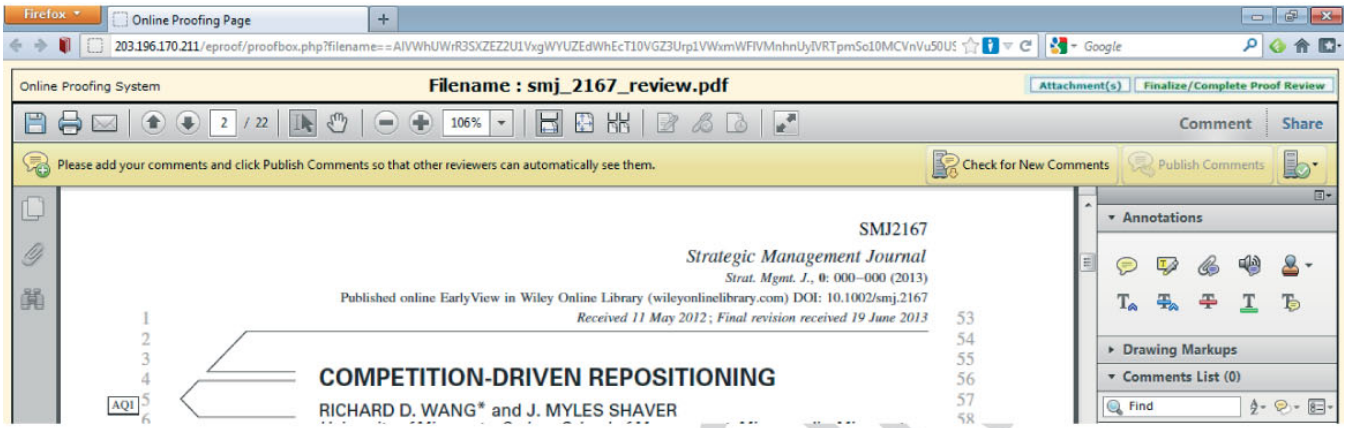
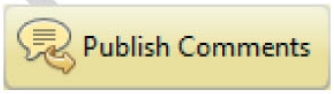
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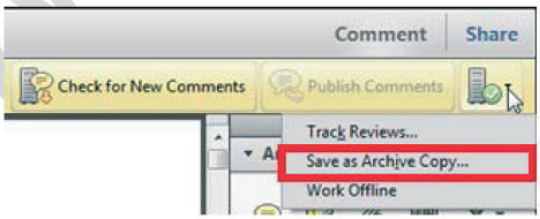
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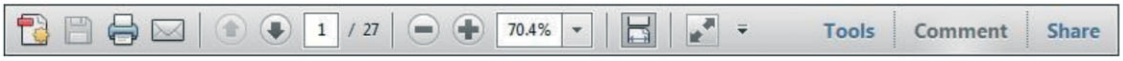
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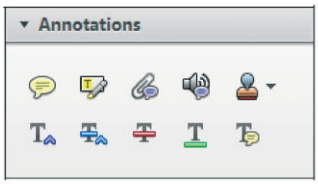
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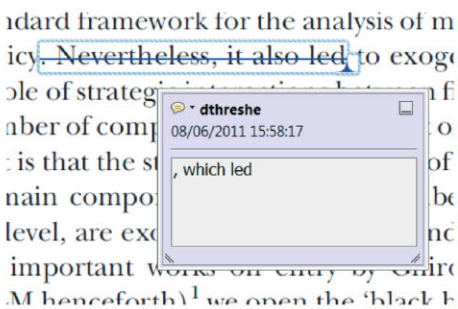


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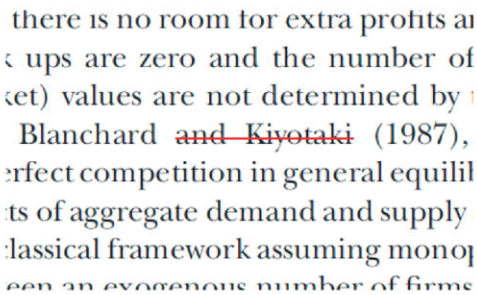


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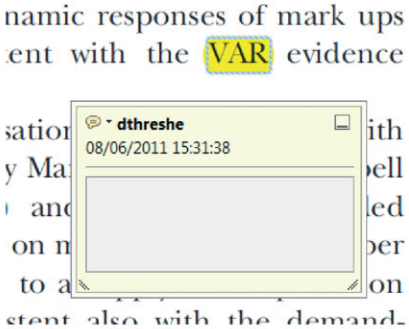


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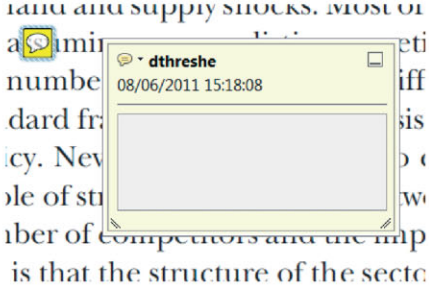


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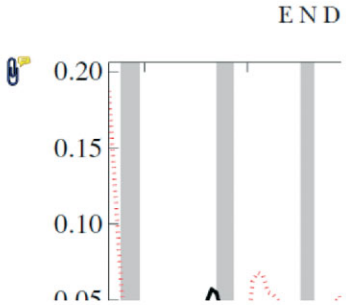
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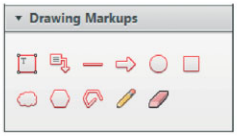
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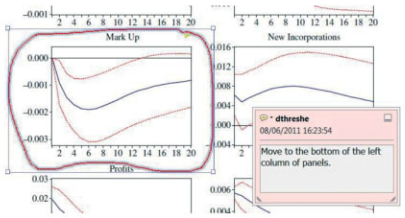
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Precipitation–temperature changes and evolution of a small glacier in the southeastern European Alps during the last 90 years

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ABSTRACT: Very small glaciers (area <0.1 km^2) have received increased scientific attention during recent years, both for their rapid responses to the climate forcing and because they are characterized by microclimatic conditions, often marginal to glacier formation. They are particularly sensitive to climate changes and characterized by a great mass turnover, particularly evident in maritime areas with high precipitation. Here we consider the evolution from 1920 of the 'Canin Eastern Glacier' (Italian Southeastern Alps) in order to correlate its evolution to the precipitation–temperature trends. We reconstructed a precipitation–temperature record at the altitude of the glacier, filling a lack of knowledge in this alpine sector. We observed a decrease in the mean annual precipitation of 10% in 90 years and a warming trend of 0.1 C decade^{-1} since 1851, and of 0.7 C decade^{-1} in the last 20 years. An inverse correlation between precipitation and mean air temperature during summer and ablation periods was also observed. Glacier dynamics revealed a phase of stability between 1945 and 1985 that seems to be a peculiar characteristic of this area. Moreover, through a general regression model the glacial terminus variations seem to be statistically influenced only by winter precipitation. This fact opens interesting perspectives for the possible future evolution of this small glacier and, more in general, to other small glaciers in maritime areas in regard to climate change scenarios.

KEY WORDS very small glaciers; climatology; precipitation; climate change; temperature; general regression model

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1. Introduction

The variations of the precipitation regime, especially at small scale, is still one of the major uncertainties of the future climate change scenarios, and one of the most challenging variables in climate science (e.g. Brugnara *et al.*, 2012; Kirtman *et al.*, 2013). Total annual precipitation (TAP) averaged over the mid-latitude land areas of the Northern Hemisphere has increased in the last century (IPCC, 2013), with a medium confidence before 1951 and an high confidence after 1951. Low-resolution analysis revealed no significant trends for TAP in the northeastern most area of Italy during the last century (Brunetti *et al.*, 2001, 2004, 2006), and detailed and reliable information about climatic trends in the eastern part of the Alpine chain are not available in the literature (Brugnara *et al.*, 2012). At the same time, for the longest period when calculation of regional trends is sufficiently complete, almost the entire globe has experienced a warming of 0.85 °C during the period from 1850 to 2012 (IPCC, 2013), but in the Alps, the temperature increased at a roughly double rate with respect to the global average over the last century (Böhm *et al.*, 2001; Auer *et al.*, 2007).

