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GHIACCIAIO DEL CALDERONE (APENNINES, ITALY): THE MASS BALANCE OF A SHRINKING MEDITERRANEAN GLACIER

ABSTRACT: PECCI M., D'AGATA C. & SMIRAGLIA C., *Ghiacciaio del Calderone (Apennines, Italy): the mass balance of a shrinking Mediterranean glacier*. (IT ISSN 1724-4757, 2008).

The *Ghiacciaio del Calderone*, the southernmost glacier in Europe, is located almost in the exact centre of the Italian peninsula. The glacier, which has been split into two ice aprons since the end of the Summer of 2000 and now could be better defined as a «*glacieret*» (or better as two «*glacierets*»), shows clear evidence of strong shrinkage, characterised by a rapid reduction in surface, volume and thickness. Twelve years (1995-2006) of mass balance data are presented here and discussed. During this period, there has been a total loss of about 4 m w.e. (with a maximum negative specific net balance of -1847 mm w.e. in 2002). Relationships with the climate trend are presented and discussed. The significant correlation between mass balances and winter precipitation made it possible to reconstruct balances for the 1920-1994 period. The balances proved to be almost constantly negative, with a total loss of about 60 m w.e.

KEY WORDS: Glacier mass balance, Mediterranean glaciers, Ghiacciaio del Calderone, Apennines (Italy).

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Il Ghiacciaio del Calderone, il più meridionale apparato glaciale europeo, è situato sulla catena degli Appennini nel centro della penisola italiana. Il ghiacciaio dal 2000 si è frammentato in due settori che potrebbero essere attualmente definiti «*glacionevati*» ed ha evidenziato chiari

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segnali di una forte contrazione con una rapida riduzione di superficie, di volume e di spessore. Nell'arco di dodici anni (1995-2006) sono stati effettuati bilanci di massa, i cui risultati sono presentati e discussi in questo lavoro. In questo periodo si è registrata una perdita complessiva di circa 4 m di equivalente in acqua (con il maggior bilancio negativo netto specifico di -1847 mm nel 2002). Vengono presentate e discusse anche le relazioni con le tendenze climatiche. La significativa correlazione fra bilanci di massa e precipitazioni invernali ha permesso di ricostruire i bilanci per il periodo 1920-1994, che sono risultati quasi costantemente negativi con una perdita totale di circa 60 m di equivalente in acqua.

TERMINI CHIAVE: Bilancio di massa dei ghiacciai, Ghiacciai del Mediterraneo, Ghiacciaio del Calderone, Appennini (Italia).

INTRODUCTION AND STUDY AREA

In the current climate situation characterized by global warming, glacier mass balances represent one of the key indicators serving to identify possible acceleration trends relating to this phenomenon (Haeberli & alii, 1999; Haeberli & alii, 2005; Haeberli & alii, 2007). The Mediterranean region is a particularly delicate area, where glaciers of limited size are found in mountain chains of relatively low altitudes (Pyrenees, Atlas Mountains, Maritime Alps, Apennines) (Messerli, 1980). The analysis of the mass balances of the Ghiacciaio del Calderone, as well as observations on snow patches in surrounding areas, can contribute to our knowledge of the current ongoing evolution of Mediterranean glaciers. In fact, the Ghiacciaio del Calderone (surface area <0.035 km²) represents a geographic and geomorphologic feature of great interest due to its position on the summit of the Gran Sasso d'Italia (2912 m a.s.l.), a mountain group located in the centre of the Apennine belt in the Mediterranean area (fig. 1).

This is the southernmost surface ice mass in Europe and the only one existing in the Apennine range. Many detailed studies have focused on the Ghiacciaio del Calderone over the past fifteen years, some also with the objective of recon-

