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THE GLACIER RETREAT IN VALLE D'AOSTA (WESTERN ITALIAN ALPS) FROM THE LITTLE ICE AGE TO THE SECOND HALF OF THE 20th CENTURY: LINEAR, AREAL, VOLUMETRIC AND EQUILIBRIUM LINE ALTITUDE CHANGES

ABSTRACT: VANUZZO C., *The glacier retreat in Valle d'Aosta (Western Italian Alps) from the Little Ice Age to the second half of the 20th century: linear, areal, volumetric and Equilibrium Line Altitude changes.* (IT ISSN 0391-9838, 2001).

This research has taken into account the areal reduction and the changes of the Equilibrium Line Altitude of 143 glaciers located in Valle d'Aosta (Western Alps, Italy), from the maximum expansion phase of the Little Ice Age (LIA), which in the study area culminated in around 1820, to 1975, date of the aerial photographs used for the elaboration of the regional topographic maps. Investigations were carried out by means of field survey, photo-interpretation, analysis of maps and historical documents and use of Geographical Information Systems.

Furthermore, the data concerning the frontal, areal and volumetric retreat of the glaciers at the heads of Valpelline and Valtournenche (Valle d'Aosta), during the same time interval, are discussed.

The areal retreat of the 143 glaciers during the past 150 years has been around 41.5%; the glaciated surface has in fact decreased from 270.6 km^2 during the LIA to 158.4 km^2 in 1975.

The mean Equilibrium Line Altitude (ELA) was equal to 2845±165 m during the LIA whereas the present one is 3015±197 m.

The ELA has attained its lowest mean value in the glaciers of the Monte Bianco group (2702±117 m in the LIA and 2896±198 m in 1975), whereas the highest is found in the glaciers of Dent d'Herens - Mt. Cervino - Mt. Rosa mountain range (2903±170 m in the LIA and 3099±225 m in 1975).

The mean ELA rise in Valle d'Aosta is equal to 139±106 m and to 129±96 m, if glaciers, which have undergone a frontal retreat without splitting up into several smaller glaciers, are only considered. The highest values of mean ELA rise correspond to the glaciers exposed to the south.

As a first approximation, the mean annual value of temperature increase, deduced from the ELA rise, is 0.8 °C.

As regards the upper Valpelline and upper Valtournenche glaciers, the values of frontal retreat are extremely variable in the glaciers investigated: from a minimum value of 400 m in the Solatset Glacier up to 3600 m in the Tsa de Tsan Glacier in Valpelline.

The areal retreat has been 42.34%. Indeed, the upper Valpelline and upper Valtournenche glaciers have decreased from an overall extension of 34.91 km^2 in the LIA to 20.13 km^2 at present. During the same period the volumetric reduction has been 0.35 km^3 of ice. This value, calculated in 17 glaciers, has been extrapolated to the whole range of the 143 glaciers studied, for which a total value of volume reduction of 2.66 km^3 of ice was obtained.

KEY WORDS: Glaciers, ELA, Little Ice Age, Climate, Valle d'Aosta, Western Alps.

RIASSUNTO: VANUZZO C., *Il ritiro dei ghiacciai nella Valle d'Aosta (Alpi Occidentali) dalla Piccola Età Glaciale alla seconda metà del XX secolo: variazioni lineari, areali, volumetriche e della altitudine della Linea d'Equilibrio.* (IT ISSN 0391-9838, 2001).

In questa ricerca, tramite indagini di terreno, fotointerpretazione, analisi di carte e documenti storici e utilizzo di Sistemi Informativi Geografici, sono state valutate la riduzione areale e le variazioni di quota della Linea d'Equilibrio di 143 ghiacciai ubicati in Val d'Aosta (Alpi occidentali, Italia), dalla ultima fase di massima espansione della Piccola Età Glaciale, culminata in Val d'Aosta intorno al 1820, al 1975, data del volo aereo utilizzato per la redazione delle Carte Tecniche Regionali utilizzate.

Sono inoltre presentati, con maggior dettaglio, i dati relativi al ritiro frontale, areale e volumetrico, sempre nello stesso intervallo di tempo, dei ghiacciai posti alla testata della Valpelline e della Valtournenche (Val d'Aosta).

Il ritiro areale dei 143 ghiacciai studiati in circa 150 anni è stato del 41,5%; la superficie glacializzata è infatti passata da 270,6 km^2 nella Piccola Età Glaciale a 158,4 km^2 nel 1975.

La quota media della Linea d'Equilibrio era pari a 2845±165 m nella Piccola Età Glaciale, mentre quella media attuale è pari a 3015±197 m.

La quota della Linea d'Equilibrio raggiunge il valore medio più basso nei ghiacciai ubicati nel gruppo montuoso del Monte Bianco (2702±117m nella Piccola Età Glaciale e 2896±198 m nel 1975) e quello più elevato nei ghiacciai ubicati nel gruppo montuoso Dent d'Herens-Monte Cervino-Monte Rosa (2903±170 m nella Piccola Età Glaciale e 3099±225 m nel 1975).

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Il valore medio di risalita della quota della Linea d'Equilibrio in Valle d'Aosta è pari a 139±106 m e a 129±96 m, se si considerano unicamente i ghiacciai che, nella fase di ritiro, non si sono suddivisi in più ghiacciai. I valori medi più elevati di risalita della ELA si hanno per i ghiacciai esposti nei quadranti meridionali.

In prima approssimazione il valore medio di incremento della temperatura media annua, deducibile dalla risalita della Linea d'Equilibrio, è pari a 0,8 °C.

Per quanto riguarda, nello specifico, i ghiacciai della Valpelline e della Valtournenche, i valori di ritiro frontale per i ghiacciai studiati sono molto variabili: da un dato minimo di 400 m per il Ghiacciaio di Solatset a 3600 m per il Ghiacciaio di Tsa de Tsan in Valpelline.

Il ritiro areale è stato del 42,34%; i ghiacciai in alta Valpelline e Valtournenche sono infatti passati da un'estensione complessiva di 34,91 km^2 nella Piccola Età Glaciale a 20,13 km^2 attuali. La riduzione volumetrica in questo stesso intervallo di tempo è stata pari a 0,35 km^3 di ghiaccio. Questo valore, ottenuto per 17 ghiacciai, è stato utilizzato per estrapolare all'intero campione dei 143 ghiacciai studiati, per i quali si è ottenuto un valore complessivo di riduzione volumetrica di 2,66 km^3 di ghiaccio.

TERMINI CHIAVE: Ghiacciai, ELA, Piccola Età Glaciale, Clima, Valle d'Aosta.

Résumé: Vanuzzo C., *Le retrait des glaciers dans les Alpes Occidentales d'Italie entre le Petit Âge Glaciaire et 1975: variations linéaires, aréolaires, volumetriques et de l'altitude de la Ligne d'Equilibre Glaciaire.* (IT ISSN 0391-9838, 2001).

Cette étude porte sur la réduction de la superficie et la variation altitudinale de la Ligne d'Equilibre Glaciaire (LEG) de 143 glaciers de la Vallée d'Aoste (Alpes Occidentales, Italie) entre la dernière avancée maximale du Petit Âge Glaciaire (PAG), qui a eu lieu dans cette région vers 1820, et 1975, date des photographies aériennes utilisées pour la réalisation de la carte topographique régionale. Enquêtes de terrain, photo-interprétation, analyse de cartes et de documents historiques et utilisation de Systèmes d'Information Géographique ont permis de mener cette recherche.

En outre, cette étude présente les données détaillées concernant le retrait frontal, aréolaire et volumétrique pendant cette même période des glaciers situés à l'amont de la Valpelline et de la Valtournenche (Vallée d'Aoste).

Le retrait aréolaire des 143 glaciers étudiés atteint 41,5% sur environ 150 ans; La superficie englacée est en effet passée de 270,6 km^2 pendant le PAG à 158,4 km^2 en 1975.

L'altitude moyenne de la LEG était de 2845±165 m pendant le PAG et de 3015±197 m en 1975. Sa valeur moyenne est la plus basse pour les glaciers du massif du Mont Blanc (2702±117 m pendant le PAG, 2896±198 m en 1975); sa valeur moyenne est la plus haute pour les glaciers du massif Dent d'Hérens-Cervin-Mont Rose (2903±170 m pendant le PAG, 3099±225 m en 1975).

La valeur moyenne de la remontée altitudinale de la LEG en Vallée d'Aoste est de 139±106 m (129±96 m si l'on ne prend en considération que les glaciers qui ne se sont pas subdivisés pendant cette période). Les valeurs les plus élevées de cette remontée correspondent aux glaciers exposés au sud.

En première approximation, l'augmentation de la température annuelle moyenne suggérée par la remontée de la LEG est de 0,8°C.

En Valpelline et en Valtournenche, les valeurs de retrait frontal des glaciers étudiés sont très variables, de 400 m pour le glacier de Solatset à 3600 m pour celui de Tsa de Tsan en Valpelline.

La diminution de superficie a été de 42,34%: la superficie des glaciers à l'amont de la Valpelline et de la Valtournenche est en effet passée de 34,91 km^2 pendant le PAG à 20,13 km^2 actuellement. Le volume de glace a pour sa part diminué de 0,35 km^3 pendant la même période.

Cette valeur volumétrique, obtenue à partir de 17 glaciers, a été extrapolée à l'ensemble des 143 glaciers étudiés, ce qui permet d'estimer la diminution de leur volume à 2,66 km^3.

