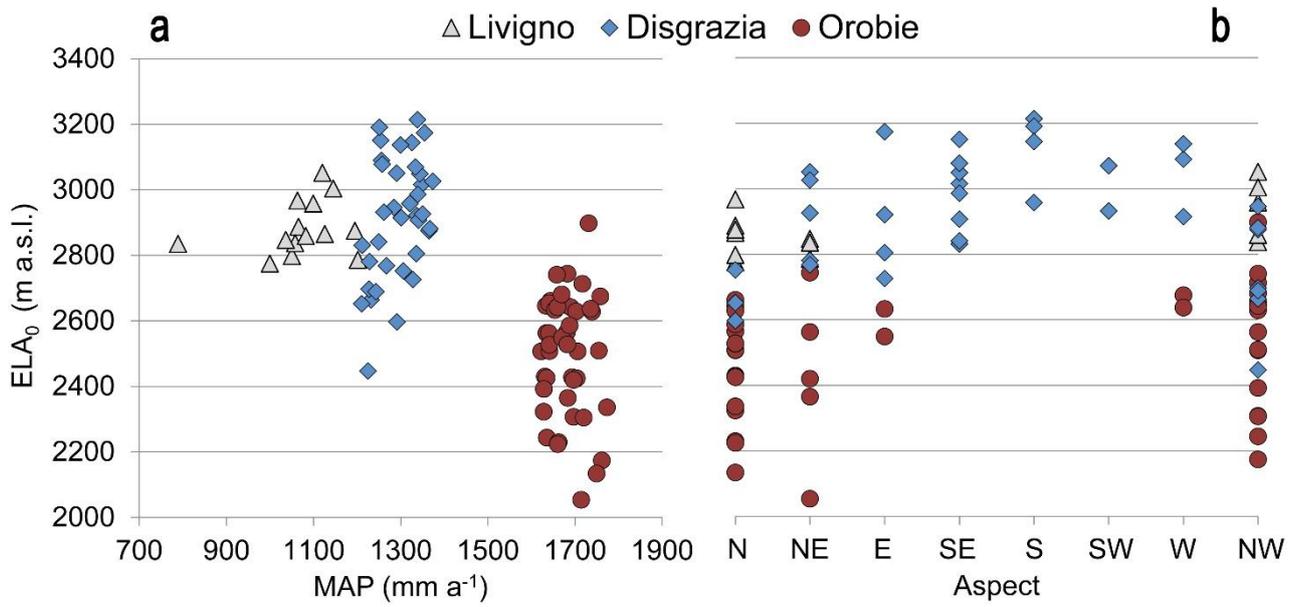
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2 Figure 5. Balanced budget equilibrium line altitude (ELA<sub>0</sub>) as a function of: (a) mean annual  
3 precipitation (MAP); and (b) slope aspect.

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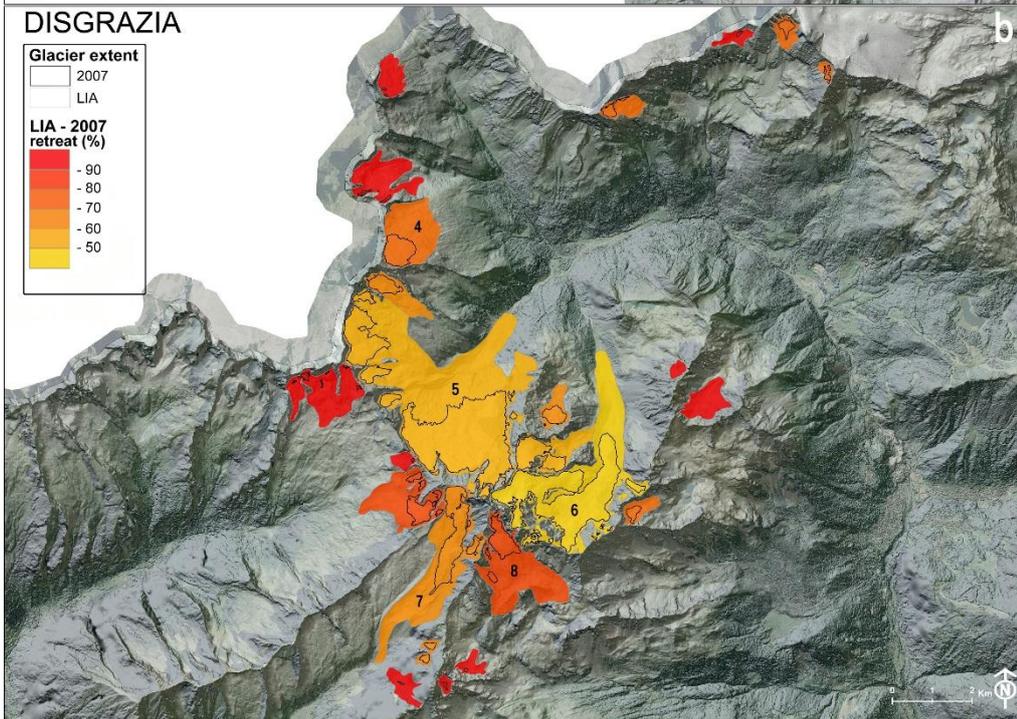
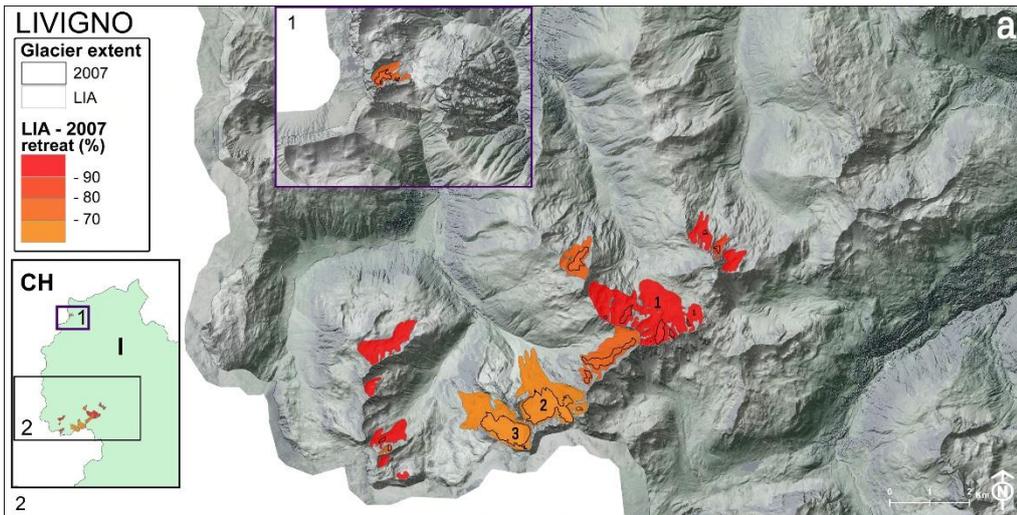
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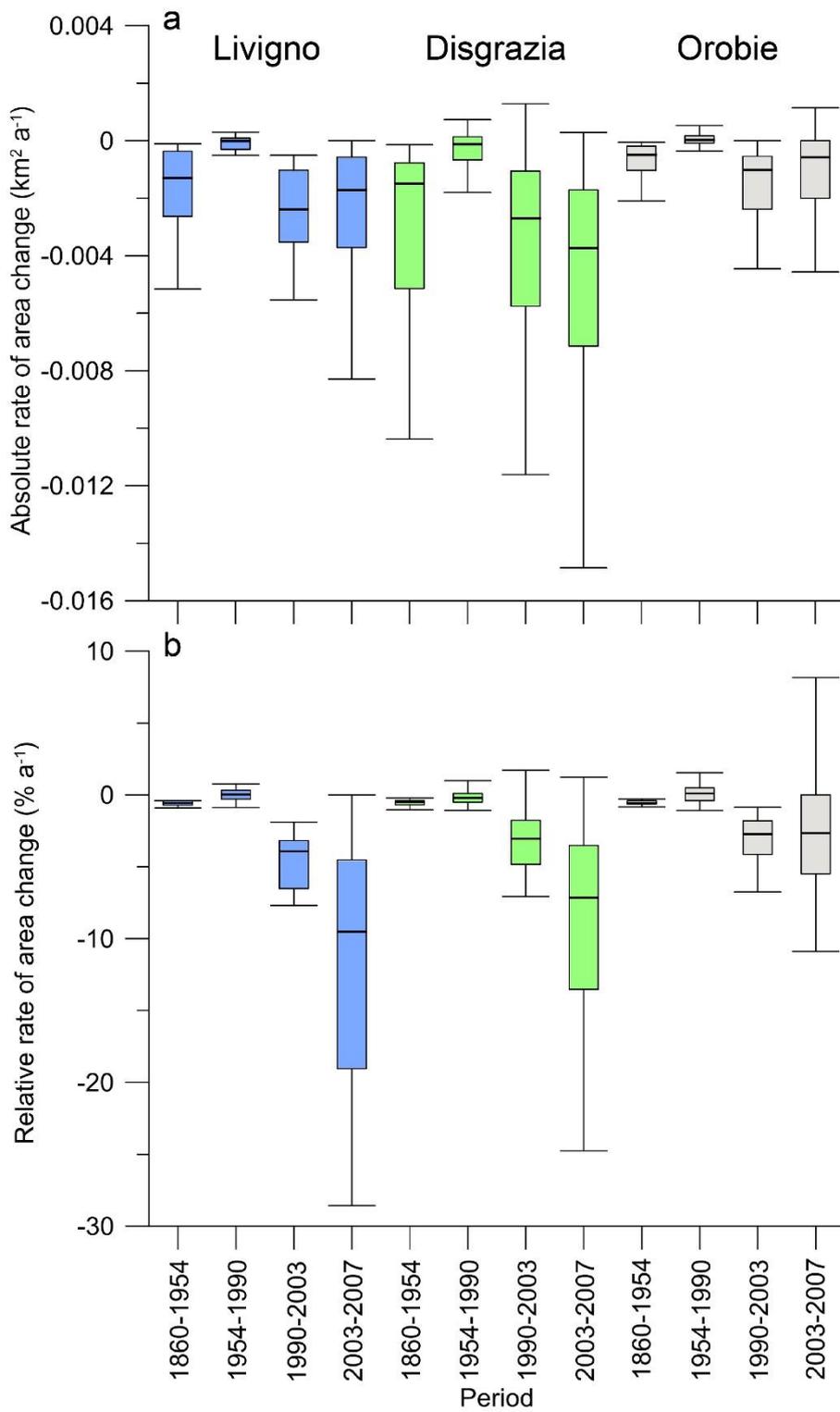
