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RESPONSE TIME OF THE LYS GLACIER (VALLE D'AOSTA). AN EXAMPLE OF A DENDROGEOMORPHOLOGICAL AND ENVIRONMENTAL STUDY

ABSTRACT: PELFINI M., BELLONI S., ROSSI G. & STRUMIA G., *Response Time of the Lys Glacier (Valle d'Aosta). An Example of a Dendrogeomorphological and Environmental Study*. (IT ISSN 0391-9838, 1997).

Glaciers respond to climatic variations through process that first involves mass balance and later frontal variations. The objective of this study was an evaluation of the response time of frontal variations for the Lys Glacier, which is located in the Monte Rosa Group.

Four mean dendrochronological curves were obtained by means of a dendrogeomorphological investigation carried out on over 200 larch trees sampled in the Gressoney Valley (AO, Western Italian Alps). These curves correspond to four morphological units left uncovered by the glacier in different time periods. The response time was obtained by correlating the dendrochronological data series obtained, with the glacier front variation data (time-distance curve). This showed that the response time was 5 years with a correlation coefficient of $r = -0.511$. Correlations using 5 years moving averages confirmed the results and increased the level of significance to $r = -0.693$. This was also confirmed by the results obtained by correlating frontal variations with the Lake Gabiet (2340 m) meteorological station temperatures. In addition, the correlations between the temperature data and the dendrogeomorphological series demonstrated that the response of the trees to temperature was virtually immediate.

KEY WORDS: Dendrogeomorphology, Response time, Glacier variations, Lys Glacier, Alps.

RIASSUNTO: PELFINI M., BELLONI S., ROSSI G. & STRUMIA G., *Il tempo di risposta del Ghiacciaio del Lys (Valle d'Aosta). Un esempio di indagine dendrogeomorfologica e ambientale*. (IT ISSN 0391-9838, 1997).

I ghiacciai rispondono alle variazioni climatiche attraverso una serie di passaggi che interessano dapprima il bilancio di massa e successivamente la posizione della fronte. I movimenti alla fronte si verificano quindi con un certo ritardo. Obiettivo del presente lavoro è la valutazione del tempo di risposta del Ghiacciaio del Lys, nel Gruppo del Monte Rosa.

Attraverso un'indagine dendrogeomorfologica, eseguita su oltre 200 larici campionati nell'alta Valle di Gressoney, sono state ricavate quattro curve dendrocronologiche medie, corrispondenti ad altrettante unità morfologiche lasciate scoperte dal ghiacciaio in tempi successivi. Correlando le serie dendrocronologiche con i dati di variazione frontale del ghiacciaio è stato ricavato il «tempo di risposta». Questo risulta essere pari a 5 anni con un coefficiente di correlazione $r = -0,511$. Le correlazioni effettuate utilizzando le medie mobili di ordine 5 confermano i risultati migliorandone la significatività, in quanto il valore di r aumenta ($r = -0,693$). Tale valore è confermato dal risultato ottenuto correlando le variazioni frontali con le temperature della stazione del Lago Gabiet (2340 m). Inoltre le correlazioni tra i dati delle temperature e le serie dendrocronologiche mostrano come la risposta della vegetazione arborea sia pressoché immediata.

TERMINI CHIAVE: Dendrogeomorfologia, Tempo di risposta, Variazioni glaciali, Ghiacciaio del Lys (Alpi).

INTRODUCTION

As is well known, glaciers represent an interesting source of information about the climate of the past in that they constitute valid recorders of climatic fluctuations. Following a general change in temperature and precipitation levels, the first response of glaciers is changes in their mass balances and equilibrium line altitudes, then their fronts advance or retreat. However, between the time of a climatic change and the shifting of the front, there is some delay.

According to Haeberli (1994, 1995) «after a certain reaction time following a change in mass balance, the length of a glacier will start changing and finally reach a new equilibrium after the response time». Expanding on this Haeberli recognizes three kinds of time response: 1) the reaction time, which is the «delay between the onset of disturbances in mass balance and the first reaction at the glacier terminus (T_{react})»; 2) the dynamic response time,

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The authors would like to thank Professor Giuseppe Orombelli and Professor Wilfrid Haeberli for their critical revision of the study, the Italian Corps of Foresters of Valle d'Aosta, which provided authorization for this study. We would like to specify that the dendrogeomorphological part of this study was compiled and written by M. Pelfini and G. Strumia; Rossi was in charge of the climatic information and S. Belloni checked the statistics. This work benefited of the contribution Murst 40% 1993 funds and Murst 60% 1997 funds (Resp. P. Casati).

which is the time for a full adjustment of the glacier to a new equilibrium. This response is related to the ratio between its maximum thickness and its annual ablation at the terminus (Johannesson et al., 1989; Haeberli, 1994); and 3) the relaxation time, which is «the time interval between the first reaction at the glacier terminus and full response to disturbances in mass balance ($t_{relax} = t_{resp} - t_{react}$)» (Haeberli, 1994, 1995).

According to Paterson (1981, 1994) the response time is the length of time for which the adjustment to a change in mass balance continues. «The first effects of the change will appear at the terminus in a much shorter time than the response time.» Typical response times in valley glaciers are in the range 2.5-25 years (Paterson, 1981).

Some researchers have dealt with this issue previously, using various methods, to estimate the response times of several sample glaciers. These methods were based on a linear correlation between the frontal variations and the trend of several climatic parameters such as temperature and precipitation. Correlating the algebraic sums of the temperatures from May to September with the frontal variations of the Sforzellina Glacier and the Dosegù Glacier, Belloni & *alii* (1990) obtained response times for the frontal variations of 8 years for the former and 10 years for the latter. For precipitation, an immediate response was found during current years, and others after 7 years and 2 years for the Sforzellina and the Dosegù Glacier respectively. Smiraglia (1986) correlated the moving averages of the frontal variations for the Ventina Glacier, with the moving averages of the temperature and precipitation residuals. The trend resulting from the correlation coefficients was a «response time» of 10 years with respect to temperature. There were no significant correlations for precipitation.

The aim of this work is to calculate the delay between the climatic input (and consequently the mass balance variations) and the full terminus response, for a sample glacier using not only meteorological measurements, but also through the use of dendrogeomorphological investigations. This delay corresponds to the reaction time defined by Haeberli (personal comm., 1998). For semplicity in this work the delay is called the response time.

The Lys Glacier was selected for this study as it is a glacier that has been studied for some time. The glacier front penetrated deep into the forest area during the last century and frontal variation data are available for this glacier starting from 1914.

