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FRONTAL FLUCTUATIONS OF GLACIERS AND CLIMATIC PARAMETERS: THE CASE OF MARITIME ALPS

ABSTRACT: PAPPALARDO M. & RAPETTI F., *Frontal fluctuations of glaciers and climatic parameters: the case of Maritime Alps*. (IT ISSN 0391-9838, 2001).

The frontal oscillation curves of three of the six small glaciers still present in the Maritime Alps have been constructed by means of the data collected since the twenties by the Comitato Glaciologico operators. The frontal oscillation using the raw data of the Cuneo observatory, for which measures are available since 1877. This work is aimed at the definition, also for this alpine sector, of the contribution of the different climatic elements to the movement of glacier fronts, and to evaluate the reaction time of these glaciers to climate inputs. The small Maritime Alps glaciers underwent a dramatic retreat during the last century and are now next to extinction. We intend therefore to highlight the relationship climate inputs and glaciers front oscillations. The statistics tool employed for this purpose consists in the development of simple and multiple linear regressions between the trend of snow mantle thickness, temperatures from May to October and time (independent variables), in function of front oscillations (dependent variable). Some development of the regressions suggested that a response time can be highlighted for thermal forcing, but not for snowfall.

KEY WORDS: Glacier fluctuations, Climatic parameters, Maritime Alps.

RIASSUNTO: PAPPALARDO M., & RAPETTI F., *Variazioni frontali dei ghiacciai e parametri climatici: il caso delle Alpi Marittime*. (IT ISSN 0391-9838, 2001).

Sono state considerate le serie di oscillazione frontale di tre dei sei piccoli ghiacciai presenti nelle Alpi Marittime, basandosi sui dati raccolti a partire dagli anni Venti dagli operatori del Comitato Glaciologico. Queste serie sono abbastanza continue, tanto da meritare, previe integrazioni effettuate grazie ai dati documentali e cartografici esistenti, di essere correlate con la serie termo-nivometrica dell'osservatorio di Cuneo che è ultracentenaria, i cui dati sono qui stati selezionati ricavando le fluttuazioni e le tendenze della temperatura media dell'aria nei mesi da Maggio ad Ottobre e quelle dell'accumulo di neve al suolo dal 1926 ad oggi.

Il lavoro si pone lo scopo di definire, anche per questo settore alpino, il contributo dei diversi elementi del clima al movimento delle fronti, e di stimare il tempo di risposta dei ghiacciai agli stimoli climatici, ad integrazione di quanto già noto per altre parti delle Alpi. In particolare, avendo i piccoli ghiacciai delle Marittime subito un drastico ritiro nel corso dell'ultimo secolo e trovandosi ora in una condizione che prelude alla loro estinzione, il presente studio si propone di indagare la relazione fra l'andamento dei parametri meteorologici e le fluttuazioni delle fronti glaciali. La metodologia statistica adottata allo scopo consiste nello sviluppo di regressioni lineari semplici e multiple fra l'andamento dello spessore del manto nevoso, quello delle temperature dei mesi da Maggio a Ottobre e il tempo (variabili indipendenti), in funzione delle fluttuazioni frontali (variabile dipendente). Alcuni sviluppi delle regressioni hanno indicato di stabilire sfasamenti temporali di 10-12 anni fra le variazioni frontali e la temperatura, mentre la correlazione con lo spessore del manto nevoso non è risultata significativa.

PAROLE CHIAVE: Fluttuazioni glaciali, Parametri climatici, Alpi Marittime.

INTRODUCTION

Since the mid nineteenth century a relationship between changes in glacier volume, area and frontal position and the trend of climatic parameters has been presumed to exist. Studies were carried out to better understand possible relationships. However, only at the beginning of the twentieth century were glacier dynamics more clearly defined and only then were meteorological data from high altitude stations available. As a result of these new data, research into the various phenomena had a more correct scientific basis, one example being the classic work by Monterin (1932), so that refined analyses could be performed. Since then, more and more glaciers have been systematically monitored in order to record their geometric parameters and meteorological nets were developed as well as calculation techniques. In spite of this it is still difficult to assess significant mathematical and statistic relationships between climatic parameters and changes in the geometry of ice bodies, although some satisfactory results have been obtained in the Italian Alps (Belloni & *alii*, 1985; Belloni & *alii*, 1990; Belloni & *alii*, 1991). The difficulties in relating glacier fluctuations to climatic parameters lie not only in the complexity of the processes involved, but also in the unavailability of suitable records, such as mass balance

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records or measurements of climatic elements from high altitude stations. Therefore in most cases frontal fluctuations are related to snowfall and summertime temperatures, which are the most influential characteristics conditioning ablation.