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1 Figure 6. Maps showing the glacier extent in 1860 (LIA) and 2007, and the spatial distribution of  
2 the relative change in glacier area in: (a) Livigno; (b) Disgrazia; and (c) Orobic. Numbers refer to  
3 glacier cited in the text. 1: Mine, 2: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

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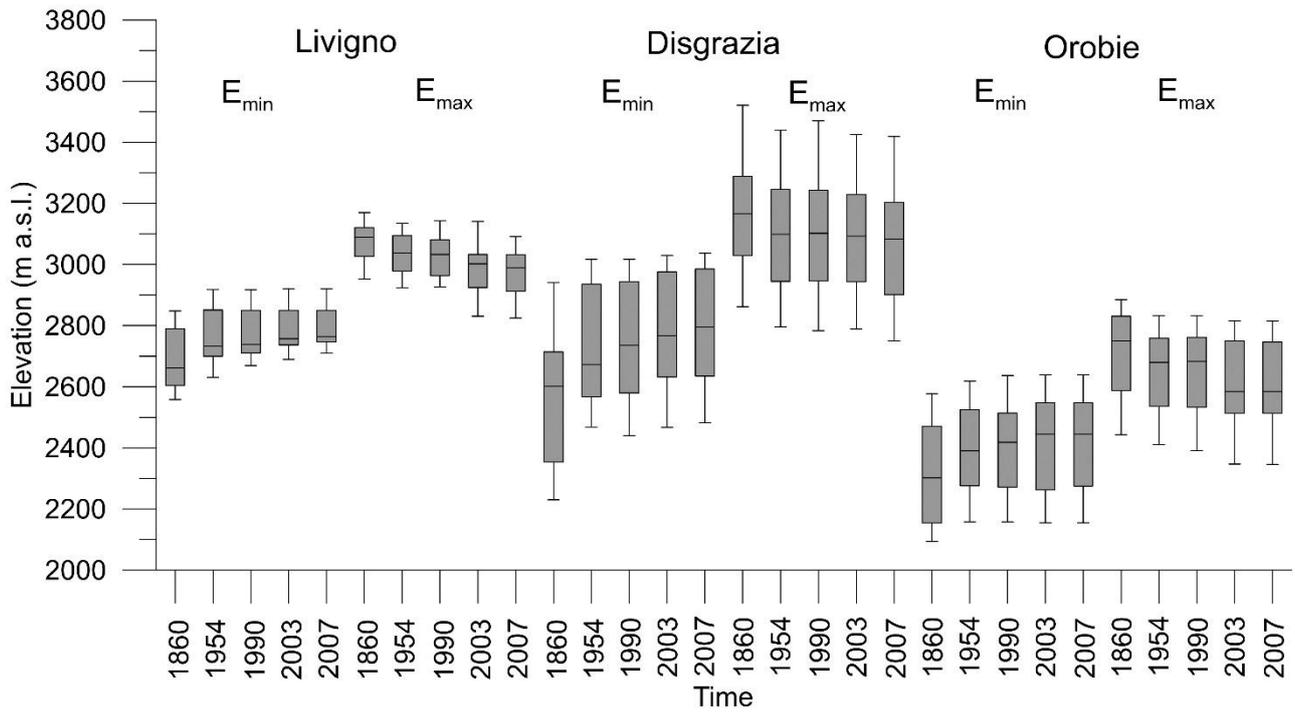