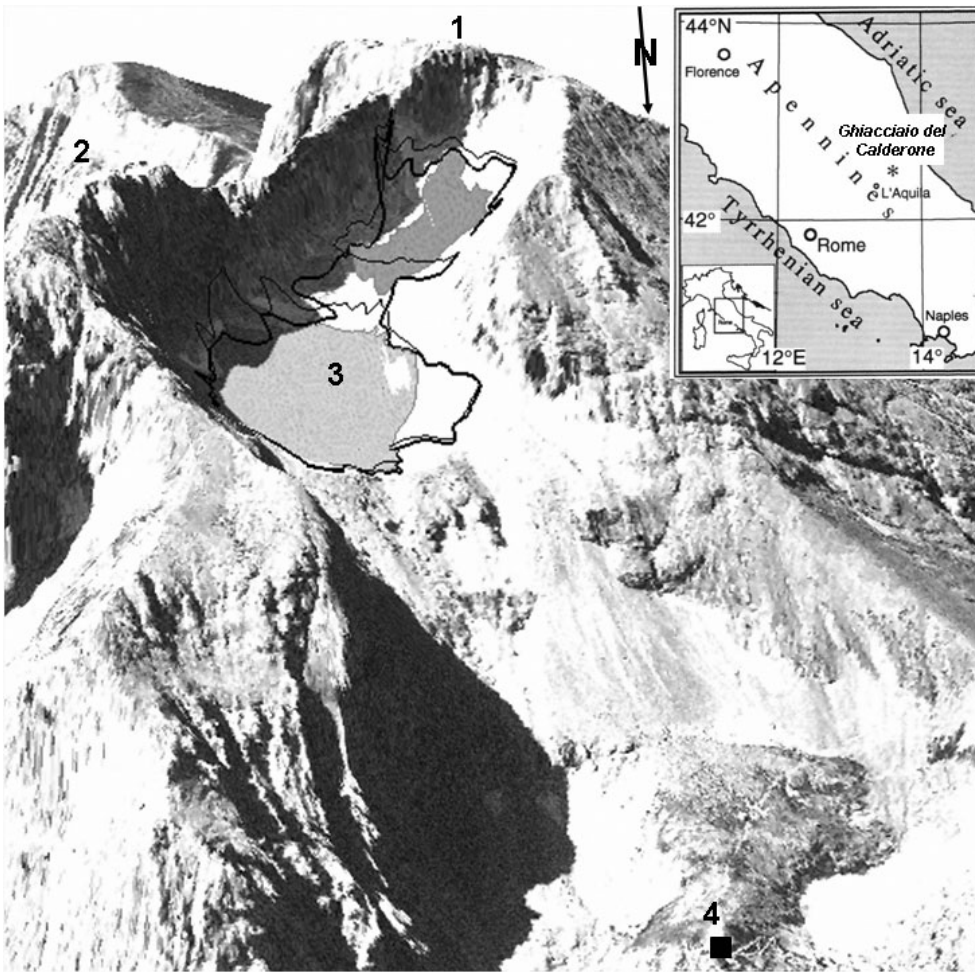


FIG. 1 - 3D air-view (aero photo mosaic draped on DTM - Digital Terrain Model derived from Regione Abruzzo, 1982) of the northern slope of the Gran Sasso d'Italia summit area: 1. Corno Grande - Vetta centrale (2912 m asl); 2. Corno Grande - Vetta occidentale (2893 m asl); 3. Ghiacciaio del Calderone; 4 (black square). Rifugio Franchetti - Franchetti Hut (Italian Alpine Club). The contraction and fragmentation are highlighted with the following graphic: with thin line: 1999 glacier border; with thick line: 2001 ice patches borders; with filled dashed grey area: 2003-2006 ice patches borders.

structing its evolution since the Little Ice Age (Gellatly & alii, 1994; D'Orefice & alii, 2000; D'Alessandro & alii, 2001; Pecci, 2001; D'Alessandro & alii, 2003; Pecci & alii, 2004; Pecci, 2006; Rovelli, 2006). Snow and ice on the Ghiacciaio del Calderone have been studied in recent years, with the glacier becoming a natural outdoor laboratory for the study of the environment (Balerna & alii, 2001; D'Alessandro & alii, 2001; Dramis & alii, 2002). As a result of the shrinking of the surface area and volume, in 2000 the glacier split into two ice aprons (D'Alessandro & alii, 2003). The glacier is now broken up into two parts and there is virtually no flow pattern of significance. Therefore, it can no longer be defined as a «glacier», for it has actually become two glacierets: the lower glacieret is situated on the floor of the cirque and is completely buried under surface debris, while the upper glacieret is found in the uppermost part of the valley and consists of ice and firm with little debris cover.

METHODS AND DATA SOURCES

Since the 1994-95 hydrological year, the mass balance of the Ghiacciaio del Calderone has been measured each year by traditional survey techniques («glaciological me-

thod»), with direct snow and ice accumulation and ablation measurements taken on stakes positioned on the surface of the glacier (Østrem & Bruggman, 1991; Kaser & alii, 2003). The annual field campaigns were organized with at least two data collection surveys: the first corresponding with the end of the accumulation season (generally end of May/beginning of June) and the second at the end of the ablation season (usually end of September/beginning of October). Further observations were made each year, during both the mid-summer and winter seasons. Starting from six initial stakes in the first five years, at present there are only three stakes still remaining (on the two existing ice aprons): one in the upper sector and two in the central-lower sector. The difficulty of maintaining a network of stakes must be noted, especially in the case of the lower, debris-covered sector, where even the readings of the changes in stake heights of the glacier surface are difficult to do. Usually a dozen of direct measures of snow accumulation thickness were taken with avalanche probes at representative sites near the beginning of the ablation season. These were usually taken in the surrounds of the ablation stakes and coupled with a snow pit in order to evaluate snow density and water equivalent.

