REPLY TO THE REVIEWERS

We would like to thank both Reviewers for their careful and constructive reviews of our paper. In response to their suggestions, we did the following main changes to the manuscript:

1) we added a figure showing the monitoring network and the surface topography of the nine analysed glaciers (Figure 2)
2) we modified the last figure (Figure 8), adding the cumulated residuals, as suggested by the Reviewer 2
3) we modified the structure as suggested by the Reviewer 1, adding a Section with the available datasets, separated from the Methods
4) we added error estimates in mass balance measurements (Section 3.1)
5) change points in time series have been identified using specific statistical tests
6) we added a discussion on the spatial representativeness of analysed glaciers
7) we quantified the relationship between seasonal and annual NAO and the seasonal and annual components of the mass balance, comparing the results from the Italian glaciers with those from other nations in the European Alps. A table was added reporting the statistics, and a discussion was added in section 4.2
8) the references suggested by the Reviewers were added to the reference list
9) we implemented the suggested changes and answered to the specific comments made by the reviewers, as detailed in the following of this document. The comments are reproduced in italic while the authors responses are reported right below. Line and page numbers are referred to the discussion paper.

Reviewer 1

R1 – 1: This paper presents a comprehensive analysis of the mass balance data acquired on all Italian glaciers since the beginning of the measurements. The authors compile data covering one to five decades that mostly have a seasonal resolution and interpret changes in mass balance in connection to climatic forcing (temperature and precipitation). Data from long-term monitoring programmes are often difficult to be published and performing innovative science based on them is challenging. The authors do a good job in exploiting the full data basis for Italian glacier mass balance to come up with sound conclusions and reasonable recommendations for the future. Nevertheless, I somewhat miss the "breaking news" in this study. Many of the findings are not actually new and the authors can often just confirm what has been said earlier. Of course, this is a problem which is not trivial to be addressed provided the availabledata that are discussed. However, by slightly shifting the focus to the more exiting and novel results I have the impression that this paper could considerably gain in quality and scope. This would mean shortening the article in certain places and providing more detailed analysis at others.

In our opinion, the value of this paper lies in the joined presentation and analysis of the mass balance data from the Italian glaciers, which had not yet been carried out. We tried improving the paper as suggested, focusing on the parts recommended by the two reviewers.

R1 – 2: I see several additional important and interesting aspects that could at least be partly addressed by the authors: Data quality: An integrated interpretation of a data set as the one presented in this paper crucially relies on the quality of the data. At present, however, only very little is said about this point and no specific analyses are performed (uncertainty of the data based on general literature values). As much as I know, no homogenization (e.g. by comparing geodetic and glaciological mass balances) has been performed for most of the Italian glaciers. To ultimately increase the value of a data set, assessing the quality and performing a homogenization would be of utmost importance and should actually be performed before interpreting the data in a climatological context. I fully understand that this is not feasible in the frame of this study but the authors might still consider to dedicate some discussion or even preliminary analyses (e.g. based on published results) regarding this aspect.

Published accuracy estimates and available comparisons between the geodetic and direct methods have been added in section '3.1 Mass balance measurements and calculations'.

R1 – 3: Information on investigated glaciers: Related to my point above, I also missed more detailed information on the sites. There are only tiny maps showing the individual glaciers that do neither contain contour lines nor the distribution of the measurement network. For such an overview study, it would be important to present the monitoring strategy so that the reader can judge the context of the data.

A new figure was added, reporting the measurement network and the contour lines for each of the nine analysed glaciers (Figure 2).

R1 – 4: Representativeness of glaciers: In my opinion, a central question of such an integrated analysis would be the representativeness of the individual series for a larger region (e.g. the Italian Alps). This would be very valuable for other scientists looking for time series that well describe the spatio-temporal mass balance variability and are not biased by local effects (such as Careseer, see Carturan et al., 2013). Unfortunately, this point is only marginally addressed in the paper. Given the approaches presented here, this aspect would be possible however to be investigated in more detail. This might allow some useful recommendations for the glaciological community.

Considerations on the spatial representativeness have been added in Section 4.1, based on available geodetic mass balance calculations.

R1 – 5: Structure: The description of the data and the study sites is placed in the Methods section, which is not ideal. These chapters definitely need to be separated, especially for a paper that principally relies on a strong data basis.

Ok, modified as suggested.

R1 – 6: Detailed comments: Page 5853, line 20: Without knowing about the distribution of the measurements (figure) the point density is difficult to be interpreted

Please, see the reply to comment R1 – 3

R1 – 7: Page 5855, line 10: Identical methods used for temperature and precipitation extrapolation? Partly unclear.

Modified to improve clarity

R1 – 8: Page 5855, line 29: Several studies have already indicated that at least some of the nine WGMS reference glaciers are not (not anymore) actually representative for the European Alps. This might influence comparisons as the one presented here.

A sentence was added in Section 4.1 to highlight this aspect

R1 – 9: Page 5861, line 20: When discussing potential NAO effects it would be important, in my opinion, to be more quantitative: The present statements are fully qualitative. If really entering this topic the authors should be more specific and provide statistical numbers and evaluations in the context of their data.

We analysed the correlation between the NAO and the seasonal/annual components of the mass balance. Please, see the reply to the comment R2 – 25.

Reviewer 2

R2 – 1: General comment. L. Carturan and co-authors provide analysis of glacier-wide mass balance times-series for 9 glaciers in the Italian Alps covering a period of record from 10 to 47 years. The link of the mass balance variations to temperature and precipitation chronicles is then investigated. Annual balances are reasonably reported to be highly connected to winter (October-to-May) precipitations and summer (June-to-September) temperatures. For the longest available records, the increase in mass loss observed since the 1980's is related to the warming and lengthening of the ablation season. Changes in correlations between mass balances and summer temperatures/winter precipitations is interpreted as possible milder accumulation seasons in the last years of the time-series, but the changes in glacier topography in response to climate cannot be ruled out.

The main value of this paper is to gather the longest mass balance records available in the Italian Alps and to propose a joint analysis. Moreover, I find the examination of the changes in correlation interesting as climate cannot be assumed in steady state in the time series analysis. Nevertheless, the authors hardly achieve in drawing new and firm conclusions on how the regional and larger-scale climate drives glacier mass changes. Despite the reported material is instructive and of quality, the paper is not enough innovative, and below and in my substantive comments I have suggested some way to strengthen it. I have three key suggestions below.

Despite mountain glaciers being recognised as excellent indicators of climate change, this paper demonstrates once again that inferring the climatic signal from a glacier mass balance series is not an easy task:

1°) A first reason is the intrinsic limit of glacier-wide balance series which includes both the climate signal and the effect of the changing glacier topography in response to climate. A time signal free from geometry changes and site effects should be first extracted from the series before investigating the potential link with the climate.

2°) Secondly, the time-structure of the extracted temporal signal should be analysed quantitatively to detect trends, change point in mean and variance with appropriate empirical statistical tests, or modern and advanced treatment like Bayesian inference.

3°) Third, the authors should take advantage of the stratigraphic-floating date system to analyse how the ablation duration may have changed from year–to–year; and subsequently derive the rates in ablation which is a way to quantify surface energy fluxes responsible for melt.

Different issues can be addressed to extract the climate signal:

- The issue raised by Elsberg and others (2001) of computing a mass balance referred to a constant topography. This requires the time change of the area and elevation of the glacier surface.
- Use point balances as adopted by Huss and Bauder (2009), or Vincent et al., (2004) which removes the effect of the surface change but still requires accounting for the lowering of the surface elevation of the glacier.
- Adopt a variance decomposition to separate the overall annual effect from the spatial variability at the glacier surface (Lliboutry, 1974; Rasmussen 2004; Eckert et al., 2011); this requires also accounting for elevation changes.

We agree with the Reviewer that part of the glacier response in terms of annual mass balance depends on the geometric adjustments. The methods for extracting the climatic signal, however, require information on the area and elevation changes, and/or the availability of point mass balances, in the observation period, which unfortunately are not available for most of the glaciers analysed in this study. The change points in the time series of mass balance have been extracted using statistical test, as suggested (see the reply to comment R2 – 15 for details). The dates of the surveys in the floating-date system do not provide useful information on ablation duration, because they have been selected based on weather conditions, accessibility of the glaciers, availability of personnel, and they did not necessarily correspond to mass balance minima.

R2 – 2: Points/limitations of minor extent are: Meteorological series are reconstructed locally from a linear composition of climatologies (constant spatial fields) and anomalies (uniform temporal deviations). Implicit is that spatial fields are stable in time and that the climate is in steady state which is a strong hypothesis.

Spatial fields in the reconstructed dataset are not stable in time. In this case only single points referred to the monitoring sites were reconstructed, but if a high resolution grid were reconstructed for e.g. the last 60 years, the result would be that spatial gradients are not constant through time because also temperature anomalies (year-to-year variability) and the long-term tendencies (trends) are characterized by a spatial gradient captured by the interpolation of the temporal component. This make the spatial gradients in climate normals not constant in time. As an example let us suppose that the vertical gradient in temperature climatology is of -0.65°C/km in 1960s and that from 1960 to 2010 there is a temperature trend which is strongest the highest is the elevation. In this case, if we extract the climate normal for the decade 2010s we will observe a vertical gradient which will be reduced with respect to the -0.65 observed in 1960s. The same is true in the other x and y components.

R2 – 3: Time-series in glacier-wide balance should be controlled and if necessary homogenized by the geodetic method (photogrammetry, laser scan or lidar altimetry) to discard any bias/trend that may corrupt the time signal and its link to climate.

The available comparisons between the geodetic and the direct methods have been added in Section 3.1. For the analysed glaciers, these assessments reveal that no calibration of direct mass balance results is required.

R2 – 4: Quantifying the link with NAO for the selected glaciers will be innovative.

We have analysed the correlation of the seasonal and annual mass balance components from the Italian glaciers and the NAO, describing the results in Section 4.2 and reporting them in Table 5 (see the reply to comment R2 – 25).

R2 – 5: There follow several detailed questions, comments, suggestions, and indications of minor flaws in the paper. Substantive comments. P5850-L22. This is true for glaciers at the melting point. For cold and polythermal glaciers, the atmospheric conditions (atm. temperature and precipitations) control the thermal regime (Hoelzle et al. 2011; Gilbert et al., 2012), and the mass balances of those glaciers are not directly connected to climate (see e.g. Vincent et al. 2007).

We agree that atmospheric conditions control the thermal regime of cold and polythermal glaciers, and that these glaciers (or upper glacier parts in the mentioned examples) respond in a different way to the same climatic forcing, compared to glaciers at the melting point. However, the mass balance of cold and polythermal glaciers is actually connected to climate (although in a different manner), and we prefer keeping the sentence as it is.

R2 – 6: P5851-L5. Use here and elsewhere in the paper the terminology "glacier-wide balance" as proposed by Cogley et al. (2011) to whom you refer appropriately.

Ok, corrected.

R2 – 7: P5851-L17. I would propose to add at the end of the sentence "reviewed and analysed jointly."

Ok, added.

R2 – 8: P5851-L22. It is not clear to me what non-linearity means here. Should the link between climate and glacier mass changes be a linear relationship? Is it rather meant that you are in search of a rupture (in mean or variance) in the mass balance time-series?

We meant feedbacks, corrected.

R2 – 9: P5852-L6. Have the mass balance records been controlled by the geodetic method and eventually calibrated as recommended by Zemp et al. (2013)?

This was done for three glaciers and the results indicate that calibration is not required. A sentence was added at the end of Section 3.1

R2 – 10: P5854-L13. In search of the max/min for the winter and annual balances, the time system in which the mass balances are measured rather refers to the stratigraphic system. An important implication of this floating-date system is the opportunity to retrieve summer ablation duration and rates, and analyse how these may have changed from year to year along the record.

Please, see reply to the coment R2 – 1.

R2 – 11: P5854-L16. Regarding error estimations of glacier-wide balance measurements, if not based on a throughout analysis for each mass balance record, I would recommend to use the value of 340 mm w.e. yr-1 provided by Zemp et al. (2013) from a data set of 14 glaciers in Europe.

In the revised manuscript we have reported the range of errors indicated by the investigators in charge of the measurements (end of Section 3.1)

R2 – 12: P5854-L19 -to- P5855-L19. I understand that this method is basically a linear variance decomposition between space and time effects in weather data. This is a strong hypothesis at it assumes a steady state climate, i.e., steady spatial gradients along the analysed period. It would be interesting to *validate this assumption at, at least, a site in the vicinity of one of the studied glaciers where a long record is available from a mountain weather station by a comparison with the reconstructed temporal series. Note that further in the paper, only correlations are in search in the time deviation signal. Then if the absolute (local mean) of the reconstructed time series is biased, it won't affect the correlations*.

The method is not a linear variance decomposition and, in particular, it does not assume a steady state climate because spatial gradients change along time, in agreement with the observed spatial gradients characterizing both long-term trends and year to year variability. The adopted interpolation methodology is widely used, documented and validated in the scientific literature (see quoted papers in the manuscript).

R2 – 13: P5856-L15. Here the limitation I mentioned in the general comments is critical. Glacier-wide, i.e. surface-integrated (averaged) balance series provided by WGMS are convolutions between climate signal and glacier geometry changes in response to climate (refer to e.g. Elsberg et al., 2001). This results in two main opposite feedback for retreating glaciers that concerns this study: ablation areas of strong negative budget are removed from the average balance, tending to make it less negative. Oppositely, a lowering of the glacier surface tends to force the surface energy balance in relation with altitudinal gradients. How these 2 feedbacks may or not compensate each other depends on each glacier (Huss et al., 2012), but generally contribute to an additional (non climatic) trend in the series. It is not clear how these 2 effects are to be differentiated in the present analysis. I would proposed to use a mass balance referred to a constant topography (Elsberg et al., 2001) or analyse point mass balances (Huss and Bauder, 2009; Vincent et al., 2004) or temporal signals retrieved from them using variance decomposition (Lliboutry, 1974; Rasmussen 2004; Eckert et al., 2011).

Please, see reply to the comment R2 – 1. We are aware of these issues, and discussed them at the end of the Discussion, where we comment the results of the moving correlation analysis between the mass balance series and the climatic variables, reporting the example of the Careser glacier.

R2 – 14: P5856-L18. I would propose to add sub-sections in the 3.1 section to make distinct analyses of Ba, Bw and Bs time series.

In our opinion it is not possible to analyse separately the three components of mass balance and we would prefer to avoid the introduction of additional sub-sections if possible.

R2 – 15: P5856-L23. How do you detect quantitatively the change point in the Ba time series? Do you use a statistical tests such as Mann-Kendall, Mann-Whitney or Pettitt tests?

We detected the change points in the Ba time series using the binary segmentation algorithm (Edwards and Cavalli-Sforza, 1965; Scott and Knott, 1974; Sen and Srivastava, 1975) implemented in the 'Changepoint' R package (Killick and Eckley, 2014). The results obtained with the binary segmentation algorithm were checked using the AMOC (at most one change) method and the segment neighborhood algorithm (Auger and Lawrence, 1989). Sentence modified and reference added in the text.

Auger I.E., Lawrence C.E., 1989. Algorithms for the optimal identification of segment neighborhoods. Bulletin of Mathematical Biology, 51(1), 39-54.
Edwards A.W.F., Cavalli-Sforza L.L., 1965. A method for cluster analysis. Biometrics, 21(2), 362-375.
Killick R., Eckley I.A., 2014. Changepoint: An R package for changepoint analysis. Journal of Statistical Software, 58(3), 1-19. DOI: 10.18637/jss.v058.i03
Scott A.J., Knott M., 1974. A cluster analysis method for grouping means in the analysis of variance. Biometrics, 30(3), 507-512.
Sen A., Srivastava M.S., 1975. On tests for detecting change in mean. The Annals of Statistics, 3(1), 98-108.

R2 – 16: P5857-L13. A winter balance abrupt change point (+23%) has been detected in 1977 in the western Alps (Eckert et al., 2011), and is representative of a regional change in winter precipitations in the French and western Swiss Alps (weather data: Durand et al., 2009ab; glacier winter balances change point 1974-76: Aletschgletscher, Valais-Switzerland, Huss and Bauder, 2009; Sarennes gletscher, France, Thibert et al., 2013;). Do you detect such a change point in your winter mass balance records?

Unfortunately the series of Bw from Careser glacier has some gaps, and therefore it is not possible to calculate change points. However, from the available data (Fig. 2) it can be argued that such an abrut change did not occurred in the area of the Careser Glacier. We have analysed change points in the Oct-May precipitation amounts and we report the results in Section 4.2 (see reply to comment R2 – 23).

R2 – 17: P5857-L15. Even when the AA has disappeared, the winter accumulation still controls the snow-toice transition date and influences the summer balance (due to the albedo feed-back). The way Bs is correlated to Bw at Careser Glacier before/after 1981 may help to quantify this.

We have checked this but the correlation is not statistically significant (r = 0.18 and 0.05 before and after 1981, respectively).

R2 – 18: P5858-L2. "…the decrease in the glacier-average albedo…". Don't you suspect any changes in the debris cover and any albedo change of the ice?

Modified as suggested. The analysed glaciers are mostly debris-free, with the exception of the lower parts of Sforzellina and Ciardoney, and of small marginal parts or medial moraines in the others. However, here the focus is on the decreased albedo from the early disappearance of the snow cover from low-lying and flat glaciers, compared to those which retain accumulation areas in their upper reaches. A short sentence was added concerning te accumulation of dust and debris on the surface.

R2 – 19: P5858-L12. How Bw correlates with October-May precipitations?

The correlations has been analysed and the results are described in Section 4.1.

R2 – 20: P5858-L19. Can you quantify the effect of the lowering of the surface in that Bs trend?

In this period and in Table 2 we compare the mean Ba, Bw, Bs and AAR of the 9 glaciers in the decade from 2004 to 2013. We are not presenting or discussing trends in Bs, and the change in geometry in this period is not available for most analysed glaciers.

R2 – 21: P5860-L3. Are Bw and Bs significantly correlated? I would add a column in Table 4 with the Bw-to-Bs correlation coefficients for each glacier.

For all the analysed glaciers there is no correlation between Bw and Bs. A sentence was added at the end of Section 4.1.

R2 – 22: P5860-L11. As proposed for section 3.1, a divide in 2 sub-sections for temperature and precipitation times series may help to structure and clarify the analysis.

Please, see reply to the comment R2 – 14.

R2 – 23: P5860-L20-22. As proposed for the mass balance time-series, you should base your detection of change point on a statistical test.

We found a change point in 1977, in analogy to the findings of the studies mentioned at comment R2 – 16. A sentence was added in section 4.2, reporting this result.

R2 – 24: P5860-L23. As the measurements are performed in the floating-date system, could winter precipitations be cumulated according to measurement dates at each glacier, and summer temperatures as well?

Please, see reply to the comment R2 – 1.

R2 – 25: P5861-L6-21. The link between mass balance seasonal terms and large scale NAO variable is unfortunately not investigated here but deserves an analysis. How the changes in the different seasonal mass balance terms are controlled by larger-scale synoptic variables remains an open question as contrasted results from bibliography are still hard to interpret. Significant relationships are indeed reported for annual mass balance in Scandinavian glaciers and Svalbard (e.g. Fealy and Sweeney, 2005), with nevertheless substantial differences between northern and southern Scandinavia (Marzeion and Nesje, 2012). For Alpine glaciers, the reported correlation is rather weak for annual balances (Reichert et al., 2001; Six et al., 2001) and decreases from positive to negative as one goes from the eastern to the southwestern Alps (Marzeion and Nesje, 2012). For the French western Alps, Durand et al. (2009b) do not find any correlation between winter/annual NAO anomalies and winter precipitations. Regarding winter balances, Thibert et al. (2013) achieve to the same conclusions at Sarennes glacier (French Alps). Only significant correlations emerge for December to February NAO anomalies, and surprisingly only with the summer balances. It will be interesting to know if this uncommon finding is confirmed or not for the Italian glaciers to see if their mass balance is connected to the NAO through their winter balance or exclusively through the summer balance.

We analysed the correlation between the NAO and the seasonal/annual components of the mass balance, comparing the results from the Italian glaciers with those from glaciers of other countries in the European Alps. The results are reported in a new table (Table 5), and they are discussed in Section 4.2.

R2 – 26: P5862-L1-12. The correlation between October-May precipitations Bw and temperatures should be investigated.

Ok, analysed. The results concerning precipitation have been described in section 4.1 (see reply to the comment R2 – 19). Here we report the only glacier with significant correlation between Bw and October-May temperature (i.e., the Careser Glacier).

R2 – 27: P5863-L3-23. Again here the analysis is limited because of the geometry artefacts that corrupt the glacier-wide Ba series.