THE MARITIME ALPS GLACIERS AND THEIR GEOGRAPHICAL AND CLIMATIC CONTEXT

Reports on glaciers in the Maritime Alps date back to the end of the nineteenth century, and during the first half of the twentieth century they were described, studied and monitored. After World War II interest in them faded and they were sporadically mentioned in reports by the Comitato Glaciologico Italiano. In the last decade, however, this alpine sector has been the object of renewed scientific interest and many papers regarding its glaciological and geomorphological characteristics have appeared in the scientific literature. The first of these studies was a preliminary study on the glacial morphology of the Gesso Valley (Federici & Pappalardo, 1991), where six glaciers and a few glacierets are still present. These are the remnants of ice bodies which at the end of the Pleistocene were extended down-valley and since then have been retreating, leaving a sequence of moraines up to the present-day fronts. Three of the glaciers reported by the observers, which were carefully described by Federici & Pappalardo (1995), are considered in this paper. Two of them are still present, i.e. the Peirabròc Glacier, n. 2 in the Italian glaciers inventory (Catasto dei Ghiacciai Italiani, CGI-CNR, 1961) and the North-Eastern Gelàs Glacier, n. 6 of the inventory, where it is named simply «Gelàs Glacier». The third, the Muraiòn Glacier, was declared extinguished in 1974. These glaciers were chosen as they are the most meaningful as regards their records of frontal fluctuations, which are sufficiently continuous to be related to climatic data.

The basin of the Gesso river occupies the central-southern part of the Maritime Alps and its watershed coincides with the French border. The glaciers present there, in spite of their small dimensions, are of remarkable glaciological interest, as they are the southernmost glaciers of the whole alpine arc and those closest to the sea. The Ligurian Sea is about forty km from these ice bodies.

In terms of dynamic meteorology, this area is affected both by the seasonal fluctuation of the polar front, to

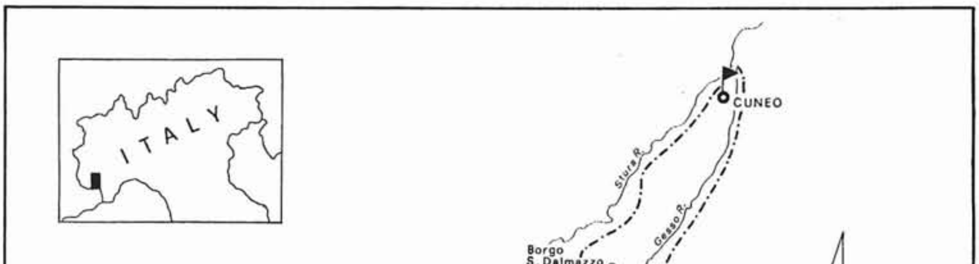

FIG. 1 - The geographical framework of the Gesso Valley, with the location of some of the meteorological stations considered (flag) and of the three glaciers: 1) Peirabròc; 2) Muraiòn; 3) Gelas NE.

which the mid-latitude atmospheric disturbances are related, and by the depressions in the lee of the Alps that form over the Léon and Genoa Gulfs, much more frequently in the cold semester. Such regional depressions, which are often synergetic with those of the zonal circulation, produce frequent air masses that move up the southern slope of the Maritime Alps. Thanks to their peculiar position they have a high humidity content. This causes extensive snowfall in the area in winter and frequent cloud cover in summer - compared to that of the northern tracts of this mountain chain, more distant from the depressionary centres of the high Tyrrhenian Sea. This provides very effective protection from solar radiation in summer. According to Peguy & Faidutti (1965) these conditions might be the main cause of the persistence of these small ice bodies which, in spite of their low latitude and proximity to the sea, still show some evidence of movement.

A CLIMATIC OUTLINE

The Cuneo station

The meteorological data of the Cuneo station are suitable to represent the climatic conditions of the study area. Despite the low elevation of this station (536 m a.s.l.), in fact, it can be considered as a good reference to describe the climate affecting the whole belt from the mountain border to the main chain watershed. This is thanks to its position, close to the outwash of the Gesso River into the plain, and thanks to the fact that the main elements of climate in this area vary with altitude according to a linear trend. This station was chosen also because it displays a centenary record (1877-1996), the longest among those of all stations present in the area. Observations were started on December 1st 1876 by Father F. Denza and G. Cossavella; in 1951 the station was moved from its primitive urban location in the Regio Istituto Tecnico (a technical school) to the building of the Chamber of Commerce. It is precisely because of this change, as well as the necessary substitution of some instruments and the natural turnover of the observers, that the record, particularly the temperature record, presents some dishomogeneities which cannot be ignored. These were analysed by Mercalli & Romano (1994) and by Cortemiglia (1999).