As regards the neighbouring snow patches, at the beginning of each hydrological year (around the beginning of October), snow thickness and other parameters (surface area and snow density) were directly measured, and an archive of photograph was collected for each mass balance year. The volume difference resulting between the surveys conducted in October each year provided the annual mass balance. All measures and surveys were geo-referenced with a GPS static survey and differential correction, when data were available from the reference station in the city of L'Aquila, ~ 20 km from the glacier. Spatial and cartographic outputs were produced in a GIS (Geographic Information System) environment.

The climate analyses are based on:

- (i) data from the station at Pietracamela (1000 m asl) concerning temperature since 1932 and precipitation since 1919. The station is located on the north slope, about 6 km from the Ghiacciaio del Calderone terminus (2650 m asl) and like the glacier terminus. The data were obtained from the hydrological annals of the Servizio Idrografico Nazionale [National Hydrological Survey].
- (ii) unpublished data from the Franchetti Hut meteorological station (2433 m asl), the highest station in the Apennine chain. The station is located about 700 m from the glacier terminus (2650 m asl), on the north slope. The data are intermittent due to damage caused by high wind speeds. During the 1998-2003 working period, the interval from 8 January 2002 to 7 January 2003 is the only complete «year of measurement».

Data from the Pietracamela Station were used also to calculate correlations between the climate variables (annual mean temperatures, summer temperatures, total annual precipitation, winter precipitation) and the glacier balances for the 1995-2003 period, which made it possible to reconstruct the balances since 1920.

RESULTS

Ghiacciaio del Calderone mass balance 1995-2006

The mass balance of the Ghiacciaio del Calderone was calculated starting from the net mass balance for the following three zones of the glacier:

- zone A) between 2650 and 2700 m asl (lower sector);
- zone B) between 2700 and 2750 m asl (middle sector)
- zone C) between 2750 and 2830 m asl (upper sector).

As mentioned previously, it is important to note that a splitting of the glacier took place in the summer of 2000 (Dramis & *alii*, 2002; D'Alessandro & *alii*, 2003; Pecci, 2006), with the disappearance of the middle sector and the clear separation of the lower sector from the upper sector. The surface area has also shown a constant decrease: from 0.062 km² in 1995 to 0.052 km² in 1999. In 2006 the surface area of the upper glacieret was equal to 0.009 km², while that of the lower one was equal to 0.027 km² (fig. 2). The glacier surface area (as a unique apparatus up to 1990 year and as the resulting sum of the two ice aprons since the 2000 year) has been directly used in the calculation of

the yearly specific mass balance, taking into account surfaces onwards minor.

The mass balance of the Ghiacciaio del Calderone from 1995 to 2006 is presented in figure 3.

From 1995 to 1999, a period in which the Ghiacciaio del Calderone was still a single ice body, there was a cumulative specific net balance of -1731 mm w.e. (-346 mm/year). From 2000 to 2006, the lower sector was experiencing an almost constant reduction in thickness, leading to a total loss of 4208 mm w.e., with a maximum loss in 2002 (-1746 mm) and the sole exceptions in 2004 (+263 mm) and in 2006 (+650 mm), leading to a balance of -3295 mm for this period. During this same period (2000-2006), the upper sector (in actual and ongoing expansion up to 2006) registered a balance that was almost always positive, for a total of 3945 mm w.e. (with a maximum of 2400 mm in 2006). The year 2002 was the sole exception, as ablation was particularly strong (2165 mm), but not sufficient to bring about a negative change in the 2000-2006 balance, which remained positive at +1780 mm w.e.

If we do consider the Ghiacciaio del Calderone as a single ice body, we can note that the glacier yielded a negative cumulative balance over the entire observation period, with a loss of 3841 mm w.e. (-320 mm/year) in total thickness, although the loss was not homogeneously distributed over time. In particular, the positive balance in 2004 (+252 mm) and in 2006 (+1090 mm) has been reached during the more recent and warm years of monitoring.