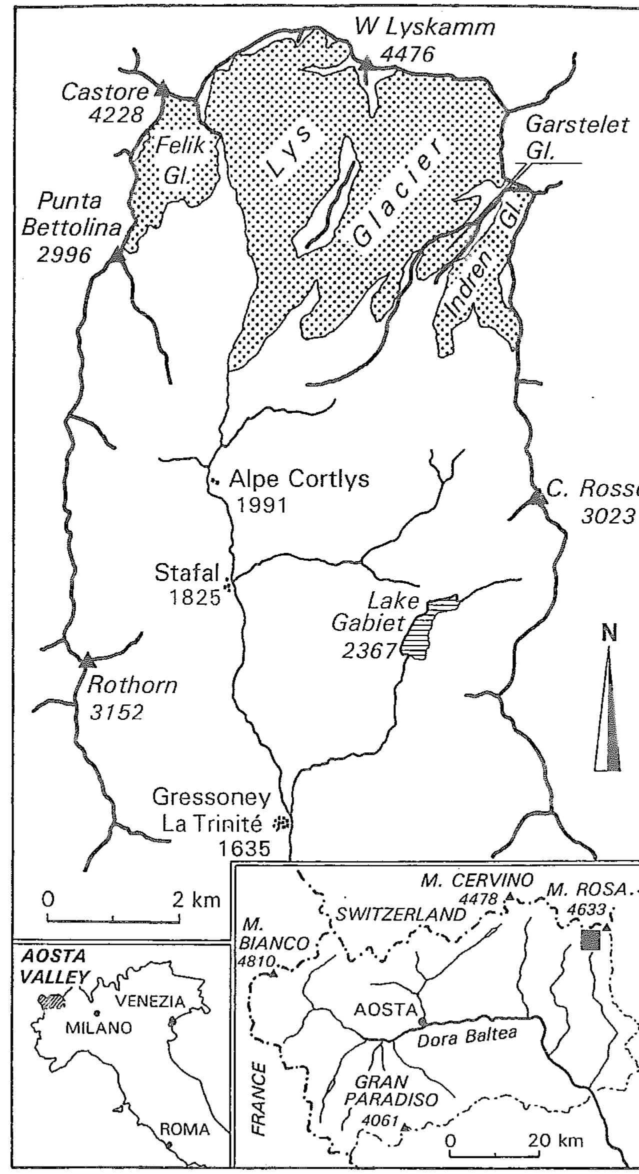

FIG. 1 - The study area: The Lys Glacier and the Gressoney Valley.

THE UPPER GRESSONEY VALLEY

The Lys Glacier is situated in the upper Gressoney Valley, in the Mt. Rosa Massif. Besides the Lys Glacier, which is one of the largest valley glaciers on the Italian side of the Alps, other glaciers in the Gressoney Valley include the Felik Glacier, the Garstelet Glacier and the Indren Glacier (fig. 1).

Data collected at the Lake Gabiet (2340 m) metereological station have been used to provide a climatic history of the Gressoney Valley. Figure 2 contains the mean annual air temperatures (2a) for the time period from 1928 to 1993, as well as the average temperature for the period July to October each year (2b), the mean monthly temperatures for the period (mean minimum temperatures, mean average temperatures and mean maximum temperatures) (2c), mean monthly precipitation (2d), and total annual precipitation (2e); figures 2a and 2b highlight the cold phase of the 1980's. It can be seen from figure 2c that the warmest month was July with a mean of 12.4°C, whereas the coldest month was January with –12.9°C, and that for the entire period from May to October, the mean temperature remained above 0°C. The precipitation was characterized by two peaks, spring and autumn. The maximum precipitation was in March with 725.3 mm and another peak occurred in October with 644.6 mm.

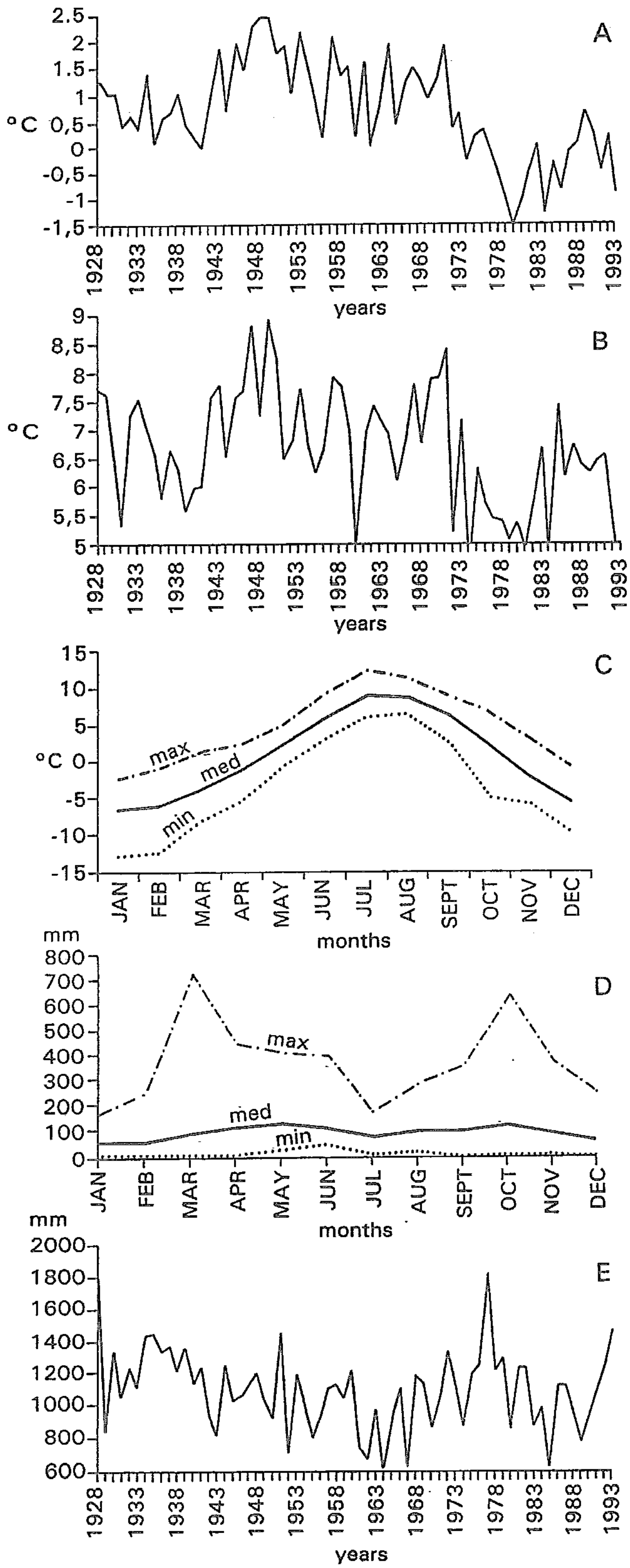

FIG. 2 - Climatic characteristics of the Lys Valley, as recorded at the Lake Gabiet meteorological station (2340 m) for the period 1928-1993: 2a) mean annual air temperatures; 2b) mean temperatures for the period July-October; 2c) means of the minimus, average and maximum monthly temperatures; 2d) mean monthly precipitation and 2e) total annual precipitation.