Mountain glaciers are considered to be sensitive indicators of climate (e.g. Chinn *et al.*, 2005; Oerlemans, 2005) and their changes are recognized as high-confident climate indicator within the international climate monitoring programmes (Haeberli *et al.*, 2007). Globally, glacier mass balance has been shown to be closely related to summer temperatures (Ohmura *et al.*, 1992; Hughes and Braithwaite, 2008), while mass-balance sensitivities to temperature and/or precipitation changes are relatively small for dry–cold climate and relatively high for warm–wet climate (Braithwaite and Raper, 2007), but the relationships between glaciers evolution and precipitation regime are still not always well understood. Various combinations of temperature/precipitation characteristics can lead to advances/retreats of a glacier in historic times (e.g. Steiner *et al.*, 2008), but more generally it was observed that the accumulation-type glaciers (*sensu* Benn and Evans, 2010) are mainly controlled by the winter balance (Nesje *et al.*, 1995, 2000). The importance of precipitation in driving glacier response, even under a general global warming trend, has been recently pointed out in the observation of the behaviour of different maritime glaciers around the world. During the Briksdalsbre event in the 1990s (Nesje and Matthews, 2012), the large glacier advances in Scandinavia was influenced by high winter precipitation ~~linked to positive the North Atlantic Oscillation (NAO) index in the winters~~ (Nesje and Matthews, 2012). In the Southern

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Alps of New Zealand, glacier fluctuations are thought to reflect the strength of westerly atmospheric circulation, which brings increased precipitation, leading to mass gains (Brook *et al.*, 2011). Increased precipitation is also seen as the main reason for the 20th century advances and/or thickening of some glaciers in central Karakoram (Hewitt, 2005). Recently, it has been supposed that an overall positive mass balance and glacier advance in western Canada and Alaska during Medieval times were most likely the result of a significant increase in winter precipitation during times dominated by la Niña conditions, caused by increased solar activity, which counteracted warmer summers (Koch and Clague, 2011). Similarly, also in the central Italian Alps Stenni *et al.* (2007) found that there was a glacier advance during the Medieval times, although summer temperatures were comparable with the actual because heavier precipitations occurred at that time.

Brown *et al.* (2010) • argue that some small cirque glaciers may be more sensitive to climate changes than others, and in general they respond more rapidly both to climate changes (e.g. Hughes, 2008) and to climatic extremes (Hoelzle *et al.*, 2003) compared to larger glaciers. Furthermore, very small glaciers frequently experience inter-annual negative or positive mass balance over the entire glacier surface (Hughes, 2008, 2010) with a great annual mass turnover. This is particularly evident in maritime areas with high precipitation (Oerlemans, 2001). Therefore, precipitation changes could be crucial in driving the response of such glaciers. Besides, this fact has an important influence on the total mass balance in a global perspective. Small glaciers can be so numerous in some areas to contain a significant fraction of the total volume. At the global scale, accuracy in volume of ±1% requires inclusion of glaciers bigger than 1 km^2, but at regional scales the threshold depends on the size distribution (Bahr and Radic, 2012). Where the maximum-area and minimum-area thresholds are respectively of the order of 100 and 0.01 km^2 or smaller, a notable source of error (in the order of 10%) can be expected. Therefore in some regions, like in the Alps, in order to obtain more accurate volume estimates, more complete inventories down to the smallest glaciers (area of 0.01 km^2 or smaller) are requested (Pfeffer *et al.*, 2014).

Recently, the study of small, maritime glaciers of the Mediterranean area have received a strong attention because of their particular behaviour in response to climate change and owing to the fact that they exist at a general low altitude, often well below the theoretical regional Equilibrium-Line Altitude (ELA; Grunewald *et al.*, 2006; González Trueba *et al.*, 2008; Hughes and Woodward, 2009). They are characterized by microclimatic conditions marginal to glacier formation, where even small changes in climate are critical for the glacier behaviour (Hughes and Woodward, 2009). Owing to the lack of significant horizontal movement they often are lens or wedge-shaped and display the largest thickness to length ratio (Kuhn, 1995).

Our case study (Canin Eastern Glacier, CEG, Figures 1 and 2) is located in the easternmost tip of the Alps and it could be considered a template for the analyses of the relationships between glacial evolution and climatic forcing in maritime areas of the world both for its small size (<0.1 km^2 and therefore with annual responses to the

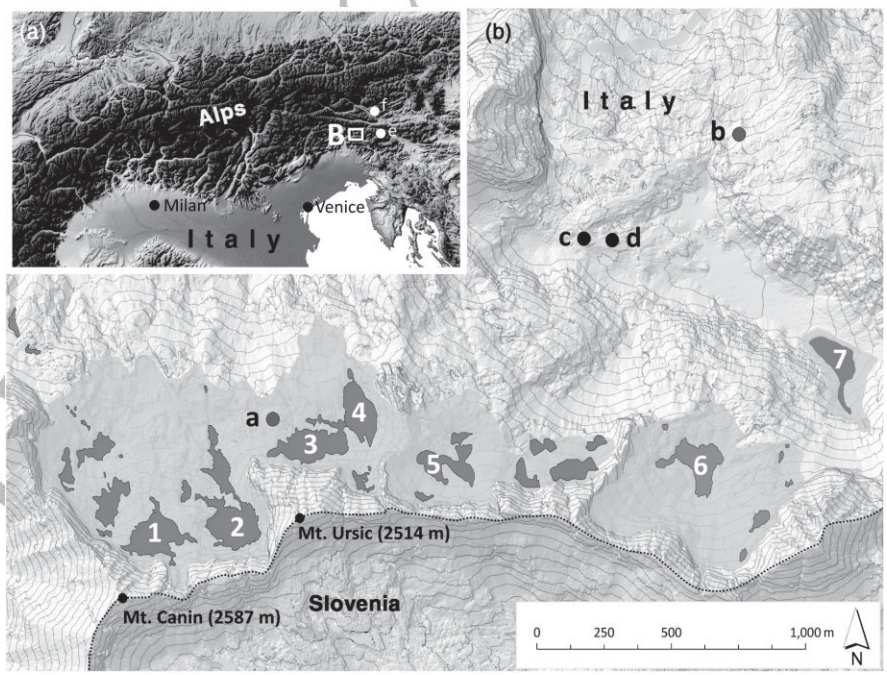


Figure 1. Location map of the study area. (a) Alpine Chain, courtesy Scilands GmbH. (b) Details of the study area with the location of the very small glaciers and snow fields in 2011 (•blue) and the Max-LIA extensions (light blue): (1) and (2) Western Canin; (3) and (4) Eastern Canin. (5) Snow fields and ice patches of former Ursic glacier; (6) Prestreljenik glacieret (former glacier); (7) Prevala glacieret. The location of (a) new AWS at 2203 m (AWS), (b) Livinal Lung AWS (LL), (c) Rifugio Gilberti hut and (d) WSA measurement's site are also illustrated. In (a) the location of (e) Triglav and (f) Villacher Alpe AWSs are also highlighted.

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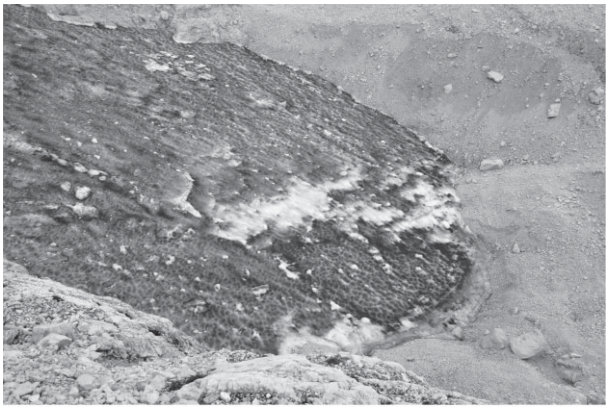


Figure 2. Terrestrial view of the CEG in October 2012. Recessional moraines post-LIA maximum are visible on the background.

climate), for the length of the glaciers terminus fluctuations record and also because this sector of the Alps is one of the wetter of Europe. This very small glacier (*sensu* Kuhn, 1995), together with other glaciers and glacierets of the study area, can be compared for their geometry and characteristics with those existing in the mountains of southern-Mediterranean Europe (Iberian Peninsula, Maritime Alps, Italian Apennines, Northern Balkans, Montenegro, Albania and Bulgaria) according to what argued by Grunewald and Scheithauer (2010).

Thus the article aims to: (1) assess and reconstruct the climate (precipitation and temperature) of this case study area and (2) understand the relationships between these two climatic parameters and the glacial evolution of this template case in a more global view.