In the time span 1926-1996, in which the front oscillation data of the glaciers are available, the mean yearly temperature was 11.0°, ranging from a minimum value of 8.9 in 1963 to a maximum of 12.9 in 1945. The mean temperatures of the extreme months were respectively 1.5 in January and 20.5 in August, corresponding to a mean yearly range of 19.0. It is necessary to consider that in 50% of cases the maximum values of the mean monthly temperatures occurred in the last decade, and were particularly frequent in 1994 (tab. 1). The mean yearly temperatures display a weak tendency (0.7/100 years) to decrease, which

TABLE 1 - Mean monthly and extreme temperatures (°C) in Cuneo (1926-1999)

	G	*F*	*M*	*A*	*M*	*Jn*	*Jl*	*A*	*S*	*O*	*N*	*D*	*year.av*
min. T	-3,5°	-4,3°	2,9°	3,7°	10,6°	15,9°	15,9°	17,9°	12,0°	8,1°	3,8°	-1,0°	8,9°
year	1947	1956	1971	1991	1984	1953	1953	1976	1972	1974	1952	1940	1963
max. T	5,3°	9,1°	11,6°	14,1°	20,2°	23,6°	23,8°	23,9°	20,2°	15,8°	9,7°	6,7°	12,9°
year	1989	1990	1994	1943	1945	1991	1994	1928	1945	1942	1994	1934	1945
mean T	1,5°	2,8°	6,5°	10,2°	14,2°	18,9°	19,0°	20,5°	17,1°	11,6°	6,2°	2,8°	11,0°

was reported also by others for this area (Giuffrida & Conte, 1991). The seasonal mean values indicate the increase of winter temperatures and the decrease of those of the other seasons, particularly spring.

The mean yearly rainfall has been calculated at 1035.4 mm, ranging from 539 mm in 1965 to 1610 mm in 1920. The rainfall regime is of the prealpine type (PAEI) (Pinna & Vittorini, 1985) with the distribution shown in tab. 2. The area examined is located along a theoretical separation line, roughly coincident with the course of the Po River. This is between the regions where the rainfall minimum occurs in summer and the areas where it occurs in winter, located northwards (Rapetti & Vittorini, 1993). The precipitations occurring from May to October, mainly in the liquid form even in the uppermost parts of the Gesso Valley, reach a value of 535.5 mm, correspondent to 51.7% of the global yearly value.

TABLE 2 - Seasonal rainfall regime (mm) in Cuneo (1877-1996)

	winter	*spring*	*summer*	*autumn*	*year*
mm	185,7	353,0	202,0	294,8	1035,5
%	17,9	34,1	19,5	28,5	100,0

The yearly rainfall trend shows a decrease of 26 mm/100 years, but as regards their distribution during the year, an increase in rainfall during summer and winter can be observed as well as a decrease in autumn and spring.

The air temperature

The air temperatures of the months from May to October should be taken into particular consideration for the purpose of this study. This is because at the altitude of the glacier equilibrium line, which in the Gesso Valley is currently estimated at about 2800 m, the mean monthly temperatures are positive in this period, and are therefore influential in terms of ice ablation. Although the Cuneo record presents some discontinuities which cannot be neglected, we preferred to use the raw data, also considering the difficulties encountered in the correction of the historical records which are due, as in our case, to the fact that coefficients suitable to link the different periods together are not available (tab. 3, fig. 2).

The temperature trend of the months from May to October shows a decrease which is greater in September (2.6/100 years) and weaker in July (0.19/100 years). On the whole, the temperatures in the warm semester, compared to the annual temperatures, show a greater decrease (1.24/100 years). The same phenomenon has been observed in other parts of the country (Rapetti & Vittorini, 1992).

The snowfall

The city of Cuneo has one of the longest and most continuous snowfall records in the whole alpine arc, which was started in 1877 and continued, without any remarkable interruption, until the present (tab. 4).

The most abundant snow precipitations occurred in January (28.9%), then in February and December, whereas we have never had any snow from June to September. Snow is quite rare in May and in October, as in the 120 years' observations only three cases were noticed in May and four in October. The general snowfall regime has a main maximum in winter (76.4%), followed by spring (15.9%) and autumn (7.7%). It is interesting to notice that the spring snowfalls cause a considerable increase in the albedo of the ice surfaces, so contrasting the reactivation of ablation which takes place in late spring. However, their contribution to the mass balance is poor and they are quickly melted out.

The trend of the snow mantle height throughout the years of observation shows some meaningful fluctuations.

TABLE 3 - Free atmosphere minimum, maximum and mean monthly temperatures from May to October (°C) in Cuneo (1926-1996)

	M	*Jn*	*Jl*	*A*	*S*	*O*	*Yearly values*
Min	10,6° (1984)	15,9° (1953)	15,9° (1953)	17,9° (1976)	12,0° (1972)	8,1° (1974)	14,5° (1972)
Max	20,2° (1945)	23,6° (1991)	23,8° (1994)	23,9° (1928)	20,2° (1926)	15,8° (1942)	20,0° (1945)
mean	14,2°	18,9°	19,0°	20,5°	17,1°	11,6°	16,9°

TABLE 4 - Some characteristic parameters of snowfall in Cuneo (1877-1996)

	G	*F*	*M*	*A*	*M*	*O*	*N*	*D*	*year*
min.	0	0	0	0	0	0	0	0	9 (1989)
max	182 (1985)	154 (1888)	85 (1878)	58 (1879)	15 (1879)	17 (1979)	120 (1894)	138 (1896)	354 (1895)
mean	36,2	29,9	15,7	4,1	0,2	0,3	9,4	29,5	125,1
years with no snow	8	13	31	80	117	116	66	18	0