MOTS-CLÉS: Glaciers, LEG, Petit Âge Glaciaire, Climat, Vallée d'Aoste, Italie.

INTRODUCTION

Owing to their sensitivity to climate change, Alpine glaciers have been considered for a long time as the most important paleoclimatic indicators.

Both glacier mass balance changes, considered as a direct signal, and areal, length and altitude changes of the Equilibrium Line, considered as an indirect sign, may be used as climate proxies. Glaciers' dynamic behaviour is controlled by energy balance and mass balance. In temperate regions the latter depends on the temperature of the ablation season and on snowfall.

Evidence, desumed from investigations on glacial deposits, allows the reconstruction of continuous or discontinuous temporal series of the trend and intensity of climate change. The study of linear, areal, volumetric and ELA changes can give an important contribution to research on environmental and climatic change affecting the Earth. Many investigations have been carried out in the Alps and in other mountain chains both in the past and present, in order to understand glaciers' dynamic behaviour and therefore obtain information on the evolution of Earth climate (Ahlmann, 1953; Hoinkes, 1968; Kuhn, 1979; Haeberli & *alii*, 1989; Oerlemans, 1989; Maish, 1992; Haeberli, 1995).

In this research the time interval considered for the study of linear, areal, volumetric and ELA changes spans from the peak of the LIA to date.

Information found in bibliography (Vanni, 1939) shows that in the study area, in particular in the Tsa de Tsan Glacier (Valpelline), the LIA maximum expansion phase took place in around 1820. In this paper, the present ice extension mentioned is the one deduced from the official regional topographic maps of Valle d'Aosta, drawn up on the basis of the aerial photo-survey of 1975.

The LIA corresponds to the last major Neoglacial advance (Porter & Denton, 1967) attained by mountain glaciers, which was coeval on most of the Earth and took place as a response to a small climate change with global effects. For many glaciers located in the Alpine region as well as in other areas of the northern hemisphere, this was the maximum Holocene expansion (Porter, 1981, 1986; Orombelli & Porter, 1982; Baroni & Carton, 1989; Nesje & *alii*, 1991; Pelfini, 1996). Also in the southern hemisphere the LIA was the «major episode of glacier expansion» (Porter, 1975) occurring in the Neoglacial. The beginning of the LIA, which was preceded by the «warm medieval Period», may be placed between the 13th and 14th centuries, whereas its maximum falls between the mid-16th and the mid-19th centuries (Grove, 1988).

THE GLACIER EXPANSION IN THE LITTLE ICE AGE

The reconstruction of the maximum glacial expansion attained in the Little Ice Age was obtained by means of field survey, aerial photo-interpretation and analysis of historical documents.

Once it had been defined, the LIA maximum expansion was represented on the regional topographic maps of Valle d'Aosta at the 1:10,000 scale. Afterwards a topographic reconstruction was made of the lowermost portion of each glacier, relative to the LIA maximum expansion (Porter, 1975).

The mapping information thus obtained was subsequently computerised and elaborated by means of Geographical Information System.

In this way data concerning the surface covered by glaciers in the LIA maximum and at present were obtained. Moreover, by utilising the data of each glacier relative to both present topography (referred to the year 1975) and to the LIA's reconstructed one (1820 ca.), it was possible to calculate the ice volume difference between the LIA maximum expansion and the present situation for the glaciers of the upper Valpelline and upper Valtournenche. Obviously, only one piece of information relative to the volumetric difference could be obtained, since no information is available about the bedrock topography of the glaciers studied and therefore the real volume of the glaciers themselves cannot be assessed.

SURFACE CHANGES

Reconstruction of the surface changes in 143 glaciers of Valle d'Aosta (fig. 1) has provided an areal reduction equal to 41.5%: from a glaciated surface of 270.6 km^2 during the LIA peak (1820 ca.) to 158.4 km^2 in 1975, with an overall ice retreat of 112.2 km^2 (VANUZZO, 1995). The surface decrease relative to the various mountain groups is shown in figure 2.

The mean surface retreat is in agreement with the value generally shown (40%) for the mean surface retreat of the Alps' glaciers from the second half of last century to date (Maisch 1992, Haeberli 1995, Pelfini, 1996, Folladori & *alii*, 1997).

THE EQUILIBRIUM LINE ALTITUDE (ELA)

Meaning of the Equilibrium Line Altitude

The Equilibrium Line Altitude in temperate glaciers is a sensitive indicator of climate conditions (Porter, 1975). This line separates the accumulation area from the ablation area and therefore it represents the locus of points, on a glacier's surface, where the mass balance is equal to zero.

ELA fluctuations take place as a response to a glacier's mass balance changes. The latter are in turn influenced by snowfall and summer temperature changes.

The climatic conditions existing at glacier «equilibrium lines are considered to be just sufficent to maintain the existence of glaciers» (Ohmura & *alii*, 1992).

With respect to the investigations directed to the identification and parametrisation of the relationships existing between ELA changes and temperature and snowfall changes, an important study was carried out by Ohmura & *alii* (1992). These authors obtained the equation (1) linking ELA changes to temperature and snowfall changes by using the data of winter mass balance, summer precipitation and summer temperature in free atmosphere, in proximity of the Equilibrium Line, for 70 glaciers of the alpine range.

$$\Delta_{z0} = \frac{\Delta T - \Delta P \left(\frac{\partial P}{\partial T}\right)^{-1}_{z0}}{\frac{\partial P}{\partial z}\left(\frac{\partial P}{\partial T}\right)^{-1}_{z0} - \frac{\partial T}{\partial z}} \qquad (1)$$

This equation expresses the direct proportion between the altitude rise of the Equilibrium Line, the increase of temperature and the decrease of precipitation. The equa-

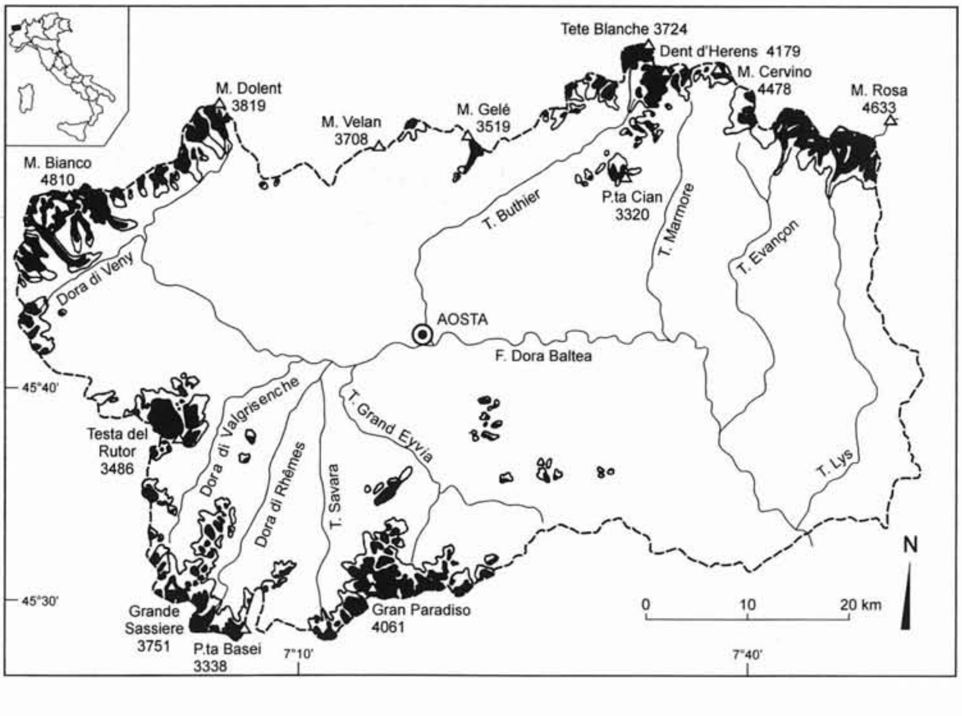

FIG. 1 - Map of the glaciers studied in Valle d'Aosta, 1975 (black) and LIA extent (heavy line).

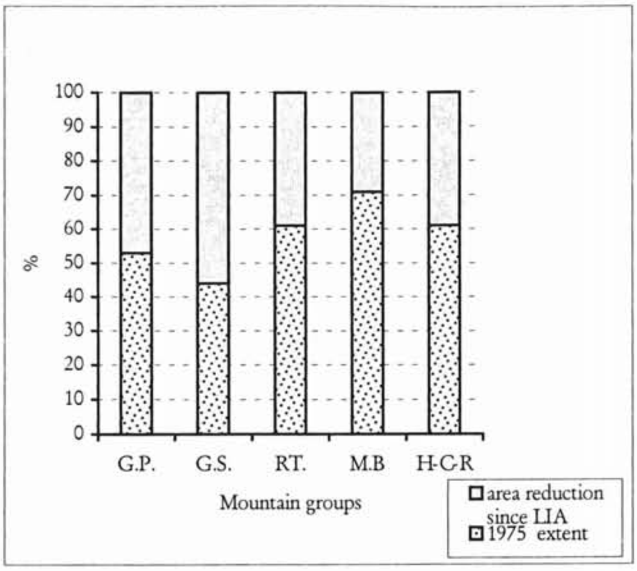

FIG. 2 - Present extent of the glaciers and area reduction from the LIA to present in different mountain groups. The LIA extent is equal to 100%. (G.P. - Gran Paradiso, G.S. - Grande Sassiere, RT - Rutor, M.B. - Monte Bianco, H-C-R - Dent d'Herens-Monte Cervino-Monte Rosa).

tion is also based on three more parameters ($\partial T/\partial z$ lapse rate, $\partial P/\partial z$ vertical gradient of precipitation, $\partial P/\partial T$ gradient of precipitation with respect to temperature) which the authors define as constant.