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3 Figure 7. Box-plots showing: (a) absolute rate of glacier area change; and (b) relative rate of glacier  
4 area change. Horizontal lines indicate median values, boxes constrain 25<sup>th</sup> and 75<sup>th</sup> percentiles, and  
5 whiskers mark 10<sup>th</sup> and 90<sup>th</sup> percentiles. Outliers are not presented due to scale constraints.

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3 Figure 8. Change in glacier maximum maximum ( $E_{max}$ ) and minimum ( $E_{min}$ ) elevation across the 4  
4 study intervals. Horizontal lines indicate median values, boxes constrain 25<sup>th</sup> and 75<sup>th</sup> percentiles,  
5 and whiskers mark 10<sup>th</sup> and 90<sup>th</sup> percentiles. Outliers are not presented due to scale constraints.

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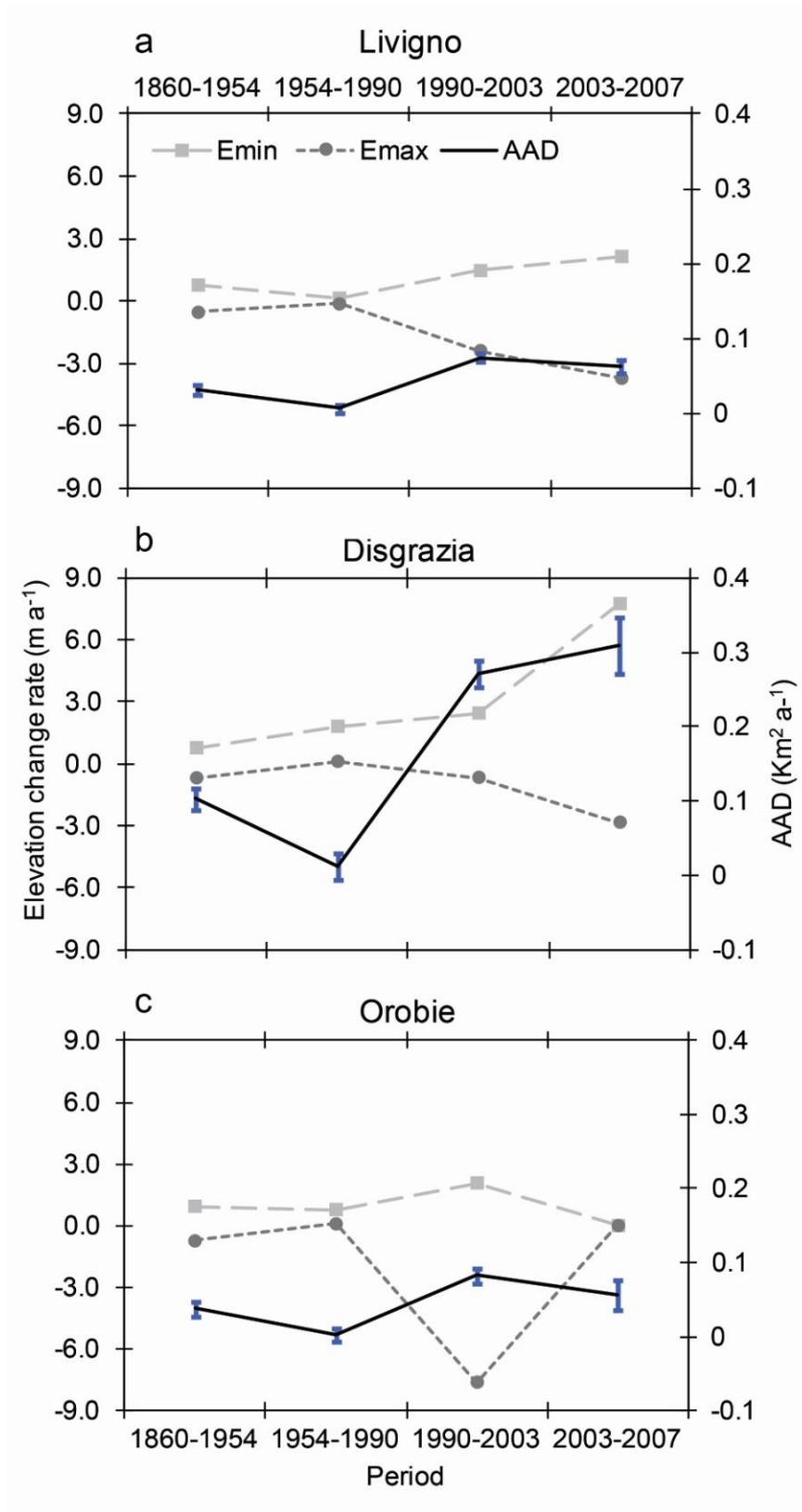