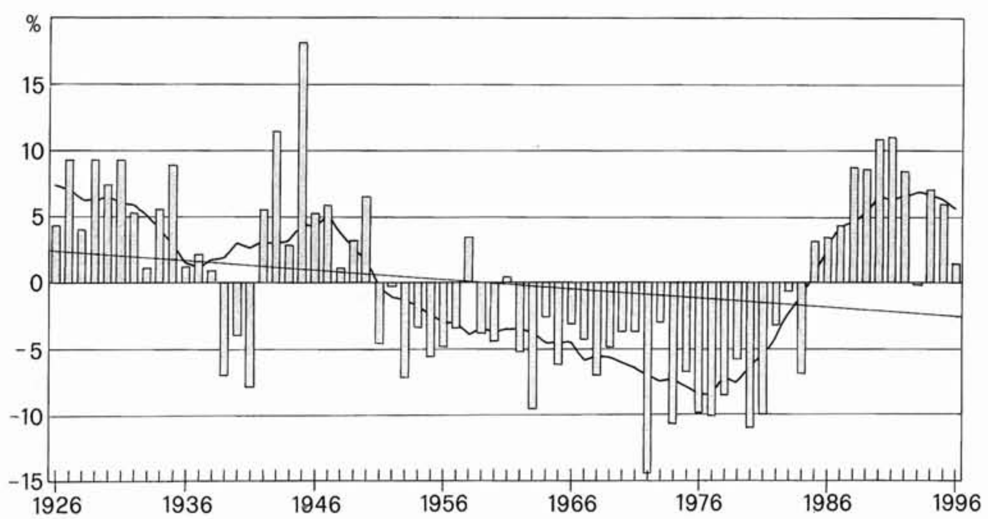

FIG. 2 - Trend of the mean temperature per cent shift of the months from May to October in Cuneo (1926-1996); the line indicates the mobile mean (x5).

In particular, the negative fluctuation which occurred at the beginning of the twentieth century and in the mid-forties is remarkable. After the latter, snowfall was quite abundant until the mid seventies. Since then, though, a dramatic decrease has taken place, with a 9 cm minimum value of the snow mantle recorded in 1989 (fig. 3). The general trend of this record is negative, with a decrease of 27 cm/100 years. During the last two decades the decrease has been sharper (6.2 cm/year), affecting every month of the year but in particular February and December. The maximum monthly values, if we ignore October, were recorded in the two last decades of the nineteenth century. This evidence is the sign of a long term variation in the general snowfall characteristics of the region.

The altitudinal dependency of precipitation and the 0° annual isothermal line

The altitudinal relationship between the 0° annual isothermal line and the glacier equilibrium line depends on the combination of morphological and climatic parameters. These include slope steepness, valley orientation, altitudinal dependency of temperature and snowfall. The former was calculated using the temperature values recorded in the stations of Cuneo (536 m a.s.l.), Diga della Piastra (959 m a.s.l.) and Diga del Chiotas (1980 m a.s.l.), located on an ideal straight line from the Cuneo Plain up to the Gesso Valley (tab. 5). The relationship between the yearly mean temperature variation and altitude is of the linear type, as is tested by the value of the monthly determination coefficient as well as that of the yearly one. The mean yearly temperature increase with altitude is 0.53°C/100 m, with a minimum of 0.34°C/100 m in December and a maximum of 0.68°C/100 m in May. The lowest values occur in Winter and are due to the persistence of dry and cold air masses in the valley bottoms, causing thermal inversion along the slopes. On the contrary, during summertime, when adiabatic slope processes are most active, we have the highest values. The 0° annual isothermal line values range from 1230 m (January) to 4345 m (July); the mean value is 2725. This is lower, as expected, than that of the calculated E.L.A. in the Gesso basin. The warm semester 0° annual isothermal line fluctuations have a crucial role in conditioning glacier dynamics, as remarkable variations may take place from year to year. In the decade 1980-1990 the annual thermic zero altitude ranged from

TABLE 5 - Parameters of the altitudinal dependency of temperature and of the 0°C isothermal line (1980-1990)

month	*best fit line*	*deter coeff* (R^2)	*0°C isothermal* (*m a.s.l.*)
G	–0,0036 (h + 4,43)	0,968	1230
F	–0,0044 (h + 5,89)	0,985	1340
M	–0,0057 (h + 10,18)	0,985	1790
A	–0,0061 (h + 13,39)	0,985	2195
M	–0,0068 (h + 18,08)	0,978	2660
Jn	–0,0067 (h + 22,02)	0,981	3290
Jl	–0,0054 (h + 23,45)	0,846	4345
A	–0,0065 (h + 24,64)	0,949	3790
S	–0,0062 (h + 21,51)	0,934	3470
O	–0,0052 (h + 15,58)	0,965	3000
N	–0,0042 (h + 8,94)	0,974	2130
D	–0,0034 (h + 5,70)	0,992	1680
year	–0,0053 (h + 14,44)	0,965	2725