Indirect methods for assessing the Equilibrium Line Altitude

The direct method for assessing the present Equilibrium Line Altitude implies the measurement of a glacier's mass balance. It is thus possible to identify the contour line where the mass balance equals zero. Nevertheless, for reconstructing ELA in the past only indirect methods may be used. Several indirect methods, which have been described and used by various researchers from the last century onwards are here quoted, as summarised by Andrews (1975), Gross & *alii* (1977), Meierding (1982), Hawkins (1985), Nesje & Dahl (1992) and Federici (1997).

They are:

- determination of the altitudes of remnant cirque-floors;
- determination of the maximum elevation of lateral moraines;
- determination of the former glacier's median elevation;
- determination of the glaciation threshold;
- determination of the toe-to-headwall altitude ratio;
- determination of the ratio of the accumulation area to the total area (Accumulation Area Ratio = AAR).

As for the definition of present ELA, mass balance data are available only for a very limited number of glaciers. For this reason also the definition of the present ELA has been carried out by means of indirect methods. Among these, worthy of note are (ANDREWS, 1975): identification of the annual snow boundary, as desumed from aerial photographs, change of concavity of the contour lines which describe a glacier's surface and the already quoted AAR method.

AAR Method

Among the methods previously listed the AAR method, which is based on the ratio between accumulation area and total area, is the most significant (Hawkins, 1985). Braithwaite & Muller (1980) quote several authors who have utilised this method in the past by using different values. A proportion between area of accumulation and area of ablation equal to 2:1, corresponding to an AAR value of 0.67 (Aacc/Atot = 0.67) is today generally accepted as valid for Alpine glaciers in equilibrium with present climatic conditions. Therefore, for the calculation of ELA, both present and related to the LIA peak, the AAR method was used for the glaciers here investigated.

This method gives a cautious assessment of ELA and is based on a concept of stationary glacier equilibrium. Therefore, it does not respect the interannual climate fluctuations but it rather shows a mean condition for a certain number of years (Andrews, 1975).

The data of the glaciers' surfaces for both 1975 and the maximum LIA expansion phase (1820 ca) have been elaborated with the aid of an electronic sheet. Afterwards, by means of a simple equation, the contour line altitude dividing the glacier was calculated so that 2/3 of the surface was localised in the area of accumulation and 1/3 in the area of ablation, thus respecting the AAR 0.67 ratio. In this way the Equilibrium Line Altitude for both 1975 and the maximum LIA expansion phase was calculated.

The Equilibrium Line Altitude in the LIA and at Present

During the LIA the mean ELA for the 143 Valle d'Aosta glaciers (1820 ca.) was 2845±165 m, whereas the mean present altitude (1975) is 3015±197 m. The distribution of ELA values for altitude intervals of 20 m is shown in figures 3 and 4.

As for the values that ELA assumed in the various mountain groups, it should be noticed that the lowermost altitudes are found in the glaciers of Monte Bianco and Rutor mountain ranges, whereas the highest ones are found in the glaciers of Dent d'Herens - Mt. Cervino - Mt. Rosa and Gran Paradiso mountain ranges (fig. 5).

Furthermore, the mean altitude of the Equilibrium Line assumes different values in function of aspect (fig. 6). The highest elevations (3189±148 m for the present altitude and 3007±105 m for the LIA) are found in the glaciers facing SW, whereas the lowest elevations characterise the northern aspects. This is in agreement with the observations carried out by Maisch (1992) on 700 glaciers situated in the Grisons (Switzerland).

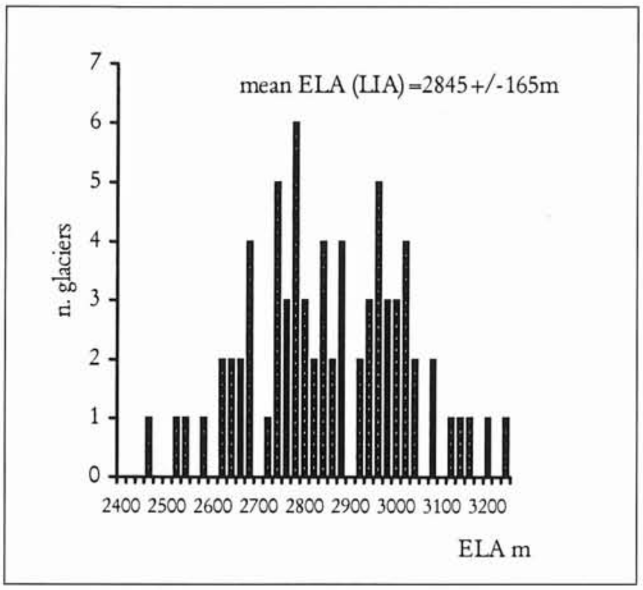

FIG. 3 - Distribution of ELA values in the LIA shown at intervals of 20 metres.

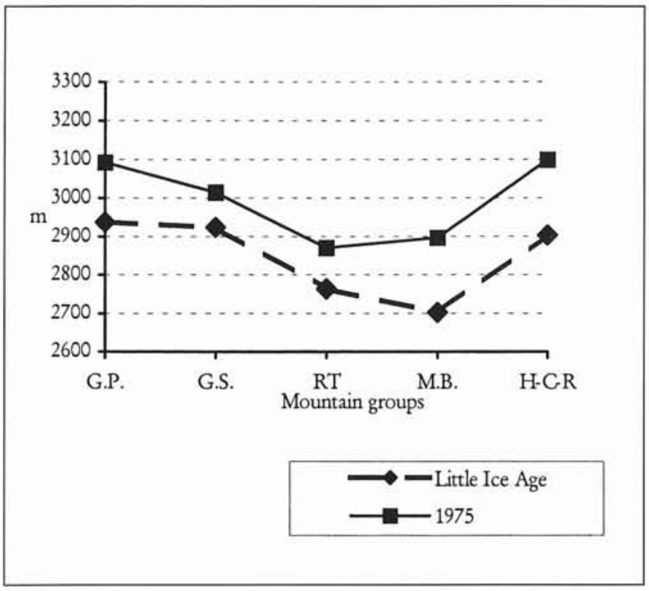

FIG. 5 - Mean ELA in 1975 and in the LIA in different mountain groups, from south to north-east clockwise. (G.P. - Gran Paradiso, G.S. - Grande Sassiere, RT - Rutor, M.B. - Monte Bianco, H-C-R - Dent d'Herens-Monte Cervino-Monte Rosa). The highest values are found for glaciers located in Dent d'Herens-Monte Cervino-Monte Rosa mountain groups and the lowest values are found for glaciers located in Monte Bianco and Rutor.

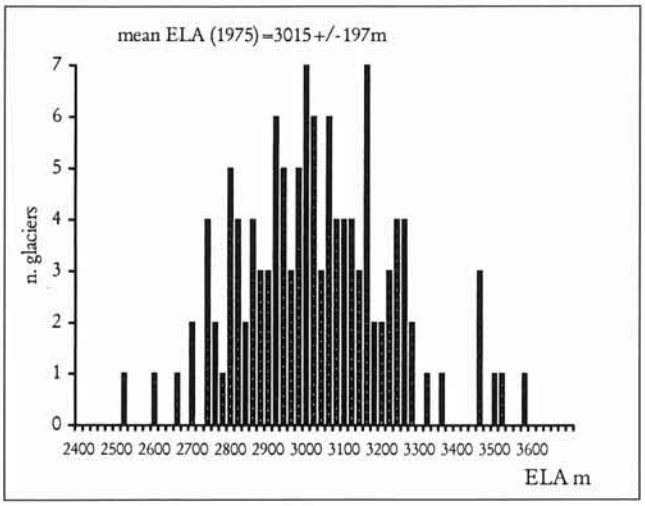

FIG. 4 - Distribution of ELA values in 1975 shown at intervals of 20 metres.

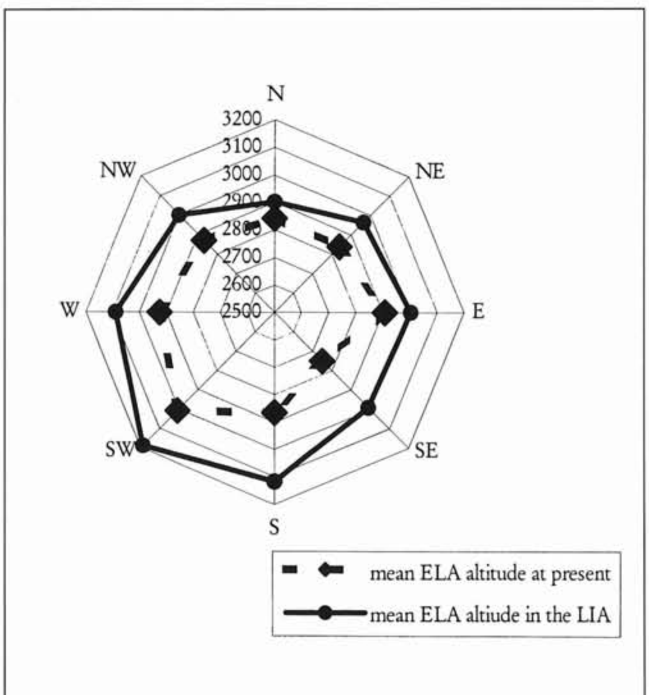

FIG. 6 - Mean ELA in 1975 and in the LIA for different aspect of glaciers. The highest value is found for those glaciers facing south-west.