We agree and are aware of the limitations related to geometric adjustments. For this reason, we reported considerations about the non-linear response of Ba to atmospheric changes at lines 11-23, showing the emblematic example of the Careser Glacier.

R2 – 28: P5865-L18. The geodetic mass balance should also help to control the glacier-wide Ba series, and construct a constant geometry mass balance record (following Elberg et al., 2001) to be connected to climate drivers.

These considerations have been added at the end of Section 4.3.

R2 – 29: P5866-L1-7. As a principal investigator of mass balance myself, I found that this paper on the longest Italian mass balance series could be an opportunity to associate all persons in charge of the measurements in a common publication.

This work was intended as a first assessment based on published data. We plan to involve the principal investigators in future publications investigating the monitored glaciers in the Italian Alps.

R2 – 30: Figures. Figure 2, 4, 5 and 6 should be enlarged.

We will check appropriate figure sizes when we have the layout.

R2 – 31: Figure 7. The residual sum could also be plotted to highlight deviations along the period.

Ok, the figure has been edited as suggested.

R2 – 32: Stylistic comments. P5850-L12. "precipitations"; "temperatures"

Ok, modified

R2 – 33: P5850-L15. "precipitations"

Ok, modified

R2 – 34: P5850-L16. "temperatures tend to become"

Ok, modified

R2 – 35: P5851-L10. As a first word in the sentence, write "twenty five" in full letters.

Ok, modified

R2 – 36: P5852-L12. "Nine monitored glaciers fulfil these characteristics"

Ok, modified

R2 – 37: P5852-L19. "in the Ortles-Cevedale (Eastern Alps, Fig. 1) since 1967."

Ok, modified

R2 – 38: P5853-L10. "…of repeated readings…"

Ok, modified

R2 – 39: P5853-L24. Spelling of "grand Etrét" has to be homogenized with upper case letter for "Grand" and acute or grave accent for "Etrèt" in text, table and captions.

Ok, corrected

R2 – 40: P5854-L14. "Typical randon errors…"

Ok, modified

R2 – 41: P5854-L15. Again, "glacier-wide"

Ok, modified

R2 – 42: P5856-L19. “The longest available series…”

Ok, corrected

Analysis of the mass balance time series of glaciers in the Italian Alps

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Abstract

This work presents an analysis of the mass balance series of nine Italian glaciers, which were selected based on the length, continuity and reliability of observations. All glaciers experienced mass loss in the observation period, which is variable for the different glaciers and ranges between 10 and 47 years. The longest series display increasing mass loss ~~rates, that~~rates, which were mainly due to increased ablation during longer and warmer ablation seasons. The mean annual mass balance (B_a) in the decade from 2004 to 2013 ranged from -1788 mm to -763 mm w.e. y^{-1}. Low-altitude glaciers with low elevation ranges are more out of balance than the higher, larger and steeper glaciers, which maintain residual accumulation areas in their upper reaches. The response of glaciers is mainly controlled by the combination of Oct-May precipitations and Jun-Sep temperatures, but rapid geometric adjustments and atmospheric changes lead to modifications in their response to climatic variations. In particular, a decreasing correlation of B_a with the Jun-Sep temperatures and an increasing correlation with Oct-May precipitations are observed for some glaciers. In addition, the Oct-May temperatures tend~~s~~ to become significantly correlated with B_a, possibly indicating a decrease in the fraction of solid precipitation, and/or increased ablation, during the accumulation season. Because most of the monitored glaciers have no more accumulation area, their observations series are at risk due to their impending extinction, thus requiring a soon replacement.

1 Introduction

The mass balance of glaciers is a key variable for monitoring strategies of the Earth climate system because it is the direct and undelayed response of glaciers to atmospheric conditions. Other reactions of glaciers to climatic changes, such as the fluctuations of the front, are more easy and immediate to measure but represent indirect, delayed and filtered signals (WGMS, 2008; Zemp et al., 2005).

The direct glaciological method (Østrem and Brugman, 1991) is the standardized method in worldwide glacier monitoring strategies. This method consists of in-situ measurements of the surface accumulation and ablation, taken at single points and then extrapolated and integrated to yield the glacier-wide surface mass balance ~~over the entire glacier~~ (Kaser et al., 2003; Cogley et al., 2011). The World Glacier Monitoring Service (WGMS) collects and publishes mass balance data of glaciers obtained by the glaciological method as part of global climate-related observation systems (Zemp et al., 2009; WGMS, 2012 and 2013, and earlier issues).

The European Alps are one of the regions of the world with the highest density of glaciers that are subject to mass balance observations. ~~25~~ Twenty five glaciers have ongoing and continuous mass balance series with at least 10 years of observations, and 11 of them are longer than 30 years (http://www.wgms.ch/metadatabrowser.html, last access: 27 September 2015). In the Italian Alps, nine glaciers have ongoing and continuous mass balance series longer than 10 years, and only one glacier (the Careser Glacier) has a series longer than 30 years.

The mass balance series of the glaciers in the Italian Alps have not yet been reviewed and analysed jointly. The Italian glaciers may have a peculiar behaviour compared to the glaciers from other regions of the European Alps, because of the differences in glacier characteristics, climatic features and trends of meteorological variables (Brunetti et al., 2006 and 2009; Auer et al., 2007). Differences may occur in the response of the glaciers in different sub-regions of the Italian Alps or with different characteristics, which have not been recognized. It is also interesting to highlight possible ~~non-linearities~~feedbacks in the response of Italian glaciers to atmospheric changes.

Therefore, this work aims to i) analyse and compare the direct mass balance series of the glaciers in the Italian Alps, ii) understand the behaviour of the measured glaciers in relation to the observed climatic trends, and iii) highlight possible future requirements for the mass balance monitoring strategy in the Italian Alps.

2 ~~Methods~~

~~2.1~~ Available mass balance series

In this work, we analyse the glaciers with at least 10 years of continuous and ongoing mass balance measurements, which were obtained using the direct glaciological methods and published in peer reviewed journals or in the WGMS publications (CGI, 1914–1977 and 1978–2011; Baroni et al., 2012, 2013, 2014; WGMS, 2012 and 2013, and earlier issues). ”Continuous” indicates the series with data gaps <10%, and ”ongoing” indicates that the mass balance observations have been performed in the last two years (i.e., the 2012 and 2013 hydrological years). These criteria ensure the comparability of the series, a sufficient length in the temporal analyses and reliability of the measurements and calculations.

Nine monitored glaciers ~~have~~ fulfil these characteristics in the Italian Alps and are clustered in three geographic areas (Fig. 1). The two monitored glaciers in the Gran Paradiso Group (Western Alps), i.e., Grand ~~Etrét~~ Etrèt (since 2002) and Ciardoney (since 1992), are rather small (area < 1 km^2) and have low mean elevations and low elevation ranges (Table 1). Snowfall is the prevailing feeding source, but windborne snow and avalanching also contribute to snow accumulation.

The longest series of mass balance measurements in the Italian Alps has been collected on the Careser Glacier, in the Ortles-Cevedale (Eastern Alps, Fig. 1) ~~from~~ since 1967. Currently, this glacier is undergoing rapid shrinking and fragmentation in smaller units. It is characterized by a flat surface, prevailing southern exposure, quite low mean elevation and feeding by snowfall. Its area decreased from 5 km^2 in 1967 to 1.6 km^2 in 2012 (Carturan et al., 2013a). In the 1980s, observations started in two other glaciers of the Ortles-Cevedale: Fontana Bianca and Sforzellina. These two small mountain glaciers (area <0.5 km^2) have different characteristics: Fontana Bianca is rather steep with negligible debris cover and mainly fed by snowfall, whereas Sforzellina is flatter, debris-covered in its lower part and fed by avalanches in its upper part. In the 2000s, mass balance observations began in the Lunga Glacier and in the southern branch of La Mare Glacier, which are larger valley glaciers (1.9 and 2.2 km^2, respectively) that reach higher elevations (3378 and 3518 m, respectively) and mainly fed by snowfall.

In Val Ridanna (Breonie Occidentali Group, Eastern Alps, Fig. 1), the measurements began in 1996 in the Pendente Glacier and were extended to the Malavalle Glacier in 2002. The first glacier is a 0.9 km^2 wide mountain glacier, characterized by a flat surface, low mean elevation, southern exposure and significant accumulation from windborne snow. The second glacier is a much larger (6.9 km^2) valley glacier with higher mean and maximum elevation and mainly fed by snowfall.

3 Methods

~~2.2~~3.1 Mass balance measurements and calculations

Point measurements of the annual mass balance in the ablation area consist of repeated readings of ablation stakes, which are made of aluminium, wood or plastic and drilled into the ice/firn using hand drills or steam drills. In the accumulation area, the depth of the snow at the end of the ablation season is measured using hand probes, and its density is determined in snowpits. Snow depth soundings and density measurements in the snowpits or by hand coring devices are also used for winter mass balance measurements, which are performed on all glaciers except Sforzellina. The summer mass balance is derived by subtracting the winter mass balance from the annual mass balance. The density of measuring points varies among different glaciers in relation to their extent, accessibility and complexity of the mass balance distribution (Fig. 2). The ablation stake density ranges from 4 points km^{-2} (Malavalle Glacier) to 45 points km^{-2} (Sforzellina Glacier). The density of snow depth soundings for the winter mass balance determination ranges from 15 points km^{-2} (Malavalle Glacier) to 142 points km^{-2} (Fontana Bianca Glacier).

Point measurements are interpolated and extrapolated to the entire area of the glaciers using different procedures. In the ~~grand~~ Grand ~~Etrét~~ Etrèt and Ciardoney glaciers, each ablation stake is assumed representative of a specific part of the glacier, where the mass balance distribution is assumed homogeneous. Then, a weighted mean is calculated, using the area of the homogeneous parts into which the glacier is subdivided as weights (http://www.pngp.it/, last access: 27 September 2015; http://www.nimbus.it/, last access: 27 September 2015). In Malavalle and Pendente glaciers, the area is divided into "sub-catchments", and for each sub-catchment, a linear regression of point balances vs. altitude is calculated and used for the spatialization (http://www.provinz.bz.it/wetter/glacierreport.asp, last access: 27 September 2015). In Careser Glacier, the even distribution of the mass balance and good coverage of measurement points enable the use of automatic interpolation algorithms (Spatial Analyst Tools) in the ESRI-ArcGIS software. Manual drawing of balance isolines is used for the remaining Sforzellina, Fontana Bianca, La Mare and Lunga glaciers (Catasta and Smiraglia, 1993; Cannone et al., 2008; http://www.provinz.bz.it/wetter/glacierreport.asp; Carturan, 2016~~ et al., 2015~~). The measurements are performed close to the time of maximum and minimum mass balance during the year, when the glacier and atmospheric conditions are favourable for field surveys. The "floating-date" time measurement system is used for all glaciers (Cogley et al., 2011).

Typical random errors reported in the literature for glacier-wide mass balance estimates obtained with these methods are of about ±200 mm w.e. y^{-1} (Lliboutry, 1974; Braithwaite and Olesen, 1989; Cogley and Adams, 1998; Cogley, 2009). The accuracy indicated by the investigators carrying out mass balance measurements in the nine Italian glaciers range between ±0.05 and 0.30 m w.e. y^{-1} (WGMS, 2015; Carturan, 2016). Assessments based on the comparison between the direct and the geodetic mass balance have been published for the Careser, La Mare and Lunga glaciers, indicating a good match of the two methods and revealing that a calibration of the direct mass balance results is not required (Carturan et al., 2013a; Galos et al., 2015; Carturan, 2016). ~~Typical errors reported in the literature for whole-glacier mass balance estimates obtained with these methods are of about ±200 mm w.e. y^{-1} (Lliboutry, 1974; Braithwaite and Olesen, 1989; Cogley and Adams, 1998; Cogley, 2009).~~

~~2.3~~3.2 Meteorological series

The climatic variables used in this work consist of synthetic records of the monthly mean temperature and total monthly precipitation, which are obtained for the centre of the three main geographic areas described in Sect. 2~~.1~~, using the procedure reported in Brunetti et al. (2012). Starting from sparse meteorological data recorded at meteorological stations, the synthetic meteorological series are generated using the anomaly method (New et al., 2000; Mitchell and Jones, 2005). This method is based on the assumption that the spatio-temporal structure of the signal of a meteorological variable over a given area can be described by the superimposition of two fields: the climatological normals over a given reference period (i.e., the climatologies) and the departures from them (i.e., the anomalies). The climatologies are linked to the geographic features of the territory and characterized by remarkable spatial gradients; the departures are linked to the climate variability and change, and they are generally characterized by higher spatial coherence.

Under this assumption, the climatologies and anomalies can be reconstructed in completely independent manners and based on different data sets. For climatologies, the priority is the high spatial resolution, and a short time span (few decades) is sufficient. A lower spatial resolution is sufficient for the anomalies, but more importance is given to the data quality and availability of long records. Thus, all series that were used for the anomaly component were subjected to homogenization.

The interpolation methods are different for the two components. The climatologies, which are characterized by high spatial gradients, were reconstructed using the procedure in Brunetti et al. (2014)~~ for the mean temperature~~, exploiting the relationship between the meteorological variable and the physical characteristics of the terrain. The anomalies, which are characterized by higher spatial coherence, were reconstructed using weighted averages as described in Brunetti et al. (2006). The weights are horizontal and vertical distance weighting functions, with the addition of an angular weight that accounts for the anisotropy in the distribution of stations around the sites. Finally, the two fields were superimposed to obtain the temporal series in absolute values for each site.

~~2.4~~3.3 Analyses of the mass balance and meteorological series

The time series of annual mass balance (B_a), winter mass balance (B_w), summer mass balance (B_s) and Accumulation Area Ratio (AAR, i.e., the ratio of the area of the accumulation zone to the area of the glacier) were analysed and compared to highlight the possible trends, break points, common behaviour and peculiarities of single glaciers and/or single years. To highlight the systematic differences among the glaciers, the mean values of B_a, B_w, B_s and AAR were calculated in the common period of observation from 2004 to 2013. The decadal means of B_a for the Italian glaciers were compared to the decadal means for a sample of nine representative glaciers of the European Alps (Zemp et al., 2005). The correlations among the B_a series of different glaciers and among B_a of single glaciers with the respective series of B_w and B_s were subsequently computed, to identify possible groups of glaciers with similar behaviours and to understand the relative importance of the seasonal components of mass balance.

Linear trends and moving averages were calculated for the time series of air temperature and precipitation to highlight the climatic drivers of the observed glacier changes. In particular, we focused on the precipitation of the accumulation season, from October to May (Oct-May), and on the air temperature of the ablation season, from June to September (Jun-Sep) (Pelto, 2008; Carturan et al., 2013b), computing their correlation with B_a and performing multiple linear regression analyses. For the four glaciers with the longest mass balance series (Careser, Fontana Bianca, Sforzellina and Ciardoney), we performed a moving correlation analysis of B_a vs. the seasonal and annual temperature and precipitation, to recognize possible changes and/or trends in their response and sensitivity to climatic fluctuations, e.g., ascribable to geometric adjustments.

~~3~~ 4 Results and discussion

~~3~~4.1 Analysis of mass balance series

The ~~longer~~ longest available series for the glaciers in the Italian Alps clearly show a trend towards more negative B_a in the observation period (Fig. ~~2~~3), and one or two change points, which were identified using the 'Changepoint' R package (Killick and Eckley, 2014). In particular, the series of Careser Glacier shows three phases: i) the period from 1967 to 1980 with near equilibrium conditions (mean B_a = -132 mm w.e. y^{-1}, STD = 540 mm w.e.); ii) the period from 1981 to 2002 with imbalanced conditions (mean B_a = -1192 mm w.e. y^{-1}, STD = 517 mm w.e.); and iii) the period after 2002 with stronger imbalance (mean B_a = -1926 mm w.e. y^{-1}, STD = 725 mm w.e.). A sudden transition in 1980-81 is also clearly visible in the series of AAR, which documents the nearly complete disappearance of the accumulation area of this glacier, which is likely responsible for the step change in its mass balance series during that period.

The transition of 2002-03 is also observable for the Fontana Bianca, Sforzellina and Pendente glaciers, whose measurements started in the 1980s and 1990s. Their mean B_a values changed from -599, -868 and -703 mm w.e. y^{-1}, before 2002, to -1257, -1471 and -1308 mm w.e. y^{-1} after 2002, respectively. This transition is less obvious for the Ciardoney Glacier, which experienced a notably negative mass balance already in 1998 and 1999. The B_w and B_s series have some gaps but suggest that the increased mass loss rates were mainly ascribable to increased ablation (and associated positive feedbacks) instead of decreased snow accumulation. These results are consistent with previous works, which indicate that the mass changes of the glaciers in the Alps, at the annual and decadal scale, are mainly driven by the summer balance (e.g., Schoner et al., 2000; Vincent et al., 2004; Zemp et al., 2008; Huss et al., 2015).

The AAR series show that the accumulation area almost vanished from all glaciers in the 2000s except the years 2001, 2010 and 2013, when several glaciers were close to balanced-budget conditions mainly as a result of the increased B_w. In these years, the highest increase in AAR occurred in the Fontana Bianca Glacier, which is steep and exposed to the east. On the contrary, the AAR did not significantly increase in the neighbouring Careser Glacier, which is flatter and mainly exposed to the south (Table 1). This behaviour is uncommon for flat glaciers because they should be more sensitive to variations of the Equilibrium Line Altitude (ELA) than the steeper glaciers (Benn and Evans, 2010), and reveals that the Careser Glacier is almost completely below the current ELA, also in the years of ELA minima. La Mare and Malavalle glaciers, which are larger and cover a wider elevation range (Table 1), show more persistent accumulation areas, although their size is too small to ensure balanced-budget conditions.

The B_a and B_s values of different glaciers tend to diverge in years with largely negative mass balance and converge in years closer to equilibrium (1993, 2001, 2010 and 2013, Fig. ~~2~~3). Reinforcing processes and feedbacks likely amplify the differences among the glaciers in imbalanced years, particularly the decrease~~d~~ in the glacier-average albedo caused by the early disappearance of snow from low-lying, flat and less topographic-shielded glaciers, and by the accumulation of dust and debris on the surface. B_w also shows the alternation of years with small/large variability among the glaciers, but this behaviour cannot be clearly related to the magnitude of the snow accumulation, as observed in the two high-accumulation years 2009 (high variability) and 2013 (low variability). In this case, the spatial variability of the precipitation during the accumulation season, which is larger than the spatial variability of air temperature in the ablation season, determines the interannual variability of B_w for single glaciers, which is further controlled by snow redistribution processes. Snow redistribution appears more effective for the Pendente,~~ and ~~Grand Etrèt and Ciardoney glaciers, leading to over-accumulation in snow-rich winters (e.g., in 2009) and larger interannual variability of B_w. Correlation coefficients calculated between B_w and October-May precipitations range between 0.73 and 0.78 are significant at the 0.05 level only for Careser, La Mare, Lunga, Fontana Bianca and Malavalle, while they are not statistically significant for Pendente, Grand Etrèt and Ciardoney, in line with the hypothesised higher importance of snow redistribution processes in these three glaciers.

In the period from 2004 to 2013, significantly higher B_w is observed for Pendente and Grand Etrèt~~these two glaciers~~, compared with the other glaciers in the same geographic area~~, likely due to windborne snow during and/or following precipitation events~~ (Table 2), ~~. The high accumulation rate explains~~explaining the persistence of these two ice bodies at such low altitude (Table 1). In the same period, the Careser Glacier had the lowest average B_a and AAR, whereas the Malavalle and La Mare glaciers had the highest average B_a,

B_s and AAR, retaining accumulation areas in their upper parts. However, the mean AARs were remarkably low for all analysed glaciers, and far from balanced-budget conditions (AAR_0 = 0.55 - 0.58, Dyurgerov et al., 2009; Mernild et al., 2013). Overall, low-altitude and flat glaciers with low elevation ranges are more out of balance than the steeper glaciers at higher altitude with higher elevation ranges, as acknowledged in various other studies (e.g., Furbish and Andrews, 1984; Benn and Evans, 2010; Carturan et al., 2013b; Fischer et al., 2015).

At the regional scale, the spatial representativeness of five Italian mass balance glaciers can be assessed on the basis of the geodetic mass balance calculations performed by Carturan et al., (2013b). In the period from the 1980s to the 2000s, the average geodetic mass balance rate of the 112 glaciers in the Ortles-Cevedale Group has been -0.69 m w.e. y^{-1}. If we consider the average geodetic mass balance in the same period as an index of the spatial representativeness for single glaciers, we obtain in decreasing order: i) La Mare with -0.64 m w.e. y^{-1}, ii) Sforzellina with -0.86 m w.e. y^{-1}, iii) Fontana Bianca with -0.90 m w.e. y^{-1}, iv) Lunga with -1.00 m w.e. y^{-1}, and v) Careser with -1.43 m w.e. y^{-1}. Geodetic calculations only exist for few areas in the Italian Alps (e.g., Galos et al., 2015) and do not include the other four mass balance glaciers analysed in this study. Therefore it was not possible to evaluate their spatial representativeness at the regional scale. Similarly, quantitative assessments of the representativeness of all the nine glaciers at the scale of the entire Italian Alps will require further investigations, integrating in-situ measurements, remotely sensed observations and numerical modelling (WGMS, 2015).