Snow patch variations

The monitoring of the Ghiacciaio del Calderone was combined with surveys of some snow patches on the northern slope (with a N-NNE aspect) of the Gran Sasso d'Italia mountain group. In this framework, systematic annual observation of the following three representative snow patches produced by snow accumulation from wind and avalanches, and located within the mountain group shown in figure 1, has been carried out since the summer of 1997.

1. Valle delle Cornacchie (WGS84 coordinates: 42°28'33, 64697"N; 13°33'45,77806"E), at an altitude of about 2447 m asl, below the Sella dei due Corni, between Corno Grande and Corno Piccolo.
2. Gravone (WGS84 coordinates: 42°26'44,40313"N; 13°44'12,99227"E), at an altitude of about 1530 m asl, below the northern slope of Monte Camicia.
3. Fondo della Salsa (WGS84 coordinates: 42°27'10, 30"N; 13°42'53,46"E), at an altitude of 1276 m asl, at the toe of the northern slope of Monte Camicia.

Taking into account the constant presence of the snow patches until 1997, as directly reported by the local inhabitants and mountaineers, the summers from 1998 to 2002 represent a focus point, causing substantial reduction of the snow patches at the higher elevations (Valle delle Cornacchie) and the extinction of the others at the lower altitudes (Fondo della Salsa and Gravone) (Dramis & *alii*,



Fig. 2 - The Ghiacciaio del Calderone in 1912 (covered by firn) and in 2007, where is also drawn the border of the glacier in 1912; for the actual borders of the ice, see fig. 1. In the foreground the Little Ice Age frontal-later moraine is detectable.

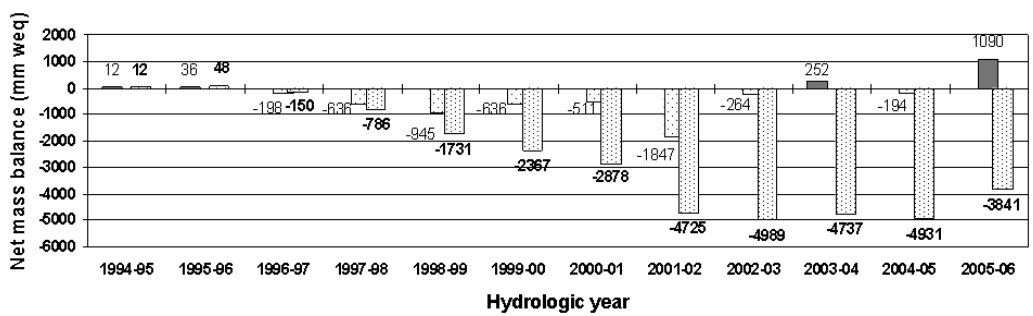
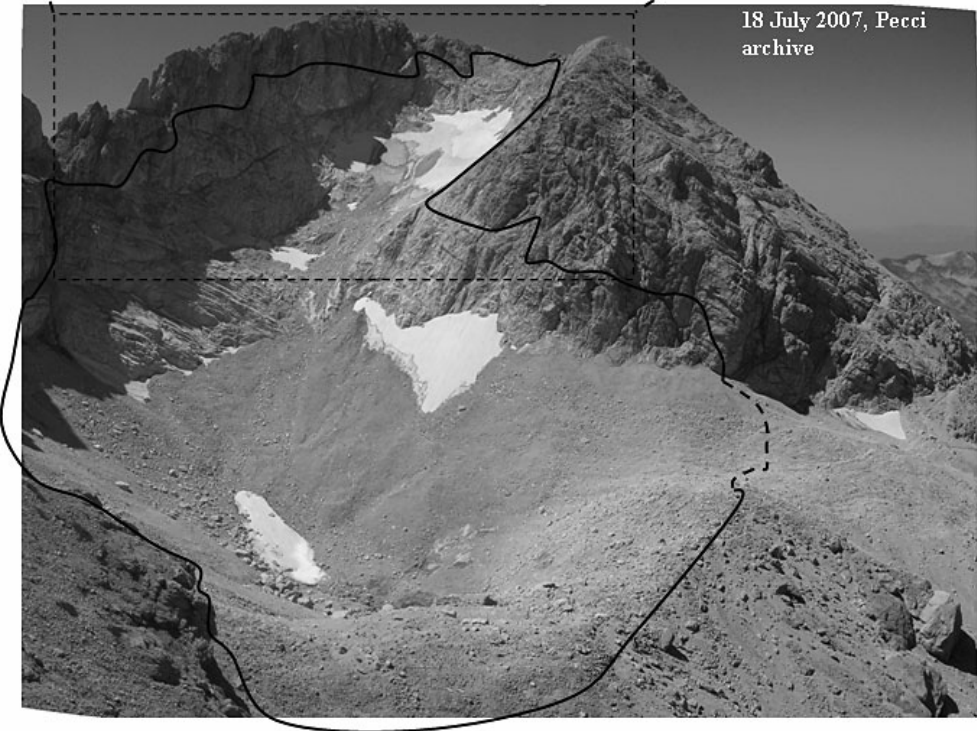