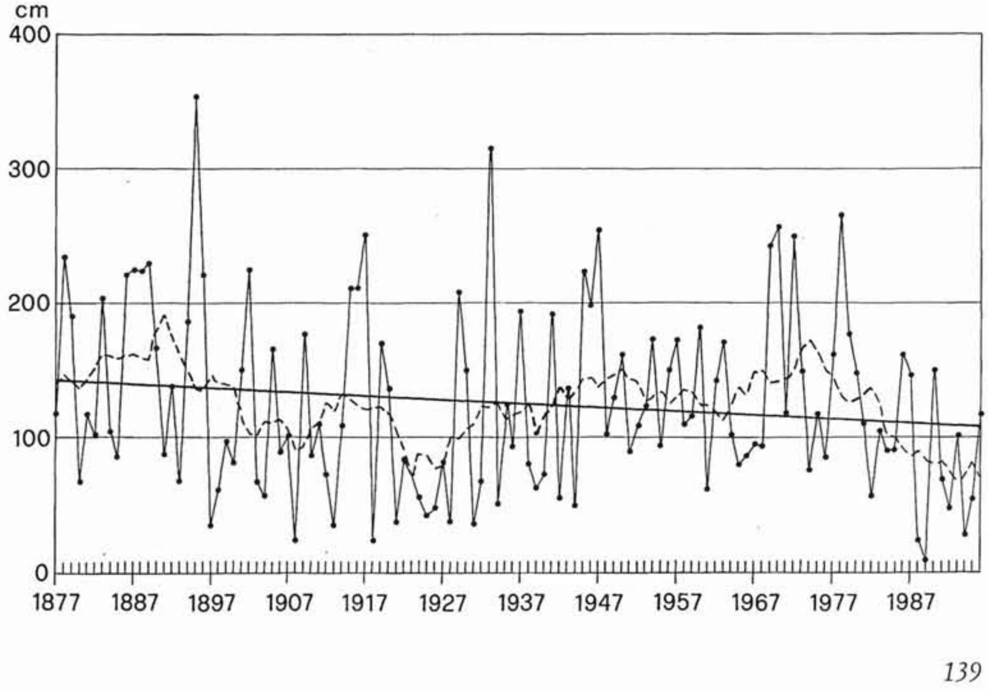

FIG. 3 - Trend of the yearly snowfall in Cuneo (1877-1996); the dashed line indicates the mobile mean (x5).

TABLE 6 - Extreme values of the 0°C isothermal line altitude (m a.s.l.) from May to October (1980-1990)

	M	*Jn*	*Jl*	*A*	*S*	*O*	*year*
min. altit.	2200 (1984)	2600 (1987)	3250 (1987)	3400 (1990)	3100 (1989)	2550 (1987)	2410 (1987)
max. altit.	3050 (1989)	3850 (1981)	4000 (1989)	4000 (1985)	4000 (1984)	3250 (1983)	3100 (1981)

2410 in 1987 to 3100 m in 1981, with a maximum difference of about 500 m; in June this difference exceeded 1000 m (tab. 6).

The altitudinal dependency of snowfall

The altitudinal dependency of snowfall was determined on the basis of the mean yearly snow mantle thickness recorded from 1980 to 1990 in the stations of Cuneo, Diga della Piastra and Diga del Chiotas., where the mean measured thickness is 93, 299 and 626 cm. The thickness of the snow mantle is dependent on altitude according to a linear function, as seen also elsewhere in the Piedmontese Alps (Biancotti A. & *alii*, 1998). In the study area the function is the following:

$$Q \text{ (cm)} = 0.3599 \cdot h \text{ (m)} - 77.48$$

The determination coefficient is 0.989. Extrapolating this lapse rate to the mean elevation of the glaciers (2600-2850 m) we can calculate a mean annual snow accumulation in this area of 850-950 cm. These values are estimated regardless of the anomalies that can arise in the uppermost parts of the relief, on slopes with particular orientation or steepness, due to the action of wind or avalanches.

THE FRONTAL FLUCTUATION RECORDS

The glaciers chosen to be related to the climatic data were cirque glaciers during the Little Ice Age. Apart from the Muraiòn, which is surely extinct, the position of their fronts is not so easy to detect because of an irregular debris cover and the extension of snowfields that persist late in summer on and all around them. This was already pointed out by the observers working at the beginning of the twentieth century. The Peirabròc was located in a typical, very regular cirque and now it is reduced to a plate of ice on a steep wall. Muraiòn was a belt shaped ice body, well sheltered from the sun rays but already very small during the thirties. Gelàs NE, finally, is one of the residual bodies of the big glacier which during the Little Ice Age occupied the northern slope of the M. Gelàs orographic knot. In tab. 7 some of the parameters that characterise them are shown as reported in the literature.