The response of Italian glaciers to the climatic conditions of the last decades is similar to that of nine representative glaciers of the entire European Alps (Zemp et al., 2005; Fig. ~~3~~4), although single glaciers display different mass loss rates (Table 2). The Italian glaciers display ~200-250 mm w.e. y^{-1} more negative B_a until 2002 and ~200 mm w.e. y^{-1} less negative B_a since then. Therefore, it can be assessed that the mean B_a values for the Italian and "European" glaciers ~~is~~ are fairly similar. ~~Similar~~Comparable results were obtained by Huss et al., (2015), who compared the decadal mean B_a of glaciers from France, Switzerland, Austria and Italy. These comparisons may be affected by the ~~, although~~ loss of spatial representativeness of some glaciers (e.g. Careser in the Italian Alps and Sarennes in the French Alps) and by the different subsets of Italian glaciers ~~are~~ which are useable ~~for~~ in the four different sub-periods.~~. Similar results were obtained by Huss et al., (2015), who compared the decadal mean B_a of glaciers from France, Switzerland, Austria and Italy.~~ In the last decade, the inclusion of La Mare and Malavalle glaciers in the Italian subset and the concurrent sharp decrease of B_a for the Sarennes, St. Sorlin and Gries glaciers explain the different behaviours of the two groups of glaciers. However, the smaller Italian glaciers (average area = 1.79 km^2) may have a shorter response time to climatic changes, adjusting their geometry faster than the larger glaciers (average area = 3.63 km^2) which are representative of the European Alps (Hoelzle et al., 2003; Abermann et al., 2009). The rapid shrinking and fragmentation of Careser Glacier is a good example: in the last decade, its area has halved, and it completely lost the parts subject to higher ablation (Carturan et al., 2013a). Changes in the general atmospheric circulation and spatial distribution of precipitation could also have played a role and will be discussed in Sect. ~~3~~4.2.

There is a generally high correlation among the B_a values of the analysed glaciers (Table 3). The series of Careser, Fontana Bianca and La Mare glaciers show a highly significant correlation with most other glaciers, even if they have different characteristics or are far away. On the contrary, the Lunga Glacier shows a lower correlation and lower statistical significance with the glaciers of the same mountain group. However, it has the shortest series, and most importantly, it does not include the highly negative B_a of 2003, which certainly increases the correlation among other glaciers. There are notably high correlations in the Ortles Cevedale between Careser and La Mare and between Fontana Bianca and La Mare glaciers. A similarly high correlation is observed between Pendente and Malavalle glaciers in Val Ridanna, whereas there is a much lower correlation between the two glaciers of the Gran Paradiso Group, which suggests that differences in local topo-climatic factors can be decisive on such small ice bodies (e.g., Kuhn, 1995; DeBeer and Sharp, 2009; Carturan et al., 2013c; Scotti et al., 2014; Colucci and Guglielmin, 2015).

For most glaciers, B_a is more correlated to B_s than to B_w (Table 4), which further confirms the importance of summer ablation. The relevance of the snow redistribution and over-accumulation on the Pendente and Grand Etrèt glaciers is indicated by the higher correlation of their B_a with B_w. On La Mare Glacier, the two seasonal components have similar correlations with B_a. However, these results are influenced by the length of the observation period and the presence/absence of extreme years with high accumulation (e.g., 2001) or high ablation (e.g., 2003) in the observation series of individual glaciers. For the analysed glaciers, no significant correlation was found between B_s and B_w.

~~3~~4.2 Climatic controls

In the period from 1961 to 2013, there are highly significant warming trends for the Jun-Sep air temperature (Fig. ~~4a~~5a, b and c); they are highest in the Gran Paradiso Group (0.40°C decade^{-1}) and lowest in Val Ridanna (0.35°C decade^{-1}). The three phases in the longer B_a and B_s series of glaciers (Fig. ~~2~~3) can be recognized as periods with stationary Jun-Sep temperature, separated by switches in the early 1980s and after the peak of 2003. The warming trends are lower in the accumulation season and range from 0.25 to 0.27°C decade^{-1} (Fig. ~~4d~~5d, e and f), but thermal inversions at the valley weather stations could have partially masked the warming at the altitude of the glaciers in this season. The transition towards higher Oct-May temperature occurred in the late 1980s, after a minimum in the first half of the same decade. A distinct warm peak in Oct-May temperature occurred in 2007.

The precipitation does not show any significant trend in the accumulation season (Fig. ~~5d~~6d, e and f). The moving averages display oscillations of 10-20% above and below the 1961-1990 mean, which lasted approximately 10-15 years and were higher in the Gran Paradiso Group than in the Ortles-Cevedale and Val Ridanna. Periods with below-average precipitation are recognized in the 1960s, first half of 1970s, and 1990s, whereas periods with above-average precipitation occurred in the second half of 1970s and the first half of 1980s. The last 10-15 years were characterized by precipitation close to the mean, with important maxima in 2001, 2009 and 2013, and minima in 2007 and 2012. Similarly to the findings from Durand et al., (2009a and b) and Eckert et al., (2011) for the French and western Swiss Alps, a change point in winter precipitation of Ortles-Cevedale and Val Ridanna series were identified in 1977, corresponding to an increase of about 10-12%. Linear trends of summer precipitation are positive but not statistically significant. The interannual variability of the Jun-Sep precipitation is remarkably higher in the Gran Paradiso Group (Fig. ~~5a~~6a, b and c).

Large scale circulation patterns, such as the North Atlantic Oscillation (NAO) and the Northern Hemisphere blocking frequency, are connected with the temporal and spatial variability of winter precipitation in the Alps (Quadrelli et al., 2001). Several studies highlighted a contrasting behaviour of precipitation anomalies in the Oct-May period between the northern and southern Alps, i.e. opposite correlation with indexed large scale circulation patterns (e.g., Quadrelli et al., 2001; Schmidli et al., 2002, Brunetti et al., 2006) and opposite long-term trends in the seasonal precipitation totals (e.g., Brunetti et al., 2006 and 2009; Auer et al., 2007). This characteristic, and the tendency towards a decreasing NAO index in the last two decades (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/JFM_season_nao_index.shtml, last access: 4

October 2015), leading to increased winter precipitation in the southern side of the Alps, may provide an additional explanation for the different behaviour of “European” and “Italian” glaciers shown in Fig. ~~3~~4. Opposite effects of the NAO on the winter precipitation and glacier mass balance in the northern and southern parts of the Eastern Alps were also reported, for example, by Marzeion and Nesje (2012).

A correlation analysis of B_w, B_s and B_a versus the seasonal and annual mean NAO index was performed, using the mass balance data of glaciers from Italy and from other nations of the European Alps (Table 5). The results show prevailing negative correlations between the B_w of Italian glaciers and the NAO in the accumulation season, whereas positive correlations prevail in other nations, with the exception of Gries Glacier which however is close to the Italian border. These results are in agreement with the mentioned literature and with our hypothesis of opposite effects of recent NAO trends in the winter precipitation of the northern and southern sides of the Alps. In line with the findings of Reichert et al., (2001), Six et al., (2001), and Thibert et al., (2013), a negative correlation was calculated between B_s/B_a and the NAO in the accumulation season. If a causal relationship can be hypothesised for the Italian glaciers, related to the albedo feedback from wet/dry winters (with low/high NAO, respectively), the same cannot be stated for glaciers in other countries, due to the prevalent positive correlation of their B_w with the winter NAO.

The examination of meteorological series confirms that increased ablation and the related feedbacks are the main causes of the increased imbalance of the analysed Italian glaciers, as observed in Sect. ~~3~~4.1. This result is further corroborated by the higher correlation of B_a with the Jun-Sep temperature than with the Oct-May precipitation, at least for the glaciers with longer observation series (Careser, Fontana Bianca, Sforzellina and Ciardoney, Table ~~5~~6). B_a of glaciers with shorter observation series is not significantly correlated with the Jun-Sep temperature; instead, two of them (La Mare and Lunga) show a correlation with the Oct-May precipitation. Combining the Oct-May precipitation and Jun-Sep temperature in a multiple linear regression model leads to highly significant coefficients for both variables, even when the single seasonal components are not correlated with B_a (e.g., for the Pendente and La Mare glaciers). Approximately two-thirds of the B_a variance can be explained by the multiple linear regression. The poorest results were obtained for the two glaciers in Val Ridanna (Pendente and Malavalle) and the Grand Etrèt Glacier. As the first two glaciers are close to the main Alpine divide, they likely benefit from the high orographic uplift that locally enhances precipitation (Schwarb, 2000), but which cannot be accounted for by the multiple regression model due to the lack of weather stations in that area. In addition, the multiple regression model does not account for accumulation by windborne snow on the Pendente and Grand Etrèt glaciers.

The Careser, Fontana Bianca and Pendente glaciers display significant negative correlations between their B_a and the Oct-May temperature. For the Careser Glacier, there is also a negative correlation between B_w and the Oct-May temperature. Normally, in this period, most precipitation falls as snow, and the glaciers have negligible ablation and low temperature sensitivity (Oerlemans and Reichert, 2000). However, increasing temperature starts to lead to significant ablation in this period and to reduce the fraction of solid precipitation as clearly detectable in the ablation season (Carturan et al., 2013b). An emblematic example is the warm accumulation season of 2006-07, when the liquid precipitation reached 3000-3100 m a.s.l. (24 October 2006), and ice ablation exceeded 50 cm at 3000 m a.s.l. on the Careser and La Mare glaciers.

The correlation between B_a of Careser Glacier and the Oct-May temperature starts to become significant in the late 1980s, as shown in the moving correlation analyses (30-year time window in Fig. ~~6~~7). In the first 20 years, the correlation was absent or not statistically significant. These results are consistent with the discussed effects of increasing temperature on the ablation and partitioning between liquid and solid precipitation (Beniston et al., 2003). Reducing the window size from 30 to 15 years leads to a noisier signal and in this case the correlation between B_a and Oct-May temperature does not reach the 95% significance thresholds. However, it is interesting to remark the reversal of the correlation sign from positive in the first years to negative in the last years.

The four glaciers in Fig. ~~6~~ 7 (Careser, Fontana Bianca, Sforzellina and Ciardoney) share a common trend towards i) a non-significant moving correlation between B_a and the Jun-Sep temperature and ii) a significant moving correlation between B_a and Oct-May precipitation. This behaviour is probably related to the snow-rich accumulation seasons of 2001, 2009 and 2013, and to the fact that the ablation season is already so warm that i) summer snow falls mostly above the highest reaches of the glaciers, which reduces the interannual variability of summer melt, and ii) conditions close to balanced-budget only occur after snow-rich accumulation seasons.

Rapid geometric changes may also lead to a non-linear response of B_a to atmospheric changes, at least for some glaciers. For example, the multiple regression residuals of the Careser Glacier, which were mostly positive in the 1980s, 1990s and 2000s, became predominantly negative after 2008 (Fig. ~~7~~8). This change may suggest that the rapid modifications occurred in the latest years could have induced a negative feedback, reducing the mass loss rate of the glacier, whose current surface and shape are strongly different from the recent past (inset in Fig. ~~7~~8). Because the multiple regression model does not use the Oct-May temperature as an explanatory variable, it cannot account for the effects of the warm accumulation season of 2006-07, which led to a very low B_w, early disappearance of winter snow and positive albedo feedback. Therefore, the year 2007 results in highly positive regression residuals.

~~3~~4.3 Future requirements

A common characteristic for all glaciers analysed is their very low mean AAR in the last decade (Table 2). Accumulation areas were almost inexistent in most glaciers, indicating that they will soon disappear, even without additional warming. Some glaciers are displaying morphological changes that indicate their impending extinction, such as rapid disintegration (e.g., Careser Glacier, Fig. ~~7~~8) and surface lowering in the upper accumulation area (e.g., Fontana Bianca Glacier). The AARs of approximately 0.25 indicate that accumulation areas still exist in the larger and higher-reaching La Mare and Malavalle glaciers. However, given that balanced-budget conditions require AAR close to 0.55, large mass loss and areal reduction are also expected for these two glaciers to reach equilibrium with the climatic conditions of the last ten years.

The forthcoming vanishing of the monitored glaciers put the continuation of their mass balance observations at risk. Recently-started monitoring programs in larger and higher-reaching glaciers, such as Malavalle and La Mare, will ensure continued observations in Val Ridanna and the Ortles-Cevedale. In line with the recommendations from the WGMS (Zemp et al., 2009), similar observation programs should start in other large and high-reaching glaciers of the Italian Alps, e.g., in the Gran Paradiso group (to substitute Ciardoney and Grand ~~Etrét~~Etrèt) and in other mountain groups. Both the initiation of observations over new glaciers and the replacement of vanishing glaciers will require an assessment of the spatial representativeness of single glaciers through the comparison of the current mass loss rates over wide geographic areas (Haeberli et al., 2013). This assessments can be obtained using modern techniques such as the multi-temporal differencing of digital elevation models, which enable the comparison of mass loss rates in the last years/decades, by means of the geodetic method, over entire regions or mountain ranges (e.g., Paul and Haeberli, 2008; Abermann et al., 2011; Carturan et al., 2013b; Berthier et al., 2014; Fischer et al., 2015). The geodetic mass balance should also help to control the glacier-wide B_a series measured with the direct glaciological method, and to construct a constant-geometry mass balance record (Elsberg et al., 2001) to be connected to climatic drivers.

~~4~~5 Conclusions

In this work, we have analysed the time series of the glaciers with mass balance observations in the Italian Alps. Based on the results of the analyses, the following conclusions can be drawn:

- All examined glaciers are experiencing imbalanced conditions, and the longer series show sustained negative trends of B_a.
- The observed behaviour was mainly caused by increased ablation, led by warmer temperature and related feedbacks. The total precipitation does not show any significant trend, but the fraction of solid precipitation decreased as a consequence of the warmer temperature.
- The B_a of the analysed glaciers is mainly correlated to B_s, except for two glaciers where windborne snow enhances the importance of B_w. For most glaciers, approximately two thirds of the B_a variance can be explained by multiple linear regression, using the Oct-May precipitation and Jun-Sep temperature as independent variables.
- The monitored Italian glaciers have comparable mass loss rates to a sample of representative glaciers of the entire European Alps. However, the moving correlation analyses and time series of residuals from multiple linear regressions suggest that the smaller (and thinner) Italian glaciers may be reacting faster to atmospheric changes.
- Most monitored glaciers have no more accumulation area and are at risk of extinction, even without additional warming. Therefore, they will soon require a replacement with larger and higher glaciers that retain accumulation areas.
- Regional assessments of the mass loss rates using the geodetic method are required to identify possible replacing glaciers, evaluate their spatial representativeness and enable the transitions from replaced to replacing glaciers, as suggested by Haeberli et al. (2013).

Author contribution

M. Brunetti processed the meteorological data and prepared the synthetic meteorological series used in this work. Thomas Zanoner compiled the database of the mass balance data and geometric characteristics of the glaciers. L. Carturan and Giulia Zuecco performed the temporal and statistical analyses of the mass balance series. L. Carturan prepared the manuscript with contributions from all co-authors.

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Tables

Table 1 – Physical characteristics of the Italian glaciers with the mass balance series analysed in this study (year 2006, NextData - DATAGRALP project: http://www.nextdataproject.it/?q=en/content/special-project-datagralp, last access: 27 September 2015; Salvatore et al., 2015).

Glacier	Geographic area	Area (km^2)	Minimum elevation (m a.s.l.(	Maximum elevation (m a.s.l.)	Median elevation (m a.s.l.)	Prevailing aspect	Average slope (°)	First survey year
Grand Etrèt	Gran Paradiso	0.47	2667	3190	2894	N	23	2002
Ciardoney	Gran Paradiso	0.59	2855	3170	3039	E-NE	18	1992
Fontana Bianca	Ortles-Cevedale	0.48	2889	3342	3166	E	23	1984
Sforzellina	Ortles-Cevedale	0.29	2790	3046	2868	NW	16	1987
Lunga	Ortles-Cevedale	1.86	2678	3378	3128	NE	19	2004
Careser	Ortles-Cevedale	2.39	2868	3279	3069	S	11	1967
La Mare (southern branch)	Ortles-Cevedale	2.16	2652	3518	3215	NE	21	2003
Pendente	Val Ridanna	0.95	2621	3064	2781	S	15	1996
Malavalle	Val Ridanna	6.92	2512	3441	2971	SE	14	2002

Table 2 – Mean values (and STD in brackets) of B_w, B_s, B_a and AAR for nine Italian glaciers in the period from 2004 to 2013 (Car = Careser, FB = Fontana Bianca, Pen = Pendente, Cia = Ciardoney, Sfo = Sforzellina, GE = Grand ~~Etrét~~Etrèt, Lun = Lunga, Mar = La Mare, Mal = Malavalle). Values expressed in mm w.e. except AAR that is in percent.

	Car	Mar	FB	Sfo	Lun	Pen	Mal	Cia	GE
B_w (9 years)	927 (330)	989 (301)	1085 (338)	\	991 (222)	1537 (425)	1194 (256)	1052 (421)	1472 (578)
B_s (9 years)	-2740 (368)	-1758 (303)	-2183 (457)	\	-2151 (368)	-2857 (525)	-2087 (386)	-2510 (378)	-2396 (321)
B_a (10 years)	-1788 (590)	-763 (395)	-1088 (642)	-1399 (505)	-1195 (466)	-1231 (692)	-825 (484)	-1419 (646)	-946 (648)
AAR (10 years)	1 (3)	25 (14)	11 (22)	\	12 (16)	4 (8)	23 (17)	3 (5)	\

Table 3 – Correlation matrix of B_a for nine Italian glaciers. * and ** indicate Spearman correlation significant at the 0.05 and 0.01 level, respectively.

	Car	FB	Pen	Cia	Sfo	GE	Lun	Mar	Mal
Car	1.00								
FB	0.82**	1.00							
Pen	0.85**	0.76**	1.00						
Cia	0.87**	0.86**	0.55*	1.00					
Sfo	0.82**	0.75**	0.65**	0.81**	1.00				
GE	0.74**	0.77**	0.66*	0.62*	0.69*	1.00			
Lun	0.70*	0.73*	0.60	0.48	0.49	0.77**	1.00		
Mar	0.90**	0.96**	0.70*	0.90**	0.82**	0.80**	0.71*	1.00	
Mal	0.87**	0.84**	0.97**	0.61*	0.65*	0.68*	0.61	0.80**	1.00

Table 4 – Correlation coefficients of B_a vs. B_w and B_s. * and ** indicate Spearman correlation significant at the 0.05 and 0.01 level, respectively.

	No of years	Bw	Bs
Car	40	0.46**	0.94**
FB	22	0.24	0.84**
Pen	12	0.84**	0.67*
Cia	22	0.51*	0.76**
GE	12	0.84**	0.66*
Lun	10	0.64*	0.69*
Mar	10	0.66*	0.64*
Mal	9	0.48	0.85**

Table 5 – Correlation coefficients of B_w, B_s and B_a vs. seasonal and annual NAO. Five-year triangular moving averages have been applied to the time series before correlation analyses. *, ** and *** indicate Spearman correlation significant at the 0.10, 0.05 and 0.01 level, respectively.