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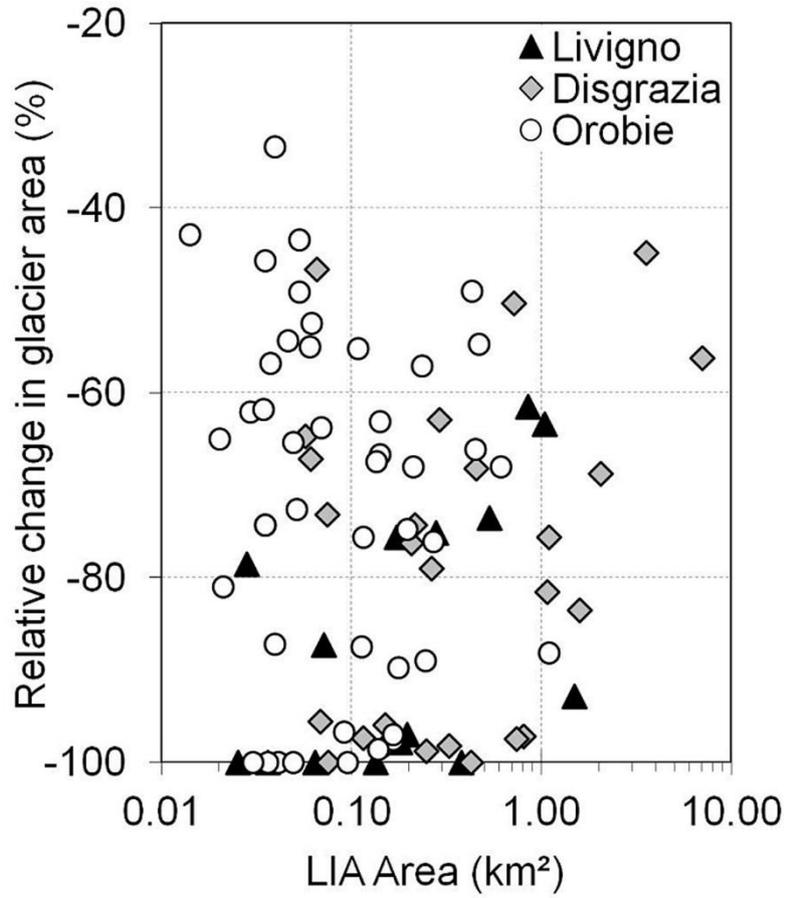
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2 Figure 9. Mean annual elevation change rate ( $\text{m a}^{-1}$ ) and average annual decrease (AAD) in glacier  
 3 area ( $\text{km}^2 \text{a}^{-1}$ ) in: (a) Livigno; (b) Disgrazia; and (c) Orobie. Bars indicate uncertainty in glacier area  
 4 delineation.