Fig. 3 - The mass balance of the Ghiacciaio del Calderone from 1995 to 2006. Annual and cumulative specific net mass balance for each year and for the entire 1995-2006 period (grey: positive balance; lightly dotted: negative balance; thickly dotted: cumulative balance).

2002). In particular, the snow patch known as the Gravone, of dimensions still remaining at 50 m x 30 m as of the survey conducted at the end of November 1998, had totally melted during the summer of 2000. From 2000 to 2003, the Valle delle Cornacchie snow patch, the one at the highest altitude, is the only surviving snow patch. Its persistence close to the Franchetti Hut is very closely linked to the topographic-morphologic conditions and its northward aspect. It is also interesting to note that since the «hot» year of 2003, the snow patches that had previously disappeared have reappeared and continue to develop, with consistent accumulation in snow/firn volume in the last hydrological year (2005-2006) of the study period. Since the 2006 year this area and the proximal close to the frontal moraine ridge of glacier (in the lower debris accumulation) have been instrumented with a soil temperature measurement network (with 4 temperature probes each) in order to verify the presence of local active permafrost occurrence. In fact such perennial ice patches are often connected to such occurrences, because they prevent the ground surface underneath from warming above 0 °C during summer but allow for winter cooling below 0 °C.

Climate parameters and mass balances

As mentioned above, the only station not far from the Ghiacciaio del Calderone and offering a sufficiently long historical series of data is Pietracamela Station. The mean summer temperatures (considering an ablation period from May to October) from 1932 to 2005 and the winter precipitation trends (considering an accumulation period from November to April) from 1919 to 2003 obtained from Pietracamela Station records are shown in figure 4.

While a slight increase of about 1 °C, compared to the mean temperature for the entire period, is evident, precipitations reveal marked irregularity in terms of temporal distribution with a decreasing tendency. However, the period of winter precipitation between 1957 and 1963 exceeded mean precipitation levels, while the summer temperatures remained below the mean, more or less in the same time period (*i.e.*, 1959-1966).

Recent studies on the thermal pattern of the area (Dramis & alii, 2002), determined the 0 °C isotherm at an elevation of about 2650 m asl and the -2 °C isotherm at an elevation between 3000 and 3050 m asl. The thermometric data collected during the period from July 1998 to October 2003 at the Franchetti Hut meteorological station (2433 m a.s.l.), albeit fitful, indicate a mean annual temperature of about 2.5 °C, while the average temperature in the same time period at the Pietracamela station proved to be 10.5 °C. The resulting vertical thermal gradient, calculated on the basis of the available data for the same reference time intervals between the Pietracamela Station and the Franchetti Hut Station, proved to be 0.56 °C/100 m, shifting the average 0 °C isotherm about 450 m above the altitude of the Franchetti Hut Station, *i.e.* to about 2880 m asl, and the -2 °C isotherm to about 3300 m asl.

As regards the mass balance period (1995-2006), correlations between the balance data and climate parameters in that same period were examined (tab. 1). The correlations of the mass balance data with temperatures in June and September and in the entire ablation period did not reach highly significant levels; however, the correlation with the annual mean temperatures reached a higher level of significance ($r = -0.49$).