		Winter balance			Summer balance			Annual balance		
Nation	Glacier	DJF NAO	Oct-May NAO	Annual NAO	DJF NAO	Oct-May NAO	Annual NAO	DJF NAO	Oct-May NAO	Annual NAO
I	Car	-0.51**	-0.34	-0.16	-0.23	-0.05	0.34	-0.30*	-0.13	0.23
I	FB	-0.11	0.18	0.00	0.22	0.10	0.25	0.07	0.35	0.41*
I	Pen	-0.70	-0.90*	-0.70	-1.00**	-0.90*	-1.00**	0.12	0.15	0.23
I	Cia	0.17	0.34	0.19	-0.03	0.10	0.27	0.13	0.27	0.36
I	GE	-0.81***	-0.74**	-0.79**	-0.88***	-0.76**	-0.91***	-0.86***	-0.76**	-0.83***
I	Lun	-0.94**	-0.94**	-0.94**	-0.94**	-0.77	-0.94**	-0.89**	-0.83*	-0.89**
I	Mar	-1.00***	-0.89**	-1.00***	0.14	0.03	0.14	-0.79**	-0.82**	-0.89***
I	Mal	-0.90*	-0.70	-0.90*	-0.50	-0.80	-0.50	-0.81***	-0.74**	-0.45
I	Sfo							0.59***	0.59***	0.61***
F	St. Sorlin							-0.44***	-0.38***	-0.04
F	Sarennes	0.36***	0.43***	0.49***	-0.53***	-0.50***	-0.19	-0.41***	-0.37***	-0.05
CH	Silvretta	0.28*	0.13	-0.05	-0.57***	-0.45***	-0.18	-0.38***	-0.28**	0.02
CH	Gries	-0.39***	-0.22	-0.18	-0.58***	-0.53***	-0.25*	-0.49***	-0.39***	-0.03
A	Sonnblick							-0.48***	-0.45***	-0.07
A	Vernagt	0.27*	0.51***	0.49***	-0.42***	-0.38**	-0.09	-0.36**	-0.26*	0.07
A	Kesselwand							-0.42***	-0.38***	-0.07
A	Hintereis							-0.55***	-0.44***	-0.10

Table ~~5~~ 6 - Spearman correlation coefficients and multiple regression results of B_a vs. seasonal mean temperature and precipitation. *, ** and *** indicate 0.05, 0.01 and 0.001 significance levels.

Air temperature – Correlation coefficients

	Car	FB	Sfo	Cia	Pen	GE	Mal	Mar	Lun
No of years	47	27	27	22	18	12	12	11	10
Jun-Sep	-0.77***	-0.49**	-0.52**	-0.64**	-0.40	0.01	-0.24	-0.16	0.49
Oct-May	-0.37**	-0.42*	-0.10	-0.18	-0.49*	-0.18	-0.57	-0.28	-0.33
Year	-0.68***	-0.49**	-0.30	-0.49*	-0.69**	-0.31	-0.71**	-0.27	-0.14

Precipitation – Correlation coefficients

	Car	FB	Sfo	Cia	Pen	GE	Mal	Mar	Lun
No of years	47	27	27	22	18	12	12	11	10
Jun-Sep	-0.15	-0.02	0.09	0.20	0.00	0.02	-0.04	0.26	-0.05
Oct-May	0.28	0.40*	0.32	0.47*	0.37	0.57	0.43	0.67*	0.71*
Year	0.11	0.36	0.39*	0.53*	0.34	0.64*	0.34	0.83**	0.53

Multiple linear regression - Coefficients

	Car	FB	Sfo	Cia	Pen	GE	Mal	Mar	Lun
No of years	47	27	27	22	18	12	12	11	10
Jun-Sep temperature	-776.453 (***)	-663.487 (***)	-575.225 (***)	-796.739 (***)	-496.521 (**)	-63.899	-355.106	-668.941 (**)	115.265
Oct-May precipitation	2.186 (***)	3.342 (***)	2.915 (***)	3.315 (***)	2.380 (*)	2.897 (**)	3.051 (*)	4.122 (**)	2.666 (*)
Intercept	-3265.013 (***)	-3311.632 (***)	-3176.797 (***)	1753.826	1011.719	-2707.559	19.212	-3380.905 (***)	-2619.872 (**)
% of explained variance	75.6	68.7	72.1	73.7	51.5	56.8	56.0	78.4	64.5

Figures

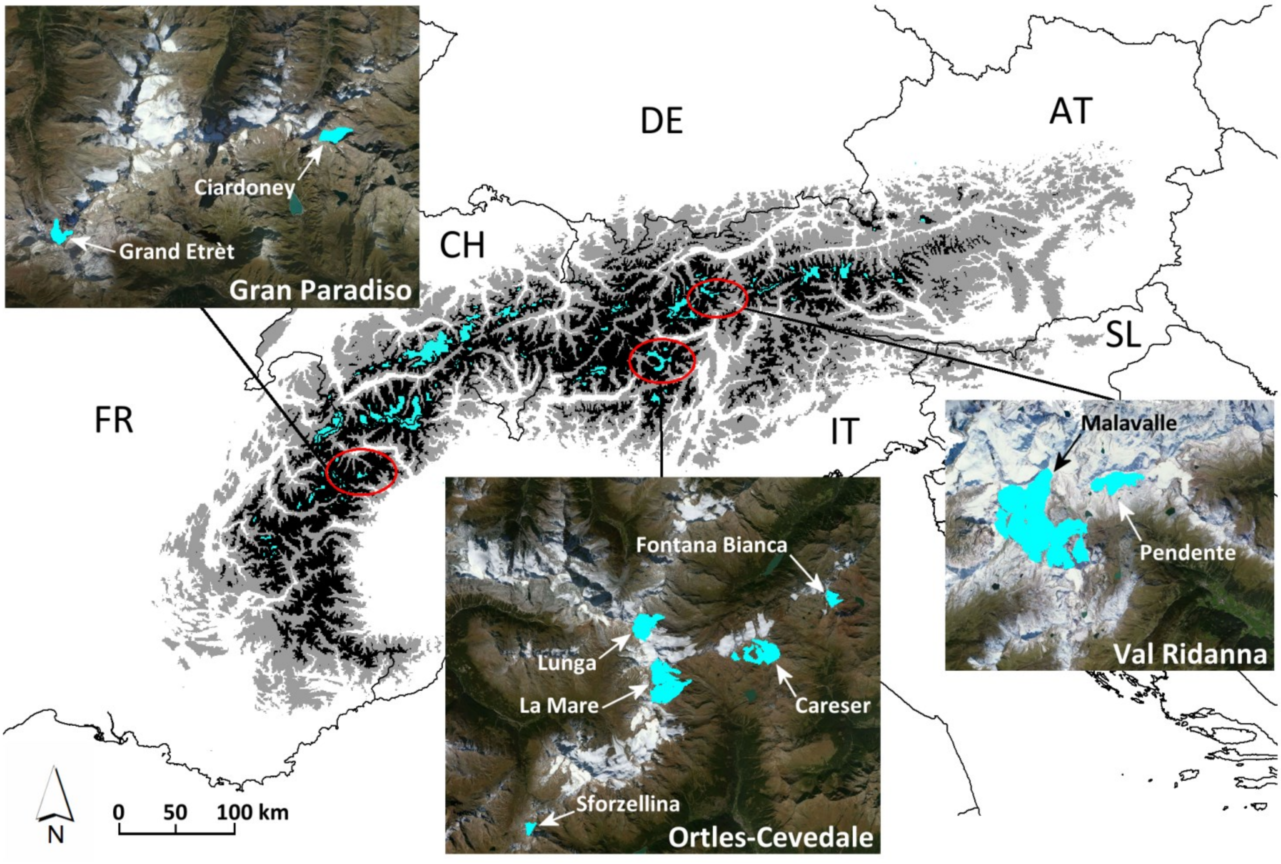

Figure 1. Geographic setting of the glaciers with mass balance measurements analysed in this work (Microsoft® BingTM Maps).

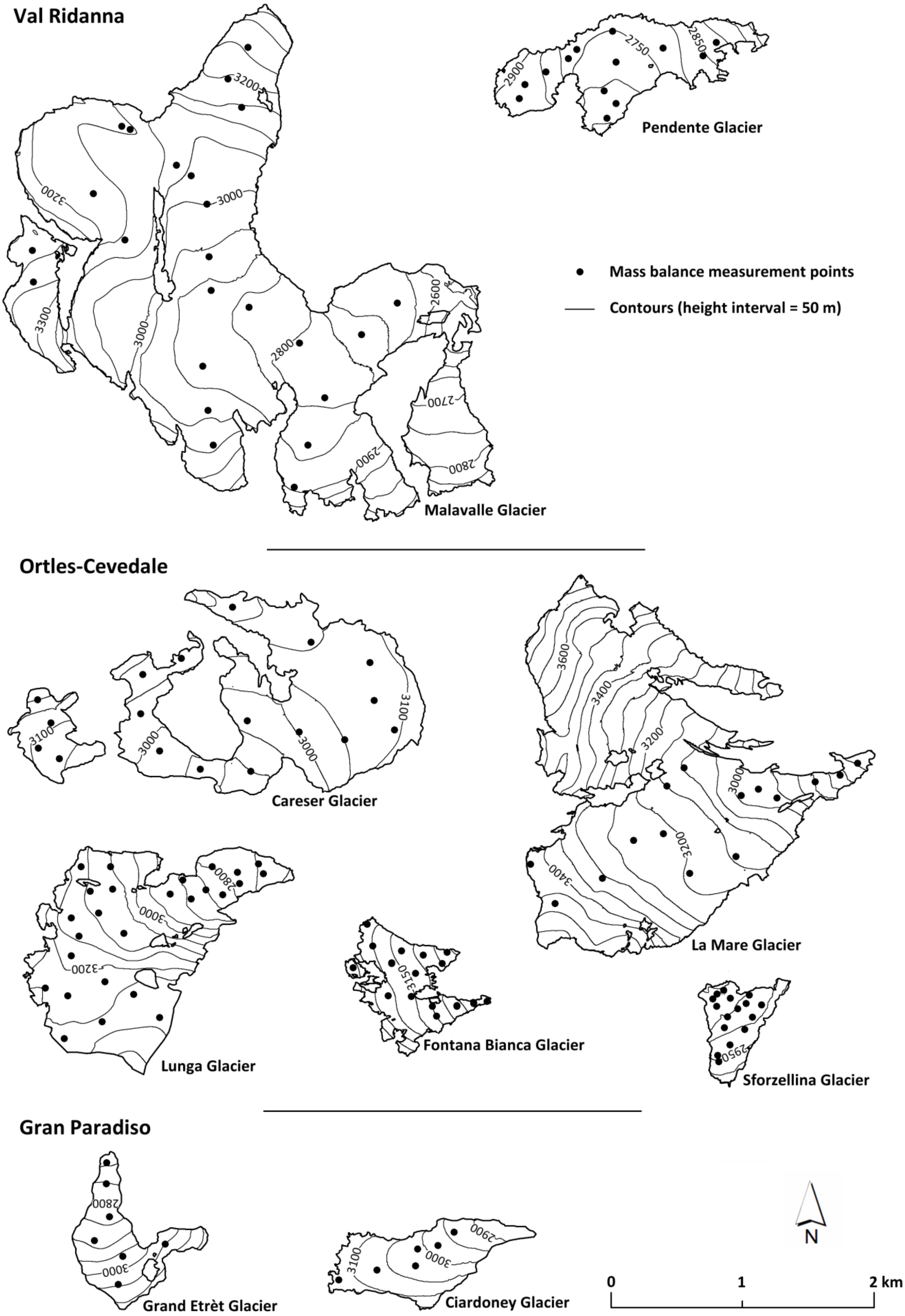

Figure 2. Surface topography and measurement network of the nine glaciers analysed in this study.

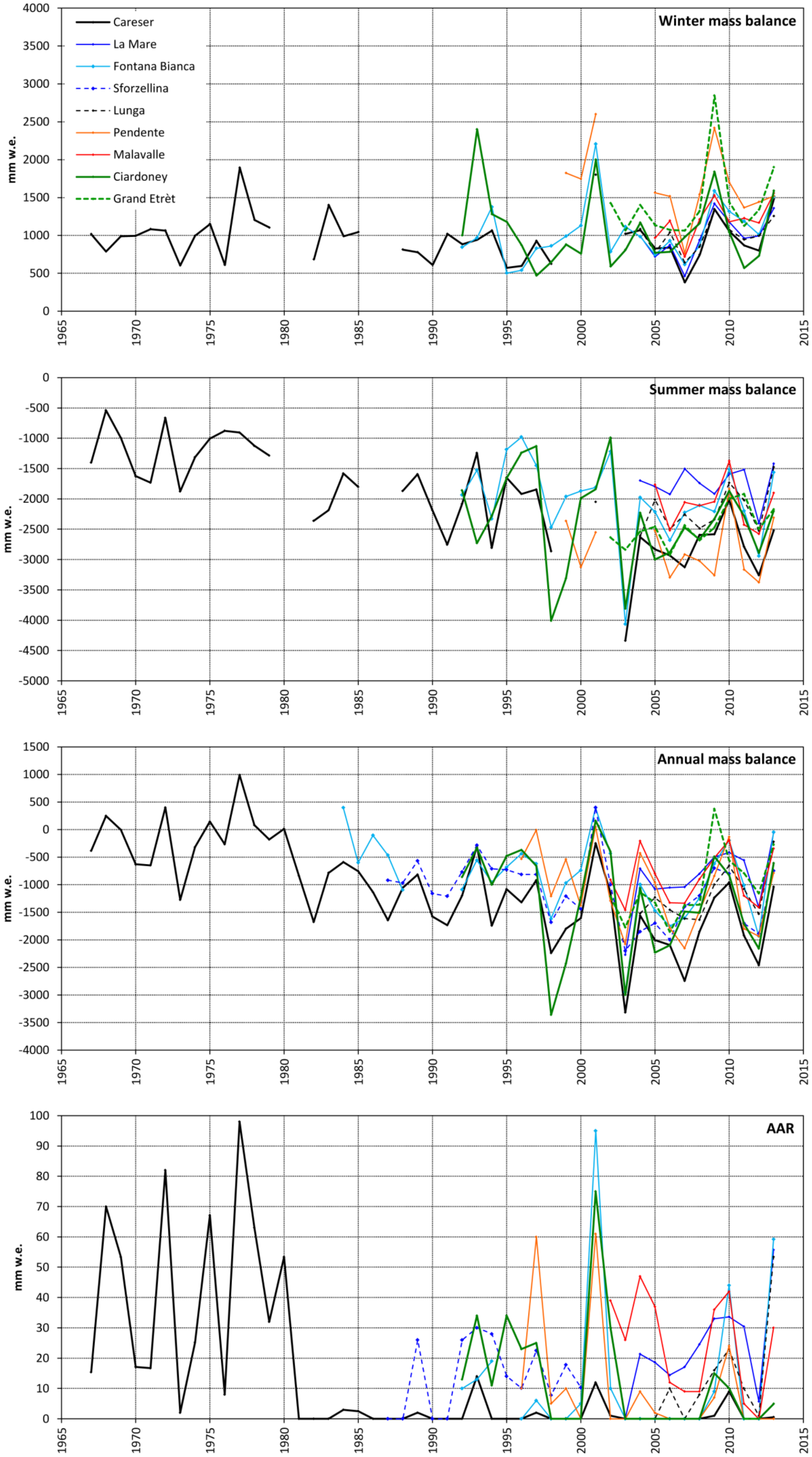
Winter mass balance
Summer mass balance
Annual mass balance
AAR
Careser
La Mare
Fontana Bianca
Sforzellina
Lunga
Pendente
Malavalle
Ciardoney
Grand Etrèt
mm w.e.
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
100
90
80
70
60
50
40
30
20
10
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015

Figure ~~2~~3. Time series of B_w, B_s, B_a and AAR for the nine Italian glaciers analysed.

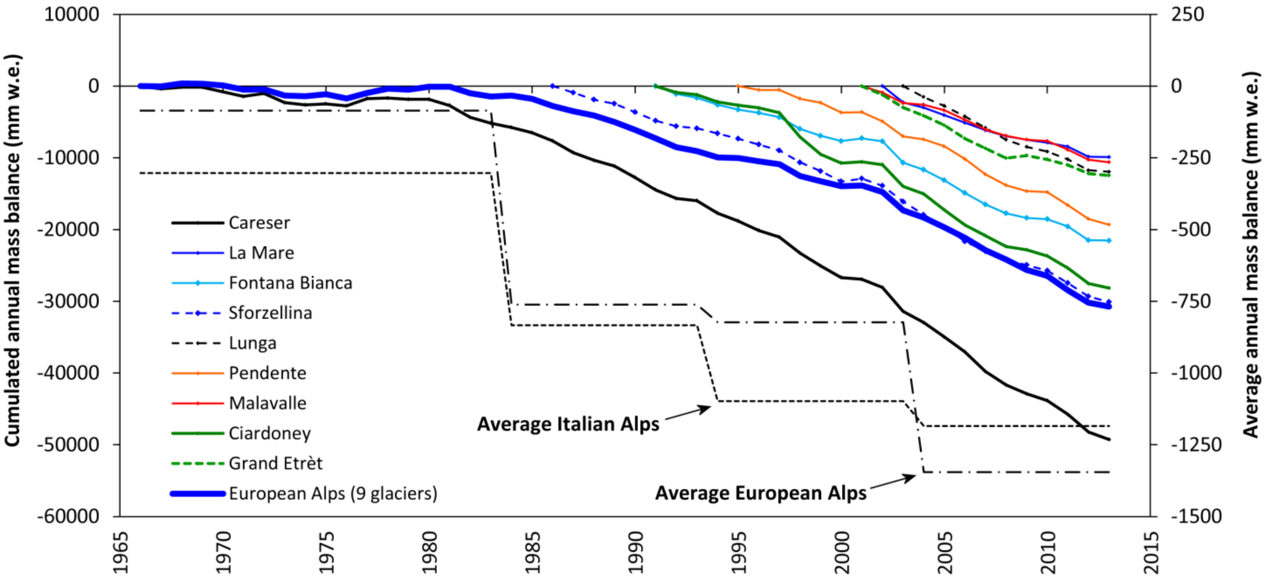

Figure ~~3~~4. Cumulative mass balance for the nine Italian glaciers and for a set of nine other glaciers representative of the European Alps. Dotted and dashed lines indicate the average B_a for the two groups of glaciers in the periods from 1967 to 1983, 1984 to 1993, 1994 to 2003 and 2004 to 2013.

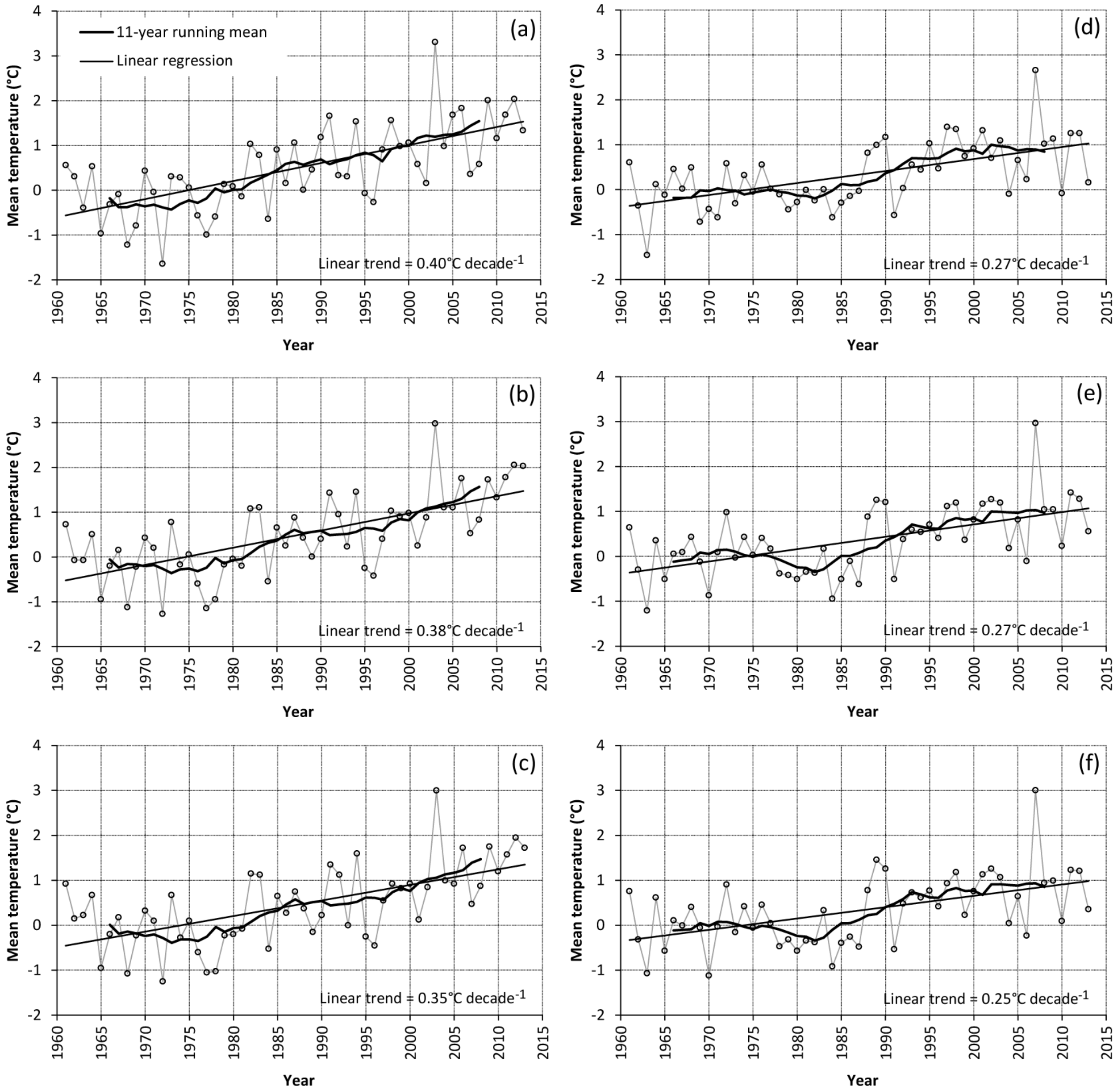

Figure ~~4~~5. Left column: mean ablation season (Jun-Sep) air temperature anomalies in (a) Gran Paradiso, (b) Ortles-Cevedale, and (c) Val Ridanna. Right column: mean accumulation season (Oct-May) air temperature anomalies in (d) Gran Paradiso, (e) Ortles-Cevedale, and f) Val Ridanna. Reference period: 1961-1990. All linear trends are significant at the 0.001 level.