ELA fluctuations from the LIA to date

Data concerning ELA fluctuations are highly dispersed: the mean of these values is 139±106 m (fig. 7).

The mean value falls within the range of values obtained by other researchers carrying out similar investigations (tab. 1).

The change of altitude of the Equilibrium Line ranges from a minimum value of –71 m to a maximum of +467 m. The high value scattering obtained may be explained

TABLE 1 - Mean ELA rise from the Little Ice Age to present in various montain groups

Author	Place	Δ ELA (m)
Porter, 1975	New Zeland	140
Maisch, 1987	Swiss Alps	77
Nesje, Dahl, 1991	Norway	130
Nesje, Kvamme 1991	Norway	150
Nesje, 1992	Norway	100/150
Pelfini, 1995	Italy (Ortles-Cevedale)	102
Vanuzzo, this work	Aosta Valley	139

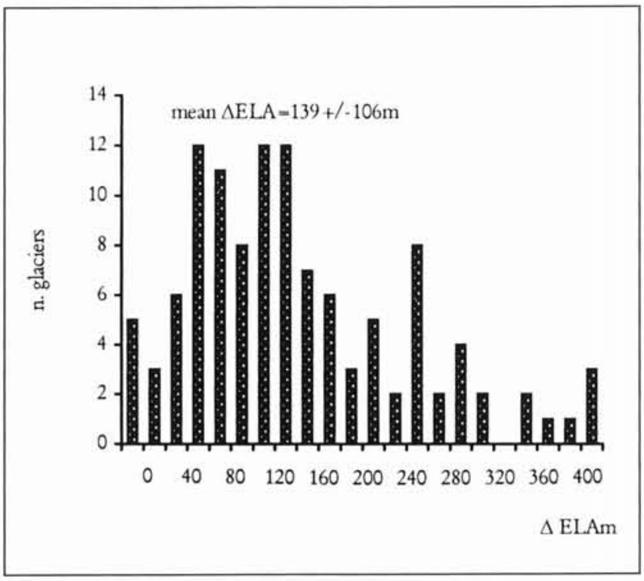

FIG. 7 - ELA rise from the LIA to 1975, shown at intervals of 20 metres. The values are widely dispersed around a large modal maximum between 40 and 140 metres. The first bar represent all the negative values.

by the influence of factors such as bedrock topography, morphology of the surrounding relief, glacier inclination, ice retreat conditions and local climatic conditions.

The Equilibrium Line Altitude rise (fig. 8) attains the lowest value in the glaciers of the Gran Sassiere (97±76 m) and Rutor groups (100±92 m) whereas the highest is found in the glaciers of Dent d'Herens - Mt. Cervino - Mt. Rosa groups (166±39 m).

The ELA rise for different glaciers' aspect is shown in figure 9: the highest values are attained in the glaciers facing south whereas the lowest are found in the glaciers facing north.

The results of these observations are shown in figure 10, where the ELA rise data and glaciers' aspect data in the various mountain groups considered, are presented together. The glaciers of Rutor and Grande Sassiere mountain groups, which have the lowest ELA rise are prevalently ex-

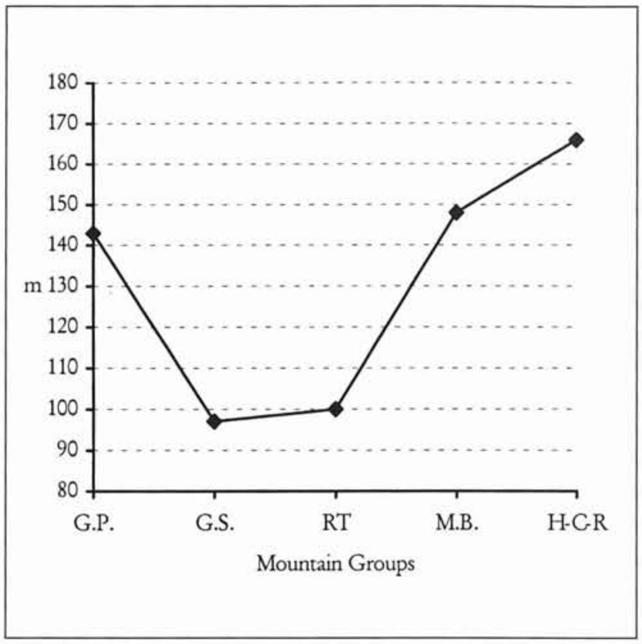

FIG. 8 - Mean ELA rise from the LIA to 1975 in the different mountain groups. (G.P. - Gran Paradiso, G.S. - Grande Sassiere, RT - Rutor, M.B. - Monte Bianco, H-C-R - Dent d'Herens-Monte Cervino-Monte Rosa).

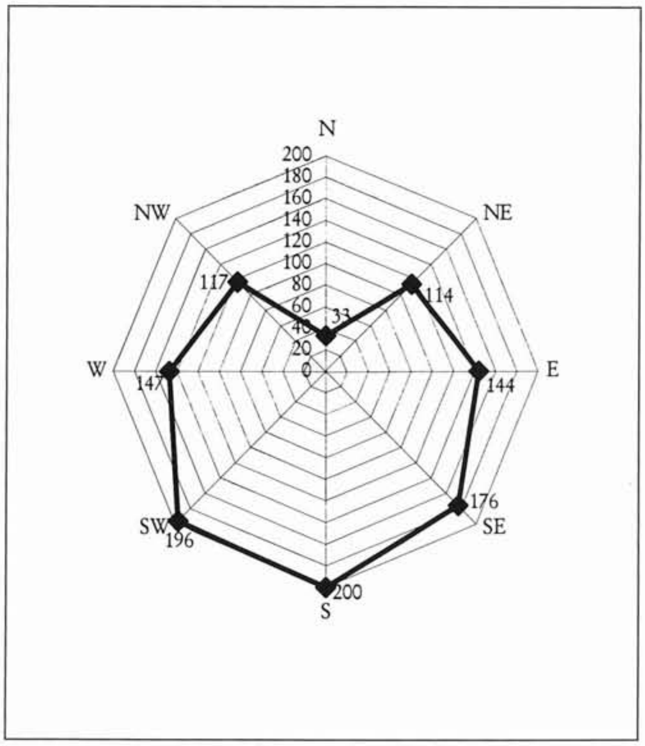

FIG. 9 - Mean ELA rise from the LIA to 1975 for different aspect of glaciers. The highest values are found for glaciers with southern aspect, the lowest for glaciers with northern aspect.

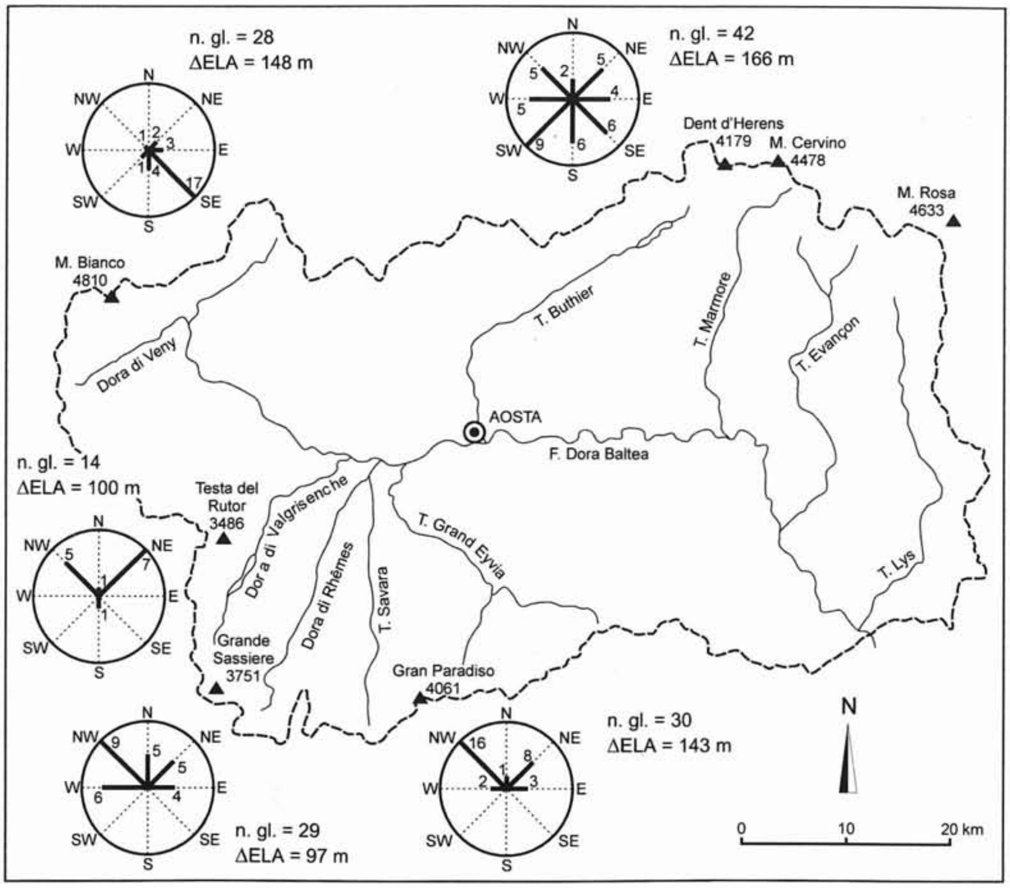

FIG. 10 - Map of the different mountain groups where the studied glaciers are located. The total number of glaciers, the number of glaciers for different aspect, and the mean ELA rise are shown for each mountain group. The highest ELA rises are found in the mountain groups with the greatest number of glaciers with a southern aspect (Dent d'Herens-Monte Cervino-Monte Rosa and Monte Bianco). The lowest ELA rises are found in the mountain groups with the greatest number of glaciers with a northern aspect (Grande Sassiere, Rutor).

posed to the north, whereas the glaciers of Dent d'Herens - Mt. Cervino - Mt. Rosa mountain range, which have the highest ELA rise values, generally show southern aspect. This clearly shows that ELA rise values are largely influenced by the glaciers' exposure with respect to insolation.