Data on their areal extent are not very reliable. If we except those reported by Camoletto for the thirties, the others derive from estimations more than from true measurements. During the thirties the extension of the Gelas NE

TABLE 7 - Main parameters of the concerned glaciers; (*) probable value; (**) according to Gellatly & *alii* (1994)

Glacier	*Peirabroc*	*Muraion*	*Gelas NE*
Min. altitude (1992) m	2520 (*)	-	2760 (*)
Max. altitude (1992) m	2720	-	2950
Area (1992) ha	8.6 (**)	-	5.2 (**)
Min. altitude (LIA) m	2400	2500	2520
Min. altitude (1939) m	2475	2500	2620
Area (1896) ha	17	not mentioned	13
Area (1935) ha	15.3	5.2	12.9

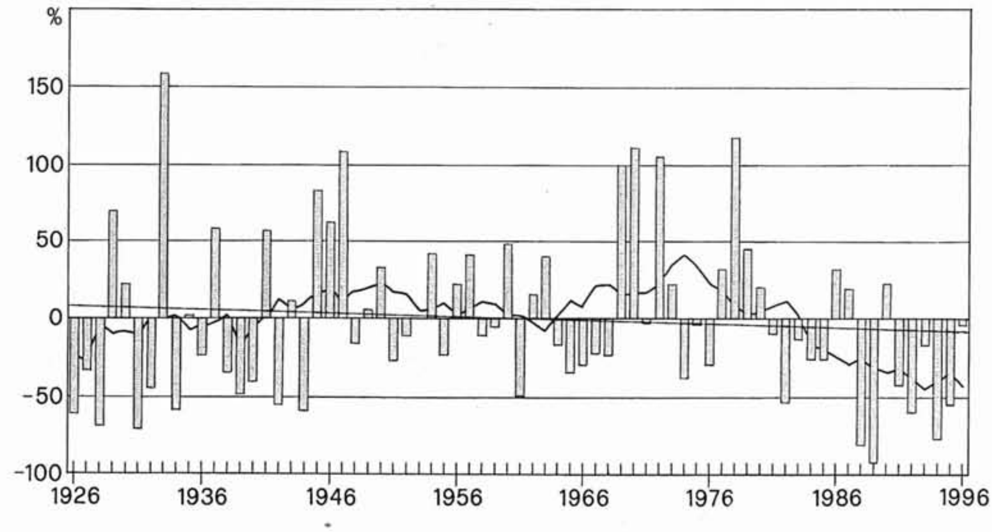

FIG. 4 - Trend of the mean snowfall per cent shift; the dashed line indicates the mobile mean (x5).

Glacier was more than twice that of the Muraiòn glacier, and the extension of Peirabròc was about three times that of the Muraiòn Glacier. During the following fifty years the two surviving glaciers diminished by about 60% (Gelàs NE) and about 70% (Peirabròc). The extension of the latter in the early nineties, as reported in tab. 7, is measured considering the front located at an altitude of 2520 m, and is therefore about one half of the area reported by Gellatly & *alii* for it. The extension values contained in the World Glacier Inventory (IAHS-UNEP-UNESCO, 1988) for 1983 must be considered unreliable as they are greatly exaggerated.

Peirabròc Glacier

The frontal fluctuation record of the Peirabròc glacier is the most complete among those available for the Gesso valley glaciers. A continuity interval can be defined for it from 1926 to 1968 and from 1978 to present. Such continuity is due mainly to the fact that it can be reached with less difficulty than the others. In fact it is the only glacier in this mountain group which was visited during the eighties and during wartime it was measured more frequently than the others.

The first part of the record, from 1926 to 1939 is reliable, as most measures are yearly, with few yearly gaps that can be filled in by using the mean of the extreme values. The second part is slightly less reliable, because of a seven year measurement and some gaps. From 1968 to 1978 measurements of frontal fluctuation are unavailable for any of the Maritime Alps glaciers. For Peirabròc we managed to fill this gap by calculating on a map the distance between the position of the front in 1939 as reported by Camoletto (1940) and the one estimated by Pappalardo (1999) for 1990. Subtracting the measured retreats from 1939 to 1968 and from 1978 to 1990 from the value obtained, a value of 30 m was obtained. This is reliable if compared to other data from literature, in particular from the Italian glaciers inventory (CGI-CNR, 1961). The final part of the record, belonging to the nineties, might be affected by some misunderstanding of the true position of the glacier front. In fact, it was considered to be located at 2440 m both by Gellatly & *alii* (1994) and by Viotti & Pappalardo (1996), but according to more recent observations (Pappalardo, 1999) it was probably underestimated.

Throughout the time span considered (72 years) the Peirabròc glacier underwent an overall retreat of 125 m. This value is consistent with the difference between the known values of maximum length of the ice body, which is now about 300 m long and in the thirties was between 400 and 450 m (Camoletto, 1932). If we trust the measurements reported by Mader (1896), we can compare this retreat with the one the glacier underwent from 1896 to 1935, which is of 250 m in only 39 years, almost double in half the time.