THE GLACIAL DEPOSITS OF THE LYS GLACIER

In the Upper Lys Valley, four moraine systems are visible; they are nearly concentric and attributable to three distinct glacial advances occurring in different historical times. The outermost system (M1 in fig. 3) is clearly visible, especially on the hydrological right slope, where it appears to be interrupted only at the Bettaforca river. A few sections of the second moraine (M2 in fig. 3), a few meters inside the first, are visible. The third moraine (M3 in fig. 3) is situated at a great distance from the previous two. Unlike the others, only the front is visible and the sides are practically non-existent. Inside the third moraine, there is

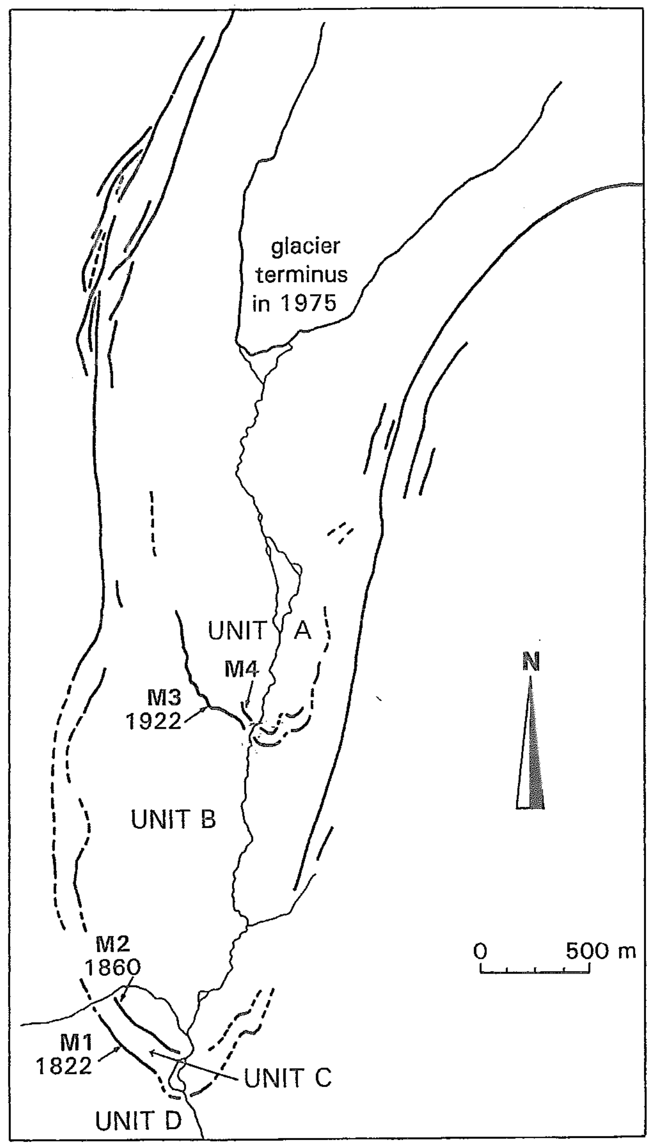

FIG. 3 - Holocene moraines of the Lys Glacier. The moraine ridges also constitute the boundaries of the morphological units used for the dendrogeomorphological investigation: *Unit A*, the area between the innermost moraine (M3) and the glacier; *Unit B*, the area between moraines M3 and M2; *Unit C*, the area between moraines M2 and M1; *Unit D*, the area below moraine M1.

another moraine ridge (M4 in fig.3). It is only slightly detectable and limited sections are present near the glacial front.

Outside of the Holocene moraine structure described above, other moraines can also be seen. They are only partially preserved and of a decidedly older appearance and a more rounded shape, and with a higher degree of vegetation with grass. These features are older structures and are probably attributable to the Late Glacial Period. They are numerous on the right slope, whereas there is only one prominent moraine, on the left slope, located at the elevation of the «Roccione di Salzen».

PREVIOUS STUDIES OF FRONTAL VARIATIONS IN THE LYS GLACIER

Due to its considerable extension and ease of access, the Lys Glacier has been the subject of many studies. The earliest record concerning the position of the front of the Lys Glacier dates back to August 10th, 1789 and is from De Saussure, who in his volume «Voyages dans les Alpes», published in 1803, relates that «the largest [glacier] is the one from which the Lys river originates, the latter lending its name to the valley. One observes three of these glaciers unite into one which descends winding its way down to the pastures of Gressoney La Trinité». From this description, one can reasonably deduce that the glacier reached as far as the pastures of Cortlys at the time a considerably more advanced position when compared to its present one.

The reconstruction of the recent history of the Lys Glacier had already been started in the early 1900's, with the important studies of Dainelli (1911) and particularly that of Monterin (1932). They supplied both detailed information and iconographic documents of the positions of the glacier during the last century. Annual surveying of the front was begun in 1914 by the staff of the Italian Glaciological Committee (Comitato Glaciologico Italiano). A study by Strada (1987) has compiled and re-processed information on the history of the glacier and proposes a reconstruction of Holocene variations of the Lys Glacier based not only on the historical documentation, but also on land surveys, lichenometric and dendrochronological investigations. According to Strada the outermost moraine is attributed to 1822, the middle moraine to 1860 and the innermost moraine to 1922.

In this century, following the advance that reached its peak in 1922, the Lys Glacier began a phase of retreat constant. Annual retreat values were relatively high, with values of more than 40 m in the years 1941, 1942 and 1950. This phase saw some interruptions only in 1953, 1960 and 1969. Very slight advances were recorded of 2 m in 1953 and 1.7 m in 1960, and equilibrium in 1969. This long retreat phase that resulted in the front retreating by more than 700 m came to a close in 1973. The subsequent and brief expansion phase, which was characteristic of numerous glaciers in Italy in the 1970's and 1980's, came to a close in 1986. Afterwards the Lys Glacier began a new phase of retreat.

DENDROGEOMORPHOLOGICAL SURVEY: STUDY METHODS

Following the completion of a morphological map of the moraines deposited, based on direct surveys of the glacial deposits and photointerpretation, a dendrogeomorphological survey was conducted.