As regards ELA increases much above the average, it was observed that high values are found in those glaciers which during the maximum expansion phase were made up of a single large ice mass and, during the following retreat phase, split up into several smaller glaciers. Finally, it should be emphasized that the glaciers showing an ELA decrease, or increase considerably lower than the average, must have undergone a very pronounced surface retreat also in the area of accumulation, contracting and shrinking to ice-snow fields, confined at the bottom of cirques protected by surrounding mountain slopes. Therefore a critical analysis of the results obtained is required.

From the elaboration of ELA fluctuation data concerning glaciers which have undergone a frontal retreat without splitting up into several smaller glaciers, a value of 129±96 m is obtained (fig. 11), sligthly smaller and with a reduced standard deviation. In this case the values relative to 29% of the glaciers investigated have been averaged out.

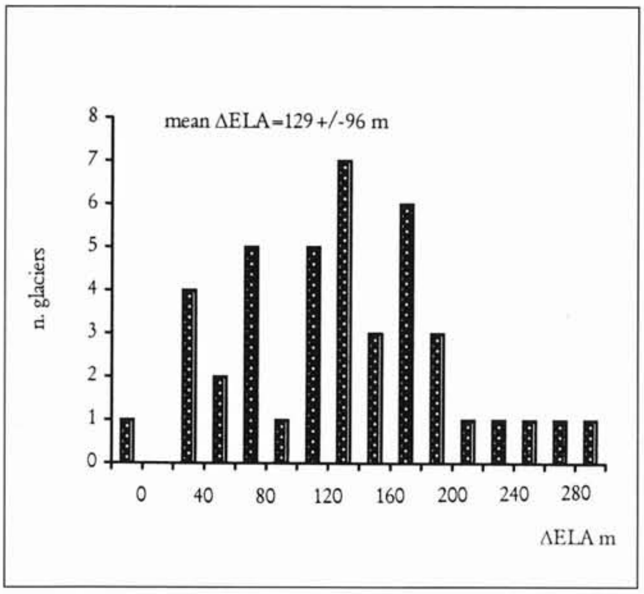

FIG. 11 - ELA rise from the LIA to 1975, shown at intervals of 20 metres, for glaciers that did not split into several smaller glaciers during the retreat phase. The first bar represent all the negative values.

Preliminary paleoclimatic remarks

ELA depends on the climatic conditions existing at the corresponding contour line. ELA changes are therefore the result of climate changes (Ohmura & *alii*, 1992). The results shown in this research suggest the prevalence of incoming solar radiation as a factor of control on ELA fluctuations. Indeed, the factor exerting most influence on the amount of ELA variation is exposure to the sun.

As for the relationships between ELA and meteorological parameters, it should be remembered that Italian glaciers show a more significant correlation between frontal and temperature changes rather than between frontal and precipitation changes (Belloni & *alii*, 1985; Smiraglia, 1986).

Finally, as regards the trend of temperature and precipitation, there is a clear general tendency for temperature to increase from the second half of the 19th century to date (Wigley, 1989; IPCC, 1995 pp. 133-192). On the contrary the precipitation trend shows a much more irregular pattern (Bradley & *alii*, 1987), thus making the identification of a possible trend more difficult. Data shown by IPCC point to a considerable variability of precipitation on a world-wide level, with an average increase of precipitation around 1% in the 20th century. More specifically, a precipitation rise has been recorded in northern Europe, whereas a drop has been observed in southern Europe.

Information on paleoclimatic characteristics may therefore be achieved, as a first approximation, transforming the mean ELA increase into a temperature change. In this research, by using the data available in literature (Janin, 1968; Giorcelli, 1982-3; King, 1990), a value of the annual mean lapse rate of 0.62 °C/100 m was obtained for Valle d'Aosta. This datum has allowed a mean rise value of the mean annual air temperature of 0.8 °C to be inferred from the LIA to the present, with an ELA variation of 129 m.

Similar values have been found in Norway by Nesje & Kvamme (1991), Nesje & Dahl (1991) and Nesje (1992) who point to a mean annual air temperature increase of 0.5 to 1 °C. Moreover, a mean annual air temperature increase of 0. 52 °C was found by Pelfini (1995) in the Ortles-Cevedale group. Finally, the data reported by IPCC (1995) point to an increase of the mean air temperature of 0.3 to 0.6 °C on a world scale from the mid-19th century to date.

Climatic conditions in Valle d'Aosta in correspondence with ELA

Climatic information about the ELA has been deduced from data in articles by Janin (1968), Giorcelli (1982-3) and King (1990) who took into account temperature series between 1950 and 1980 in Valle d'Aosta.

The mean annual 0°C isotherm corresponds to 2530 m a.s.l.; the present ELA (3015 m a.s.l.) corresponds to –3 °C, i.e. 485 m above the 0 °C isotherm.

During the LIA the ELA was located at 2845 m a.s.l. At present the mean annual air temperature corresponding to this altitude is –1.9 °C. If the mean temperature rise calculated from the LIA to the present (0.8 °C) is subtracted from this figure, a value of –2.7 °C is obtained, which approximately shows the mean annual air temperature in correspondence with the ELA during the LIA. This value slightly diverges from the present one of –3 °C.

By utilising data from the whole Alpine chain, from Monte Bianco to the Ötztal Alps, Ohmura & *alii* (1992) remarked that in the Alps the ELA is positioned on average 700 m above the 0 °C isotherm. On the other hand, by considering data relative to the Italian side of the Alpine chain from the Maritime Alps to the Dolomites, Belloni & *alii* (1993) pointed out that in the Alps the ELA is positioned in correspondence with the –3.8 °C isotherm, at the altitude of 2890 m a.s.l., 633 m above the 0 °C isotherm.

The data obtained in this research, deduced from few climatic series, are different from those obtained by Ohmura & *alii* (1992) for all the Alpine chain and by Belloni & *alii* (1993) for all the Italian Alps. For this reason they have to be considered only a first approximation to the problem.

THE GLACIERS OF VALPELLINE AND VALTOURNENCHE

The glaciers positioned at the head of Valpelline are, from west to east respectively: the Mont Braoulé Glacier, the Tsa de Tsan Glacier, the Grandes Murailles Glacier, the Petites Murailles Glacier, the Château des Dames Glacier, the Bella Tza Glacier and the Solatset Glacier. The Valtournenche glaciers are, from west to east respectively: the Mont Tabel Glacier, the Cherillon Glacier, the Alto and Basso Leone Glacier, the Tyndall Glacier, the Cervino Glacier, the Forca Glacier, the Teodulo Glacier and the Valtournenche Glacier.

All these glaciers are shown in the geomorphological sketch map in fig. 12.

Frontal changes

In tables 2 and 3 are shown the glaciers' maximum and minimum altitudes and the glaciers' lenght referred to the present and to the LIA extent. As for the frontal changes, the surveyors of the Comitato Glaciologico Italiano have recorded these changes from the beginning of the 20th century with continuity. The data were published in the bulletins of the Comitato Glaciologico Italiano until 1977 and, subsequently, in the journal *Geografia Fisica e Dinamica Quaternaria*.

Among the glaciers of the upper Valpelline, the Tsa de Tsan Glacier shows the longest temporal sequence of measurements. Owing to its large size, this glacier has always aroused particular interest among researchers, as witnessed by the articles by Revelli (1917), Sacco (1918), Vanni (1939), Smiraglia (1975), as well as the numerous studies by the Abbot Henry.

The Tsa de Tsan Glacier has undergone a frontal retreat of 3600 m from the maximum expansion phase in the Little Ice Age to present.