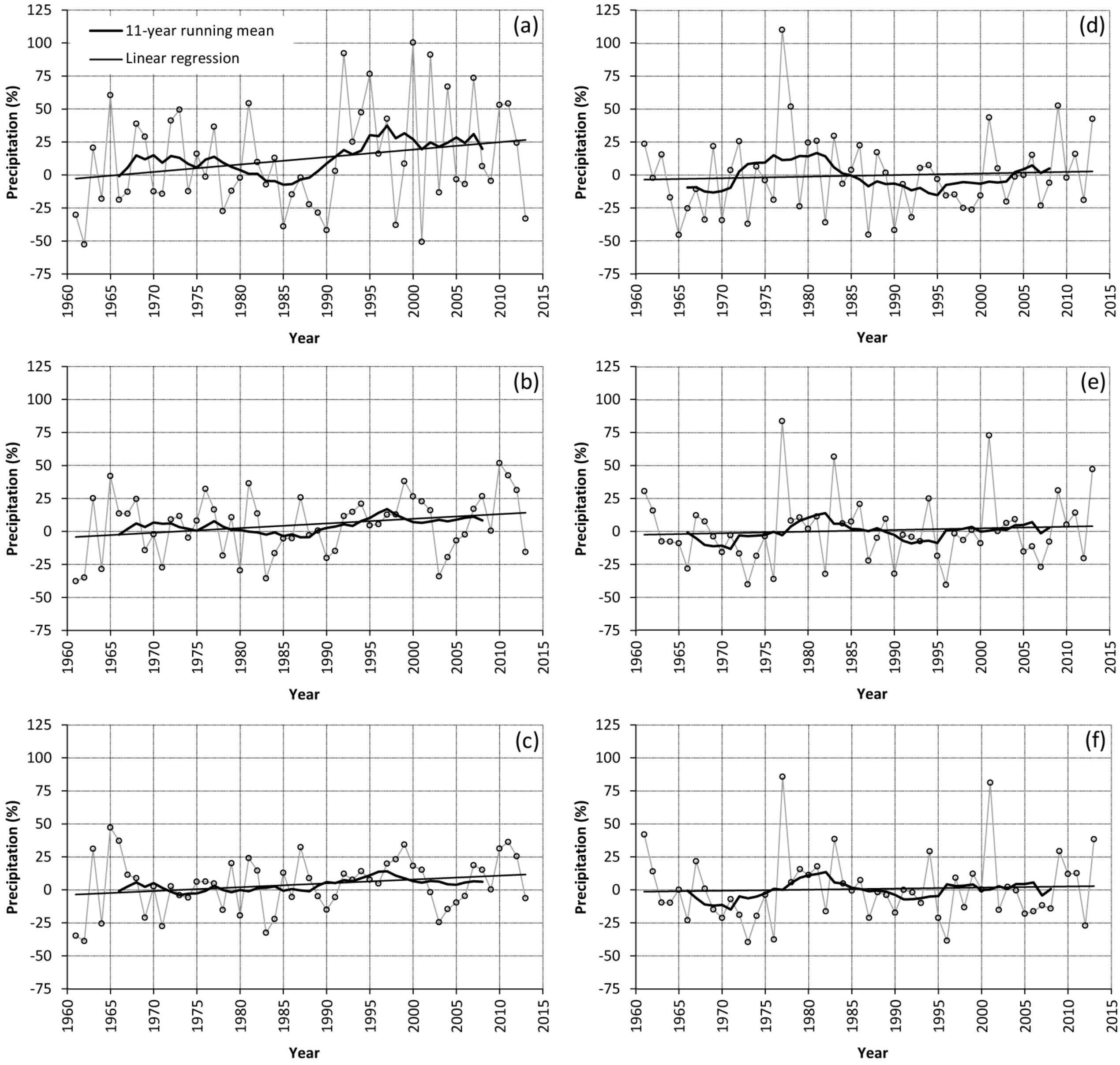

Figure ~~5~~6. Left column: ablation season (Jun-Sep) total precipitation anomalies in (a) Gran Paradiso, (b) Ortles-Cevedale, and (c) Val Ridanna. Right column: accumulation season (Oct-May) total precipitation anomalies in (d) Gran Paradiso, (e) Ortles-Cevedale, and f) Val Ridanna. Reference period: 1961-1990. None of the linear trends is significant at the 0.05 level.

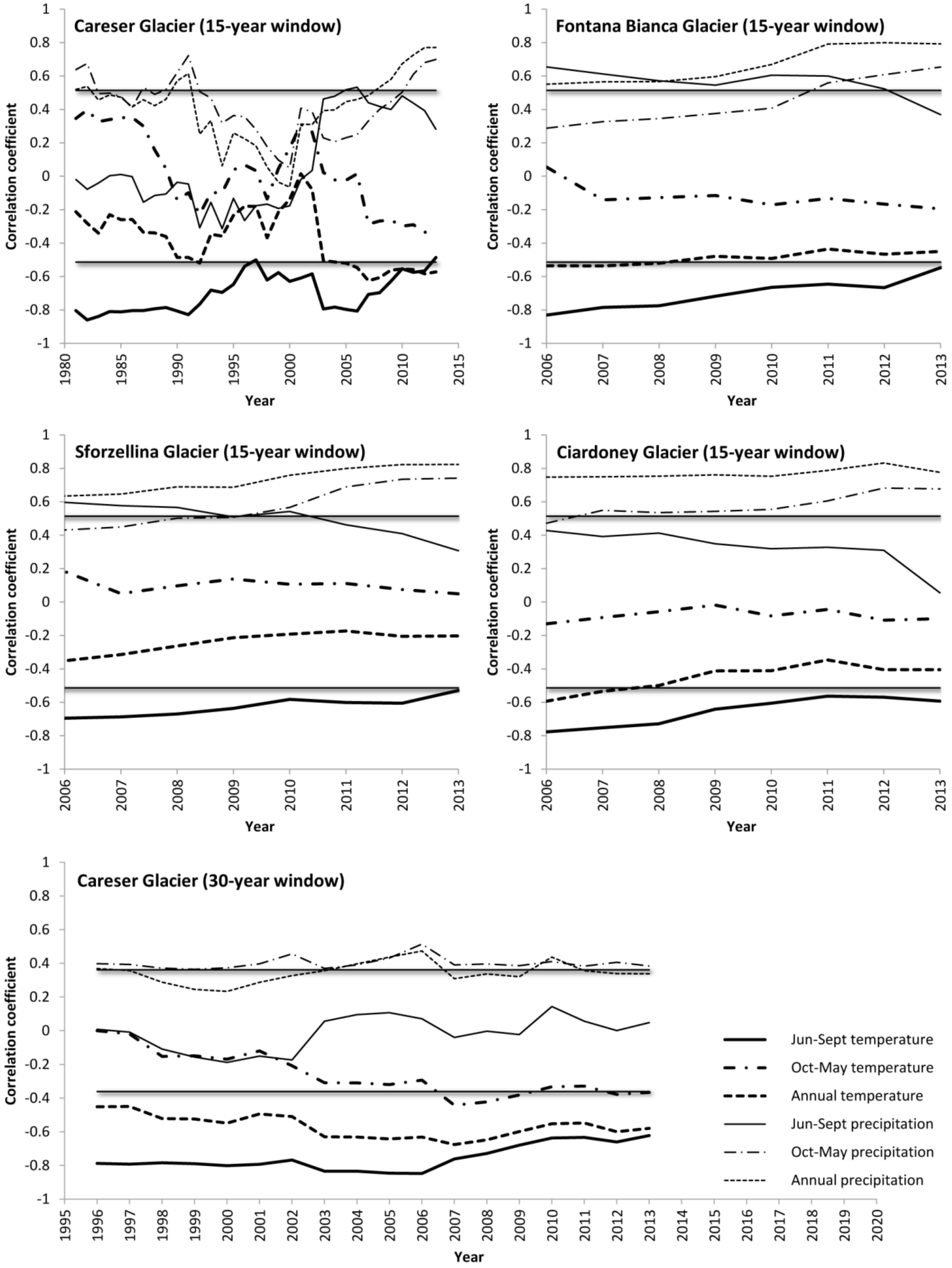

Figure ~~6~~7. Bootstrapped moving correlation coefficient between annual mass balance and seasonal values of air temperature and precipitation. Shaded straight lines indicate significance at 95% level.

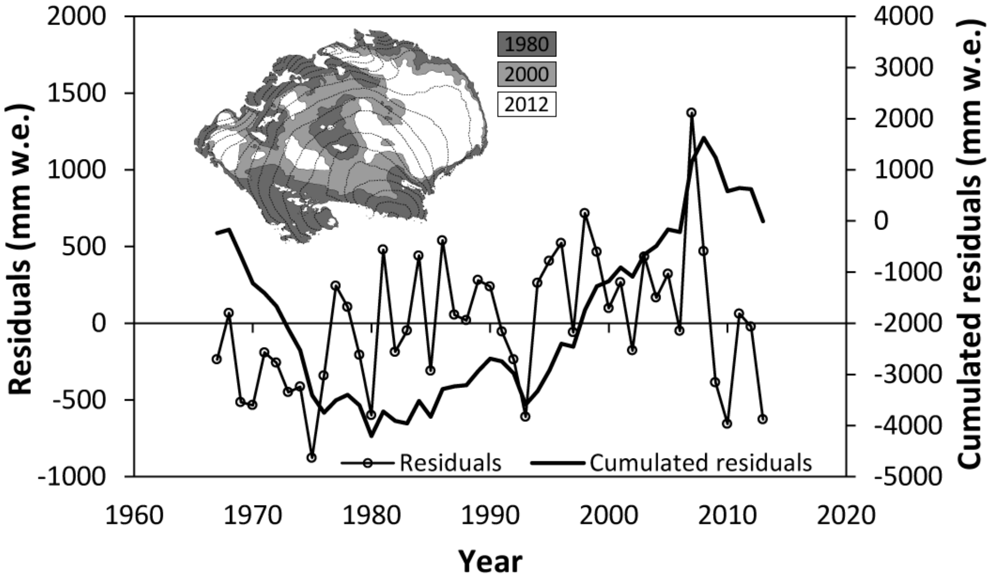

Figure ~~7~~8. Plot of residuals of the multiple linear regression of B_a vs. Oct-May precipitation and Jun-Sep temperature on the Careser Glacier. Multiple regression coefficients are reported in Table ~~5~~6. The inset shows the extent of the glacier in three different years.

Analysis of the mass balance time series of glaciers in the Italian Alps

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Abstract

This work presents an analysis of the mass balance series of nine Italian glaciers, which were selected based on the length, continuity and reliability of observations. All glaciers experienced mass loss in the observation period, which is variable for the different glaciers and ranges between 10 and 47 years. The longest series display increasing mass loss ~~rates, that~~rates, which were mainly due to increased ablation during longer and warmer ablation seasons. The mean annual mass balance (B_a) in the decade from 2004 to 2013 ranged from -1788 mm to -763 mm w.e. y^{-1}. Low-altitude glaciers with low elevation ranges are more out of balance than the higher, larger and steeper glaciers, which maintain residual accumulation areas in their upper reaches. The response of glaciers is mainly controlled by the combination of Oct-May precipitations and Jun-Sep temperatures, but rapid geometric adjustments and atmospheric changes lead to modifications in their response to climatic variations. In particular, a decreasing correlation of B_a with the Jun-Sep temperatures and an increasing correlation with Oct-May precipitations are observed for some glaciers. In addition, the Oct-May temperatures tend~~s~~ to become significantly correlated with B_a, possibly indicating a decrease in the fraction of solid precipitation, and/or increased ablation, during the accumulation season. Because most of the monitored glaciers have no more accumulation area, their observations series are at risk due to their impending extinction, thus requiring a soon replacement.

1 Introduction

The mass balance of glaciers is a key variable for monitoring strategies of the Earth climate system because it is the direct and undelayed response of glaciers to atmospheric conditions. Other reactions of glaciers to climatic changes, such as the fluctuations of the front, are more easy and immediate to measure but represent indirect, delayed and filtered signals (WGMS, 2008; Zemp et al., 2005).

The direct glaciological method (Østrem and Brugman, 1991) is the standardized method in worldwide glacier monitoring strategies. This method consists of in-situ measurements of the surface accumulation and ablation, taken at single points and then extrapolated and integrated to yield the glacier-wide surface mass balance ~~over the entire glacier~~ (Kaser et al., 2003; Cogley et al., 2011). The World Glacier Monitoring Service (WGMS) collects and publishes mass balance data of glaciers obtained by the glaciological method as part of global climate-related observation systems (Zemp et al., 2009; WGMS, 2012 and 2013, and earlier issues).

The European Alps are one of the regions of the world with the highest density of glaciers that are subject to mass balance observations. ~~25~~ Twenty five glaciers have ongoing and continuous mass balance series with at least 10 years of observations, and 11 of them are longer than 30 years (http://www.wgms.ch/metadatabrowser.html, last access: 27 September 2015). In the Italian Alps, nine glaciers have ongoing and continuous mass balance series longer than 10 years, and only one glacier (the Careser Glacier) has a series longer than 30 years.

The mass balance series of the glaciers in the Italian Alps have not yet been reviewed and analysed jointly. The Italian glaciers may have a peculiar behaviour compared to the glaciers from other regions of the European Alps, because of the differences in glacier characteristics, climatic features and trends of meteorological variables (Brunetti et al., 2006 and 2009; Auer et al., 2007). Differences may occur in the response of the glaciers in different sub-regions of the Italian Alps or with different characteristics, which have not been recognized. It is also interesting to highlight possible ~~non-linearities~~feedbacks in the response of Italian glaciers to atmospheric changes.

Therefore, this work aims to i) analyse and compare the direct mass balance series of the glaciers in the Italian Alps, ii) understand the behaviour of the measured glaciers in relation to the observed climatic trends, and iii) highlight possible future requirements for the mass balance monitoring strategy in the Italian Alps.

2 ~~Methods~~

~~2.1~~ Available mass balance series

In this work, we analyse the glaciers with at least 10 years of continuous and ongoing mass balance measurements, which were obtained using the direct glaciological methods and published in peer reviewed journals or in the WGMS publications (CGI, 1914–1977 and 1978–2011; Baroni et al., 2012, 2013, 2014; WGMS, 2012 and 2013, and earlier issues). ”Continuous” indicates the series with data gaps <10%, and ”ongoing” indicates that the mass balance observations have been performed in the last two years (i.e., the 2012 and 2013 hydrological years). These criteria ensure the comparability of the series, a sufficient length in the temporal analyses and reliability of the measurements and calculations.

Nine monitored glaciers ~~have~~ fulfil these characteristics in the Italian Alps and are clustered in three geographic areas (Fig. 1). The two monitored glaciers in the Gran Paradiso Group (Western Alps), i.e., Grand ~~Etrét~~ Etrèt (since 2002) and Ciardoney (since 1992), are rather small (area < 1 km^2) and have low mean elevations and low elevation ranges (Table 1). Snowfall is the prevailing feeding source, but windborne snow and avalanching also contribute to snow accumulation.

The longest series of mass balance measurements in the Italian Alps has been collected on the Careser Glacier, in the Ortles-Cevedale (Eastern Alps, Fig. 1) ~~from~~ since 1967. Currently, this glacier is undergoing rapid shrinking and fragmentation in smaller units. It is characterized by a flat surface, prevailing southern exposure, quite low mean elevation and feeding by snowfall. Its area decreased from 5 km^2 in 1967 to 1.6 km^2 in 2012 (Carturan et al., 2013a). In the 1980s, observations started in two other glaciers of the Ortles-Cevedale: Fontana Bianca and Sforzellina. These two small mountain glaciers (area <0.5 km^2) have different characteristics: Fontana Bianca is rather steep with negligible debris cover and mainly fed by snowfall, whereas Sforzellina is flatter, debris-covered in its lower part and fed by avalanches in its upper part. In the 2000s, mass balance observations began in the Lunga Glacier and in the southern branch of La Mare Glacier, which are larger valley glaciers (1.9 and 2.2 km^2, respectively) that reach higher elevations (3378 and 3518 m, respectively) and mainly fed by snowfall.

In Val Ridanna (Breonie Occidentali Group, Eastern Alps, Fig. 1), the measurements began in 1996 in the Pendente Glacier and were extended to the Malavalle Glacier in 2002. The first glacier is a 0.9 km^2 wide mountain glacier, characterized by a flat surface, low mean elevation, southern exposure and significant accumulation from windborne snow. The second glacier is a much larger (6.9 km^2) valley glacier with higher mean and maximum elevation and mainly fed by snowfall.

3 Methods

~~2.2~~3.1 Mass balance measurements and calculations

Point measurements of the annual mass balance in the ablation area consist of repeated readings of ablation stakes, which are made of aluminium, wood or plastic and drilled into the ice/firn using hand drills or steam drills. In the accumulation area, the depth of the snow at the end of the ablation season is measured using hand probes, and its density is determined in snowpits. Snow depth soundings and density measurements in the snowpits or by hand coring devices are also used for winter mass balance measurements, which are performed on all glaciers except Sforzellina. The summer mass balance is derived by subtracting the winter mass balance from the annual mass balance. The density of measuring points varies among different glaciers in relation to their extent, accessibility and complexity of the mass balance distribution (Fig. 2). The ablation stake density ranges from 4 points km^{-2} (Malavalle Glacier) to 45 points km^{-2} (Sforzellina Glacier). The density of snow depth soundings for the winter mass balance determination ranges from 15 points km^{-2} (Malavalle Glacier) to 142 points km^{-2} (Fontana Bianca Glacier).

Point measurements are interpolated and extrapolated to the entire area of the glaciers using different procedures. In the ~~grand~~ Grand ~~Etrét~~ Etrèt and Ciardoney glaciers, each ablation stake is assumed representative of a specific part of the glacier, where the mass balance distribution is assumed homogeneous. Then, a weighted mean is calculated, using the area of the homogeneous parts into which the glacier is subdivided as weights (http://www.pngp.it/, last access: 27 September 2015; http://www.nimbus.it/, last access: 27 September 2015). In Malavalle and Pendente glaciers, the area is divided into "sub-catchments", and for each sub-catchment, a linear regression of point balances vs. altitude is calculated and used for the spatialization (http://www.provinz.bz.it/wetter/glacierreport.asp, last access: 27 September 2015). In Careser Glacier, the even distribution of the mass balance and good coverage of measurement points enable the use of automatic interpolation algorithms (Spatial Analyst Tools) in the ESRI-ArcGIS software. Manual drawing of balance isolines is used for the remaining Sforzellina, Fontana Bianca, La Mare and Lunga glaciers (Catasta and Smiraglia, 1993; Cannone et al., 2008; http://www.provinz.bz.it/wetter/glacierreport.asp; Carturan, 2016~~ et al., 2015~~). The measurements are performed close to the time of maximum and minimum mass balance during the year, when the glacier and atmospheric conditions are favourable for field surveys. The "floating-date" time measurement system is used for all glaciers (Cogley et al., 2011).