The study of annual tree rings is a long estabilished dating and study method in geomorphology. The information that can be obtained is not only limited to counting the rings to determine the minimum age of the substratum on which the tree is growing. The analysis of the data series can also be used to obtain both climatic information and information pertaining to environmental changes that have characterized a certain area.

Plant growth is a function of numerous factors such as temperature, precipitation, moisture, soil conditions, sunlight and wind. Thus, besides factors such as the specific plant species and physiology, the width of annual rings also depends on the environmental and climatic factors. Particularly wide rings or particularly narrow rings are called «characteristic rings». They are useful and significant in that if they are detected in more than one sample, they permit the identification of the «pointer years». Pointer years are years in which an event has taken place that characterises an entire area (Schweingruber, 1988). Characteristic sequences of years, called pointer intervals, permit the synchronization of growth curves obtained from various trees and the compilation of reference curves (standard curves) for a certain species and for a given area. Such curves may then be used, for example, to date dead tree trunks. If the latter are found still in situ within a moraine, it is possible to accurately date a glacial advance.

The simplest method of tree rings analysis is to measure the width of the annual rings. For this study, this analysis was performed using the Aniol instrument, after having sanded the samples in order to render the rings more visible. For each sample, a dendrochronological curve was obtained, providing a record of pattern over time. The individual curves were then synchronized using «catras» software and then the means calculated in order to obtain a reference curve. The dendrochronological data were then subdivided into four groups, corresponding to four morphological units (see section 5). The four mean dendrochronological curves were then correlated with the frontal variations of the glacier in order to obtain the response times for such variations (section 7.1). The frontal variations data were then correlated with the temperature data series for Lake Gabiet in order to evaluate response times with respect to a single climatic parameter. Lastly, an attempt was made to correlate the best dendrochronological data series with the temperature data series to assess if the vegetation response is simultaneous.

The dendrogeomorphological study of the Lys Glacier area was carried out by collecting 216 larch-tree samples (*Larix decidua* Mill.), each with a diameter of 5 mm, using a Pressler borer at a height of 1 m from the ground. The holes made by the core barrel were closed with grafting wax.

Priority was given to sampling in the areas in the immediate vicinity of the moraines, selecting the oldest trees. The samples were then subdivided into four groups corresponding to four morphological units, using the moraines as a basis for definition. The morphological units definited were:

Unit A: The area within moraine M3 (fig. 3) which is at the highest altitude, 2160-2200 m. Only six trees were sampled as the specimens present were very young. Moreover, the forest is very sparse and the area is still undergoing recolonization by vegetation.

Unit B: The area between moraines M3 and M2 (fig. 3). This area represents the most extensive morphological unit and it extends from an altitude of 2000 m to as far as moraine M3. Within this unit, 111 samples were collected.

Unit C: The area between moraines M2 and M1 (fig. 3). This is a narrow strip, which is not always easy to distinguish because the older moraines are not visible in several very steep tracts. In this area, situated at an altitude of about 1950-2000 m, 29 larch trees were sampled.

Unit D: The area outside moraine M1. This is the morphological unit that extends down to the lower altitudes, outside of the oldest moraine. Although the area is very extensive, all of the 70 samples taken were collected from trees found in the area immediately adjacent to the position of the Lys Glacier in 1822 (Monterin, 1932), and which corresponds to the maximum Holocene advance. Special attention was given to the larch forest near the deep gorge of the Lys river, where the oldest specimens were found.

THE GROWTH PATTERN

Unit A: Only 4 of the samples could be synchronized, placing doubts in the validity of the mean curve that was obtained, shown in fig 4. The curve showed a minimum for 1975. It is interesting to note that the mean temperature curve for the July-August period showed a «drop» in 1974. The years that followed this low point show a gradual renewal of growth which was especially evident for the years 1976, 1979 and 1986. However, there were also years that interrupted the trend namely 1977, 1981 and 1985.

Unit B: One hundred and eleven samples were utilized to obtain the mean curve. After minimal growth in 1912 and 1913, there was a marked increase in the ring widths in the two-year period, 1914-1915. Slight reductions in growth were evident for the years 1926, 1932 and 1939. During the 1950's there was a general trend of growth reduction which ended in 1961. In the 1970's the growth pattern was similar to that of Unit A, with marked reductions in the annual ring widths in 1972, 1975 and 1977. The year 1975 also represented the lowest point for the entire curve. This negative period ended in 1979, although other narrow rings were also found in 1983 and 1985.

Unit C: The third curve was obtained by synchronizing 25 of the 29 samples. There is a decreasing trend until 1913, which corresponds to a very narrow ring. The renewal of growth reaching levels similar to those for the years preceding 1913, are found starting from 1915. A low point was registered for this unit as well, starting from the two-year period, 1953-1954. Growth started again in 1964-1965. In the more recent years a pattern very similar to the patterns of the curves already discussed occurred, with reductions in widths in the middle of the 1970s and in 1983, and increases in the years 1979, 1982 and 1986.

Unit D: This curve was obtained from 52 samples covering a period of almost 250 years. Numerous high frequency variations can be noted for the earliest years, due to the fact that the trees covering this time span were very few in number. During the last century, several major low points may be noted: 1801, 1819-1821 and around 1840. The year 1821 is the lowest point on the entire curve. The narrowness of the ring may be also due to physical damage caused by the glacier directly, considering the position of one of the trees sampled and the fact that the outermost moraine is attributed to 1822. During this century, the curve of Unit D showed the characteristic fluctuations observed in the other curves, that is, the low point for the1912 ring is almost identical to that found for the Unit C curve. (It must keep in mind that during 1912 there was the Katmai volcanic eruption). For the period 1953-1955, almost all the rings showed a sharp reduction in width and a renewal of growth in 1964. The worsening of climatic conditions of 1970s, is very evident on the dendrochronological curve, showing sharp reductions in ring widths in 1972, 1973 and in 1977. Renewal was evident for the same years previously observed, 1982 and 1986.

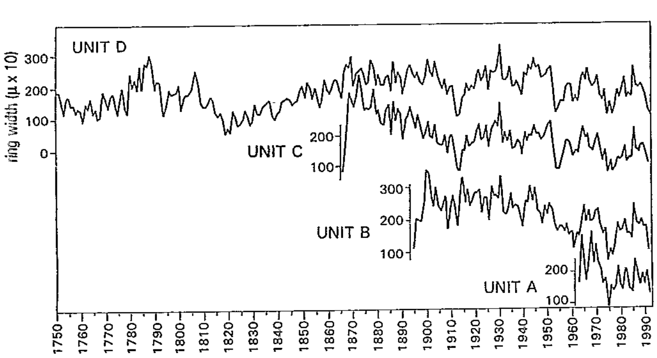

FIG. 4 - Mean dendrochronological curves for the 4 morphological units: Unit A-D. The similarity with the 19th-century tendency is evident. The 1912-1914 peak and the 1821 peak are given mention as being amongst the most evident. The 1821 peak corresponds to the maximum expansion during the Little Ice Age and is observable only in curve D.