Up to the mid-1950s, the Grandes Murailles Glacier flowed into the Tsa de Tsan Glacier forming the Basso Tsa de Tsan Glacier (Frisa, 1956; Vanni, 1965). The ob-

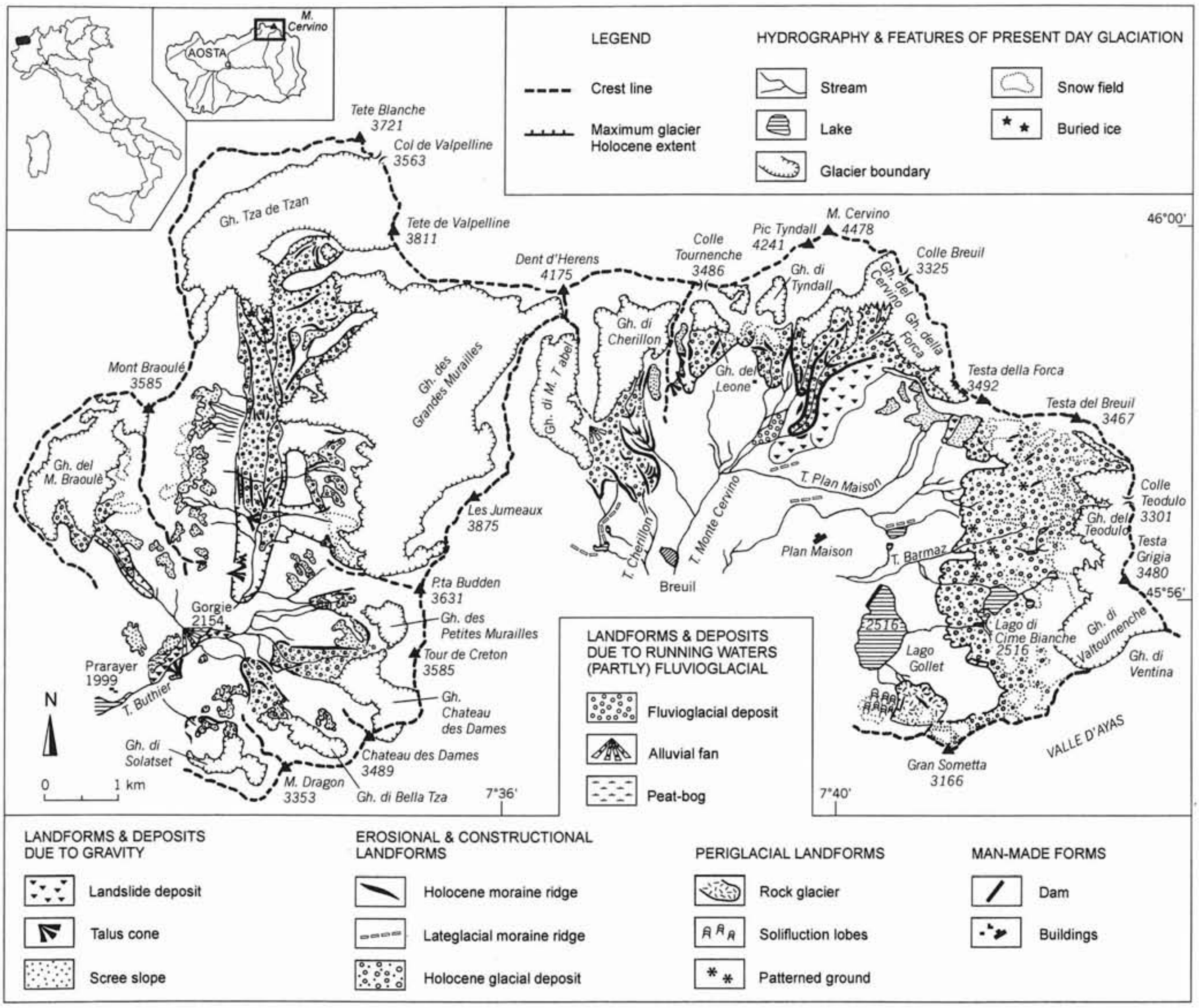

FIG. 12 - Geomorphological sketch map of high Valpelline and Valtournenche.

TABLE 2 - Valpelline glaciers: aspect, elevation and length

Glacier from	aspect	max elevation (m)	minimum altitude of snout in LIA (m)	minimum altitude of snout at present (m)	glacier lenght in LIA (m)	glacier lenght at present (m)	glacier retreat the LIA to present (m)
Mont Braoulé	SE	3580	2300	2850	3300	2260	1040
Tsa de Tsan	SW	3810	2150	2560	7200	3600	3600
Gr. Murailles	SW	4000		2330		4200	
Pet. Murailles	W	3250	2520	2910	1400	700	700
Chateau des D.	W	3390	2400	2800	2300	1300	1000
Bella Tsa	NW	3040	2350	2560	1890	1170	720
Solatset	NW	3250	2430	2700	1200	800	400

TABLE 3 - Valtournenche glaciers: aspect, elevation and lenght

Glacier	aspect	max elevation (m)	minimum altitude of snout in LIA (m)	minimum altitude of snout at present (m)	glacier lenght in LIA (m)	glacier lenght at present (m)	glacier retreat from the LIA to present (m)
Mont Tabel	S	3650	2400	2560	2300	1850	450
Cherillon	S	3540	2150	2600	3400	1900	1500
Basso Leone	S	3190	2680	2950	1050	400	650
Alto leone	S	3561	2970	3300	813	340	473
Tyndall	S	3510	2740	3000	1450	650	800
Cervino	S	3360	2600	2870	2227	1600	627
Forca	S	3435	2450	2900	2600	1000	1600
Teodulo	W	3450	2700	2970	2333	867	1466
Valtournenche	W	3695	2700	3010	2933	1467	1466
Sometta	N	3075	2850		400		

FIG. 13a - Grandes Murailles and Tsa de Tsan glaciers (late 19th early 20th century). (Photo Ferrari, Collezione Sella, Biella).

FIG. 13b - Grandes Murailles Glacier at the confluence with Tsa de Tsan Glacier in the late 1930s (Vanni, 1939).

FIG. 13c - Grandes Murailles Glacier. To the left the lateral right moraine showing the maximum extent reached in the LIA, when the glacier flowed into the Tsa de Tsan Glacier (photo C. Vanuzzo, 1994).

servation of three photos: the first (property of the «Fondazione Sella di Biella») took by Dr. Ferrari who was born in 1875 and died in 1934, the second printed in the article by Vanni (1937) and the third taken in 1994 at the point where the Grandes Murailles Glacier flowed into the Tsa de Tsan Glacier, clearly shows the evolution of these two glaciers in a century (figs. 13a, b, c).

The retreat of the Tsa de Tsan and Grandes Murailles glaciers since the early 20th century is shown in figure 14. These data are derived from the reports of the glaciological surveys collected in the *Bollettino del Comitato Glaciologico Italiano* and in *Geografia Fisica e Dinamica Quaternaria.*

The figure shows the constant retreat of the glacier's front up to the second half of the 1960s, followed by the minor readvance of the 1970s-80s, which started in 1971 for the Tsa de Tsan Glacier and in 1968 for the Grandes Murailles Glacier.

The Tsa de Tsan Glacier shows an alternation of advance and retreat from 1973 to 1991, while from 1991 to 1997 a costant retreat can be observed.

The Grandes Murailles Glacier shows a phase of costant advance from 1968 to 1981 (excluding 1976), from 1981 to 1990 there is a lack of data and then from 1992 to

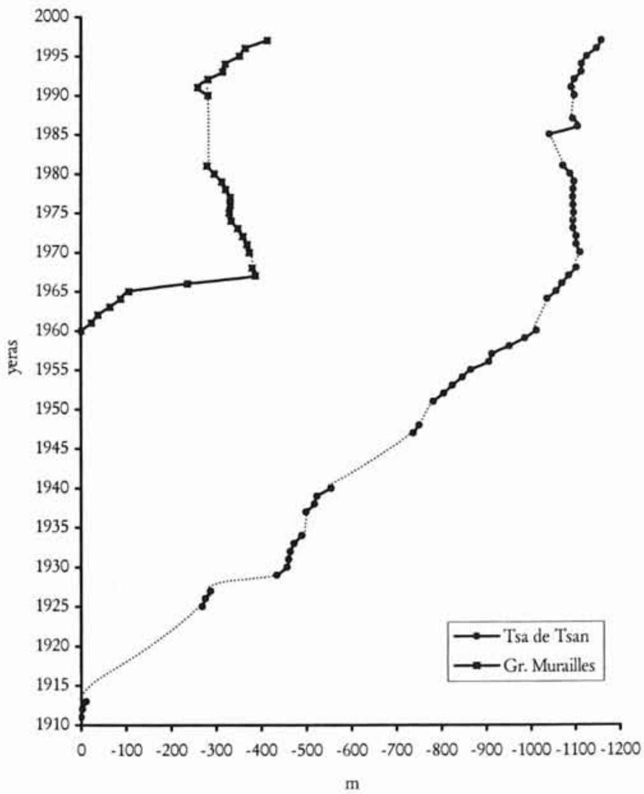

FIG. 14 - Frontal retreat of Tsa de Tsan and Grandes Murailles glaciers. Data are deduced from the bulletins of the Comitato Glaciologico Italiano and from the journal «Geografia Fisica e Dinamica Quaternaria». The hatching represents a lack of annual data. Grandes Murailles Glacier separated from Tsa de Tsan Glacier in the first half of 1950s and measurements started in 1961.