2. Study area

The Mt Canin massif (Julian Alps) is located in the Eastern Alps (46°21′N, 13°26′E) along the borderline between Italy and Slovenia. The higher peaks reach altitudes slightly higher than 2500 m (e.g. Canin 2587 m, Ursic 2514 m). At the foot of the northern rock wall between 1830 and 2340 m a.s.l., some very small glaciers, glacierets and ice patches still remain (Eastern and Western Canin, Ursic, Prestreljenik, Prevala) (Figure 1). All of them (except Prevala never inventoried before 2013) were listed as glaciers until the end of the 1980s (•Haeberli *et al.* 1989), while since the 1990s they have been more properly classified as cirque-glacierets (•Colucci *et al.* submitted), fed also by avalanches and drifting snow. The underlying lithology (limestone) is also relevant owing to high albedo typically exhibited by light-coloured carbonate rock types (Hughes *et al.,* 2007) and to karstification, which is able to quickly drain away melt water (e.g. no cirque lakes persist as thermal storage system). Also the complex karstic topography is here crucial in promoting the survival of perennial snow and ice at much lower altitudes. The presence of dolines and caves provide opportunities for the build-up of thick snow accumulation leading to permanent ice (Hughes, 2010). These small glaciers and glacierets were jointed in a single larger ice-mass till the end of the 19th century (Figure 1). During the Little Ice Age (LIA), the Ursic glacier (melted away) was included in this glacial body. The ELA of the Canin Glaciers during the LIA has been estimated at about 2190 m a.s.l. (Monegato, 2012). After the LIA, the general shrinking trend of the glacier was interrupted by some moderate re-advances occurring 1910–1920 and 1946–1961 (Desio, 1927; Rebagliati and Serandrei Barbero, 1982; Serandrei Barbero *et al.*, 1989).The acceleration of the glacial recession rate observed since 1986 until 2006 promoted such a large mass loss that the glaciers stopped their movement downward and, until 2007, they were almost completely covered by debris (Armando *et al.*, 2006; Colucci *et al.*, submitted). Finally, during the winter season 2008/2009, an exceptional event of snow accumulation and the following years promoted a quite large mass increase. At the end of the ablation season 2012, the lower ice/*firn* surface was totally exposed and characterized by irregularly spaced convex bands of rich ice fine sediment (Figure 2(a)). These features are consistent with variations in ice/*firn* velocity across the glacier, with the fastest flow away from the ice margins (Hughes 2007) actually suggesting a possible weak ice movement.

2.1. Climatological settings

The area of Julian Alps is known for being a region of heavy precipitation in the Alps where particularly large annual mean values are observed (Isotta *et al.*, 2014). The mean annual precipitation (MAP) shows a strong gradient from the coastal areas to the inner alpine valleys up to 3300 mm on Mt Canin massif, representing one of the highest mean values for the Alps and Europe. (Gregorcic *et al.*, 2001; Norbiato *et al.*, 2007). This is mainly owing to the orographic blocking induced by first alpine reliefs to the moist southerly winds coming from the Adriatic see and from the Mediterranean (Ceschia *et al.*, 1991). Precipitation over the region generally originates from synoptic fronts with the exception of the first summer months (May to July) when local convective origin prevails. Snow is very abundant in the area. The data available since 1972 for the Rifugio Celso Gilberti at 1830 m a.s.l. (Figure 1, limited to December to April) show a mean winter snow accumulation (c_w) for the period 1972–2012 of 7.0 m, although summer snowfalls are not uncommon even in July and August. The annual mean maximum snow thickness (3.2 m) is generally reached between late March and mid April. Since 2006 c_w was higher than the mean with a maximum of 13.4 m (2008–2009), the highest on record.

The only available data of air temperature over 1800 m a.s.l. in the area, starting in 2000 at Livinal Lung (LL, Figure 1) Automatic Weather Station (AWS) where the mean annual air temperature (MAAT) was 3.9 ± 0.8 °C for the period 2000–2012. Assuming the normal vertical lapse rate of 0.0065 °C m^{-1} (Barry, 1992), in the same period the MAAT at the glaciers (2200 m a.s.l.) should have been 1.5 ± 0.8 °C.

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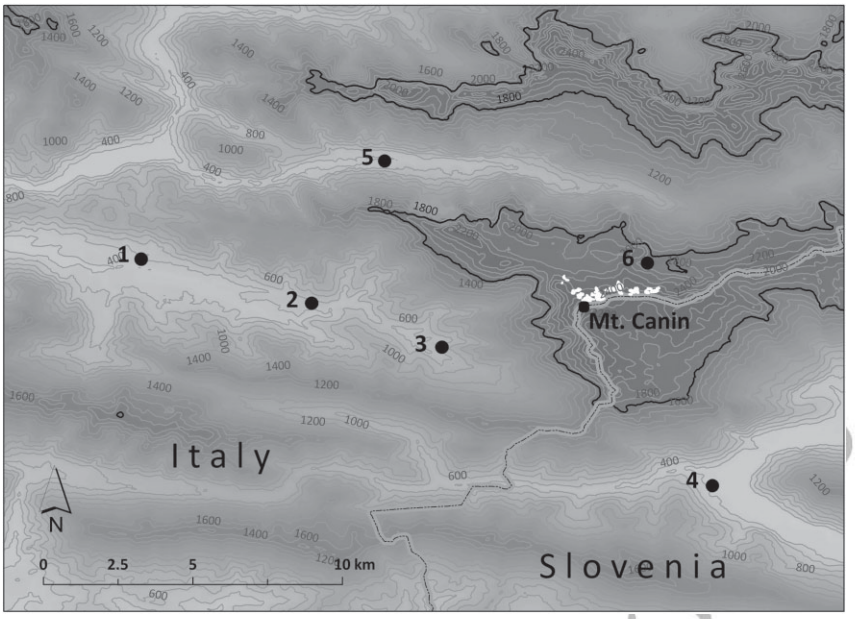


Figure 3. Location of the rain gauges (black dots): (1) Resia; (2) Stolvizza; (3) Coritis; (4) Žaga; (5) Saletto; (6) Livinal Lung; in white is highlighted the location of Canin's glaciers, glacierets and snow fields in October 2011; The 1800 m contour lines have been also highlighted in black bold.

Table 1. Location, altitude and data period of the rain gauges used for the precipitation reconstruction.

Rain gauge	Altitude [m a.s.l.]	Lat N	Long E	Period of operation
Coritis	641	46°20′	13°23′	1925–1967; 2002–2012
Saletto	506	46°24′	13°22′	1924–2012
Žaga	353	46°21′	13°29′	1961–2012
Resia	492	46°21′	13°17′	1924–2012
Stolvizza	579	46°21′	13°21′	1970–2012

3. Methods

3.1. Precipitation

Despite the availability of a very good data set (1955–2012) recorded at the Triglav-Kredarica (Slo) observatory at 2515 m ~~a.s.l. we~~ preferred not to use it because the region of Mt. Triglav in winter and summer has been observed to constitute a precipitation cluster by itself (Ceschia *et al.*, 1991). Considering the precipitation pattern around Mt Canin, we selected the pluviometric stations of Coritis, Saletto, Žaga, Resia and Stolvizza (Figure 3, Table 1) for the 1925–2012 period. The daily total accumulation values were spatially distributed using the inverse distance weighted (IDW) method (e.g. Chen and Liu, 2012; Nusret and Dug, 2012 •; Hasan and Croke, 2013 •). The weights for the periods in which some gaps of data were present were recalculated considering the values of the nearest station available. The weights were calculated using Equation (1)

$$w_i = \frac{d_i^{-2}}{\sum_{i=1}^{5} d_i^{-2}} \quad (1)$$

where d_i is the distance between the CEG and the location of the five pluviometric stations. The Canin Precipitation (from now called P_{Canin}) record was therefore created using Equation (2)

$$P_{\mathrm{Canin}} = \frac{\sum_{i=1}^{5} p_i w_i}{\sum_{i=1}^{5} w_i} \quad (2)$$

where p_i are daily precipitations amount in mm of water equivalent (mm w.e.) of each station. This procedure permitted the filling of the longest gaps. Another filter, linked to the effectiveness occurrence of precipitation, was also applied. Depending on the station considered for each one of the five periods (see Table 1), 0 mm w.e. were always considered to have fallen if no precipitation occurred for any given day in Coritis or Stolvizza.

In order to obtain the MAP of the glaciers area we corrected the obtained P_{Canin} using a mean vertical precipitation gradient of 0.2 mm a^{-1} m^{-1}, considering the vertical precipitations gradients map derived from PRISM (Parameter-elevation Regression on Independent Slope Model). The obtained precipitation data set at the glacier area was named P_{Cag}. The used gradient seems to be reasonable because it is comparable with the values of Tirol region and the South side of the Alps (Schwarb, 2000), and it is consistent with the mean snow vertical lapse rate of 0.15 m × 100 m^{-1} estimated by Barbolini *et al.* (2006) for the Julian Alps. Moreover Manzato *et al.* (2013), analysing a subset of cases 'above mean' (more significant snowfalls) during three winters from 2010 to 2013, found a specific linear fit equation for Sella Nevea area having a slope of 0.32 m × 1000 m^{-1}.