COMPARISON OF THE DENDROCHRONOLOGICAL CURVES

Considering all the curves together, there is a striking similarity between them in the 20th century trend. Several identical low and high points were evident, albeit with differing intensity, in the trees record obtained from all the units, for example the pick occurring between 1912 and 1914, and the low point in 1953-54. The last significant variation recorded of the present century is the one between 1972 and 1978 with a clear characteristic sequence found in all of the samples. The climatic change of 1970s responsible for the moderate advance of the Alpine glaciers which led to the deposition of the small moraines bordering the glacier fronts, is reflected in the temperature recorded at Lake Gabiet meteorological station. This advance was also recorded by the Lys Glacier which advanced between 1973 and 1985. Afterwards the temperature increased again. Just in 1992 the mean temperature was lower. This change has also been observed both in the tree cores and in the mass balances of glaciers. For example, according to Barsanti & Smiraglia (1994), for the Sforzellina Glacier in the Ortles-Cevedale Group there was a less negative deficit mass balance of –119.950 m in 1993, compared to a mean of -331.329 m in the six preceding years.

THE FRONTAL VARIATIONS OF THE LYS GLACIER, TREE GROWTH AND TEMPERATURE

As already explained, the width of tree rings depends upon numerous climatic and environmental parameters, which are difficult to evaluate individually and are not commonly available as long-term data series. Trees already represent in themselves an overall response to those same climatic conditions which are recorded by glaciers and their response is immediate. By contrast glaciers, due to their size and dynamics, respond to the climatic input after a series of transitions which first involves the mass balance, thus their volume and only thereafter the movement of their fronts, the only parameter for which long-term data series exist.

Naturally, that part of the frontal movement that depends most directly upon the year's meteorological conditions also plays a part in these complex after-effects. For example, the impact of a few very hot summer months is directly reflected in a negative frontal variation measured that same year. (For more details see Haeberli, 1994; 95 and Johannesson & *alii*, 1989).

Correlation between the frontal variations of the Lys Glacier and the dendrochronological data series

A Cross-correlation was carried out between each growth curve of the four morphological units and the algebraic sums of the yearly frontal variations of the Lys Glacier (Time-Distance curve).

Cross correlation, as well known, is a misure of the correlation between two data series, carried out at a successive lags in time, in order to investigate time dependencies. The cross correlation was calculated for successive yearly lags of frontal variations to tree growth rates for up to 10 years. In other words, it was initially postulated that the impact of climate is immediately transmitted to the trees and then to the glacier; thus ring width, for example the 1914 ring, was correlated with glacier variations in the year 1914. Subsequently, the 1914 frontal variation was correlated with the 1913 ring, with the supposition that the effect of climate would be felt by the glacier the following year and that the glacier response would occur with a delay of one year. Therefore, the 1914 variation of the front was correlated with the 1912 ring, the 1911 ring, and so forth until a ten-year time interval was covered.

The trends revealed by the correlation, r, was then examined. Only negative correlation coefficients were considered because trees react to negative climatic phases with a drop in growth, whereas glaciers react with an expansion of their fronts (fig. 5 and tab. 1). The minimum in the curve represents the best correlation between the two data series and consequently it represents the «response time» of the Lys Glacier.

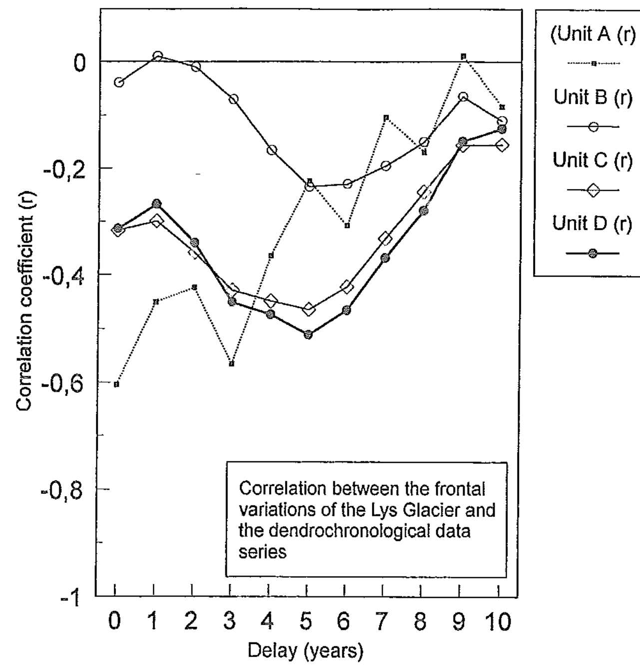

FIG. 5 - Coss-correlation between the mean dendrochronological data series for the 4 morphological units and the front variation curve for the Lys Glacier, for lag periods ranging from 0 to 10 years.

TABLE 1 - Correlation between the mean dendrochronological data series for the 4 morphological units and the front variation curve for the Lys Glacier: correlation coefficients, r, referring to the sample utilized, the coefficients ρ corresponding to the correlation coefficient referring to the infinite population. The bold figures indicate the accettable values. The numbers underlined correspond to minimum/us; when ρ = 0 the r values were rejected. The years of delay, 0-10, appear on the x-axis

	0	1	2	3	4	5	6	7	8	9	10
Unit A (r)	<u>-0,604</u>	-0,45	-0,423	-0,565	-0,364	-0,223	-0,308	-0,104	-0,169	0,011	-0,083
ρ	-0,426	-0,148	-0,286	-0,017	0,01	0,05	-	-	-	-	-
Unit B (r)	-0,039	0,01	-0,012	-0,077	-0,165	-0,234	-0,229	-0,195	-0,15	-0,065	-0,11
ρ	0,18	0,2	0,20	0,2	0,2	0,01	0,01	-	-	-	-
Unit C (r)	-0,317	-0,299	-0,358	-0,428	-0,448	<u>-0,464</u>	-0,422	-0,332	-0,244	-0,156	-0,155
ρ	-0,108	-0,075	-0,153	-0,756	-0,261	-0,273	-0,224	-0,108	-0,02	-	-
Unit D (r)	-0,314	-0,267	-0,34	-0,45	-0,473	<u>-0,511</u>	-0,465	-0,368	-0,279	-0,149	-0,125
ρ	-0,097	-0,01	-0,13	-0,261	-0,286	-0,339	-0,286	-0,164	-0,064	-	

Unit A: correlation coefficients were all negative, except the ninth. A minimum level was observed for the year 0 and another for a lag of 3 years. Another less pronounced minimum was found to correspond to a delay equal to 6 years.