Typical random errors reported in the literature for glacier-wide mass balance estimates obtained with these methods are of about ±200 mm w.e. y^{-1} (Lliboutry, 1974; Braithwaite and Olesen, 1989; Cogley and Adams, 1998; Cogley, 2009). The accuracy indicated by the investigators carrying out mass balance measurements in the nine Italian glaciers range between ±0.05 and 0.30 m w.e. y^{-1} (WGMS, 2015; Carturan, 2016). Assessments based on the comparison between the direct and the geodetic mass balance have been published for the Careser, La Mare and Lunga glaciers, indicating a good match of the two methods and revealing that a calibration of the direct mass balance results is not required (Carturan et al., 2013a; Galos et al., 2015; Carturan, 2016). ~~Typical errors reported in the literature for whole-glacier mass balance estimates obtained with these methods are of about ±200 mm w.e. y^{-1} (Lliboutry, 1974; Braithwaite and Olesen, 1989; Cogley and Adams, 1998; Cogley, 2009).~~

~~2.3~~3.2 Meteorological series

The climatic variables used in this work consist of synthetic records of the monthly mean temperature and total monthly precipitation, which are obtained for the centre of the three main geographic areas described in Sect. 2~~.1~~, using the procedure reported in Brunetti et al. (2012). Starting from sparse meteorological data recorded at meteorological stations, the synthetic meteorological series are generated using the anomaly method (New et al., 2000; Mitchell and Jones, 2005). This method is based on the assumption that the spatio-temporal structure of the signal of a meteorological variable over a given area can be described by the superimposition of two fields: the climatological normals over a given reference period (i.e., the climatologies) and the departures from them (i.e., the anomalies). The climatologies are linked to the geographic features of the territory and characterized by remarkable spatial gradients; the departures are linked to the climate variability and change, and they are generally characterized by higher spatial coherence.

Under this assumption, the climatologies and anomalies can be reconstructed in completely independent manners and based on different data sets. For climatologies, the priority is the high spatial resolution, and a short time span (few decades) is sufficient. A lower spatial resolution is sufficient for the anomalies, but more importance is given to the data quality and availability of long records. Thus, all series that were used for the anomaly component were subjected to homogenization.

The interpolation methods are different for the two components. The climatologies, which are characterized by high spatial gradients, were reconstructed using the procedure in Brunetti et al. (2014)~~ for the mean temperature~~, exploiting the relationship between the meteorological variable and the physical characteristics of the terrain. The anomalies, which are characterized by higher spatial coherence, were reconstructed using weighted averages as described in Brunetti et al. (2006). The weights are horizontal and vertical distance weighting functions, with the addition of an angular weight that accounts for the anisotropy in the distribution of stations around the sites. Finally, the two fields were superimposed to obtain the temporal series in absolute values for each site.

~~2.4~~3.3 Analyses of the mass balance and meteorological series

The time series of annual mass balance (B_a), winter mass balance (B_w), summer mass balance (B_s) and Accumulation Area Ratio (AAR, i.e., the ratio of the area of the accumulation zone to the area of the glacier) were analysed and compared to highlight the possible trends, break points, common behaviour and peculiarities of single glaciers and/or single years. To highlight the systematic differences among the glaciers, the mean values of B_a, B_w, B_s and AAR were calculated in the common period of observation from 2004 to 2013. The decadal means of B_a for the Italian glaciers were compared to the decadal means for a sample of nine representative glaciers of the European Alps (Zemp et al., 2005). The correlations among the B_a series of different glaciers and among B_a of single glaciers with the respective series of B_w and B_s were subsequently computed, to identify possible groups of glaciers with similar behaviours and to understand the relative importance of the seasonal components of mass balance.

Linear trends and moving averages were calculated for the time series of air temperature and precipitation to highlight the climatic drivers of the observed glacier changes. In particular, we focused on the precipitation of the accumulation season, from October to May (Oct-May), and on the air temperature of the ablation season, from June to September (Jun-Sep) (Pelto, 2008; Carturan et al., 2013b), computing their correlation with B_a and performing multiple linear regression analyses. For the four glaciers with the longest mass balance series (Careser, Fontana Bianca, Sforzellina and Ciardoney), we performed a moving correlation analysis of B_a vs. the seasonal and annual temperature and precipitation, to recognize possible changes and/or trends in their response and sensitivity to climatic fluctuations, e.g., ascribable to geometric adjustments.

~~3~~ 4 Results and discussion

~~3~~4.1 Analysis of mass balance series

The ~~longer~~ longest available series for the glaciers in the Italian Alps clearly show a trend towards more negative B_a in the observation period (Fig. ~~2~~3), and one or two change points, which were identified using the 'Changepoint' R package (Killick and Eckley, 2014). In particular, the series of Careser Glacier shows three phases: i) the period from 1967 to 1980 with near equilibrium conditions (mean B_a = -132 mm w.e. y^{-1}, STD = 540 mm w.e.); ii) the period from 1981 to 2002 with imbalanced conditions (mean B_a = -1192 mm w.e. y^{-1}, STD = 517 mm w.e.); and iii) the period after 2002 with stronger imbalance (mean B_a = -1926 mm w.e. y^{-1}, STD = 725 mm w.e.). A sudden transition in 1980-81 is also clearly visible in the series of AAR, which documents the nearly complete disappearance of the accumulation area of this glacier, which is likely responsible for the step change in its mass balance series during that period.

The transition of 2002-03 is also observable for the Fontana Bianca, Sforzellina and Pendente glaciers, whose measurements started in the 1980s and 1990s. Their mean B_a values changed from -599, -868 and -703 mm w.e. y^{-1}, before 2002, to -1257, -1471 and -1308 mm w.e. y^{-1} after 2002, respectively. This transition is less obvious for the Ciardoney Glacier, which experienced a notably negative mass balance already in 1998 and 1999. The B_w and B_s series have some gaps but suggest that the increased mass loss rates were mainly ascribable to increased ablation (and associated positive feedbacks) instead of decreased snow accumulation. These results are consistent with previous works, which indicate that the mass changes of the glaciers in the Alps, at the annual and decadal scale, are mainly driven by the summer balance (e.g., Schoner et al., 2000; Vincent et al., 2004; Zemp et al., 2008; Huss et al., 2015).

The AAR series show that the accumulation area almost vanished from all glaciers in the 2000s except the years 2001, 2010 and 2013, when several glaciers were close to balanced-budget conditions mainly as a result of the increased B_w. In these years, the highest increase in AAR occurred in the Fontana Bianca Glacier, which is steep and exposed to the east. On the contrary, the AAR did not significantly increase in the neighbouring Careser Glacier, which is flatter and mainly exposed to the south (Table 1). This behaviour is uncommon for flat glaciers because they should be more sensitive to variations of the Equilibrium Line Altitude (ELA) than the steeper glaciers (Benn and Evans, 2010), and reveals that the Careser Glacier is almost completely below the current ELA, also in the years of ELA minima. La Mare and Malavalle glaciers, which are larger and cover a wider elevation range (Table 1), show more persistent accumulation areas, although their size is too small to ensure balanced-budget conditions.

The B_a and B_s values of different glaciers tend to diverge in years with largely negative mass balance and converge in years closer to equilibrium (1993, 2001, 2010 and 2013, Fig. ~~2~~3). Reinforcing processes and feedbacks likely amplify the differences among the glaciers in imbalanced years, particularly the decrease~~d~~ in the glacier-average albedo caused by the early disappearance of snow from low-lying, flat and less topographic-shielded glaciers, and by the accumulation of dust and debris on the surface. B_w also shows the alternation of years with small/large variability among the glaciers, but this behaviour cannot be clearly related to the magnitude of the snow accumulation, as observed in the two high-accumulation years 2009 (high variability) and 2013 (low variability). In this case, the spatial variability of the precipitation during the accumulation season, which is larger than the spatial variability of air temperature in the ablation season, determines the interannual variability of B_w for single glaciers, which is further controlled by snow redistribution processes. Snow redistribution appears more effective for the Pendente, ~~and~~ Grand Etrèt and Ciardoney glaciers, leading to over-accumulation in snow-rich winters (e.g., in 2009) and larger interannual variability of B_w. Correlation coefficients calculated between B_w and October-May precipitations range between 0.73 and 0.78 are significant at the 0.05 level only for Careser, La Mare, Lunga, Fontana Bianca and Malavalle, while they are not statistically significant for Pendente, Grand Etrèt and Ciardoney, in line with the hypothesised higher importance of snow redistribution processes in these three glaciers.

In the period from 2004 to 2013, significantly higher B_w is observed for Pendente and Grand Etrèt~~these two glaciers~~, compared with the other glaciers in the same geographic area~~, likely due to windborne snow during and/or following precipitation events~~ (Table 2), ~~. The high accumulation rate explains~~explaining the persistence of these two ice bodies at such low altitude (Table 1). In the same period, the Careser Glacier had the lowest average B_a and AAR, whereas the Malavalle and La Mare glaciers had the highest average B_a,

B_s and AAR, retaining accumulation areas in their upper parts. However, the mean AARs were remarkably low for all analysed glaciers, and far from balanced-budget conditions (AAR_0 = 0.55 - 0.58, Dyurgerov et al., 2009; Mernild et al., 2013). Overall, low-altitude and flat glaciers with low elevation ranges are more out of balance than the steeper glaciers at higher altitude with higher elevation ranges, as acknowledged in various other studies (e.g., Furbish and Andrews, 1984; Benn and Evans, 2010; Carturan et al., 2013b; Fischer et al., 2015).

At the regional scale, the spatial representativeness of five Italian mass balance glaciers can be assessed on the basis of the geodetic mass balance calculations performed by Carturan et al., (2013b). In the period from the 1980s to the 2000s, the average geodetic mass balance rate of the 112 glaciers in the Ortles-Cevedale Group has been -0.69 m w.e. y^{-1}. If we consider the average geodetic mass balance in the same period as an index of the spatial representativeness for single glaciers, we obtain in decreasing order: i) La Mare with -0.64 m w.e. y^{-1}, ii) Sforzellina with -0.86 m w.e. y^{-1}, iii) Fontana Bianca with -0.90 m w.e. y^{-1}, iv) Lunga with -1.00 m w.e. y^{-1}, and v) Careser with -1.43 m w.e. y^{-1}. Geodetic calculations only exist for few areas in the Italian Alps (e.g., Galos et al., 2015) and do not include the other four mass balance glaciers analysed in this study. Therefore it was not possible to evaluate their spatial representativeness at the regional scale. Similarly, quantitative assessments of the representativeness of all the nine glaciers at the scale of the entire Italian Alps will require further investigations, integrating in-situ measurements, remotely sensed observations and numerical modelling (WGMS, 2015).

The response of Italian glaciers to the climatic conditions of the last decades is similar to that of nine representative glaciers of the entire European Alps (Zemp et al., 2005; Fig. ~~3~~4), although single glaciers display different mass loss rates (Table 2). The Italian glaciers display ~200-250 mm w.e. y^{-1} more negative B_a until 2002 and ~200 mm w.e. y^{-1} less negative B_a since then. Therefore, it can be assessed that the mean B_a values for the Italian and "European" glaciers ~~is~~ are fairly similar. ~~Similar~~Comparable results were obtained by Huss et al., (2015), who compared the decadal mean B_a of glaciers from France, Switzerland, Austria and Italy. These comparisons may be affected by the ~~, although~~ loss of spatial representativeness of some glaciers (e.g. Careser in the Italian Alps and Sarennes in the French Alps) and by the different subsets of Italian glaciers ~~are~~ which are useable ~~for~~ in the four different sub-periods. ~~. Similar results were obtained by Huss et al., (2015), who compared the decadal mean B_a of glaciers from France, Switzerland, Austria and Italy.~~ In the last decade, the inclusion of La Mare and Malavalle glaciers in the Italian subset and the concurrent sharp decrease of B_a for the Sarennes, St. Sorlin and Gries glaciers explain the different behaviours of the two groups of glaciers. However, the smaller Italian glaciers (average area = 1.79 km^2) may have a shorter response time to climatic changes, adjusting their geometry faster than the larger glaciers (average area = 3.63 km^2) which are representative of the European Alps (Hoelzle et al., 2003; Abermann et al., 2009). The rapid shrinking and fragmentation of Careser Glacier is a good example: in the last decade, its area has halved, and it completely lost the parts subject to higher ablation (Carturan et al., 2013a). Changes in the general atmospheric circulation and spatial distribution of precipitation could also have played a role and will be discussed in Sect. ~~3~~4.2.

There is a generally high correlation among the B_a values of the analysed glaciers (Table 3). The series of Careser, Fontana Bianca and La Mare glaciers show a highly significant correlation with most other glaciers, even if they have different characteristics or are far away. On the contrary, the Lunga Glacier shows a lower correlation and lower statistical significance with the glaciers of the same mountain group. However, it has the shortest series, and most importantly, it does not include the highly negative B_a of 2003, which certainly increases the correlation among other glaciers. There are notably high correlations in the Ortles Cevedale between Careser and La Mare and between Fontana Bianca and La Mare glaciers. A similarly high correlation is observed between Pendente and Malavalle glaciers in Val Ridanna, whereas there is a much lower correlation between the two glaciers of the Gran Paradiso Group, which suggests that differences in local topo-climatic factors can be decisive on such small ice bodies (e.g., Kuhn, 1995; DeBeer and Sharp, 2009; Carturan et al., 2013c; Scotti et al., 2014; Colucci and Guglielmin, 2015).

For most glaciers, B_a is more correlated to B_s than to B_w (Table 4), which further confirms the importance of summer ablation. The relevance of the snow redistribution and over-accumulation on the Pendente and Grand Etrèt glaciers is indicated by the higher correlation of their B_a with B_w. On La Mare Glacier, the two seasonal components have similar correlations with B_a. However, these results are influenced by the length of the observation period and the presence/absence of extreme years with high accumulation (e.g., 2001) or high ablation (e.g., 2003) in the observation series of individual glaciers. For the analysed glaciers, no significant correlation was found between B_s and B_w.

~~3~~4.2 Climatic controls

In the period from 1961 to 2013, there are highly significant warming trends for the Jun-Sep air temperature (Fig. ~~4a~~5a, b and c); they are highest in the Gran Paradiso Group (0.40°C decade^{-1}) and lowest in Val Ridanna (0.35°C decade^{-1}). The three phases in the longer B_a and B_s series of glaciers (Fig. ~~2~~3) can be recognized as periods with stationary Jun-Sep temperature, separated by switches in the early 1980s and after the peak of 2003. The warming trends are lower in the accumulation season and range from 0.25 to 0.27°C decade^{-1} (Fig. ~~4d~~5d, e and f), but thermal inversions at the valley weather stations could have partially masked the warming at the altitude of the glaciers in this season. The transition towards higher Oct-May temperature occurred in the late 1980s, after a minimum in the first half of the same decade. A distinct warm peak in Oct-May temperature occurred in 2007.

The precipitation does not show any significant trend in the accumulation season (Fig. ~~5d~~6d, e and f). The moving averages display oscillations of 10-20% above and below the 1961-1990 mean, which lasted approximately 10-15 years and were higher in the Gran Paradiso Group than in the Ortles-Cevedale and Val Ridanna. Periods with below-average precipitation are recognized in the 1960s, first half of 1970s, and 1990s, whereas periods with above-average precipitation occurred in the second half of 1970s and the first half of 1980s. The last 10-15 years were characterized by precipitation close to the mean, with important maxima in 2001, 2009 and 2013, and minima in 2007 and 2012. Similarly to the findings from Durand et al., (2009a and b) and Eckert et al., (2011) for the French and western Swiss Alps, a change point in winter precipitation of Ortles-Cevedale and Val Ridanna series were identified in 1977, corresponding to an increase of about 10-12%. Linear trends of summer precipitation are positive but not statistically significant. The interannual variability of the Jun-Sep precipitation is remarkably higher in the Gran Paradiso Group (Fig. ~~5a~~6a, b and c).

Large scale circulation patterns, such as the North Atlantic Oscillation (NAO) and the Northern Hemisphere blocking frequency, are connected with the temporal and spatial variability of winter precipitation in the Alps (Quadrelli et al., 2001). Several studies highlighted a contrasting behaviour of precipitation anomalies in the Oct-May period between the northern and southern Alps, i.e. opposite correlation with indexed large scale circulation patterns (e.g., Quadrelli et al., 2001; Schmidli et al., 2002, Brunetti et al., 2006) and opposite long-term trends in the seasonal precipitation totals (e.g., Brunetti et al., 2006 and 2009; Auer et al., 2007). This characteristic, and the tendency towards a decreasing NAO index in the last two decades (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/JFM_season_nao_index.shtml, last access: 4

October 2015), leading to increased winter precipitation in the southern side of the Alps, may provide an additional explanation for the different behaviour of "European" and "Italian" glaciers shown in Fig. ~~3~~4. Opposite effects of the NAO on the winter precipitation and glacier mass balance in the northern and southern parts of the Eastern Alps were also reported, for example, by Marzeion and Nesje (2012).

A correlation analysis of B_w, B_s and B_a versus the seasonal and annual mean NAO index was performed, using the mass balance data of glaciers from Italy and from other nations of the European Alps (Table 5). The results show prevailing negative correlations between the B_w of Italian glaciers and the NAO in the accumulation season, whereas positive correlations prevail in other nations, with the exception of Gries Glacier which however is close to the Italian border. These results are in agreement with the mentioned literature and with our hypothesis of opposite effects of recent NAO trends in the winter precipitation of the northern and southern sides of the Alps. In line with the findings of Reichert et al., (2001), Six et al., (2001), and Thibert et al., (2013), a negative correlation was calculated between B_s/B_a and the NAO in the accumulation season. If a causal relationship can be hypothesised for the Italian glaciers, related to the albedo feedback from wet/dry winters (with low/high NAO, respectively), the same cannot be stated for glaciers in other countries, due to the prevalent positive correlation of their B_w with the winter NAO.

The examination of meteorological series confirms that increased ablation and the related feedbacks are the main causes of the increased imbalance of the analysed Italian glaciers, as observed in Sect. ~~3~~4.1. This result is further corroborated by the higher correlation of B_a with the Jun-Sep temperature than with the Oct-May precipitation, at least for the glaciers with longer observation series (Careser, Fontana Bianca, Sforzellina and Ciardoney, Table ~~5~~6). B_a of glaciers with shorter observation series is not significantly correlated with the Jun-Sep temperature; instead, two of them (La Mare and Lunga) show a correlation with the Oct-May precipitation. Combining the Oct-May precipitation and Jun-Sep temperature in a multiple linear regression model leads to highly significant coefficients for both variables, even when the single seasonal components are not correlated with B_a (e.g., for the Pendente and La Mare glaciers). Approximately two-thirds of the B_a variance can be explained by the multiple linear regression. The poorest results were obtained for the two glaciers in Val Ridanna (Pendente and Malavalle) and the Grand Etrèt Glacier. As the first two glaciers are close to the main Alpine divide, they likely benefit from the high orographic uplift that locally enhances precipitation (Schwarb, 2000), but which cannot be accounted for by the multiple regression model due to the lack of weather stations in that area. In addition, the multiple regression model does not account for accumulation by windborne snow on the Pendente and Grand Etrèt glaciers.

The Careser, Fontana Bianca and Pendente glaciers display significant negative correlations between their B_a and the Oct-May temperature. For the Careser Glacier, there is also a negative correlation between B_w and the Oct-May temperature. Normally, in this period, most precipitation falls as snow, and the glaciers have negligible ablation and low temperature sensitivity (Oerlemans and Reichert, 2000). However, increasing temperature starts to lead to significant ablation in this period and to reduce the fraction of solid precipitation as clearly detectable in the ablation season (Carturan et al., 2013b). An emblematic example is the warm accumulation season of 2006-07, when the liquid precipitation reached 3000-3100 m a.s.l. (24 October 2006), and ice ablation exceeded 50 cm at 3000 m a.s.l. on the Careser and La Mare glaciers.

The correlation between B_a of Careser Glacier and the Oct-May temperature starts to become significant in the late 1980s, as shown in the moving correlation analyses (30-year time window in Fig. ~~6~~7). In the first 20 years, the correlation was absent or not statistically significant. These results are consistent with the discussed effects of increasing temperature on the ablation and partitioning between liquid and solid precipitation (Beniston et al., 2003). Reducing the window size from 30 to 15 years leads to a noisier signal and in this case the correlation between B_a and Oct-May temperature does not reach the 95% significance thresholds. However, it is interesting to remark the reversal of the correlation sign from positive in the first years to negative in the last years.

The four glaciers in Fig. ~~6~~ 7 (Careser, Fontana Bianca, Sforzellina and Ciardoney) share a common trend towards i) a non-significant moving correlation between B_a and the Jun-Sep temperature and ii) a significant moving correlation between B_a and Oct-May precipitation. This behaviour is probably related to the snow-rich accumulation seasons of 2001, 2009 and 2013, and to the fact that the ablation season is already so warm that i) summer snow falls mostly above the highest reaches of the glaciers, which reduces the interannual variability of summer melt, and ii) conditions close to balanced-budget only occur after snow-rich accumulation seasons.