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3.2. Air temperature

In order to obtain a temperature data set at an altitude comparable with the Canin glaciers we used a linear regression method, interpolating monthly data of the only two stations located above 1800 m a.s.l. (LL, 1837 m a.s.l. Figure 3, and Triglav-Kredarica 2537 m a.s.l. Figure 1) for the period 2000–2012 when the data gaps were not common. Successively we calculated the monthly mean temperature lapse rate (TLR). A low pass filter (30 days simple running mean) was applied to the mean monthly TLR in order to infer the mean daily TLR. The daily TLR were thus used to estimate the daily mean temperature at the altitude of the Canin glacier. To validate the daily mean data temperature of Canin glacier area, we correlated the modelled data with those recorded close to the glacier at an altitude of 2200 m, for the only available year (2012), thanks to the new AWS here installed in the fall 2011 (Canin AWS, 'a' in Figure 1). Moreover, for the same year, the radio-sounding temperature data set of Udine Campoformido station (16044-LIPD) was used to calculate the instant daily TLR (G) according to Equation (3)

$$G = 10^2 \left(\mathrm{AT}_{g850} - \mathrm{AT}_{g700}\right) \left(h_{g850} - h_{g700}\right)^{-1} \quad (3)$$

where AT_{g850} and AT_{g700} respectively represent the air temperature observed at 12 UTC at the geopotential heights of 850 and 700 hPa, while h_{g850} and h_{g700} represent the altitude, in metres above sea level, of the 850 and 700 hPa geopotential height. Therefore, with the Equation (4), the estimated temperature at the elevation of 2200 m a.s.l. in the free atmosphere was found (T_{2200})

$$T_{2200} = \left[G \left(2200 - h_{g850}\right) 10^{-2}\right] - \mathrm{AT}_{g850} \quad (4)$$

Applying the obtained TLR to all the historical daily records of temperatures measured since 1955 at Triglav, considering obviously the altitude difference (317 m) between Triglav and the Canin glacier area, a 58 years long record (1955–2012) of daily temperatures for the Canin glacier area was obtained (Canin_{2200}).

Finally, in order to extend back in time the data set, the Canin_{2200} was furthermore correlated with the mean monthly temperature measured at Villacher Alpe (VA, Austria, located 32 km northeast of Canin, Figure 1) belonging to HISTALP database (Auer *et al.,* 2007) thus calculating the TLR between Canin glacier area (2200 m a.s.l.) and VA (2140 m a.s.l.).

3.3. Glacial evolution

Glacier terminus fluctuations were analysed from 1920 to 2012, in order to evaluate the glacier response (i.e. retreat *vs* advance) and to calculate the rates of these changes. These data have been collected from a network of ground control points (GCPs) located on the glacier fore-field without interruptions, providing a data set of the glacier evolution for the last 92 years (CGI 1920–2012). The older data started since 1896 were not used here because there were some gaps due to the First World War (1914–1918) and because the previous authors used different GCPs not well correlated with the new ones. Several years, especially between 1960 and 1981, are referred to the distance between the snow cover at the end of the ablation season (snow line) and the GCPs, and not from the glacial ice and the GCPs.

In order to compare also the areal variations of all the glaciers and glacierets of the main cirque where CEG reside, we analysed old maps, aerial photos and high-resolution (25 cm) orthophotographs pictures (Regional Adm. of FVG), photogrammetry measures from archive images (Triglav Čekada *et al.*, 2014) and modern LiDAR surveys, obtaining eight areal extension between 1908 and 2011, of which four are related to the last 12 years (Table 4). These data are presented in Figure 13.

In addition, to evaluate the relationships between climate and glacial evolution, a linear regression between terminus fluctuations and the single climatic parameters, as well as a multivariate analyses (general regression model – GRM) among the terminus variations and all the available climatic parameters, were calculated through the software Statistica 9.0.

4. Results

4.1. Precipitation

The modelled P_{Canin} record has been compared with the original records for each of the five selected stations, giving R values between 0.89 (Saletto) and 0.99 (Coritis). The P_{Cag} values were tested with the only data set available in the area above 1800 m a.s.l., although limited to short time (2008–2012, and only during the ablation period between May and October) recorded at LL. A very high correlation ($R = 0.96$ and slope $= 0.93$) between measured values and P_{Cag} has been obtained as shown in Figure 4 confirmed the good quality of P_{Cag} data set.

Assuming that P_{Cag} were representative of the precipitation in the Canin glacier area for all the year, the

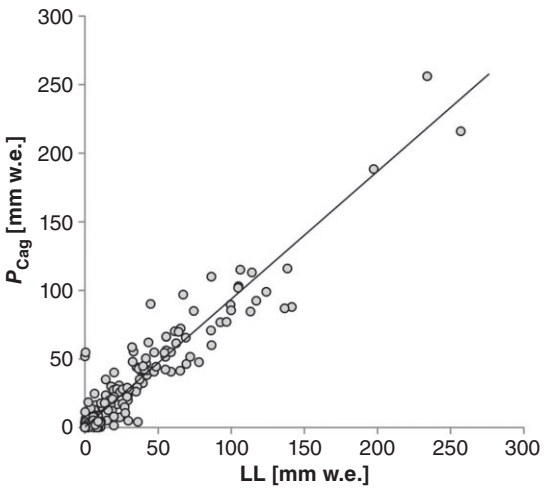


Figure 4. Correlation between mean daily precipitation measured during the ablation period from May and October at LL and the modelled PCag for the same period between 2008 and 2012.

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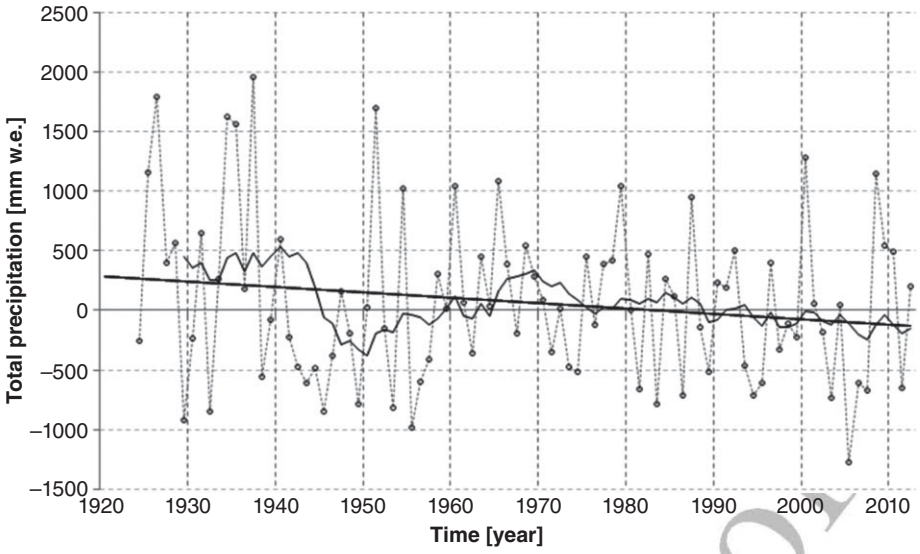


Figure 5. Pattern of • P_{Cag} anomaly (1924–2012) calculated with respect to the 1981–2010 mean. The black solid line represents a 10-year running mean, while the light solid line is the linear regression for the period.

1924–2012 period showed a general decreasing trend (45 mm decade^{-1}, Figure 5) with a dryer period in the 1940s and a much wetter period between 1924 and 1940 and in the 1960s. The inter-annual fluctuations are quite large, especially between 1924 and 1955 and during the last 13 years.

Analysing the seasonal trends of the total precipitations (Figure 6) it is possible to observe as only winter precipitations are slightly increasing, whereas the greater decrease is in summer. This pattern is reflected also in the accumulation and ablation period with the latter characterized by a stronger decrease than the former. The winter 1950–1951, with more than 2200 mm w.e. (about 1500 mm w.e. more than the average 1981–2010), represents an exceptional event and in many local chronicles, information about that exceptional snowy winter are also reported. P_{Cag} data set averaged over the period 1981–2010 shows a MAP of 3335 mm w.e., with February the driest month (180 mm w.e.) and November the wettest month (460 mm w.e.).