Gelàs NE Glacier

Among the Gelàs Glaciers the north eastern has been the most frequently visited one and is at present the biggest. Its record of frontal fluctuations is made up of yearly measurements without any gap from 1930 to 1965, if we ignore wartime for which some approximation must be made. In 1995 its front was supposedly located at an altitude of 2720 m, but during subsequent glaciological surveys this could no longer be found because it was buried under a thick snow cover (Viotti & Pappalardo, 1996). Gellatly & *alii* (1994) do not propose a precise value for its minimum altitude, but according to a topographical sketch in their paper, a probable value lower than 2850 can be inferred. The exact position of its front cannot be identified at present, but it is surely located not far from a big *roche moutonnée* at an altitude of 2800 m. From the record we infer that it underwent a retreat of 28 m in 35 years. Its maximum length can currently be estimated at roughly 350 m. Unfortunately, the data reported in the Italian glaciers inventory contain various bad errors, so that no comparison can be made between its present day length and its length in the fifties.

Muraiòn Glacier

The Muraiòn Glacier record covers the time span from 1926 to 1968, as it was declared extinct in 1974 but it might have completely disappeared a few years before. It is made up of yearly data with very few annual gaps, apart from a couple of exceptions: during wartime the fluctuation is calculated in five years and the measurement in 1949 is related to the position in 1947. This glacier was chosen because its frontal fluctuations record, which is of good quality, documents its evolution during the four decades previous to its disappearance. The relationship between frontal fluctuations and climatic parameters can in this case be investigated in the crucial moment immediately before extinction. According to the record it withdrew globally by 50 m in 42 years. Values of its length in the past are not easy to obtain. It was not known by the nineteenth century observers and as it is belt-shaped the data of Camoletto (1932) are not suitable for an estimation of its length. From the Italian glaciers inventory it can be inferred that at the end of the fifties it was 60-70 m long.

STATISTICAL ANALYSIS OF THE AVAILABLE DATA

In order to relate the different data sets available to one another, simple and multiple linear regressions were performed in which the total amount of snow (cm), the mean temperature from May to October (°C) and time are the independent variables and the cumulated glacier front oscillations is the dependent variable, according to the general expressions:

$$\text{Cum. Var}_{(\text{measured})} = A \cdot [\text{temperature}]_{i\text{-}k} + \text{cost}$$

$$\text{Cum. Var}_{(\text{measured})} = A \cdot [\text{snow}]_{i\text{-}k} + \text{cost}$$

$$\text{Cum. Var}_{(\text{measured})} = A_1 \cdot [\text{snow}]_{i\text{-}k} + A_2 \cdot [\text{temperature}]_{i\text{-}k} + A_3\,[\text{year}]_i + \text{cost}$$

where k is the temporal shift between the cumulated frontal oscillations and the values of the meteorological parameters.