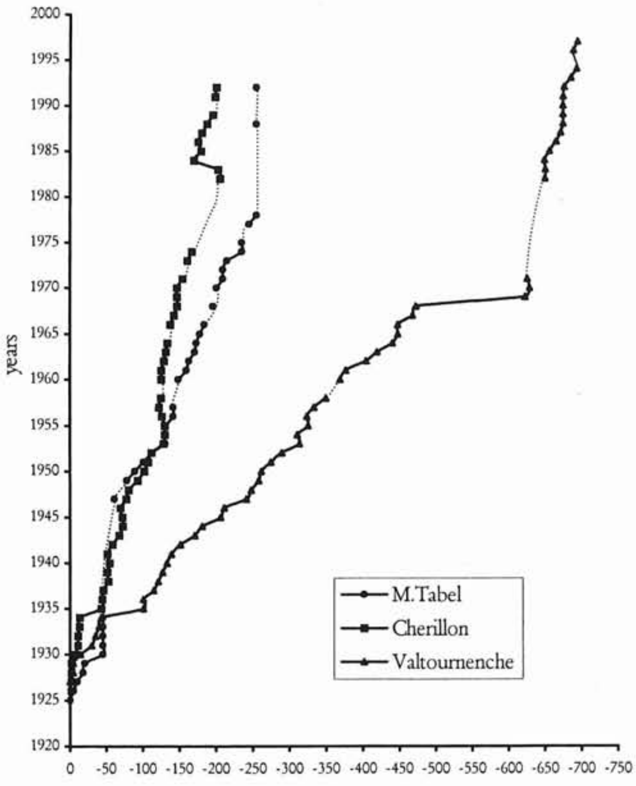

FIG. 15 - Frontal retreat of Mont Tabel, Cherillon and Valtornenche glaciers. Data are deduced from the bulletins of the Comitato Glaciologico Italiano and from the journal *Geografia Fisica e Dinamica Quaternaria*. The hatching represents a lack of annual data.

1997, as for Tsa de Tsan glacier, a costant retreat can be observed.

As regards the upper Valtournenche, four glaciers (Cherillon, Forca, Teodulo, Valtournenche) have experienced a frontal retreat of about 1500 m whereas another four (Mont Tabel, Alto and Basso Leone, Cervino) of about 500 m. Data collected by researchers of the Comitato Glaciologico Italiano on the Mont Tabel, Cherillon and Valtournenche glaciers are sufficiently continuous.

The extent of the retreat which affected these glaciers since the 1920s is depicted in figure 15, where the constant retreat of the fronts is clearly observable. The Cherillon Glacier is the only one which recorded the modest advance of the 1980s. Nevertheless it should be noticed that the data concerning the trend of the front of Mont Tabel Glacier from 1979 to 1987 are not available.

Surface changes

From the LIA peak to the present day the glaciers of the upper Valpelline have undergone a surface retreat of 29.21 %. The glaciated surface has in fact dropped from 20.13 km^2 during the LIA to the present 14.25 km^2, with a total reduction of 5.88 km^2 (tab. 4, fig. 16).

TABLE 4 - Valpelline glaciers: areal variations

Glacier	aspect	glacier area in the LIA (km^2)	present glacier area (km^2)	area reduction from LIA to present (km^2)	area reduction from LIA to present (%)
Mont Braoulé	SE	2,21	1,63	0,58	26,24
Tsa de Tsan	SW	15,13	3,75	4,08	26,97
Gr. Murailles	SW		7,3		
Pet. Murailles	W	0,54	0,23	0,31	57,41
Chateau des Dames	W	1,09	0,68	0,41	37,61
Bella Tsa	NW	0,63	0,3	0,33	52,38
Solatset	NW	0,53	0,36	0,17	32,07
Totale		20,13	14,25	5,88	29,21

The largest glaciers (Tsa de Tsan and Grandes Murailles) have experienced a surface reduction of only 26.97 %, although on an absolute scale they have contributed more than all the others to the extent of the glacial retreat. They are valley glaciers with wide accumulation basins and narrow, well developed tongues. Whereas the former have hardly been affected by surface reduction, the latter have undergone a considerable retreat. The other glaciers have experienced a surface retreat up to 57 %.

Thanks to the data published in the study by Vanni & *alii* (1953), it was possible to reconstruct some stages of the retreat phase affecting the Mont Braoulé, Tsa de Tsan and Petites Murailles glaciers (tab. 5).

The retreat of the glaciers situated at the head of Valtournenche has been greater than that affecting the Valpelline glaciers. On the whole, during the LIA maximum expansion phase the glaciers investigated covered a surface equal to 14.78 km^2, whereas at present the glaciated surface is only 5.88 km^2, with a reduction of 8.9 km^2 equal to 60.21 % (tab. 6, fig. 17).

TABLE 5 - Area extent of some glaciers located in High Valtournenche in different years. 1929 and 1952 data are deduced from Vanni & *alii* (1953). The present area is deduced from aerial photos of 1975. Tsa de Tsan and Grandes Murailles glaciers are considered together

Glacier	aspect	LIA area (km^2)	%	area in 1929 (km^2)	%	area in 1952 (km^2)	%	present area (km^2)	%
Mont Braoulé	SE	2,21	100	1,93	87,3	1,73	78,3	1,63	73,76
Tsa de Tsan +	SW	15,13		5,01		4,54		3,75	
Gr. Murailles			100	8,13	86,8	7,32	78,4	7,3	73
Pet. Murailles	W	0,54	100	0,25	46,3	0,15	27,8	0,23	42,59

TABLE 6 - Valtournenche glaciers: areal variations

Glaciers	aspect	glacier area in the LIA (km^2)	present glacier area (km^2)	area reduction from LIA to present (km^2)	area reduction from LIA to present (%)
Mont Tabel	S	1,16	0,88	0,28	24,14
Cherillon	S	1,9	1,09	0,81	42,63
Basso Leone	S	0,44	0,14	0,3	68,18
Alto Leone	S	0,16	0,09	0,07	43,75
Tyndall	S	0,53	0,16	0,37	69,81
Cervino-Forca	S	2,48	1,52	0,96	38,71
Teodulo-Valtourn.	W	8,11	2	6,11	75,34
Totale		14,78	5,88	8,9	60,22

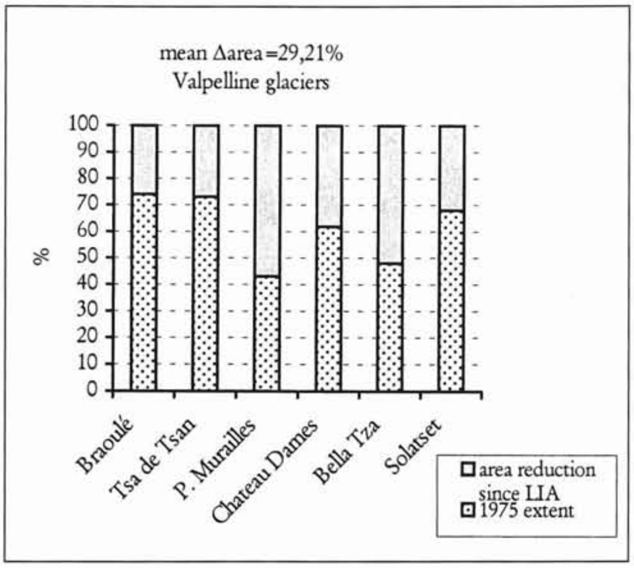

FIG. 16 - Present extent of the glaciers and area reduction from the LIA in high Valpelline. The LIA extent is equal to 100%.

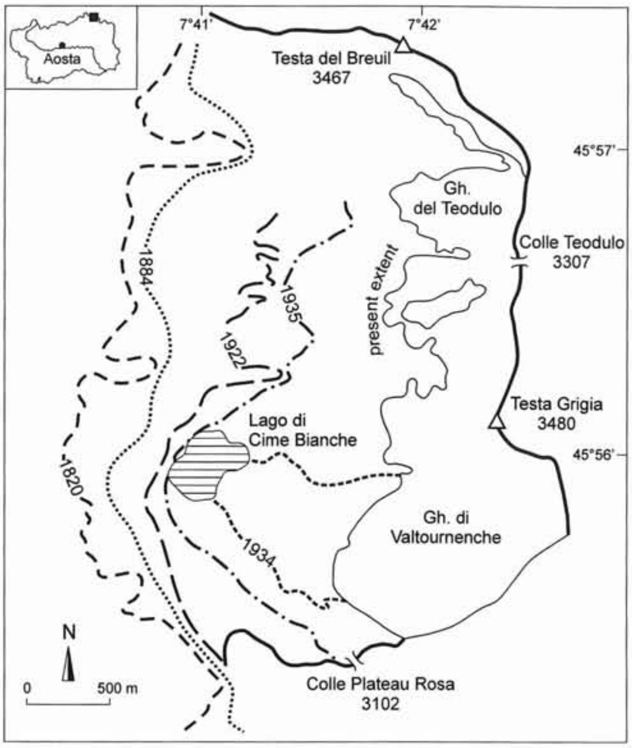

FIG. 18 - Subsequent retreat phases of the Valtournenche Glacier, as deduced from maps and surveys listed in literature (Lesca & *alii,* 1955).

The glaciers that have contributed most to the retreat are those of Valtournenche and Teodulo. During the LIA these two glaciers, together with the now extinct Gran Sometta Glacier made up a vast single glacial mass.

In particular, it should be noticed that at Present (1998) the extension of the Teodulo Glacier is much more reduced with respect to the surface shown in fig. 12, which was deduced from the 1976-77 aerial photographs, owing to recent excavations for the construction of ski lifts and ski runs.

In the LIA these glaciers occupied a 8.11 km^2 surface whereas now they stretch over 2 km^2, with a retreat of 6.11 km^2, corresponding to 75.34%. Such a high value may be explained by the bedrock and glaciers morphology. Owing to the almost flat and gently sloping bedrock topography, the glaciers have always had a limited thickness and covered the whole slope with uniformity. Therefore even a limited change of mass balance has resulted in a considerable retreat. The subsequent retreat phases of the Valtournenche glacier, as deduced from maps and surveys listed in literature (Lesca & *alii,* 1955), are summarised in figure 18.