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

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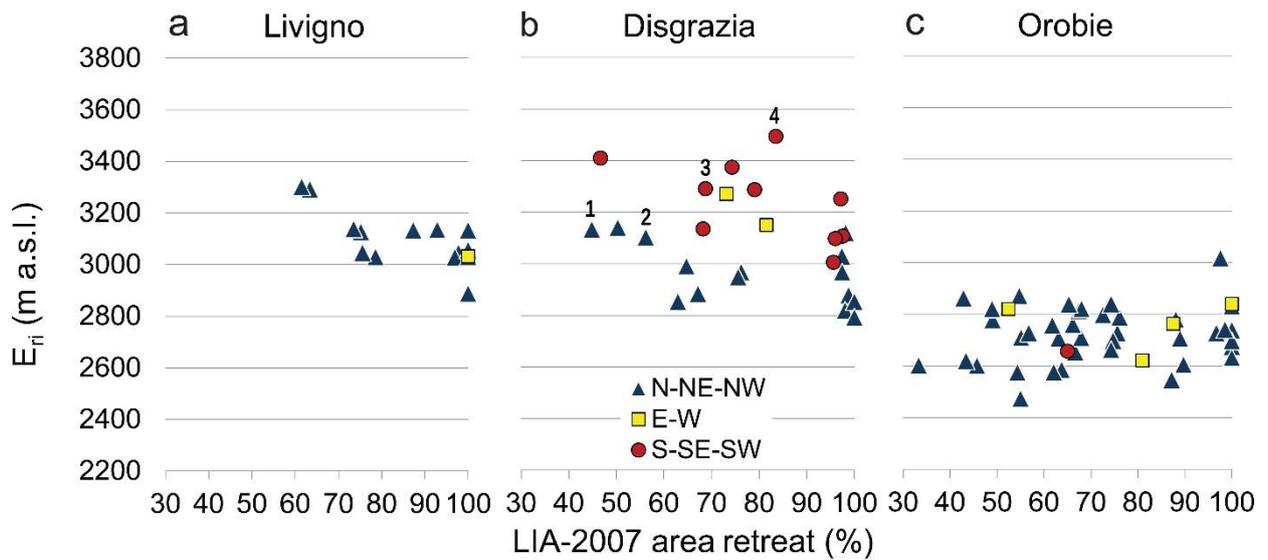
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2 Figure 11. Relative area retreat in (1860-2007) as a function of  $E_{ri}$  (ridgecrest elevation upslope of  
 3 the glacier) in: (a) Livigno; (b) Disgrazia; and (c) Orobie. Glaciers are stratified by dominant slope  
 4 aspect (note different symbols).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

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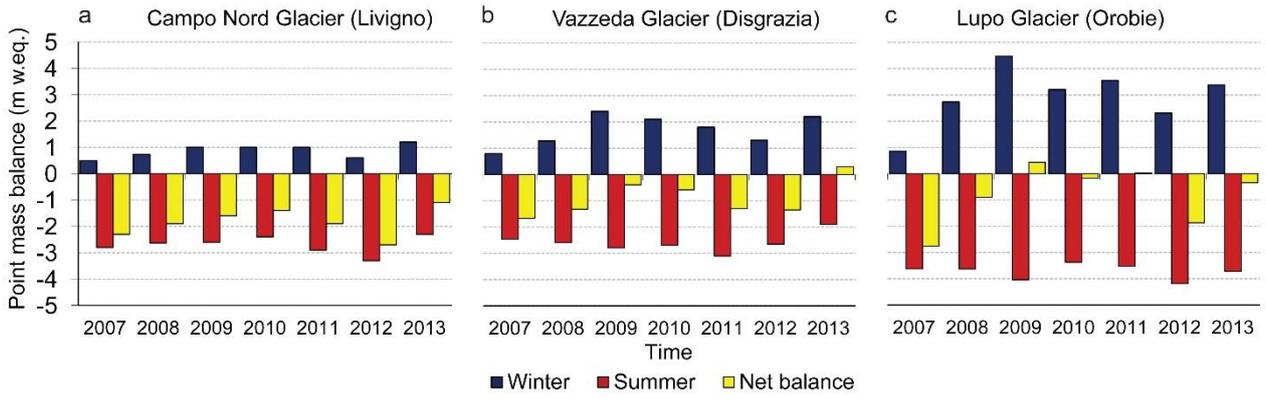