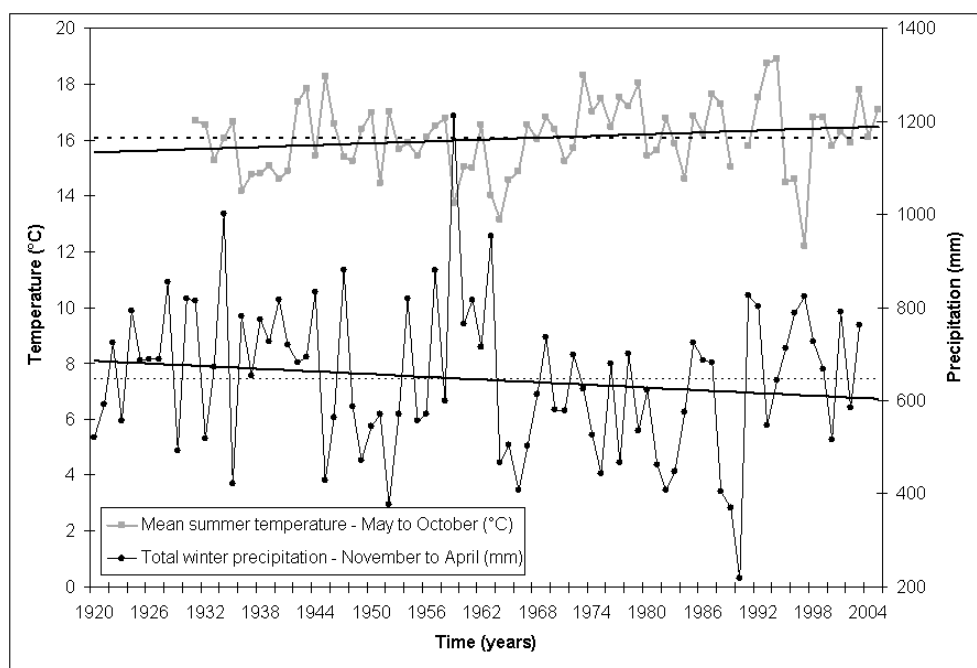


FIG. 4 - Mean summer temperatures (1932-2005) and winter precipitation (1919-2003) at Pietracamela station. The dotted lines indicate mean values, while the solid lines indicate the trend, showing a warming tendency coupled to a decreasing in precipitations.

TABLE 1 - Correlation coefficients between the annual mass balance of the Ghiacciaio del Calderone and meteorological parameters at Pietracamela Station (1995-2005 for temperature; 1995-2003 for precipitation)
 T_y = mean annual temperatures; T_s = mean summer temperatures; T_{Jun} = mean June temperatures; T_s = mean September temperatures; ΔT = summer/winter temperature difference.

P_y = total annual precipitation; P_w = total winter precipitation; P_D = December precipitation; P_{Ja} = January precipitation; P_F = February precipitation

T_y	T_s	T_{Jun}	T_s	ΔT
-0.49	-0.47	-0.41	-0.25	-0.11

P_y	P_w	P_D	P_{Ja}	P_F
0.19	0.63	0.44	0.56	0.39

As regards precipitation, winter precipitation (November-April) yielded the highest correlation ($r = 0.63$) with the balance data.

Application of the equation for the regression line ($b = 3.6_{P_w} - 3103.6$) to the winter precipitation values (P_w) registered at Pietracamela Station made reconstruction of the Calderone mass balances (b) possible for the years from 1920 to 2003. Figure 5 permits a comparison between the balances resulting from field measurements taken between 1995 and 2003, as well as the complete sequence of balances reconstructed starting from 1920.

The comparison of the measurement data and «reconstructed» or «simulated» data reveals that although they are relatively similar, the reconstructed data tend towards an overestimation of the loss resulting in the balances. In

any case, it is estimated that from 1920 to 1994 (reconstructed data), the loss in thickness on the Ghiacciaio del Calderone was approximately equal to 60 m in w.e., to which another 4 m should be added (data measured on the glacier surface with ablation stakes), as 4 m were lost between 1995 and 2006. Thus, the total loss from 1920 to 2006 amounts to about 64 m (see the following paragraph for the discussion on total thickness changes), corresponding to -0.74 mm of w.e. annually.

DISCUSSION

As concerns the balances obtained from field surveys, after two initial stationary years (1995-1996), the glacier yielded a continuous negative balance from 1997 to 1999, leading to a loss of about 1.7 m w.e., followed by the formation of the two separate glacierets in 2000. A dual regime seems to have begun thereafter; unlike the lower ice body, the upper ice body often yields a positive balance. If, however, we continue to consider the two glacierets as a single unit, the balance remains negative until 2003. After 2003, the balance is either clearly positive (as in 2006) or only slightly negative (as in 2005), while, as we have seen, the snow patches tend to re-form and persist also at lower altitudes (about 1200-1500 m asl) and facing north.