Some stages of the surface reduction phase affecting Mont Tabel, Cherillon, Basso and Alto Leone, Pic Tyndall, Cervino-Forca and Teodulo-Valtournenche glaciers have been reconstructed.

The relative data are shown in table 7. The 1929 and 1952 extensions are taken from Vanni & *alii* (1953). The 1941 data, relative to the Cherillon, Pic Tyndall, Cervino, Forca, Teodulo and Valtournenche glaciers, are taken from Vanni (1942). The percentage values of surface reduction as a function of time, reported in tables 5 and 7, are shown in figure 19, which emphasizes a phase of intense retreat between 1930 and 1950 and a slowdown in the 1960-1980 period.

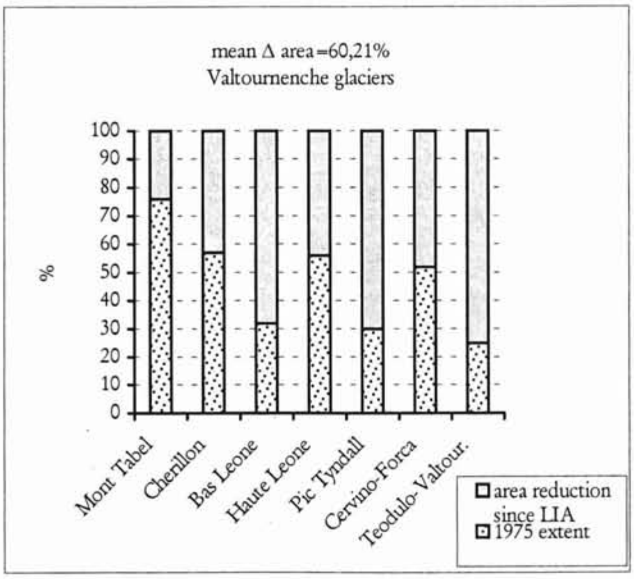

FIG. 17 - Present extent of the glaciers and area reduction from the LIA in high Valtournenche. The LIA extent in equal to 100%.

TABLE 7 - Area extent for some glaciers located in High Valpelline in different years. 1929 and 1952 data are deduced from Vanni & *alii* (1953), 1941 data are deduced from Vanni (1942). The present area is deduced from aerial photo

Glaciers	aspect	LIA area (km^2)	%	area in 1929 (km^2)	%	area in 1941 (km^2)	%	area in 1952 (km^2)	%	present area (km^2)	%
Mont Tabel	S	1,16	100					1,04	89,7	0,88	75,9
Cherillon	S	1,9	100	1,5	78,9	1,15	60,5	1,15	60,5	1,09	57,4
Basso Leone	S	0,44	100	0,24	54,5			0,16	36,4	0,14	31,8
Alto Leone	S	0,16	100								
Tyndall	S	0,53	100	0,41	77,4	0,36	67,9	0,29	54,7	0,16	30,2
Cervino-Forca	S	2,48	100	1,8	72,6	1,8	72,6			1,3	52,4
Teod.-Valtourn.	W	8,11	100	4,41	54,4	4,8	59,2	2,6	32,1	2	24,7

Volume changes

The use of Geographical Information Systems has allowed the volume changes of the glaciers situated at the heads of Valpelline and Valtournenche to be calculated.

By reconstructing the topography of each glacier in correspondence with the LIA maximum expansion and by comparing it with the present one, it was possible to assess the volume difference in this time interval.

Since information on the bedrock and in particular on the glacier thickness is not yet available, it was not possible to determine the glacier volumes in two subsequent phases; therefore only the volume change was estimated. The data obtained for the 17 glaciers investigated have produced a value of volume reduction from the LIA maximum expansion to 1975 of around 0.35 km^3 of ice (0.315 km^3 water equivalent).

The results obtained in this research have been compared with those reported by Maisch (1992) for the Swiss glaciers of the Grisons. For this purpose, it was hypothesized that the volume loss (0.35 km^3 of ice) took place on the ice surface lost from the LIA to the present (14.78 km^2); in this way the mean thickness of the melted ice portion was about 24 m of ice.

The value obtained is in agreement with what reported by MAISCH (1992) who calculated a surface reduction of 40% from the LIA to the present day, equal to 185 km^2 with a volume reduction of 4.6 km^3. The mean thickness of the melted glaciated surface would therefore be about 25 m.

The results of this research should be critically examined, since they are underestimated. In fact, in drawing up the glaciers' patterns, only the topography of the ablation zone has been reconstructed, whereas the topography of the area of accumulation has been considered unchanged. Therefore, the loss of ice occurring in the area of accumulation, which must have taken place as a considerable loss of thickness, has not been considered in the calculation of the volume retreat.

These data on thickness reduction, calculated for the 17 glaciers situated at the heads of Valpelline and Valtournenche, may be utilised for assessing approximately the extent of volume loss in all 143 glaciers investigated in Valle d'Aosta. By considering the mean thickness reduction of the ice portion, which melted away from the LIA maximum expansion to date equal to 24 m, and the loss of glaciated surface in the same interval as 112.2 km^2, it results that the 143 Valle d'Aosta glaciers have undergone a volume loss equal to 2.66 km^3 of ice.

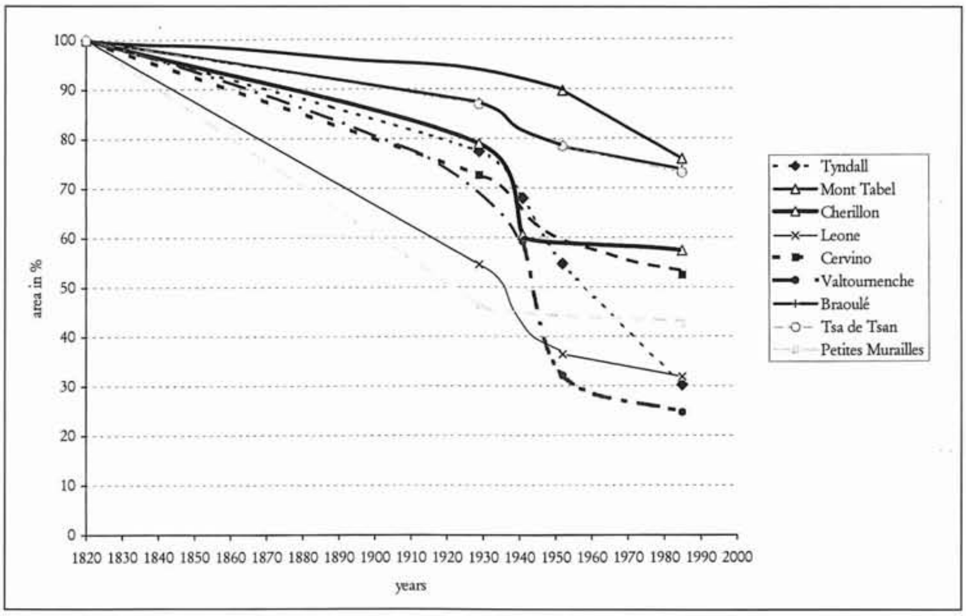

FIG. 19 - Percentage values of surface reduction as a function of time for some of the studied glaciers. The source data are those reported in tables 5 and 7. The figure emphasizes a phase of intense retreat between 1930 and 1950 and a slowdown in the period 1960-1980.

CONCLUSIONS

The general trend of the retreat observed in temperate glaciers is considered one of most evident indicators of the warming phase which started in the mid-19th century. The climatic system is considered intrinsically unstable; the instability may also depend on human activity. This problem is still debated inside the scientific world itself; however it is clear that glaciers offer a significative instrument of research.

Although the results obtained during this research are of regional significance, they confirm the generally observed trend for the Alpine glaciers with respect to linear, areal, volumetric retreat and the rise of the Equilibrium Line Altitude.

The ELA mean value in the Little Ice Age in Valle d'Aosta was 2845±165 m, whereas at present it is found at 3015±197 m; the mean rise value is therefore 139±106 m. The high standard deviation is due to the great variability of glacier retreat patterns as well as to topographic and aspect conditions. In particular, if one considers only the glaciers which have undergone just a frontal retreat in the reduction phase, without splitting up into several smaller glaciers, an ELA rise of 129±69 m is obtained.

The analysis of ELA fluctuations, as a function of glaciers' aspect, suggests that those exposed to the south show an ELA rise greater than those situated on the northern slopes. This fact emphasizes that aspect, and therefore solar radiation, is the most important factor affecting ELA fluctuations.

The temperature increase responsible for the ELA rise from the LIA to the present is 0.8 °C.

Surface retreat calculated on the 143 glaciers investigated is 41.5 %. The glaciated surface has decreased from 270.6 km^2, during the LIA peak, to the present 158.4 km^2. As regards the specific values of the 17 glaciers situated in the upper Valpelline and upper Valtournenche, a surface retreat of 42.3 % and a volume loss of 0.35 km^3 of ice were calculated. By using the value of the mean ice thickness lost in the melted portion in 24 m in the upper Valpelline and upper Valtournenche glaciers, it was possible to calculate, by extrapolation, a mean volume loss of 2.66 km^3 for the 143 Valle d'Aosta glaciers investigated in the present study.

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