4.2. Temperature

The very high correlation between the mean daily air temperature between LL and Triglav ($R = 0.97$, Figure 7) allows to calculate the mean air temperature at the Canin glacier area (2200 m a.s.l., data set named Canin$_{2200}$). This temperature data set has been tested with the data measured at the Canin AWS, although for the only available year (2012). Despite of the short period of testing, the excellent correlation ($R = 0.99$), and also the excellent correlation ($R = 0.98$) with the daily mean air temperatures in the free atmosphere, obtained with the radio-sounding allows us to be highly confident with the Canin$_{2200}$ data set.

Moreover, the high coherence between the Canin$_{2200}$ and the VA series for 1955–2008 ($R = 0.995$) confirmed the reliability of this method for reconstructing the Canin$_{2200}$ data set. The calculated monthly time lapse rate between Canin$_{2200}$ and VA (Table 2) extrapolated from the 1955–2008 period has been subsequently applied to the 1851–1954 record, obtaining a 161 years long record (1851–2012) at the Canin glacier area (Canin2200VA, Figure 8). The reconstructed MAAT for the Canin glacier area shows an increasing trend (0.11 °C decade^{-1}) with a strong acceleration in the last decade (0.7 °C). Since the decade 1941–1950, the mean air temperature has been always above 0 °C and after 1984 there were no more single years with MAAT below 0 °C. The coldest decade was the 1851–1860 (−0.8 °C), while the warmest was the last one (+1.9 °C). The increasing trend is almost equally distributed during the year (Figure 9), only the summer mean (JJA) is lower than 0.1 °C decade^{-1} while all the other seasons are above this threshold. In Figure 9(c) are remarkable also the exceptional hot summer of 2003 (11.3 °C, which represents an anomaly of 3.0 σ in respect to the average 1981–2010) followed by the summer 2012 (10.1 °C) and the spring 2006 (5 °C). The most remarkable cold events are represented by the fall 1912 and the winters 1929 and 1956.

Moreover, since 1955 when we can consider daily mean data, the thawing degree days (TDDs, °C day^{-1}) trend are almost stable except for summer and the ablation season that are strongly increasing (Figure 10). The TDD trend is characterized by the stronger increase of temperature mainly during the summer as shown in Figure 10 and above all since 1978. The Canin glacier area data set, averaged over the period 1981–2010, shows a MAAT of 1.1 ± 0.6 °C, with February the coldest month (−6.0 ± 2.9 °C) and July the warmest month (9.2 ± 1.3 °C).

4.3. Glacial evolution

The Canin glacier showed a total recession of 84 m and an upward shift of the terminus of about 40 m since 1921.

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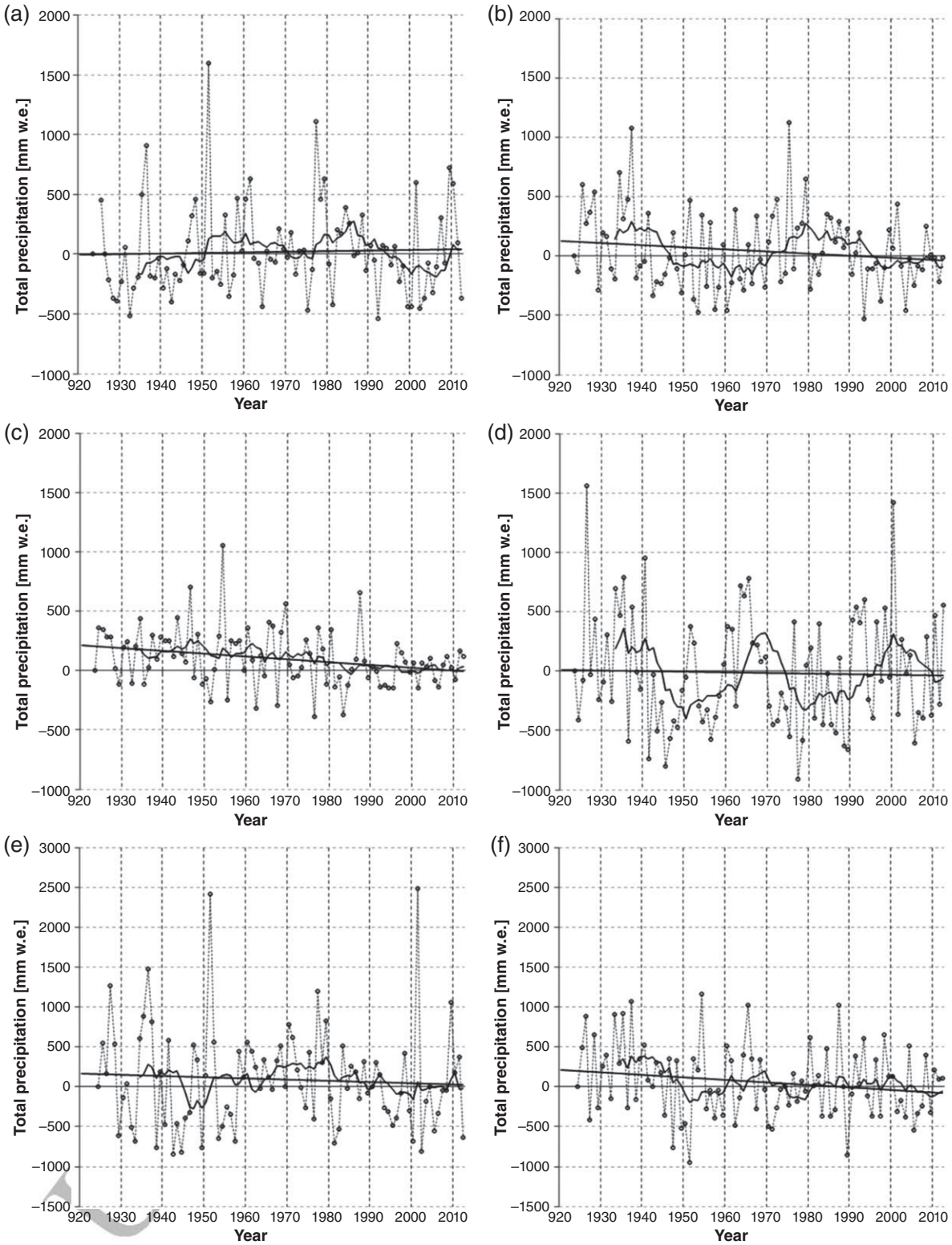


Figure 6. Seasonal trends of total precipitation anomaly with respect to the 1981–2010 mean: (a) winter (DJF); (b) spring (MAM); (c) summer (JJA); (d) fall (SON); (e) accumulation season (NDJFMA); (f) ablation season (MJJASO). Thick black line represents a 10-year running mean, while the light black line is the linear regression for the period.

The glacial fluctuations of the terminus showed an interesting pattern (Figure 11) with a substantial stability between 1946 and 1985 interrupted by some years of slight regression (1962–1965; 1974–1977; 1980–1982) followed by a more severe recession in the 1990s and by the successive slight increase between 2007 and 2011.

Considering the mean of the terminus variations in each decade (Table 3) we can see that from 1951 to 1980 we recorded a long stability phase followed by the more

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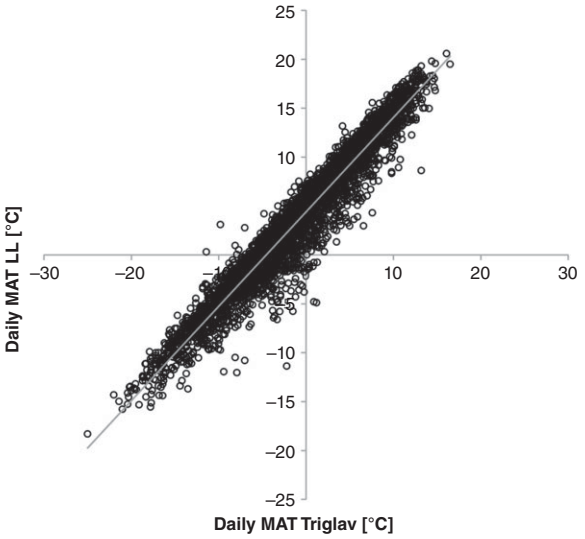


Figure 7. Correlation between daily mean air temperature at LL and Triglav (period 2000–2012; 4366 days).

Table 2. Mean annual glacial terminus variation for each decade and its standard deviation.