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2 Figure 12. Histogram showing winter, summer, and net point mass balance at: (a) Campo Nord  
 3 glacier (Livigno); (b) Vazzeda glacier (Disgrazia); and (c) Lupo glacier (Orobie) from 2007 to  
 4 2013. Point mass balance data are measured with two ablation stakes placed across the ELA<sub>0</sub> of  
 5 each glacier (see Table 5 for further details).

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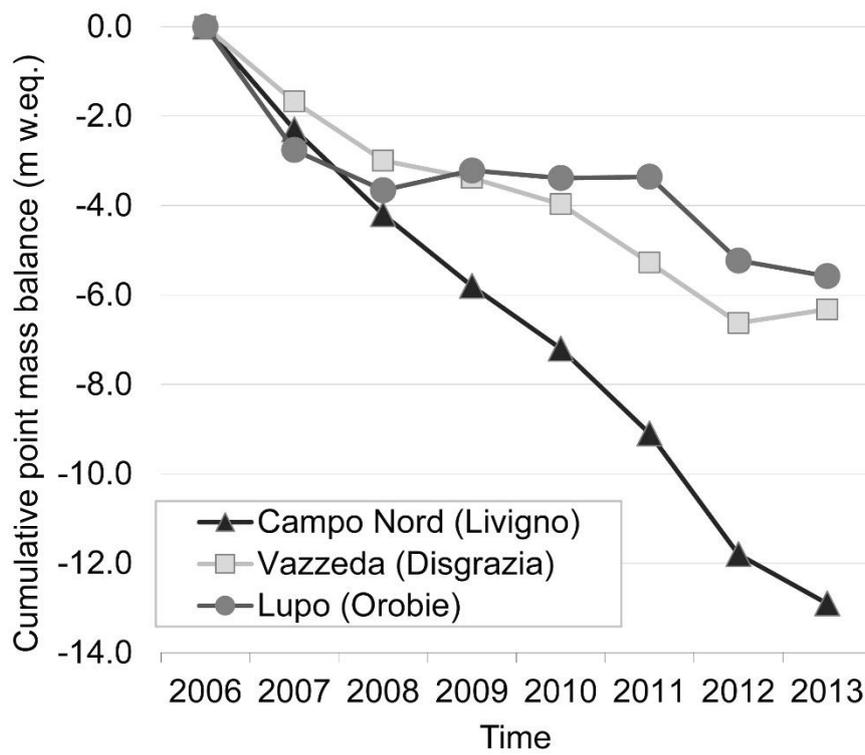
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2 Figure 13. Cumulative point net mass balance in Campo Nord (Livigno), Vazzeda (Disgrazia), and  
 3 Lupo (Orobie) glaciers from 2007 to 2013 (see Table 5 for further details).