In a glacier like the Ghiacciaio del Calderone, the nourishment of which is conditioned not only by snowfall, but also by wind and avalanches, which redistribute the snow, the linkages between climatic forcing factors and mass bal-

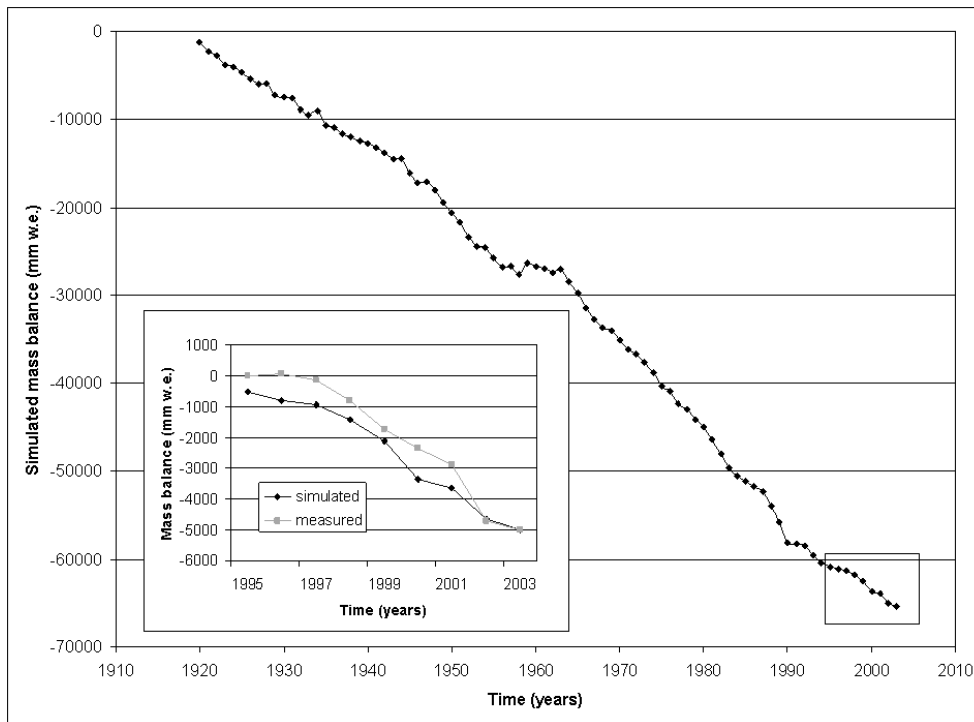


FIG. 5 - Reconstructed mass balance and comparison between measured balances and reconstructed balances; in the detailed box the analysis for the studied period of the Ghiacciaio del Calderone.

ances are certainly not linear; local effects also contribute, particularly those caused by the morphology of the cirque occupied by the glacier, as well as those caused by its northern exposure. In fact, taking into account the data from the Pietracamela Station, we can note that after the high summer semester temperatures registered between 1973 and 1994 (in this latter year the temperature of 18.9 °C was reached, the highest ever recorded during the 1931-2005 period), summers became cooler (reaching «only» 17.8 °C at Pietracamela even during the «hot» summer of 2003), with the lowest temperature (12.2 °C) of the entire historical series being recorded in 1997.

Along with the slight drop in temperatures after 1994 (which, however, did not determine a change in the century-long warming trend), the slight increase in winter precipitation starting in 1993 should also be considered. In more recent years (2004 to 2006), particularly high snow accumulation has been recorded in mid-June on the glacier (7-10 m in the upper sector and 4-7 m in the lower sector). Although the effects of snow avalanches and wind action on snow accumulation should always be kept in mind, it is possible that the alternation of positive and negative balances in the 1995-2006 period is due to these factors (i.e., the slight drop in temperatures and increased snowfall), an alternation that leads to a total cumulative balance that is not extremely negative (loss in mean w.e. thickness: about 3.8 m, or 0.3 m/year). These results contrast markedly with events affecting glaciers in the Italian Alps and reported in the same period. Data on the glaciers in the Italian Alps indicate only one year (2001) with a positive balance and the total and annual mean balances are much more negative. This emerges even more clearly in a comparison with small glaciers like Ghiacciaio della Sforzellina in the Lombardy Alps. Although it is a larger glacier, its altitudinal range and aspect are comparable to those of the Ghiacciaio del Calderone. In the 1995-2006 period, the loss in thickness of Sforzellina was about 12 m w.e., with an annual mean of 1.1 m. Similar results differing from the Ghiacciaio del Calderone are reported for other, slightly larger glaciers in Italy such as the Dosdè Orientale in the Piazzi-Campo Group or Ciardoney Glacier in the Gran Paradiso Group, in similar periods (e.g. Dosdè Orientale 1996-2006: -11 m w.e., with an annual mean of 1 m according to data supplied by G. Diolaiuti, Comitato Glaciologico Italiano; Ciardoney glacier 1992-2006: -19.7 m w.e., with an annual mean of -1.3 m according to data reported by L. Mercalli, Società Meteorologica Italiana).