Time frame	Mean [m]	Standard deviation [m]
1921–1930	−2.8	2.2
1931–1940	0.7	1.8
1941–1950	−1.8	4.8
1951–1960	2.7	1.3
1961–1970	0.0	6.2
1971–1980	−0.1	3.3
1981–1990	−3.0	5.4
1991–2000	−4.6	1.0
2001–2010	0.9	2.6

important recession between the 1980s and the 2000s. On the contrary, the last decade was characterized by a slight advance with the peak of 2010 (+6.9 m) that is one of the three larger advance recorded since 1921.

Since 1998 and even in the last decade, no evidence of crevasses or other indications of downward movement were reported probably because the glacier mass was too thin to be dynamically active.

5. Discussion

5.1. Climate

Considering the Great Alpine Region (GAR), Brunetti *et al.* (2006) highlighted that precipitation trends showed an opposite long-term behaviour between Northern and Southern sub-regions with the former sub-regions becoming wetter and the later dryer. The most marked split in about the past 140 years is present between the NW and the SE areas. Our results show a decreasing trend in the Canin area with a yearly reduction of about 10% in the last 90 years, confirming the results from the Central Alps given by Brugnara *et al.* (2012). Both the maximum in the 1930s and the minimum in the late 1940s of the Canin record are also present in the GAR data set. On the seasonal basis, Canin record shows different patterns with respect to GAR, above all in summer and in spring. Indeed, in summer, instead of the minimum of the 1940s, a quite continuous decreasing trend it is present with a greater variability during the 1940–1990 period. In spring, the minimum observed in the GAR in the late 1940s, appear prolonged till the late 1960s in the Canin record and it is again present in the late 2000s.

As already highlighted for all the GAR area, temperatures are characterized by a strong increase. The maximum during the last 10–20 years likely represents the highest temperature ever recorded in the last 250 years, as observed for the GAR. The most remarkable event at seasonal level is represented by the summer 2003 which characterized all the GAR with the highest anomaly in the NW (+4.9 °C) and the lowest in the NE (+3.9 °C) (see, e.g. Schär *et al.*, 2004; Brunetti *et al.*, 2006, 2009).

The comparison between temperature and precipitation records gives evidence of a tendency to display a clear opposite behaviour in spring and, especially, in summer with increasing temperature and decreasing precipitation.

5.2. Glacial evolution

In order to understand if the recent evolution of the CEG is representative of a more regional behaviour or if it is strongly related to the site characteristics, we compare our data with the data available from some very small glaciers (Figure 12) of southern Austria (Eiskar) (Hohenwarter, 2013), Slovenia (Zeleni Sneg – Triglav) (Triglav Čekada *et al.*, 2012, 2014), Montenegro (Debeli Namet) (Hughes, 2007; Hughes, 2009; Grunewald and Scheithauer, 2010; Hughes *et al.*, 2011; Djurovič, 2012) and the Swiss Alps (Pizol) (Glaciological Reports (1881–2011); Huss, 2010; Fischer *et al.*, 2012; Fischer *et al.*, 2013). Also in the Prokletjie mountain of Albania, some very small maritime cirque glaciers have been detected at an altitude of about 2000 m (Milivojevič *et al.*, 2008; Hughes, 2009). Indeed it is possible that these glaciers are some of the lowest altitude glaciers (1980–2420 m) at this latitude (42.5°N) in the world (Hughes, 2009), here not taken into account due to the too short data record. Available and measured data are often referred to areal extent variations and not terminus fluctuations, except for the Pizol and Eiskar glaciers, not continuous and for a slightly shorter period.

These glaciers are all very small (between 0.01 and 0.1 km^2) and located on the north-northwestern slopes along a transect between SE and NW (Figure 12) from the south eastern Alps to the south eastern Europe . For comparison along this transect we chose a glacier on the northern side of the Alps (Pizol glacier). Among these glacial bodies, the CEG is located at one of the lowest altitudes, in fact only the Debeli Namet glacier (2000 m a.s.l.) is located at lower altitude of CEG and it is one of the lowest glaciers, at that latitude, in the Northern Hemisphere (Hughes, 2008, 2009). This cirque glacier is the southernmost of the transect in the Durmitor massif of Montenegro (Grunewald and Scheithauer, 2010) and

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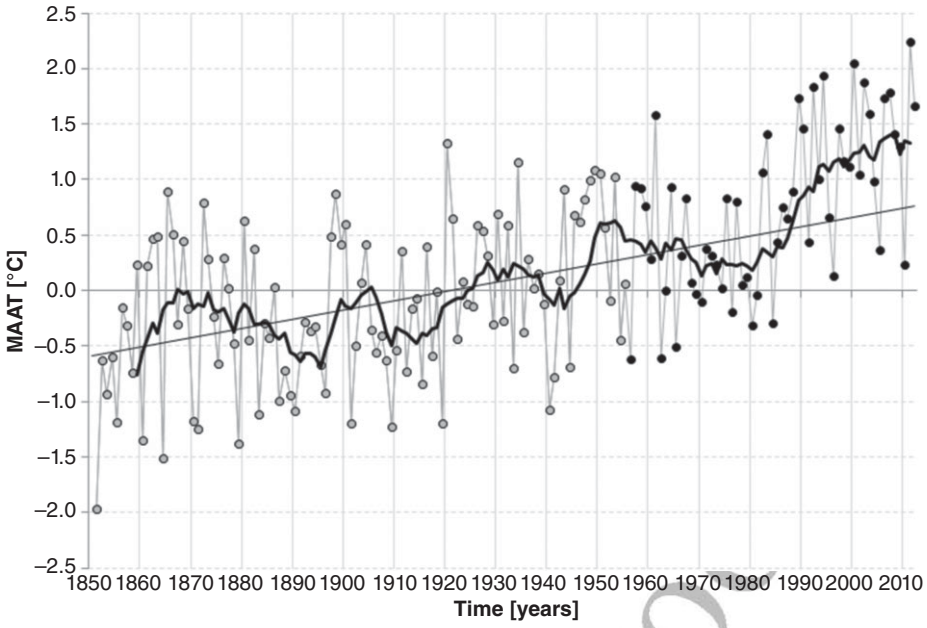


Figure 8. Reconstructed MAAT for the Canin glacier's area since 1851 through the VA data set (Canin2200VA, grey dots), and Triglav data set ($Canin_{2200}$, black dots). Bold black line represents a 10 years moving average, while the thin black line is the linear regression.

is in similar climate conditions of CEG with high MAP (2500–3000 mm) and quite warm MAAT (0.9 °C). Closer to CEG area (32 km) the Zeleni Sneg – Triglav glacier (Slovenia) is located at an altitude comprised between 2400 and 2500 m (Triglav Čekada *et al.*, 2012) in colder and dryer climatic conditions with a 1981–2010 MAP of 2060 mm and a 1981–2010 MAAT of −1.0 °C. Slightly northward the Eiskar, the southernmost glacier of Austria receives roughly the same annual amount of precipitation of Zeleni Sneg – Triglav (Hohenwarter, 2013). For comparison, on the NW side of the Alps along the transect, the Pizol glacier is located at the highest altitude (2630–2789 m a.s.l., Huss, 2010) and suffers the driest and coldest conditions of the transect. The 1981–2010 MAP of Bad Ragaz (496 m a.s.l.; open access data MeteoSwiss), located in the valley 10 km east of the glacier, is equal to 850 mm w.e., while applying the normal vertical time lapse to the 1981–2010 MAAT, we obtained a MAAT of about −4.0 °C at the glacier's altitude.

With the available data we can compare the trends of their areal changes (Figure 13) and the changes of their terminus fluctuations (Figure 14).

The Debeli Namet glacier revealed a different trend of areal changes sometimes even opposite to CEG especially since 2006 when the first experienced a progressive shrinkage after a rapid but consistent expansion phase during the period 2003–2006 mainly due to the strong increase of winter precipitation and cooler summers (Hughes, 2008).

On the contrary, CEG had a similar evolution to the Triglav glacier at least until 1988, when the former suffered a much more pronounced recession.

During the last 40 years also the Eiskar glacier revealed a similar behaviour to CEG, even if the recessional phase of the 1990s and early 2000s seems more damped.

For comparison the Pizol glacier showed a much more contrasted pattern, especially concerning the timing in the recessional phases. This is particularly evident in the minimum of 1964 (Figure 14) that occurred 18 years later then that one of 1946 of Canin. Also the two secondary minima of 1934 and 1973 are delayed with respect to Canin ones. The dramatic recession phase of the last three decades seems to start simultaneously in 1985 for both Pizol and Canin, even if the first experienced a short stability phase in the 1990s.