Unit B: correlation coefficients were all lower than those for Unit A. The minimum levels were found for the year 0 and the fifth year but the r values are to low to be acceptable.

Unit C: correlation coefficients patterns are very similar to those for Unit B and here the r values are higher. In this case also, an initial minimum point was observed for the year 0, followed by another after 5 years of delay.

Unit D: very similar results were again obtained; after a minimum for the year 0, the correlation coefficient decreased only to increase up to a maximum corresponding to the 5th year.

Testing the level of significance of the correlation coefficients

As two variables are being considered the distribution is assumed to be binomial. The correlation coefficient of the sample is given by r, and that of the population by ρ. One may therefore postulate a theoretical correlation coefficient for the population, indicated by ρ, which is estimated by means of the r correlation coefficient for the population. The null hypothesis was tested that r was not a sample from a population with a mean ρ = 0. This was done using Fisher's z-transformation, with a two-tailed 95% confidence level.

After testing the null hypothesis, some values were rejected. The acceptable r values are the bold ones in tables 1-4. The sample correlation for a lag of 5 years were all significant. Refer to tables for the result values.

From the correlation coefficients for the samples and significance tests, it can be inferred that the glacier showed an initial response in the current year, which can be seen in curve A, and another after 5 years, shown by curves C and D.

There is also a gradually increasing level of significance as the distance from the glacier front increases. This is probably due to the fact that Unit D reflects the more generalized climate of the valley without undergoing the microclimatic fluctuations associated by proximity to the glacier, as is observable in Unit A. The latter, however, are also the youngest and most isolated trees and thus experience less uniform conditions than more distant trees.

The response for the year 0 is a result of movement dependent upon the conditions of that year, as mentioned previously. This could explain the presence of significant correlation coefficients at no lay.

The use of running means in the correlation between the dendrochronological data series and the front variation data series

An attempt was also made to filter the data series by means of 3, 5 and 11 year moving averages (Fritts, 1976). With the new time data series obtained, the cross correlation analyses were repeated, again using lag periods of up to 10 years to evaluate the delay in glacier response. The time series that supplied the best results was that constructed using the 5 year moving average, and the results are shown in fig. 6 and tab. 2.

Unit A presented an initial minimum of r = –0.757 with zero lag. The correlation coefficient increased until it became positive at a 10 year lag. For *Unit B,* the correlation coefficients confirmed a minimum at a lag of 6 years but the r values are too low to be acceptable. For *Unit C*, the correlation had minimus between 4 and 5 years of delay (r = –0.662 and r = –0.661 respectively). *Unit D* had a minimum at a lag of 5 year. (r = –0.693).

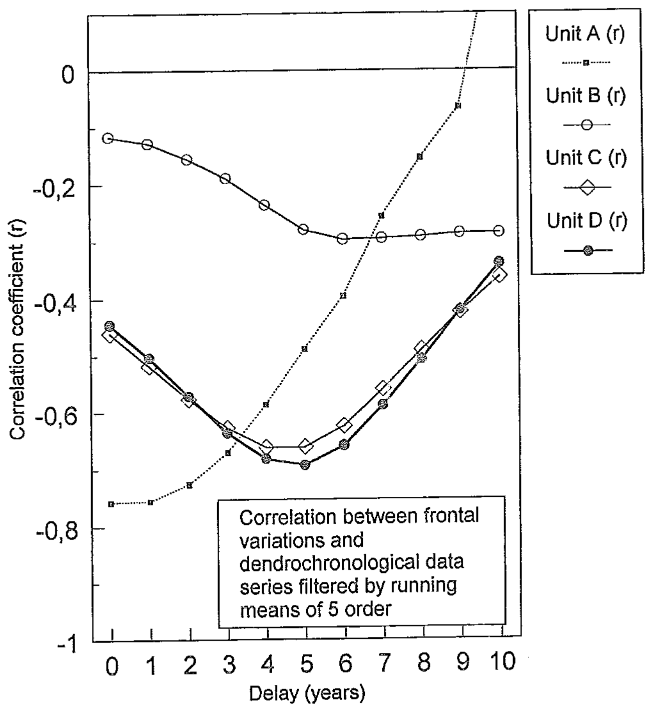

FIG. 6 - Cross-correlation obtained by correlating the series for the 4 morphological units with the front variation data series, filtered by means of a 5 year moving average.

TABLE 2 - Correlation between Lys frontal variations ang dendrochronological data, filtered through running means of 5th order. ρ corresponds to the test of the null hypothesis

	0	1	2	3	4	5	6	7	8	9	10
Unit A (r)	-0,757	-0,755	-0,726	-0,671	-0,587	-0,488	-0,396	-0,258	-0,155	-0,066	0,264
ρ	-0,666	-0,656	-0,561	-0,465	-0,326	-0,051	-0,041	-	-	-	-
Unit B (r)	-0,116	-0,128	-0,156	-0,190	-0,237	-0,280	-0,297	-0,295	-0,292	-0,287	-0,287
ρ	-	-	-	-	-	-0,020	-0,063	-0,085	-0,080	-0,063	-0,063
Unit C (r)	-0,460	-0,518	-0,577	-0,628	-0,662	-0,661	-0,625	-0,560	-0,490	-0,424	-0,363
ρ	-0,285	-0,351	-0,437	-0,516	-0,568	-0,568	-0,516	-0,408	-0,311	-0,223	-0,152
Unit D (r)	-0,445	-0,503	-0,572	-0,637	-0,682	-0,693	-0,659	-0,589	-0,507	-0,421	-0,340
ρ	-0,260	-0,324	-0,423	-0,533	-0,604	-0,623	-0,568	-0,453	-0,324	-0,223	-0,129

The Fisher's z-transformation showed again that the values obtained for units C and D are all acceptable and it showed also that the sample correlation for a lag of 5 years was the more significant.

As can be seen, the results were very similar to those obtained from the mean curves plotted from the raw data. Again the curve for Unit D yielded the most significant correlation between tree vegetation growth and front variations, with a delay period of 5 years.

CORRELATION BETWEEN THE FRONT VARIATIONS OF THE LYS GLACIER AND THE CLIMATIC DATA SERIES

With the aim of evaluating the reliability of the method, the «response time» of the Lys Glacier was also calculated based on temperature and precipitation fluctuations, using a method previously adopted by Belloni & *alii* (1991).