Rapid geometric changes may also lead to a non-linear response of B_a to atmospheric changes, at least for some glaciers. For example, the multiple regression residuals of the Careser Glacier, which were mostly positive in the 1980s, 1990s and 2000s, became predominantly negative after 2008 (Fig. ~~7~~8). This change may suggest that the rapid modifications occurred in the latest years could have induced a negative feedback, reducing the mass loss rate of the glacier, whose current surface and shape are strongly different from the recent past (inset in Fig. ~~7~~8). Because the multiple regression model does not use the Oct-May temperature as an explanatory variable, it cannot account for the effects of the warm accumulation season of 2006-07, which led to a very low B_w, early disappearance of winter snow and positive albedo feedback. Therefore, the year 2007 results in highly positive regression residuals.

~~3~~4.3 Future requirements

A common characteristic for all glaciers analysed is their very low mean AAR in the last decade (Table 2). Accumulation areas were almost inexistent in most glaciers, indicating that they will soon disappear, even without additional warming. Some glaciers are displaying morphological changes that indicate their impending extinction, such as rapid disintegration (e.g., Careser Glacier, Fig. ~~7~~8) and surface lowering in the upper accumulation area (e.g., Fontana Bianca Glacier). The AARs of approximately 0.25 indicate that accumulation areas still exist in the larger and higher-reaching La Mare and Malavalle glaciers. However, given that balanced-budget conditions require AAR close to 0.55, large mass loss and areal reduction are also expected for these two glaciers to reach equilibrium with the climatic conditions of the last ten years.

The forthcoming vanishing of the monitored glaciers put the continuation of their mass balance observations at risk. Recently-started monitoring programs in larger and higher-reaching glaciers, such as Malavalle and La Mare, will ensure continued observations in Val Ridanna and the Ortles-Cevedale. In line with the recommendations from the WGMS (Zemp et al., 2009), similar observation programs should start in other large and high-reaching glaciers of the Italian Alps, e.g., in the Gran Paradiso group (to substitute Ciardoney and Grand ~~Etrét~~Etrèt) and in other mountain groups. Both the initiation of observations over new glaciers and the replacement of vanishing glaciers will require an assessment of the spatial representativeness of single glaciers through the comparison of the current mass loss rates over wide geographic areas (Haeberli et al., 2013). This assessments can be obtained using modern techniques such as the multi-temporal differencing of digital elevation models, which enable the comparison of mass loss rates in the last years/decades, by means of the geodetic method, over entire regions or mountain ranges (e.g., Paul and Haeberli, 2008; Abermann et al., 2011; Carturan et al., 2013b; Berthier et al., 2014; Fischer et al., 2015). The geodetic mass balance should also help to control the glacier-wide B_a series measured with the direct glaciological method, and to construct a constant-geometry mass balance record (Elsberg et al., 2001) to be connected to climatic drivers.

~~4~~5 Conclusions

In this work, we have analysed the time series of the glaciers with mass balance observations in the Italian Alps. Based on the results of the analyses, the following conclusions can be drawn:

- All examined glaciers are experiencing imbalanced conditions, and the longer series show sustained negative trends of B_a.
- The observed behaviour was mainly caused by increased ablation, led by warmer temperature and related feedbacks. The total precipitation does not show any significant trend, but the fraction of solid precipitation decreased as a consequence of the warmer temperature.
- The B_a of the analysed glaciers is mainly correlated to B_s, except for two glaciers where windborne snow enhances the importance of B_w. For most glaciers, approximately two thirds of the B_a variance can be explained by multiple linear regression, using the Oct-May precipitation and Jun-Sep temperature as independent variables.
- The monitored Italian glaciers have comparable mass loss rates to a sample of representative glaciers of the entire European Alps. However, the moving correlation analyses and time series of residuals from multiple linear regressions suggest that the smaller (and thinner) Italian glaciers may be reacting faster to atmospheric changes.
- Most monitored glaciers have no more accumulation area and are at risk of extinction, even without additional warming. Therefore, they will soon require a replacement with larger and higher glaciers that retain accumulation areas.
- Regional assessments of the mass loss rates using the geodetic method are required to identify possible replacing glaciers, evaluate their spatial representativeness and enable the transitions from replaced to replacing glaciers, as suggested by Haeberli et al. (2013).

Author contribution

M. Brunetti processed the meteorological data and prepared the synthetic meteorological series used in this work. Thomas Zanoner compiled the database of the mass balance data and geometric characteristics of the glaciers. L. Carturan and Giulia Zuecco performed the temporal and statistical analyses of the mass balance series. L. Carturan prepared the manuscript with contributions from all co-authors.

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Tables

Table 1 – Physical characteristics of the Italian glaciers with the mass balance series analysed in this study (year 2006, NextData - DATAGRALP project: http://www.nextdataproject.it/?q=en/content/special-project-datagralp, last access: 27 September 2015; Salvatore et al., 2015).

Glacier	Geographic area	Area (km^2)	Minimum elevation (m a.s.l.(	Maximum elevation (m a.s.l.)	Median elevation (m a.s.l.)	Prevailing aspect	Average slope (°)	First survey year
Grand Etrèt	Gran Paradiso	0.47	2667	3190	2894	N	23	2002
Ciardoney	Gran Paradiso	0.59	2855	3170	3039	E-NE	18	1992
Fontana Bianca	Ortles-Cevedale	0.48	2889	3342	3166	E	23	1984
Sforzellina	Ortles-Cevedale	0.29	2790	3046	2868	NW	16	1987
Lunga	Ortles-Cevedale	1.86	2678	3378	3128	NE	19	2004
Careser	Ortles-Cevedale	2.39	2868	3279	3069	S	11	1967
La Mare (southern branch)	Ortles-Cevedale	2.16	2652	3518	3215	NE	21	2003
Pendente	Val Ridanna	0.95	2621	3064	2781	S	15	1996
Malavalle	Val Ridanna	6.92	2512	3441	2971	SE	14	2002

Table 2 – Mean values (and STD in brackets) of B_w, B_s, B_a and AAR for nine Italian glaciers in the period from 2004 to 2013 (Car = Careser, FB = Fontana Bianca, Pen = Pendente, Cia = Ciardoney, Sfo = Sforzellina, GE = Grand ~~Etrét~~Etrèt, Lun = Lunga, Mar = La Mare, Mal = Malavalle). Values expressed in mm w.e. except AAR that is in percent.

	Car	Mar	FB	Sfo	Lun	Pen	Mal	Cia	GE
B_w (9 years)	927 (330)	989 (301)	1085 (338)	\	991 (222)	1537 (425)	1194 (256)	1052 (421)	1472 (578)
B_s (9 years)	-2740 (368)	-1758 (303)	-2183 (457)	\	-2151 (368)	-2857 (525)	-2087 (386)	-2510 (378)	-2396 (321)
B_a (10 years)	-1788 (590)	-763 (395)	-1088 (642)	-1399 (505)	-1195 (466)	-1231 (692)	-825 (484)	-1419 (646)	-946 (648)
AAR (10 years)	1 (3)	25 (14)	11 (22)	\	12 (16)	4 (8)	23 (17)	3 (5)	\

Table 3 – Correlation matrix of B_a for nine Italian glaciers. * and ** indicate Spearman correlation significant at the 0.05 and 0.01 level, respectively.

	Car	FB	Pen	Cia	Sfo	GE	Lun	Mar	Mal
Car	1.00								
FB	0.82**	1.00							
Pen	0.85**	0.76**	1.00						
Cia	0.87**	0.86**	0.55*	1.00					
Sfo	0.82**	0.75**	0.65**	0.81**	1.00				
GE	0.74**	0.77**	0.66*	0.62*	0.69*	1.00			
Lun	0.70*	0.73*	0.60	0.48	0.49	0.77**	1.00		
Mar	0.90**	0.96**	0.70*	0.90**	0.82**	0.80**	0.71*	1.00	
Mal	0.87**	0.84**	0.97**	0.61*	0.65*	0.68*	0.61	0.80**	1.00

Table 4 – Correlation coefficients of B_a vs. B_w and B_s. * and ** indicate Spearman correlation significant at the 0.05 and 0.01 level, respectively.

	No of years	Bw	Bs
Car	40	0.46**	0.94**
FB	22	0.24	0.84**
Pen	12	0.84**	0.67*
Cia	22	0.51*	0.76**
GE	12	0.84**	0.66*
Lun	10	0.64*	0.69*
Mar	10	0.66*	0.64*
Mal	9	0.48	0.85**

Table 5 – Correlation coefficients of B_w, B_s and B_a vs. seasonal and annual NAO. Five-year triangular moving averages have been applied to the time series before correlation analyses. *, ** and *** indicate Spearman correlation significant at the 0.10, 0.05 and 0.01 level, respectively.

		Winter balance			Summer balance			Annual balance		
Nation	Glacier	DJF NAO	Oct-May NAO	Annual NAO	DJF NAO	Oct-May NAO	Annual NAO	DJF NAO	Oct-May NAO	Annual NAO
I	Car	-0.51**	-0.34	-0.16	-0.23	-0.05	0.34	-0.30*	-0.13	0.23
I	FB	-0.11	0.18	0.00	0.22	0.10	0.25	0.07	0.35	0.41*
I	Pen	-0.70	-0.90*	-0.70	-1.00**	-0.90*	-1.00**	0.12	0.15	0.23
I	Cia	0.17	0.34	0.19	-0.03	0.10	0.27	0.13	0.27	0.36
I	GE	-0.81***	-0.74**	-0.79**	-0.88***	-0.76**	-0.91***	-0.86***	-0.76**	-0.83***
I	Lun	-0.94**	-0.94**	-0.94**	-0.94**	-0.77	-0.94**	-0.89**	-0.83*	-0.89**
I	Mar	-1.00***	-0.89**	-1.00***	0.14	0.03	0.14	-0.79**	-0.82**	-0.89***
I	Mal	-0.90*	-0.70	-0.90*	-0.50	-0.80	-0.50	-0.81***	-0.74**	-0.45
I	Sfo							0.59***	0.59***	0.61***
F	St. Sorlin							-0.44***	-0.38***	-0.04
F	Sarennes	0.36***	0.43***	0.49***	-0.53***	-0.50***	-0.19	-0.41***	-0.37***	-0.05
CH	Silvretta	0.28*	0.13	-0.05	-0.57***	-0.45***	-0.18	-0.38***	-0.28**	0.02
CH	Gries	-0.39***	-0.22	-0.18	-0.58***	-0.53***	-0.25*	-0.49***	-0.39***	-0.03
A	Sonnblick							-0.48***	-0.45***	-0.07
A	Vernagt	0.27*	0.51***	0.49***	-0.42***	-0.38**	-0.09	-0.36**	-0.26*	0.07
A	Kesselwand							-0.42***	-0.38***	-0.07
A	Hintereis							-0.55***	-0.44***	-0.10

Table ~~5~~ 6 - Spearman correlation coefficients and multiple regression results of B_a vs. seasonal mean temperature and precipitation. *, ** and *** indicate 0.05, 0.01 and 0.001 significance levels.

Air temperature – Correlation coefficients

	Car	FB	Sfo	Cia	Pen	GE	Mal	Mar	Lun
No of years	47	27	27	22	18	12	12	11	10
Jun-Sep	-0.77***	-0.49**	-0.52**	-0.64**	-0.40	0.01	-0.24	-0.16	0.49
Oct-May	-0.37**	-0.42*	-0.10	-0.18	-0.49*	-0.18	-0.57	-0.28	-0.33
Year	-0.68***	-0.49**	-0.30	-0.49*	-0.69**	-0.31	-0.71**	-0.27	-0.14

Precipitation – Correlation coefficients

	Car	FB	Sfo	Cia	Pen	GE	Mal	Mar	Lun
No of years	47	27	27	22	18	12	12	11	10
Jun-Sep	-0.15	-0.02	0.09	0.20	0.00	0.02	-0.04	0.26	-0.05
Oct-May	0.28	0.40*	0.32	0.47*	0.37	0.57	0.43	0.67*	0.71*
Year	0.11	0.36	0.39*	0.53*	0.34	0.64*	0.34	0.83**	0.53

Multiple linear regression - Coefficients

	Car	FB	Sfo	Cia	Pen	GE	Mal	Mar	Lun
No of years	47	27	27	22	18	12	12	11	10
Jun-Sep temperature	-776.453 (***)	-663.487 (***)	-575.225 (***)	-796.739 (***)	-496.521 (**)	-63.899	-355.106	-668.941 (**)	115.265
Oct-May precipitation	2.186 (***)	3.342 (***)	2.915 (***)	3.315 (***)	2.380 (*)	2.897 (**)	3.051 (*)	4.122 (**)	2.666 (*)
Intercept	-3265.013 (***)	-3311.632 (***)	-3176.797 (***)	1753.826	1011.719	-2707.559	19.212	-3380.905 (***)	-2619.872 (**)
% of explained variance	75.6	68.7	72.1	73.7	51.5	56.8	56.0	78.4	64.5

Figures

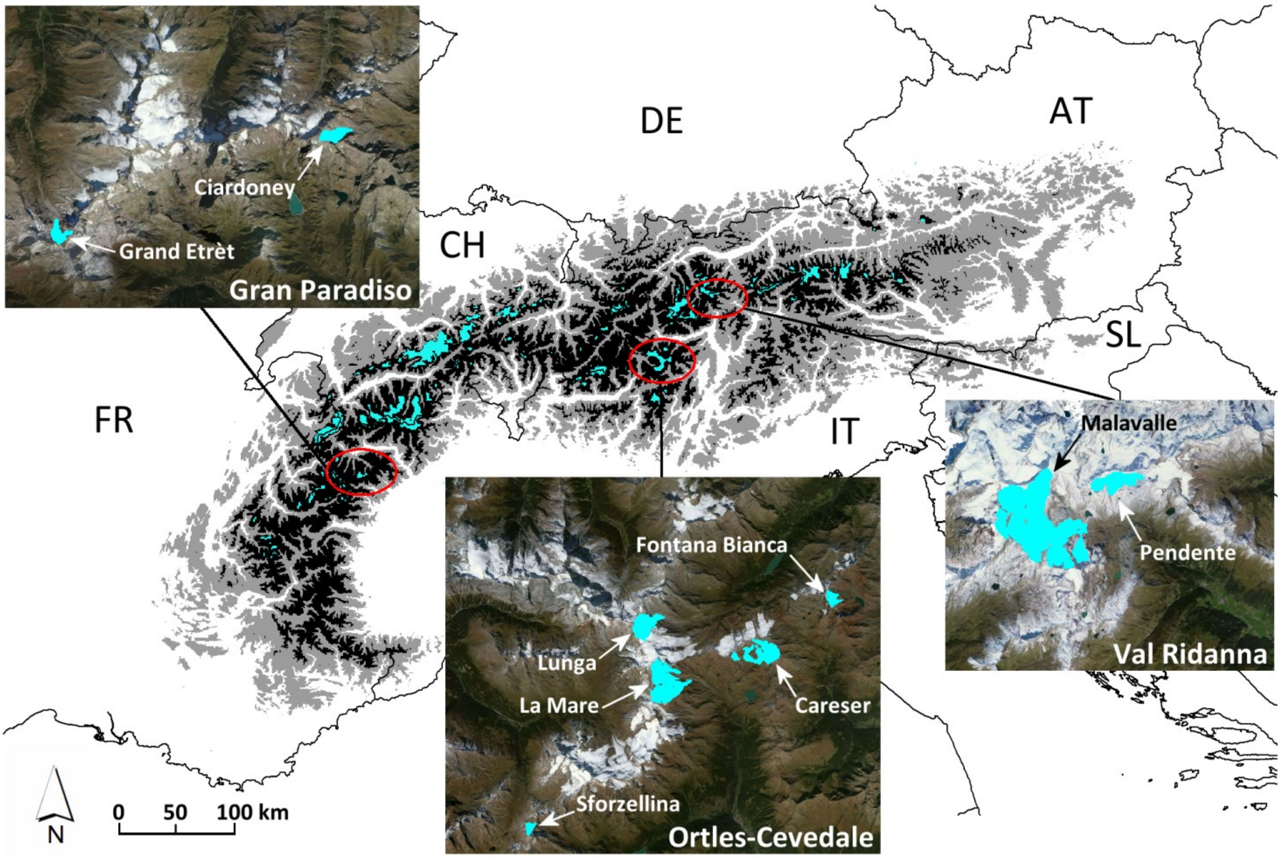


Figure 1. Geographic setting of the glaciers with mass balance measurements analysed in this work (Microsoft® BingTM Maps).

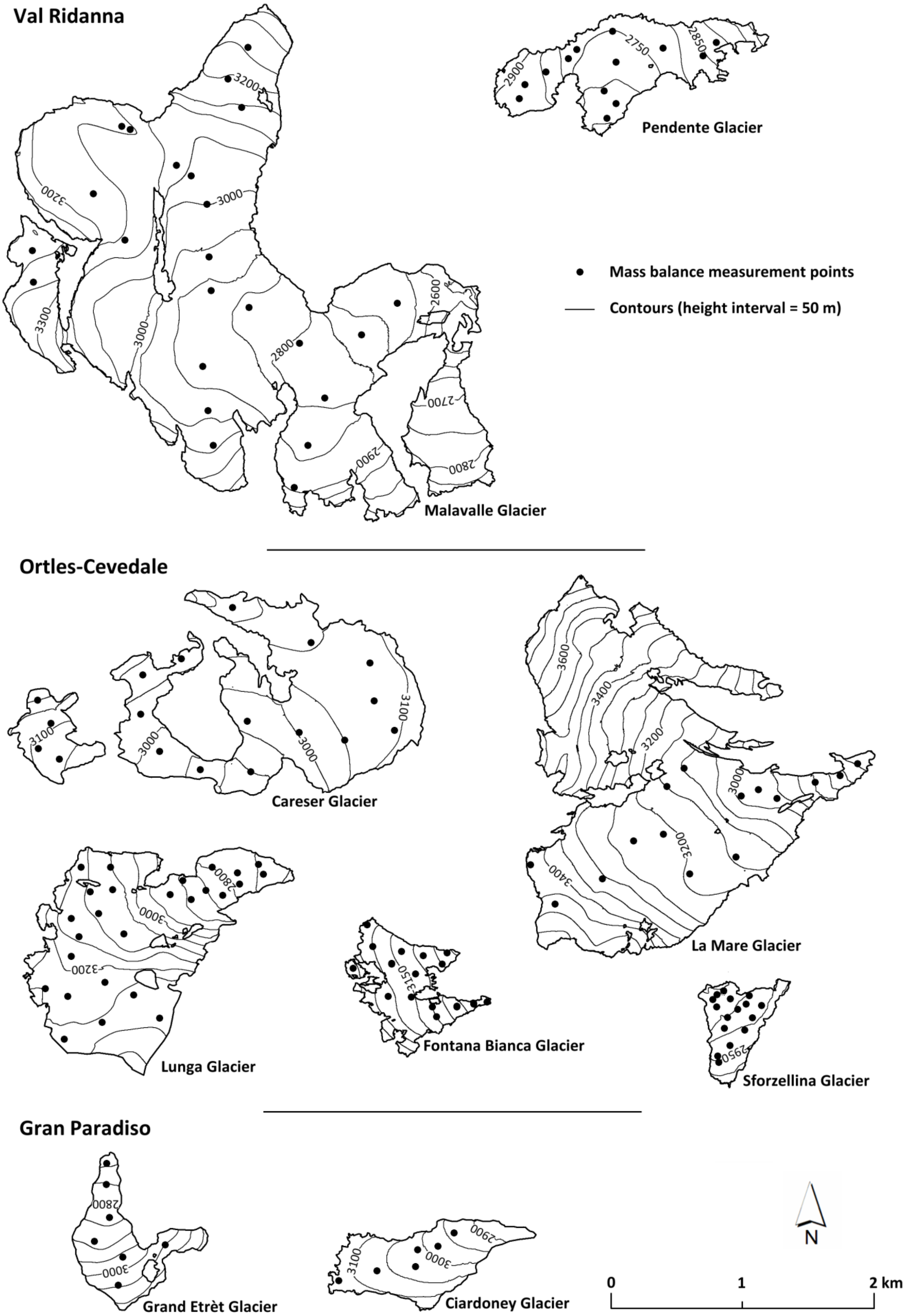
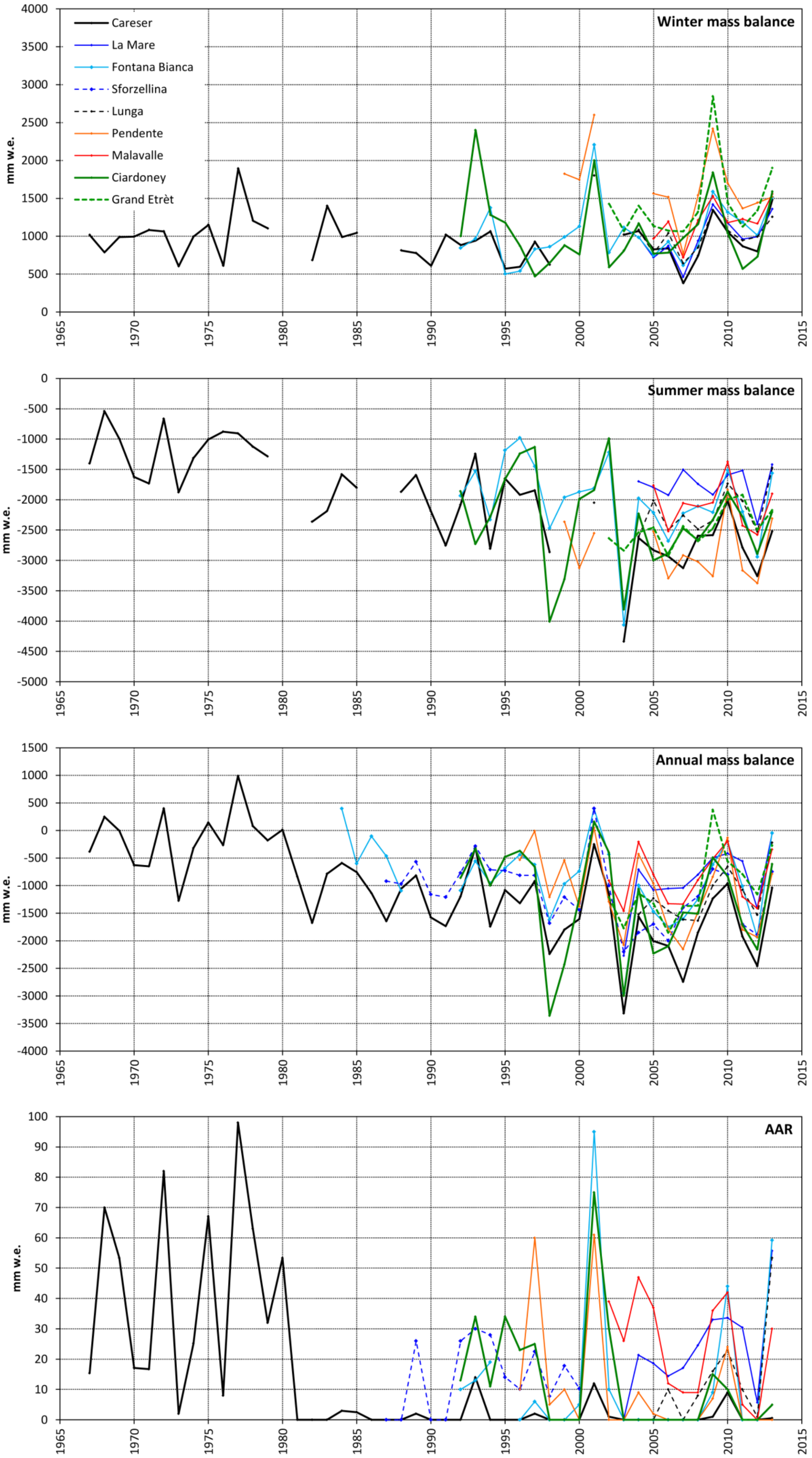


Figure 2. Surface topography and measurement network of the nine glaciers analysed in this study.