Moreover, the long stability and recovery of CEG between 1945 and 1985 is unrecorded of on western Italian Alps (e.g. Diolaiuti *et al.*, 2012) and central Italian Alps (Cannone *et al.*, 2008; Carturan *et al.*, 2013a •) and it is quite a rare feature in the world occurring only in some maritime glaciers of Norway (Nesje *et al.*, 2008). This peculiar characteristic of the Julian Alps is likely related with a general pattern of winter precipitation higher than the average recorded in the same period (Figure 11).

AQ8

5.3. Relationships between climate and glacial evolution

Among the different climatic parameters it is remarkable that there is an inverse correlation between precipitation and mean air temperature during summer and ablation periods. Only winter and accumulation season precipitation have a statistically significant Spearman correlation rank (as shown in Table 4). If instead we consider the GRM (backward stepwise selection) to analyse the multivariate possible relationships among all the considered climatic parameters for the 1925–2012 period, the glacial terminus variations are influenced only by winter precipitation ($F = 4.45$; $p = 0.038$). This is in agreement with what supposed also by Carturan *et al.* (2013b, 2013c) for the

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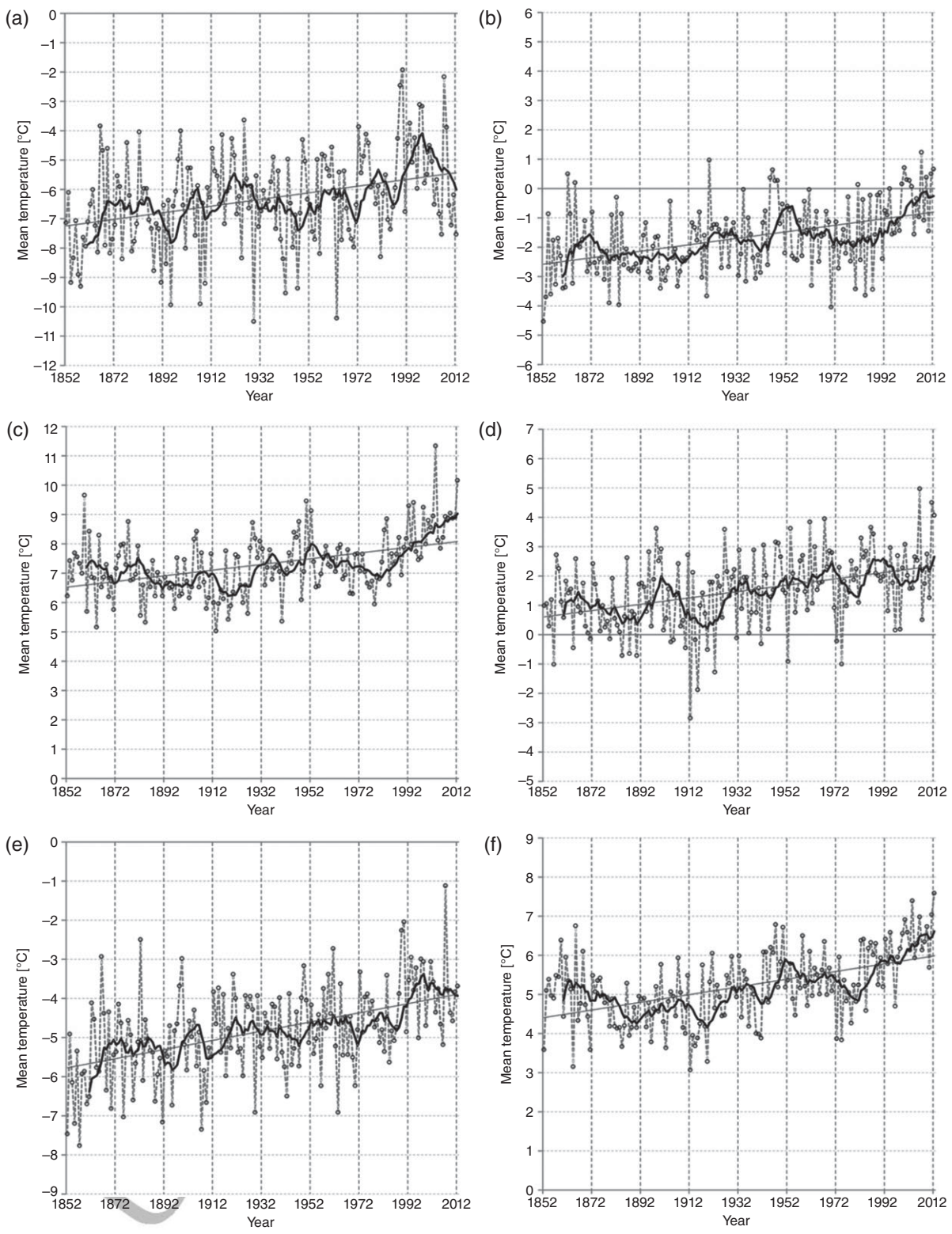


Figure 9. Seasonal trends of air temperature: (a) winter (DJF); (b) spring (MAM); (c) summer (JJA); (d) fall (SON); (e) accumulation season (NDJFMA); (f) ablation season (MJJASO). Thick black line represents a 10-year running mean, while light black line is the linear regression for the period.

Montasio Occidentale glacier, a very small glacier close to the Canin study area. The high sensitivity to winter precipitation of CEG opens new perspectives for the alpine area and the Balkans showing as glaciers, in a warm–wet climate, can advance with positive mass balance if the effect of increased melting caused by higher temperatures is exceeded by a greater rate of increased snow accumulation. Giorgi and Lionello (2008) • and Gao *et al.* (2006) forecast an increase in winter (DJF) precipitation of more than 25% for the 2071–2100 period with respect to 1961–1990.

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Table 3. Areal variations of Debeli Namet and Zeleni Sneg – Triglav glaciers compared with Canin.

Year	Surface [km^2] Debeli Namet MONTENEGRO	Year	Surface [km^2] Zeleni Sneg – Triglav SLOVENIA	Year	Surface [km^2] Canin ITALY
1954	0.022	1897	0.22	1893	0.41
1971	0.04	1900	0.30	1908	0.43
1981	0.04	1937	0.27	1948	0.38
1993	0.02	1946	0.14	1971	0.16
1997	0.02	1948	0.16	1975	0.16
1998	0.01	1950	0.13	1986	0.25
2003	0.02	1952	0.13	2003	0.05
2005	0.04	1956	0.14	2006	0.06
2006	0.01	1958	0.14	2011	0.14
2007	0.04	1959	0.11		
2008	0.03	1962	0.22		
2009	0.03	1964	0.10		
2010	0.03	1973	0.12		
2011	0.03	1976	0.18		
		1977	0.22		
		1979	0.24		
		1982	0.11		
		1989	0.07		
		1992	0.04		
		1995	0.03		
		1997	0.03		
		1999	0.01		
		2000	0.01		
		2003	0.01		
		2007	0.01		
		2011	0.02		

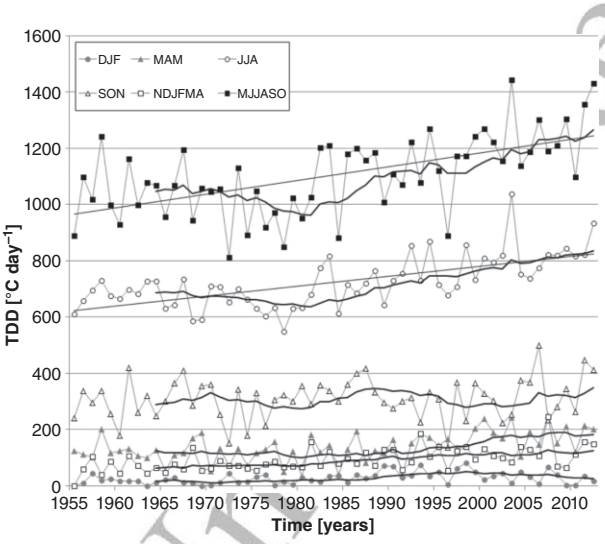


Figure 10. TDD (°C day^{-1}) since 1955 at Canin glacier's area. Only summer (JJA) and ablation period (MJJASO) are increasing significantly. Bold black line represents a 10-year running mean, while the thin line is the linear regression for the period.