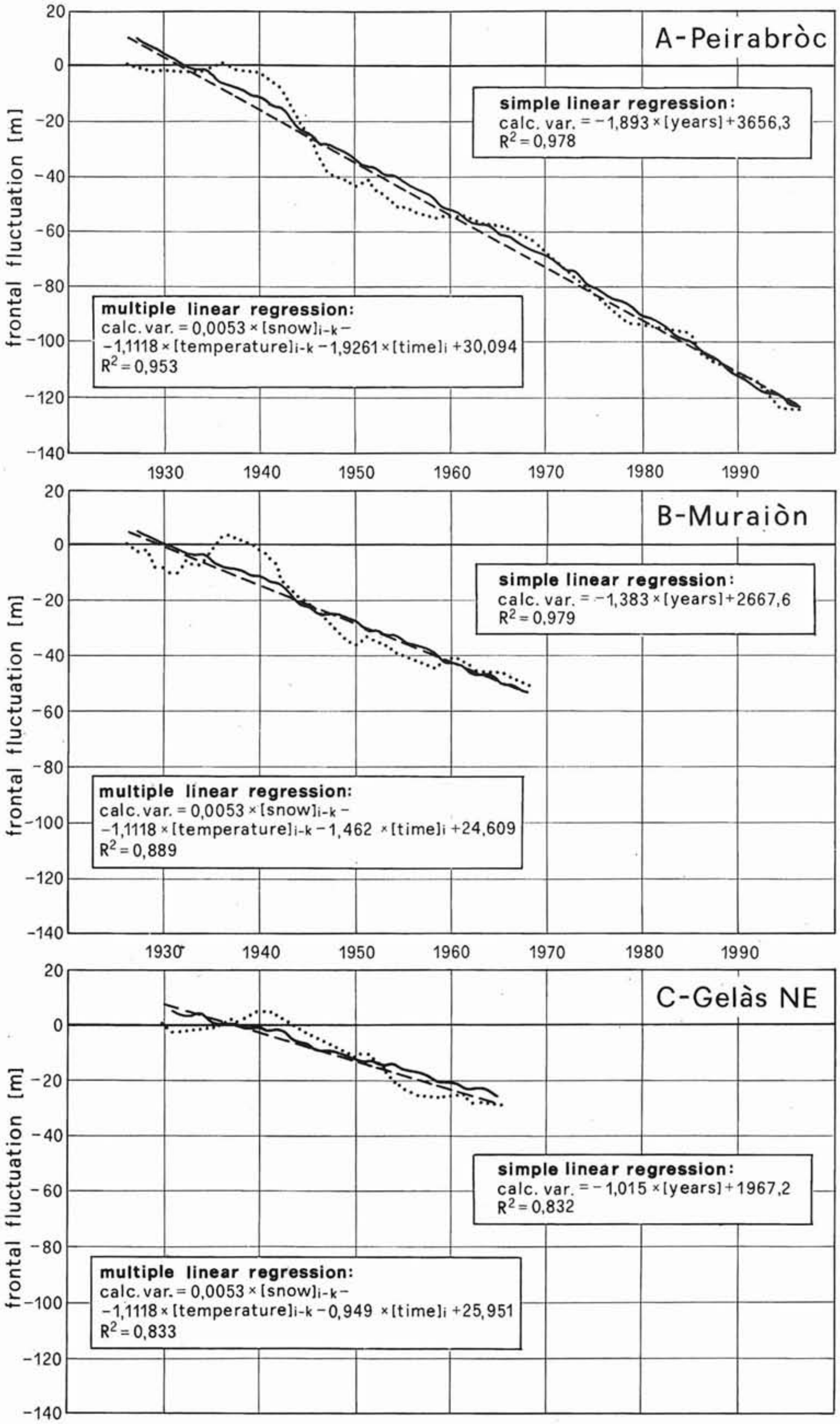

FIG. 5 - Simple linear regression between the cumulated frontal oscillations (dotted line) and time (dashed line); multiple linear regression (continuous line) between the cumulated glacier front oscillations, the total amount of snow (cm), the mean temperatures from May to October (°C) and time.

It is necessary to remark that for some time spans, in which no yearly measurements of the glaciers front oscillations were made, only mean values for each time span are available. For this reason the time-distance curve is artificially rectilinear, affecting the reliability of the regression results.

The simple regressions prove that the Cuneo snowfall record is not suitable for highlighting response time of the chosen glaciers to snowfall changes. This due to the low significance of the regression between frontal oscillation and snowfall testified by the t and p-values.

Temperatures from May to October, instead, show the best correlation with frontal oscillations after 10-12 years, but a not neglectable correlation is comparatively supplied by unshifted data, suggesting, as shown elsewhere in the Italian Alps, a first, imediate, and a second, delayed response of glaciers to thermal forcing.

The multiple regression, in which the existence of a linear relationship between each of the considered parameters and the dependent variable is stated, determines a best fit line which does not fit the points better than the trend line of frontal variation plotted in function of time. The determination coefficient remains however rather high, 0.953 for the Peirabròc Glacier (fig. 5A). Some tentative development of the multiple linear regression suggested that the shift in time between the recorded frontal oscillations and the climatic parameters taken into account should be considered extremely short or even zero. The values obtained in the different cases for determination coefficients, which in fact indicate how the line fits the points spread, indicate that the wider the shift the worse the line fits the points spread (tab. 8)

In the case of the Gelàs NE Glacier there is no great difference between the values of the determination coefficient in the simple (fig. 5C) and in the multiple regression, although the best fit line does not approximate in a satisfactory way the points spread. The same can be said for the Muraiòn Glacier, but in this case the determination coefficient is slightly greater for the multiple than for the simple regression (fig 5B).

CONCLUSIONS

The present temptative statistical analysis is aimed at testing the methodologies employed in other alpine sectors (Belloni & *alii*, 1991), in the Maritime Alps. Some original developments of such methods were suggested by the the nature of available data.

The correlation between glaciers frontal oscillations and May-October temperature data from Cuneo station suggest a first, immediate response and a second one delayed of 10-12 years. No correlation seems instead possible between frontal shift and Cuneo snowfall record.

Since the Little Ice Age the fronts of the Maritime Alps glaciers have undergone a remarkable retreat and most of them disappeared at the beginning of the twentieth century (Federici & Pappalardo, 1996; Federici & Stefanini, in press). The retreat of the few glaciers left has occurred since 1940, at first very quickly, then at a slower pace.

According to the processing of the data available at present it is possible to explain in two different ways the statistical results obtained: since the beginning of the recording period of their frontal fluctuations, the Maritime Alps glaciers have been scarcely sensitive to any of the short term climatic changes occurring in this time span. This means that in the twenties they had already reached a critical mass, variable from glacier to glacier according to local topographic and climatic conditions. Even the remarkable progression of the alpine glaciers occurring in the seventies was not recorded by these small glaciers. In this case if there is a future increase of snowfall and decrease of summertime temperatures, at least within the variability range of the last 120 years, no progression of these glaciers is to be expected, but only a slowing down of their regression.

Alternatively we can stress the importance of the thermic factor in their mass balance and reject the possibility to relate the Cuneo snowfall record to the Maritime Alps accumulation conditions.

TABLE 8 - Shift (years) between snowfall and temperatures in the multiple regression formula and the resulting R^2 values

snowfall	*T*	R^2
0	0	0.957
+1	+1	0.953
+2	+1	0.935
+3	0	0.923

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