Winter mass balance
Summer mass balance
Annual mass balance
AAR
Careser
La Mare
Fontana Bianca
Sforzellina
Lunga
Pendente
Malavalle
Ciardoney
Grand Etrèt
mm w.e.
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
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-4500
-5000
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90
80
70
60
50
40
30
20
10
1965
1970
1975
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2015

Figure ~~2~~3. Time series of B_w, B_s, B_a and AAR for the nine Italian glaciers analysed.

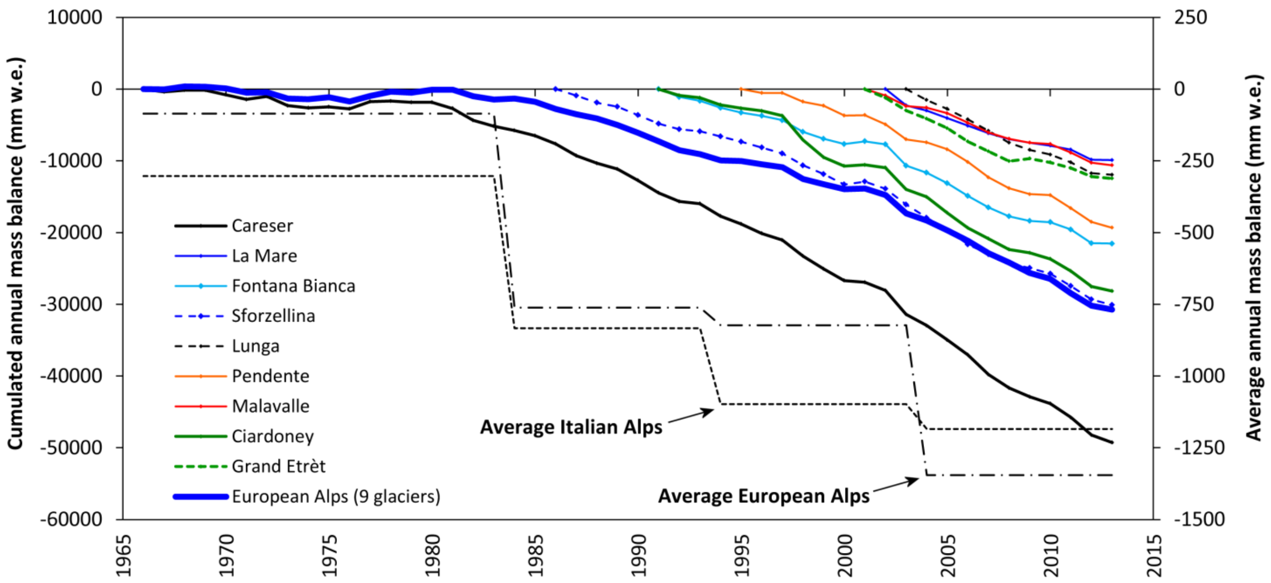

Figure ~~3~~4. Cumulative mass balance for the nine Italian glaciers and for a set of nine other glaciers representative of the European Alps. Dotted and dashed lines indicate the average B_a for the two groups of glaciers in the periods from 1967 to 1983, 1984 to 1993, 1994 to 2003 and 2004 to 2013.

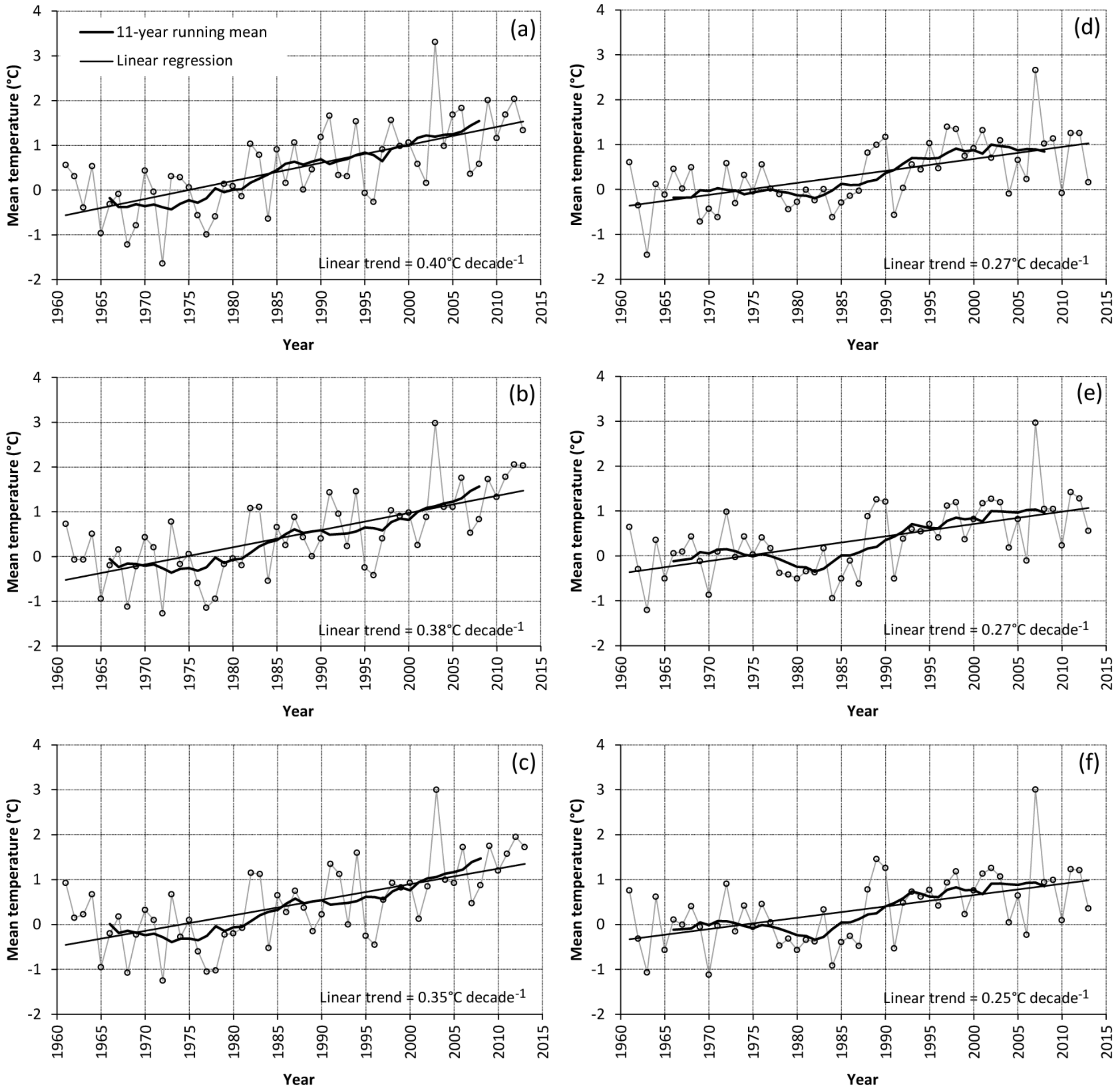

Figure 45. Left column: mean ablation season (Jun-Sep) air temperature anomalies in (a) Gran Paradiso, (b) Ortles-Cevedale, and (c) Val Ridanna. Right column: mean accumulation season (Oct-May) air temperature anomalies in (d) Gran Paradiso, (e) Ortles-Cevedale, and f) Val Ridanna. Reference period: 1961-1990. All linear trends are significant at the 0.001 level.

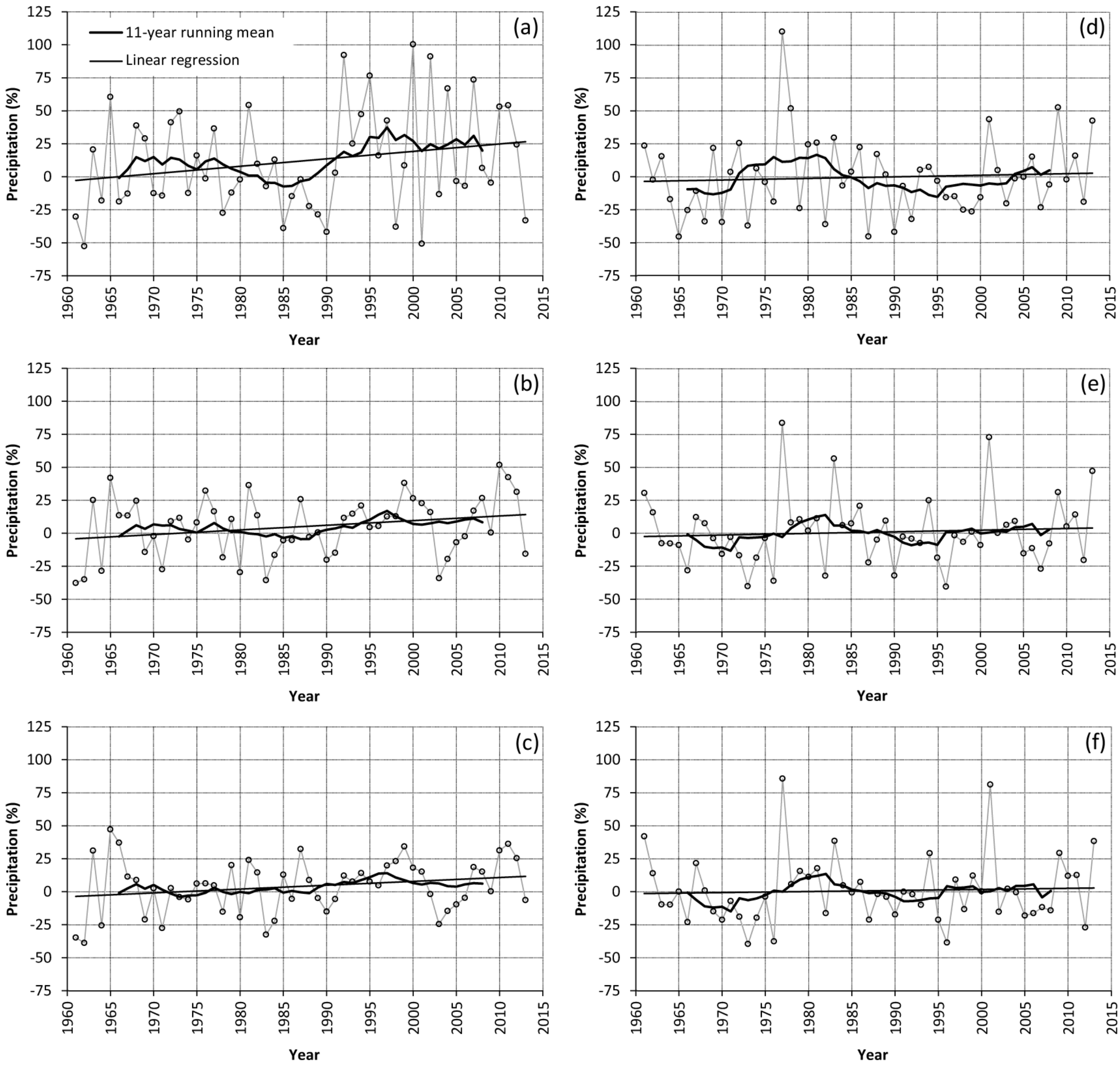

Figure ~~5~~6. Left column: ablation season (Jun-Sep) total precipitation anomalies in (a) Gran Paradiso, (b) Ortles-Cevedale, and (c) Val Ridanna. Right column: accumulation season (Oct-May) total precipitation anomalies in (d) Gran Paradiso, (e) Ortles-Cevedale, and f) Val Ridanna. Reference period: 1961-1990. None of the linear trends is significant at the 0.05 level.

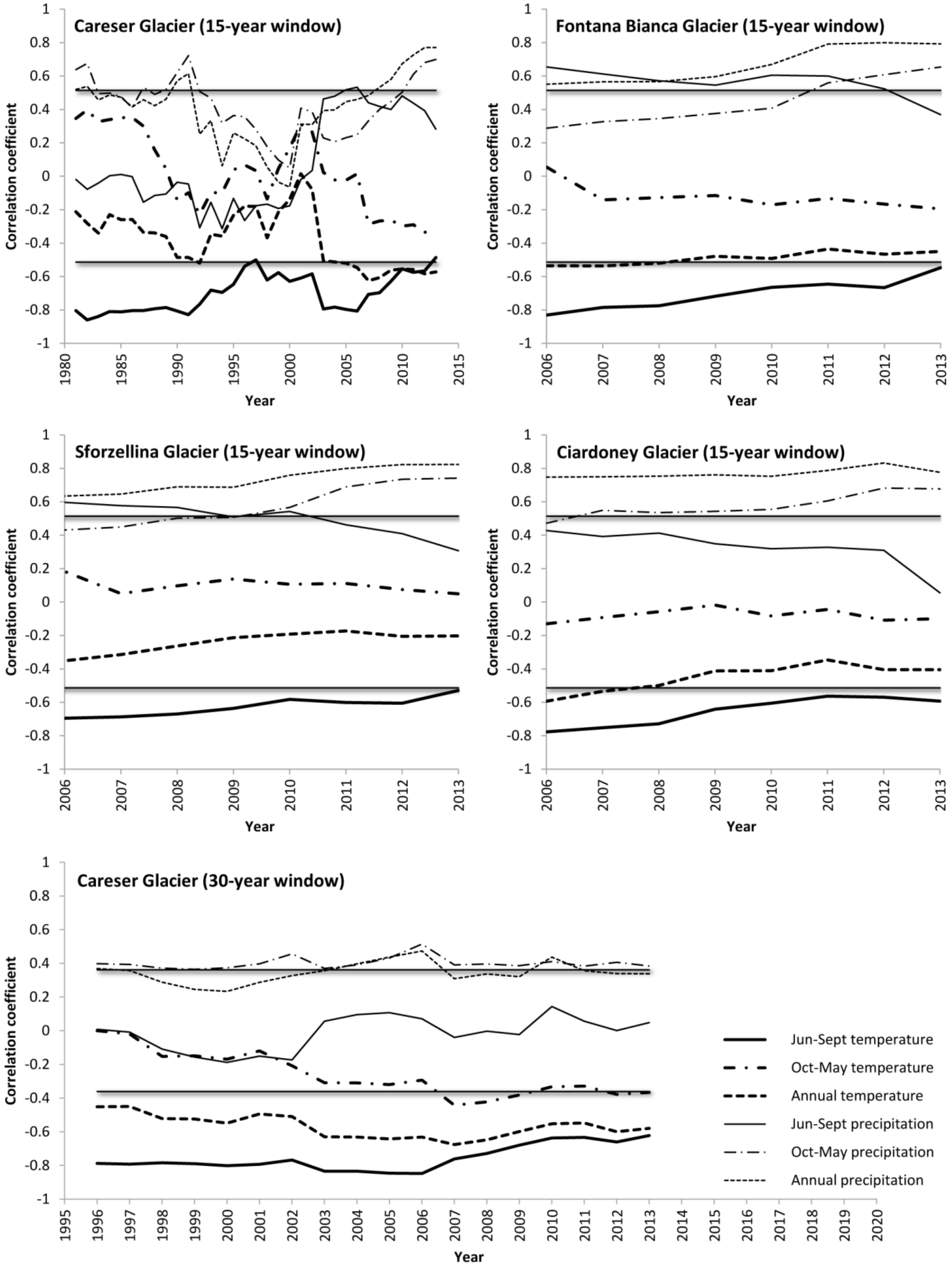

Figure ~~6~~7. Bootstrapped moving correlation coefficient between annual mass balance and seasonal values of air temperature and precipitation. Shaded straight lines indicate significance at 95% level.

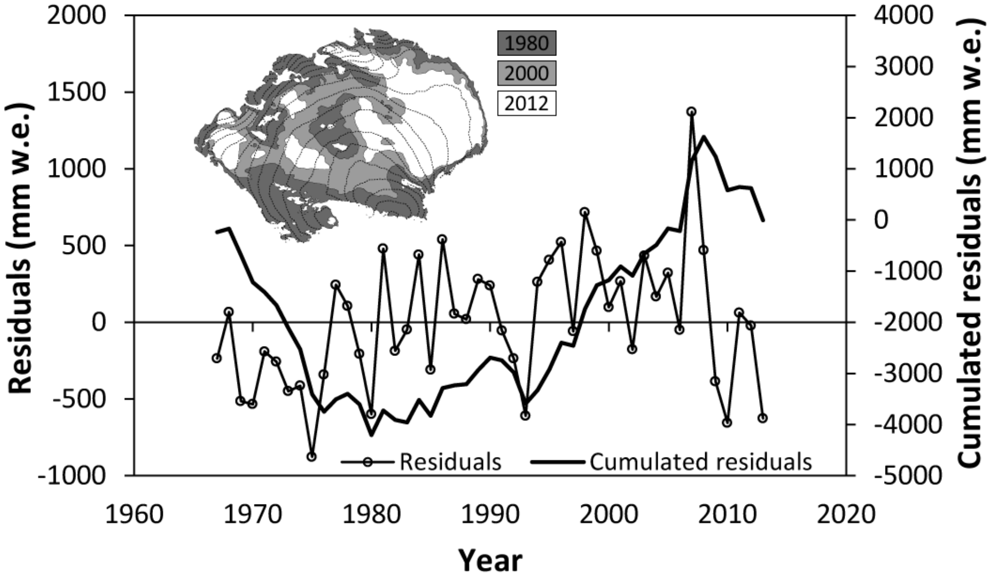

Figure ~~7~~8. Plot of residuals of the multiple linear regression of B_a vs. Oct-May precipitation and Jun-Sep temperature on the Careser Glacier. Multiple regression coefficients are reported in Table ~~5~~6. The inset shows the extent of the glacier in three different years.