The annual frontal variations of the Lys glacier were thus correlated with the sums of summer monthly mean temperatures as recorded at the Lake Gabiet (2350 m) meteorological station. The correlations were made using the sums of the mean monthly temperatures for the months: May to June; May to July; May to August; May to September; June to September; July to September and August to September. For each period considered, the cross correlation was also determined using lags of up to 10 years as in

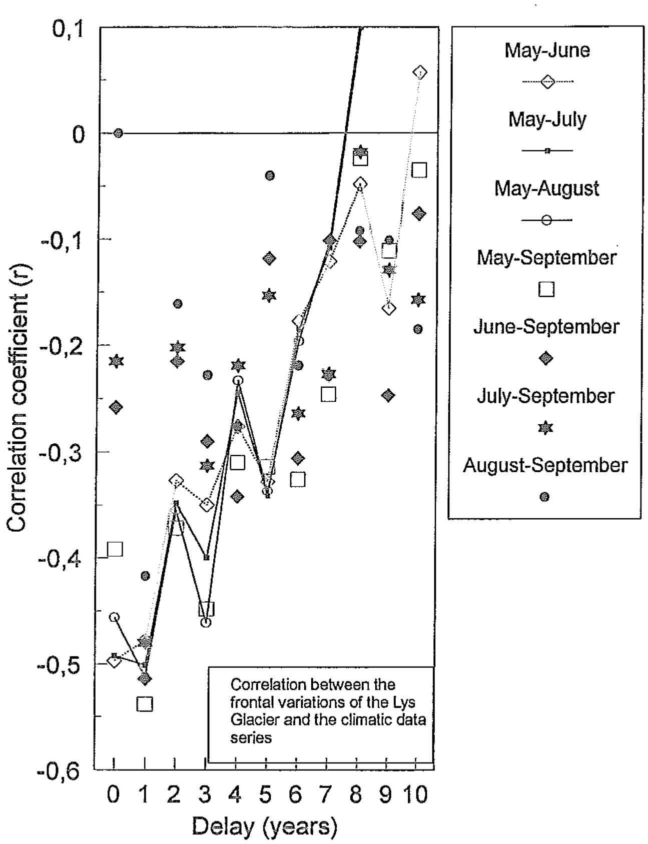

FIG. 7 - Cross-correlations obtained by correlating the temperature sum data series for the May-September period at Lake Gabiet with the front variation data series for the Lys Glacier (Time distance-curve).

TABLE 3 - Correlation between the temperature sum data series for the May to September period at Lake Gabiet and the front variation data series for the Lys Glacier: correlation coefficients, r, referring to the sample utilized. The bold figures indicate the accettable values. The numbers underlined correspond to minimum/us. The years of delay, 0-10, appear on the x-axis

	0	1	2	3	4	5	6	7	8	9	10
May-June (r)	-0,497	-0,478	-0,327	-0,350	-0,276	-0,328	-0,177	-0,121	-0,048	-0,165	0,057
May-July (r)	-0,492	-0,501	-0,348	-0,400	-0,244	-0,341	-0,185	-0,108	0,100	0,180	0,153
May-August (r)	0,164	-0,456	-0,512	-0,355	-0,461	-0,233	-0,337	-0,196	-0,101	0,114	0,215
May-September (r)	-0,392	-0,538	-0,372	-0,448	-0,310	-0,314	-0,326	-0,246	-0,024	-0,111	-0,035
June-September (r)	-0,258	-0,514	-0,215	-0,290	-0,342	-0,118	-0,306	-0,101	-0,102	-0,247	-0,076
July-September (r)	-0,215	-0,480	-0,202	-0,313	-0,219	-0,153	-0,264	-0,227	-0,018	-0,129	-0,157
August-September (r)	-0,000	-0,417	-0,161	-0,228	-0,276	-0,040	-0,219	-0,229	-0,092	-0,101	-0,185

the preceding section. As with tree growth rings, there is an inverse relationship between temperature and the glacier response. Thus only the negative correlation coefficients should be taken into consideration (fig. 7 and tab. 3). As is observable from table 3, the absolute minimum proved to emerge for the 1-year delay and for the May-September interval ($r = -0.538$). It is also interesting to note that the early summer months, the May-June and May-July intervals, presented a minimum for the lags of 0, 3 and 5 years, and that the minimum shifted to 1, 4 and 6 year lags as the summer progresses. The relation that linked the summer temperatures to the variations of the Lys Glacier front showed an additional 3 year time delay, which the dendrochronological records did not reveal. Also the late summer months are primarily recorded, by frontal variations in the following year. By contrast the influence of the late spring or early summer is greatest in frontal variations of the current year.

Cross correlation was also carried out between the frontal variation data and precipitation as recorded at the Lake Gabiet meteorological station from 1935 and 1986 (October to May). However, there were no significant results. Whilst it is true that area and front variations of a glacier depend on both temperature and precipitation, Alpine glaciers seem to be much more sensitive to temperature variations than to fluctuations in precipitation (Belloni & *alii*, 1985; Smiraglia 1986).

CORRELATIONS BETWEEN CLIMATIC PARAMETERS AND GROWTH RING WIDTH

Trees have an immediate response to climatic fluctuations (Schweingruber, 1988) and this response already in itself represents the synthesis of the climatic and environmental variations in the trees' surroundings. To verify a simultaneousness in the response of the vegetation, the dendrochronological curves were correlated with the same climatic parameters used for comparison with glacier frontal fluctuations; the sums of the temperatures from May to September. As with temperature increases, there is an increase in the tree growth rates, only the positive correlation coefficients were considered. In addition only the mean curve for Unit D was utilized because it showed highest correlation with the variations of the glacier front. The results are shown in fig. 8 and tab. 4.

For the intervals May-June, May-July, May-August, May-September and June-September, the highest correlation was always at the year 0, suggesting that there is no time delay between cause and effect. The highest correlation of r = 0.338 was for the May-August interval. For the July-September and the August-September intervals, the correlation maximum was at a lag of 1 year, the maximum being r = 0.495 for the August-September interval.

The results of the comparisons between the temperature data and ring width data were largely as to be expected. They show that there was no delay in the response of the vegetation to temperature changes. Furthermore the temperature correlations to the various monthly periods show that temperature during the late spring months and early summer have an influence on growth during that same year, whereas late summer temperatures, particularly August and September temperatures, influence growth in the following year.