Even in the case of the Ghiacciaio del Careser, which offers the longest series of mass balances existing for the Italian Alps, the balance for the 1995-2005 period was extremely negative, yielding a thickness reduction of about 16 m w.e. (-1.4 m per year) (Carturan & Seppi, 2007).

As regards the Ghiacciaio del Calderone balance estimates for previous decades with respect to the measurement period considered here, it should be noted that a growing number of mass-balance series have been reconstructed using climatic records (P and T) in linear regression, i.e. statistical correlations between meteorological da-

ta and measured mass balances (for instance Letréguilly & Reynaud, 1990; Kuhn & alii, 1997; Vincent & Vallon, 1997). Other researchers have taken a theoretical approach and employed models to reconstruct mass balance records (e.g. Oerlemans, 2002). A «rougher» and simpler linear regression method has been utilized in our study, using monthly/seasonal/annual air temperature and precipitation data.

The results obtained in our study can be compared with the results obtained using other methods. D'Orefice & alii (2000) and D'Alessandro & alii (2001) have evaluated the surface area and volume of the Ghiacciaio del Calderone in various periods from the Little Ice Age to 1990, processing data from historical and cartographic sources in a GIS environment.

Utilizing the surface area variations and the relative variations in volume presented in the above-mentioned studies, the total reduction in the thickness of the Ghiacciaio del Calderone between 1916 and 1990 proves to be equal to 51 m (-0.69 m/year), the equivalent of about 46 m w.e. (-0.62 m/year). Our «reconstructed» values indicate a reduction of 58 m w.e. (-0.82 m/year) in the 1920-1990 period. Keeping in mind the limits and approximation inherent in processing methods and in the comparison procedures, these results do indeed seem overestimate the loss rate we calculated; however, they can offer a fairly indicative estimate of the glacier's balance over a period of seventy years.

CONCLUSIONS

The Ghiacciaio del Calderone, which is often termed the only «glacier» in the Apennines and the southernmost glacier in Europe, actually consists of two glacierets formed in the year 2000 due to a breaking up of the pre-existing single glacier body. The 1995-2006 mass balance of the Ghiacciaio del Calderone, considered as a single glacier unit, was globally negative, (except years 2004 and 2006 clearly positive and in contrast with patterns recorded in the Italian Alps), with a total cumulative loss of about 4 m w.e.. At the same time the snow patches surrounding the glacier, which had previously disappeared, had also reappeared by the end of the observation period. The evolution pattern of the Ghiacciaio del Calderone can be attributed to a slight drop in summer temperatures (at Pietracamela Station: 15.8 °C between 1995 and 2005, versus 17.0 °C between 1985 and 1994), accompanied by a slight increase in total winter snowfall (from about 5900 mm in the 1985-1994 period to about 6400 mm in the 1995-2003 period). This latter factor merits special attention, as owing to snowdrifting and avalanches leading to redistribution of the snow, it permitted persistence of 10 m of snow accumulation in the upper sector of the glacier as of the end of the winter season in 2006, with a clearly positive balance as of the end of the summer season. The debris cover on a large part of the glacier probably also played an additional role in reducing ablation.

The correlation between the winter snowfall and the 1995-2003 balances proved to be clearly more significant

than the correlation between the balances and summer temperatures. The resulting equation was utilized for a reconstruction of the balances for previous decades. The reconstructed balance for the period from 1920 to 1994 was continuously negative (with the exception of a brief interval in the late 1950s and the early 1960s), with the glacier losing a thickness of about 60 m w.e., which should be added to the 4 m resulting for the monitored 1995-2006 period. Over the span of 86 years, the annual mean balance could be estimated as -0.74 m. A comparison of these results with those obtained from the examination of previously published historical and cartographic material leads us to suspect that the results of the reconstructed balances slightly underestimated the loss, although they are sufficiently indicative of a global trend (a balance of -46 m w.e. for the 1916-1990 period resulting from the examination of cartographic material, whereas a balance of -58 m w.e. was obtained for the 1920-1990 period using statistical methods).

Continuation of the traditional type of monitoring based on direct measurements of accumulation and ablation by means of a network of stakes, appears to be an unlikely prospect. Measurements on set points are difficult and lack precision especially in the lower sector, which is entirely covered with debris. Therefore, GPS laser surveys will be also employed, together with these traditional measurement methods, as they could supply precise information on altimetric variations affecting the glacier surface (D'Aquila & alii, 2007).

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