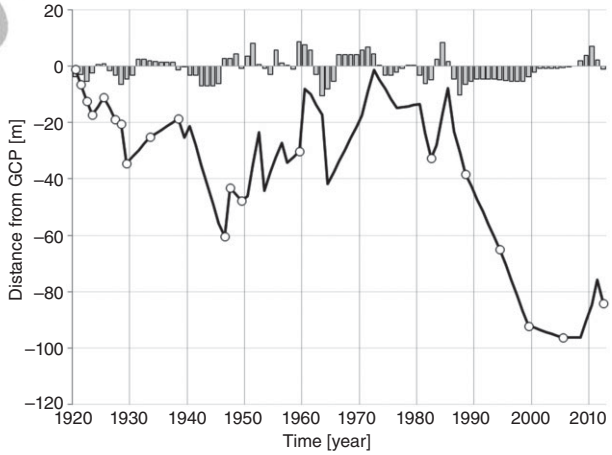


Figure 11. Glacial terminus fluctuations since 1920. In the upper part of the graph the black bars indicates the annual terminus variation in metres, while in the lower part it is reported the cumulated distance of the glacial terminus from the GCPs (solid line). The empty dot are the measurements referred to a snow free glacier's surface and therefore more accurate than the other years.

In the short term, Kirtman *et al.* (2013) forecast an increase of winter precipitation up to 10% in the 2016–2035 period. Assuming that the observed long-term temperature trend at CEG will not change in the future, we can forecast a period of glacier stability or even a small glacier advance in this sector of the European Alps, instead of a rapid and complete disappearance of these small glaciers under global warming conditions.

6. Conclusions

The climate of Canin area in the last 90 years showed a general decreasing trend (10%) of MAP and an increasing trend of MAAT (0.1 °C decade^{-1}). In summer, the decreasing precipitation's trend is almost continuous since the 1940s, while there are not significant long-term trends for the other seasons. Moreover, from the late 1940s to the 1980s many winters showed precipitation above

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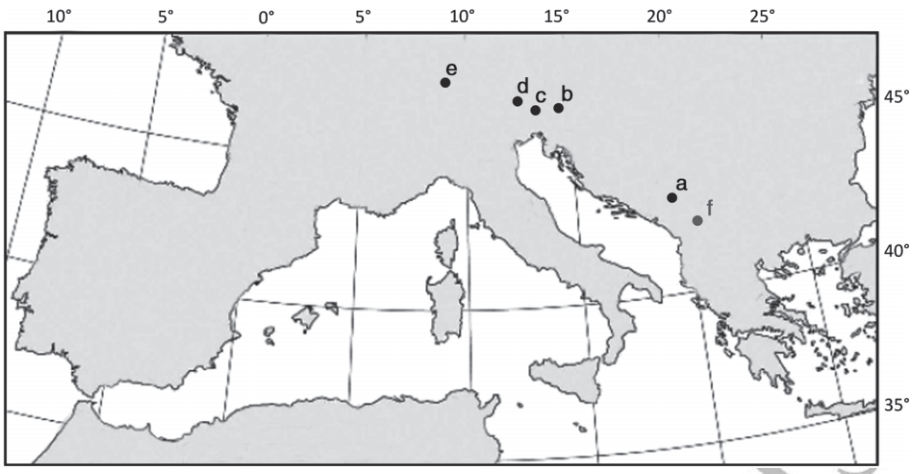


Figure 12. Location of the very small glaciers along a virtual transect SE–NW. (a) Debeli Namet (Montenegro); (b) Zeleni Sneg-Triglav (Slovenia); (c) Canin (Italy); (d) Eiskar (Austria); (e) Pizol (Switzerland); (f) location of Albanian glaciers not taken into account due to short-period data record.

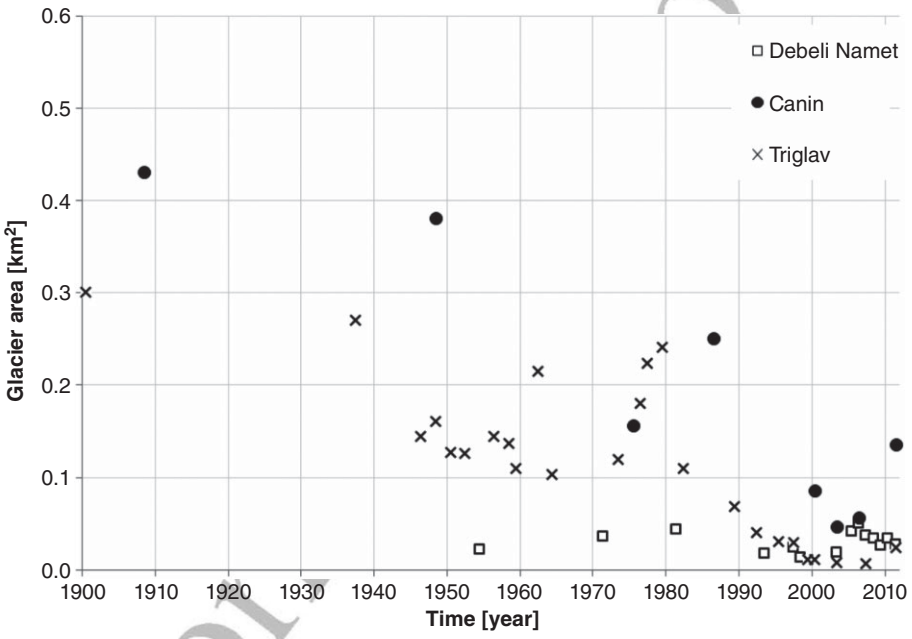


Figure 13. Areal variations since 1900 of Debeli Namet and Zeleni Sneg – Triglav compared with Canin.

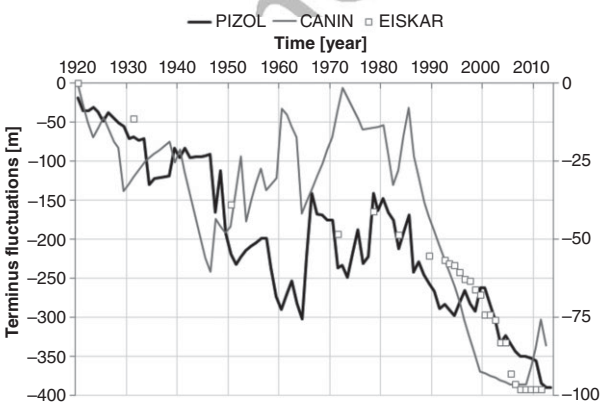


Figure 14. Canin, Eiskar and Pizol glacier terminus fluctuations (metres) since 1920. See grey right *y*-axis for Canin and Eiskar glaciers.

average. Mean annual and all seasonal air temperatures showed an increasing trend, particularly strong in summer since 1980s (0.7 °C decade^{-1}). In this scenario, the CEG showed a rather different pattern of terminus fluctuations in respect to the majority of the glaciers in the Alps and in the world. Indeed, a substantial glacier stability phase was observed between 1945 and 1985 at CEG. Moreover, the CEG is influenced mainly by winter precipitations as shown by the GRM and therefore the frequent years with above average winter precipitation in the 1940–1985 period could be the reason for this glacier stability. If this relationship between precipitation and glacier dynamic will continue in the future, considering the climate projections that forecast an increasing winter precipitation up to 10% over the Alps in the next decades (Kirtman *et al.*, 2013), and the warming trend will be

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Table 4. Spearman correlation rank among different climatic parameters and between glacial terminus fluctuactions (GTF) and the same climatic parameters since 1925.

	P (DJF)	P (NDJFMA)	MAAT	T (JJA)	T (MJJASO)	T (MAM)
P (DJF)	1.000	**0.541**	−0.024	−0.105	−0.096	−0.070
P (MAM)	0.145	**0.519**	−0.140	−0.147	−0.183	−0.175
P (NDJFMA)	**0.541**	1.000	−0.020	−0.078	−0.096	−0.046
P (JJA)	−0.020	0.040	−0.197	**−0.375**	**−0.294**	−0.069
P (MJJASO)	−0.030	−0.030	**−0.295**	−0.194	**−0.368**	**−0.285**
MAP	**0.249**	**0.459**	0.178	−0.166	**−0.244**	**−0.225**
GTF	**0.432**	**0.348**	−0.067	−0.108	−0.099	−0.127

In bold are the correlations that are statistically significant ($p < 0.05$). P (DJF), winter precipitation; P (MAM), spring precipitation; P (NDJFMA), precipitation of accumulation season (November–April); P (JJA), summer precipitation; P (MJJASO), precipitation of ablation season (May–October); MAP, mean annual precipitation; MAAT, mean annual air temperature; T (JJA), mean summer air temperature; T (MJJASO), mean air temperature of ablation period (May–October); T (MAM), mean spring air temperature.

comparable with what observed in the last century, we can forecast a new glacier stability phase or even years of possible advance in the very small glaciers of this sector of the Alps.

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