TABLE 4 - Correlation between the dendrochronological data series obtained for Unit D and the temperature sums for the May-September period: correlation coefficients, r, referring to the sample utilized. The bold figures indicate the accettable values. The numbers underlined correspond to minimum/us. The years of delay, 0-10, appear on the x-axis

	0	1	2	3	4	5
May-June (r)	0,321	0,117	-0,197	-0,172	-0,111	-0,073
May-July (r)	0,375	0,146	-0,188	-0,094	-0,134	-0,143
May-August (r)	0,388	0,147	-0,232	-0,141	-0,221	-0,180
May-September (r)	0,324	0,260	-0,249	-0,075	-0,161	-0,180
June-September (r)	0,313	0,309	-0,250	-0,190	-0,136	-0,167
July-September	0,193	0,400	-0,126	-0,123	-0,095	-0,208
August-September (r)	0,085	0,495	-0,073	-0,074	-0,041	-0,132

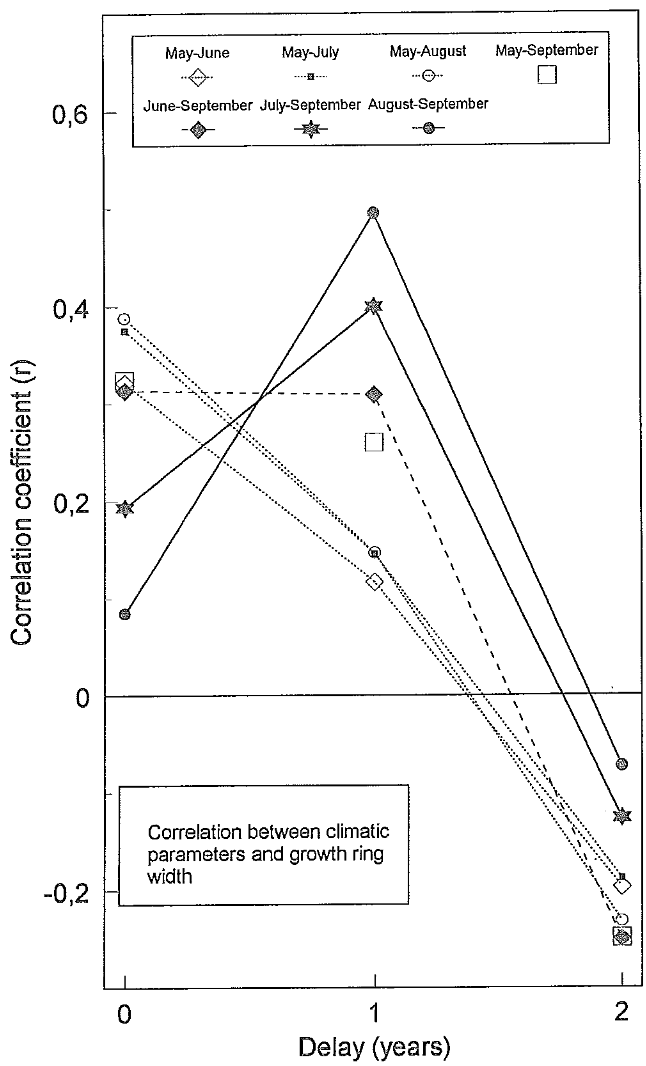

FIG. 8 - Cross-correlation obtained by correlating the dendrochronological data series for Unit D with the temperature sums for the May-September period.

DISCUSSION

The methods used in this study allows several interesting conclusions to be made. First of all, the method is applicable as the results obtained by correlating the mean dendrochronological curves to the frontal variations of the Lys Glacier, were similar to those obtained from correlations between temperature and the frontal variations. However, it must be kept in mind that the Lake Gabiet meteorological station is not situated in the vicinity of the Lys Glacier, but is separated from it by a mountain ridge. Consequently the microclimate could differ slightly. The use of moving averages as a filtering mechanism has proved to be useful as it highlights main low frequency variations whilst smoothing out the high-frequency noise variations. This is revealed by the definite decrease in the correlation coefficients for the year corresponding to the delay in the glacier response to the climatic variations recorded immediately by the vegetation.

The Fishers'z transformation allowed to reject the correlation with $\rho = 0$ and to confirm the «response time» corresponding to a lag of 5 years.

The r values tended to increase after the year 0, which corresponds to an initial immediate response of the glacier, only to then decrease until reaching the minimum, with an r value that is lower than for the year 0, corresponding to the delay in the glacier response to climatic variations. The r value then tended to increase again until becoming null or unacceptable.

The reliability of using the dendrochronology to evaluate the response times of Alpine glaciers was also confirmed by the fact that there was no delay (or a little delay) between climatic input and tree response.

CONCLUSIONS

This study showed that it is possible to estimate the response time of the Lys Glacier using dendrochronology. The trees that were most suited to this type of investigation were those situated outside the maximum Holocene advance of the glacier. These trees probably react to the climate in the valley head, without being disturbed by the influence of the glacier on microclimate.

The response time of the Lys Glacier to climatic variations as a whole, proved to be a delay of about 5 years. This response time obtained refers only to the 20^{th} century and therefore can only be considered representative for the time period considered. The 5 year delay is considered to be reliable as the response of trees to temperature fluctuations was immediate and the response of the glacier to temperature alone occurred after 5-6 years of delay.

It should be kept in mind that glaciers respond to a number of climatic parameters, even though for Alpine glaciers temperature is the most decisive parameter. Therefore, the use of a dendrochronological data series as the reference series represents a starting point that is quite reliable because the delay is calculated on the basis of a synthesis of the climatic variables, as implemented by the tree itself. Moreover, this method has the potential for a wide range of applications. In fact, numerous valley glaciers reached wooded areas during advance phases starting the Little Ice Age on. Tree records of the events are therefore available everywhere. So this method can be used when adequate series of meteorologial data are not available, as is commonly the case. Even in areas where glaciers did not reach wooded areas during the Little Ice Age and thereby directly influencing tree vegetation growth, as in the cases of smaller glaciers, the trees still recorded the same climatic fluctuations that were responsible for the glacier advances. Therefore, the use of dendrogeomorphological studies could become a useful instrument for investigations in many situations.

It should be kept also in mind, however, that this type of investigation did not take into account topographical factors, exposition, volume, etc., factors which, at any rate, play important roles in the dynamics of a glacier, especially for one as complex as the Lys Glacier.

Lastly, the possible application of this method to forecasting should also be kept in mind. In this case, the investigation was performed only on one glacier and the results are thus of localized significance. Should further investigations supply results of a larger scope, this method could be used to predict the loss in glacier mass with vast impact of environmental significance. For example, the impact of a particularly hot summer on the Lys Glacier, would yield not only a negative mass balance for the year in progress, but also a stronger response after 5 years. Therefore, dendrochronological data series can indeed represent a valid tool for the estimating the response times of Alpine glaciers.

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